A participatory modelling approach to developing a numerical sediment dynamics model

Nicholas David Jones

A thesis submitted in partial fulfilment of the requirements of the University of the West of England, Bristol, for the degree of Doctor of Philosophy. Faculty of Environment & Technology, University of the West of England, Bristol, UK

September 2016

Abstract

Despite the recognition of fluvial geomorphology as an important scientific input to the management of river catchments, limited knowledge exchange has occurred between scientific researchers and river management stakeholders. An example of this issue can be found within the limited uptake of numerical models of sediment dynamics by river management stakeholders. The uptake of these models is important as they have the potential to demonstrate how, at the catchment-scale, the impacts of land management strategies affect sediment dynamics and resulting channel quality.

In this thesis, a new transdisciplinary approach which involves river management stakeholders in an iterative and reflexive participatory modelling process is described and evaluated. This approach aimed to create an environment for knowledge exchange and social learning between the stakeholders and the researcher in the process of co-constructing a catchment-scale sediment dynamics model. This process involved four groups of UK river catchment stakeholders, who were involved in several stages of the participatory modelling process including: requirements analysis, model design, model development, model assessment, and an evaluation of the process. Stakeholders input into a number of aspects of the modelling process, such as: data requirements, user interface, modelled processes, model assumptions, model applications, and model outputs.

The findings from the participatory modelling process provided valuable insights into the requirements of river management practitioners, and identified a number of gaps in knowledge for future research. The results from the process evaluation demonstrated that a multiple case-study approach using pre-existing management groups overcame issues surrounding uniqueness and active participation. The interactive activities were identified to be the most important aspect of the process for promoting knowledge exchange and social learning. The model assessment found that the stakeholders considered the developed model to be a more useful model than an existing sediment dynamics model. In conclusion, the findings from the research support the call to develop more intermediate-temporal and spatial-scale models relevant to river management practitioners. Importantly, this research emphasises the requirement for these models to also include the abilities needed by river management practitioners, such as manipulating land cover condition.

Acknowledgements

As I reach the end of this journey of my PhD research, I would like to extend my thanks to all those people and organisations that have helped me throughout the research process.

Firstly, I am grateful for the financial support from the University of the West of England, which has allowed me to complete my doctoral research. I would also like to extend my thanks to the large number of stakeholders and organisations that have been involved in this research and the valuable time and effort that they have contributed to this project. In particular, I would like to thank Jeremy Taylor, Brett Grosvenor and Tom Fletcher from the Environment Agency, Alasdair Matheson from the Scottish Environment Protection Agency, Liz Henderson from the Spey Catchment Initiative, Hazel Kendal from West Country Rivers Trust, and Kate Allingham and Claire Fitzgibbon from Natural England.

I would also like to extend my greatest thanks to my supervisory team who have provided considerable assistance throughout my studies, and to whom I am indebted for training me as a researcher and enabling me to achieve my goals. To Professor Lindsey McEwen, Dr Chris Parker and Professor Chad Staddon, thank you for all of your advice, support and feedback on my thesis throughout my journey to producing this final document.

I would like to extend these acknowledgements to my PhD colleagues in 4Q57 who supported me during my time in this amazing office and who have continued to support and include me after I changed to part-time. In particular, I would like to thank Edward, Hannah, Owen, Jenna, Anna, Shadan, and Michael; you have been a pleasure to share an office with and for that I will always be grateful.

Last but not least I would like to thank my friends and family, the support you have given me throughout this process has enabled me to reach this point. You enabled me to escape from the loneliness that can be PhD research and reduce the stress of the last three and a half years. For my friends who have helped with the proof reading, Jon, James and Andy your time and input proof reading chapters has been a significant help for which I am sincerely grateful. To Kate, my Mum and Dad; I could not have done this without your encouragement and patience.

'On the way to the impossible, we might find something imminently doable.' (Brian Cox, describing the scientific endeavour)

Contents

Chapter One: Introduction ... 1
1.1. Context setting ... 1
1.2. Aims and objectives ... 2
1.3. Research process and structure ... 3
Chapter Two: Literature review ... 7
2.1. The importance of fluvial geomorphology to river catchment management ... 7
2.1.1. Introduction to fluvial geomorphology ... 7
2.1.2. Fluvial geomorphology and management of the ecological status of river channels ... 11
2.1.3. Fluvial geomorphology and the management of flood risk ... 15
2.1.4. The role of interdisciplinarity in fluvial geomorphology's contribution to river management ... 18
2.1.5. The importance of knowledge exchange in promoting fluvial geomorphology's contribution to river management ... 22
2.2. Modelling of river catchment sediment dynamics ... 28
2.2.1. History of approaches to modelling river catchment sediment dynamics ... 29
2.2.2. Reduced-complexity cellular modelling of river catchment sediment dynamics ... 35
2.3. Participation and environmental management ... 39
2.3.1. Introduction to participation ... 40
2.3.2. Typologies of participation ... 45
2.3.3. The adoption and application of participation theory in environmental management and research ... 47
2.3.4. Social learning and participation ... 50
2.3.5. Participation in legislation and policy ... 52
2.4. Participatory modelling (PM) ... 55
2.5. Synthesis ... 64
Chapter Three: Methodology ... 65
3.1. Research strategy ... 65
3.1.1. Theoretical and methodological rationale ... 65
3.1.2. Fundamental model structure ... 75
3.2. Participatory modelling process ... 76
3.2.1. Stakeholder and case study catchment selection ... 76
3.2.2. Requirements analysis ... 81
3.2.3. Co-designing ... 86
3.2.4. Ongoing engagement ... 88
3.2.5. Model demonstration ... 91
3.3. Participatory modelling process evaluation ... 93
3.4. Model assessment of usefulness and usability ... 95
3.4.1. Model comparison ... 96
3.4.2. Model use ... 97
3.5. Research ethics ... 98
3.6. Synthesis ... 99
Chapter Four: Integrated results from the participatory modelling process ... 101
4.1. Requirements analysis ... 103
4.1.1. Sediment impacts and influences ... 103
4.1.2. Model applications ... 109
4.1.3. Model characteristics ... 113
4.1.4. Questionnaire ... 117
4.2. Conceptual model ... 129
4.3. Co-designing ... 133
4.4. Draft model ... 138
4.5. Model demonstration ... 142

4.6. Revised model 150
Chapter Five: The ENGAGE model 154
5.1. Model description 154
5.1.1. Input data 154
5.1.2. Data preparation 157
5.1.3. Hydrology 164
5.1.4. Flow accumulation 175
5.1.5. Erosion and deposition 176
5.1.6. Output data 184
5.2. Model assessment 190
5.2.1. Model use (hypothetical decision-making scenario) 190
5.2.2. Model comparison 198
5.3. Implications from the model assessment 211
Chapter Six: Evaluation of the participatory modelling process 215
6.1. The participatory modelling process and development of the model 215
6.1.1. The requirements analysis and the conceptual model 216
6.1.2. Co-designing and the draft model 222
6.1.3. Model demonstration and the revised model 225
6.2. Participatory modelling process evaluation 228
6.2.1. Online questionnaire 229
6.2.2. Follow-up interviews 240
6.2.3. Researcher's reflections on the process 252
6.3. Implications from the participatory modelling process evaluation 258
6.4. A revised participatory modelling approach 266
Chapter Seven: Conclusions, implications, and future research 270
7.1. Contributions to knowledge and key findings 270
7.2. Implications for transdisciplinary fluvial geomorphological research and river management practitioners 276
7.3. Future research 278
Appendices 312
Appendix A – Requirements analysis post-session questionnaire 312
Appendix B - Participatory modelling process evaluation online questionnaire 313
Appendix C - Participatory modelling process evaluation interview topic guide 319
Appendix D – Model assessment of usability and usefulness. Activity 1: Questionnaire 321
Appendix E - Model assessment of usability and usefulness. Activity 2: Model A or Model B 323
Appendix F - Using ENGAGE to assist in a hypothetical decision-making process 325
Appendix G – Land cover types and conditions that users can input into the model 334

Table of figures

Figure 1-1: The research process (left) in relation to the thesis structure (right). 6
Figure 2-1: Breaking the paradigm lock between fluvial geomorphology and river management. Blue skies fluvial geomorphological research is shown on the left and river managers and stakeholders are shown on the right. Adapted from: Gregory (2004, p. 6). 24
Figure 2-2: Schematic view of different model types for simulating river systems. (a) landscape evolution; (b) reach-scale cellular automaton; (c) reach-scale CFD; (d) alluvial stratigraphy; (e) meandering. Source: Coulthard and Van De Wiel (2012, p. 2125). 31
Figure 2-3: Schematic of key components and processes operating within a cellular model of sediment dynamics. 36
Figure 2-4: The eight rungs of a ladder of citizen participation. Adapted from: Arnstein (1969, p. 217). 46
Figure 2-5: Davidson's wheel of participation. Source: Heritage and Dooris (2009, p. 48)........ 47
Figure 2-6: Catchment Based Approach linkages to other groups and initiatives. Adapted from: DEFRA (2013, p. 9). 55
Figure 2-7: Schematic representation of the traditional 'decide announce defend' (DAD) approach (A) and a participatory modelling approach to model development (B). 57
Figure 3-1: Conceptual diagram of the participatory modelling methodology for developing a cellular model of sediment dynamics. The numbers refer to the location within this chapter that each aspect is covered. 71
Figure 3-2: Conceptual diagram of the flows of knowledge in the participatory modelling process. This includes the methods used and outputs generated from each of the sessions. .. 74
Figure 3-3: Case-study river catchments. 79
Figure 3-4: Example of stakeholders' notes on one of the topics for debate. 83
Figure 3-5: Bulls-eye diagram used by stakeholders to sort the intrinsic elements (e.g. land-use), extrinsic elements (e.g. government subsidies) and excluded factors (e.g. elements beyond the scope of this modelling). Note: The basic model elements of land cover, soil and rainfall were automatically added to the bulls-eye as without them the model would not function. 87
Figure 3-6: The Model website (www.engage-rivers.org.uk) which was established as a portal for stakeholders to visit to get up-to-date information on the model's development. 89
Figure 3-7: Git-hub Engage model development blog located on the engage website. 90
Figure 3-8: The Engage model tutorials provide stakeholders with brief demonstration videos of aspects of the models operation (on ENGAGE site). 90
Figure 3-9: Example of the stakeholder feedback on post-it notes placed into the corresponding theme. 92
Figure 3-10: Screenshots and descriptions from the participatory model demonstrations. 92
Figure 4-1: Overview of the methodology used in this thesis. The numbers highlighted relate to the sections in which the results are presented in this chapter. 102
Figure 4-2: Thematic map of sediment impacts and influences identified through the coding of the requirements analysis transcripts. The colours and thickness of the lines relate to the catchment and the number of catchments each code appears in. 104
Figure 4-3: Treemap of sediment impacts and influences identified through the coding of the requirements analysis transcripts. 'Refs' refers to the total number of times a theme was coded. 105
Figure 4-4: Thematic map of model applications identified through the coding of the requirements analysis transcripts. The colours and thickness of the lines relate to the catchment and the number of catchments each code appears in. 110
Figure 4-5: Treemap of model applications identified through the coding of the requirements analysis transcripts. 'Refs' refers to the total number of times a theme was coded. 110

Figure 4-6: Thematic map of model characteristics identified through the coding of the requirements analysis transcripts. The colours and thickness of the lines relate to the catchment and the number of catchments each code appears in. 113
Figure 4-7: Treemap of the model characteristics identified through the coding of the requirements analysis transcripts. Refs refers to the total number of times a theme was coded. 114
Figure 4-8: Results by catchment and combined to the question 'How many times have you used a model in your current role in the past year?' 118
Figure 4-9: Results by catchment and combined to the question 'In your current role how important is it for you to understand how a model works and generates outputs?'. Note one stakeholder on the Taw did not complete this question. 119
Figure 4-10: Ranking of factors in order of their importance when using a model (scale of 1 (most important) to 6 (least important)). Note one stakeholder on the taw did not complete this question. 121
Figure 4-11: Results by catchment and combined to the question: 'Who do you think should be responsible for running the model?'. Note that stakeholders were able to select more than one option. 123
Figure 4-12: Results by catchment and combined to the question: 'Who would you consider to be the target audience for the model outputs?'. Note that stakeholders were able to select more than one option. 125
Figure 4-13: Results by catchment and combined to the question: 'Which of these outputs would you consider to be useful in aiding sediment management in river catchments?'. Note stakeholders were able to select more than one option. 126
Figure 4-14: Conceptual model created after the requirements analysis session. 130
Figure 4-15: Thematic map of conceptual model feedback identified through the coding of the co-designing transcripts. 136
Figure 4-16: Revised Conceptual model created after the co-designing session. 139
Figure 4-17: Thematic map of model characteristics identified through the coding of the participatory demonstration transcripts. The colours and thickness of the lines relate to the catchment and the number of catchments each code appears in. 143
Figure 4-18: Treemap of model characteristics identified through the coding of the model demonstration transcripts. 'Refs' refers to the total number of times a theme was coded.... 144
Figure 4-19: Revised conceptual model created after the model demonstration session....... 150
Figure 5-1: Overall model structure and the sections in which they are covered in this chapter for the six stages of the models operation. 154
Figure 5-2: Input data for the ENGAGE model. 155
Figure 5-3: Data preparation tools for the ENGAGE model and the order in which they are run. *Note only stage 2 and 3 are required to run the model. the others are optional processes. 157
Figure 5-4: Example of the ENGAGE interface within ArcGIS 10.2.2. On the left is the ENGAGE folder structure viewed from ArcCatalog. On the right is the raw data processing script interface. 158
Figure 5-5: Schematic representation of the merge raster tiles aspect of the data preparation stage. 159
Figure 5-6: Schematic representation of the burn in river channel aspect of the data preparation stage. 159
Figure 5-7: Schematic representation of the pour point to river catchment aspect of the data preparation stage. 160
Figure 5-8: Schematic representation of the raw data processing aspect of the data preparation stage. 161

Figure 5-9: Schematic representation of the add in-channel barrier aspect of the data preparation stage. 162
Figure 5-10: Schematic representation of the alter precipitation aspect of the data preparation stage. 162
Figure 5-11: Schematic representation of the alter land cover aspect of the data preparation stage. 163
Figure 5-12: Schematic representation of the baseflow calculation aspect of the data preparation stage. 164
Figure 5-13: Hydrology processes in ENGAGE model and the order in which they are run. *Note that stage 4 is an optional requirement. 165
Figure 5-14: Schematic representation of the process for calculating precipitation in the hydrology stage. 167
Figure 5-15: Schematic representation of the process for calculating evapotranspiration in the hydrology stage. 168
Figure 5-16: Schematic representation of the process for calculating surface runoff in the hydrology stage. 170
Figure 5-17: Schematic representation of the process for calculating baseflow in the hydrology stage. 175
Figure 5-18: Flow accumulation processes in the ENGAGE model. 175
Figure 5-19: Schematic representation of the process for calculating discharge in the flow accumulation stage. 176
Figure 5-20: Erosion and deposition processes in ENGAGE model and the order in which they are run. 177
Figure 5-21: Schematic representation of the process for calculating hillslope sediment using the MULSE. 179
Figure 5-22: Schematic representation of the process for calculating the sediment timestep in the erosion and deposition stage. 180
Figure 5-23: Schematic representation of the process for calculating the Active and inactive layer depth in the erosion and deposition stage. 181
Figure 5-24: Schematic representation of the process for calculating net sediment transport in the erosion and deposition stage. 182
Figure 5-25: Schematic representation of the process for calculating elevation adjustment in the erosion and deposition stage. 183
Figure 5-26: Schematic representation of the process for calculating mass wasting. 184
Figure 5-27: Output data from the ENGAGE model. 185
Figure 5-28: Example input data for the hypothetical decision-making scenario 186
Figure 5-29: Example hydrology monthly total outputs from the hypothetical decision-making scenario prior to land cover changes being made 187
Figure 5-30: Example in-channel net sediment transport monthly total from the hypothetical decision-making scenario prior to land cover changes being made 188
Figure 5-31: Parcel of land cover changed from pasture to broadleaf woodland during the hypothetical decision-making scenario 189
Figure 5-32: Change in surface runoff and net sediment transport following the change of land cover type in the hypothetical decision-making scenario. 189
Figure 5-33: Thematic map of themes and sub-themes identified through the coding of the hypothetical decision making scenario transcripts. The colours and thickness of the lines relate to the catchment and the number of catchments each code appears in. 191
Figure 5-34: Treemap of themes and sub-themes identified through the coding of the model use (hypothetical decision making scenario) transcripts. 'Refs' refers to the total number of times a theme was coded. 192

Figure 5-35: Ranking of factors in order of their importance when using a model (scale of 1 (most important) to 10 (least important)). 200
Figure 6-1: Combined and individual catchment results to the question: 'Which activities in the participatory modelling process did you enjoy?'. Note: stakeholders were able to select more than one option. 233
Figure 6-2: Combined and individual catchment results to the question: 'How do you think the participatory modelling process could be improved?'. Note that stakeholders were allowed to make more than one selection. 237
Figure 6-3: Combined and individual catchment results to the question: 'Who else do you think should have been involved in the participatory modelling process?'. Note that stakeholders were allowed to make more than one selection. 239
Figure 6-4: Thematic map of the process evaluation identified through the coding of the interview transcripts. 241
Figure 6-5: Treemap of the process evaluation theme and sub-themes from the thematic analysis of the process evaluation interviews. 'Refs' refers to the total number of coding references under each of the themes. 242
Figure 6-6: A revised participatory modelling process based on the findings from the process evaluation and model assessment. 267

Table of tables

Table 2-1: Attributes of fluvial geomorphological systems important for generating or contributing to ecosystem services. Source: (Everard and Quinn, 2015, p. 492). 12
Table 2-2: Quality elements for the classification of ecological status in rivers under the Water Framework Directive (WFD). Source: Newson and Large (2006, p.1609). 14
Table 2-3: Some examples of methods of communication between geomorphologists and river management practitioners identified in Gregory *et al.* (2008, p.161-162). 25
Table 2-4: Sample of catchment-scale landscape evolution models developed from the 1980's onwards. 33
Table 2-5: Summary of the main benefits of using participatory approaches split into normative and pragmatic claims. 43
Table 2-6: Typologies of participation. Source: Reed (2008, p. 2419) 45
Table 2-7: Summary of main participatory modelling approaches. 58
Table 2-8: Participatory modelling challenges identified through the review of the literature. 61
Table 2-9: Comparison of frameworks for categorising participatory modelling processes. Source: Hare (2011, p.388) 62
Table 2-10: Summary of Hare's (2011) Participatory modelling framework 63
Table 3-1: The participatory methodology adopted in this research situated within Hare's (2011) participatory modelling framework. 72
Table 3-2: Breakdown of the roles and organisations of each stakeholder who were present in each participatory modelling session. 80
Table 3-3: Participatory modelling challenges identified through the review of the literature and the solutions implemented in this methodology. 99
Table 4-1: Results from a Kruskal-Wallis H test to the questions 'How many times have you used a model in your current role in the past year?' and 'In your current role how important is it for you to understand how a model works and generates outputs?'. 120
Table 4-2: Themes, sub-themes and elements emerging from the analysis of the requirements analysis data. 128
Table 4-3: Summary of the stakeholder requirements, whether they were incorporated into the conceptual model, the justification behind this decision, and the method of inclusion or consideration. The shaded areas are those prioritised in the co-designing session. 131
Table 4-4: Results from each catchment using the bulls-eye diagram to rank model elements. This is ranked based on the position of each element in the bulls-eye activity for each group. Where: A – Intrinsic, B – Extrinsic and C – Excluded. Note that the top four shaded rows were identified to stakeholders as intrinsic to developing the model and therefore stakeholders were not required to prioritise these model elements. 134
Table 4-5: Results of the ranking exercise of the potential model applications. 135
Table 4-6: Summary of the stakeholder requirements, whether they were incorporated into the draft model, the justification behind this decision, and the method of inclusion or consideration. The shaded areas are unchanged from the conceptual model. 140
Table 4-7: Summary of the stakeholder requirements, whether they were incorporated into the revised model, the justification behind this decision, and the method of inclusion or consideration. The shaded areas are unchanged from the draft model. 150
Table 5-1: Data requirements for the ENGAGE model 156
Table 5-2: Assignment of SCS runoff curve numbers for the United Kingdom based on LCM2000 and LCM2007 code. Adapted from: (SEPA, 2011) 172
Table 5-3: Summary of conversion of HOST soil classes to SCS soil classes. Source: (SEPA, 2011) 172

Table 5-4: Descriptive and statistical (Kruskal-Wallis H test) analysis of the data collected in the model comparison exercise where stakeholders were asked to: ‘Please rank the following model characteristic from the most important (1) to the least important (10)’. 201
Table 5-5: Results for the incorrectly completed forms in the model comparison exercise where stakeholders were asked to ‘Please rank the following model characteristic from the most important (1) to the least important (10)’. 205
Table 5-6: Results from the model comparison exercise where stakeholders were asked to provide “a rating out of 10 (High) below for each model in relation to the likelihood that you would use in your day job if you had a need to conduct an investigation that required the use of a sediment dynamics model or as part of a decision making process”. 208
Table 6-1: Summary of the relationship between the literature, reduced-complexity cellular models, and the human and natural influences described by the stakeholders in the requirements analysis sessions. 217
Table 6-2: Results from the: ‘To what extent do you agree with the following statements’ questions. These questions used a scale of 1 (Strongly Disagree) to 5 (Strongly Agree). SE is the standard error of the mean. 230
Table 6-3: Results from the: ‘To what extent do you agree with the following statements’ questions. These used a scale of 1 (Strongly Disagree) to 5 (Strongly Agree). SE is the standard error of the mean. 234
Table 6-4: Combined and individual catchment results to the question: ’How useful to your work has your participation in the participatory modelling process been?’. This used a scale of 1 (Not at all useful) to 10 (Very useful). SE is the standard error of the mean. 236

Chapter One: Introduction

1.1. Context setting

> *'As population increases and the pressure on Earth resources grows, the competition for water, timber, open space, fuels, and environmental desires will bring a need for more knowledge and more data on the processes and the factors in geomorphology. Its importance to both science and to daily life can only increase.'*
>
> (Leopold, 2004, p.10)

Humans are altering the Earth surface at scales greater than ever before through urbanisation, intensification of agriculture and technological innovations. As a result the scientific community is proposing that we entered a new geological epoch in 1950 (although the exact date is contested (Smith and Zeder, 2013; Lewis and Maslin, 2015)), referred to as the Anthropocene, whereby humans have become the dominant process shaping and changing the Earth (Crutzen and Stoermer, 2000; Haff, 2010; Steffen *et al.*, 2007). Therefore, in order to sustainably manage the impacts of humans on the Earth, an increase in the communication of geomorphological processes to policy makers and stakeholders is required (Gregory *et al.*, 2014). Barnosky *et al.* (2014) and Mychajliw *et al.* (2015) argue that the recognition of the Anthropocene provides a unique opportunity to open a dialogue of science communication and knowledge exchange to help solve societal problems. The research presented in this thesis focuses on the practical applications of fluvial geomorphology and how communication and knowledge exchange can be increased between academic and practitioner communities. As Gregory *et al.* (2014) acknowledge, communicating geomorphology 'beyond the academy' is one of the ultimate challenges facing the discipline in the 21st century.

This debate is developed by reflecting upon the current and future importance of fluvial geomorphology and sediment dynamics modelling, to river catchment management in the United Kingdom. This research explores the recognition of fluvial geomorphology (under 'hydromorphology') in the European Unions' (EU) Water Framework Directive (WFD) (2000/60/EC), and the benefits this can bring to ensuring the sustainable management of river catchments. In particular, the research identifies the potential uses of sediment dynamics models to improve river management, and discusses their limited uptake to date. Following this, the research critically reviews the social science of participation and identifies a participatory approach to developing models referred to as participatory modelling (PM). PM is suggested to increase the uptake of research developed models by practitioners as the process can increase model quality, acceptance, and integration into existing stakeholder systems and processes (Borowski and Hare, 2007; Barreteau *et al.*, 2010).

In its analysis of existing literature and new empirical data, this research describes and evaluates a new transdisciplinary approach to developing a cellular model of sediment dynamics through the involvement of stakeholders in a PM process, which to date has not been applied in the discipline. This process was delivered through co-working with four river catchment stakeholder groups across the United Kingdom.

1.2. Aims and objectives

The aim of this thesis is to establish, implement and critically analyse a participatory modelling approach for developing and evaluating a catchment-scale cellular model of sediment dynamics. This model should be usable by management stakeholders engaging in decision-making for sustainable river catchment management. From this aim, the following objectives are derived:

1. Identify and situate the importance of sediment dynamics to sustainable river catchment management, and evaluate existing approaches to modelling of catchment-scale sediment dynamics, including the cellular modelling approach;

2. Investigate existing approaches to stakeholder engagement and participation in modelling, with a particular focus on those used within environmental management;
3. Assemble and describe a new participatory modelling approach to developing a catchment-scale cellular model of sediment dynamics;
    A. Use the new participatory modelling approach to identify, refine and prioritise the requirements of management stakeholders when creating and using a catchment-scale sediment dynamics model in river catchment management;
    B. Use the new participatory modelling approach to assemble and describe a new model of river catchment sediment dynamics;
4. Critically evaluate the developed participatory modelling approach as a methodology for:
    A. Engaging with stakeholders in model development to reduce the number of unused research models, improve model quality, acceptance of the model, and integration of the model with stakeholder management processes;
    B. Promoting knowledge exchange and social learning between fluvial geomorphologists and river management practitioners;
5. Critically assess the new cellular model as a tool for use within river management.
6. Propose a refined participatory modelling approach based on the results from the process evaluation and model assessment.

1.3. Research process and structure

The overall research process and structure of the thesis is shown in Figure 1-1.

Chapter One provides a brief background to the research project, the research process, thesis structure, and presents the aim and objectives that need to be answered in order to successfully complete this research.

Chapter Two contextualises the research by exploring the academic and professional literature. In particular, the importance of fluvial geomorphology to river management in terms of ecological status and flood risk, as well as its representation in legislation and policy. Once this has been established, this chapter moves on to describe how fluvial geomorphology needs to become part of an integrated interdisciplinary river science, creating the knowledge and tools that river managers and practitioners require. Following this, a recognised challenge facing the discipline of limited knowledge exchange between fluvial geomorphologists and river management practitioners is described. An example is highlighted in the development and practical application of reduced complexity cellular sediment dynamic models. Finally, Chapter Two reviews and analyses the potential role of participation as a solution to the challenges described in the previous sections. In doing so, this chapter examines a participatory approach to developing models, termed participatory modelling.

Chapter Three describes the development of a new participatory modelling approach to developing a cellular model of sediment dynamics. This begins with a discussion of the over-arching research strategy and theoretical rationale. Next, the justification behind the use of a fundamental modelling structure within this approach is presented. Following this, the developed participatory modelling process is described in detail. This comprises of an explanation of the criteria used to select the stakeholder groups and case study catchments, as well as description of each of the participatory sessions. Next, the chapter presents the methodology used for evaluating the participatory modelling process with the stakeholders. The final section presents the methods for assessing the developed model in relation to its usability and usefulness as a tool for use within river management.

Chapter Four presents the results and analysis from each of the sessions with the stakeholders in the participatory modelling process and how these were used in the development of the model. More specifically, this comprises of the outputs from the analysis of the data captured throughout the participatory process. These results are then related to the resulting model at each of the stages in the process, from the conceptual to the draft and then the final model. Following on from this, *Chapter Five* presents a detailed description of the final model, called 'ENGAGE'. The chapter moves on to outline and discuss the results from the assessment of the developed model as a tool for use by river managers.

Chapter Six develops a discussion by critically reflecting on how the results relate to the aim and objectives, as well as how the knowledge generated is situated within the literature. This is achieved by discussing the findings at each stage of the participatory modelling process, and the development of the model. Following this, the chapter presents and then discusses the results from the evaluation of the process with the stakeholders. This includes the researchers' reflections on the methodology which identify a number of methodological considerations and recommendations for future research. Finally, the last section proposes and discusses a revised participatory modelling approach.

Chapter Seven summarises the key contributions to knowledge, collates the findings, considers the implications of these findings for future participatory modelling research, and identifies areas for future research.

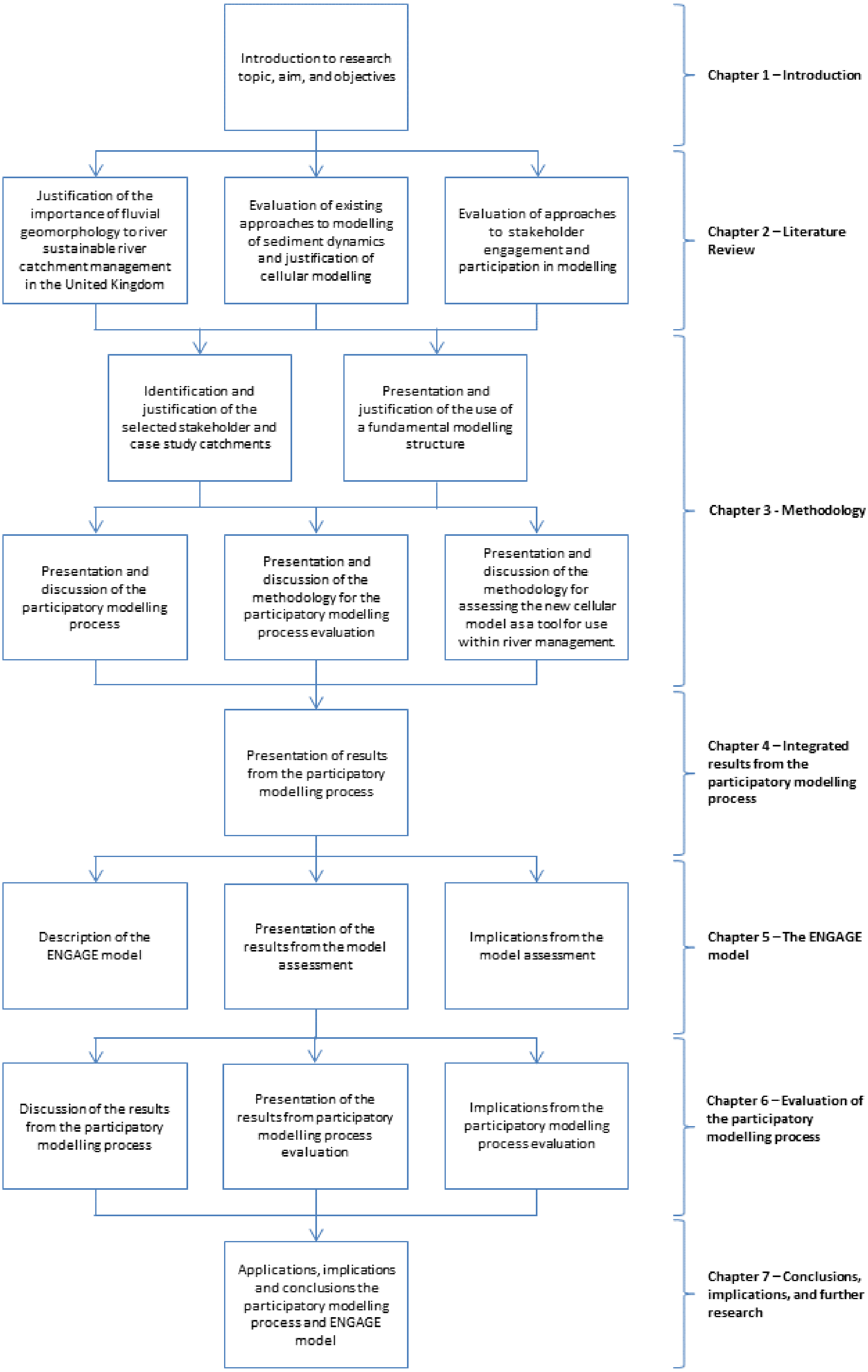


FIGURE 1-1: THE RESEARCH PROCESS (LEFT) IN RELATION TO THE THESIS STRUCTURE (RIGHT).

Chapter Two: Literature review

This chapter explores the international academic and professional debates within literature relating to fluvial geomorphology and participation in order to provide the context for this transdisciplinary research project. To achieve this, four key themes will be critically examined in this chapter:

- The importance of fluvial geomorphology to river management (Objective 1);
- Modelling of river catchment sediment dynamics (Objective 1);
- Participation and environmental management (Objective 2);
- Participatory modelling (Objective 2).

In doing so, this chapter identifies a knowledge gap in the use of participatory modelling to promote knowledge exchange and increase the practical application of sediment dynamics models by river management practitioners.

2.1. The importance of fluvial geomorphology to river catchment management

2.1.1. Introduction to fluvial geomorphology

Across the globe, rivers are found in different climatic environments and in a variety of different forms. Rivers are complex systems comprised of forms and processes which interact in a non-linear and often chaotic fashion over varying spatio-temporal scales as they facilitate the movement of water within catchments, but also as they erode, transport and then deposit sediment (Lane and Richards, 1997). This sediment transfer impacts on the availability of fertile soil across river catchments (Woodward and Foster, 1997; Ockenden *et al.*, 2014), the channel flood conveyance capacity (Lane *et al.*, 2007), causes damage to infrastructure (Anthony and Julian, 1999) (e.g. damage to bridges during the UK Cumbria floods of December 2015 (Russell *et al.*, 2016)), and alters channel biodiversity and geodiversity (Collins and Anthony, 2008; Hooke, 2015). Therefore, it is important to understand how sediment is eroded, transported and deposited in order to manage river catchments sustainably. The discipline that studies these processes is fluvial geomorphology, often defined as:

> *'…the study of sediment sources, fluxes and storage within the river catchment and channel over short, medium and longer timescales and of the resultant channel and floodplain morphology.'*
>
> (Sear *et al.*, 2004, p. 2)

River management practitioners have realised the importance of fluvial geomorphology since the beginning of the 20th century, at which point, it was thought that practical demands of the mining industry were responsible for the formation of fluvial geomorphology as a recognised science. One of the earliest examples of fluvial geomorphological analysis dates back to the 8th December 1904. Clifford (2008) describes how the California Miners' Association petitioned President Roosevelt to investigate erosion and sedimentation in the Sacramento and San Joaquin valleys, where, in 1884, restraints had been placed on the discharge of material into navigable waterways due to complaints from local farmers concerned about river instability and flooding. This resulted in the shutting down of the hydraulic mining industry in the area and an estimated $100,000,000 property was left idle (Clifford, 2008). Geologist Karl Grove Gilbert (1917) studied the delivery of sediment from hydraulic mining and discovered that the river had adjusted to the increased sediment supply, arguing in favour of the miners. Gilbert is now considered to be one of the founders of fluvial geomorphological science. At the same time, throughout Europe, the practical need to understand how sediment influenced channel flows and geometry propelled fluvial geomorphological science forward. This was particularly driven by colonial canal engineers in India and Pakistan who formulated and refined 'regime theory' in alluvial channels (Clifford, 2008). The engineers used their practical experience to inform their theories, including the realisation that channel slope and shape significantly influenced channel bank stability and sediment transfer in canal systems.

As mentioned in the introduction, the discipline of geomorphology has recently acknowledged that we have entered a new geological epoch, the 'Anthropocene', whereby the influence of humans on the earth has had an overwhelming influence on the Earth system, including fluvial systems (Brown *et al.*, 2013; Lewin and Macklin, 2014). For example, soil erosion has increased globally as a result of intensification of agriculture (Hoffmann *et al.*, 2015), mining (Wantzen and Mol, 2013), forestry (Borrelli *et al.*, 2015), and urbanisation (Whitney *et al.*, 2015). Estimates suggest that in parts of the world, humans are responsible for displacing more soil than is being produced by an order of several magnitudes (Montgomery, 2007). Haff (2010) suggests that rivers are the only land-based geomorphic system that moves more sediment than human technological 'mass-wasting'. Similarly, Syvitski *et al.* (2005) estimate that humans are responsible for an increase in annual global sediment transport by rivers (2.3 ± 0.6 billion metric tons). However, the quantity reaching the oceans has decreased due to impoundments and associated reservoir trapping (4 ± 0.3 billion metric tons).

Anthropogenically induced climate change is likely to exacerbate natural mass-wasting and sediment transport through the intensification of the hydrological response of river catchments (Lane *et al.*, 2007). However, as Lane *et al.* (2007) recognise, predicting this response and subsequent impacts are difficult due to the complexity and non-linearity of the system. Geomorphological research is beginning to recognise this, and subsequently a wealth of new research on this topic has emerged (e.g. Bauch and Hickin, 2011; Foulds *et al.*, 2014; Lu *et al.*, 2010; Praskievicz, 2015). On the other hand, Lane (2012) poses the question 'Where has all the geomorphology gone' in respect to the limited reference made to geomorphology in the IPCC Fourth Assessment Report (2007). Furthermore, a review of the Fifth Assessment Report (2014) suggests little has changed, with only 5 direct references.

From the late 20th century, fluvial geomorphology has been moving towards a new methodology of practical application of knowledge in the context of river management (Sear *et al.*, 1994; Thorne *et al.*, 1997; Downs and Gregory, 2004; Rinaldi *et al.*, 2013). Fluvial geomorphology is now partially established as an important consideration in the management of river systems within Europe (e.g. WFD, 2000/60/EC), North America (e.g. the Clean Water Act (1972) and the Endangered Species Act (1973)), South Africa, Australia and New Zealand (Gregory and Goudie, 2011; Hudson and Middelkoop, 2015; Sear *et al.*, 2004). This change has been driven by a number of factors, including:

1. the financial and environmental costs of ignoring natural system processes (Evans *et al.*, 2004). For example, in 2012/13 the Environment Agency (EA) spent £45 million on channel maintenance, some of which may have been avoided with better environmental stewardship (Environment Agency, 2014);
2. increasing recognition that catchment management decisions are influenced by and impact on sediment transport and storage (Lane and Thorne, 2006). For example, instream structures such as dams (see: Jones and Parker, 2015) and changes to catchment characteristics through land use change (see: McIntyre and Thorne, 2013). DEFRA estimates soil degradation and the resultant impacts (e.g. flooding) costs the UK £0.2 billion–£0.3 billion per year (DEFRA, 2009); and
3. an evolution in the way river systems are treated, with the traditional approach of river engineering changing to river management (Williams, 2001), and the replacement of hard engineering by more adaptive 'softer' engineering approaches (Brierley and Fryirs, 2005; Downs and Gregory, 2004). Recently, natural flood management (Pearson *et al.*, 2015; Wilkinson *et al.*, 2014) has been rising up the UK political agenda as a result of the flooding in 2013/14 on the Somerset Levels and the winter floods of 2015/16 in Cumbria (e.g. articles in the Guardian (Anon., 2016) and Independent (Lean, 2016)).

The following two sections will explore two currently distinct areas of river management that can benefit from increased input of fluvial geomorphological knowledge of the ecological status of river channels, and flood risk. These two separate areas are becoming interwoven as there is a drive towards an ecosystem services approach to river management, of which a critical component is fluvial geomorphology (Everard and Quinn, 2015; Iacob *et al.*, 2014).

2.1.2. Fluvial geomorphology and management of the ecological status of river channels

Fluvial geomorphology is important to the biodiversity of rivers as, globally, the fluvial sediment system determines the habitat of approximately 175,000 species of animals and plants (Palmer *et al.*, 1997). The management of the ecological status of river channels can benefit from fluvial geomorphological input due to the close connectivity and interactions between ecological, hydrological and geomorphological systems (Sear *et al.*, 2004; Croke *et al.*, 2013), referred to as ecohydromorphology (Vaughan *et al.*, 2009). This is reinforced by Table 2-1 from Everard and Quinn (2015) who build upon Bergeron and Eyquem's (2012) work on identifying the relationships between geomorphological systems and ecosystem services.

Understanding fluvial geomorphological processes is particularly important for river management practitioners, as anthropogenic activities can cause damage to ecosystems by disrupting their natural functioning (Harper and Everard, 1998). These include: (i) direct impacts which modify the channel habitat itself (e.g. weirs and dams (Rollet *et al.*, 2014), channelization (Baattrup-Pedersen *et al.*, 2005) and mining of sediments (Rinaldi *et al.*, 2005)), and (ii) indirect impacts (e.g. from deforestation (Owens *et al.*, 2005), agriculture (Gido *et al.*, 2010), urbanisation (Uehlinger *et al.*, 2002) and mining (Smolders *et al.*, 2003)) which can affect the flow and sediment regimes, which will, in turn, alter the channel habitat.

TABLE 2-1: ATTRIBUTES OF FLUVIAL GEOMORPHOLOGICAL SYSTEMS IMPORTANT FOR GENERATING OR CONTRIBUTING TO ECOSYSTEM SERVICES. SOURCE: (EVERARD AND QUINN, 2015, P. 492).

Attribute	Description
Water quantity (amount of flow)	Channel flow is a defining feature of fluvial systems, from which society derives the significant benefit of water supply
Water delivery (timing of flow)	Fluvial geomorphology and catchment-scale geomorphological and hydrological processes play key roles in determining the timing of flow, including ameliorating flood impacts by attenuation and supplying baseflow during droughts
Water quality	*Physical* Fluvial geomorphological processes determine water *velocity, turbulence, temperature, conductivity* and *clarity* (*suspended sediment*), all of which influence other ecosystem processes, directly or indirectly contributing to various ecosystems services *Chemical* Processes occurring in the fluvial environment contribute to maintaining *dissolved oxygen* as well as the *chemical character* and *odour* of river water *Biological* Fluvial geomorphological processes involving the interaction of water and sediment with channel morphology generate a diversity of habitats supporting *microorganisms, plants, invertebrates, fish, wildlife* and their associated *genetic diversity*, all contributing to *ecosystem health* or *biotic integrity*
Sediment characteristics	*Suspended sediment load* Fluvial geomorphological processes determine the *size fraction, amount* and *timing* of erosional and transport processes, influencing primary production in the water column and the redistribution of sediment in the watercourse and floodplain *Bed substrate* Fluvial geomorphological processes determine the *bed material size, amount, distribution* and *form* (bars and bedforms) determining the nature of benthic habitat, influencing the characteristics of water flowing over it
Morphological characteristics	*Channel and floodplain morphology* Fluvial geomorphological processes determine the c*hannel gradient, dimensions, form, pattern,* and *associated depositional* (e.g. point bar, floodplain) and *erosional* (e.g. cut bank) features: key attributes of the template of a river valley providing the physical basis for habitat and associated ecosystem services *Bed stability* Characteristics of the bed substrate, together with flow conditions and sediment load, determine bed stability *Bank stability* Characteristics of the bank, together with flow conditions and sediment load, determine bank stability

River gravels are an important habitat for salmon spawning and influence fish size (Moir *et al.*, 1998). Modern intensive agricultural practices, such as greater stocking densities and the conversion of pasture to arable land have altered the sediment dynamics of river systems causing increased fine sedimentation and the degradation of these habitats (Hendry *et al.*, 2003; Newson and Newson, 2000; Gido *et al.*, 2010). For example, Soulsby *et al.* (2001) found that reduced salmonid numbers on the River Don in Aberdeenshire were in large measure the result of intensive cultivation increasing fine sedimentation leading to higher egg mortality rates. River channelization has been found to significantly reduce the diversity and abundance of species due to significant changes in the natural sediment dynamics of the system (Brookes, 1985; Oswalt and King, 2005). Furthermore, processes such as dredging and de-snagging remove important geomorphic features such as pools, riffles and bars, and disturb the bed sediment as a result of higher velocities and stream power (Downs and Gregory, 2004). This was shown in a study of the extractive industries on the Hawkesbury-Nepean River in New South Wales, Australia where these processes significantly impacted on the biological environment, resulting in the loss of macrophytes and riparian vegetation, weed invasion, fish kills and reduced diversity of aquatic habitat (Erskine, 1998). More recently, a study on the impacts of a hydropower damming in the Mekong River Basin through an ecological network analysis found an initial 30% cumulative impact, with species at the top of the food chain significantly more impacted (e.g. mollusca, benthic-feeding fish and zooplanktivorous fish) (Chen *et al.*, 2015).

The significance of fluvial geomorphology to the ecology of river systems is now recognised, to a degree, in policy and legislation (Newson and Large, 2006). In particular, the Water Framework Directive (WFD) (2000/60/EC) set a target for all waters in Europe to achieve a 'good ecological status' or 'good ecological potential' for heavily modified waterbodies by 2027. In the spatio-temporal assessment of compliance with the regulations of the WFD, fluvial geomorphology (referred to under 'hydromorphology') is now recognised as a supporting parameter (Table 2-2) for ecosystems (e.g. appropriate spawning and breeding habitat (Borja and Elliott, 2007)) and engineering (e.g. scour at bridges and hydraulic structures (May *et al.*, 2002)). Planning and progression for the WFD continues in 6 year cycles of developing and implementing River Basin Management Plans (RBMPs) until 2027. Initial reports suggest that the EA will soon release figures stating that only 17% of rivers in England and Wales will achieve good ecological status in 2015 (Harrabin, 2015).

Over the past 15 years, a significant amount of research and progress has been made in respect to: (i) the assessment and monitoring of hydromorphological condition (e.g. Allan *et al.*, 2006; Rowan *et al.*, 2006; Rinaldi *et al.*, 2013; Shuker *et al.*, 2015) and (ii) the effects of hydromorphological restoration measures (for a review see: Kail *et al.*, 2016). Despite this, there are still knowledge gaps that will need to be addressed in order to be able to utilise the insights from hydromorphology effectively to achieve 'good ecological status'. Vaughan *et al.* (2009), Death *et al.* (2015), and Everard and Quinn (2015) provide detailed analysis and description of these knowledge gaps. Two emergent themes from these reviews are of relevance to this thesis. Firstly, the requirement to develop practically applicable eco-hydromorphological models and tools to assist practitioners in decision-making processes. Secondly, there is an ever greater requirement for truly interdisciplinary research through the breakdown of traditional disciplinary barriers to develop greater understanding of, and be able to model eco-hydromorphological relationships. These two key themes are explored in greater depths later in this chapter (Sections 2.1.4 and 2.2).

TABLE 2-2: QUALITY ELEMENTS FOR THE CLASSIFICATION OF ECOLOGICAL STATUS IN RIVERS UNDER THE WATER FRAMEWORK DIRECTIVE (WFD). SOURCE: NEWSON AND LARGE (2006, P.1609).

Quality element	Description
Biological elements	Composition and abundance of aquatic flora Composition and abundance of benthic invertebrate fauna Composition, abundance and age structure of fish fauna
Hydromorphological elements supporting the biological elements	Hydrological regime Quantity and dynamics of water flow Connection to groundwater bodies River continuity Morphological conditions River depth and width variation Structure and substrate of the river bed Structure of the riparian zone
Chemical and physico-chemical elements supporting the biological elements	Thermal conditions Oxygenation conditions Salinity Acidification status Nutrient conditions Specific pollutants Pollution by all priority substances identified as being discharged into the body of water Pollution by other substances identified as being discharged into the body of water

In addition to the WFD, there are several other policy drivers influencing the practical application of fluvial geomorphology to the management of riverine ecology in the UK and Europe, including: United Kingdom Biodiversity Action Plans (BAPs), European Habitats Directive (92/43/EEC), Freshwater Fisheries Directive (2006/44/EC), Wildlife and Countryside Act (WCA) and Natural Heritage (Scotland) Act. Additionally, the Environment Agency (EA) and Scottish Environmental Protection Agency (SEPA) have a number of corporate targets, responsibilities and works that require fluvial geomorphological input, such as habitat protection (Sear *et al.*, 2004). Compliance with WFD regulations and other policy drivers, has and will in future require river management to be informed by research in fluvial geomorphology (Eyquem, 2007).

2.1.3. Fluvial geomorphology and the management of flood risk

The ongoing urbanisation of river catchments (Ahilan *et al.*, 2014; Nardi *et al.*, 2015), combined with an increasing frequency of extreme rainfall events (Jones *et al.*, 2013; Darch *et al.*, 2016) has significantly altered the flood hydrograph of many rivers in the United Kingdom. To combat this, engineers have used a series of traditional techniques to control and manage river flows, such as channelization, impoundments, embankments and training structures (Gilvear, 1999). Numerous floods and infrastructure failings in the UK in recent years, have demonstrated that this approach is neither particularly successful nor sustainable (e.g. Anon., 2012; Dransfield, 2015). In particular, these approaches fail to take into account the dynamics of the fluvial geomorphological system and therefore neglect increases in channel incision, and flood peaks downstream (Wyzga, 1996; Gilvear, 1999; Lane *et al.*, 2007; Mikuś *et al.*, In Press). For example, on the Mimmshall Brook in Hertfordshire, UK, a number of flood alleviation measures were carried out including upstream channelization, widening of the channel downstream, and raising the river banks (Sear *et al.*, 1994). This resulted in an increased supply of sediment to the downstream section, causing significant accumulations of sediment, increasing the flood risk and triggering substantial environmental degradation of the river channel (Darby and Thorne, 1992). The importance of understanding fluvial systems for flood risk management is exemplified in a recent study by Slater *et al.* (2015) who observed significant changes in flood hazards as a result of natural changes to channel capacity, which is often assumed to be static in the design of flood defences.

There are several important contributions that fluvial geomorphologists can make to improve flood risk management, these are:

- To demonstrate the interconnectivity of the fluvial system and the complex dynamic system of positive and negative feedbacks that exist between river planform, profile, and cross-section (Ashworth and Ferguson, 1986);
- To emphasise the importance of treating fluvial systems as a physical system with a history, recognising the importance of spatio-temporal scales over which geomorphological processes operate (Schumm, 1977);
- To highlight the sensitivity of the fluvial systems to change through the concepts of 'threshold behaviour' and 'complex response', as well as promoting the existence of non-linearity in the relationship between channel form and geomorphic processes (Lane and Richards, 1997). Additionally, recognising the importance of understanding eco-hydromorphology as an approach to achieving ecologically acceptable engineering (Vaughan *et al.*, 2009);
- To use the above knowledge to provide recommendations sensitive to how management practices (e.g. dredging and desnagging) may impact upon flood conveyance and suggest solutions to resolve or reduce issues surrounding channel instability (e.g. river bank erosion) (for a review see: Gregory *et al.*, 2008).

Lane *et al.* (2007) argue that in order to manage future flood risk, it will be important to understand how the sediment dynamics of the system will alter river channels, and in turn the resulting flood risk. In a case study modelling future flood risk, Lane *et al.* (2007) combined historic river cross-sections and instream sediment sensors to assess and predict the influence of geomorphological processes on flood inundation extents in a reach of the Upper Wharfe in the Yorkshire Dales. The results from the study indicate that coarse sediment aggradation was responsible for around 50% of the inundation extent increase expected from climate change for the same event in 2050. A number of limitations are associated with the use of this approach, such as the sediment sensors only covering a small part of the active channel and uncertainties in climate change scenarios (Lane *et al.*, 2007). Additionally, this approach is extremely time-consuming, requiring significant amounts of technology and expertise. As a result, applying this approach on a whole river system or at a large scale is not easily achievable or cost-effective. Models of catchment-scale sediment dynamics could be a way of overcoming some of these limitations. Arnaud-Fassetta *et al.* (2009, p. 124) recognised this, stating that:

> *'Modelling should be an essential tool for re-learning to live with rivers and fluvial changes, accepting and understanding floodplain processes and the wider environment in which societies choose to live.'*

The potential of these models to contribute to flood risk management will be explored later in Section 2.2.

An example where fluvial geomorphology has successfully been integrated with flood risk management is in the definition of flood extents. This was achieved by analysing floodplain geomorphology in order to create maps of physical floodplain extents, which were then compared with modelled 1 in 100 or 1 in 200 year flood recurrence events (Thompson and Clayton, 2002). Thompson and Clayton (2002) found that during the autumn 2000 floods in the United Kingdom, many of the rivers filled the natural extent of their floodplains, exceeding the EA's modelled flood extents. Another example can be found in France, where in the last decade hydrogeomorphological maps of some French rivers (36% of a sample studied by Montané *et al.* (2015)) have been created to inform flood risk maps. These hydrogeomorphological maps contain detail not included in traditional flood maps, in particular, the theoretical model of the spatial and temporal evolution of the channel, information on historic floods, and how anthropogenic influences (e.g. land use) are likely to modify the hydraulics of the channel in the long term (Arnaud-Fassetta *et al.*, 2009).

However, this approach requires a significant amount of data (e.g. historical and field data) and resources (e.g. manpower and expertise) therefore, to date, only a small number of hydrogeomorphological maps of important sections of rivers in France have been created (Arnaud-Fassetta *et al.*, 2009; Montané *et al.*, 2015).

Effectively managing future flood risk and preventing further damage to flood defence infrastructure will require the practical application of fluvial geomorphological knowledge to be reflected in legislation. In England and Wales, Catchment Flood Management Plans (CFMPs) and River Basin Management Plans (RBMPs) have been established in the last decade (Wilby *et al.*, 2006), requiring fluvial geomorphological assessments to be conducted to understand the processes at work (Evans *et al.*, 2002). These assessments entail understanding of how sediment dynamics and channel evolution vary across a catchment, as well as the close interrelationships that exist between fluvial geomorphology, hydrology, ecology and geology (Eyquem, 2007). However, the production of the next phase of Flood Risk Management Plans (FRMPs) required by the EU Floods Directive (2007/60/EC), does not include a direct geomorphological assessment, and only a single reference is made to geomorphology as an 'environmental objective' in the guidance (DEFRA, 2014b).

2.1.4. The role of interdisciplinarity in fluvial geomorphology's contribution to river management

The previous two sections have demonstrated that fluvial geomorphology has an important role to play in the sustainable management of river catchments, in particular in achieving 'good ecological status' and improving flood risk management. However, in order to achieve this, fluvial geomorphology will need to become part of an applied integrated interdisciplinary river science and create the tools and knowledge that river management practitioners require (Rice *et al.*, 2010; Meitzen *et al.*, 2013). This is especially relevant as public sector funders and users of applied research are demanding that the knowledge created is relevant to society, increases productivity, and promotes environmental and societal benefits (Harris and Lyon, 2013). The role of interdisciplinarity in fluvial geomorphology's contribution to river management will be explored in this section.

One of the most widely recognised and cited definitions of interdisciplinary research (Repko *et al.*, 2013) was issued jointly by The National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine in the USA (2005, p. 26):

> *'a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice.'*

Sear *et al.* (2004, p.4) recognised the importance of interdisciplinarity when applying fluvial geomorphology in river management, arguing that the fundamental philosophy should be:

> *'…to understand, through interdisciplinary science, the causes of river management problems arising from river channel sediment transport processes, and to consider the implications of any proposed activity to address the problem on the local and regional sediment system.'*

As well as in the application of fluvial geomorphology, Rice *et al.* (2010) argue that interdisciplinarity is important in fluvial geomorphological research. The concept of interdisciplinary research in fluvial geomorphology is not new. For example, fluvial geomorphologists have long recognised the importance of instream and riparian ecological processes influencing sediment and water flow (e.g. Johnson *et al.*, 2009; Gottesfeld *et al.*, 2004). Despite interdisciplinary research efforts being recognised as a vital component of progressing knowledge and understanding fluvial systems (Downs and Gregory, 2004), real interdisciplinary research in fluvial geomorphology remains uncommon

(Hillman, 2009; Rice *et al.*, 2010). This is in part due to the current nature of science and interdisciplinary research requiring a change in the current processes of knowledge creation and dissemination. The main reasons for limited interdisciplinary research in general terms (beyond fluvial geomorphology) are suggested to be:

- Communication – the time required to learn and understand the vocabulary, theory and methodologies of other disciplines (Boulton *et al.*, 2008);
- Incentives – institutional reward and timescales of publication due to personal styles and locations, although Sievanen *et al.* (2012) suggest recently there has been a shift towards funding and recognition of the value of this type of research in ecosystem based approaches;
- Frameworks and processes – the challenge of incorporating social and political knowledge into the positivist scientific form (Campbell, 2005);
- Loss of the single discipline mastery due to the commitment and time to learn other disciplines, resulting in a perception that interdisciplinary researchers are less competent (Naiman, 1999).

This is also reflected in the way in which hydrology, geomorphology and ecology interact, as each discipline has its own methodological approach and perspective. Therefore to date, these disciplines have tended to operate in 'a parallel, multidisciplinary mode rather than in an integrated, interdisciplinary mode to address questions of mutual scientific interest' (Rice *et al.*, 2010, p. 65).

Multidisciplinary research involves several disciplines researching the same theme or goal but with individual disciplinary aims. Researchers within a multidisciplinary project, exchange knowledge between disciplines but 'do not aim to cross subject boundaries to create new knowledge and theory' (Tress *et al.*, 2005, p. 15). Interestingly, the conclusions of Rice *et al.* (2010) are supported by a study of over 3300 journal articles, which identified multidisciplinary activity in the four core disciplines of hydrology and water resources, limnology, fisheries and fish research, and geomorphology (Vugteveen *et al.*, 2014). Despite this, Vugteveen *et al.* (2014, p. 85 and 92) conclude that 'the different river research fields are not strongly connected in terms of knowledge exchange' and that 'river science has not (yet) emerged as an interdisciplinary research field'.

Researchers in hydrology, geomorphology and ecology over the past decade have begun to emphasise the requirement for interdisciplinary collaboration under the term 'ecohydromorphology' to understand the complex temporal and spatial relationships between ecological and physical habitats (e.g. Vaughan *et al.*, 2009; Meitzen *et al.*, 2013; Kohlhagen *et al.*, 2013). However, as Vugteveen *et al.* (2014) identify, the use of this new approach is yet to materialise in published research. In this thesis, a detailed review of the literature yields one potential ecohydromorphological study (although the study does not use the term). In this study, Freidman *et al.* (2014) investigated the impact of the degradation of peatlands in Australia's Blue Mountains by human activities on the geomorphic processes, and ecological and hydrological services. The study identified key indicators for geomorphic processes (e.g. peat formation) to help inform the conservation and management of the peat swamps for ecological and hydrological services.

Some researchers go further and argue that future partnerships must be formed between not just the hydrologists, ecologists and geomorphologists but also engineers and social scientists (Palmer and Bernhardt, 2006; Pahl-Wostl *et al.*, 2007; Hillman, 2009). Palmer and Bernhardt describe the integration with social science as the 'final frontier' suggesting that few, if any river restoration studies have involved integration with social science. Vugteveen *et al.* (2014) support this, finding few citations to social science literature from the traditional natural science journals (with the exception of Water Resources). However, Vugteveen *et al.*'s (2014) investigation could be more convincing if newer interdisciplinary and open-access journals had been included in their analysis as publishing interdisciplinary research can be difficult in traditional journals (Miller *et al.*, 2008).

This integration with social science is important, as even if all the best scientific information is available to guide river restoration, without social science input the knowledge is unlikely to be used or valued (Palmer and Bernhardt, 2006). Palmer and Bernhardt (2006) suggest this is because river restoration decisions are rarely based purely on environmental concerns. Instead, they are heavily influenced by the values and beliefs of different groups within society (e.g. the planners, managers, and citizens). Therefore, if scientists and planners understand the needs and values of stakeholders, they can develop solutions that better balance social and environmental needs.

The following is clear from the previous sections: (i) fluvial geomorphology has developed significantly as a discipline over the past century; (ii) fluvial geomorphology is an important consideration in the management of river catchments (especially from ecology and flood risk perspectives); and (iii) a new agenda of interdisciplinary working with other disciplines including the social sciences is emerging. Despite this, there are still very few direct references to fluvial geomorphology in policy and legislation, which could be the result of the disconnect between fluvial geomorphological research and the 'take-up' of practical applications by river management practitioners.

2.1.5. The importance of knowledge exchange in promoting fluvial geomorphology's contribution to river management

Despite increased recognition of the importance of fluvial geomorphology to sustainable river catchment management, Sear *et al.* (2004) suggest that river management practitioners have only begun to recognise the need for specialist input from fluvial geomorphology. Gregory (2004) first recognised this as an issue, arguing that limited knowledge exchange is occurring between the 'blue skies' scientific researchers and river management practitioners and stakeholders. Newson and Large (2006) also recognise this, suggesting that to achieve 'good ecological status' requires increased knowledge exchange between researchers and practitioners (Newson and Large, 2006). Gregory *et al.* (2008) proposed that a paradigm lock (Figure 2-1 – Current situation) exists as the 'blue skies' researchers have limited knowledge of the requirements of river managers and stakeholders, and conversely the practitioners/stakeholders do not perceive the potential impacts of available 'cutting edge' scientific knowledge. However, as Endreny (2001) and Hillman (2009) explain, practitioners cannot be expected to be aware of all the detailed science published in books and papers, as there are often issues with accessibility and resource requirements.

Some fluvial geomorphologists have attempted, in some cases successfully, to communicate research outputs outside of academia through a variety of different traditional methods (Table 2-3) (Gregory *et al.*, 2008). Most recently, Gregory *et al.* (2014, p. 479) proposes that a challenge for geomorphology in the 21st century is 'to demonstrate its relevance beyond the academy, communicating what it is and why it is important'. Furthermore, Gregory *et al.* (2014, p. 484) propose a number of methods through which this can be achieved, such as inviting 'non-members to attend and participate in meetings so that they can appreciate the current status of geomorphology and its potential' and writing chapters on Geomorphological Techniques. However, even with the increase in the recognition of the need to communicate beyond academia by senior academics within Geomorphology, the majority of methods suggested are one-way and top-down processes of knowledge exchange. *The lower half of* Figure 2-1 – 'ideal future scenario' demonstrates the ideal situation, whereby the paradigm lock is broken and knowledge is exchanged freely between the two sides, promoting a shared understanding of the current 'state-of-the-art' knowledge, as well as the future challenges.

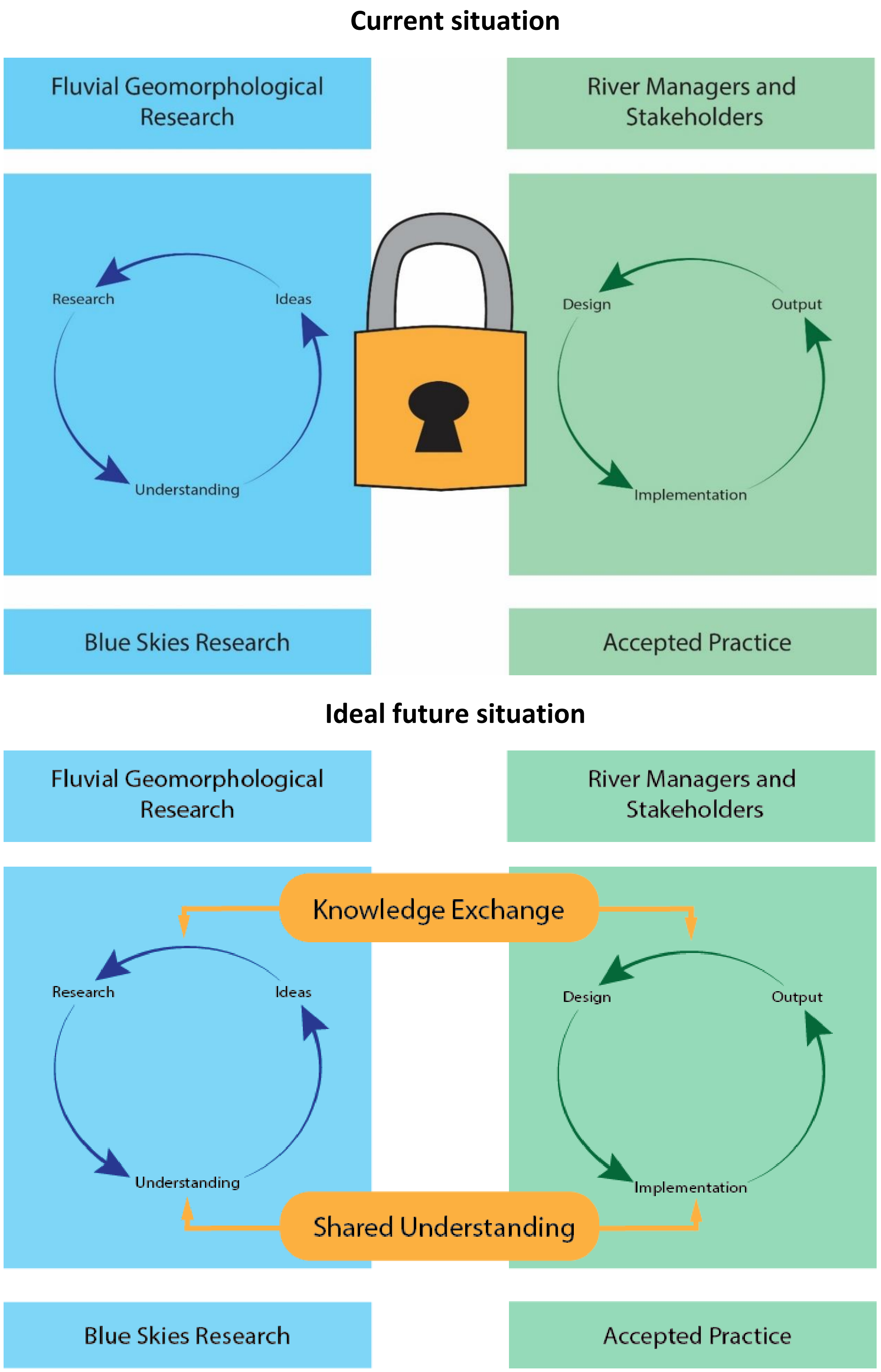


FIGURE 2-1: BREAKING THE PARADIGM LOCK BETWEEN FLUVIAL GEOMORPHOLOGY AND RIVER MANAGEMENT. BLUE SKIES FLUVIAL GEOMORPHOLOGICAL RESEARCH IS SHOWN ON THE LEFT AND RIVER MANAGERS AND STAKEHOLDERS ARE SHOWN ON THE RIGHT. ADAPTED FROM: GREGORY (2004, P. 6).

Table 2-3: Some examples of methods of communication between geomorphologists and river management practitioners identified in Gregory *et al.* (2008, p.161-162).

Method of communication	Description	Example	Potential issues
Papers	Research papers with potential for application	Proposal of scheme for urban catchment management plan (Gregory, 2002)	Accessibility – cost to access journals and level of technical knowledge required to understand (e.g. terminology) Passive engagement method – requires practitioner to actively search, understand, and apply knowledge to management practices Traditional type of communication – does not target 'millennial' river management practitioners
	Review papers identifying potential applications	Integrating geomorphological tools in ecological and management studies (Kondolf *et al.*, 2003)	
	Applied research papers submitted to non-academic journals	Solving an urban river erosion problem on the Tilmore Brook, Hampshire (UK) (Brookes *et al.*, 2005)	
Books / Book chapters	Book or chapters in volume on specific subject intended to include readership beyond the discipline	Geomorphology for engineers (Fookes, 2005)	Accessibility – cost to access textbooks and level of technical knowledge required to understand (e.g. terminology) Passive engagement method – requires practitioner to actively search, understand, and apply knowledge to management practices Traditional type of communication – does not target 'millennial' river management practitioners Management organisations do not have central libraries or repositories for textbooks (in the authors experience)
	Book of edited contributions intended to include readership beyond the discipline	Applied Fluvial Geomorphology for River Engineering and Management (Thorne *et al.*, 1997)	
Reports	Contracted to outline the state-of-the-art in application	Guidebook of Applied Fluvial Geomorphology: R and D Technical Report FD1914 (Sear *et al.,* 2004)	Passive engagement method – requires practitioner to

			actively search, understand, and apply knowledge to management practices Traditional type of communication – does not target 'millennial' river management practitioners
Educational outreach	Geomorphologists participation in non-geomorphology conferences	Attending and contributing to multidisciplinary and other discipline conferences e.g. ASCE, restoration-based conferences	Accessibility – cost /time required to attend and level of technical knowledge required to understand (e.g. terminology) Assumption that river management practitioners will attend other disciplinary conferences or geomorphology workshops Passive engagement method – requires practitioner to actively search for conference, attend, understand, and apply knowledge to management practices Traditional type of communication – does not target 'millennial' river management practitioners
	Geomorphology-centred workshop to inform state-of-the-art beyond the discipline	ESF LESC workshop on large wood in European Rivers: dynamics, human perception, challenge for restoration and application to other areas (Piégay and Gregory, 2005)	
	Geomorphology shortcourses/training	Principles and practice of stream restoration and geomorphology and sediment transport in channel design channel classification course. Utah State University Department of Aquatic, Watershed, and Earth Resources courses (Rosgen and Silvey, 1996)	
	Geomorphology contributions to public education	Flood education and flood perception (Benito and Thorndycraft, 2004)	
Other	Chartered status	Chartered geographer (C.Geog Geomorph) www.rgs.org/CGeogApplication	

A recent example of a communication failure between scientists, river management practitioners, and the public occurred during the winter 2013/14 floods on the Somerset Levels in South West England, during which over 16,000 acres of land and approximately 40 properties flooded (McEwen *et al.*, 2014; Hannaford *et al.*, 2014). This was the result of 'an exceptional run of winter storms'

(Slingo *et al.*, 2014, p. 3). The politics of public opinion and pressure from local residents overrode the overwhelming scientific and practitioner opinion that channel maintenance through dredging would have a limited effect (CIWEM, 2014). In fact, Thorne (2014, p. 301) explains that dredging *'fails to treat the cause of the problem, which simply recurs in a few months or years as sediment supplied from the catchment again accumulates in the channel.'*. In March 2014, in order to show that the government was 'doing something', a new five million pound dredging scheme to remove the silt that has built up along the banks of the rivers Parrett and Tone was approved (Morris, 2014). The researcher considers this to be an example of knowledge exchange failure as river management practitioners understood through modelling, cost-benefit analysis, and environmental analysis that dredging would have little long term effect on flood risk (CIWEM, 2014). However, this knowledge was not adequately communicated to the general public or politicians. Therefore, when pushed by politicians and members of the public as to why dredging did not take place, the EA needed to be able to effectively communicate the hydrological, ecological, and geomorphological evidence behind the decision.

At this point it is important to introduce the concept of transdisciplinary research, which encapsulates the two themes (interdisciplinary research and knowledge exchange) discussed in the current and the previous section. Mollinga (2009, p. S199) defines transdisciplinary research as:

> *'…interdisciplinary research that is strongly embedded in the problem context. In transdisciplinary research so-called 'stakeholders' (interest groups) are intimately involved in research formulation and implementation, affecting the way "science is done" deeply ... It is often "participatory" in nature, with strong understandings of participation implied'.*

Transdisciplinary research is particularly useful in situations where the issues relate to societal problems that are unknown, the scientific knowledge of a problem is disputed or important decision-making processes are involved (Pohl and Hadorn, 2007). Funtowicz and Ravetz (1995) propose that engaging with stakeholders through transdisciplinary research can shape research agendas and provide new types of data. As a result, adopting transdisciplinary research approaches could play a pivotal role in assisting fluvial geomorphologists promote knowledge exchange about complex and disputed issues relating to the management of river catchment sediment dynamics. However, the transdisciplinary research approach raises the same challenges as interdisciplinary research (e.g. differing terminologies, methods, conceptual challenges), and raises additional questions about the incentives for collaboration, and how trust is created between stakeholders and researchers (Harris and Lyon, 2013). Transdisciplinary research is suggested to originate from 'post-normal science', an epistemological approach which shifts away from the way in which traditional science is conducted in ignorance of methodological, societal and ethical impacts (Funtowicz and Ravetz, 1995; Funtowicz and Ravetz, 2003). Transdisciplinary research and post-normal science will be explored in greater detail in the next chapter within the theoretical and methodological framing of this research (Section 3.1.1.).

This section has emphasised that despite the progress in knowledge exchange made by some academics in fluvial geomorphology, there is a significant amount of work required to convince politicians, river management practitioners, stakeholders and the general public that understanding geomorphological processes and applying geomorphological research is vital in order to sustainably manage our river catchments.

2.2. Modelling of river catchment sediment dynamics

One of the challenges facing river management practitioners is the need to understand how fluvial systems change through time as a result of river channel morphological adjustment (Gregory *et al.*, 2008). In recent history, this has been achieved through field based fluvial audits (Rinaldi *et al.*, 2009; Sear *et al.*, 2004) and complex hydrodynamic models (e.g. ISIS, 2006; Brunner, 2010). However, these methods require significant resources (e.g. required input data for mobile boundary hydrodynamic models include channel geometry and bed material grain-size distributions) for them to be applied effectively in river management (Bizzi and Lerner, 2015). Brasington and Richards (2007) suggest that reduced-complexity computational numerical modelling and simulation tools have the potential to address this by requiring fewer resources. A computational model of river evolution can be defined as *'simplified abstractions of river systems that aim to represent the salient processes and properties that affect changes river form and dynamics'* (Coulthard and Van de Wiel, 2012, p. 2123). Coulthard and Van de Wiel (2012) suggest there are two advantages to using numerical models. Firstly, they allow for the repeatable simulation of past or future events, for which observations can be compared against. Secondly, models allow users to investigate how different factors, such as environmental conditions, influence a river's evolution.

In order to understand how we have reached the present position and explore the potential future role of computational models in river catchment management, this section is split into two parts. The first part focuses on providing a history of the development of sediment dynamics modelling. The second part will examine one of the most recent and prominent approaches to modelling river catchment sediment dynamics, reduced-complexity cellular modelling.

2.2.1. History of approaches to modelling river catchment sediment dynamics

The first models of sediment dynamics find their origins in the first geomorphological models created after the establishment of the discipline of geomorphology in the 19th century. These models attempted to represent how rivers develop through time as a result of geomorphological processes (Chorley *et al.*, 1964). William Morris Davis is considered to be one of the first to propose and describe a model of landscape geomorphic evolution, whereby the landscape progressively changes through time, the 'geographical cycle' (Chorley *et al.*, 1973). This cycle did not explicitly refer to the role of sediment dynamics; however, Davis clearly understood the role of sediment dynamics through his descriptions of processes in his work, which have now been termed 'sediment transport capacity' and 'sediment supply' (Davis, 1902 cited in Chorley *et al.,* 1973).

A number of alternative approaches to modelling sediment dynamics were developed after Davis's conceptual model of the 'geographical cycle'. These include Gilbert's functionalist approach to the transportation of debris by running water (Gilbert and Murphy, 1914; Church, 2010), Lane's analytical model of equilibrium (Lane, 1955; Clifford, 2008), regime theory (Kennedy, 1895 cited in Clifford, 2008; Garrett, 1909 cited in Clifford, 2008; Lindley, 1919 cited in Clifford, 2008; Lacey, 1934; Lacey, 1939; Inglis, 1949; Blench, 1957), hydraulic geometry (Leopold and Maddock, 1953), and Schumm's fluvial system (Schumm, 1969).

An important pre-computational contributor to modelling is Stanley A. Schumm, who published a number of key articles that refined and developed upon Gilbert's functionalist concept of landforms being in a 'dynamic equilibrium'. Schumm made two more significant contributions. Firstly, Schumm successfully communicated that fluvial systems should be treated as a physical system with a history, recognising the importance of spatio-temporal scales over which geomorphological processes operate (Schumm, 1977). Secondly, Schumm (1973; 1977) identified and developed the concept of threshold behaviour and complex response within fluvial systems through a 'system theory' framework. It is worth noting that Chorley (1962; 1971) had proposed the concept of geomorphology as a system science prior to Schumm developing the idea, but Schumm (1973) is the most widely cited. Further development from the work of Schumm and Chorley resulted in the realisation of the existence of non-linearity in the relationship between channel form and geomorphic processes (Lane and Richards, 1997). This opened the doors to novel ways of thinking and the development of system models that attempt, with some success (e.g. Hancock *et al.*, 2002), to represent the complex feedbacks and interactions in the fluvial system (Church, 2010). One way this has been achieved is through the use of computers to create computational numerical models of fluvial systems.

Over the past 40 years, a broad array of computational models of fluvial systems based upon differing aims, objectives and assumptions have been developed (Figure 2-2). In the United Kingdom, having 'fit for purpose' numerical modelling and simulation tools is now considered essential given the techno-centric approach to river management (Brasington and Richards, 2007). Future fluvial geomorphologists will be required to use numerical models and simulation tools to articulate and visualise how, at the catchment-scale, land-use management strategies effect sediment dynamics and resulting channel quality (Sear *et al.*, 2004).

Computational Fluid Dynamics (CFD) models represent the fundamental physics of flow by solving the computationally expensive St. Venant equations. Therefore, their application has been restricted to short spatial and temporal scales, such as single flood events on a channel reach (Lane *et al.*, 1999). One-dimensional hydraulic models, such as the Hydrologic Engineering Centre's River Analysis System (HEC-RAS) (Brunner, 2010) and ISIS (ISIS, 2006) (Note: ISIS is now referred to as "Flood Modeller Pro"), allow for sediment dynamics simulation through associated sediment modules, which use flood hydrographs and channel/floodplain cross-sections to calculate sediment transport. Even with a lower resolution, one-dimensional hydraulic models are computationally expensive and require significant resources to operate.

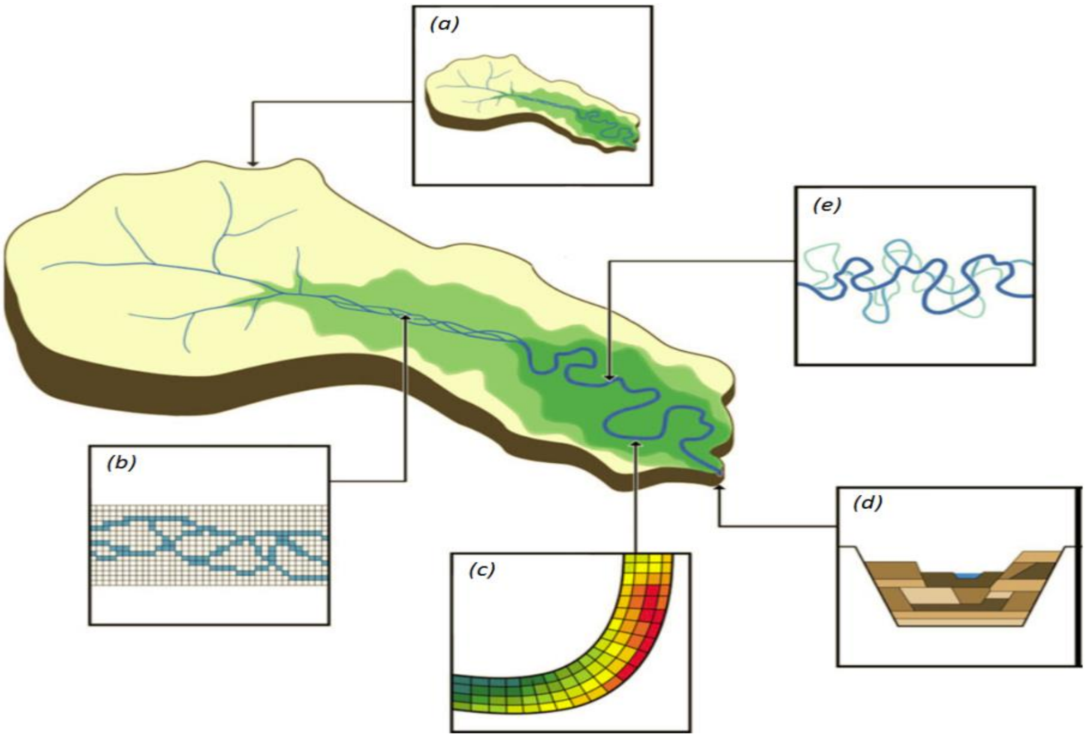


FIGURE 2-2: SCHEMATIC VIEW OF DIFFERENT MODEL TYPES FOR SIMULATING RIVER SYSTEMS. (A) LANDSCAPE EVOLUTION; (B) REACH-SCALE CELLULAR AUTOMATON; (C) REACH-SCALE CFD; (D) ALLUVIAL STRATIGRAPHY; (E) MEANDERING. SOURCE: COULTHARD AND VAN DE WIEL (2012, P. 2125).

(USED WITH PERMISSION OF THE ROYAL SOCIETY PUBLISHING)

Reach-based sediment balance models (e.g. RAT (Graf, 1996), SIAM (Gibson and Little, 2006), REAS (Wallerstein *et al.*, 2006) and ST:REAM, (Parker *et al.*, 2015)) have been developed to operate at the intermediate temporal scale, and provide simplified representations of sediment dynamics over entire river catchments. Parker *et al.* (2015) propose that models such as ST:REAM could be used to inform sediment management planning within river basin and flood risk management. Recently, the Scottish Environment Protection Agency (SEPA) have used ST:REAM to establish the sediment balance for river catchments in Scotland. The outputs from this work have been published on SEPA's flood map website (http://map.sepa.org.uk/floodmap/map.html). Reach-based sediment balance models operate by dividing the catchment network into a series of discrete reaches, averaging the geomorphological characteristics within each reach (Parker, 2010). The amount of sediment stored in each reach changes with incoming and outgoing net sediment transport and the result is then used to determine whether or not a reach is likely to be in a state of aggradation or degradation (Parker *et al.*, 2015). These reach-based models make a number of assumptions and simplifications and therefore, whilst they are computationally inexpensive, they suffer from uncertainty in accuracy and have significant calibration requirements (Parker *et al.*, 2015).

Geomorphological models of landscape evolution simulate catchment-scale sediment dynamics over long temporal scales (1,000-10,000,000 years) and over large spatial areas (1 – 1000km^2), encompassing entire river catchments. The first wave of these models were developed in the 1970s and tended to be simplistic representations of catchment evolution which focused on changing the elevations of a mesh of grid cells or triangular irregular network (TIN) based upon the calculations of slope, and the erosion or deposition of sediment (Coulthard, 2001). Technological advances and topographical data through the 1980s and 1990s saw more complex models developed, with an increased number of modelled variables at a higher resolution (Table 2-4) (Tucker *et al.*, 2001). These models were not solely focussed on fluvial processes, incorporating a large number of slope processes including creep, wash and mass movement (Coulthard and Van de Wiel, 2012). To date, these models have proven to be a valuable tool for understanding the complex nature of fluvial systems (Kondolf, 2016).

The majority of landscape evolution models suffer from a number of technical limitations including: (i) use of simplified equations of flow; (ii) low spatial grid cell resolutions (50-100m); (iii) omission of temporal and spatially variable rainfall and runoff; and (iv) lack of sediment sorting and lateral erosion within channels (Tucker and Hancock, 2010). Coulthard and Van De Wiel (2012) argue that some of these limitations exist as a result of the long temporal scales they operate over, and therefore could restrict their application to purely theoretical catchments. However, landscape evolution models have moved from modelling abstract to real landscapes. For example, these models have been used to investigate the surface stability of post-mining rehabilitated landforms or small catchment areas (Evans *et al.*, 1998; Hancock *et al.*, 2000), and to evaluate the effectiveness of rehabilitation designs on mine sites (Coulthard *et al.*, 2012). Most recently, Hancock *et al.* (2015) applied two landscape evolution models (SIBERIA and CAESAR-Lisflood) to assess a conceptual rehabilitation plan for the RANGER uranium mine in Australia over a 1000 year period. These models identified that short-term erosional processes were dominant on the proposed landform, resulting in large quantities of material being eroded and transported downslope.

TABLE 2-4: SAMPLE OF CATCHMENT-SCALE LANDSCAPE EVOLUTION MODELS DEVELOPED FROM THE 1980'S ONWARDS.

Model Name	Temporal Scale	Spatial Scale	Methods and processes	Purpose	Sources
SIBERIA	1,000 to 100,000 years	Grid cell resolution scalable to available computing power.	Multiple flow routing, fluvial erosion and deposition, slope processes, armouring, engineered structures	Relationships between hydrology, tectonics and catchment form	(Hancock *et al.*, 2002)
GOLEM	100,000 to 10,000,000 years	50m by 50m to1km by 1km grid cells	Flow routed via steepest-descent, slope processes, tectonic uplift, bedrock	Understanding long-term landscape evolution and the relationship between tectonics and erosion	(Tucker and Bras, 1998)
CASADE	1,000,000's of years	Adaptive irregular mesh, TIN (Triangular Irregular Network).	Flow routed via steepest-descent, Diffusive slope processes, simple fluvial erosion and deposition.	Specifically for use in complex geometries and horizontal tectonic uplift.	(Braun and Sambridge, 1997)

CHILD	1,000 to 1,000,000's of years	Adaptive irregular mesh, TIN (Triangular Irregular Network).	Flow routed via steepest-descent, climate forcing, fluvial erosion and deposition (allows multiple grain sizes), slope processes including soil creep, overbank sedimentation and tectonic deformation.	Understand in detail the feedbacks between hillslope processes, channel hydrology and landscape evolution.	(Tucker *et al.*, 2001)
CAESAR	Individual flood to 10,000 years	Small grid cells ($1m^2$ to $50m^2$)	Multiple flow scanning algorithm, active layer system that allows for the formation of bed armouring and alluvial stratigraphy and detailed fluvial erosion and deposition, soil creep and mass movement	Applied to model catchment response to land-use change and climate change.	(Coulthard *et al.*, 2002)
LAPSUS	1-2,000 years	Grid cell resolution scalable to available computing power.	Multiple flow routing, depending on convergence factor p, routes water to lower neighbouring cells, steepest-descent behaviour, fluvial erosion and deposition, tillage redistribution, landslide redistribution, creep and solifluction	Understand and simulate hill-slope erosion and deposition on a catchment-scale, using annual timescales.	(Schoorl *et al.*, 2000)

Brasington and Richards (2007) argue that many of the approaches to modelling described in this section are not suitable for use by river management practitioners. This is a result of a gap between process-based hydraulics and fluvial sediment transport research focused on flume and computational fluid dynamics (CFD), and larger scale, longer term research into climate and land-use. Therefore, there is a need for 'reduced-complexity' cellular models which operate at the 'intermediate-scale', characterise behaviour and evolution of rivers and catchments, are appropriately simplified, computationally efficient, and targeted at spatial and temporal scales (1-100 years and 1-100km^2) relevant to environmental management (Brasington and Richards, 2007; Keesstra *et al.*, 2014). These intermediate scale 'reduced-complexity' cellular models are described in the next section.

2.2.2. Reduced-complexity cellular modelling of river catchment sediment dynamics

Intermediate scale reduced-complexity cellular models operate by representing the landscape as a grid of interconnected cells which, based upon simulation of water and sediment flux across the landscape, have their attributes modified to represent modelled changes in the state of the river catchment (Figure 2-3) (Coulthard, 1999). The first and most influential example of a reduced-complexity cellular model is the braided river model developed by Murray and Paola (1994). The aim of this model was to understand the essential processes that control patterns of braiding within river systems, through the use of simple steady-state flow routing and stream power sediment transport laws. The model represented a river reach through a grid of randomly textured cells (22 x 200); water was then routed through to lower neighbouring cells to quantify sediment transport using the calculated flow and lateral erosion (Coulthard and Van de Wiel, 2012). Despite this simplicity, the model reproduced the dynamic process of river braiding and produced quantitatively representative results. This approach was considered to be one of the most important advances in fluvial geomorphology (Nicholas, 2005), subsequently triggering a paradigm shift away from focusing on reductionist approaches and towards increasing simplicity and reducing computational requirements (Coulthard *et al.*, 2007; Nicholas and Quine, 2007).

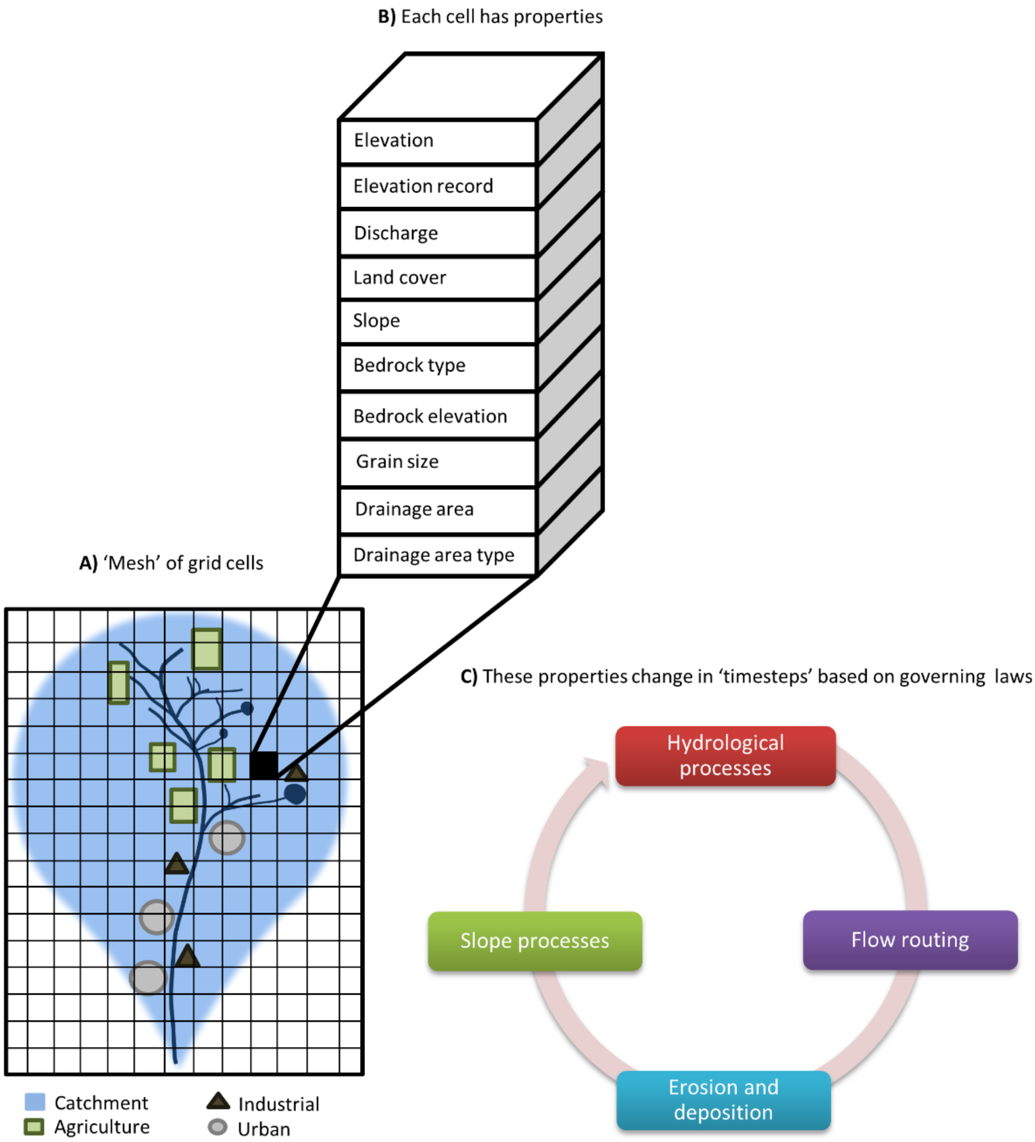


FIGURE 2-3: SCHEMATIC OF KEY COMPONENTS AND PROCESSES OPERATING WITHIN A CELLULAR MODEL OF SEDIMENT DYNAMICS.

Murray and Paola's (1994) work inspired other researchers to adopt the cellular modelling approach in their own models. Notable early attempts include Thomas and Nicholas's (2002) braided river model, which included more physical detail by incorporating multi-directional flow to downstream cells and generated results comparable to those of significantly complex two-dimensional flow models. Another model called CAESAR (Coulthard *et al.*, 2002; Coulthard and Van De Wiel, 2007) added more layers of complexity through the incorporation of flow depth calculations, any directional flow, and multiple grainsizes. Over the past decade, this trend has continued with catchment-scale sediment dynamics models becoming increasingly physically-based and sophisticated, such as through the incorporation of 2D hydrodynamic flow modelling (Coulthard *et al.*, 2013) and high temporal and spatial resolution precipitation (De Vente and Poesen, 2005). As a result, the argument could be made that these models have moved away from their reduced-complexity roots to become intermediate scale complex models, which may be more accurate, but in doing so add unique data requirements, become difficult to use, and require site specific calibration (Keesstra *et al.*, 2014).

Two recent and prominent state-of-the-art models, CAESAR (now CAESAR-Lisflood) and LAPSUS-D have both sought to operate at the intermediate-scale using the reduced-complexity cellular modelling approach (Coulthard *et al.*, 2013; Keesstra *et al.*, 2014). These cellular models are able to integrate hydrology and sediment transport at the intermediate temporal (1-100 years) and spatial (0.5-500km^2) scales and output data in formats (GIS rasters) that are relevant to sustainable river catchment management. As a result, these models have been applied to real river catchments. For example, Ziliani *et al.* (2013) found that CAESAR was able to produce reasonable results for macromorphological changes and annual bed load sediment estimates. On the other hand, CAESAR was not able to accurately reproduce in-channel characteristics of braided rivers. Ziliani *et al.* (2013) concluded that reduced-complexity cellular models should not be restricted to use in a purely explorative manner but could also be used in quantitative investigations. Similarly, Keesstra *et al.* (2014) found that LAPSUS-D was able to produce hydrological parameters with a high degree of accuracy and sediment yield within reasonable accuracy (within a degree of magnitude) (Keesstra *et al.*, 2011). However, to date, there has been no standardised approach to the assessment of these types of models (Keesstra *et al.*, 2011).

Despite the potential of these models to inform river catchment management, to date they have not been designed, been made available for use, or been used by typical practitioners. More specifically, from the researchers' experience in the Environment Agency, these models have only been used three times to inform river restoration projects. For example, the Environment Agency have been assessing the impacts of weir removal on Lea Marston siltation lakes and a weir removal on the River

Dove using CAESAR-Lisflood (Bulcock *et al.*, 2016). However, in both these cases the modelling has either been contracted out to specialists or university researchers. Furthermore, the researcher searched several internal Environment Agency systems (the intranet, 'Enviropedia' – an internal version of Wikipedia, and Yammer – an internal networking forum) finding 0 references for 'geomorphology modelling', 'sediment dynamics model', and 'cellular modelling'. This could be because important aspects for end-users, such as data requirements, ease of use, user-interface, model flexibility and effective visualisation of outputs have not been considered in model development (Lynam *et al.*, 2007). Importantly, the absence of these considerations in research developed models should not come as a surprise because most models are usually created for a specific research project or geographical area (e.g. Schoorl *et al.*, 2000; Greco *et al.*, 2012), rather than as a 'product' or 'tool' with multiple end users. Furthermore, as the drivers such as funding, for research move toward 'Impact outside of academia' (HEFCE, 2016), these considerations may have to become a part of the research process of developing models. These tools will need to be accessible for 'non-specialists', with the ability to be routinely applied in the context of achieving the WFD and flood risk management objectives (Newson and Large, 2006).

Sear *et al.* (2010) questions the utility of these models to make quantitative predictions that can be used in river management, as the values of sediment transport generated are usually indicative rather than absolute. This raises an important question as to whether accuracy or the potential knowledge that can be exchanged through these models as a platform are important. Whatever the end-use, it is clear the outputs produced can be a great opportunity for knowledge exchange through encouraging a greater understanding of how fluvial geomorphological systems operate (Coulthard and Van de Wiel, 2012). This is especially true as these models have the ability to display the output from hypothetical scenarios through sequences of animated visuals and maps of landscape change, and provide *'a powerful stimulus to the imagination and enhance our ability to interpret the landscape'* (Tucker and Hancock, 2010, p. 30).

Since the initial call from Brasington and Richards (2007), there has been little research into developing intermediate scale reduced complexity cellular models that can *be* used in catchment management (Keesstra *et al.*, 2014). Therefore, there is still a need to develop practical modelling tools for practitioners that can be consistently and routinely applied at the catchment-scale to inform strategic planning through increased understanding of geomorphic processes (Bizzi and Lerner, 2015).

2.3. Participation and environmental management

A potential solution has been emerging over the past 15 years to the limited practical application of these models by river management practitioners through a new approach to modelling termed 'participatory modelling'. The aim of this section is to review and critique the literature on participation and participatory approaches in environmental management to provide the foundation for the participatory modelling approach described in the final section. In order to achieve this, the chapter is split into four parts; the first part will provide a brief examination and reflection on the history and evolution of participation. The second focuses on evaluating the typologies of participation that have been developed. The third section will move on to critically explore how participation has achieved widespread and rapid implementation within environmental management. The final part discusses how participation has become incorporated into legislation and policy.

2.3.1. Introduction to participation

Participation is defined by the World Bank as:

> *'…a process through which stakeholders influence and share control over development initiatives and the decisions and resources which affect them.'*
>
> (Bhatnagar *et al.*, 1996, p. xi).

Participation has become a mainstream approach in several disciplines (Hickey and Mohan, 2004) and has been implemented through participatory processes operating from local community to international scale (Harris *et al.*, 2013). These processes have been initiated from the 'bottom-up' and 'top-down' as people demand to be involved in decision-making processes, and governments realise the potential benefits of participation (Berry and Mollard, 2010). Participation has also been adopted in national and international policy as a result of the many claimed benefits, although as Reed (2008) concludes, these claims have not always been realised. In environmental management the rapid uptake of participation in decision-making processes has been driven by increasing environmental awareness, public scepticism of science, and recognition in policy (Reed, 2008).

Participation first emerged at the end of the 1960s with the growing radical critique of 'modern society' (a review is available in Van Tatenhove and Leroy, 2003). At that time, participation was seen as an antidote to a perceived neocorporatism in decision-making that always favoured the interests of economic and political elites. Participation continued to develop through the 1970s as an approach specifically intended to reconfigure the relationship between state and citizens by incorporating local values and knowledge into all phases of the planning process (Pretty, 1995). The 1980s saw techniques such as rapid and participatory rural appraisal (PRA) develop and gain recognition (Chambers, 1994a), before the agenda switched in the 1990s to focus on increasing participation as a part of sustainable development (Macnaghten and Jacobs, 1997). For water managers, both the January 1992 Dublin Conference and the June 1992 Rio Conference imposed the radical new responsibility, with the Dublin Principles declaring that

'Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels.'

(Staddon, 2010b, p. 49)

A few years later, the Aarhus Convention created an obligation on states to promote access to information and public participation in environmental matters (Hartley and Wood, 2005). This political and policy context led to the WFD, which was referred to earlier in this chapter.

Participation came under heavy criticism during the early 2000s as a result of a number of identified limitations and issues (e.g. Cooke and Kothari's (2001) book entitled 'Participation: The new tyranny'). More recently the focus has moved on, reflecting on this history to produce a critical understanding of participatory approaches and methods (e.g. books by Hickey and Mohan (2004) 'Participation: From tyranny to transformation?' and Kesby (2014) 'Retheorizing empowerment-through-participation as a performance in space: Beyond tyranny to transformation.' responding to the criticisms of Cooke and Kothari).

The uptake and development of participation has taken place in a diverse range of disciplinary and application contexts, including: ecology (Mapinduzi *et al.*, 2003), social activism (Freire, 1970), healthcare (Abelson *et al.*, 2003), adult education (Cross, 1981), modelling (Hare *et al.*, 2003), and flood risk management (Wehn *et al.*, 2015). Through the wide range of disciplines and contexts in which participation has been applied, a wealth of literature with differing ideological, social, political and methodological meanings has been created (Lawrence, 2006). Harris *et al.* (2013) propose this is a major issue with use of participation in water governance as there is a significant diversity in terminology and suggested methods, often confusing and frustrating participants. Specific methodologies have also been developed, for example participatory rural appraisal (PRA), which Chambers (1994a, p. 953) defines as:

'a family of approaches and methods to enable rural people to share, enhance, and analyse their knowledge of life and conditions, to plan and act.'

PRA increasingly has been seen as a way for validating local knowledge and empowering local people (Hildyard *et al.*, 2001), as well as enhancing the contribution of local knowledge to development plans (Cooke, 2001). A number of methods have been developed by PRA practitioners, including mapping, ranking and diagramming (Pretty *et al.*, 1995). These methods are predominately visual, and therefore are near-universal in their ability to communicate, and empower the disadvantaged in developing countries (Chambers, 1994b).

Table 2-5 details the theoretical benefits of adopting a participatory approach, divided into normative and pragmatic claims. Normative claims are based on the ideology that people have a democratic right to participate in decision-making, whereas pragmatic are where participation is used as the means to an end through delivering higher quality decisions (Thomas, 1993; Beierle, 2002). These two themes are suggested by Reed (2008) as the overarching arguments often used to describe the benefits of participatory approaches. Rouillard *et al.* (2014) provide a detailed analysis of a participatory process between land managers and government agencies in the transboundary Bowmont-Glen catchment in Scotland and England set up in response to two major flood events. The study found that the participatory process increased uptake of land management techniques and policy compliance, as well as improving relationships between the land managers and government agencies. Interestingly, there were limited levels of social learning, although Rouillard *et al.* (2014) suggest this was as a result of the way the participatory process was implemented and with amendments (e.g. increased opportunity for debate and self-reflection), this could be improved.

TABLE 2-5: SUMMARY OF THE MAIN BENEFITS OF USING PARTICIPATORY APPROACHES SPLIT INTO NORMATIVE AND PRAGMATIC CLAIMS.

Normative claims (Benefit for democracy)	Pragmatic claims (Quality and durability of decisions)
Increase the likelihood that stakeholders on the margins of society are included in decision-making processes (Martin and Sherington, 1997)	Deliver higher quality interventions and technologies that are suitable for the socio-cultural and environmental conditions, meeting the needs of the people (Reed, 2007, Reed and Dougill, 2010)
Increases public trust in decisions – participatory processes should be transparent, considering different viewpoints (Richards *et al.*, 2004) Empower stakeholders through increasing their ability to understand and use co-generated knowledge (Okali *et al.*, 1994)	Increase the rigour of research by providing high quality input data (Hansen, 1994, Reed *et al*., 2006, 2008) Incorporating local views into the design early can increase the success in achieving the needs and priorities of participants (Dougill *et al*., 2006)
Promote social learning, whereby the participants learn from each other through the participatory process, as well as raising the importance of recognising each participants' viewpoints (Blackstock *et al.*, 2007; Fritsch and Newig, 2009)	Building trust between participants and establishing a common ground can build a sense of ownership of the project resulting in long-term support, and subsequently increasing the likelihood of the implementation of outputs of decision-making processes (Richards *et al.,* 2004, Stringer *et al.,* 2006)
Reduce the probability that environmental decisions are seen as unfair, as participatory processes include a diverse range of views (Richards *et al.*, 2004)	Deliver high quality decisions by preventing the occurrence of negative outcomes through the increased completeness of data and knowledge created on an issue (Fischer, 2000, Beierle, 2002, Koontz and Thomas, 2006, Fritsch and Newig, 2009).

As mentioned above, Cooke and Kothari (2001) were among the first to adopt a critical view on participation, arguing that there is a real lack of empirical evidence that in the long-term participatory projects achieve real change or lead to improved decision-making. Cleaver (2001) supports this, suggesting that there needs to be more detailed empirical evidence on the effects of participation in development studies. More recently, Harris *et al.* (2013) summarise the criticisms of participation into 'four fatal flaws'. Firstly, participation is enshrined in the theory of decentralisation and devolution through shifting the power from the state to the people. However, in many cases there is a failure to commit the required resources (Goldin, 2003; Goldin, 2010; Hayes and Persha, 2010). Secondly, participation is increasingly being driven by supply rather than demand, as policymakers require policies to be generated from the people. Additionally, participatory processes may be used as a method of coercion to legitimise a predetermined agenda (Cooke, 2001). Thirdly, more often than not participation is left as a vague term, resulting in those creating and involved in participatory research drawing different meanings as to what the process and outcomes should be (Goldin, 2003;

Goldin, 2010). Finally, participatory processes tend to focus on the form rather than the substance due to the current dominant discourses of participation, which regularly are slow to adapt to suitable forms for use in other projects. Harris *et al.* (2013) describe this as a 'checklist' approach that participatory projects are expected to conform to, resulting in an overemphasis on the execution of the participatory techniques, making participatory processes feel like 'managerial exercises' (Cleaver, 2001).

There are many examples in which genuine participation has not been achieved (Cooke and Kothari, 2001). For example, Kadirbeyoğlu and Kurtiç (2013) studied participation in water governance in Turkey, and identified that in the case of irrigation schemes and water management, genuine participation was not being achieved. Instead, the participatory processes were helping the commoditisation and privatisation of irrigation structures in Turkey. Another example is the Water Allocation Groups set up in Brazil as a part of a participatory water governance agenda. The Brazilian Government undermined the participatory decision-making process by giving the Government's Water Council the power to overrule decisions, this resulted in the credibility of the whole process coming into question, as well as declining engagement by stakeholders (Broad *et al.*, 2007).

Despite these examples of where participation has failed, many researchers (Hickey and Mohan, 2004; Harris *et al.*, 2013; Kesby, 2014; Rouillard *et al.*, 2014; Wehn *et al.*, 2015) are keen to argue that carefully constructed and analysed participatory projects can achieve their aims and objectives. Furthermore, building upon Cooke and Kothari's (2001) criticisms of participation in development, Cooke (2004) proposed a series of rules to resolve some of the earlier described issues. Studies such as Waddington and Mohan (2004) have successfully addressed the issues raised, in particular through identifying ways in which participatory processes can challenge existing structures of exclusion in decision-making processes in rural Ghana and Sierra Leone. Overall, studies like this highlight the complexity of participation and the need to understand the resources, limitations and knowledge required to conduct successful participatory processes.

2.3.2. Typologies of participation

A number of typologies have been developed to provide the foundations for understanding existing participatory processes, as well as assisting in the selection of methods when designing new approaches (Table 2-6) (Reed, 2008). The first typology emerged in the form of Arnstein's (1969) ladder of citizen participation (Figure 2-4), and is often considered to be one of the most influential pieces of participation theory. Arnstein proposed a 'ladder' metaphor to represent different 'levels' of stakeholder engagement that exist, from the bottom of the ladder representing a one-way process of knowledge dissemination (e.g. 'Manipulation') to the higher rungs (e.g. 'Citizen Control'), whereby a more meaningful level of participation is achieved and participants directly control the decision-making process. This 'true' type of participation cannot be achieved without meaningful sharing and redistribution of power to citizens (Arnstein, 1969).

TABLE 2-6: TYPOLOGIES OF PARTICIPATION. SOURCE: REED (2008, P. 2419)

Basis of typology	**Examples**
Typology based on different degrees of participation on a continuum. Numerous alternative terms suggested for different rungs of the ladder (e.g. Biggs, 1989; Pretty *et al.*, 1995; Pretty, 1995; Farrington, 1998; Goetz and Gaventa, 2001; Lawrence, 2006)	Arnstein's (1969) ladder of participation. Sometimes presented as a wheel of participation Davidson (1998)
Typology based on the nature of participation according to the direction of communication flows	Rowe and Frewer (2000)
Typology based on theoretical basis, essentially distinguishing between normative and/or pragmatic participation	Thomas (1993), Beierle (2002)
Typology based on the objectives for which participation is used	Okali et al. (1994), Michener (1998), Warner (1997), Lynam et al. (2007), Tippett et al. (2007)

(USED WITH PERMISSION OF ELSEVIER)

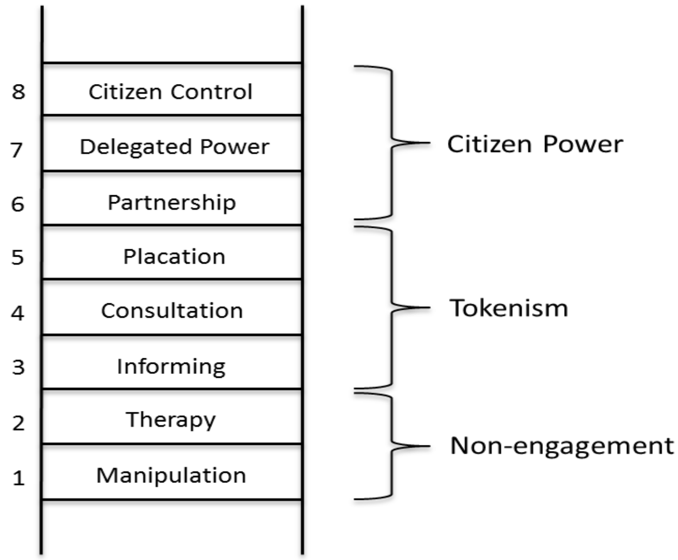


FIGURE 2-4: THE EIGHT RUNGS OF A LADDER OF CITIZEN PARTICIPATION. ADAPTED FROM: ARNSTEIN (1969, P. 217).

(USED WITH PERMISSION OF TAYLOR & FRANCIS ONLINE)

Building upon Arnstein's landmark paper, numerous alternatives for the rungs on the ladder have been proposed (e.g. Farrington, 1998; Lawrence, 2006; Pretty *et al.*, 1995). One of the most widely cited is Biggs (1989) who described engagement through a relationship that can be 'contractual', 'consultative', 'collaborative' or 'collegiate'. Following this, Davidson (1998) defined a 'wheel of participation' (Figure 2-5) arguing that the level of engagement required is highly dependent on the contextual situation. The theory behind Davidson's wheel of participation is supported by Campbell and Marshall (2000) who argue that academics and decision makers often assume that the higher rungs on Arnstein's ladder are the desired outcome. This was reflected in a study carried out by Bailey and Grossardt (2010) who identified in a review of professionals and members of the public involved in transportation infrastructure (TI) planning, that not one person chose 'citizen control' as the preferred option. Bailey and Grossardt (2006) have termed this the 'Arnstein Gap' as the level of participation aimed for should be highly dependent on the contextual situation and objectives of the research.

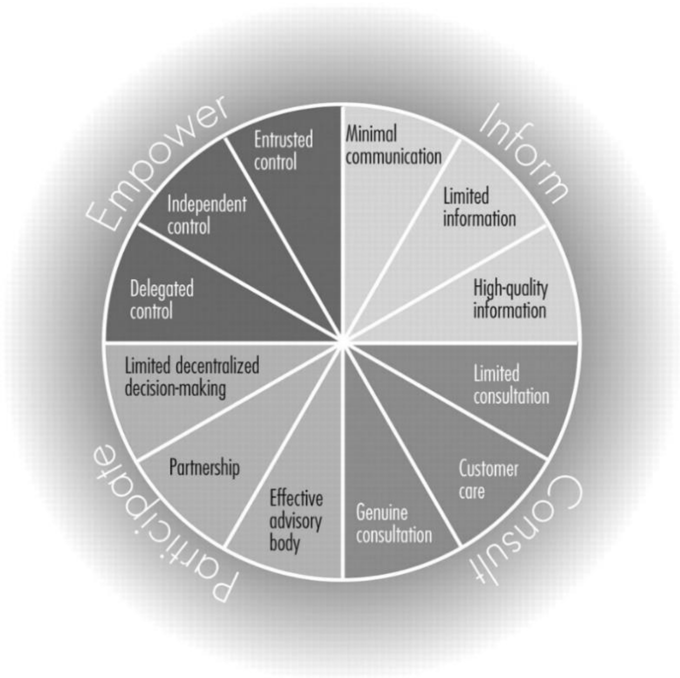


FIGURE 2-5: DAVIDSON'S WHEEL OF PARTICIPATION. SOURCE: HERITAGE AND DOORIS (2009, P. 48) (USED WITH PERMISSION OF OXFORD UNIVERSITY PRESS)

The other typologies shown in Table 2-6 include those that focus on the theoretical foundation of a study, usually through identifying whether participation is either normative or pragmatic. Alternatively, the remaining typologies focused on the nature of the engagement in the participatory process (e.g. Rowe and Frewer, 2000) or the objectives of the research project (e.g. Tippett *et al.*, 2007; Lynam *et al.*, 2007). When using any of these typologies it is important to understand their differences and choose elements of those most appropriate to the goals of the participatory process (Reed, 2008).

2.3.3. The adoption and application of participation theory in environmental management and research

Traditionally, those involved in environmental management approach participation in a 'top-down' manner that often neglects the knowledge, preferences and values of the people most directly linked to the environments being managed (Lynam *et al.*, 2007). Thus, for example, management planning of waterbodies was, before the WFD, undertaken without reference to or involvement of communities dependent on or adjacent to those same waterbodies. As a result, this expert-led and top-down planning model was also highly adversarial, with the courts, and sometimes the streets, becoming the loci for affected communities to make their voices heard. However, the old paradigm for environmental management has been changing, and now stakeholder participation is being heralded as a method for achieving resilient and sustainable socio-ecological systems through social learning and better understanding of community latent adaptive capacities (Pahl-Wostl *et al.*, 2008). The inclusion of stakeholders' attitudes, beliefs and preferences in environmental management has been linked to higher quality policies and increased uptake (Ramirez, 1999; Considine, 2005; Rouillard *et al.*, 2014).

Whilst a variety of definitions of the term 'Stakeholder' have been suggested, the definition of Freeman (1984) from his seminal text, *Strategic Management: A Stakeholder Approach*, which stakeholders are defined as those who are affected by or can affect a decision is adopted in this thesis. Reed (2008) suggests this definition is most suitable for studies of stakeholder participation as it targets those people who are of primary focus in the decision-making process of environmental management.

Since the turn of the century, the literature on participatory approaches in environmental management has been rapidly expanding (e.g. Blumenthal and Jannink, 2000; Van den Hove, 2000; Hare *et al.*, 2003; Dunn, 2007; Cook *et al.*, 2013), with a great diversity in purpose, process design and implementation. Reed (2008) suggests that many of the reasons for this originate from the literature on participation in the development discipline, such as the ability to improve the quality of outcomes from environmental decision-making processes. These were discussed in the previous section and are shown in Table 2-5. More specifically in applied environmental research, Barreteau *et al.* (2010) relate this uptake to the view that participatory processes are seen as a method for science to contribute effectively to the 'public good'. For example, Reed *et al.* (2008) used a participatory process to develop a new set of environmental sustainability indicators, and found that through this process, a set of familiar and easily understandable indicators were created, therefore improving the quality of outputs. This emphasises the importance of how stakeholders' knowledge can be used or integrated to improve existing tools and policies. Lastly, social learning is heralded as one of the main beneficial outcomes of participatory processes in environmental management (e.g. Keen *et al.*, 2005). The concepts and relationships between participatory processes and social learning will be explored in greater detail in the next section (2.3.4).

There are many issues associated with this rapid growth in participatory approaches, many of which were discussed in the previous section. Some of these are more relevant and documented in environmental management. For example, Barreteau *et al.* (2010) describe how it is important to gain participants' trust and acceptance. This is often not achieved in participatory environmental management processes, usually as a result of the stakeholders not knowing what to expect, or the process being overly complicated through the involvement of large numbers of stakeholders with competing demands and obligations (Barreteau *et al.*, 2010). Therefore, it is important that the purpose and process is clearly explained to the stakeholder groups, and the power relations with groups of stakeholders understood and acknowledged. This is especially important when working with broad multi-stakeholder groups (Diaw and Kusumanto, 2005). Lynam *et al.* (2007) suggest two methods for achieving this are Colfer's (1995) 'Who Counts Matrix' and Venn diagrams (Pretty *et al.*, 1995). Colfer's 'Who Counts Matrix' is a simple and effective tool for assessing the different groups of stakeholders involved in forest management against a series of criteria to determine their importance (see: Colfer *et al.*, 1999). Whereas, Venn diagrams are a visual tool used to explore and analyse the causal relationships between the stakeholders within the group of interest (Lynam *et al.*, 2007).

There are several other common issues experienced within participation processes in environmental management, these include: (i) hijacking by special interest groups that do not reflect the wider public opinion; (ii) the participation of stakeholders in the process is mere 'tokenism' and they have no real power to influence the decisions made (Newig *et al.*, 2008); and (iii) the disillusionment of stakeholders with the process as they find it difficult to contribute in scientifically complex situations

(Broad *et al.*, 2007), which can often result in certain 'key' players within groups having a more significant influence on the decisions made (Howarth, 2009).

When considering the application of participation theory in applied research with stakeholders, Cornwall and Jewkes (1995) suggest that the most important aspect is not the methods used but the attitudes of the researchers and their ability to place power in the hands of the participants. Additionally, a real challenge for researchers involved in these processes is to maintain their scientific objectivity as the lines between research and action become blurred (Lynam *et al.*, 2007). However, despite the disagreements and limitations, the overarching acceptance of the benefits deriving from participation of stakeholders has resulted in it becoming a driving force within environmental management (Lynam *et al.*, 2007). One of the drivers behind the uptake of participation mentioned earlier is the recognition that social learning can be one of the outcomes from participatory processes.

2.3.4. Social learning and participation

Over the past decade, there has been much debate over the definition and interpretation of social learning (see: Keen *et al.*, 2005; Rist *et al.*, 2007; Ison and Watson, 2007; Reed *et al.*, 2010; Egunyu and Reed, 2015). One of the most widely cited and recognised is Reed *et al.*'s (2010, p. 6) definition that social learning is a process which instigates

> *'a change in understanding that goes beyond the individual to become situated within wider social units or communities of practice through social interactions between actors'.*

Social learning takes place through social interactions and activities between individuals and groups; these interactions fall into two categories. The simplest form is the learning of new information through direct transmission; the other is deliberation, whereby ideas and perceptions are changed through a persuasive exchange of ideas and arguments (Newig *et al.*, 2010; Reed *et al.*, 2010)

There are many case studies examining social learning in the literature (e.g. Webler *et al.*, 1995; Pahl-Wostl *et al.*, 2007; Berkes *et al.*, 2008; Yuen *et al.*, 2013). More specifically, environmental management research has recognised the potential value of social learning in developing new policies and managing natural resources in both developed and developing countries (Reed *et al.*, 2010). For example, Rist *et al.* (2007) analysed the process and outcomes of social learning in the sustainable management of natural resources using three case studies in rural India, Bolivia, and Mali. The results from the study demonstrated the use of deliberative workshops that enabled the participants (local and external) to work towards a common set of guidelines for sustainable management. This was only achieved by allowing the participants the space to critically reflect upon the different roles, norms, and belief systems within the groups.

There are several challenges associated with undertaking an approach to facilitate social learning, some of which are closely related to those described in the previous section. For example, social learning processes can be hijacked by special interest groups that do not reflect the wider public opinion (Broad *et al.*, 2007). One of the biggest challenges to effectively facilitating social learning is to ensure that all participants within the process are able to contribute. Research suggests that social learning benefits those who are able to participate and contribute the most to the process (McDermott, 2009; McDougall *et al.*, 2013; Egunyu and Reed, 2015). The ability to contribute is controlled by many factors, such as education, culture, and gender (Senecah, 2004). Therefore, successful social learning processes must ensure they provide an environment and support for all participants to engage in the process (Egunyu and Reed, 2015). Another challenge arises in the measurement of outcomes from a social learning process. In particular, surface level cognitive learning of factual knowledge and skills is easier to attribute to an individual activity or interaction. It is more difficult to identify the causal factors behind deeper normative learning of beliefs, roles, norms, and attitudes (Lebel *et al.*, 2010). Finally, social learning research projects should not assume that through the use of participation that social learning will automatically occur (Reed *et al.*, 2010). There are several examples of participatory processes which have failed to facilitate social learning (e.g. Ison and Watson, 2007; Bull *et al.*, 2008). Despite this, links between well-designed participatory processes and social learning are well established (e.g. Webler *et al.*, 1995; Tippett *et al.*, 2005; Cundill and Rodela, 2012).

2.3.5. Participation in legislation and policy

Stakeholder participation in decision-making processes is emerging as a key requirement in policy and legislation (see: Bulkeley and Mol, 2003; Jessel and Jacobs, 2005; Pohjola and Tuomisto, 2011). In the European Union, this uptake has been driven by two seminal pieces of international legislation which call for participation in environmental decision-making. These are the United Nations Economic Commission for Europe's 1998 Aarhus Convention, and Principle 10 of the Declaration from the United Nations Conference on Environment and Development of 1992, the 'Rio Conference' (Howarth, 2009). Environmental interest groups are increasingly asserting these principles to ensure their participation in environmental decision-making (Reed, 2008). The WFD reflects the uptake of the international legislation in the European Union by encouraging proactive engagement with stakeholders in the management of water resources (2000/60/EC), and in the creation of River Basin Management Plans (RBMPs) (Wilby *et al.*, 2006). The WFD is considered to be the most ambitious and significant piece of European legislation created, as it seeks to introduce a multi-level system of governance and involve previously excluded 'non-environmental' sectors (Howarth, 2009). In addition to the WFD, there have been several other significant pieces of European Union legislation that advocate the importance of participation in environmental issues, such as the Strategic Environmental Assessment Directive (2001/42/EC), the EU Public Participation Directive (2003/35/EC), and the European Flood Directive (2007/60/EC).

The implementation of the participatory element of the WFD has proved difficult in many European countries, with significant increase in the quantity and quality of participation needed in order to achieve the WFD requirements (De Stefano, 2010). For example, in Catalonia, Spain the Agència Catalana de l'Aigua (ACA – Catalan Water Agency) attempted to adopt the principles of participation with regards to integrating the *'economical, social and environmental aspects into the sustainable* *management of the hydrological system.'* (Broekman, 2013, p. 234). However, despite the ACA's best intentions, changing political and economic conditions in 2012 rendered the participatory processes conducted in the creation of RBMPs between 2006 and 2010 meaningless. Instead of implementing the outcomes of these processes, the government shifted back to allowing people in positions of power to make the decisions, usually based on an individual's private interests (Broekman, 2013). Research by Staddon (2010a) suggested that public participation requirements would assimilate themselves differently within each EU member country, with former Eastern Bloc member countries facing the largest challenges in making participation 'work'.

In order to achieve the goals of the WFD in the United Kingdom, the Environment Agency (EA), as environmental regulator, proposed a hierarchy of stakeholder involvement from the national to community levels, with participation ranging from the provision of information to deliverables on the ground (Environment Agency, 2015). Linking back to Arnstein's ladder, these methods suggest the EA is attempting to achieve a more consultative relationship with stakeholders and members of the public, transitioning away from traditional approaches of 'non-engagement'. At the same time, it was clear that the EA, perhaps with the statutory requirements in mind, was not prepared to yield significant control over the outcomes or the process, leading many critics to label the process as 'sham consultation'. More recently, in the United Kingdom, the Department for Environment, Food and Rural Affairs (DEFRA) announced the 'Catchment Based Approach: Improving the quality of our water environment' (Corbelli and Conlan, 2012). This Catchment Based Approach has two key objectives:

- To deliver positive and sustained outcomes for the water environment by promoting a better understanding of the environment at a local level;
- To encourage local collaboration and more transparent decision-making when both planning and delivering activities to improve the water environment.

This approach first started in April 2011 with the establishment of 25 pilot catchments and comprised of groups of 'key' stakeholders referred to as 'catchment partnerships' (Environment Agency, 2012). Following a successful pilot stage (Corbelli and Conlan, 2012), from May 2013 the Catchment Based Approach has been rolled out across the United Kingdom. The pilot stage indicated that catchment level collaboration can better inform river basin district planning and improve decision making 'on the ground'. One of the primary objectives of the catchment partnerships is to inform the river basin district planning process in developing the second cycle of RBMPs (Figure 2-6). However, the catchment partnerships have no statutory responsibilities or direct decision making power; instead the EA acts as an intermediary between the production of RBMPs and the catchment partnership groups (DEFRA, 2013). The terminology of 'Partnerships' and 'Collaboration' suggests that through this approach, DEFRA and the EA are hoping to move further up Arnstein's ladder to achieve 'citizen power'. On the other hand, as with some of the earlier criticisms of participatory approaches in development (e.g. Chambers, 1994a), it could be argued the Government is failing to provide adequate resourcing and decision-making power to citizens through these processes. This raises real questions around the incentives for organisations to participate in the Catchment Based Approach. However, in the end participatory approaches to environmental decision-making succeed or fail depending on whether participants see that their time and energy is being used productively and respectfully to inform outcomes. While it may not always necessary for decision-making processes to ascend to the very top of Arnstein's Ladder (Citizen Power), responsible bodies such as the EA need to be absolutely clear about the purpose of their participation.

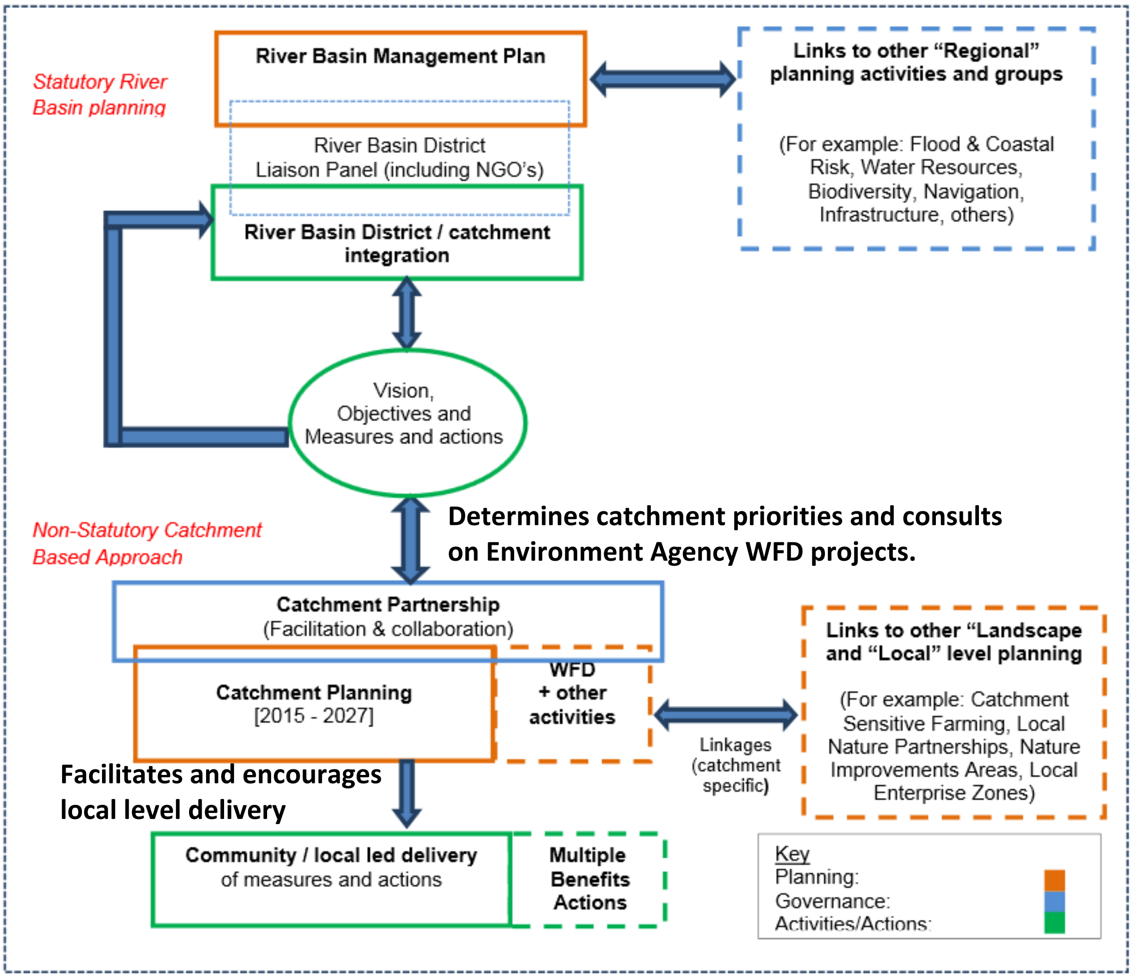


FIGURE 2-6: CATCHMENT BASED APPROACH LINKAGES TO OTHER GROUPS AND INITIATIVES. ADAPTED FROM: DEFRA (2013, P. 9).

(USED UNDER THE OPEN GOVERNMENT LICENCE)

2.4. Participatory modelling (PM)

Traditional modelling exercises have been carried out by those with specific training and expertise in representing natural systems. Typically, stakeholder feedback on these processes would be non-existent or controlled (Bailey and Grossardt, 2010). Modellers have tended to use what is termed the DAD, 'decide, announce and defend' approach to the development of new models (Figure 2-7 - A). The paradigm is slowly shifting towards involving individuals or groups of stakeholders in this process (Voinov and Bousquet, 2010). This new paradigm is being termed participatory modelling (PM) (Figure 2-7 - B), which is defined as:

'A diverse range of modelling activities whose common element is that they involve stakeholders in one or more stages of the modelling process.'

(Hare, 2011, p.386)

PM approaches such as group modelling building (Richardson and Andersen, 1995; van den Belt, 2004) and companion modelling (Bousquet *et al.*, 1999; Becu *et al.*, 2008) are situated within a dialogic epistemology, as they promote the exchange of values and knowledge between stakeholders and modellers, through an iterative dialogic process. The individual terms of 'participation' and 'modelling' are quite broad. For example, a model can take many forms from a simple written representation of stakeholders' values to complex numerical computer-based representations of physical systems (Jones *et al.*, 2009). As a result, PM has been applied in a wide variety of disciplines with a large diversity in purpose, process design and implementation. Table 2-7 reviews the main participatory modelling approaches described in the literature.

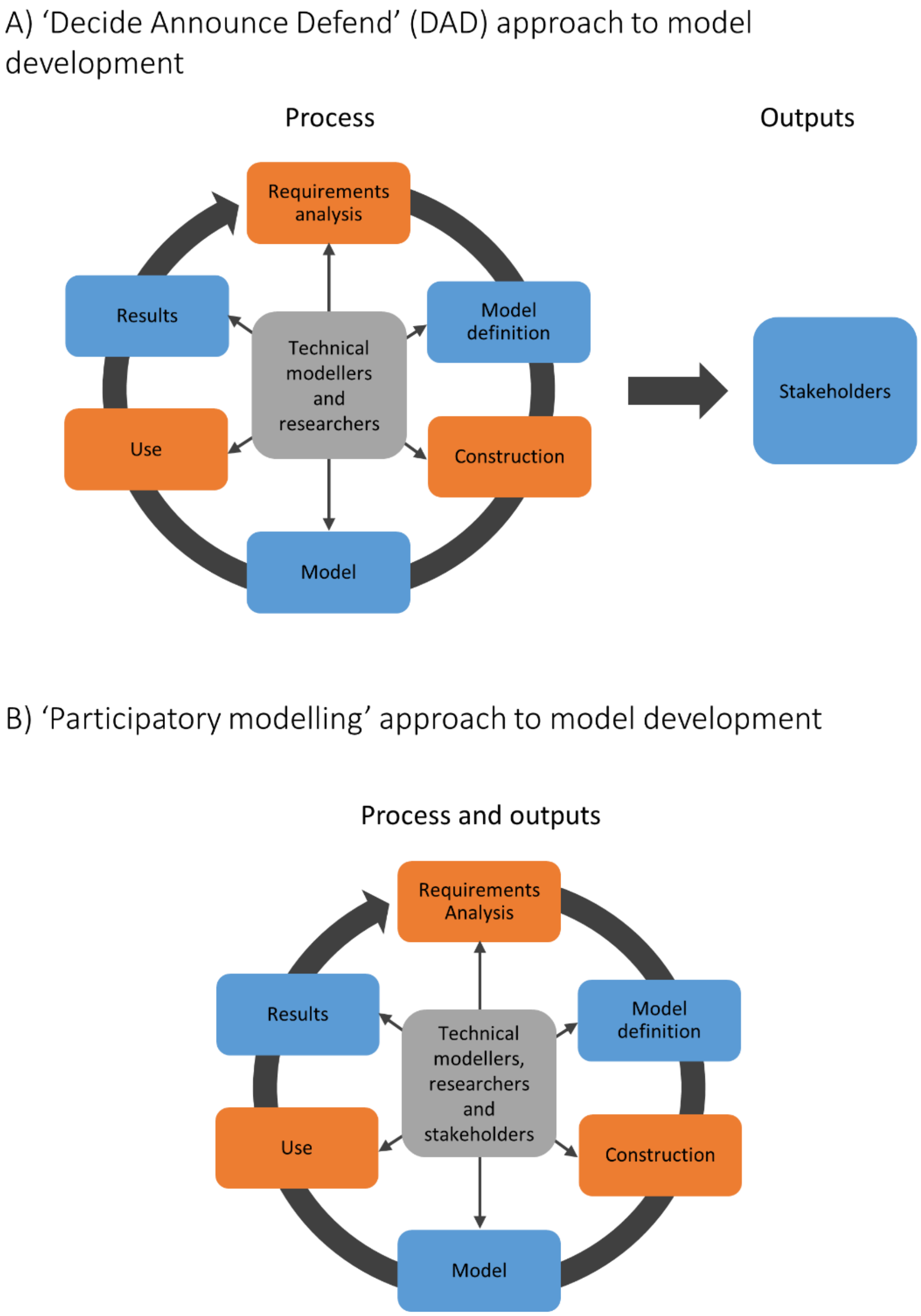


FIGURE 2-7: SCHEMATIC REPRESENTATION OF THE TRADITIONAL 'DECIDE ANNOUNCE DEFEND' (DAD) APPROACH (A) AND A PARTICIPATORY MODELLING APPROACH TO MODEL DEVELOPMENT (B).

TABLE 2-7: SUMMARY OF MAIN PARTICIPATORY MODELLING APPROACHES.

Participatory modelling approach	Description	References
Group Model Building (GMB)	This approach is based on informal modelling, utilising causal loop diagrams and other visual modelling tools. This may include the use of system dynamics tools (e.g. DYNAMO or Stella) or Delphi. Typically, the GMB process involves a group of stakeholders in the process of developing a conceptual model with a neutral facilitator. To date, GMB has mainly been used in business applications and environmental management.	(Richardson and Andersen, 1995; Vennix, 1996; Andersen and Richardson, 1997; den Exter and Specht, 2003)
Mediated Modelling (MM)	Trademarked by a company called Mediated Modelling Partners, LLC, MM is slightly different from GMB as it focuses on environmental application and uses icon-based software. Stakeholders provide input into the development of a dynamic model. The process is time and resource expensive, requiring a high level of stakeholder commitment.	(Metcalf *et al.*, 2010; van den Belt, 2004)
Companion Modelling (CM)	CM involves the use of role-playing games and/or agent-based models with stakeholders in the development of a model. The purpose of a CM process is to promote the views of the stakeholders and any consequences associated with their actions (including those of the scientists). Expected outcomes from a CM process are social learning or organisational/technological innovations.	(Anselme *et al.*, 2010; Campo *et al.*, 2010; Simon and Etienne, 2010)
Participatory simulation (PS)	In a similar manner to CM, PS involves the use of role-playing games in a software simulation package. PS was developed in the 1960's by the system dynamics group at MIT. Examples of PS include: StarLogo and NetLogo. The primary aim of these two examples is to teach object-orientated programming to groups of young people. This software has been developed further for environmental management purposes. In particular, through allowing users to play the role playing games over the internet.	(StarLogo, 2015; NetLogo, 2015; Meadows *et al.*, 1986; Wilensky and Stroup, 2002; Wilensky and Stroup, 1999)
Shared Vision Planning (SVP)	SVP was an approach developed by and a trademark of the US Army Corps of Engineers. SVP has predominately been used to resolve issues around the management of resources. There is little published peer-reviewed material on SVP.	(Delli Priscoli, 1995; Palmer *et al.*, 1999)
Computational Participatory Modelling (CMP)	CMP is a new term developed in this thesis to encompass a new type of participatory modelling not defined in the reviewed literature. CMPs are processes that involve stakeholders in development or refinement of computational models. This would also include the PM approach developed and implemented in this thesis.	(Lane *et al.,* 2011; Barnaud *et al.,* 2013; Carmona *et al.,* 2013; Bommel *et al.,* 2014; Maskrey *et al.,* 2016)

Stakeholders can be involved in many stages of a PM process including: data collection, model design and assumptions, model construction, scenario development and the interpretation of results (Becu *et al.*, 2008). There are many different PM approaches and these differ depending on characteristics such as, the aim of the process, the timing of participation and level of participation required (van den Belt, 2004). A correctly designed and implemented PM process can achieve the higher rungs on

Arnstein's (1969) ladder of citizen participation, as it encourages a two-way process of knowledge exchange, benefiting the scientific research or decision-making process, and the stakeholder communities (Bots and van Daalen, 2008). For example, Newig *et al*. (2008) conducted a series of PM activities with groups of stakeholders with the goal of improving their knowledge of the WFD and aiding the implementation of groundwater protection measures in the Hase sub-basin in Germany. Newig *et al*. (2008) concluded the methods employed achieved the aims of the research, these were: (i) to promote knowledge exchange, and (ii) social learning between participants.

PM has gained popularity and recognition as a useful method for improving communication and knowledge exchange between stakeholders and scientists over the last decade (Hare, 2011; Maskrey *et al.*, 2016). PM has been suggested as a solution to the problem of limited uptake of research-developed models by practitioners (Borowski and Hare, 2007). The result of activities, such as group model building, have resulted in a greater understanding of system dynamics through encouraging groups to share their understanding of natural systems. This breaks down some perceptions of 'black-box' modelling as a result of knowledge exchange (Ridder *et al.*, 2006; Laniak *et al.*, 2013). Furthermore, legislation such as the WFD now requires environmental managers and policy makers to engage with stakeholders in their work (see: Jessel and Jacobs, 2005; Staddon, 2010b). Finally, there has been increased funding for research which has been focused on investigating, using and analysing PM methodologies (see: Bots and van Daalen, 2008; Hare, 2011; Haase, 2013).

There are several examples of traditional scientific disciplines, such as hydrology and ecology utilising PM approaches in their research (e.g. Lane *et al.,* 2011; Barreteau *et al.,* 2010; Etienne *et al.,* 2011; Maskrey *et al.,* 2016). In hydrology the use of PM has focused around the interface with societal issues, in particular flood risk management. For example, Lane *et al.* 2011 developed two new flood models through a PM process with a local group of stakeholders in Pickering, North Yorkshire, United Kingdom. In this study, the physical scientists did not set out to develop new models. Instead, the researchers planned to use existing hydrological models to run scenarios and generate outputs to engage with the stakeholders in a new method of *'trying out a different means of practising science'*. However, after engaging with the group of stakeholders, the types of modelling identified by the scientists were considered to not be suitable. Lane *et al.* (2011) concluded the results generated from the process demonstrated an environment of co-production and sharing of knowledge between the stakeholders and the researchers. More recently, Maskrey *et al.* (2016) utilised participatory modelling approach with flood risk experts and local stakeholders to co-construct a Bayesian network model in order to understand local flood risk.

The process of PM is not without criticism, particularly around degree of engagement with stakeholders; in most cases stakeholders are only paid 'lip service' and engagement is limited (Voinov and Bousquet, 2010). Additionally, PM processes sometimes over-use qualitative methods, which are considered to lack the rigour and systematic process for analysing and representing the views from participants (Mendoza and Prabhu, 2005). However, Newig *et al.* (2008) emphasise the importance of achieving the correct balance between formalised (or structured) and informal methods in PM processes. Formalised methods are suggested to act as a 'filter', omitting certain types of information, risking that insufficient information is collected; however, formalised methods have the advantage of providing *'focused, clear and unambiguous information'* and *'counterbalance unwanted group dynamics such as the tendency towards the convergence of ideas'* (Newig *et al.*, 2008, p. 425). On the other hand, formalised methods are time intensive and require technical expertise and equipment; as a result stakeholders may have difficulty in understanding and actively engaging in the process (Newig *et al.*, 2008).

The combination of participatory methods and numerical modelling is recognised to be problematic, specifically when the project drifts too far away from the participatory approach. This disconnection often leads to stakeholders leaving the project, and the validity of the PM modelling approach coming into question (Becu *et al.*, 2008). Another difficulty discussed when combining numerical modelling in PM modelling is the 'translation' process between the qualitative output from the PM process and quantitative model elements. Walz *et al*. (2007) suggest that improved documentation of the process will result in better integration of the two. Finally, in many cases, the PM process tends to be based on a single case or group, so there are fears around uniqueness or artificial conditions surrounding the outcomes of each case (Etienne *et al.*, 2011). Table 2-8 provides a summary of these issues alongside other participatory challenges identified and discussed throughout this section of the chapter.

TABLE 2-8: PARTICIPATORY MODELLING CHALLENGES IDENTIFIED THROUGH THE REVIEW OF THE LITERATURE.

Challenges	**References**
Hijacking by special interest groups that do not reflect the wider opinion.	(Broad *et al.*, 2007)
Participation of stakeholders in the process is mere 'tokenism' and they have no real power to influence the decisions made.	(Voinov and Bousquet, 2010)
Disillusionment of stakeholders with the process as they find it difficult to contribute in scientifically complex situations. This can often result in certain 'key' players within groups having a more significant influence on the decisions made.	(Broad *et al.*, 2007; Newig *et al.*, 2008)
Researchers involved in these processes find it difficult to maintain their scientific objectivity as the lines between research and actions become blurred.	(Newig *et al.*, 2008)
Over-use of qualitative methods, which are considered to lack the rigour and systematic process for analysing and representing the views from participants.	(Mendoza and Prabhu, 2005)
The project drifts too far away from the participatory approach. This disconnection often leads to stakeholders leaving the project.	(Becu *et al.*, 2008)
Translation process between the qualitative output from the PM process and quantitative model elements.	(Walz *et al.*, 2007)
The participatory process tends to be based on a single-case or single group, so there are fears around uniqueness or artificial conditions surrounding outcomes of each case.	(Etienne *et al.*, 2011)

There have been several frameworks for classifying participatory modelling studies; these are shown in Table 2-9. Bots and van Daalen's (2008) framework aims to assist analysts in the design of PM processes. To do this, they focus on three areas: modelling exercise, model type and method, and participation model. Within each area, the framework outlines decisions that the analyst must make when designing a process and provides a typology for each. Hare (2011) adapted Bots and van Daalen's framework by splitting, and developing upon, each of the three areas (Table 2-10); in some cases, this has resulted in a simplification, such as in defining the model type. This framework is centred on seven themes, with an aim to aid in the clarification of participatory modelling exercises.

TABLE 2-9: COMPARISON OF FRAMEWORKS FOR CATEGORISING PARTICIPATORY MODELLING PROCESSES. SOURCE: HARE (2011, P.388)

Framework	**Criteria used**									**Main purpose of framework**
	Participatory modelling purpose	*Participatory structure*	*Control of flow of information between stakeholders*	*Timing of events*	*Participation mode*	*Model type*	*Participatory methods used*	*Stakeholders involved at each stage*	*Skills needed*	
Hare *et al.* (2003)	X	X								Analyse links between participatory structure and process implementation
Barreteau *et al.* (2010)			X	X	X					Provide clear description of process (manage expectations); monitoring and evaluation
Bots and van Daalen (2008)	X			X	X	X	X			Support process design
Hare (2011)	X			X	X	X	X	X	X	Identify general forms of participatory modelling

Table 2-10: Summary of Hare's (2011) Participatory modelling framework

Participatory categories	Sub-categories			Supporting materials and studies
Participatory modelling purpose	Direct decision-making			(Ridder *et al.*, 2006; Bots and van Daalen, 2008; Barreteau *et al.*, 2010)
	Social learning			
	Model improvement	Quality		
		Acceptance		
		Integration		
Model type	Simulation			(Wainwright and Mulligan, 2005; Barreteau *et al.*, 2010)
	Conceptual			
Stakeholders involved	Organising team			(Hare, 2011)
	Stakeholder types			
Timing of events (Modelling stages)	Data collection			(Squires and Renn, 2011)
	Model definition			
	Model construction			
	Model verification/validation			
	Model use			
Participatory methods	Data collection	Participatory monitoring and surveys		(Squires and Renn, 2011)
		Stakeholder contributed data		
	Model definition	Structured or unstructured interviews		(Hare and Pahl-Wostl, 2002; Rugg and McGeorge, 2005)
		Card sorting		
		Cognitive mapping		(Vennix, 1996)
		ARD stages of ARDI		(Etienne *et al.*, 2011)
		Requirements analysis		(Ramanath and Gilbert, 2004)
		Joint application design workshops		
		Prototyping		
		User panels		
	Model construction	Group model building		(Vennix, 1996)
		ARDI co-construction method		(Etienne *et al.*, 2011)
		Hexagon modelling		(Hodgson, 1992)
	Model verification/validation	Show and tell verification		(Vennix, 1996; Squires and Renn, 2011)
		Show and tell validation		
		Focus groups		
		Questionnaires		
	Model use	Stakeholder model use	Direct use	(Hare, 2011)
			Mediated use	
		Use-by-demand		
		Simulation-by-hand		
Participation mode	Stakeholders involved as individuals			(Bots and van Daalen, 2008)
	Stakeholders involved as group with homogeneous interests			
	Stakeholders involved as a group with heterogeneous interests			
Skills needed to organize and implement the participatory modelling.	Modelling skills			(Hare, 2011)
	Facilitation skills			
	Knowledge acquisition skills			

2.5. Synthesis

The literature explored in this chapter emphasises the importance of fluvial geomorphology to sustainable river catchment management (Objective 1); in particular, the role that fluvial geomorphology has in contributing knowledge to the management of ecological status and flood risk of river channels. This is now reflected to a degree in European legislation through the recognition of the importance of fluvial geomorphological processes under hydromorphology in the WFD and through the creation of CFMPs and RBMPs. Despite this, there are still very few direct references to fluvial geomorphology within river management legislation and practice. This suggests that fluvial geomorphologists are struggling to communicate effectively this importance to river management practitioners and stakeholders. Gregory refers to this as a ‘paradigm lock’, arguing that in such cases limited knowledge exchange is taking place. This has been reflected by senior academics within Geomorphology recognising the need to communicate more effectively beyond academia. However, the majority of methods suggested by concerned fluvial geomorphologists are one-way, top-down processes of knowledge exchange.

One of the areas in which there has been limited practical application is in the modelling of sediment dynamics. This is despite a growing demand to develop a scientifically rigorous model of sediment dynamics to assist in the sustainable management of river catchments. More specifically, this could be achieved through the use of intermediate scale reduced-complexity cellular models (e.g. CAESAR-Lisflood).

A possible methodological approach to increase the practical application of models referred to as participatory modelling was identified through a review of approaches to participation and stakeholder engagement in environmental management and modelling (Objective 2). The literature suggests this methodological approach can reduce the limited uptake of research-developed models by practitioners and increase model quality, acceptance and integration. Furthermore, participatory modelling is recognised as a method of promoting knowledge exchange between scientists and stakeholders, and has the ability to create an environment for social learning between participants.

Chapter Three: Methodology

The aim of this chapter is to present the participatory methodology used to develop and evaluate a new, stakeholder-informed, cellular model of river sediment dynamics. To begin with, this chapter presents the overarching research strategy. This includes a discussion of the theoretical and methodological rationale, and explains the use of a fundamental model structure. The second section focuses on the participatory process, including an exploration of the selected stakeholder groups and a comprehensive discussion of each participatory modelling (PM) session. The third section presents the methods for evaluating the PM process with the stakeholders. The fourth examines the methodology for assessing the created model in relation to its usability and usefulness. The final two sections detail the ethical considerations related to this thesis and summarise the material covered.

3.1. Research strategy

3.1.1. Theoretical and methodological rationale

The discussion below moves through the different theoretical approaches in science and identifies the ontology and epistemology adopted in this thesis. There are three dominant epistemological approaches in science: positivism (or empiricism) (Comte, 1868), critical realism (Bhaskar, 1975) and constructivism (or interpretivism) (Berger and Luckmann, 1966). Positivist researchers believe that the world can be defined objectively and aim to produce transcendent truths about observed phenomenon (Robson, 2002). For example, a positivist approach suggests that physical systems such as rivers can be measured and represented objectively, and that once 'understood', they stay understood, unperturbed by shifts in human perception. The positivist approach therefore attempts to remove entirely or reduce the role and influence of the researcher on the object being researched (for a review see: Hacking, 1983). In the social sciences, positivist aligned studies have come under heavy criticism as the knowledge and understanding produced are inherently much more subjective in nature and influenced by personal experiences and motives than (most) positivists are prepared to admit. For example, few would propose reducing studies of social change to immutable data on demographic trends. Therefore, understanding the cultural and social aspects that influence the observer of the phenomena are important (Robson, 2002).

The opposite of positivism is constructivism which states that reality and knowledge are located in the minds of individuals; therefore, an objective reality cannot be known since it cannot be entirely separated from the context in which it was created (which is why this epistemology is sometimes called contextualism or interpretivism) (Robson, 2002). Importantly, constructivism proposes that knowledge about the world is constructed, through individuals' experiences and linguistic reflections on the phenomenon around them (Savin-Baden and Major, 2013). The classic statement of this epistemology in social science was published in 1966 in Peter L Berger and Thomas Luckmann's 'The social construction of reality'. Geographers have arrived at the same epistemological stance via different routes, for example work by Michel Callon and Bruno Latour on 'Actor Network Theory' (e.g. Latour, 1999).

Critical realism, in contradistinction to both of the above, occupies the middle ground between the pure constructivist and the pure positivist positions, taking aspects from each (for a review see: Archer *et al.*, 1998). With positivist and post-positivist perspectives, realists argue that there is indeed an objective empirical realm that exists separate from discursive representation. However, they also acknowledge that all but the simplest systems are 'open' and indeterminate – a truth demonstrated by the fact that even a relatively 'closed' topic such as sediment dynamics in a fluvial system admits sufficient openness and indeterminacy of links between variables which fail to satisfy the strict requirements of positivist explanation. Consequently, critical realists suggest that there is a distinct difference between objective (how things really are – bias free) and subjective reality (our interpretations and knowledge – influenced by social, cultural and historical factors). Hence, a critical realist's perspective accepts that an independent reality exists outside our subjective interpretations (Mingers *et al.*, 2013).

There is a wealth of theoretical literature detailing how knowledge generated through the research process is influenced by the values held by the researcher. Furthermore, these values affect the judgements made on the methods chosen and the questions asked (see: Shipman, 1997; Hammersley, 2000; Flyvbjerg, 2001). Therefore, the role and influence of the researcher in analysing the data and generating results is recognised in this thesis, as Halfpenny (2001) suggests 'true' objectivity can never be achieved in any research. Two of the crucial components in recognising this influence on the research, are that: the 'researcher makes their (epistemological and other) assumptions explicit' (Braun and Clarke, 2006, p. 5); and as, Braun and Clarke (2006, p. 9) suggest, the researcher acknowledges that:

> *'any theoretical framework carries with it a number of assumptions about the nature of the data, what they represent in terms of "the world", "reality, and so forth" and it is important to make this "transparent"'.*

This is supported by Hammersley (1995), among others, who promotes the importance of engaging with the values and assumptions responsible for the research aims and methodology so that knowledge can be situated within the context in which it is generated.

The recognition of the importance of social, cultural and historical factors has culminated in a socially aware approach to knowledge production, termed 'post-normal science' (Funtowicz and Ravetz, 1995). Through engagement on issues with an 'extended peer community' and dialogue with affected stakeholders 'post-normal science' aims to increase both the quality of the science and policies. 'Post-normal science' is considered to be an approach to science in the age of global environmental issues, such as climate change, where the communicated risks are constantly changing as our knowledge advances (Hulme, 2007). In particular, computer models are a useful example of post-normal science as these are the best tools available for making predictions, but are inherently impossible to comprehensively validate (Lane and Richards, 2001). Therefore, in highly contested situations such as environment and economic policy, there is a shift from the 'facts' to the values held by society, emphasising the importance of recognising these values in scientific research (Funtowicz and Ravetz, 2003).

Traditionally, the development of models of sediment dynamics could be argued has been entirely situated within the positivist epistemology developed in the physical sciences (for a discussion of positivism in Physical Geography, see: Richards, 2009). However, a PM process is used in this research to explore individual stakeholders' understanding of sediment dynamics and uses their views – that are partial, fragmentary and unsystematic – to inform and direct the development of a model. Therefore, a critical realist epistemology and 'post-normal science' approach is adopted in this thesis, recognising that fluvial systems exist independently of individuals' interpretations and experiences of them. Sayer (2000, p. 2) supports this, proposing that:

> *'it is the evident fallibility of our knowledge – the experience of getting things wrong, of having our expectations confounded, and crashing into things – that justifies us in believing that the world exists regardless of what we happen to think about it'.*

Consequently, three important aspects regarding the knowledge generated within this PhD are acknowledged. Firstly, the knowledge generated from the PM process represents the researcher's interpretation of the subjective meaning that stakeholders give to their experiences and understanding of sediment dynamics and models. This accepts that the researcher has, to a degree, impacted on the knowledge produced and there is the possibility of alternative valid accounts (Maxwell, 2012). Secondly, through the participatory PM processes, knowledge was exchanged from the researcher to the stakeholders, vice versa and between stakeholders; therefore, exemplifying the above point. Thirdly, the model created through this process will be the product of this interpretation and that, in creating this model, the processes represented are simplifications of reality that seek to characterise aspects of real-world phenomenon (Grüne-Yanoff and Weirich, 2010), in this case river catchment sediment dynamics. Therefore, the numerical computer-based model created through this process attempts to provide, through imitating real world processes (Hartmann, 1996), an accurate but incomplete account of sediment dynamics (including the influence of the researcher's knowledge). As Lane (2011) recognises, every model can be readily shown to be invalid due to their nature of numerical approximations and the difference between modelled outputs and field measurements.

These insights into the theoretical perspectives that underpin science have been used to inform the researchers' epistemological stance, methodological approach and methods outlined below. The methodology adopted develops a transdisciplinary post-normal PM approach (see Section 2.1.5 for a definition of transdisciplinary research), combining numerical computational cellular modelling with social science data collection and analysis techniques with groups of stakeholders. The aims of undertaking this approach were: (i) to improve model quality; (ii) increase acceptance, trust and understanding of the model by stakeholders; (iii) enable integration of the created model with existing stakeholder management processes and systems; (iv) to promote knowledge exchange between fluvial geomorphologists and stakeholders that will enrich the professional practice of both; (v) to facilitate an environment for social learning to occur, whereby the stakeholders gain an improved understanding of the science and other stakeholders' perspectives of the management and modelling of sediment dynamics, and the researcher gains an improved understanding of the requirements and challenges faced by river management practitioners; and finally (vi) to compare the developed approach with the traditional approaches to modelling.

This methodological approach involves the use of qualitative and quantitative mixed-methods to allow for sufficient data reflective of stakeholders' opinions to be collected, analysed (Objective 3.A.) and implemented in the process of developing a cellular model of sediment dynamics (Objective 3.B.). This methodology hinged on designing and implementing a collaborative process (as recognised by Prell *et al.*, 2007), whereby the views and opinions of the stakeholders are incorporated throughout model development. Stakeholders were not able to directly challenge established physical processes or equations (e.g. Wilcock and Crowe's (2003) sediment transport equations) within the model. However, they were able to select which processes were represented and other important aspects, such as the selection of adjustable parameters, outputs and interfaces. Stakeholders were involved from the initiation of the project in a reflexive, dialogical, flexible, interactive and iterative manner.

The literature presented in the previous chapter identified that a novel approach to developing models has emerged over the past two decades in various forms of PM (e.g. Mediated Modelling or Companion Modelling (Table 2-7)). In order to achieve the aims described above, a PM process was developed based upon Hares' (2011) general framework for classifying PM processes. Figure 3-1 illustrates conceptually how each of the selected and developed participatory methods fit together with the stages of developing a numerical computational model. Table 3-1 shows an overview of how this innovative process fits within Hares' framework, shown previously in Table 2-10. This framework was chosen as a basis for developing this process as this was the most detailed and refined of those reviewed in Section 2.4.

The process shown in Figure 3-1 utilises the co-construction form of PM. This was chosen over other methods, such as developing the model without involving stakeholders in the process, or a form of 'back-end' modelling, where the stakeholders are only involved at the end (Hare, 2011). These approaches are closer to the 'traditional' DAD approach to model development and, as discussed in the literature review, to date such processes have failed to produce an effective tool consistently used in sustainable river catchment management. Through a co-construction form of PM, the stakeholders go through the same thinking processes as a modeller and gain an understanding of the model's assumptions, limitations and end-uses (see: Castelletti and Soncini-Sessa, 2007). Furthermore, this form of PM provides the stakeholders with several opportunities for knowledge exchange and social learning to occur through a diverse range of activities.

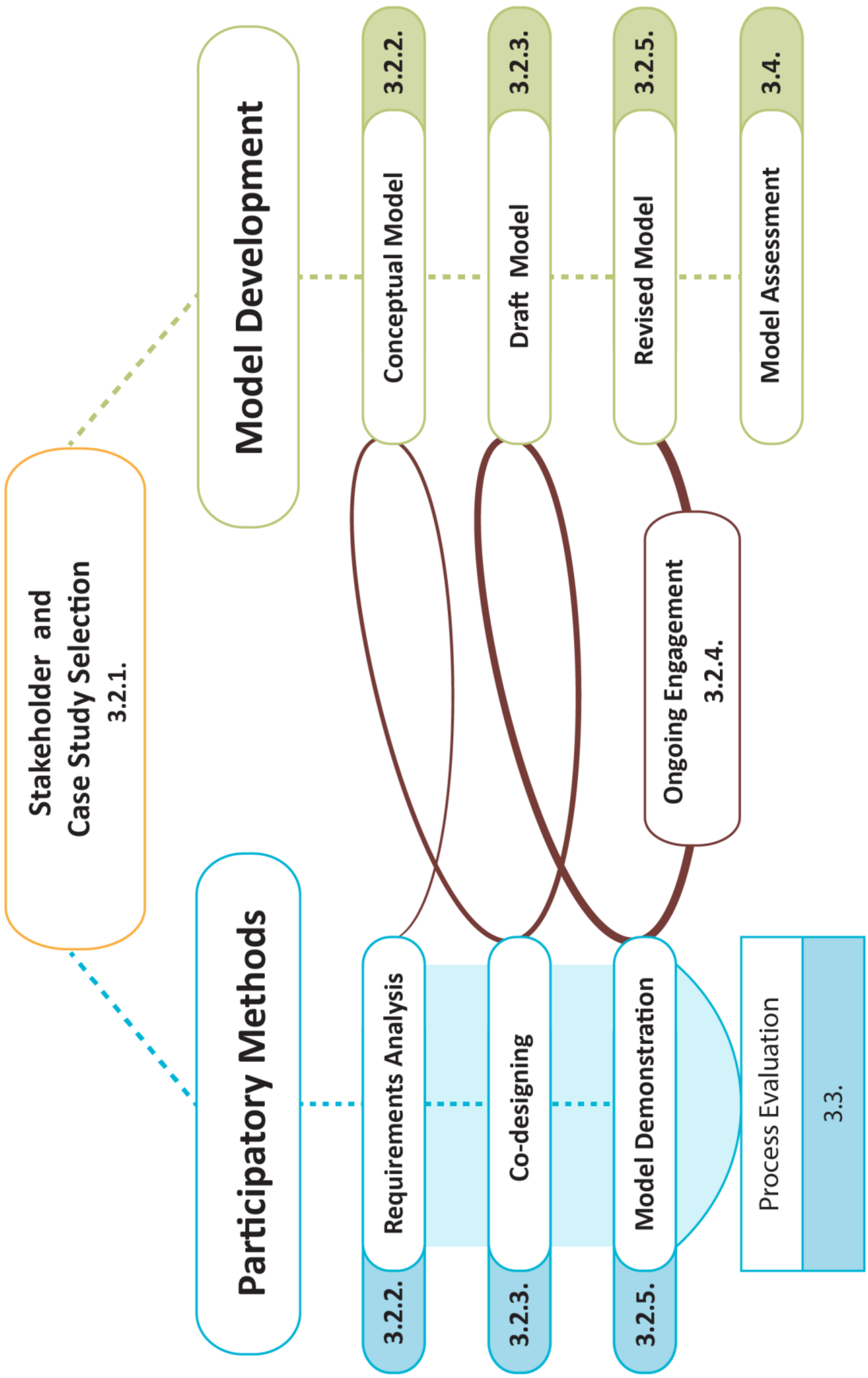


FIGURE 3-1: CONCEPTUAL DIAGRAM OF THE PARTICIPATORY MODELLING METHODOLOGY FOR DEVELOPING A CELLULAR MODEL OF SEDIMENT DYNAMICS. THE NUMBERS REFER TO THE LOCATION WITHIN THIS CHAPTER THAT EACH ASPECT IS COVERED.

TABLE 3-1: THE PARTICIPATORY METHODOLOGY ADOPTED IN THIS RESEARCH SITUATED WITHIN HARE'S (2011) PARTICIPATORY MODELLING FRAMEWORK.

<table>
<tr><th>Participatory categories</th><th colspan="3">Selected areas of focus</th></tr>
<tr><td rowspan="4">Participatory modelling purpose</td><td colspan="3">Social learning and knowledge exchange</td></tr>
<tr><td colspan="2" rowspan="3">Model improvement</td><td>Quality</td></tr>
<tr><td>Acceptance</td></tr>
<tr><td>Integration</td></tr>
<tr><td>Model type</td><td colspan="3">Simulation</td></tr>
<tr><td rowspan="2">Stakeholders involved</td><td colspan="3">Organising team</td></tr>
<tr><td colspan="3">Stakeholder types</td></tr>
<tr><td rowspan="5">Timing of events (Modelling stages)</td><td colspan="3">Data collection</td></tr>
<tr><td colspan="3">Model definition</td></tr>
<tr><td colspan="3">Model construction</td></tr>
<tr><td colspan="3">Model verification/validation</td></tr>
<tr><td colspan="3">Model use</td></tr>
<tr><td rowspan="5">Participatory methods</td><td>Model definition</td><td colspan="2">Requirements analysis</td></tr>
<tr><td>Model construction</td><td colspan="2">Group model building</td></tr>
<tr><td>Model verification/validation</td><td colspan="2">Show and tell validation/ verification</td></tr>
<tr><td rowspan="2">Model use</td><td rowspan="2">Stakeholder model use</td><td>Direct use</td></tr>
<tr><td>Mediated use</td></tr>
<tr><td>Participation mode</td><td colspan="3">Stakeholders involved as group with homogenous interests</td></tr>
<tr><td rowspan="3">Skills needed to organize and implement the participatory modelling.</td><td colspan="3">Modelling skills</td></tr>
<tr><td colspan="3">Facilitation skills</td></tr>
<tr><td colspan="3">Knowledge acquisition skills</td></tr>
</table>

To date, the co-construction PM approach has 'almost exclusively' been used for the development of conceptual and non-numerical models (Hare, 2011, p. 394). There are some recent examples of numerical models, such as agent based models (e.g. Barnaud *et al.*, 2013; Bommel *et al.*, 2014) and others combining the use of Bayesian networks with numerical models (e.g. Carmona *et al.*, 2013; Maskrey *et al.*, 2016). However, the combination of model development and the co-construction PM approach used in this thesis is considered to be unique. Additionally, at the time of writing and to the best knowledge of the researcher, there has been no similar research in the field of fluvial geomorphology, and only limited examples in other disciplines (e.g. Daniell *et al.*, 2010; Newig *et al.*, 2008; Maskrey *et al.*, 2016).

Methodologically, the Hase case study by Newig *et al.* (2008) is the most closely related to the methodology used in this thesis (described in Section 2.4.). In particular, the Hase case study used a variety of participatory methods, including: interviews, focus groups, cognitive mapping, and group model building exercises to develop a conceptual model. Several of these methods have been adapted for this thesis; however, some innovative methods were developed by the researcher to engage stakeholders in the development of a numerical computational model.

The developed PM process adopts a combination of formalised and non-formalised mixed-methods to collect appropriate qualitative and quantitative data to achieve the aims and objectives. Figure 3-2 breaks down the developed PM process into its individual components. This figure demonstrates how the outputs from each stage are used to inform the development of the model or feed into the next PM session.

To avoid confusion in the reporting of the methods and results, the terminology suggested in Newig *et al.* (2008) when referring to the flows of information in the PM process are adopted in this thesis:

- *Giving information* – information transfer from the project team to the stakeholders;
- *Extracting information* – the flow of information from the stakeholders to the project team;
- *Mutual exchange of information* – a two-way interactive exchange of information.

The next section discusses the use of a fundamental modelling approach as a platform for the PM process to build upon.

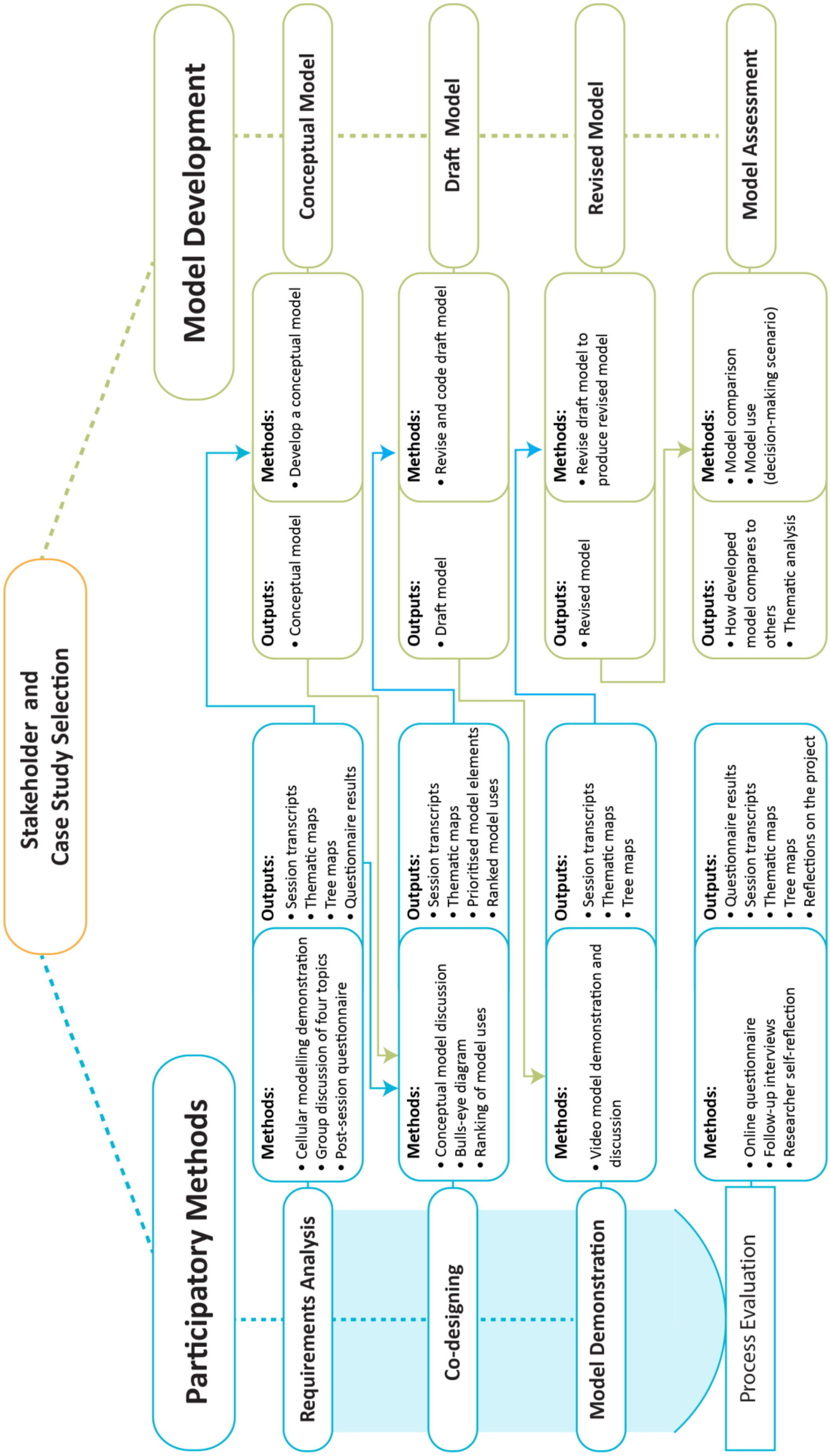


FIGURE 3-2: CONCEPTUAL DIAGRAM OF THE FLOWS OF KNOWLEDGE IN THE PARTICIPATORY MODELLING PROCESS. THIS INCLUDES THE METHODS USED AND OUTPUTS GENERATED FROM EACH OF THE SESSIONS.

3.1.2. Fundamental model structure

The fundamental modelling approach in the case of this research is defined as the initial model structure and function that was adapted and developed, based on the results from the PM process. This section will briefly describe the fundamental approach used in the research, which was established through the literature review (Chapter 2). Any adaptations and improvements to this approach were primarily governed by the results from the PM process; and therefore the approach evolved as the process progressed.

The fundamental modelling approach was based upon a set of important model requirements identified through the literature review. These were that the model should: (i) operate at temporal and spatial scales relevant to river management practitioners, (ii) allow for easy integration of outputs into existing stakeholder systems, and (iii) be scientifically robust. The idea of applying a fundamental modelling approach when engaging stakeholders could be seen as constrictive to the reflexivity and iterative nature of the proposed PM process (Campo *et al.*, 2010). The researcher recognises that this limits this part of the PM process to 'informing' on Arnstein's ladder of participation. However, in recognition of achieving the research aim and objectives, using an initial modelling approach as a starting point was considered to be the most suitable methodology, despite this limitation. Voinov and Bosquet (2010) support this decision, suggesting that although the stakeholders may drive the participatory process, choosing the questions the model seeks to answer, the structure and function of the model must also be scientifically sound and defensible.

Reduced-complexity cellular modelling was chosen over the other approaches and models of sediment dynamics described in Section 2.2.1. These approaches do not integrate sediment transport and fluid flow at the intermediate temporal (1-100 years) and spatial (0.5-500km^2) scales that are relevant to sustainable river catchment management. Furthermore, the reduced-complexity cellular modelling approach allows for the integration of widely available GIS data into the model (in the raster format), whereas other models, such as CASCADE, use an irregular mesh or TIN (Triangular Irregular Network) which are not easily incorporated with GIS (Coulthard, 2001). Finally, coding a reduced-complexity cellular model was considered to be achievable within the project timescale and available funding. A discussion of what reduced-complexity cellular models are and how they operate was described earlier in Section 2.2.2 (see: Figure 2-3). The fundamental modelling approach here only refers to the principles of the model; the modelled processes were informed by the PM process.

This methodology therefore adopted the fundamental modelling structure that the model would use the principles of reduced complexity cellular modelling. From this, the following three characteristics were used in the participatory modelling process:

- The model will be based on cellular automata and allow for varying grid cell sizes;
- Processes within the model operate based on the laws governing the processes within and between these cells. Although stakeholders will inform which parameters can be changed, the methods used to represent these processes must be scientifically defensible;
- The model is as simplistic as possible to ensure the model stays true to the reduced-complexity modelling paradigm.

3.2. Participatory modelling process

3.2.1. Stakeholder and case study catchment selection

One of the early decisions was to adopt a multiple-case study approach. This addressed an issue identified in the literature that participatory processes tend to focus on a single-case or single group, resulting in fears of uniqueness or artificial conditions (Etienne *et al.*, 2011). Additionally, the evidence generated from multiple cases is considered to be more compelling than a single case study (Herriott and Firestone, 1983). Furthermore, this increases the number of stakeholders involved in the process, likely increasing its impact and exposure within the diverse number of organisations involved in river catchment management (for a review of case study research, see: Yin, 2011). This section focuses on the method and rationale behind how each stakeholder group and case study catchment was selected.

One of the considerations when using this approach was replication logic. This is similar to what one must reflect on when designing experiments, i.e. that the replications try to recreate the conditions of the previous experiment. It was decided that a standardised set of replicable participatory methods with the stakeholder groups would be used (shown in Figure 3-2), thus treating them as direct replications of each other. This allowed for some cross-case conclusions to be drawn (Yin, 2008). However, the exact replication of methods is difficult to achieve in participatory processes (Castelletti and Soncini-Sessa, 2007); therefore, the results from each individual case study will be examined in detail in the results chapter.

The definition of a 'case' in this research is 'management groups of stakeholders' that have a management or policy role involved at the river catchment-scale. These groups consist of stakeholders that operate or work at the river catchment level, and include representatives of statutory bodies and other interest groups, determining catchment priorities and co-operating on the preparation of RBMPs. This is one of the operating levels that the Environment Agency has established as a result of the WFD requirements (Environment Agency, 2015). There were several reasons for deciding to work with stakeholders at this catchment, and not at the local management level. Firstly, it was recognised that the proposed PM methodology would require the stakeholders to have access to data and software that would not be available to local level stakeholders. Secondly, it was considered that the level of expertise and comfort with modelling terminology of these stakeholders would allow for more productive discussions. Finally, the purpose of the PM exercise is to create a sediment dynamics model that potentially could be used for any catchment nationally, therefore it was thought likely that in certain cases unique local level issues would not be able to be incorporated into the model.

For the purpose of this research, three catchments and catchment partnership groups from the DEFRAs' Catchment Based Approach were selected to act as case studies for the process of design and development of the model. The composition of stakeholders within each 'steering group' varies from one catchment to another (Environment Agency, 2012). The variation in composition justified the use of a selection of different catchments, as this allowed for the capture of a larger sample of stakeholders' opinions and ensured that the findings of this study were not specific to one particular stakeholder group. A limitation associated with using these pre-established groups is that views of stakeholders who are not considered 'key' to river catchment planning by DEFRA or the Environment Agency would not be incorporated into the process (a limitation recognised by Reed, 2008).

However, given the structure and resources available to the project, it was not possible to incorporate the views of other stakeholders into the research project.

To select the catchments, three catchment co-ordinators based at the Environment Agency Offices in Bridgewater, Exeter and Bodmin were approached regarding the potential involvement of catchment partnership groups in this process. These catchment co-ordinators then contacted other catchment co-ordinators on behalf of the researcher, resulting in the proposition of the project to six catchment stakeholder groups in the South West. The South West was chosen as this was logistically preferable for the researcher given the available resources. The limitation with undertaking this approach is that the findings may only be limited to catchments in the South West. The final catchments were chosen based on: (i) the willingness of the catchment partnership group to participate in the process; (ii) the diversity in composition of stakeholders within and between catchments; and (iii) inclusion in the aforementioned DEFRA-led 'Catchment Based Approach'. The selected catchments based upon this definition are the Bristol Avon, the Camel and the Taw (the difference between each stakeholder groups composition will be presented at the end of this section).

The Spey catchment, Scotland was added after the initial catchments were selected. The researcher was approached by the equivalent of a catchment-coordinator for the Spey catchment as they had heard of this research project and requested inclusion. The Spey catchment is under different governance and geographical drivers than the Bristol Avon, the Camel, and the Taw. However, the definition of the stakeholder group was still valid as the 'Spey Catchment Initiative' consists of statutory bodies and other interest groups determining catchment priorities and co-operating on the development of RBMPs. The costs and benefits of having the Scottish stakeholder perspective incorporated into the model design and development were thoroughly evaluated, including time demands and cost. The benefits of the inclusion of the Spey catchment were an increased awareness and outreach of the model, and an opportunity to test the applicability of the model in a different geographical region of the United Kingdom compared to the three catchments in the South West. Therefore, this allowed the researcher to identify to what degree the findings from the three South

West catchments were be applicable to a geographically different river catchment management group.

The final catchments and associated stakeholder groups are shown in Figure 3-3. The composition and attendance of each stakeholder group in the PM process is shown in Table 3-2. Note that for the Camel the group was comprised of solely Environment Agency and Natural England stakeholders. This was due to the catchment group being established at the same time as the PM sessions began, and external stakeholders had not yet been invited to join the group. Once external stakeholders had been invited and joined the group, two PM sessions had taken place and it was decided to exclude the new stakeholders in the final engagement session. Due to funding constraints, several of these catchments were also amalgamated into larger catchment 'groups' part way through this project. In particular, the Taw was combined with the Torridge to create the North Devon catchment group and the Camel combined with the Lynher, Fal, Fowey and the Hayle to create the North & East Cornwall catchment group.

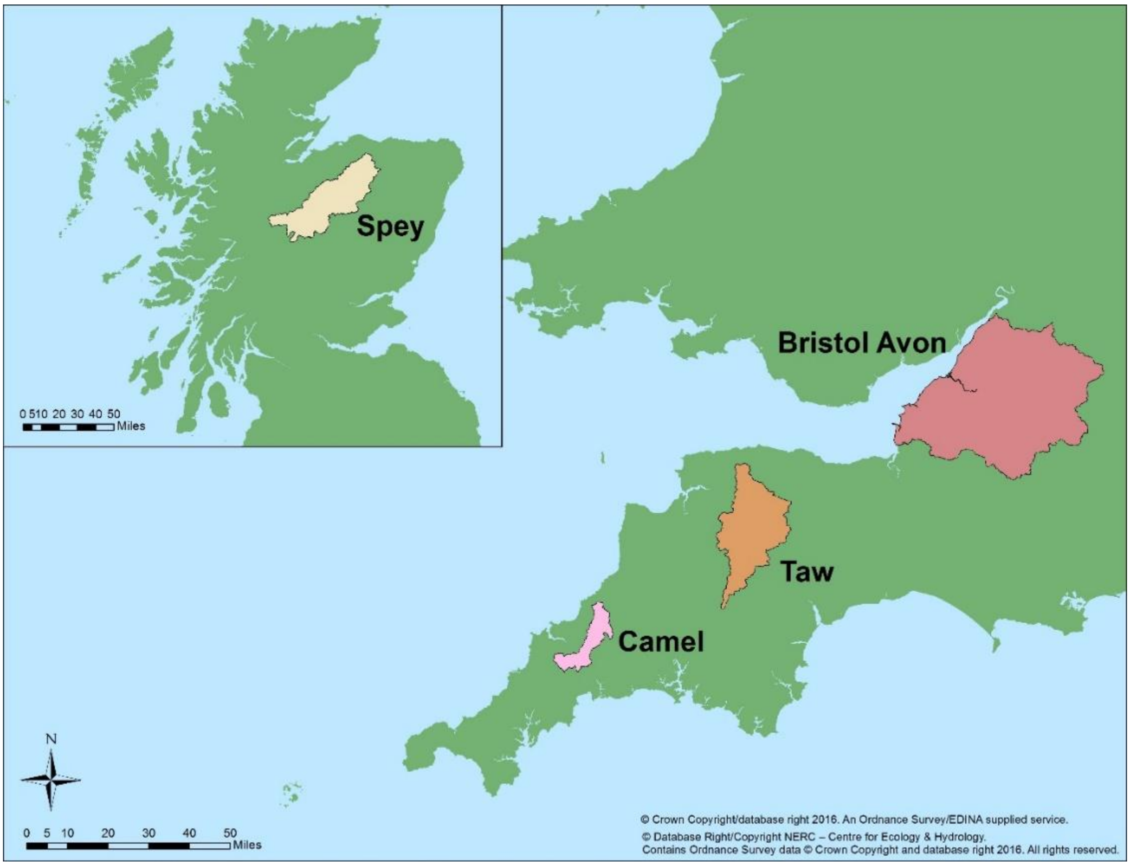


FIGURE 3-3: CASE-STUDY RIVER CATCHMENTS.

Table 3-2: Breakdown of the roles and organisations of each stakeholder who were present in each participatory modelling session.

Catchment Stakeholder Group	Organisation	Role	Requirements Analysis	Co-designing	Model Demons-tration	Final Presentation Session
Bristol Avon	Avon Frome Partnership	Partnership Coordinator	✓	×	✓	×
	Avon Wildlife Trust	Director of Conservation	✓	×	×	×
	Bath and North East Somerset Council	Ecologist	✓	✓	✓	×
		Project co-ordinator River Avon	×	×	×	✓
	Bristol Avon Rivers Trust	Secretary	✓	✓	×	×
	The Rivers Trust	Head of GIS & Data Management	×	×	×	✓
	Bristol City Council	Environment Team Manager	✓	✓	×	×
		Flood Risk GIS Officer	×	×	×	✓
	Environment Agency	Catchment Coordinator	✓	✓	✓	✓
	Wessex Water	Environment and Catchment Strategy Manager	✓	×	×	×
		Catchment Co-ordinator	×	×	✓	✓
		Regulatory Scientist	×	×	×	✓
	Bristol Water	Catchment Strategy Manager	×	×	✓	✓
	Wiltshire Council	Landscape and Design Manager	✓	×	×	×
	Farming and Wildlife Advisory Group	Farm Advisor	×	×	×	✓
Total	**11**	**15**	**8**	**4**	**4**	**8**
Camel	Environment Agency	Catchment Co-ordinator	✓	✓	✓	×
		Environment Monitoring Officer	✓	✓	×	✓
		Environment Planning Specialist	×	×	×	✓
		Environment Officer	✓	✓	✓	×
		Environment Officer	×	×	✓	✓
		Environment Officer	×	×	✓	×
		Senior Environment Officer	✓	✓	×	×
		Environment Planning Officer	✓	✓	✓	×
	Natural England	Catchment Sensitive Farming Officer	✓	×	✓	✓
		Land Management Advisor	✓	✓	✓	✓
		Soils for Profit	✓	×	×	×
Total	**2**	**11**	**7**	**6**	**7**	**5**
Spey	Scottish Environment Protection Agency	Senior Hydromorphologist	✓	✓	✓	✓
		Senior Hydromorphologist	×	×	×	✓
		Senior Hydromorphologist	×	×	×	✓
		Senior Hydromorphologist	×	×	×	✓
	Scottish Natural Heritage	Freshwater Advisor	✓	✓	✓	×
	Spey Catchment Initiative	Project Officer	✓	✓	✓	✓
	Spey Fishery Board	Director	✓	×	×	×
		Operations Manager	×	✓	×	×

	Cairngorms National Park Authority	Land Management Advisor	×	×	✓	×
		Ecological Advisor	×	✓	×	×
Total	**5**	**10**	**4**	**5**	**4**	**5**
Taw	Devon Wildlife Trust	Adviser	✓	✓	×	×
		Advisory Officer	✓	✓	×	×
		Project Manager	✓	✓	×	×
	Environment Agency	Catchment Co-ordinator	×	×	✓	×
		Technical Officer Biodiversity	✓	×	×	×
		Geomorphologist	×	×	✓	×
	Farming and Wildlife Advisory Group	Agricultural Advisor	✓	✓	×	×
		Business Manager	✓	✓	×	×
	North Devon Biosphere Service	Biodiversity Officer	✓	✓	×	×
	Silvanus Trust	Project Manager	✓	✓	×	×
		Associate	×	✓	✓	×
	West Country Rivers Trust	Head of Catchment Management	✓	×	×	✓
		Project Officer	✓	✓	✓	✓
Total	**6**	**13**	**10**	**9**	**4**	**2**
Grand Total	**21**	**49**	**29**	**24**	**19**	**21**

3.2.2. Requirements analysis

The first of the three participatory methods of the PM process (Figure 3-1) was the requirements analysis. The overall aim of this session was to identify the requirements of stakeholders when using a model of catchment-scale sediment dynamics in the practice of sustainable river catchment management (Objective 3.A.). The requirements analysis was conducted using focus groups with each stakeholder group (one in each catchment). The use of the focus groups allowed for the building of a rapport with the stakeholders, and an explanation of the process, and provided an environment for the exploration of the wider range of insights, perspectives and ideas from the stakeholders. The same scope, spontaneity, diversity of views, and social learning would not have been achievable with individual interviews (as recognised by Stewart and Shamdasani, 2006; and Reed *et al.*, 2010). Each session was audio recorded, with stakeholder consent, to allow for transcripts to be produced, and to enable the researcher to focus on facilitating the group. This provided a less intrusive method for recording, reducing un-intended cues, often caused through note-taking (Ritchie and Lewis, 2003). Throughout the PM process as a facilitator, the researcher was as objective and impartial as possible in each of the sessions, and was not treated as a direct stakeholder in the analysis (as suggested by Voinov and Bousquet, 2010).

The requirement analysis sessions took place during the stakeholder steering group quarterly meetings (Autumn 2013). This option of utilising an existing meeting location was chosen because it was more likely that attendance would be high, and that the workshop would be treated in a serious and professional manner (Videira *et al.*, 2009). Furthermore, participants from pre-existing groups bring knowledge of shared experiences, beliefs and promote note-worthy discussion and debate (Kitzinger, 1994). However, using this approach, the group may already have an established a group dynamic, whereby certain members are more authoritative and others may feel that they are not able to disclose true opinions (Bloor *et al.*, 2001). To mitigate this issue, the researcher aimed to prevent individuals dominating the discussion and, where possible, encourage all stakeholders to make an equal contribution.

The researcher started each session by conducting introductory activities including: a brief review of the research project's aim and objectives; the completion of informed consent forms; a reminder of the importance of the participants' views; and a review of the topics for discussion. Next, the first of the three methods was completed (Requirements Analysis, Figure 3-2), this involved the researcher explaining the nature of a cellular model of sediment dynamics and the outputs generated (an example of 'giving information'). This aspect of the sessions was important as it was the first time many of the stakeholders had been introduced to complex modelling concepts (Voinov and Bousquet, 2010). Following on from this, the stakeholders were then asked to debate a series of topics and note down their responses on pieces of A3 paper (an example is shown in Figure 3-4).

FIGURE 3-4: EXAMPLE OF STAKEHOLDERS' NOTES ON ONE OF THE TOPICS FOR DEBATE.

This type of exercise was selected as a means of promoting divergent thinking (as suggested by Andersen and Richardson, 1997). Stakeholders, in small groups (3-4), were asked to debate the following topics:

1. What are the current sediment issues affecting your river catchment?
2. How do you think a catchment-scale sediment dynamics model could be used to help manage them?
3. What do you think will be the most useful and helpful outputs generated by a sediment dynamics model?
4. If you were to apply the type of model I have described, what do you think are the most important characteristics that would determine whether you would use it?

This method ensured that the facilitator did not over control the group discussion, as the purpose of this methodology is to extract information in the form of stakeholder's opinions and knowledge – not those of the researcher (Bloor *et al.*, 2001). The use of small groups was chosen to encourage knowledge exchange and social learning by providing an opportunity for the expression of each individual stakeholders' opinions and knowledge of sediment and modelling.

The speech recorded in the transcripts was grammatically 'cleaned up' as the researcher was not concerned with the detail of expression or language used (Gibbs, 2008). These transcripts were then systematically analysed using thematic analysis. Thematic analysis is defined by Braun and Clarke (Braun and Clarke, 2006, p.79) as a 'method for identifying, analysing and reporting patterns within data'. This flexible method of qualitative analysis allows for the detailed reporting of complex patterns or themes, and was well-suited to analysing the collected data (Braun and Clarke, 2006). Additionally, thematic analysis is not bound by the assumptions of any particular theoretical perspectives described at the beginning of this chapter, and is considered to be an accessible form of analysis for less experienced qualitative researchers (Braun and Clarke, 2006). The process of carrying out thematic analysis follows a series of six key stages described by Braun and Clarke (2006). These include: (i) data familiarisation; (ii) code generation and data coding (using Nvivo); (iii) searching for themes; (iv) reviewing themes; (v) defining and naming themes; and (vi) presenting the completed themes. A theme is defined by Braun and Clarke (Braun and Clarke, 2006, p. 10) as:

> *'…something important about the data in relation to the research question, and represents some level of patterned response or meaning within the data set.'*

The two main approaches when identifying themes in the data are: (i) inductive or 'bottom up' data-driven approach, in which the data is not placed into an existing framework; and (ii) the theoretical approach or 'top down', whereby the analysis is driven by the research questions and theory (Braun and Clarke, 2006). This research adopted an inductive approach to thematic analysis. Therefore, the themes and sub-themes identified are strongly linked to the data in a similar manner to grounded theory (Patton, 1990).

The final decision when using thematic analysis is to choose the level at which the themes are created. The semantic approach, adopted in this thesis, seeks to explain the form and meaning of the data, rather than the latent approach which identifies the *'underlying ideas, assumptions, and conceptualisations – and ideologies within the data'* (Braun and Clarke, 2006, p. 13). The process of conducting thematic analysis involved the use of line by line coding on computer-assisted qualitative data analysis software (CAQDAS), specifically in this case NVivo. The use of a CAQDAS system assisted in the production of accurate, transparent and reliable analysis (Gibbs, 2008). Fielding and Lee (1998) argue that the use of computer software can lead to a disconnection with the data; however, most recent versions of the software have mitigated this issue through allowing the user to easily view and examine the data across multiple sources.

At the end of the session, the stakeholders were asked to complete a short questionnaire (Appendix A). This was to further explore individual stakeholders' experiences of modelling, and perspectives on the use of this type of modelling to inform sustainable river catchment management. The questionnaires gave each member of the stakeholder groups a place to reflect on some of the group discussions, and give their own opinions on the important factors within sediment dynamics modelling. In the design of the questionnaire, aspects such as language, layout and the types of questions were considered (for a review of key concerns in questionnaire design see: Munn and Drever, 1990; Adams and Ian, 2006). The language used was deemed at an appropriate level for stakeholders involved in river management at the catchment-scale, and any technical terminology had been covered in the introduction to the requirements analysis. Another important factor considered was the length of the questionnaire. This was designed to be a quick snapshot of individual stakeholder values; therefore, it was designed to fit onto a single side of A4 and comprised of a mixture of open and closed questions.

The data collected from the questionnaires were analysed using the Kruskal-Wallis H statistical test to compare results between catchments. This could only be applied to the closed questions on the questionnaire; however, this was a quick and effective technique to identify themes or patterns within the data (Gillham, 2008).

The responses to the open questions and the stakeholder notes on the A3 pieces of paper (shown in Figure 3-4) were typed up, coded and analysed using thematic analysis. The results of the analysis were then used to identify conceptual model elements, applications and overall structure. The flow of the knowledge generated is shown by the arrows connecting the different components in Figure 3-2. These were then presented and discussed with the stakeholder groups in the co-designing session, which will be examined in the next section.

3.2.3. Co-designing

This section examines the structure and rationale for the co-designing session in the PM process (Figure 3-1). The aim of the session was to discuss a conceptual model structure, propose revisions and prioritise the key model elements. Prior to the workshop, a list of model elements, model applications, and a conceptual model structure (Conceptual Model, Figure 3-2) were derived from the analysis of the data generated in the requirements analysis. These results and the conceptual model diagram will be described in detail in the next chapter (Section 4.2). The session (approximately one hour in duration) was audio recorded and carried out during each stakeholder's group quarterly meeting (Spring 2014). In these workshops, stakeholders were required to move from the type of divergent thinking used in the requirements analysis to convergent thinking, focusing on defining the model structure (as described in Andersen and Richardson, 1997).

At the start of the session, the researcher gave a brief introduction on the modelling and an update on the progress of the research project. Following this, a simplified version of the conceptual model structure drawn up by the researcher was presented and explained to the stakeholders. Once the stakeholders were comfortable with this simplified version, additional layers of complexity were added to provide the full and detailed description of the relationships, causalities, influences, and interactions in the model. This method recognised that, as suggested by the results shown in the previous section, many of the stakeholders were not regular model users. Therefore, this method allowed the stakeholders to gradually become comfortable with working with a conceptual model structure (as suggested by Andersen and Richardson, 1997). Stakeholders were then encouraged to ask any questions they might have and provide feedback on the overall model structure. This allowed researcher to gain important feedback and support through a mutual exchange of information with the stakeholders on the model structure and basic functioning at this early stage of model development (Co-designing, Figure 3-2).

Following on from this, the stakeholders then took part in two interactive activities which aimed to encourage knowledge exchange and social learning, as well as providing a steer to the researcher for the next stage of the model's development. Firstly, stakeholders were asked to take part in a discussion activity. This required the prioritisation of model elements into intrinsic, extrinsic and excludable categories. The intrinsic factors are the elements that the stakeholders consider to be an essential part of the model. Whereas, extrinsic factors are those which stakeholders consider are not essential parts of the model, and finally excludable factors are those considered to be outside of the scope of the modelling project. Stakeholders were given cards with model elements on (derived from the thematic analysis of the data generated in the previous session), and asked as a group to discuss, and place each element into a section on a 'bulls-eye' diagram (Figure 3-5; (as used by Metcalf *et al.*, 2010)). Stakeholders were also given blank cards to write any additional model elements that they considered to be important.

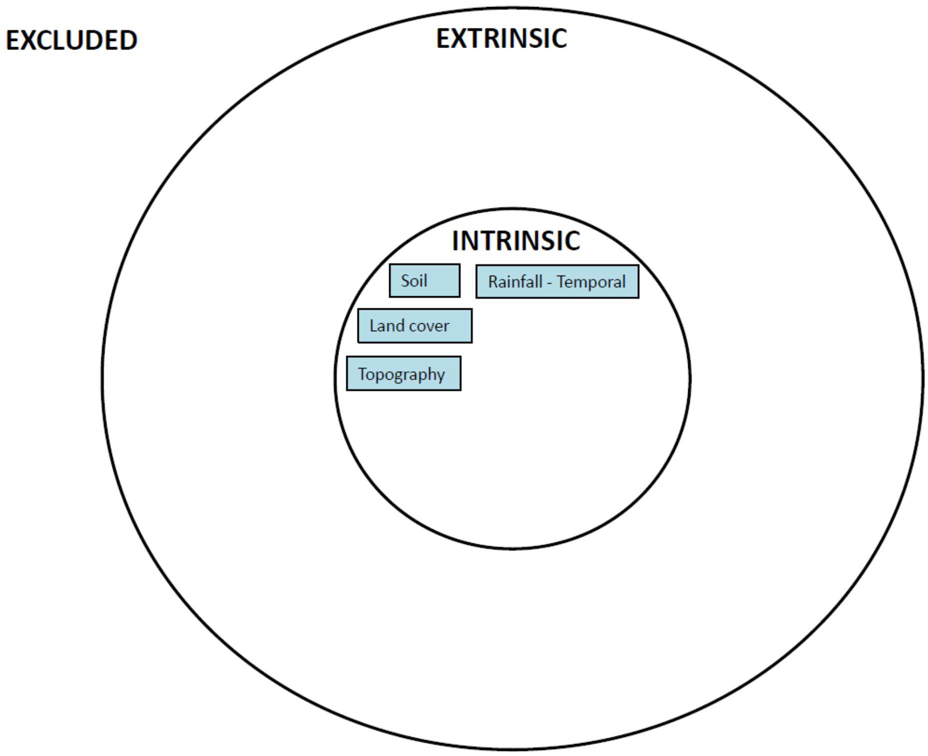


FIGURE 3-5: BULLS-EYE DIAGRAM USED BY STAKEHOLDERS TO SORT THE INTRINSIC ELEMENTS (E.G. LAND-USE), EXTRINSIC ELEMENTS (E.G. GOVERNMENT SUBSIDIES) AND EXCLUDED FACTORS (E.G. ELEMENTS BEYOND THE SCOPE OF THIS MODELLING). NOTE: THE BASIC MODEL ELEMENTS OF LAND COVER, SOIL AND RAINFALL WERE AUTOMATICALLY ADDED TO THE BULLS-EYE AS WITHOUT THEM THE MODEL WOULD NOT FUNCTION.

The final stakeholder activity was a ranking exercise of the model applications (also derived from the thematic analysis of the data generated in the requirements analysis). Stakeholders were given six coloured 'sticky dots' referred to as 'importance votes' and asked to place them on a large printed sheet of the model applications (as in Andersen and Richardson, 1997). The total number of sticky dots in each box were then counted and ordered from the highest ranked to the lowest ranked application. At the end of the workshop, the outputs from the activities were brought together with the conceptual model structure, and the stakeholders were then asked if they had any final questions, comments and feedback on the model. This included the data requirements (as in Cockerill *et al.*, 2011). Transcripts of the audio were produced and analysed using thematic analysis.

After the co-designing session had taken place, the feedback gained was used to produce a refined conceptual model. When revising the conceptual model, the researcher had a crucial role in carefully considering what was practically achievable with the level of expertise and the time constraints of the research project (as experienced by Metcalf *et al.*, 2010). This revised conceptual model was then used to help the researcher create the computational model that could then be used in the PM sessions described later (Draft Model, Figure 3-2). However, as the process of developing a numerical computational model was time consuming (circa. 9 months), there was the requirement for ongoing online engagement and communications with stakeholders throughout the process.

3.2.4. Ongoing engagement

One of the difficulties described in the literature was the risk of stakeholders becoming disconnected with the PM process during the time intensive model building stage of the research (Walz *et al.*, 2007). This was especially important in this setting given the co-construction participatory methodology employed, which to date has primarily been applied to conceptual model building. To overcome this, several new methods were developed and implemented in order to keep the stakeholders engaged in the research while the model coding was taking place. Most of the methods described below promote the ‘giving of information’ rather than a two-way process of engagement.

Firstly, a model website (Figure 3-6) was developed (www.engage-rivers.org.uk) to act as a portal for the stakeholders. The website contains all the information related to the model, including explanations of key terminology and concepts. Secondly, a model blog was created and updated on a nearly daily basis with progress on the model development (Figure 3-7). The final method employed was the development of a series of short (under 3 minute) videos detailing certain aspects of the model development as well as instructional videos on how to use the model (Figure 3-8). This resource was requested by stakeholders in the co-designing session. Through the combination of these techniques, it was envisaged that stakeholders would feel that they were still connected with the participatory process and not become disconnected or feel disappointed with a lack of progress. This was a critical component of the evaluation with the stakeholders and the researchers' reflections, which is described later in Section 3.3.

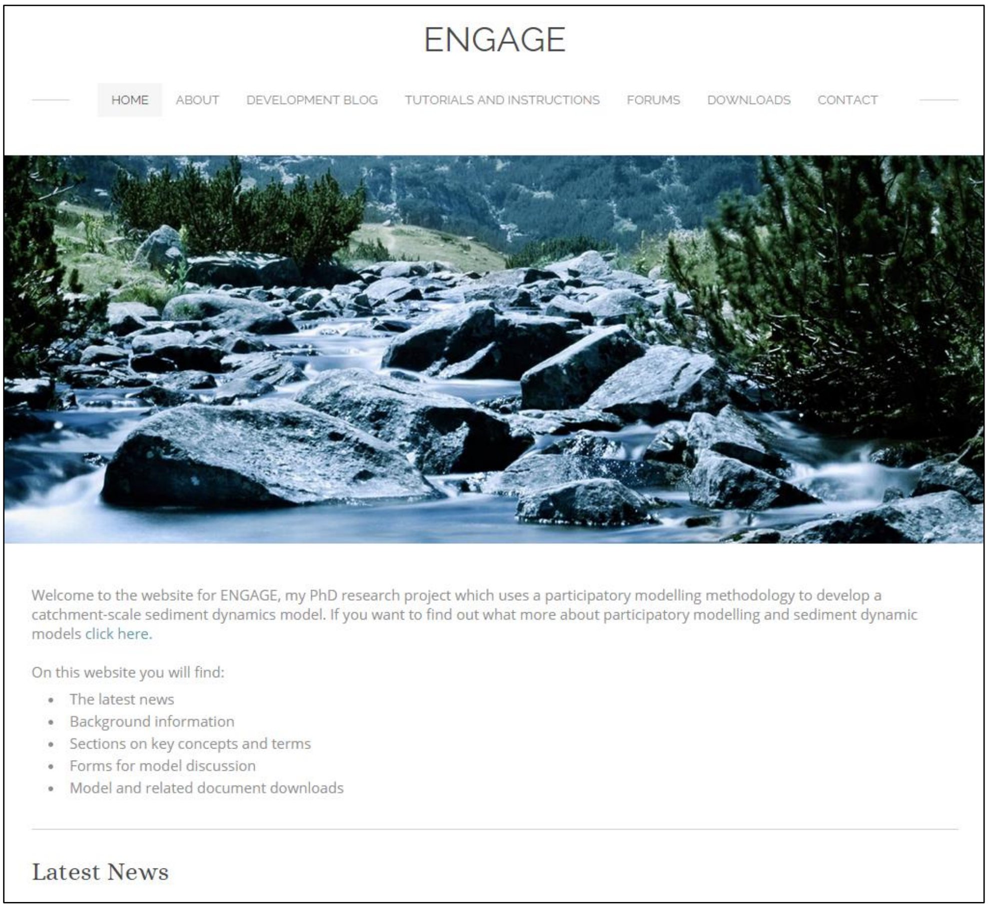


FIGURE 3-6: THE MODEL WEBSITE (WWW.ENGAGE-RIVERS.ORG.UK) WHICH WAS ESTABLISHED AS A PORTAL FOR STAKEHOLDERS TO VISIT TO GET UP-TO-DATE INFORMATION ON THE MODEL'S DEVELOPMENT.

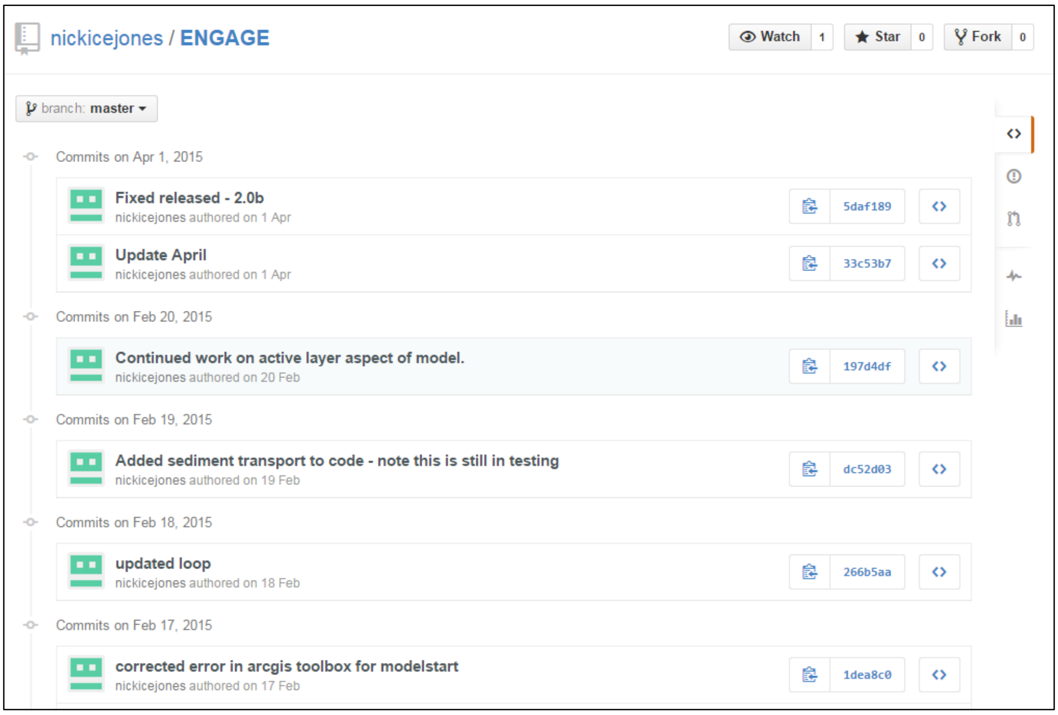


FIGURE 3-7: GIT-HUB ENGAGE MODEL DEVELOPMENT BLOG LOCATED ON THE ENGAGE WEBSITE.

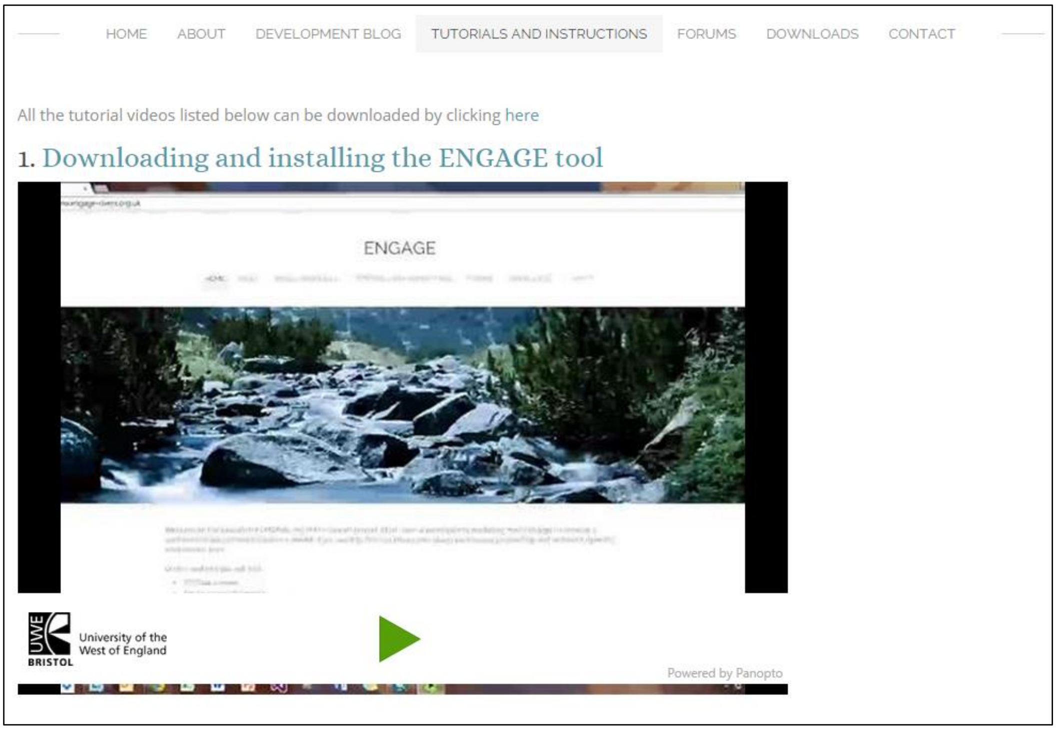


FIGURE 3-8: THE ENGAGE MODEL TUTORIALS PROVIDE STAKEHOLDERS WITH BRIEF DEMONSTRATION VIDEOS OF ASPECTS OF THE MODELS OPERATION (ON ENGAGE SITE).

3.2.5. Model demonstration

The aim of the model demonstration session (Figure 3-1) was to provide an environment for feedback and discussion on the created model, as well as a space to present the model's processes, assumptions, operation and outputs to the stakeholders. In this session, a mutual exchange of information took place between the researcher and the stakeholders, which Gaddis *et al.* (2010) consider to be important in a successful PM effort. The model demonstration lasted approximately one and a half hours, was audio recorded and, if possible, carried out during the stakeholder's steering group quarterly meetings (Winter 2014/15). However, for two of the stakeholder groups (Bristol Avon and Taw), the next quarterly meeting was delayed by several months, therefore a specific meeting was set up to conduct the participatory model demonstration. By this stage of the research, the Catchment Based Approach groups had become established and each had evolved into their own unique structure. For example, in the Bristol Avon, the main group now only meets once a year and several sub groups have been set up.

The model demonstration followed a similar style to that used by Videira *et al.* (2009) whereby, due to the number of stakeholders present in the groups, the model was displayed on a large screen using an LCD projector (Model Demonstration, Figure 3-2). At the start of the session, the researcher gave a brief introduction on the modelling and an update on the progress of the research project. After this, each stakeholder was given a pen and a pad of sticky notes. Four A3 pieces of paper were then placed on the central table and the researcher explained that each piece of A3 paper had a discussion theme written at the top. There four themes were: (i) data requirements; (ii) model interface; (iii) processes and assumptions; and (iv) usefulness and outputs. Stakeholders were then asked to write model feedback on the sticky notes and place it on the corresponding theme throughout the model demonstration (see: Figure 3-9 for an example). This allowed for the capture of feedback throughout the session rather than only at set discussion points. The session was then structured into a series of short demonstration videos relating to each theme (< 10 minutes, examples are shown in Figure 3-10) followed by a discussion.

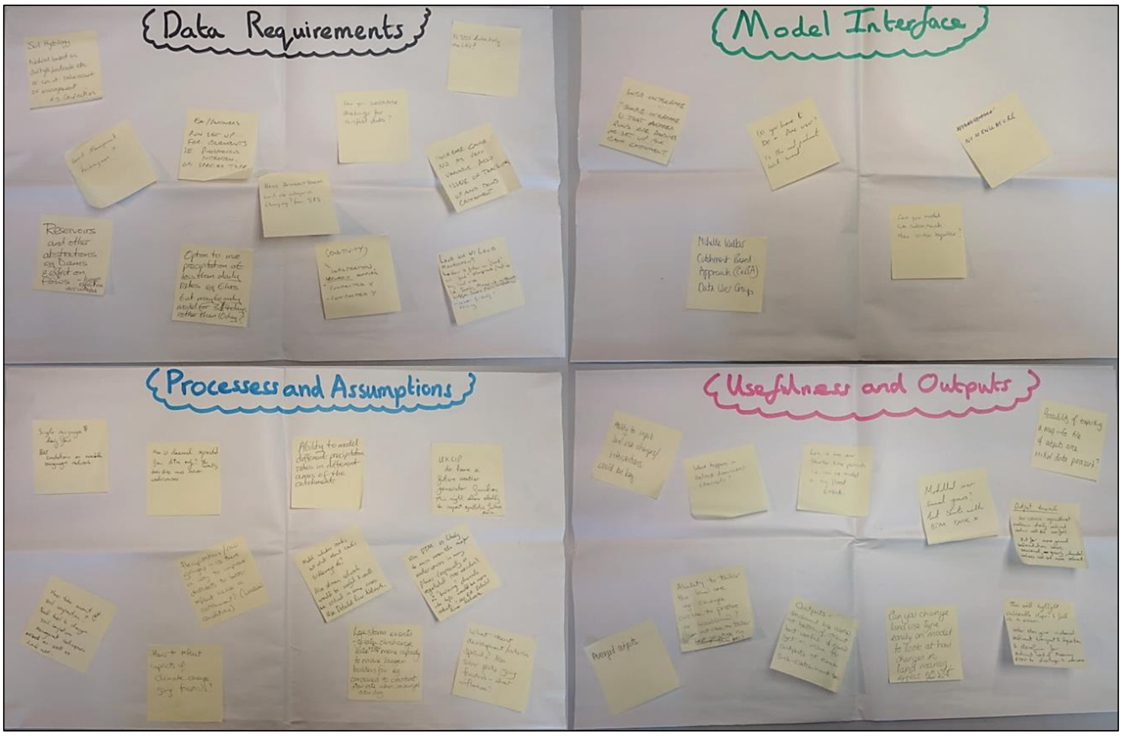
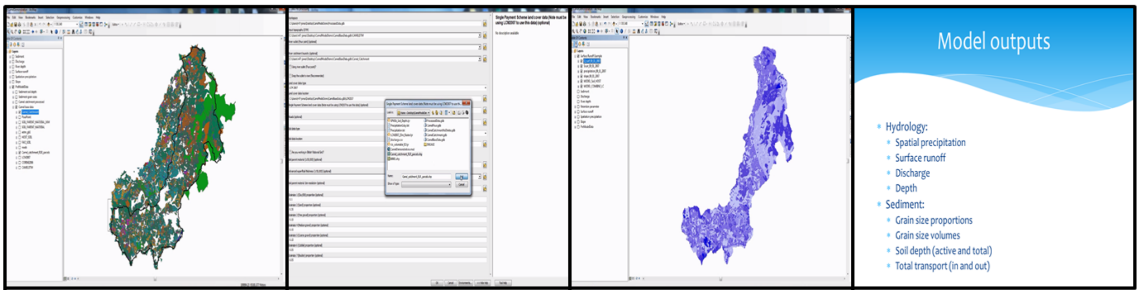


FIGURE 3-9: EXAMPLE OF THE STAKEHOLDER FEEDBACK ON POST-IT NOTES PLACED INTO THE CORRESPONDING THEME.



Data requirements – example of Natural England Single Farm Payment data, which can be used as an land cover input into the model.	Model interface – example of the data input interface of the model.	Processes and assumptions – example of how the model calculates spatially distributed runoff	Usefulness and outputs – examples of the current outputs from the model.

FIGURE 3-10: SCREENSHOTS AND DESCRIPTIONS FROM THE PARTICIPATORY MODEL DEMONSTRATIONS.

The use of live model demonstrations was not chosen as unforeseen technical issues may have arisen, disrupting the natural flow of the session. Therefore, the use of pre-recorded demonstrations of the various aspects of the model was decided to be more suitable and an effective use of time in these sessions. However, in recognition that stakeholders would likely want to explore some of the model's features during the discussion, the model was available on a laptop. The researcher also had a wireless mouse available so that the stakeholders could interact with the model and model outputs live on screen, encouraging active engagement and discussion by stakeholders.

At the end of the session, the stakeholders were then asked if they had any final questions, comments and feedback on the model. After the session, the post-it notes were typed up and combined with the transcripts of audio from the discussion and analysed using thematic analysis. The outputs from thematic analysis were used to organise the feedback and inform the production of the revised model (Revised Model, Figure 3-2).

3.3. Participatory modelling process evaluation

This section describes the methods used to evaluate the PM process (Objective 4.A and 4.B, Figure 3-1). The aim was to evaluate the PM process as a methodology for engaging with stakeholders in the development of sediment dynamics models, and for promoting knowledge exchange and social learning between fluvial geomorphologists and river management practitioners. This evaluation required close inspection of the methods adopted in the PM process and assessment of whether they were successful in achieving the desired outcomes (as suggested by Hisschemöller *et al.*, 2001; Siebenhüner and Barth, 2005). Barreteau *et al.* (2010) suggest that participants should be, if possible, debriefed after each engagement activity in a PM process. However, due to time constraints of the stakeholder groups, this was impractical and therefore a single post-process evaluation was carried out with the stakeholders. This comprised of a two-part process (Process Evaluation, Figure 3-2), an online questionnaire and follow-up telephone interviews to gain an understanding of stakeholders' experiences (conducted Spring/Summer 2015).

The online questionnaire and follow-up telephone interviews were adapted from the 'Participant Evaluation Guide' (PEG), which is part of the Protocol of Canberra (PoC) Evaluation Framework developed by Jones *et al.* (2009). The PoC provides a flexible framework for evaluating PM processes. The PoC framework is more useful when used throughout a process and in decision-making PM processes (Jones *et al.*, 2009). Therefore, the PoC framework was adapted so that it could be used in this context. This allowed the researcher to go beyond 'what works' to answer the important questions of 'why it works' and 'how it could work better' (as suggested by Creighton cited in Webler, 1999). The main themes of interest were: (i) which aspects of the process the stakeholders liked or disliked, (ii) whether or not they felt comfortable taking part in this type of process, (iii) what and how they learnt through the process, and (iv) how the process could be improved.

The questionnaire design followed the same considerations that were discussed earlier in Section 3.2.2, including question order, phrasing of questions and the format of response required from participants. The questions were worded using terminology and language that the stakeholders would understand and ordered such that earlier questions would not influence later responses. Finally, the questionnaire consisted of a mixture of closed and open questions to capture suitable information to answer the areas of interest, as well as allowing the identification of themes for use in the follow-up in telephone interviews. A copy of the online questionnaire can be found in Appendix B.

Stakeholders' responses to the questionnaire were anonymous unless they specified that they were willing to take part in a follow-up semi-structured exploratory telephone interview. The rationale for the interviews was to strengthen and develop the themes captured in the online survey. More specifically, the use of semi-structured interviews allowed the researcher to ask probing questions relating to the stakeholders' responses to the online questionnaire. This created a depth and richness in the data collected (as recognised in Reed *et al.*, 2008). A topic guide (Appendix C) of themes for further in-depth discussion was produced from the analysis of the responses to the online questionnaire. This acted as an aide-mémoire for the interviewer and not as a rigid structure for the interview. The three themes covered in the interview were: (i) the PM process; (ii) outcomes from the PM process; and (iii) improving the PM process. This was in recognition that the purpose of the interview was not to test a hypothesis but to seek out new information and perspectives (Kvale, 2008).

At the start of the interview, the researcher explained the purpose and the structure of the interview, how the information would be used, and the required informed consent forms were filled in. The researcher then asked a series of questions and encouraged the interviewee to respond in an open and flexible manner (as suggested by Gray, 2009). The researcher varied the phrasing and order of the questions to fit the flow of the interview with the aim of promoting a natural discussion. During the interview, the researcher occasionally repeated interpretations of the participant's answers back, giving them the opportunity to clarify the meaning of their responses. If the interviewee strayed too far from the area of discussion, then the researcher used a prompt such as asking another question to move the interview back on track. However, deviation from the topic specifics was encouraged. At the end of the interview, the interviewee was asked if they had any questions or additional comments they would like to make. Each interview was recorded and lasted approximately 30 minutes. Interview transcripts were produced and analysed using thematic analysis.

Another important aspect of evaluating a PM process is to capture the project team's experience; Jones *et al.* (2009) refer to this as the 'Designer's Questionnaire'. Project teams usually consist of several researchers from a mixture of physical and social science backgrounds, however, in this research the project 'team' was a single researcher. The researcher's experiences were captured in this thesis by recording reflections on the PM process in a methodology log.

3.4. Model assessment of usefulness and usability

This section covers the methods utilised to answer Objective 5 – to critically assess the new cellular model as a tool for use within river management. The term 'assessment' was chosen over two terms that are often used incorrectly in modelling studies: 'validation' and 'verification'. Verification refers to testing that computational structure (e.g. algorithms and the flow of logic) in the model are correct, whereas validation is the process of testing that the model suitably represents reality. As Lane and Richards (2001) suggest, it is impossible to comprehensively 'validate' a numerical model as there are an infinite magnitude of potential temporal and spatial scenarios, which make empirical testing an unfeasible task. Recognising these difficulties, Lane and Richards (2001) argue that 'assessment' is a more suitable term to use as a positive result does not imply that perfection has been achieved. Additionally, criteria that define a model's 'validity' vary depending on the criteria established by an assessor. Therefore, importance lies not in the 'predictive success of a model, but in understanding how and why a model fails' (Parker, 2010, p. 285).

In this thesis, the model assessment adopts an approach that challenges the conventional positivist approaches to validation (falsification or validation). Instead, the assessment described below attempts to gauge the developed models 'usability' and 'usefulness' for stakeholders in sustainable river catchment management. Usability is used here to mean the ease of use and learnability of ENGAGE, whereas, usefulness refers to the effectiveness of ENGAGE as a decision-making tool for river management practitioners. Two methods of participatory data gathering were used with the four catchment stakeholder groups during the final ENGAGE model presentation session; these are referred to as model comparison and model use (Model Assessment, Figure 3-2, conducted during Winter 2015/2016).

3.4.1. Model comparison

The aim of the model comparison was to assess whether or not stakeholders considered the model developed using a PM approach (ENGAGE) to be an improvement on the existing cellular models of sediment dynamics developed using the traditional 'DAD' approach (in this case CAESAR-Lisflood). Stakeholders were not informed these characteristics related to two actual models. This allowed the researcher to assess whether or not through the PM process, a model was created with a greater number of the characteristics stakeholders consider to be important.

The researcher began these sessions by carrying out introductory activities, including: (i) getting participants to sign informed consent forms, (ii) describing the structure of the session, and (iii) a brief reminder of cellular modelling of sediment dynamics. Following this, the stakeholders were then asked to complete a model comparison activity comprising of two parts.

The first consisted of a short questionnaire (Appendix D) which, due to the evolution of the stakeholder groups, included questions relating to their experiences of, and opinions about, modelling and model outputs (questions 1 to 4). These questions were replicated from the first questionnaire completed by the stakeholder groups in the requirements analysis (described in section 3.2.2). An additional question (5) was added, requiring stakeholders to rank 10 model characteristics (5 from ENGAGE, the model developed through this PM process, and 5 from CAESAR-Lisflood, a traditional research led and developed model) and explain their reasoning.

In the second activity, stakeholders were required to read and reflect on table outlining two models, referred to as Model A and Model B. This table can be found in Appendix E. As in the previous activity, the stakeholder groups were not informed that the specifications related to two actual models (CAESAR-Lisflood and ENGAGE). The stakeholders were then asked to rate each model based on the likelihood they would 'use this model in your day job if you had a need to conduct an investigation that required the use of a sediment dynamics model', and encouraged them to provide a qualitative justification for their selection. This approach allowed the stakeholders to reflect in detail on two models and provide an additional level of detail to support the evidence gathered in the previous activity. A limitation with this method is that the stakeholders may have realised through reading the description of the models that one of the two descriptions was ENGAGE.

3.4.2. Model use

The second participatory activity involved the group, facilitated by the researcher, using the ENGAGE model in a hypothetical decision-making scenario. To begin, each group were asked to nominate a user to operate the model and were provided with a short tutorial document to follow through (Appendix F). The stakeholder groups were given the following scenario (created using the researcher's experience of working in the Environment Agency):

"The Environment Agency has announced a pot of money for planting broad leaf woodland and the catchment you are responsible for working on is eligible to receive some of this funding. The criteria for this funding are:

- *The areas of tree planting must demonstrate **multi-benefit outcomes** for both reducing surface runoff, sediment erosion on fields and deposition downstream.*
- *The area for planting must be **strategically** placed in areas that contribute the greatest runoff and sediment erosion."*

Over the next 30-45 minutes the stakeholders followed through a series of exercises on the document, and were required to interpret the outputs generated by the model. The following four areas were covered in the integrated modelling exercise:

1. Downloading, installing and opening the model;
2. Preparing the data for use in the model;
3. Running the model and selecting the desired outputs;
4. Opening and using the outputs from the model.

The aim of the exercise was to get the stakeholders to assess ENGAGE against the identified key criteria of model usability (e.g. data requirements and ease of use) and usefulness (e.g. processes represented and outputs generated). The researcher was present observing throughout the activity, assisting when required and taking supplementary notes. Each task was followed by an opportunity for critical reflection during which the researcher posed a series of closed and open questions. This integrated modelling exercise was audio recorded, transcripts were produced and analysed using thematic analysis.

3.5. Research ethics

This research involved stakeholders as human participants; therefore, ethical consideration was required in the design of this methodology. This research has followed the standard university procedures for ethical social research, primarily relating to confidentiality, anonymity and the right to withdraw from the research at any point for participants. The stakeholders, referred to as participants, were given information sheets on the project, including a brief summary of the research, an explanation of the aims and objectives of the research, and a description of outputs generated from the research. In addition, participants were required to sign consent forms prior to involvement within the research. This was communicated in writing to participants at the start of the research project that they could leave at any point if they wished. If a participant withdrew from the project they had the option, prior to publication, of having their data destroyed. Due to the nature of this project, it was possible that stakeholders might have withdrawn from the stakeholder group (e.g. job change) but not withdrawn from the PhD research. In this case, unless requested, their data was not removed. Anonymity was not offered as default (except in the online questionnaire – discussed in Section 3.3) as the project did not handle any sensitive material or put the stakeholders in a situation where they felt they could not speak freely. As this was a flexible process, if any changes occurred in the process an amendment form for ethical approval was submitted. At the end of piece of this research no stakeholders had requested to withdraw from the process or request anonymity.

3.6. Synthesis

This chapter has explained in detail the methodology adopted in this thesis. This began with an exploration of the epistemological and ontological positioning of this thesis and its research strategy. Next, the discussion moved on to present each of the sessions in the PM process, including the methods used and the process of capturing and analysing the data. The methods employed attempted to address the issues commonly experienced within participatory projects. Table 3-3 shows these challenges and the solutions that were implemented in this project. Following on from this, the methods for evaluating the PM process with stakeholders were described. Finally, the last section presented the approach for assessing the model as a tool for use in river management in regards to its usability and usefulness as a tool for river managers.

TABLE 3-3: PARTICIPATORY MODELLING CHALLENGES IDENTIFIED THROUGH THE REVIEW OF THE LITERATURE AND THE SOLUTIONS IMPLEMENTED IN THIS METHODOLOGY.

Challenges	**Solutions**
Hijacking by special interest groups that do not reflect the wider public opinion.	This process used multiple management level stakeholder groups. Therefore, local level special interest groups were not able to dominate the process. Additionally, the number of local level special interest groups present in this process was limited.
Participation of stakeholders in the process is mere 'tokenism' and they have no real power to influence the decisions made.	A priority of the process was to ensure that stakeholder opinions and ideas are captured through the different participatory modelling sessions and then translated into decisions made within the model. An important stage linked to this, is the feedback structures put in place, such as the YouTube videos and model blog.
Disillusionment of stakeholders with the process as they find it difficult to contribute in scientifically complex situations. This can often result in certain 'key' players within groups having a more	The stakeholder groups were primarily comprised of stakeholders that would be comfortable with river management terminology and concepts. However, where possible complex terminology was avoided. If complex terminology was required then it was explained to the stakeholder groups. The website provided a glossary of key terms and an explanation of concepts for the

significant influence on the decisions made.	stakeholders to refer to. In addition, at the start of each session an overview of modelling and the principle of cellular models were presented.
Researchers involved in these processes find it difficult to maintain their scientific objectivity as the lines between research and actions become blurred.	A fundamental model structure was used to encourage the creation of a scientifically sound and defensible model. The supervisory team also remained external to the participatory process and provided input to the model development.
Over-use of qualitative methods, which are considered to lack the rigour and systematic process for analysing and representing the views from participants.	A mixed-methods approach using both quantitative and qualitative methods was adopted.
The project drifts too far away from the participatory approach. This disconnection often leads to stakeholders leaving the project.	The participatory process used a co-construction methodology which required iterative and ongoing engagement methods.
Translation process between the qualitative output from the PM process and quantitative model elements.	Thematic analysis of transcripts was used to translate what the stakeholders said into model elements and components. The process is documented and explained in detail.
The process tends to be based on a single-case or single group, so there are fears around uniqueness or artificial conditions surrounding outcomes of each case.	This research uses a multiple-case study approach.
Participatory processes should comprise of a comprehensive evaluation and substantive reflections on the lessons learnt.	This research incorporates a participatory process evaluation with the stakeholders, as well as presenting detailed reflections of the process by the researcher.

Chapter Four: Integrated results from the participatory modelling process

The purpose of this chapter is to present the results from the participatory modelling (PM) process. To achieve this, the chapter is structured around the PM process shown in Figure 4-1. For how each individual part relates to the flows of knowledge, refer to Figure 3-2 in the previous chapter. The participatory methods sections (4.1, 4.3, and 4.5) present the results of the analysis of the data collected in the participatory sessions (Objective 3.A). These sections include a description of the translation process from the participatory outputs into the physical modelling components and characteristics. The model development sections (4.2, 4.4, and 4.6) will explain the model that has been created or revised following the results from the participatory sessions (Objective 3.B). A full description of the resultant model is presented in the next chapter.

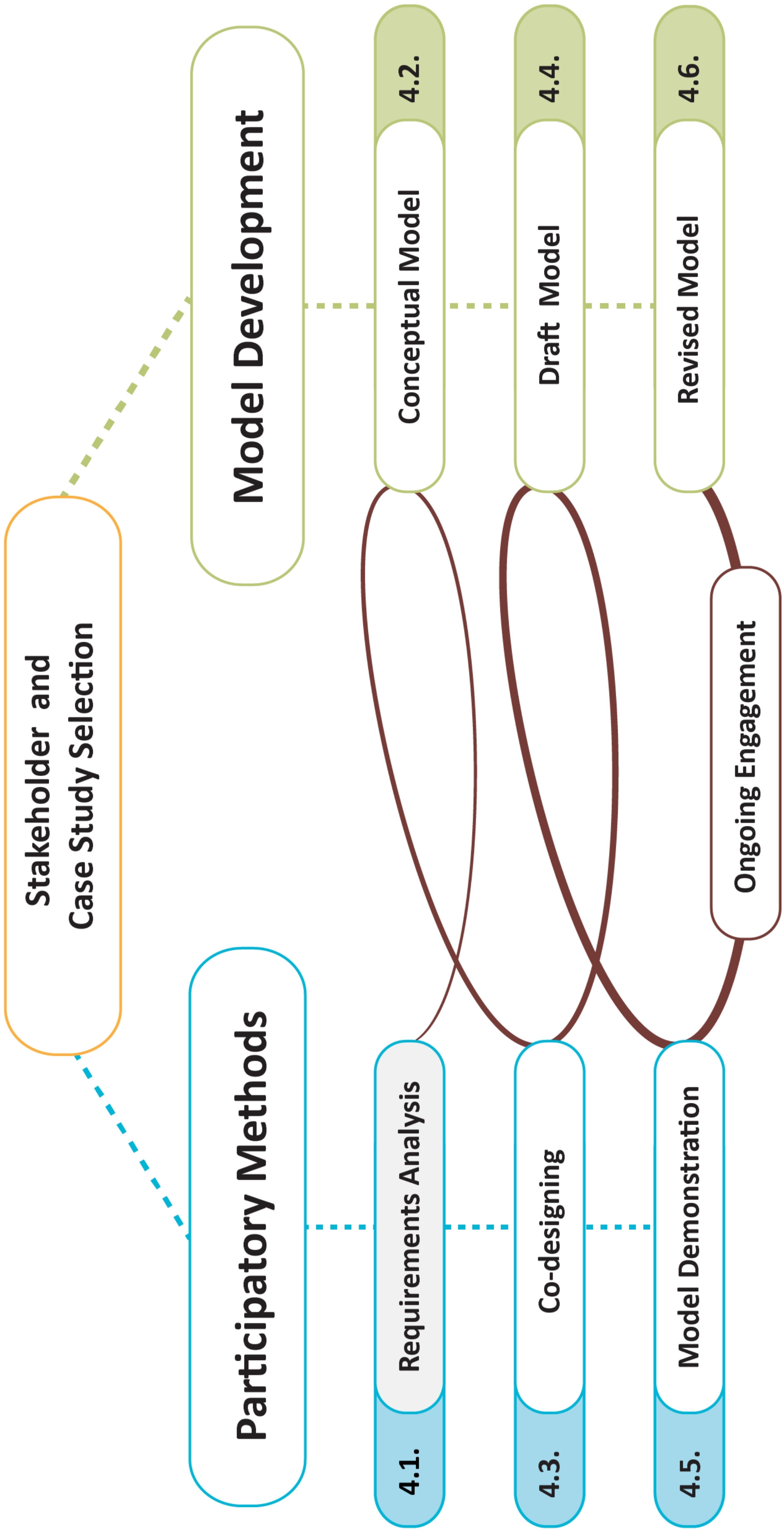


FIGURE 4-1: OVERVIEW OF THE METHODOLOGY USED IN THIS THESIS. THE NUMBERS HIGHLIGHTED RELATE TO THE SECTIONS IN WHICH THE RESULTS ARE PRESENTED IN THIS CHAPTER.

4.1. Requirements analysis

In this section, the results from the requirements analysis (described in Section 3.2.2) will be presented. The purpose these sessions was to identify the requirements of management stakeholders when creating and using a catchment-scale sediment dynamics cellular model in river catchment management. The results include the thematic analysis of the transcripts of the focus group discussions and notes (over 100 pages of material), as well as the short questionnaires completed at the end of the requirements analysis sessions. The use of thematic analysis allowed for cross-case analysis of the data generated from each of the catchments. This is presented through thematic maps and tree maps supported by extracts from the transcripts of the audio recordings. A thematic map uses the mind map principle to allow the researcher to explore and present 'the relationship between codes, between themes, and between different levels of themes' (Braun and Clarke, 2006, p. 20). Treemaps on the other hand, display visual hierarchical data using size and colour coding. The treemaps produced in this thesis contain the number of times each theme or sub-theme was referenced in the transcripts. Three thematic maps and tree diagrams were created around: (i) Sediment Impacts and Influences (Figure 4-2 and Figure 4-3); (ii) Model Applications (Figure 4-4 and Figure 4-5); and (iii) Model Characteristics (Figure 4-6 and Figure 4-7).

4.1.1. Sediment impacts and influences

Figure 4-2 shows the thematic map of sediment impacts and influences that was created from the thematic analysis of the transcripts. This is split into the individual catchments and the thickness of each line relates to the number of catchments in which each theme or sub-theme was discussed. Figure 4-3 displays a treemap of the themes and sub-themes. This was created using the number of times a theme or sub-theme was coded in the transcripts, illustrating the relative importance of the different themes. The same extract of text can be attributed to multiple themes and sub-themes. As a result, the reference (ref) values in the treemaps from sub-themes will not add up to the themes total. The impacts sub-theme will not be explored here as this aspect is covered in more detail in the next section under model applications. Note that unless specified, the sub-theme occurred in all of the catchments.

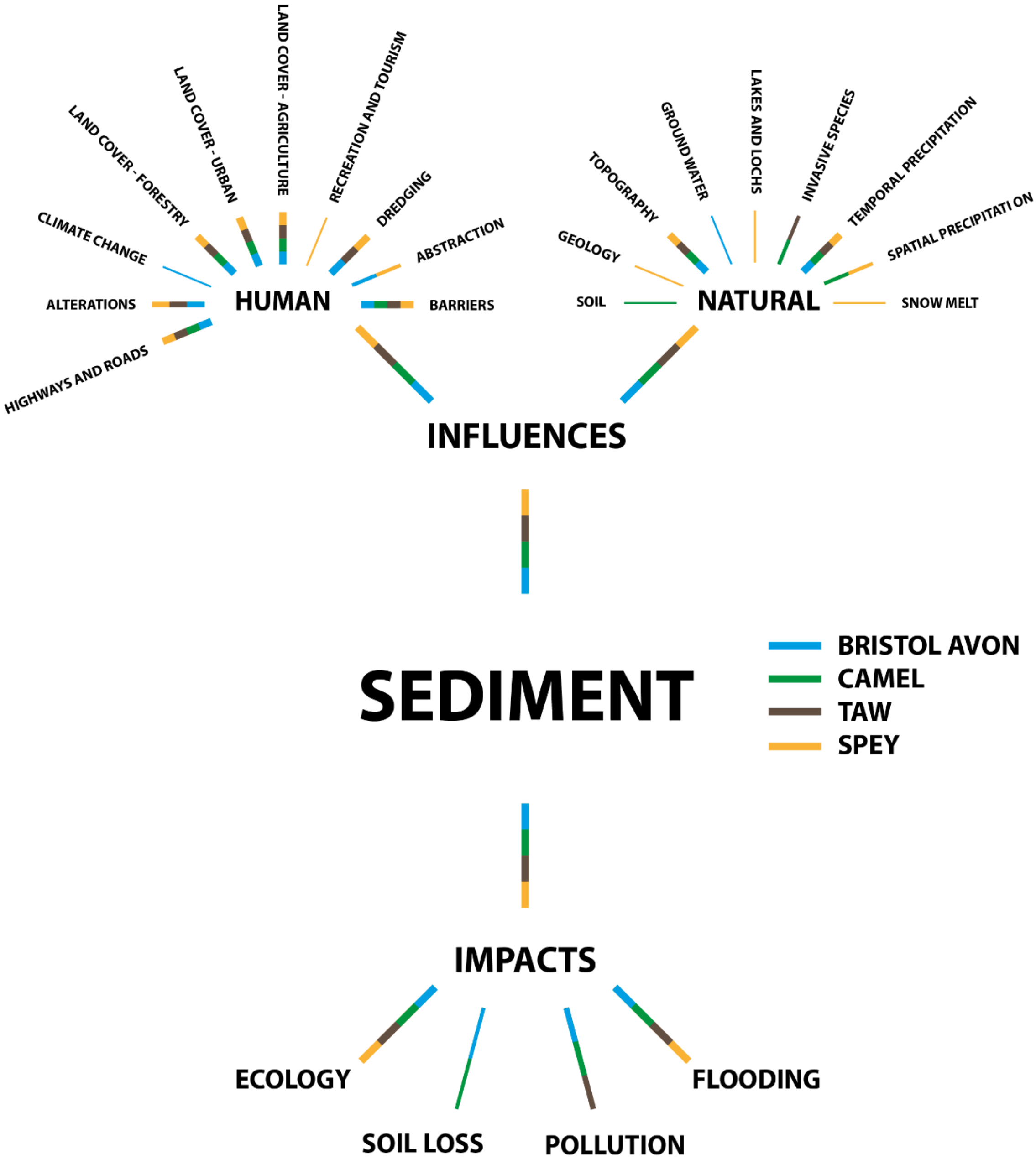


FIGURE 4-2: THEMATIC MAP OF SEDIMENT IMPACTS AND INFLUENCES IDENTIFIED THROUGH THE CODING OF THE REQUIREMENTS ANALYSIS TRANSCRIPTS. THE COLOURS AND THICKNESS OF THE LINES RELATE TO THE CATCHMENT AND THE NUMBER OF CATCHMENTS EACH CODE APPEARS IN.

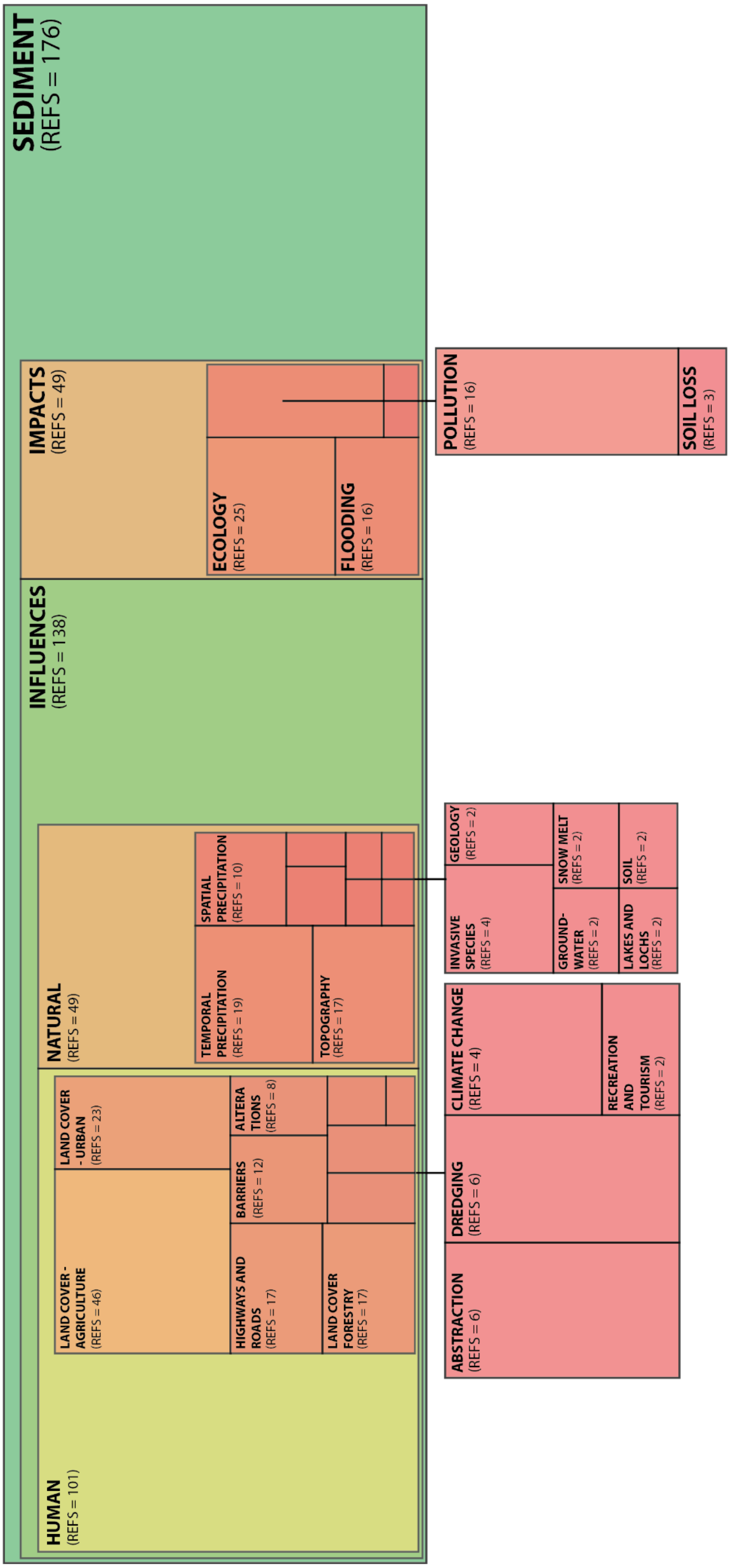


FIGURE 4-3: TREEMAP OF SEDIMENT IMPACTS AND INFLUENCES IDENTIFIED THROUGH THE CODING OF THE REQUIREMENTS ANALYSIS TRANSCRIPTS. 'REFS' REFERS TO THE TOTAL NUMBER OF TIMES A THEME WAS CODED.

The first division in the sediment thematic map was into two themes: (i) influences; and (ii) impacts. The influences theme was further divided into natural and human influences (Refs = 49 and 101), and then again into the individual model elements. One of the human influences on sediment most articulated by stakeholders was land cover. This 'influence' specifically focuses on the three dominant types in the UK, **agriculture, urban and forestry** (Refs = 46, 23 and 17). Each of the catchment groups included land cover as a priority for a model of catchment-scale sediment dynamics. Stakeholders also considered an important aspect to be the condition of the land and how it is managed, as these are closely related to the amount of runoff generated and the amount of sediment leaving farmers' fields. These additional factors centred on land management for agriculture, in particular the poor management of arable and pasture land. The quotes below illustrate the complexity of land cover and its association with sediment as described by the stakeholders.

'If we know an area of agricultural land is compacted, can we change the model so the infiltration rate is changed accordingly to reflect that?' (Environment Agency, Bristol Avon)

'So you've got arable and permanent pasture land use and then you've got management of that arable and that pasture.' (Devon Wildlife Trust, Taw)

'I figured that the downstream end had obviously been managed quite a bit for agriculture and this was possibly the reason why lots of sediment was ending up downstream and why it was so dynamic.' (Scottish Environment Agency, Spey)

These quotes emphasise the perceived widespread influence of **agriculture** – land use and management within each catchment, and its recognition as an important issue to be considered by a catchment-scale model. The influence of **urban** areas and the impact of their rapid expansion over the past few decades and into the future was conveyed by stakeholders in the Camel, Bristol Avon and Spey catchments.

'The other thing I was thinking of in terms of usefulness was maybe in developments…' (Environment Agency, Camel)

'Urban development in the upper catchment, I reckon housing has almost doubled some areas of the upper catchment in the last 20 years.' (Spey Catchment Initiative, Spey)

Forestry was also raised as another type of land cover that can influence the sediment dynamics of a catchment and something that should be included. In particular, in a similar manner to management of agricultural land, the management of forestry is seen as a key factor.

'Poorly managed forestry operations on steep ground.' (Extract from one of the Taw group's notes)

'Lack of trees and buffer strips in high erosion riparian areas' (Extract from one of the Taw group's notes)

The idea that in-channel **barriers** (Refs = 12) are influencing sediment transport and storage is a recurring theme through all of the catchments. However, the Scottish context was more concerned with larger hydro-power dams and abstraction than the weirs described by the South West catchment stakeholder groups.

'The abstraction is controlled by 3 or 4 dams in the upper catchment. [Describing the influence of dams on sediment]*'* (Project Officer, Spey Catchment Initiative, Spey)

'… the role of structures in the actual river itself and how they influence where sediment goes, as they build up sediment behind and stop sediment going down further down the catchment' (Environment Planning Officer, Environment Agency, Camel)

Other important human influences described include the effect of **highways and roads** (Refs =17, all catchments) acting as artificial channels often described by stakeholders as 'pathways' for the runoff during high rainfall events. Linked to this, stakeholders emphasised that 'road verge erosion' was an additional source of sediment reaching the river channel. Some of the lesser mentioned human influences on river catchment sediment dynamics were **alterations (to the channel), abstraction,**

dredging, and **climate change** (Refs = 8 (Bristol Avon, Taw, and Spey), 6 (Bristol Avon and Spey), 6 (Bristol Avon, Taw, and Spey) and 4 (Bristol Avon)); these are captured in the quotes below.

'Abstraction of river flow in the upper catchment for hydro-power. It is estimated 25% of river flow is diverted to the River Tay. There are other sources of abstraction throughout the catchment such as the distillery.' (Extract from the Spey group notes)

'…sediment coming from upstream resulting in costly dredging operations downstream.' (Environment Agency, Bristol Avon)

'[Being able to] *know what is the natural amount* [of sediment erosion] *and what is due to climate change and more intense rainfall.'* (Bath and North East Somerset Council, Bristol Avon)

In terms of natural influences, two of the most discussed sub-themes are the differences in **spatial** and **temporal precipitation** (Refs = 10 (Camel and Spey) and 19). This especially related to the model having credibility with local level stakeholders.

'… if you want your model to have credibility with stakeholders, they will say it always rains loads more here and it is always more intense here, compared to down there, so I think there would need to be some recognition of that.' (Natural England, Camel).

'And what you find is that the rainfall gradient [is significant] *because in the Cairngorms you'll get possibly 2-3 metres of rain sometimes in a year, whereas in Garmouth, on other side of the country on the East coast, you might only get 600-700 mm a year.* [These are inaccurate estimations of rainfall, although they do emphasise the differences in precipitation levels]' (Scottish Environment Protection Agency, Spey)

Other natural influences described by stakeholders in the sessions include **topography**, **invasive species**, **ground water**, and **soil** characteristics (Refs = 17, 4 (Camel and Taw), 2 (Bristol Avon) and 2 (Taw)). The quotes below explore some of the stakeholders' reflections on how these different elements influence catchment sediment dynamics. Some of the quotes emphasise how that in some cases the extracts can integrate multiple themes.

'A typical Spey tributary would be steep, firing lots of sediment down onto the floodplain…' (Extract from Spey group notes)

'I think what has happened is we fenced off a lot of the river, [therefore] *the cattle don't go in so you get this build-up of sediment which is not being disturbed by the cattle moving in and out of the river and also enables the hemlock to get established within the river and stabilise the sediments and make banks of stable sediment within the river.'* (Catchment Sensitive Farming Officer, Camel)

The Spey in Scotland had a few unique codes for model elements which were not expressed in any of the catchments in South West England. These were: **snowmelt**; **lakes and lochs**; **recreation and tourism**; and **geology** (Refs = 2, 2, 2 and 2 (Spey)). The quotes below demonstrate some of the unique elements that the stakeholders describe within the Spey catchment. The recreation and tourism sub-theme particularly relates to the use of river banks along the Spey for fishing and how landowners modify 10 metre buffer strips by planting areas of grass and other vegetation to try to stabilise the banks.

'We are talking about a loch that is several metres deep, several miles long and a bit of the river system. The water can rise as high as this room in this huge floodplain area in the river.' (Scottish Environment Protection Agency, Spey)

'…you get the snow melt and if you get a rapid thaw, that can have a significant effect…' (Spey Catchment Initiative, Spey)

The different model elements that were identified through the thematic analysis and displayed in the influences element of Figure 4-2 were then used as an input into the bulls-eye prioritisation activity in the co-designing session (described in Section 3.2.3). The outputs of this will be explored in Section 4.3.

4.1.2. Model applications

Figure 4-4 shows the four themes of the model applications thematic map. Figure 4-5 shows a tree map of the number of times each sub-theme was referred to in the transcript analysis. From these figures and supporting material, there are a number of similarities and overlaps between each of the defined themes. Despite this, there are subtle differences, which will be explored throughout this section.

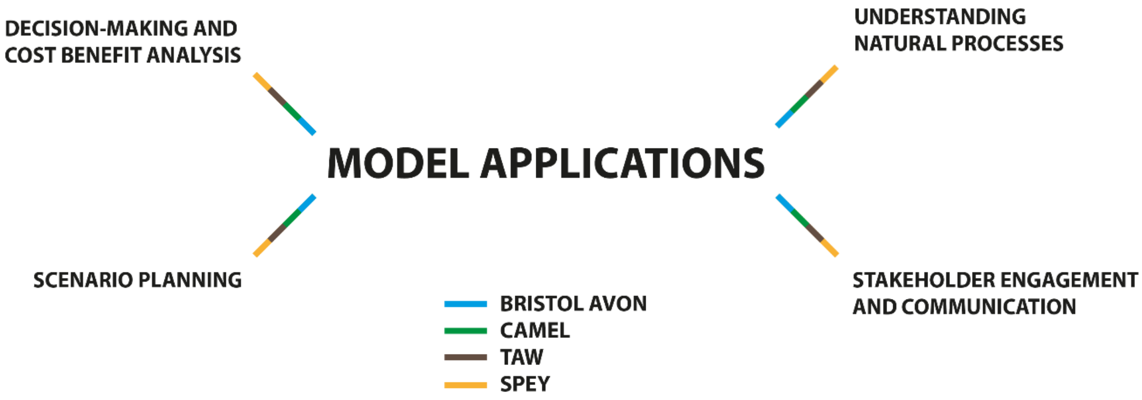


FIGURE 4-4: THEMATIC MAP OF MODEL APPLICATIONS IDENTIFIED THROUGH THE CODING OF THE REQUIREMENTS ANALYSIS TRANSCRIPTS. THE COLOURS AND THICKNESS OF THE LINES RELATE TO THE CATCHMENT AND THE NUMBER OF CATCHMENTS EACH CODE APPEARS IN.

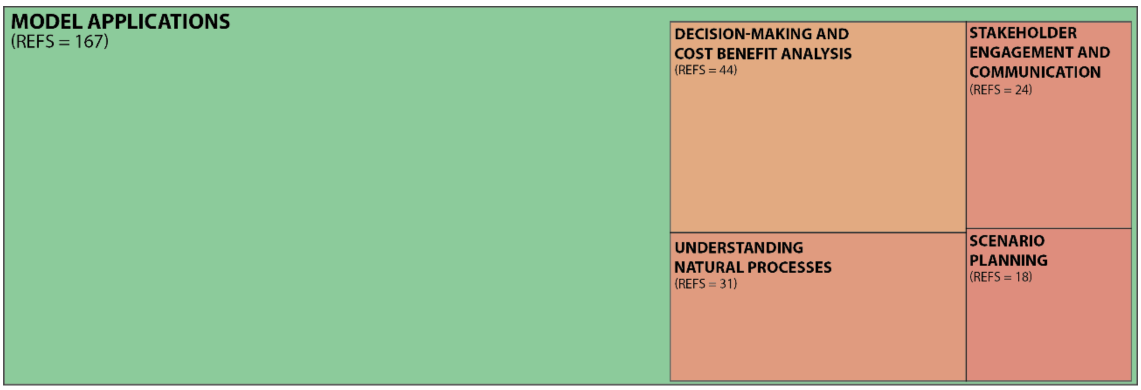


FIGURE 4-5: TREEMAP OF MODEL APPLICATIONS IDENTIFIED THROUGH THE CODING OF THE REQUIREMENTS ANALYSIS TRANSCRIPTS. 'REFS' REFERS TO THE TOTAL NUMBER OF TIMES A THEME WAS CODED.

One of the themes identified was **scenario planning** (Refs = 18), whereby the cause and effect of different model input parameters could be tested. Three key scenario planning examples were described in the transcripts. These were the impact of: (i) removing discontinuities; (ii) land cover changes; and (iii) climate change.

'The one thing we did note was looking at different scenarios, starting from the natural system and then looking at things like climate change scenarios. In terms of what we would like the model to do, is to be able to explore those change of scenarios and see what those outcomes would be…' (Environment Agency, Bristol Avon)

'… so if you were in a more urban part of the catchment and there are proposals for building houses or whatever… that could help look at what might happen…' (Environment Agency, Camel)

The approach of **understanding natural processes** (Refs = 31) within river catchments before implementing management options emerged as another theme. The quotes below demonstrate how the stakeholders wanted a model that could explain how the natural system is behaving before implementing any changes. In particular, two aspects of the natural processes were evident in the thematic analysis: (i) the sediment dynamics of the system (erosion and deposition); and (ii) the total sediment yield.

'We are not sure what natural base load is normal and what is anthropogenic or could be managed better.' (Environment Agency, Bristol Avon)

'At the moment we tend to look at sediment when it enters the watercourse but we have no idea where it is going to end up.' (North Devon Biosphere Service, Taw)

'We need a model like this to show how a whole catchment works before you start doing sticking plaster repairs at the bottom end, when you don't actually know what quite what it is you are dealing with.' (Spey Catchment Initiative, Spey)

The third theme revolved around the idea of using the outputs from the model to inform strategic **decision-making and cost benefit analysis** (Refs = 44) in river management. This emerged in three specific areas: (i) prioritising interventions and management options (e.g. higher level stewardship); (ii) habitat restoration; and (iii) dredging.

'It could be useful for cost benefit analysis, for instance we are doing some cost benefit calculations at the moment…it would be good to stack up where it is reasonable to spend your money, getting the best bang for your bucks.' (Wessex Water, Bristol Avon)

'It could be good for priorities areas such as with salmonids, through the degree of sedimentation and [the model] *will be a good tool to focus efforts on species e.g. pearl mussels.'* (Environment Agency, Taw)

'… [to show] *areas where gravel is being silted up and this could show that...'* (Natural England, Camel).

The final theme to come out of the analysis of the transcripts was the use of model outputs for **stakeholder engagement and communication** (Refs = 24). Stakeholders commented on the power of communication that can be achieved by using the outputs from the model as a useful tool for engaging with stakeholders at the local level (e.g. landowners and homeowners). Two specific examples of where the model could be used were: (i) identifying hotspots for soil erosion and sedimentation within a catchment; and (ii) understanding the impacts of farm management.

'I think these sorts of models are massively important for engagement. If you can show people they live in one of these areas and the impacts are important then it can really help to get them onside, much more than the algebra.' (Bristol Avon Rivers Trust, Bristol Avon)

'…the power of having something like this, which is interesting to show… the power of that, even though it not necessarily what you set out to do, it is a way of making it interesting and engaging. That is really useful even if it is not always accurate…' (Environment Agency, Camel)

'…this is a step up in you know as its sort of a tangible scientific output that says, look if you do X here then Y is going to occur here. It's a sort of mathematical way of almost describing something in a sort of readily available format.' (Scottish Natural Heritage, Spey)

The model applications identified through the thematic analysis of the transcripts (Figure 4-4) were then used as an input in the model applications ranking exercise in the co-designing session (described in Section 3.2.3). The outputs of which are presented in Section 4.3.

4.1.3. Model characteristics

Figure 4-6 shows the two themes of **usefulness** and **usability** (Refs = 189 and 115) identified through the analysis of the transcripts. Figure 4-7 shows the number of times each theme and sub-theme were referred to in the form of a treemap.

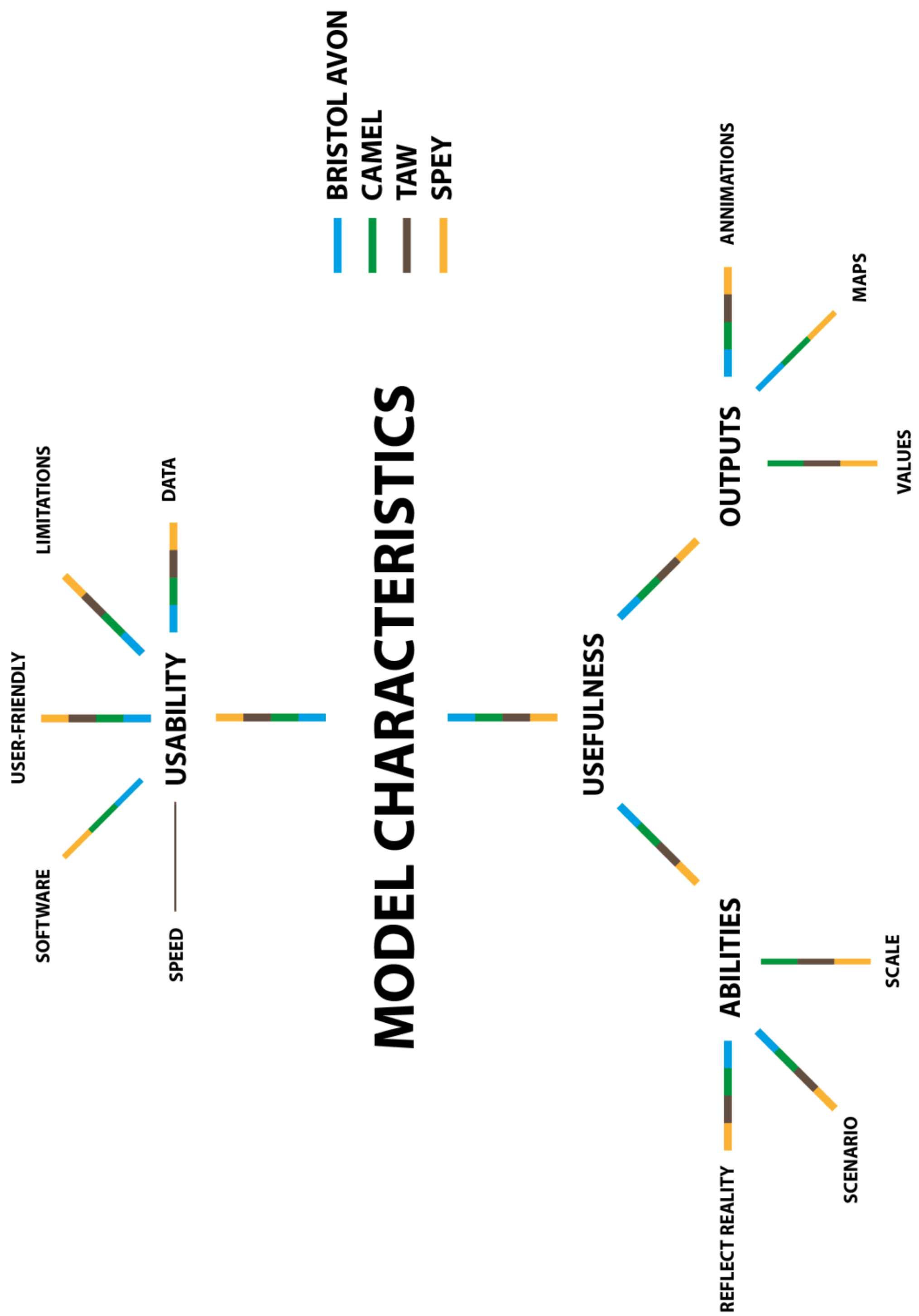


FIGURE 4-6: THEMATIC MAP OF MODEL CHARACTERISTICS IDENTIFIED THROUGH THE CODING OF THE REQUIREMENTS ANALYSIS TRANSCRIPTS. THE COLOURS AND THICKNESS OF THE LINES RELATE TO THE CATCHMENT AND THE NUMBER OF CATCHMENTS EACH CODE APPEARS IN.

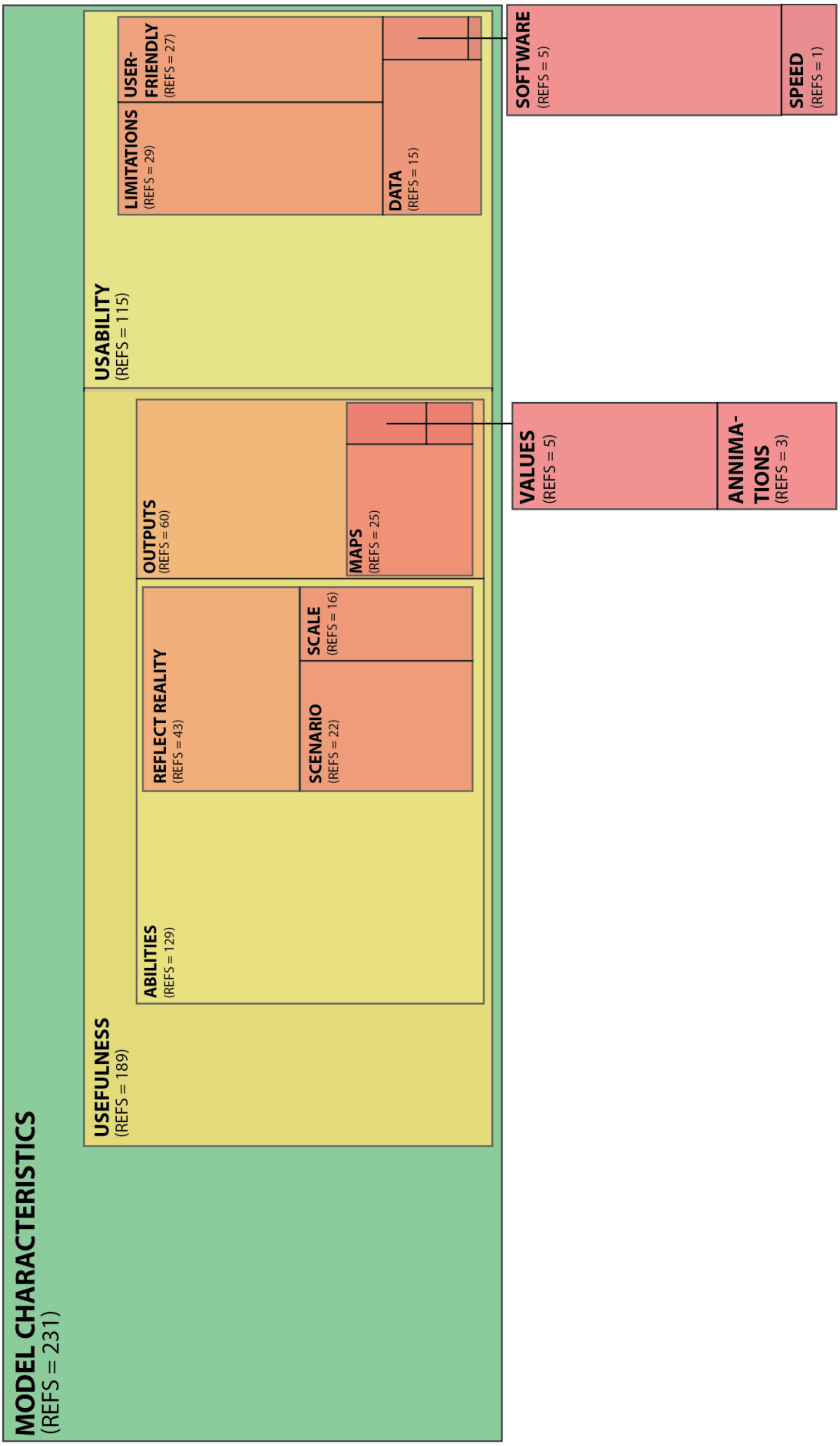


FIGURE 4-7: TREEMAP OF THE MODEL CHARACTERISTICS IDENTIFIED THROUGH THE CODING OF THE REQUIREMENTS ANALYSIS TRANSCRIPTS. REFS REFERS TO THE TOTAL NUMBER OF TIMES A THEME WAS CODED.

The **usefulness** theme was split into two sub-themes; the first of these related to the model's **abilities** (Refs = 129), and was closely linked to the applications of the model discussed in the previous section. Stakeholders emphasised that this kind of model should **reflect reality** (Refs = 43, all catchments), allow for use at different **scale**s (Refs = 16 (Camel, Taw, and Spey)), and enable the running of different **scenarios** (Refs = 22). The quotes below relate to each of these different model abilities described by stakeholders, except for 'scenarios' as several extracts relating to this were presented in the previous section.

'Models tend to be too theoretical and not relevant to the real world.' (Bath and North East Somerset Council, Bristol Avon)

'An important part of the output would be that you do not want to show people the whole catchment in the model, but in most meetings you will want to isolate bits of the catchment to see what is happening there...' (Spey Catchment Initiative, Spey)

The second sub-theme relates to the **outputs** stakeholders considered to be important for the model to produce. More specifically, this involved the different types of outputs and target audiences. Three type of outputs were expressed by the stakeholder groups, the highest coded of these was the ability to output **maps** (Refs = 25 (Bristol Avon, Camel, and Spey) of where sediment was being eroded and deposited. Closely related to this, was the ability to know a **value** (or quantity) (Refs = 5 (Camel, Taw, and Spey), rather than the common relative values given in current sediment models (e.g. ST:REAM and SCImap). The final and least coded type of output was **animations** (Refs = 3 (Bristol Avon, Camel, and Spey). The quotes on the next page demonstrate how the stakeholders described some of these aspects.

'… [it is about] *knowing whether it is absolute, so that's how much sediment is coming in or relative where this has got more than this part of the map…'* (West Country Rivers Trust, Taw)

'It would be nice to be able to say if something was changed by this much, then a visual output and get it in different figures and graphical forms. Some visuals allow you to understand it more and get it in your brain.' (Avon Frome Partnership, Bristol Avon)

'Some of the guys who go out and work with the farmers do not want to get into the detail of the model. They just want a very simple product that they can get their head around...' (Environment Agency, Camel)

Some of the other outputs suggested were outside the scope of this research, for example, an app, a Minecraft game and an interactive online web-based application. The second theme of **usability** focuses on the factors that influence whether or not a stakeholder would use a model to inform their work. The quotes below emphasise the topics that were referred to by the stakeholders, including: understanding the **limitations** (Refs = 29); **user-friendl**iness (Refs = 27); **data** requirements (Refs =15); **software** requirements (Refs = 5 (Bristol Avon, Camel, and Spey)); and model **speed** (Refs = 1 (Taw)).

'…there is a mistrust of scientists and questions will be: "Are you sure about that, why should we believe you"…and I know if I was presenting this to people, they would grill me on the accuracy a bit, "can you really be sure that's going to happen". You kind of feel disingenuous if you are presenting something you do not understand completely and you are trying to convince people something is the right thing…' (Scottish Natural Heritage, Spey)

'Easy to use, but easy to understand as well, if you use it and then make claims or decisions based on it. And because there are lots of assumptions made, you need to know the caveats or the limitations.' (Avon Frome Partnership, Bristol Avon)

'I think keeping it simple is the key because you tend to think of these models as being so complicated or going to take ages to get my head around.' (Environment Agency, Camel)

'What data you need... data that is freely available, so people can use it.' (West Country Rivers Trust, Taw)

'…it would be useful to have it in MapInfo files instead of just ArcView for example...' (Devon Wildlife Trust, Taw)

These model characteristics were then used in the designing of the conceptual model and model assessment (Sections 4.2 and 5.2).

4.1.4. Questionnaire

In addition to the session transcripts, stakeholders were asked to complete a short questionnaire at the end of the session. The results from these questionnaires are presented below in order to explore stakeholders' requirements when using a model. In two of the questions five subsets of stakeholders were used as the responses, these were:

i. Technical modellers: a person with a technical skillset and position which requires the operation of river catchment models;
ii. Small selection of management stakeholders: a selection of members from the Catchment Based Approach groups;
iii. Management stakeholders: all members of the Catchment Based Approach groups;
iv. All stakeholders: any person with an involvement or interest in river management;
v. General public: those with no direct involvement or interest in river management.

The results to the questions relating to technical expertise and preferences of the stakeholders in relation to modelling in their work questions are displayed in Figure 4-8 and Figure 4-9. Figure 4-8 shows that in three out of four catchments the majority (>50%) had not used (i.e. operated – clarified verbally) a model (numerical – clarified verbally using examples e.g. CAESAR) in the past year, with the overall figure at 59% of stakeholders. In Figure 4-9, the majority of stakeholders (83%) in all of the catchments recorded that they felt it was moderately to extremely important that they understood how models work and generate outputs. Statistically, a Kruskal-Wallis H test showed that there was not a statistically significant difference ($p > 0.05$) in response between the different stakeholder groups to either question (Table 4-1). These results were used to inform the design of the following sessions in the PM process. In particular, the co-designing and model demonstration sessions.

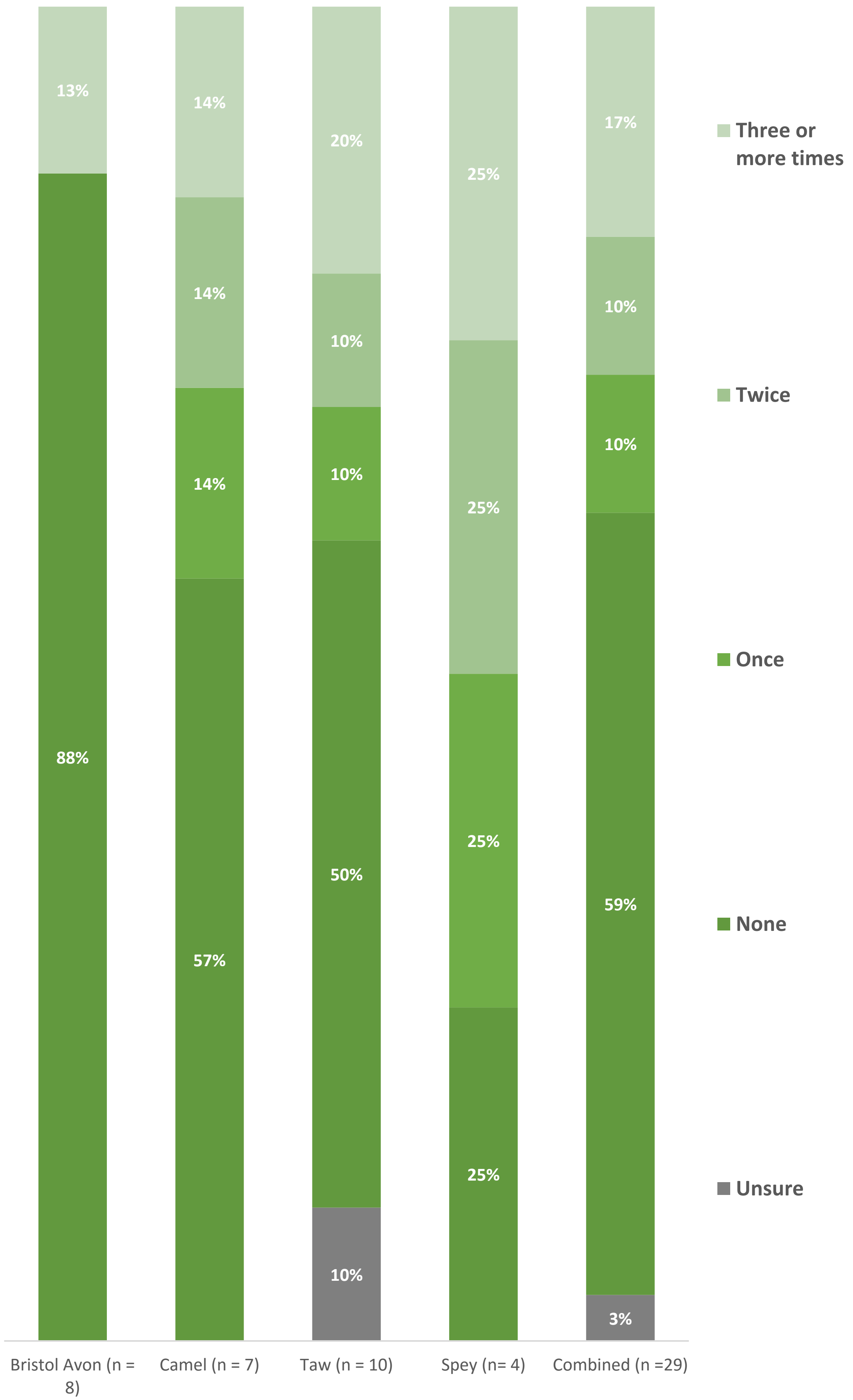


Figure 4-8: Results by catchment and combined to the question 'How many times have you used a model in your current role in the past year?'

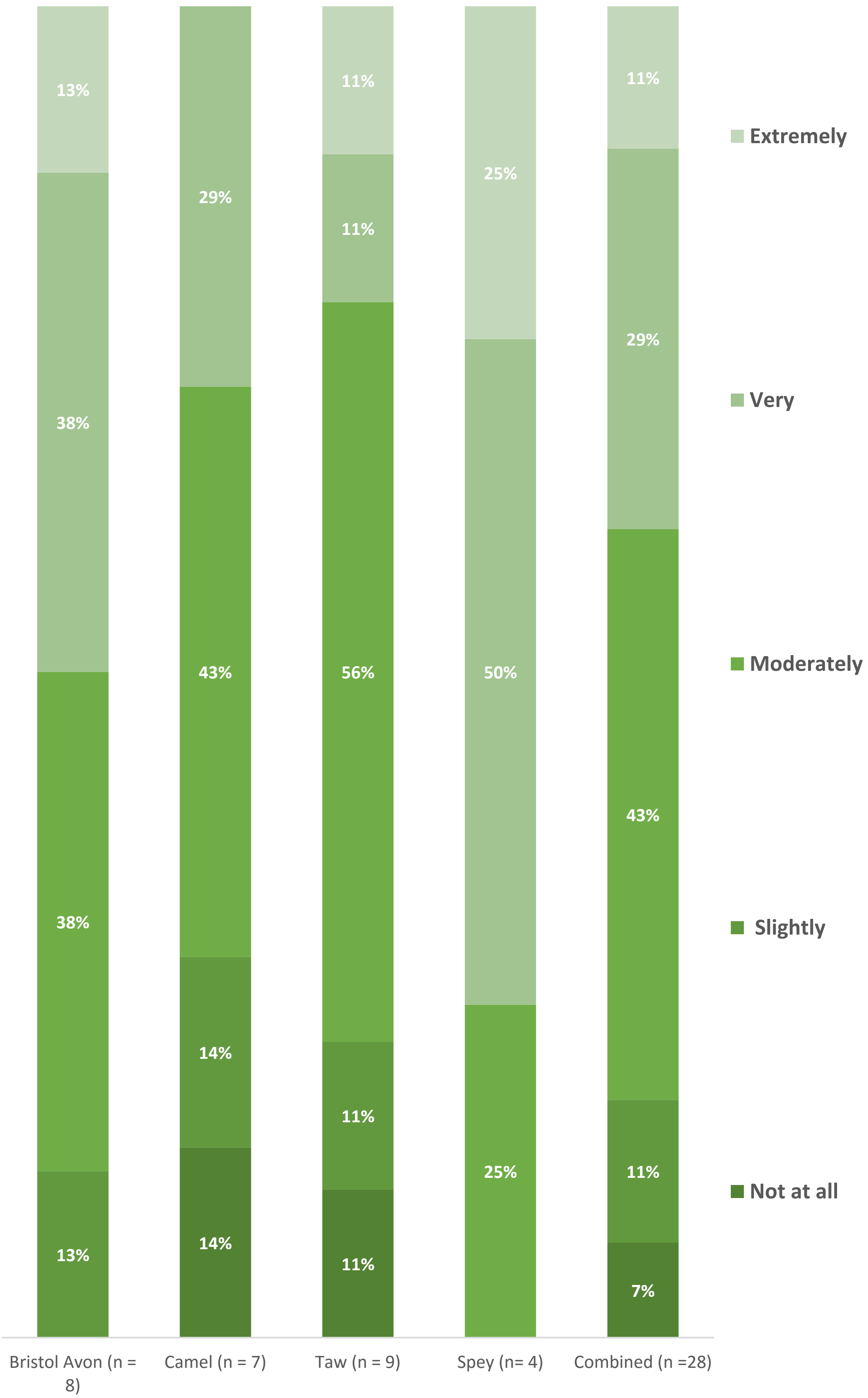


Figure 4-9: Results by catchment and combined to the question 'In your current role how important is it for you to understand how a model works and generates outputs?'. Note one stakeholder on the Taw did not complete this question.

TABLE 4-1: RESULTS FROM A KRUSKAL-WALLIS H TEST TO THE QUESTIONS 'HOW MANY TIMES HAVE YOU USED A MODEL IN YOUR CURRENT ROLE IN THE PAST YEAR?' AND 'IN YOUR CURRENT ROLE HOW IMPORTANT IS IT FOR YOU TO UNDERSTAND HOW A MODEL WORKS AND GENERATES OUTPUTS?'.

Question	Catchment	N	Mean Rank
How many times have you used a model in your current role in the past year?	Bristol Avon	8	12.00
	Camel	7	14.67
	Taw	10	14.45
	Spey	4	19.38
	Total	29	
	$\chi^2(3)$	2.788	
	p =	0.425	
In your current role how important is it for you to understand how a model works and generates outputs?	Bristol Avon	8	16.00
	Camel	7	12.50
	Taw	9	12.50
	Spey	4	20.38
	Total	28	
	$\chi^2(3)$	3.888	
	p =	0.274	

The responses to the question asking stakeholders to rank model factors in order of their importance (Scale of 1 (most important) to 6 (least important)) are shown in Figure 4-10. No clear preference emerged for model accuracy or data requirements, with similar numbers of stakeholders ranking these at both ends of the scale. Unsurprisingly, a large number of stakeholders (36%) rated ease of use as the most important factor when using a model. The outputs generated and accuracy ranked highly, with over two thirds of stakeholders (68%) ranking these factors within the top half. Similarly in the case of model abilities, 64% of the overall, stakeholders ranked it within the top 3. Stakeholders in general rated the speed of the model as the least important factor (61%), with all stakeholders ranking it as 4 or lower. Visually, there were some small differences between catchments, for example the stakeholders on the Spey ranked model abilities higher, and data requirements lower than the other catchments.

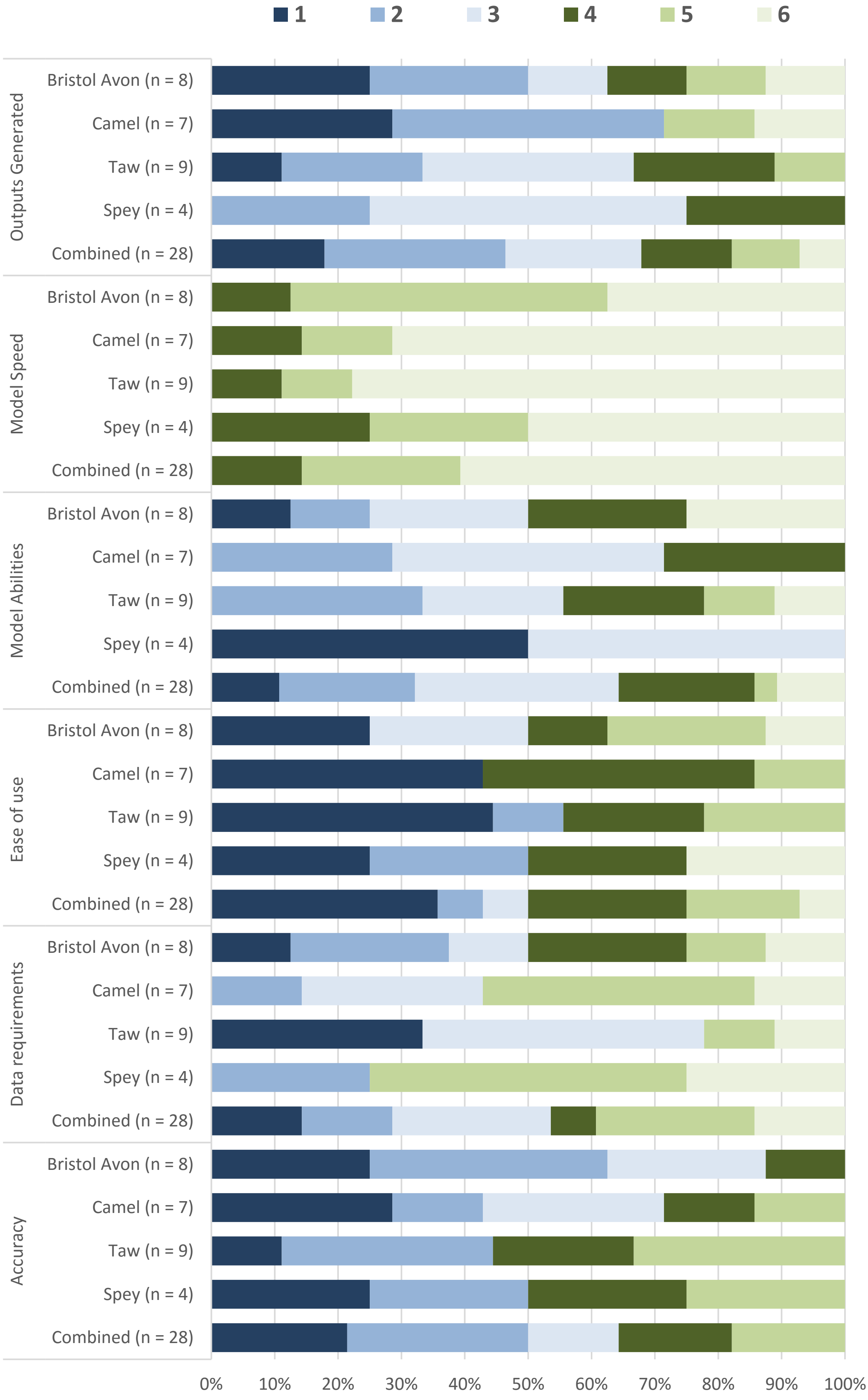


FIGURE 4-10: RANKING OF FACTORS IN ORDER OF THEIR IMPORTANCE WHEN USING A MODEL (SCALE OF 1 (MOST IMPORTANT) TO 6 (LEAST IMPORTANT)). NOTE ONE STAKEHOLDER ON THE TAW DID NOT COMPLETE THIS QUESTION.

Overall stakeholders had mixed views when asked who should be responsible for running the model (Figure 4-11), with 34% selecting that management stakeholders should be responsible for running the model, 24% chose a small selection of management stakeholders, and just over a quarter (26%) selected technical modellers, whereas only 16% selected all stakeholders. From a visual inspection, there are some variations between the stakeholder groups, for example none of the stakeholders in the Spey selected that 'all stakeholders should be responsible for running the model', whereas in the other catchments, the agreement with this statement ranged between 15-22%. Additionally, 46% and 33% of selections were made for technical modellers on the Taw and Spey, compared to 10% and 11% on the Bristol Avon and Camel.

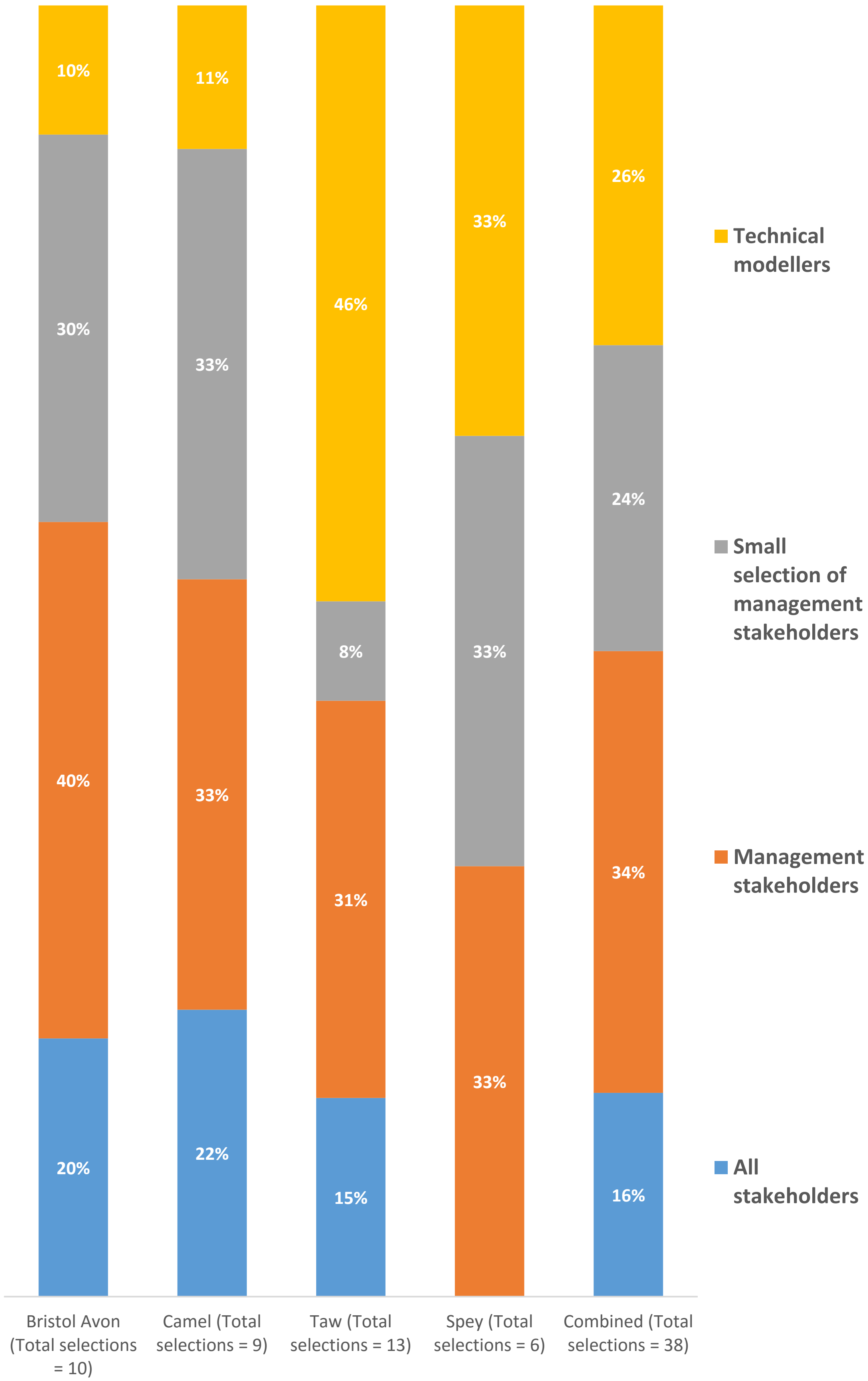


FIGURE 4-11: RESULTS BY CATCHMENT AND COMBINED TO THE QUESTION: 'WHO DO YOU THINK SHOULD BE RESPONSIBLE FOR RUNNING THE MODEL?'. NOTE THAT STAKEHOLDERS WERE ABLE TO SELECT MORE THAN ONE OPTION.

When asked about whom the outputs should be targeted at, the results reversed with ‘all stakeholders’ (60%) being the overall preferred option (Figure 4-12). There was some variation between the catchments in response to this question. Stakeholders in the Taw catchment were the only group to use the ‘other’ box, and of the two stakeholders who selected this box both specified this to be landowners. Additionally, of the Bristol Avon group, 89% of the total selections were for ‘all stakeholders’.

In the final closed question, stakeholders were asked about the types of model outputs. Stakeholders were able to select more than one option. The most popular choice for stakeholders was maps, which was selected by every stakeholder (31% of the total selections). From Figure 4-13, it is apparent that the number of selections for ‘tables’ varied between the catchments. In particular, the Bristol Avon (16% of selections) and Camel (5% of selections) had some selections, compared to 0 selections in the other catchments.

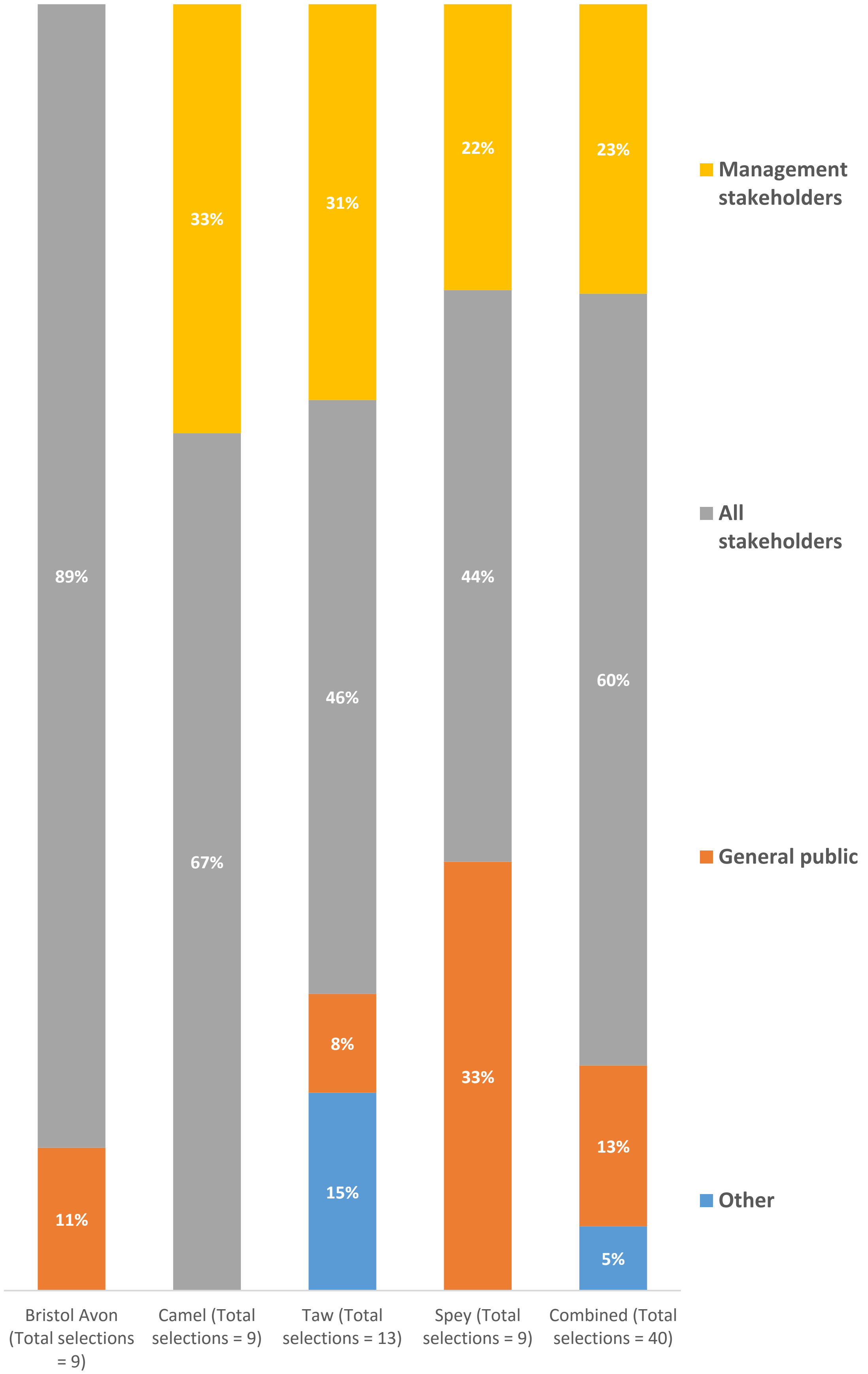


FIGURE 4-12: RESULTS BY CATCHMENT AND COMBINED TO THE QUESTION: 'WHO WOULD YOU CONSIDER TO BE THE TARGET AUDIENCE FOR THE MODEL OUTPUTS?'. NOTE THAT STAKEHOLDERS WERE ABLE TO SELECT MORE THAN ONE OPTION.

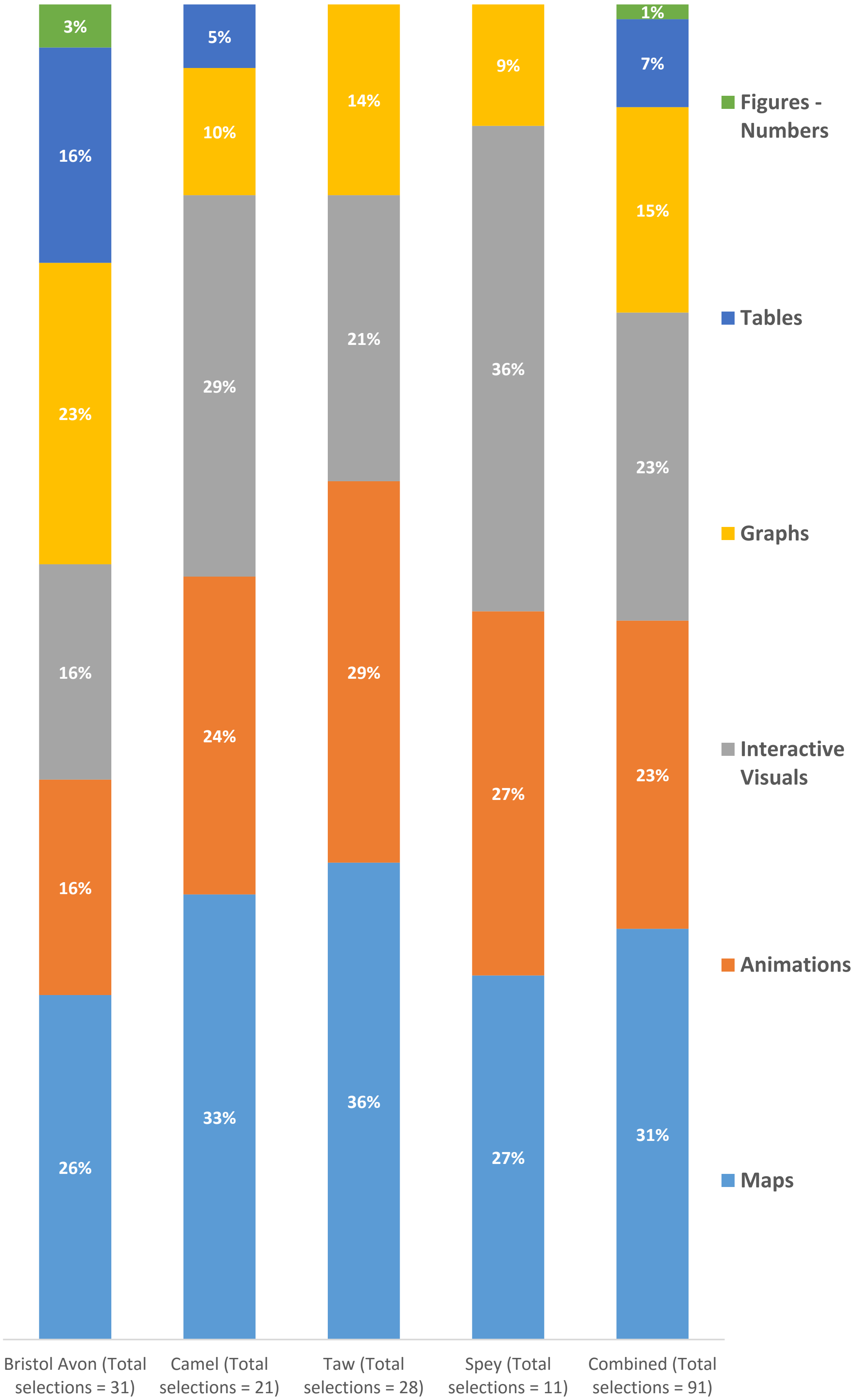


FIGURE 4-13: RESULTS BY CATCHMENT AND COMBINED TO THE QUESTION: 'WHICH OF THESE OUTPUTS WOULD YOU CONSIDER TO BE USEFUL IN AIDING SEDIMENT MANAGEMENT IN RIVER CATCHMENTS?'. NOTE STAKEHOLDERS WERE ABLE TO SELECT MORE THAN ONE OPTION.

In addition to the closed questions presented above, there were two open questions. In the first, stakeholders were asked what they thought was the most important feature or ability the model should have. The qualitative responses to this question follow the theme of using the model to predict how sediment changes as a result of land use change. These quotes capture the essence and tone of many responses:

'To predict how targeted management could reduce sediment loss from a particular sub-catchment and what would be the most effective management!' (Natural England, Camel)

'Scenario modelling and the outcomes from changes in land cover.' (Avon Frome Partnership, Bristol Avon)

'Land use, map sediment pathway, high risk areas.' (Environment Agency, Camel)

The second open question asked stakeholders if they thought there was anything else which it would be useful for the model to be capable of simulating. The majority of stakeholders left this box empty. However, of those who did fill in the box, two ideas emerged: (i) could the model incorporate flood risk, and (ii) could model included the movement of phosphate associated with the sediment.

The results of the questionnaire indicated that overall there were mixed views on who should be operating and using the model. However, when considering the model outputs, the majority thought that all stakeholders involved in catchment management were the target audience. When considering the outputs, maps were the most frequent choice, with every stakeholder selecting it as a desired output. Table 4-2 provides a summary of the thematic analysis translated into a table format.

Table 4-2: Themes, sub-themes and elements emerging from the analysis of the requirements analysis data.

Theme	Key findings		
Sediment	Pressures	Human Influences	Natural Influences
		In-channel barriers	Soil characteristics
		Land cover - urban	Geology
		Land cover – agriculture	Spatial precipitation
		Abstraction	Temporal precipitation
		Climate change	Snowmelt
		Highways and roads	Lakes and lochs
		Dredging	Invasive species
		Alterations	Ground water
		Land cover – forestry	Topography
		Recreation and tourism	
	Impacts	Soil loss	
		Ecology	
		Flooding	
		Pollution	
Model Applications	Understanding natural processes	Sediment yield	
		Sediment dynamics	
	Decision-making and cost-benefit analysis	Prioritise interventions and management options	
		Dredging	
		Habitat restoration	
	Scenario planning	Impact of removing discontinuities	
		Impact of climate change	
		Impact of land cover change	
	Stakeholder engagement and communication	Understanding impacts of farm management	
		Identifying hotspots for soil erosion and sedimentation	
Model characteristics	Usability	Software	
		User-friendly	
		Limitations	
		Speed	
		Data	
	Usefulness	Outputs	Maps
			Animations
			Values
		Abilities	Scenario
			Scale
			Reflect reality

4.2. Conceptual model

After the requirements analysis sessions had been conducted with the four stakeholder groups, the next stage in the PM process was to develop a conceptual model. The results from the previous session, provided a wealth of information in regards to stakeholders' thoughts on general modelling and more specifically, sediment modelling. Due to the large number of model influences and applications identified through the analysis, the decision was taken that initially a simple conceptual model would be developed. This left the more detailed conceptual model to be created after the co-designing sessions, where the stakeholders moved from divergent to convergent thinking, reducing the scope of the project.

Figure 4-14 shows the simple conceptual model that was created using the results from the requirements analysis session and the researcher's knowledge of sediment dynamics modelling. Table 4-3 shows how results were used either in the design of the conceptual model or left to be prioritised in the co-designing session. This conceptual model was used in the co-designing session with the stakeholders, providing them with an opportunity to comment at this very early stage in the model's development.

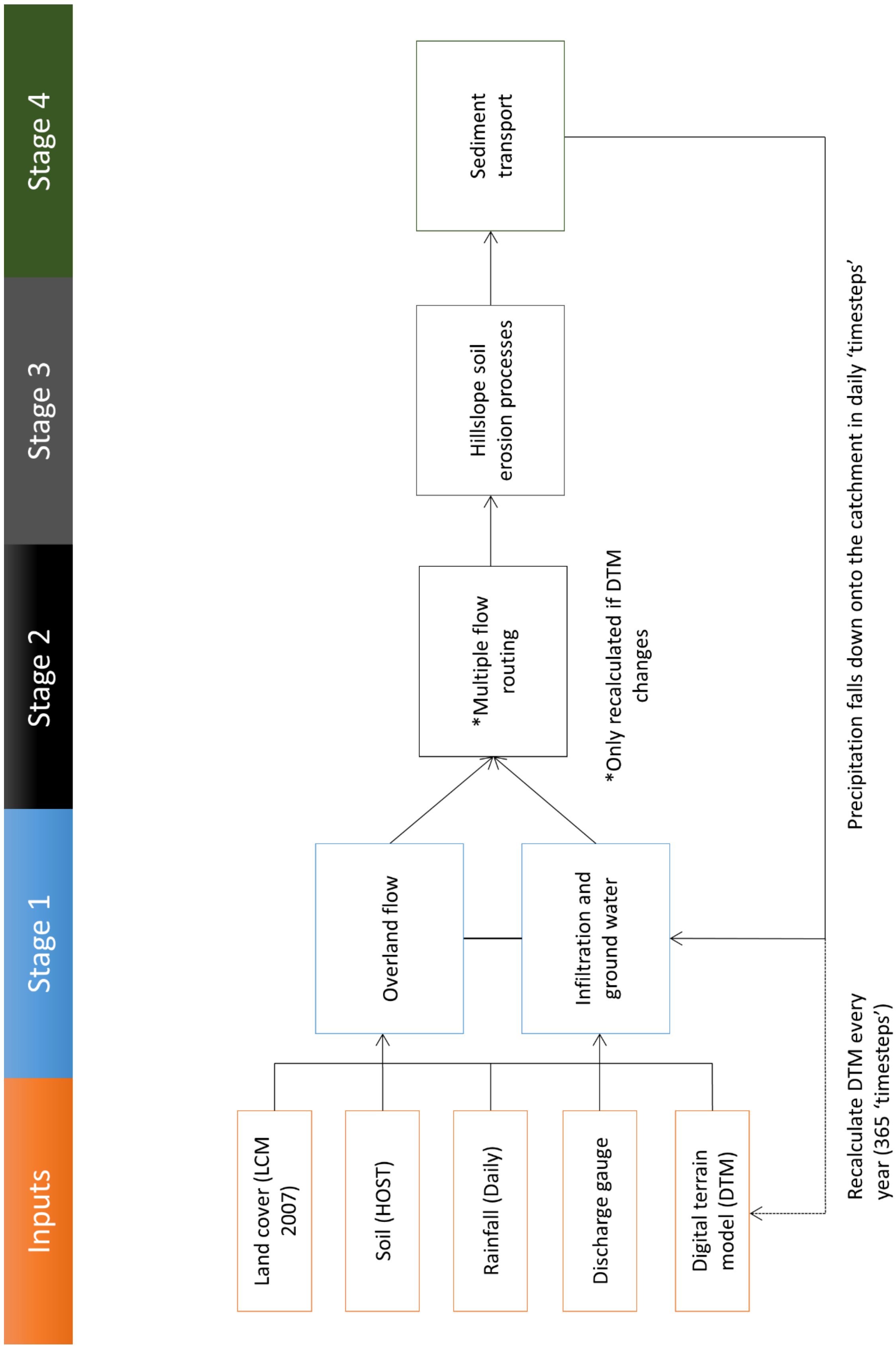


FIGURE 4-14: CONCEPTUAL MODEL CREATED AFTER THE REQUIREMENTS ANALYSIS SESSION.

Table 4-3: Summary of the stakeholder requirements, whether they were incorporated into the conceptual model, the justification behind this decision, and the method of inclusion or consideration. The shaded areas are those prioritised in the co-designing session.

<table>
<tr><th colspan="2">Model characteristics</th><th>Inclusion or consideration in conceptual model</th><th>Justification (Refs)</th><th>Method of inclusion or consideration in design</th></tr>
<tr><td rowspan="22">Inputs</td><td>Temporal precipitation</td><td>✓</td><td>Critical component of model and highest referenced natural influence (19)</td><td>Rainfall input – Daily gauge record</td></tr>
<tr><td>Soil hydrological properties</td><td>✓</td><td>Critical component of model identified by the researcher</td><td>Soil input – HOST</td></tr>
<tr><td>Land cover</td><td>✓</td><td>Highest referenced human influence (86)</td><td>Land cover input - LCM 2007</td></tr>
<tr><td>Topography</td><td>✓</td><td>Critical component of model and second highest referenced natural influence (17)</td><td>Elevation input – DTM 5-30m</td></tr>
<tr><td>Spatial precipitation</td><td>×</td><td rowspan="18">Left undecided at this stage in this process due to the large number and diversity of model influences identified in the requirements analysis</td><td rowspan="18"></td></tr>
<tr><td>Land cover - agriculture</td><td>×</td></tr>
<tr><td>In-channel barriers</td><td>×</td></tr>
<tr><td>Soil characteristics (grainsizes)</td><td>×</td></tr>
<tr><td>Geology</td><td>×</td></tr>
<tr><td>Land cover - urban</td><td>×</td></tr>
<tr><td>Highways and roads</td><td>×</td></tr>
<tr><td>Land cover – forestry</td><td>×</td></tr>
<tr><td>Alterations</td><td>×</td></tr>
<tr><td>Dredging</td><td>×</td></tr>
<tr><td>Abstraction</td><td>×</td></tr>
<tr><td>Climate change</td><td>×</td></tr>
<tr><td>Ground water</td><td>×</td></tr>
<tr><td>Invasive species</td><td>×</td></tr>
<tr><td>Lakes and lochs</td><td>×</td></tr>
<tr><td>Snowmelt</td><td>×</td></tr>
<tr><td>Recreation and tourism</td><td>×</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Outputs</td><td>Maps</td><td>✓</td><td>Maps were the highest selected ‘Model output’ in the questionnaire</td><td>Investigated the potential for integration</td></tr>
</table>

			(31%) and referenced (25) in the transcripts	within a GIS software package
	Animations	×	Not considered due to limited references to values (5) and animations (3) in the transcripts. No references were made to the other types of outputs in the transcripts	
	Tables	×		
	Graphs	×		
	Interactive visuals	×		
	Figures – Numbers (values in thematic analysis)	×		
Target users	All stakeholders	×	Based on the questionnaire results where 16% of stakeholder selections for 'All stakeholders' as responsible for running the model	Limited consideration at this stage of the process. The model will use data and software accessible to management stakeholders
	Small selection of management stakeholders	✓		
	Management stakeholders	✓		
	Technical modellers	✓		
Target audience	All stakeholders	✓	Based on the questionnaire results where 13% of stakeholder selections for 'General public' and 5% for others as the target audience for the model outputs	Limited consideration at this stage of the process. Except that the outputs from the process in the form of maps will need to be suitable for all stakeholders
	Management stakeholders	✓		
	General public	×		
	Other	×		
Model applications	Sediment yield	×	Left undecided at this point in this process due to the large number and diversity of model applications identified in the requirements analysis	
	Sediment dynamics	×		
	Prioritise interventions and management options	×		
	Dredging	×		
	Habitat restoration	×		
	Impact of removing discontinuities	×		
	Impact of climate change	×		
	Impact of land cover change	×		
	Understanding impacts of farm management	×		

	Identifying hotspots for soil erosion and sedimentation	×		
Model characteristics (merged questionnaire and themes)	Model speed	×	Based on the questionnaire results, in particular: Model speed was the lowest ranked parameter and a single reference in the transcripts Ease of use was the highest ranked parameter and the second referenced (27)	Limited direct evidence of consideration at this stage in the process. However, these provided the overarching principles on which the model was based. A model that: • Reflects reality; • Is easy to use and understand the limitations; • Operates at multiple scales; • Able run using freely available data.
	Model abilities - Scenario	✓		
	Outputs generated	✓		
	Model abilities - Scale	✓		
	Model abilities - Reflect reality	✓		
	Ease of use (user-friendly)	✓		
	Data requirements	✓		
	Accuracy	✓		
	Limitations	✓		
	Software	✓		

4.3. Co-designing

The co-design sessions utilised outputs from the requirements analysis. Firstly, the model elements used in the bulls-eye prioritisation activity were taken from the influences aspect of the sediment thematic map (Figure 4-2). Secondly, the model applications used in the ranking activity were adapted from the model applications thematic map (Figure 4-4). As described in the methodology, the purpose of these two activities was to move the stakeholders on from the divergent thinking in the requirements analysis, to convergent thinking, focusing on what would be achieved in this PM process.

The first activity required the stakeholders to prioritise model elements using a bulls-eye diagram. The results for each catchment are summarised in Table 4-4. Based on the conceptual model, the elements of temporal precipitation, land cover, topography, and soil hydrology were automatically placed in the intrinsic part of the model diagram. Spatial precipitation was the only additional model element placed within the intrinsic box by all four stakeholder groups. The next important element was land cover - agriculture (selected as intrinsic in three of the four catchments – Bristol Avon, Taw, Spey), followed by in-channel barriers, soil characteristics, and geology (selected as intrinsic in two out of four catchments). All of the stakeholder groups selected to exclude tourism and snowmelt. The three South West catchments selected to exclude lakes and lochs from the model, whereas the Spey catchment ranked this as intrinsic. In this activity, the stakeholders were allowed to create additional model elements.

Table 4-4: Results from each catchment using the bulls-eye diagram to rank model elements. This is ranked based on the position of each element in the bulls-eye activity for each group. Where: A – Intrinsic, B – Extrinsic and C – Excluded. Note that the top four shaded rows were identified to stakeholders as intrinsic to developing the model and therefore stakeholders were not required to prioritise these model elements.

Rank	Model element	Bristol Avon			Camel			Taw			Spey		
		A	B	C	A	B	C	A	B	C	A	B	C
Not Applicable	Temporal precipitation	✓			✓			✓			✓		
	Soil hydrological characteristics	✓			✓			✓			✓		
	Land cover	✓			✓			✓			✓		
	Topography	✓			✓			✓			✓		
1	Spatial precipitation	✓			✓			✓			✓		
2	Land cover - agriculture	✓				✓		✓			✓		
3	In-channel barriers	✓				✓			✓		✓		
	Soil characteristics (grain sizes)		✓		✓			✓				✓	
	Geology		✓		✓				✓		✓		
4	Land cover - urban	✓				✓			✓			✓	
	Highways/roads		✓		✓			✓					✓
	Land cover – forestry			✓		✓		✓			✓		
	Channel alterations	✓				✓				✓	✓		
5	Dredging		✓		✓					✓		✓	
	Abstraction		✓			✓				✓	✓		
	Climate change	✓				✓				✓		✓	
6	Ground water		✓			✓				✓		✓	
	Invasive species		✓			✓			✓				✓
7	Lakes and lochs			✓			✓			✓	✓		
8	Snowmelt			✓			✓			✓			✓
	Tourism			✓			✓			✓			✓
	Total selections	10	7	4	9	9	3	9	4	8	12	5	4

Table 4-5 shows the results from the second activity, where stakeholders ranked potential model applications using plastic counters. The most popular choice was 'Understanding impacts of farm management' with 20 counters (74%), closely followed by 'Prioritise interventions and management options (e.g. Higher Level Stewardship (HLS) and advice)' with 19 counters (70%). In the Spey, 'Understanding the impacts of farm management' was the joint bottom selected application (1 counter), whereas this was the highest selected application in the three South West catchments (6, 5, and 8 counters). The most selected application in the Spey was 'Prioritise interventions and management options (e.g. HLS and advice)' and 'Habitat restoration' (both with 4 counters).

TABLE 4-5: RESULTS OF THE RANKING EXERCISE OF THE POTENTIAL MODEL APPLICATIONS.

			Number of counters				
Rank	**Theme**	**Application**	**Taw**	**Bristol Avon**	**Spey**	**Camel**	**Total**
1	Stakeholder engagement and communication	Understanding impacts of farm management	6	5	1	8	**20**
2	Decision-making and cost-benefit analysis	Prioritise interventions and management options (e.g. Higher Level Stewardship (HLS) and advice)	6	3	4	6	**19**
3	Stakeholder engagement and communication	Identifying hotspots for soil erosion and sedimentation	5	3	2	5	**15**
4	Scenario planning	Impact of land cover change	5	5	1	3	**14**
5	Decision-making and cost-benefit analysis	Habitat restoration	5	3	4	1	**13**
6	Natural processes	Natural Processes: Sediment dynamics (Movement upstream to downstream)	4	3	3	2	**12**
7	Scenario planning	Impact of removing discontinuities (obstructions – e.g. dams)	2	2	2	1	**7**
8	Scenario planning	Impact of climate change	1	2	3	0	**6**
8	Natural processes	Natural Processes: Sediment yield (baseline sediment amount)	2	2	2	0	**6**
8	Decision-making and cost-benefit analysis	Dredging	2	1	2	1	**6**
9	Stakeholder added applications	Impact of abstractions	N/A	N/A	3	N/A	**3**
9		Ecosystem services	N/A	N/A	N/A	3	**3**
10		Bank erosion	N/A	N/A	2	N/A	**2**

In the co-designing session, the stakeholder groups were also given the opportunity to provide feedback on the conceptual model (Figure 4-14). The stakeholders were positive about the simplistic conceptual model and therefore did not provide a substantial amount of feedback, however, any feedback provided was transcribed and analysed using thematic analysis. From this, a thematic map of the three over-arching themes of **processes**, **applications**, and **data availability** was created (Figure 4-15).

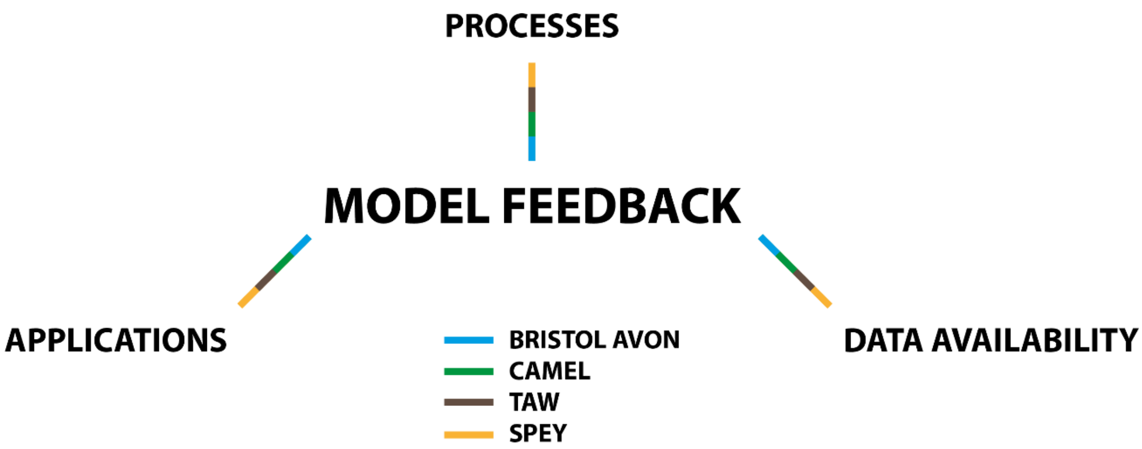


FIGURE 4-15: THEMATIC MAP OF CONCEPTUAL MODEL FEEDBACK IDENTIFIED THROUGH THE CODING OF THE CO-DESIGNING TRANSCRIPTS.

The theme of **applications** represents stakeholders' feedback on how this type of model could be used to assist them in their work. These responses were prompted to a degree by the model applications activity, however, the stakeholders then expanded upon the potential uses of the model. The quotes below emphasise two particular applications that stakeholders perceived this model could be targeted towards. These were: assessing downstream effects of upstream changes and targeting of interventions within the catchment.

'What we are really worried about is upstream effects coming downstream, so that might be very valid. If you develop x amount upstream that is in your local plan and that might have this effect.' (Bath and North East Somerset Council, Bristol Avon)

'[If we] *could use it as a targeting tool then, could you fiddle around with these parameters to get an accurate picture of what the catchment is doing and then you get your high risk sub-catchments or fields which you then go off to do something in those areas.'* (Environment Agency, Camel)

The theme of **processes** relates to the feedback gained from the stakeholders on the processes represented in the model. Primarily, the stakeholder groups of the Bristol Avon, Camel and Taw perceived that it was extremely important that the model took into account the type of agriculture and management practices. This is reflected in the quotes below.

'Different soils have different rainfall acceptance potential depending on their natural state, but what about compaction, reducing infiltration?' (Farming and Wildlife Advisory Group, Taw)

'Can you factor in good farm management practice and bad farm management practice?' (Environment Agency, Bristol Avon)

'If you think of a field over winter with 2 cattle compared to 30 cattle, it is a completely different effect' (Natural England, Camel)

Each of the catchment groups discussed the possibility of representing certain processes in the model. These were:

- Bristol Avon – Tidal and dredging
- Camel – Hedgerows and storms
- Taw – Invasive species
- Spey – Abstraction

However, after some discussion between the stakeholders, they decided that this would either be too difficult or that there would not be suitable data available. This links to the final theme of **data availability**, an example of which was the Camel stakeholder group discussion of the importance of agriculture. Here DEFRA's farm Single Payment Scheme (SPS) data was suggested as a method for representing land cover within catchments in greater detail.

'There is not much data on that [dredging]*. There is only one bit that I know of, and that is when we do occasional dredging in the harbour.'* (Bristol City Council, Bristol Avon)

'DEFRA data on the single farm scheme payment data tells you if land is permanent grassland, pasture land and what crop it is, so I think you can make use of that sort of data and fit it into your 10 metre squares' (Environment Agency, Camel)

The results from the two activities were combined with the oral feedback, and used in the development of a draft model.

4.4. Draft model

The next stage in the PM process was the development of a draft model. The first part of this process was to create a more detailed conceptual model using the feedback gained in the previous sessions with the stakeholders (Figure 4-16). Table 4-6 shows an updated version of the stakeholder requirements based on the results gathered in the co-designing session. As described in Chapter 3, the development of the draft conceptual model involved the combination of the researcher's knowledge of cellular modelling of sediment dynamics with the results from the participatory sessions. This model was coded using the Python programming language (over 15,000 lines of code) in a process that took circa. 9 months. This model was then shown to the stakeholders in the model demonstration session and detailed feedback captured.

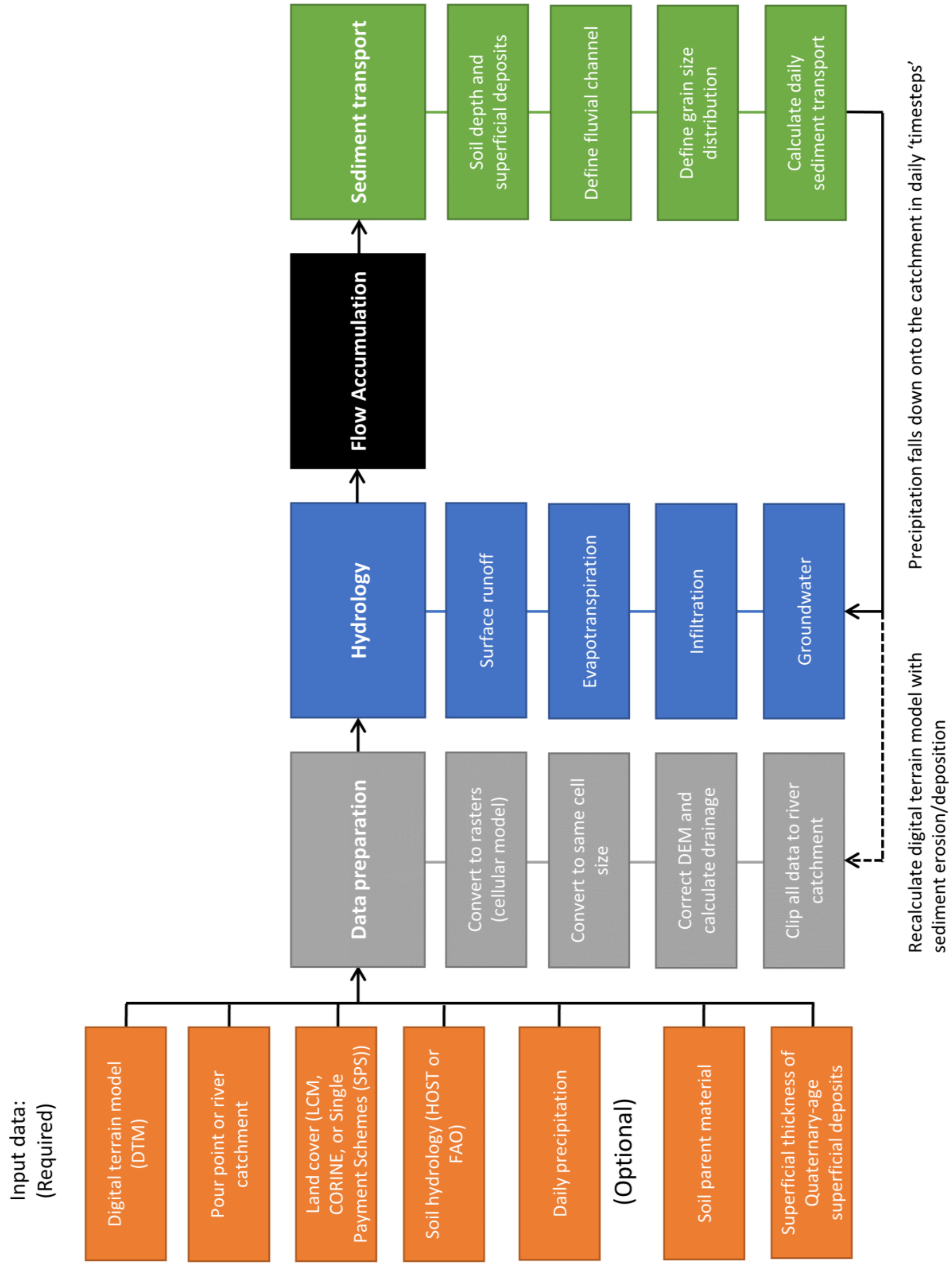


FIGURE 4-16: REVISED CONCEPTUAL MODEL CREATED AFTER THE CO-DESIGNING SESSION.

Table 4-6: Summary of the stakeholder requirements, whether they were incorporated into the draft model, the justification behind this decision, and the method of inclusion or consideration. The shaded areas are unchanged from the conceptual model.

Model characteristics		Inclusion or consideration in draft model	Justification (Refs)	Method of inclusion or consideration in design
Inputs	Temporal precipitation	✓	Critical component of model and highest referenced natural influence (19)	Rainfall input – Daily gauge record
	Soil hydrological properties	✓	Critical component of model identified by the researcher	Soil input – HOST or FAO
	Land cover	✓	Highest referenced human influence (86)	Land cover input - LCM 2007 or CORINE or Farm Single Payment Scheme (SPS)
	Topography	✓	Critical component of model and second highest referenced natural influence (17)	Elevation input – DTM 5-30m
	Spatial precipitation	✓	Based on the ranking of model elements using bulls-eye diagram in the co-designing session	Chapter Five a detailed description of how these were incorporated
	Land cover - agriculture	✓		
	In-channel barriers	✓		
	Soil characteristics (grainsizes)	✓		
	Geology	✓		
	Land cover - urban	✓		
	Highways and roads	✓		
	Land cover – forestry	✓		
	Alterations	×		
	Dredging	×		
	Abstraction	×		
	Climate change	×		
	Ground water	×		
	Invasive species	×		
	Lakes and lochs	×		
	Snowmelt	×		
	Recreation and tourism	×		

Outputs	Maps	✓	Maps were the highest selected 'Model output' in the questionnaire (31%) and referenced (25) in the transcripts	Built in the most popular commerical GIS software - ArcGIS
	Animations	×	Not considered due to limited references to values (5) and animations (3) in the transcripts. No references were made to the other types of outputs in the transcripts	
	Tables	×		
	Graphs	×		
	Interactive visuals	×		
	Figures – Numbers (values in thematic analysis)	×		
Target users	All stakeholders	×	Based on the questionnaire results where 16% of stakeholder selections for 'All stakeholders' as responsible for running the model	The model uses data and software accessible to management stakeholders
	Small selection of management stakeholders	✓		
	Management stakeholders	✓		
	Technical modellers	✓		
Target audience	All stakeholders	✓	Based on the questionnaire results where 13% of stakeholder selections for 'General public' and 5% for others as the target audience for the model outputs	The outputs from the model are in the form of maps that are suitable for all stakeholders
	Management stakeholders	✓		
	General public	×		
	Other	×		
Model applications	Understanding impacts of farm management	✓	Based on the ranking exercise of potential model applications and technical feasibility at this scale	Chapter Five provides a detailed description of how these were incorporated
	Prioritise interventions and management options (e.g. Higher Level Stewardship (HLS) and advice)	✓		
	Identifying hotspots for soil erosion and sedimentation	✓		
	Impact of land cover change	✓		
	Habitat restoration	×		
	Natural Processes: Sediment dynamics (Movement upstream to downstream)	✓		
	Impact of removing discontinuities	✓		

	(obstructions – e.g. dams)			
	Impact of climate change	✓		
	Natural Processes: Sediment yield (baseline sediment amount)	✓		
	Dredging	×		
	Impact of abstraction	×		
	Ecosystem services	×		
	Bank erosion	×		
Model characteristics (merged questionnaire and themes)	Model speed	×	Based on the questionnaire results, in particular: Model speed was the lowest ranked parameter and a single reference in the transcripts Ease of use was the highest ranked parameter and the second referenced (27)	
	Model abilities - Scenario	✓		Chapter Five a detailed description of how these were incorporated
	Outputs generated	✓		
	Model abilities - Scale	✓		
	Model abilities - Reflect reality	✓		
	Ease of use (user-friendly)	✓		
	Data requirements	✓		
	Accuracy	✓		
	Limitations	✓		
	Software	✓		

4.5. Model demonstration

In this section, the results from the thematic analysis of the model demonstration transcripts are presented. These outputs include a thematic map (Figure 4-17) and treemap (Figure 4-18) of the themes, sub-themes and individual codes. Figure 4-17 comprises of a number of themes: (i) **processes** (Refs = 43); (ii) **abilities** (Refs = 41); (iii) **ease of use** (Refs = 27); (iv) **outputs** (Refs = 27); and (v) **data** (Refs = 22). Each of these themes will be explored in detail and supported by extracts from the model demonstration transcripts.

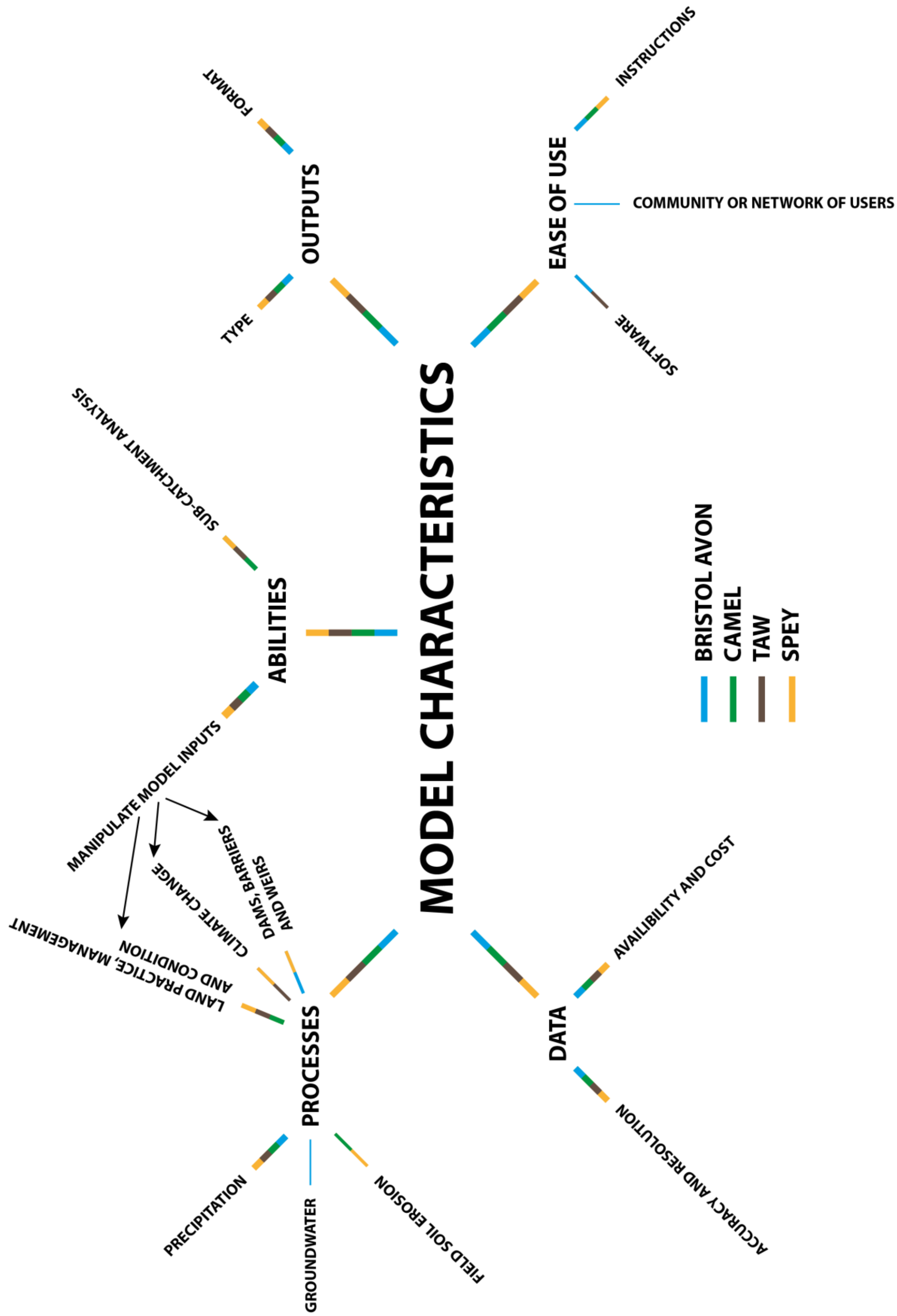


Figure 4-17: Thematic map of model characteristics identified through the coding of the participatory demonstration transcripts. The colours and thickness of the lines relate to the catchment and the number of catchments each code appears in.

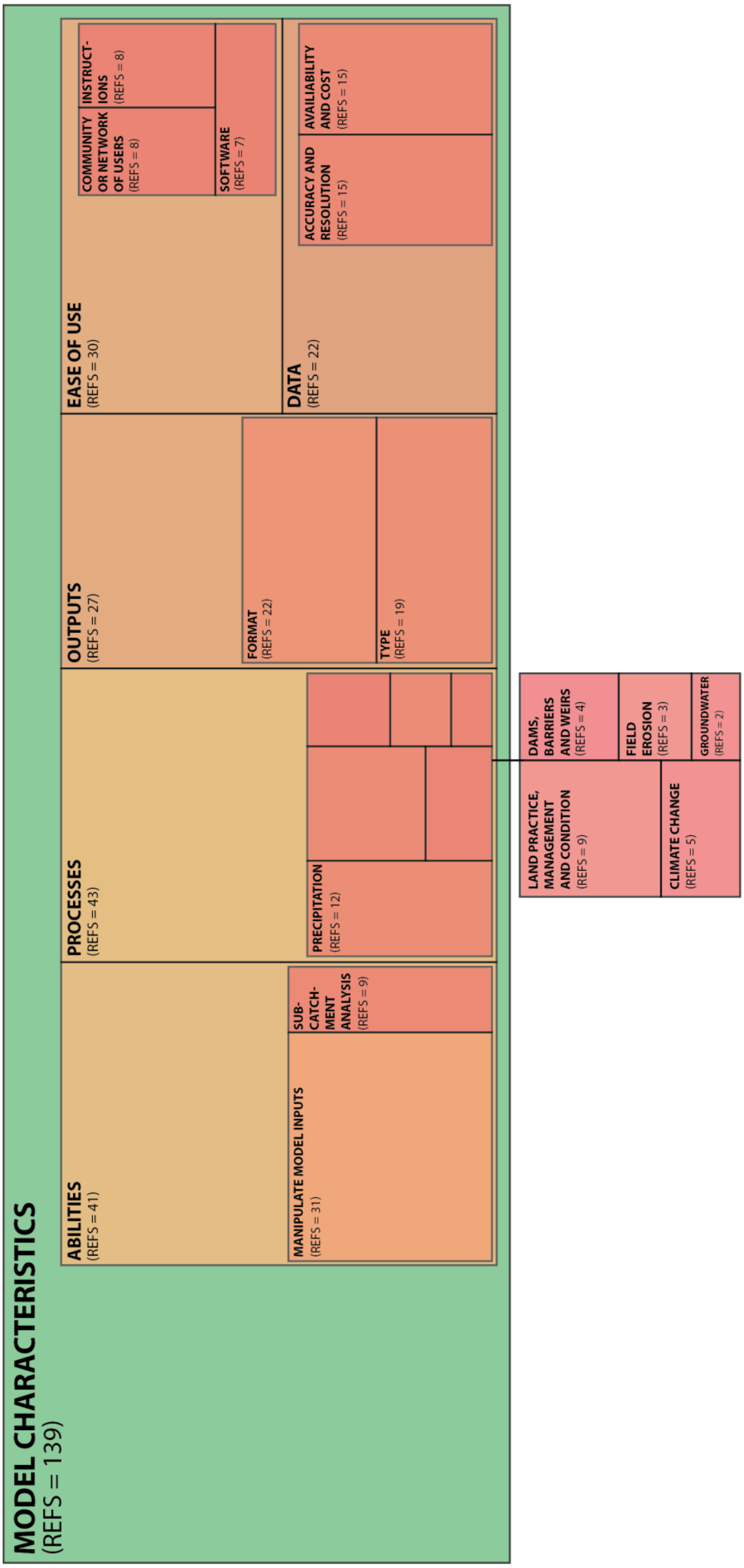


FIGURE 4-18: TREEMAP OF MODEL CHARACTERISTICS IDENTIFIED THROUGH THE CODING OF THE MODEL DEMONSTRATION TRANSCRIPTS. 'REFS' REFERS TO THE TOTAL NUMBER OF TIMES A THEME WAS CODED.

The theme of model **abilities** comprises of comments made by the stakeholders of model uses. The first and most prominent of these was the ability for the user to **manipulate model inputs** (Refs = 31). In particular, this related to the user being able to change the input data. Thus, allowing the stakeholder to run a number of scenarios.

'I think it is nice to have an option where you can tailor things…. I can change it [the inputs] *and tailor them from what it currently is, to what I am desiring or not desiring depending what you are trying to illustrate… and then re-run it showing what that change is.'* (West Country Rivers Trust, Taw)

One of the types of data that the stakeholders were most interested in being able to change was the land cover.

'Is there a way of changing the datasets you have got? …. For example, can you say I am going to change the catchment to be all permanent pasture and what happens if I do that? ...We would want to do selective changes...' (Bath and North East Somerset Council, Bristol Avon)

'So if you said for example this area is seeing a lot of erosion, what if we change that land use?' (West Country Rivers Trust, Taw)

Another of these was the ability to take away in-channel barriers, which would allow the user to see the effects of removing one of these structures.

'In-channel barriers like weirs … if you had the ability to factor those in where the sediment is likely to build up behind them… if they weren't there the model runs fine and the sediment ends back out to sea... if we could have the model so you could run it with the barriers and without the barriers and see what the difference is…' (Environment Agency, Bristol Avon)

'This is the fascinating thing because if you could build a barrier you would get some good results. I was on the next catchment down, the Tay, and we were looking at hydro schemes down there and it was very clear that there used to be a layer of sediment until they built this dam.' (Scottish Environment Protection Agency, Spey)

The other model ability described by the stakeholders was the ability for the model to work with different **sub-catchments** (Refs = 9 (Camel, Taw, and Spey)), as the user selected them, rather than the model looking at the whole catchment.

> *'Could you use it to look at the effect of woodland planting within a sub catchment? So if a landowner said you know I am thinking of planting trees on all these fields. Could you look at a sub catchment level?'* (Natural England, Camel)

The theme of **processes** (Refs= 43) reflects feedback from the stakeholders on the processes that were operating within the model. The most articulated process sub-theme was **precipitation** (Refs = 12). In particular, this related to the model's daily 'timestep', several stakeholders commented that sub-daily rainfall events can be very important. Therefore, it is important to acknowledge the limitations of the model. Some of this discussion is captured in the quotes below.

> *'I expect it would be reflected in a day's rainfall. But that was the specific thing about if you go to the North West of this country, Bertha* [a winter storm] *was really quite special in that regard our hydrologists are telling us. It wasn't an exceptional daily rainfall event, it was an exceptional three hour rainfall period.'* (Scottish Environment Protection Agency, Spey)
>
> *'Especially the high intensity ones, so self-perpetuating convective storms where they can literally be dry over 500 metres, such as Boscastle. But also the element of tracking so if you get sort of an average daily rainfall there is a problem of wetting and rewetting and that affecting the hydrology.'* (Environment Agency, Taw)

The sub-theme of **land practice, management and condition** (Refs = 9 (Camel, Taw, and Spey)) refers to how the model incorporates the practice, management and condition of the land cover. The stakeholders considered that although the inclusion of detailed land cover within the model to be positive, however, there needed to be the incorporation of the practices, management and condition of the land cover. This sub-theme is interlinked with the **manipulate model inputs sub-theme** (Refs = 31), as shown in Figure 4-17. The quotes below demonstrate this linkage and the effect that different types of land management have on woodland runoff rates.

'…that in a way is going to be one of the biggest tools that we are going to have to influence is actually how you are managing the land… often you will not be able to change the land use.' (Environment Agency, Taw)

'Managed woodland would obviously be having quite a positive effect because there would be reduced runoff.' (Silvanus Trust, Taw)

Climate change (Refs = 5 (Taw and Spey)) arose as a sub-theme in two of the catchments. These stakeholder groups understood that climate change is particularly difficult to model. Instead, enquiring if climate change could be included in the model by changing the input precipitation data.

'Can we model climate change for example, through messing around with precipitation and seeing what happens?' (Scottish Environment Protection Agency, Spey)

'I suppose you could do it as simply increasing it to be 10% more precipitation... you could pick any figure and you can still query if it is accurate or not. The whole point is just having that ability to look at different scenarios.' (West Country Rivers Trust, Taw)

The sub-theme of **dams, barriers** (in-channel) **and weirs** (Refs = 4 (Bristol Avon and Spey)) was presented earlier in this section under the abilities theme. More specifically, under the sub-theme of manipulating model inputs, stakeholders felt it was important that users could add and remove structures within the model. The two least coded sub-themes were **field erosion** (Refs = 3 (Camel and Spey)) and **groundwater** (Refs = 2, Bristol Avon) and described specific processes that could be incorporated into the model.

'Will this be able to show soil erosion...the reason I ask is we have a soil person in our organisation who is very interested in this model. She is interested in it for runoff from the land.' (Scottish Environment Protection Agency, Spey)

'… [if] *you are in a ground water fed catchment and you know the water table is saturated then from the point of view of a water company we would be interested in getting that incorporated.'* (Wessex Water, Bristol Avon)

The theme of **ease of use** (Refs = 30) comprises of five sub-themes relating to the feedback from the stakeholders on what they thought was crucial in determining whether or not the model was easy to use, and therefore would be used. The sub-theme of **instructions** (Refs = 8 (Bristol Avon, Camel, and Spey)) was coded during three of the catchment sessions as there was clearly a need for an information guide targeted at stakeholders for using the model.

'Is there any proposal to make an instruction manual and idiots guide?' (Environment Agency, Bristol Avon)

'I think that needs to be guided by what feedback you have got from people why would they use this model and having a simple kind of user guide built into it to say are you interested in finding out X, then *this is a quick guide to how you could do it.'* (Wessex Water, Bristol Avon)

A **community or network of users** (Refs = 8 (Bristol Avon)) was described in the Bristol Avon group and comprises of three aspects. Firstly, the stakeholders suggested setting up a network of users, who could run and operate the model. Secondly, the stakeholders identified the need to publicise and get 'other people involved' in using the model. Finally, the stakeholders suggested the need to use the outputs from the model as a part 'strategic' thinking to locate multiple-benefit projects. The final sub-theme of ease of use relates to the **software** (Refs = 7 (Bristol Avon and Taw)) in terms of the outputs generated and the software the model is integrated within.

'So could you output at this point data that MapInfo could use?' (Bath and North East Somerset Council, Bristol Avon)

'...it would be great if it was web-based.' (Environment Agency, Taw)

The **outputs** (Refs = 27) theme emerged from stakeholders' feedback when the researcher presented some of the outputs being generated by the model. This feedback was divided into two sub-themes of the **format** (Refs = 22) and **types** (Refs = 19) of outputs. However, due to the way the data was coded there is significant overlap between the two sub-themes. The quotes below reflect the feedback from the stakeholders on the outputs generated.

'[So] *you could build up a picture of a catchment that you could stick on a wall and see those two parts of the catchment are the areas at risk for that particular parameter…'* (Environment Agency, Camel)

'So if you run it for a year you are going to have 365 outputs ... would there be a way of having it produce just one that shows change over time or something like that?' (Silvanus Trust, Taw)

'I think it would be useful to have it come out very clearly to be able to show very demonstrable results, then this is the benefit to you in managing your land and have figures in as well.' (Silvanus Trust, Taw)

The final theme related to something that has been discussed at length throughout the PM process, **data** (Refs = 22), in particular, its **availability and cost** (Refs = 15). The stakeholders (especially those outside of the Environment Agency) do not want to spend a large amount of time gathering data from other organisations. Furthermore, stakeholders did not want to have to sign license agreements, which were seen as a resource intensive task.

'I am just thinking on accessibility and usability and this model and tool, we had to fight to get the data from the EA. I know it is being worked on now, hopefully that will be improved and we will have learnt from that process.' (Wessex Water, Bristol Avon)

The model demonstration sessions also gave the researcher the opportunity to ask stakeholders about data they have access to. For example, the quote below is the response from a stakeholder regarding the question of a similar dataset to the Single Payment Scheme (SPS) in England.

'It would be Scotland development policies, which is about to re-launch in February, some of the codes will remain the same but some of the payments systems will change. But there will be a department that does a similar thing up here.' (Spey Fisheries Board, Spey)

The other sub-theme referred to the **accuracy and resolution** (Refs = 15) of the data that was, or could, be used in the model. Furthermore, these discussions tended to focus on more accurate or higher resolution dataset. The quotes below from the two hydromorphologists/fluvial geomorphologists within SEPA and the EA reflect the essence of these discussions.

'In terms of DTM we have some coverage of LIDAR, can you use that instead?' (Scottish Environment Protection Agency, Spey)

'…you could put in things like tracks if you had that in GIS, the other thing would be having a stream network in there. Because I think in some cases you know it is going to be the tracks, the roads and even small little water courses which are going to be quite important in sediment transport…' (Environment Agency, Taw)

4.6. Revised model

This section briefly describes how the outputs from the previous session were used to revise the draft model to create the revised model (Figure 4-19). A summary of the model characteristics identified through the PM process, and whether or not they have been incorporated into the revised model, is shown in Table 4-7. A detailed description of the individual components and processes operating in revised model shown in Figure 4-19, called 'ENGAGE', will be presented in the next chapter.

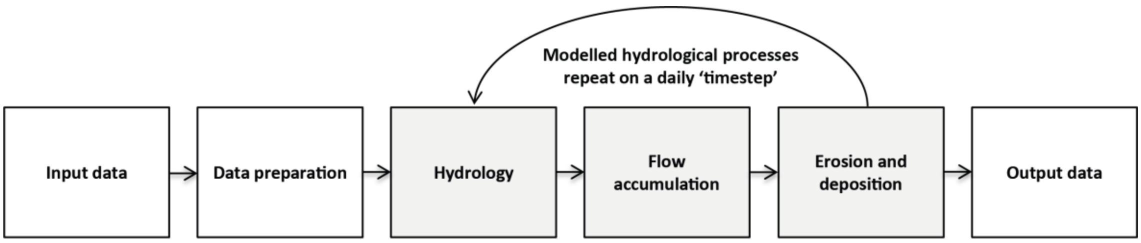


FIGURE 4-19: REVISED CONCEPTUAL MODEL CREATED AFTER THE MODEL DEMONSTRATION SESSION.

TABLE 4-7: SUMMARY OF THE STAKEHOLDER REQUIREMENTS, WHETHER THEY WERE INCORPORATED INTO THE REVISED MODEL, THE JUSTIFICATION BEHIND THIS DECISION, AND THE METHOD OF INCLUSION OR CONSIDERATION. THE SHADED AREAS ARE UNCHANGED FROM THE DRAFT MODEL.

Model characteristics		Inclusion or consideration in revised model	Justification (Refs)	Method of inclusion or consideration in design
Inputs	Temporal precipitation	✓	Critical component of model and highest referenced natural influence (19)	Rainfall input – Daily gauge record
	Soil hydrological properties	✓	Critical component of model identified by the researcher	Soil input – HOST or FAO
	Land cover	✓	Highest referenced human influence (86)	Land cover input - LCM 2007 or CORINE or Farm Single Payment Scheme (SPS)
	Topography	✓	Critical component of model and second highest referenced natural influence (17)	Elevation input – DTM 5-30m
	Spatial precipitation	✓	Based on the ranking of model elements using bulls-eye diagram in the co-designing session	Precipitation (Daily recorded) and Precipitation Gauge Elevation
	Land cover - agriculture	✓		Land cover input - LCM 2007 or CORINE or Farm Single Payment Scheme (SPS)
	In-channel barriers	✓		User defined
	Soil characteristics (grainsizes)	✓		Soil parent material (1:50,000)
	Geology	✓		Soil parent material (1km resolution)
	Land cover - urban	✓		Land cover input - LCM 2007 or CORINE or Farm Single Payment Scheme (SPS)
	Highways and roads	✓		OS Open Roads
	Land cover – forestry	✓		Land cover input - LCM 2007 or CORINE or Farm Single Payment Scheme (SPS)
	Alterations	×		Not included
	Dredging	×		
	Abstraction	×		
	Climate change	×		
	Ground water	×		
	Invasive species	×		
	Lakes and lochs	×		
	Snowmelt	×		
	Recreation and tourism	×		
	River network	✓	Discussed in the model demonstration sessions	Model can use the Detailed River Network

				or OS Open Rivers to burn in river network
Outputs	Maps	✓	Maps were the highest selected 'Model output' in the questionnaire (31%) and referenced (25) in the transcripts	Built in the most popular commercial GIS software - ArcGIS
	Animations	×	Not considered due to limited references to values (5) and animations (3) in the transcripts. No references were made to the other types of outputs in the transcripts	
	Tables	×		
	Graphs	×		
	Interactive visuals	×		
	Figures – Numbers (values in thematic analysis)	×		
Target users	All stakeholders	×	Based on the questionnaire results where 16% of stakeholder selections for 'All stakeholders' as responsible for running the model	The model uses data and software accessible to management stakeholders
	Small selection of management stakeholders	✓		
	Management stakeholders	✓		
	Technical modellers	✓		
Target audience	All stakeholders	✓	Based on the questionnaire results where 13% of stakeholder selections for 'General public' and 5% for others as the target audience for the model outputs	The outputs from the model are in the form of spatial data which can easily be used to create maps that are suitable for all stakeholders
	Management stakeholders	✓		
	General public	×		
	Other	×		
Model applications	Understanding impacts of farm management	✓	Based on the ranking exercise of potential model applications and technical feasibility	Ability to change land cover using SPS data and hydrological condition in the model
	Prioritise interventions and management options (e.g. Higher Level Stewardship (HLS) and advice)	✓		
	Identifying hotspots for soil erosion and sedimentation	✓		Outputs generated allow the user to see areas of the catchment experiencing these issues
	Impact of land cover change	✓		Ability to change land cover and hydrological condition built into the model
	Habitat restoration	×		
	Natural Processes: Sediment dynamics (Movement	✓		Outputs generated allow the user to see areas of the catchment

	upstream to downstream)			experiencing these issues
	Impact of removing discontinuities (obstructions – e.g. dams)	✓		Ability to input to incorporate in channel structures
	Impact of climate change	✓		Ability to alter precipitation
	Natural Processes: Sediment yield (baseline sediment amount)	✓		Output excel file of daily total sediment leaving the catchment at the pour point
	Dredging	×		
	Impact of abstraction	×		
	Ecosystem services	×		
	Bank erosion	×		
Model characteristics (merged questionnaire and themes)	Model speed	×	Based on the questionnaire results, in particular: Model speed was the lowest ranked parameter and a single reference in the transcripts Ease of use was the highest ranked parameter and the second referenced (27)	
	Model abilities - Scenario	✓		Not directly incorporated in the model. However, tools such as add in-channel structures, alter precipitation and alter land cover allow the users to change the starting conditions
	Outputs generated	✓		Outputs are generated in a GIS mapping format
	Model abilities -Scale	✓		Model can operate at several grid cell resolutions
	Model abilities - Reflect reality	✓		Incorporation of detailed land cover using SPS / LCM data
	Ease of use (user-friendly)	✓		Data preparation module built into the model
	Data requirements	✓		Can operate using freely available or commercial datasets.
	Accuracy	✓		The structure and function of the model is scientifically sound and defensible
	Limitations	✓		Limitations of the draft model articulated to the stakeholders in the model demonstration session and in the final model presentation
	Software	✓		Built in the most popular GIS software – ArcGIS

Chapter Five: The ENGAGE model

This chapter presents a comprehensive description of the model created through the participatory modelling process, details the results from the model assessment, and considers the implications of these results for the developed model. The name for the model was chosen based on the ethos through which it has been developed, engaging with stakeholders.

5.1. Model description

The ENGAGE model is based upon cellular modelling principles which allow the model to be incorporated into existing GIS software and uses readily available GIS data in the raster format. In order to maintain the reduced-complexity principle, and allow the model to operate at the intermediate temporal (1-100 years) and spatial scales (0.5 – 500km) relevant to sustainable river catchment management, simplistic techniques were used to incorporate some of the modelled processes. This section is split into six sub-sections; each describing a different component of the ENGAGE model (Figure 5-1).

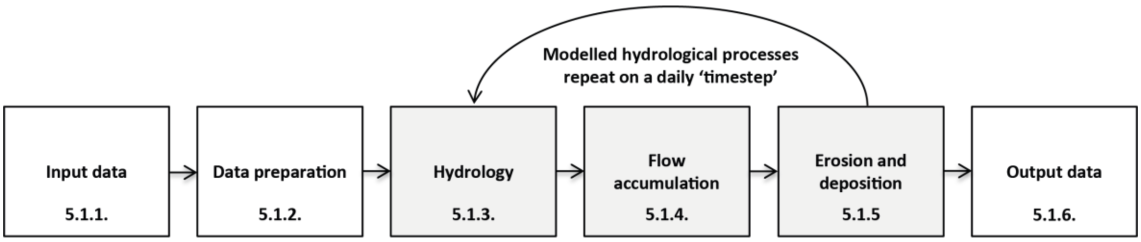


Figure 5-1: Overall model structure and the sections in which they are covered in this chapter for the six stages of the models operation.

5.1.1. Input data

The first component is the data selected for use in the ENGAGE model. Figure 5-2 shows the input data used by ENGAGE, split into required and optional data. One of the requirements described by the stakeholders was the ability for the model to run on freely available data. Therefore, ENGAGE can operate on a number of different combinations of data, allowing the user to use their best available data. Table 5-1 provides a more detailed description of the input datasets, including download locations and cost. Note that datasets such as the Single Payment Scheme (SPS) data and the Road Network were communicated as important inclusions by the stakeholders in the PM sessions. Others, such as the soil parent material and superficial thickness were identified by the researcher, as optional datasets that could improve the accuracy with which hydrological and geomorphological processes are represented.

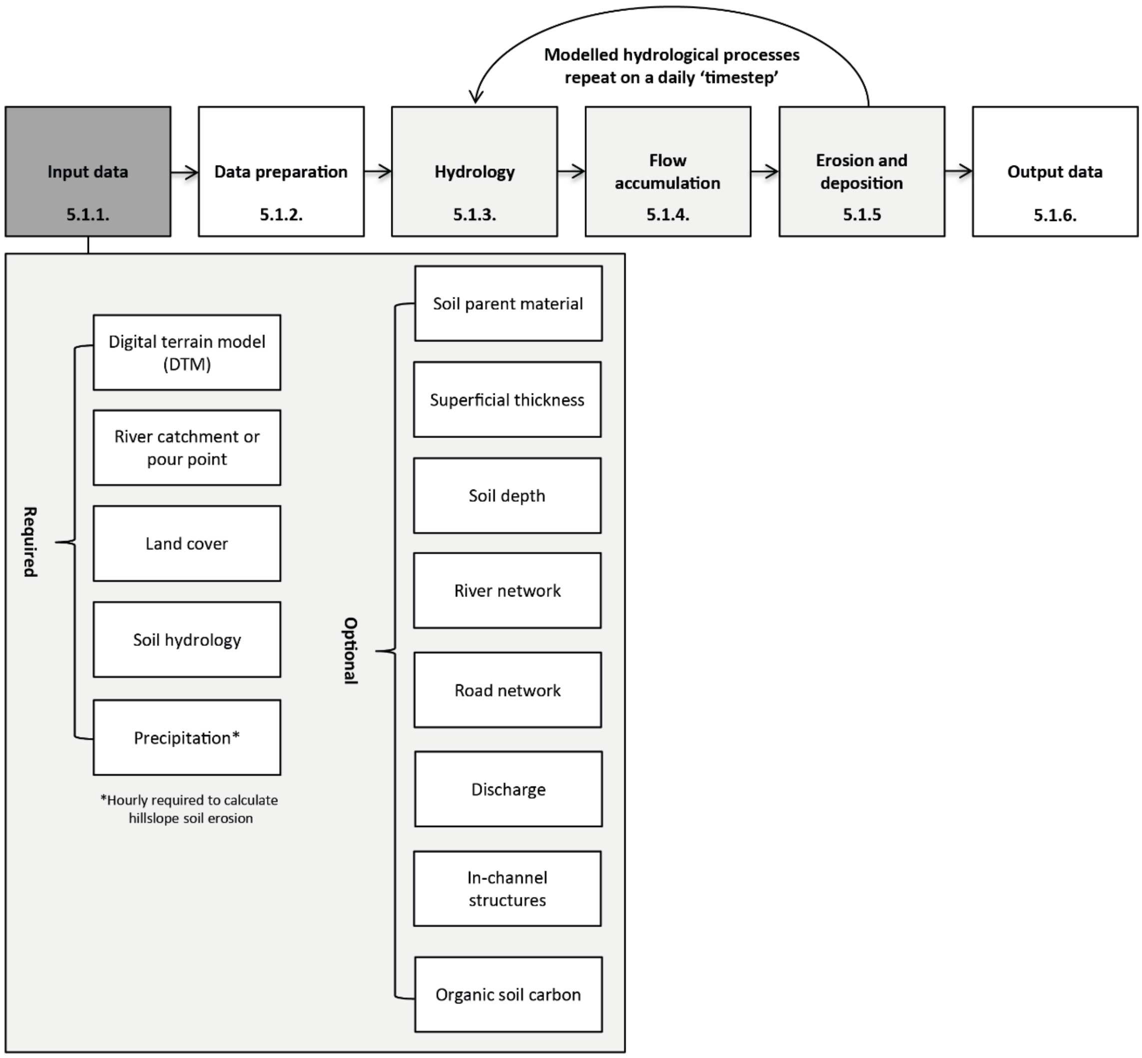


FIGURE 5-2: INPUT DATA FOR THE ENGAGE MODEL.

Table 5-1: Data requirements for the ENGAGE model

Data type	Examples	Cost	Source	Required or Optional
Digital terrain model (DTM)	OS Terrain 50 OS Terrain 5	Free Unknown	Ordnance survey http://www.ordnancesurvey.co.uk/business-and-government/products/terrain-50.html	Required
Pour point or river catchment boundary	User created, or from CEH/EA.	Free	Environment Agency or CEH http://www.ceh.ac.uk/data/nrfa/	Required
Land cover (Choose one of LCM or CORINE, others are optional)	LCM 2007 CORINE 2006 SPS – SINGLE FARM PAYMENT OS Open Roads	Associated cost (quote required) Free Unknown Free	CEH http://www.ceh.ac.uk/landcovermap2007.html EEA Europe http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-3 Natural England/DEFRA Ordnance survey https://www.ordnancesurvey.co.uk/business-and-government/products/os-open-roads.html	Required Optional Optional
Soil hydrology (Choose one)	HOST Soil Class FAO	Unknown (quote required) Free	CEH http://www.ceh.ac.uk/products/hydrology-of-soil-types.html FAO http://data.fao.org/map?entryId=446ed430-8383-11db-b9b2-000d939bc5d8	Required
Precipitation (Daily recorded) Precipitation Gauge Elevation		Free	Environment Agency http://data.gov.uk/dataset/quality-controlled-daily-and-monthly-raingauge-data-from-environment-agency-gauges-afa148	Required
Discharge Gauge (Daily recorded) Base Flow Index 50% Exceedance (Q50)	National River Flow Archive	Free	National River Flow Archive http://nrfa.ceh.ac.uk/	Optional
River soil depth	Advanced superficial deposit depth	15p per km^2	British Geological Society http://www.bgs.ac.uk/products/onshore/superficialThickness.html	Optional
Sediment grain sizes	Soil parent material (1:50,000)	30p per km^2	British Geological Society http://www.bgs.ac.uk/products/onshore/soilPMM.html	Optional
Catchment soil depth	Soil parent material (1km resolution)	Free	British Geological Society http://www.bgs.ac.uk/products/onshore/soilPMM.html	Optional
Organic carbon content	European Soil Database v2.0	Free	The user should download the download the Joined Shape File. http://esdac.jrc.ec.europa.eu/resource-type/european-soil-database-soil-properties	Optional
River network	Detailed River Network OS Open Rivers	Unknown Free	Environment Agency - http://data.gov.uk/dataset/detailed-river-network-wms https://www.ordnancesurvey.co.uk/business-and-government/products/os-open-rivers.html	Optional

5.1.2. Data preparation

One of the findings from the stakeholder sessions was their lack of expertise in using GIS data and models. Stakeholders mentioned on several occasions that ease-of-use was an important consideration. In order to simplify the modelling process, a set of data preparation tools were created. These are shown in Figure 5-3. Additionally, the model interface was kept as simple and easy to use as possible through incorporation into the industry standard GIS software package (ArcGIS 10.2.2.). An example of the interface is shown in Figure 5-4.

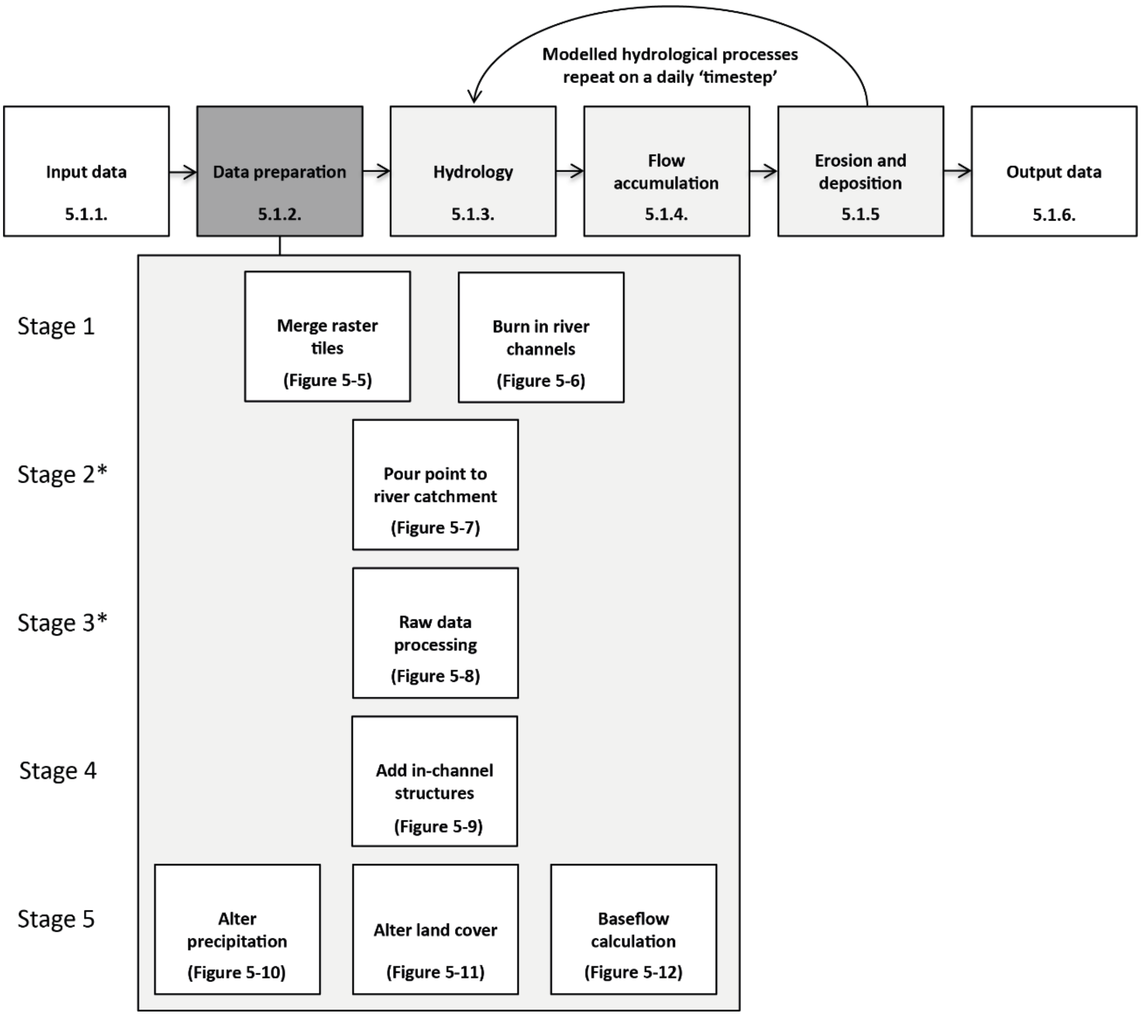


FIGURE 5-3: DATA PREPARATION TOOLS FOR THE ENGAGE MODEL AND THE ORDER IN WHICH THEY ARE RUN. *NOTE ONLY STAGE 2 AND 3 ARE REQUIRED TO RUN THE MODEL. THE OTHERS ARE OPTIONAL PROCESSES.

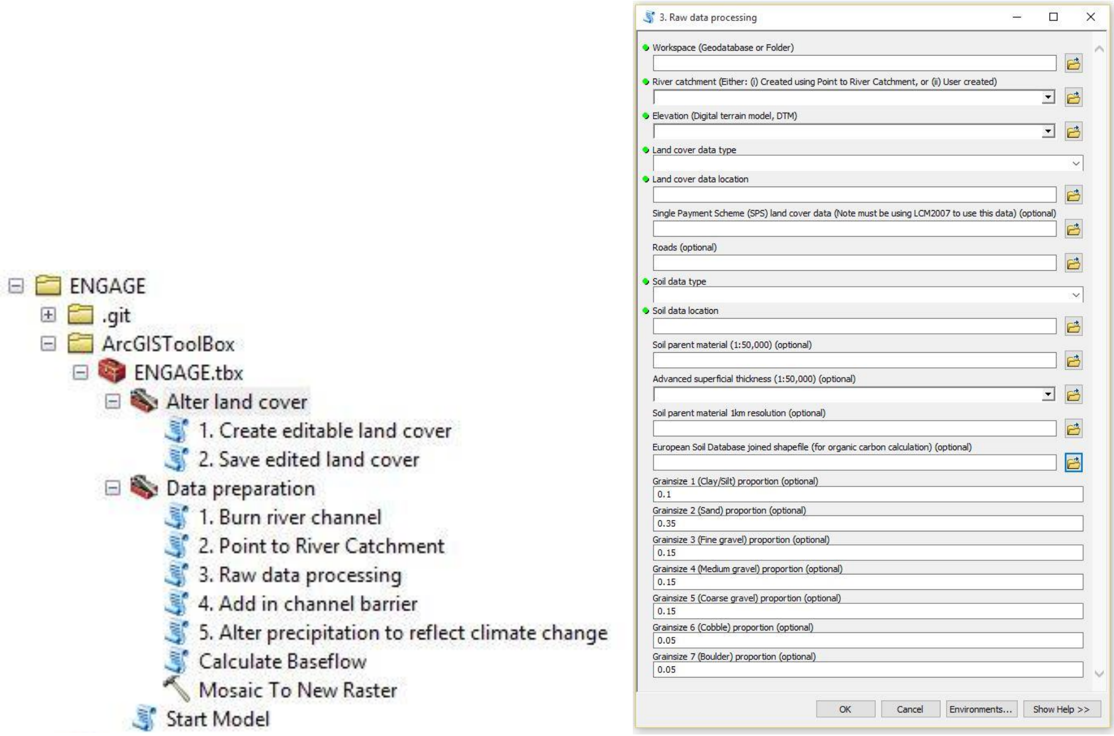


FIGURE 5-4: EXAMPLE OF THE ENGAGE INTERFACE WITHIN ARCGIS 10.2.2. ON THE LEFT IS THE ENGAGE FOLDER STRUCTURE VIEWED FROM ARCCATALOG. ON THE RIGHT IS THE RAW DATA PROCESSING SCRIPT INTERFACE.

To assist stakeholders in creating and using a hydrologically correct digital terrain model (DTM) in the model, two tools were developed (Stage 1): (i) merge raster tiles (Figure 5-5); and (ii) burn in river channels (Figure 5-6). The merge raster (Mosaic to New Raster) tool allows the user to create a uniform DTM of a catchment by combining a series of raster tiles together. To create a more hydrologically accurate DTM, users have the option to 'burn' the river channels into the DTM. The stream burning technique used in ENGAGE follows the Whitebox GAT Decay Coefficient algorithm described by Lindsay (2014). This procedure reduces the elevation grid cells along the user input stream network using Equation 5-1:

$$Z = E - (G/(G + D))^{k} * H$$

EQUATION 5-1

Where:

Z = new grid cell elevation (m), E = old grid cell elevation (m), G = grid resolution (m), D = distance from a stream cell (m), k = decay coefficient (default = 1), and H = elevation decrement (m).

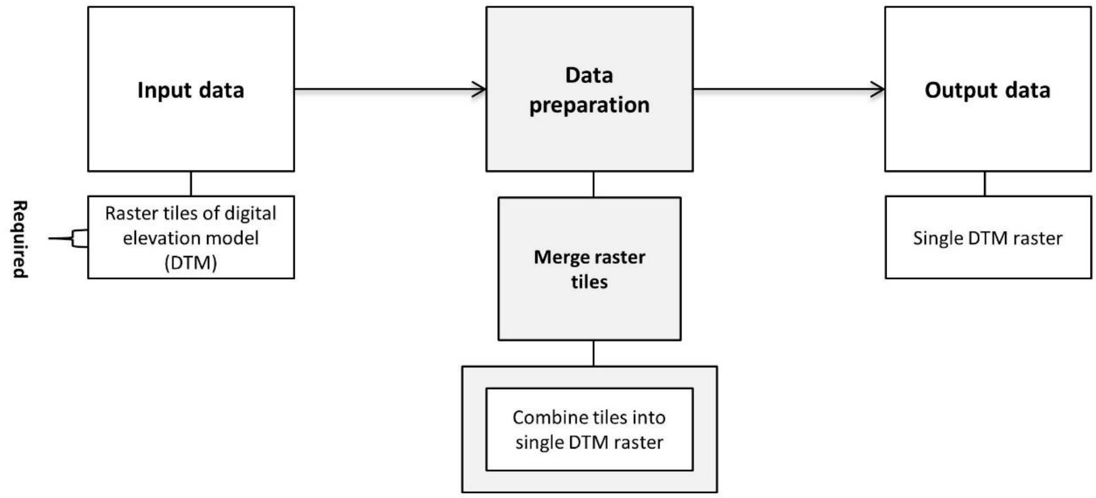


FIGURE 5-5: SCHEMATIC REPRESENTATION OF THE MERGE RASTER TILES ASPECT OF THE DATA PREPARATION STAGE.

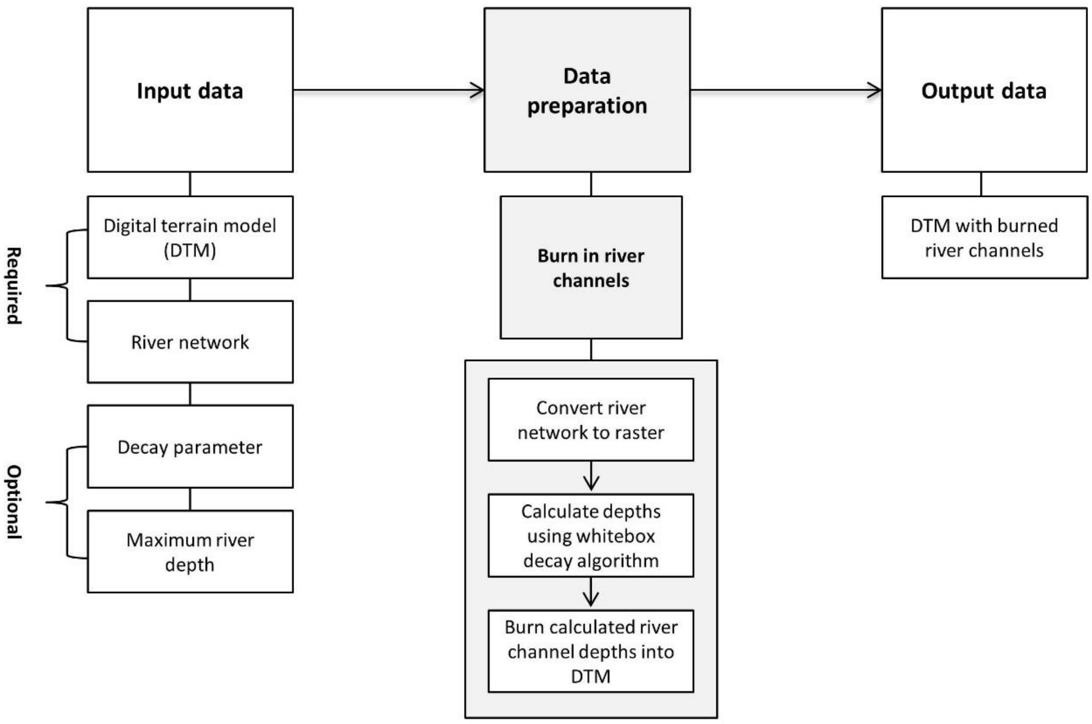


FIGURE 5-6: SCHEMATIC REPRESENTATION OF THE BURN IN RIVER CHANNEL ASPECT OF THE DATA PREPARATION STAGE.

The ability to model any river catchment or sub-catchment (referred to under 'scale') was a requirement described by the stakeholders in the PM process. A tool was developed (Stage 3: Pour point to river catchment (Figure 5-7)) which utilises a DTM and user-defined pour point to calculate the catchment boundary. This tool utilises several of ArcGIS's built in hydrological processes, including: (i) Fill DTM; (ii) Flow Direction; (iii) Flow Accumulation; and (iv) Watershed (see: ESRI, 2014).

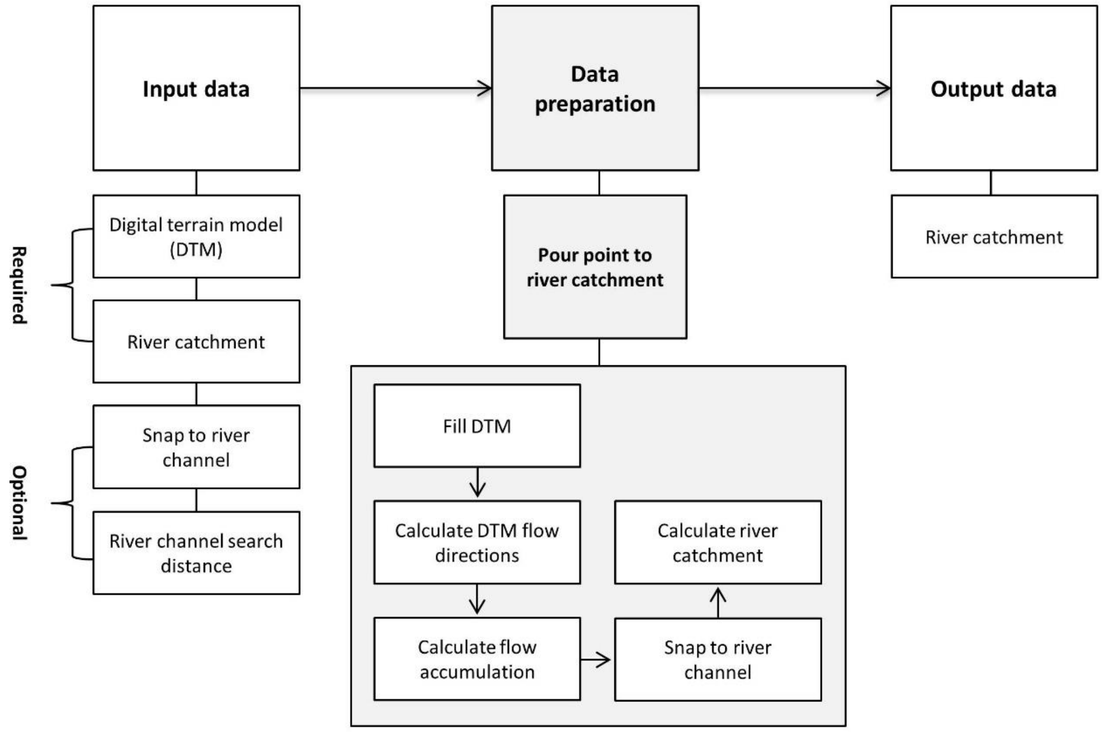


FIGURE 5-7: SCHEMATIC REPRESENTATION OF THE POUR POINT TO RIVER CATCHMENT ASPECT OF THE DATA PREPARATION STAGE.

A key attribute described by the stakeholders was the ease-of-use of the model. To improve the ease-of-use, a tool was developed that transforms the raw data into the format required (Stage 3: Raw data processing (Figure 5-8)). This tool utilises several of ArcGIS's built in processes, including: (i) Clipping, (ii) Projection Tools, and (iii) Raster Conversation Tools (see: ESRI, 2014).

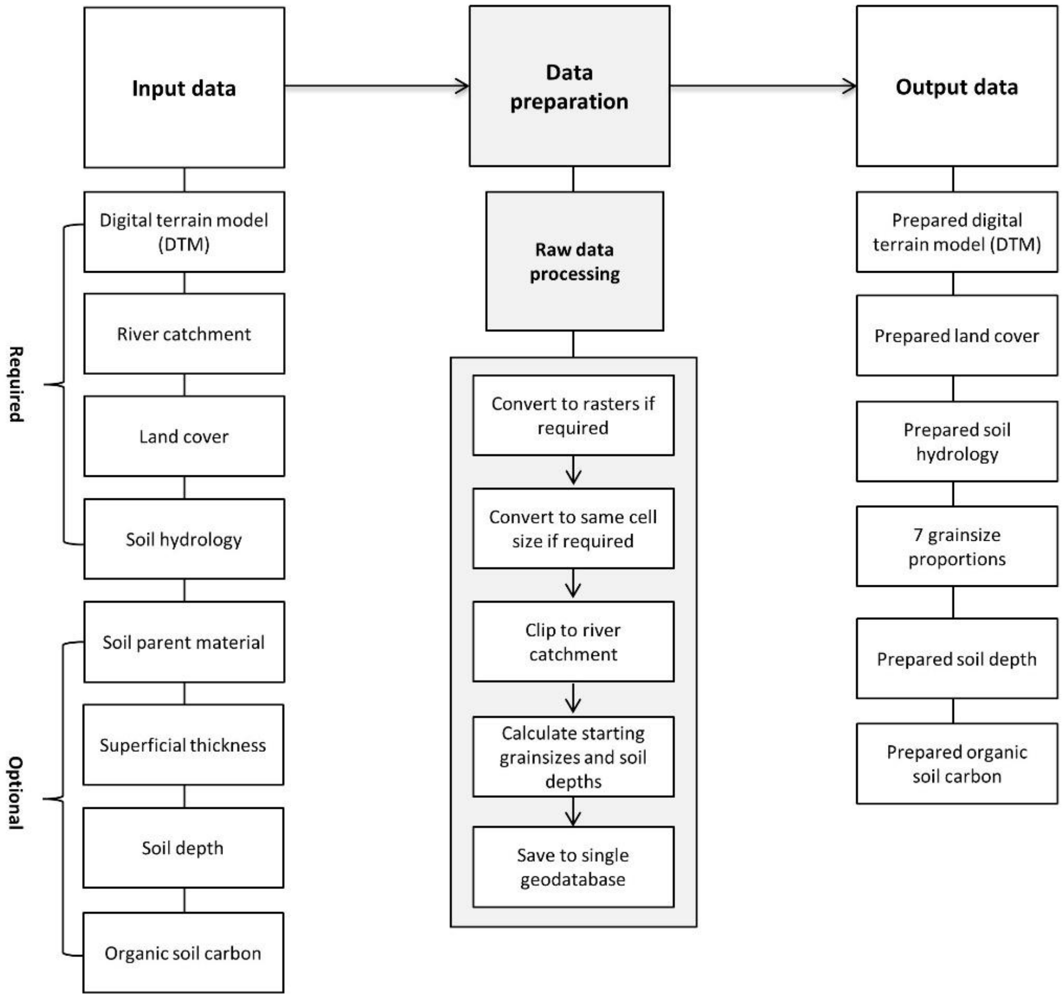


FIGURE 5-8: SCHEMATIC REPRESENTATION OF THE RAW DATA PROCESSING ASPECT OF THE DATA PREPARATION STAGE.

Stakeholders described the ability to simulate the effect of adding structures on the sediment transport as an important model component. To achieve this, a very simple tool (Stage 4: Add in-channel structures (Figure 5-9)) that uses an area of influence to create a flat section of area within the DTM was developed to create an area of zero slope and encourage the deposition of sediment. This is a crude untested method developed by the researcher, therefore the results generated could be inaccurate. However, this allows model users to visualise the effects that in channel structures could have on sediment dynamics (an important use of modelling described by stakeholders).

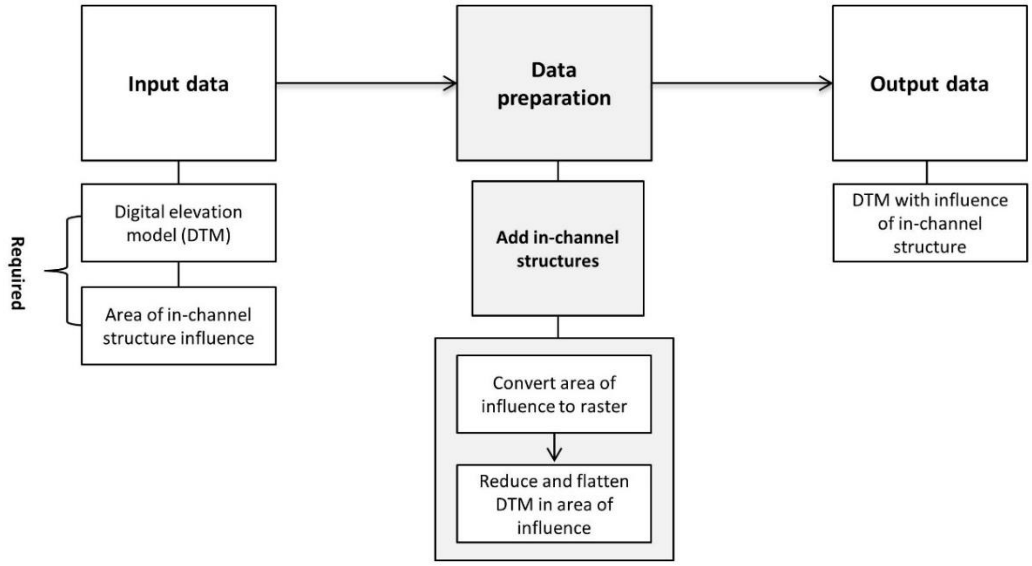


FIGURE 5-9: SCHEMATIC REPRESENTATION OF THE ADD IN-CHANNEL BARRIER ASPECT OF THE DATA PREPARATION STAGE.

The stakeholders communicated in the final PM session the importance of reflecting the influence of climate change. However, recognising that this was outside the scope of this research project, they suggested an alternative simplistic method of scaling all precipitation values up or down. A simple tool (Stage 5 – Alter precipitation) was developed to do this based on the user's input (shown in Figure 5-10).

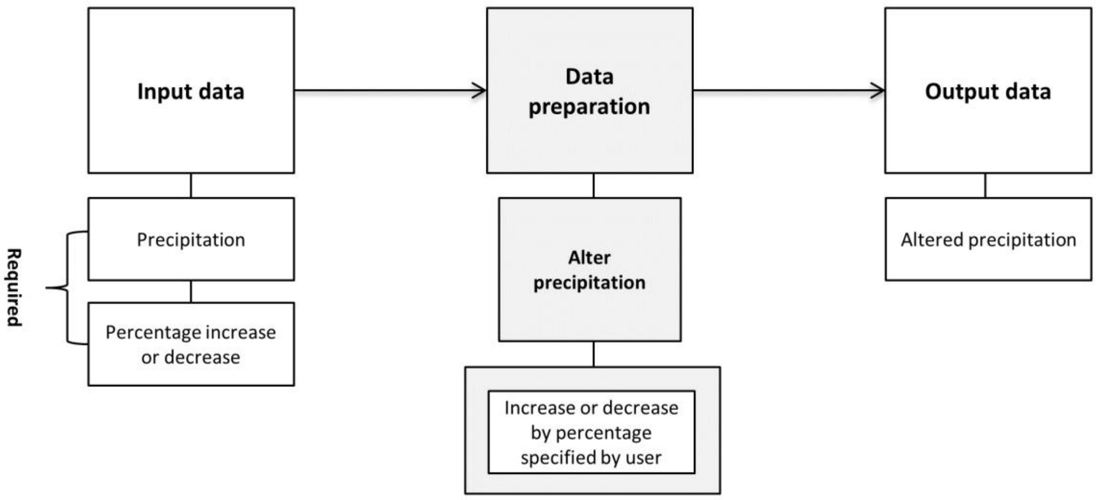


FIGURE 5-10: SCHEMATIC REPRESENTATION OF THE ALTER PRECIPITATION ASPECT OF THE DATA PREPARATION STAGE.

A key model characteristic required by the stakeholders was the ability to alter land cover and management (two important factors the stakeholders can influence). ENGAGE was therefore designed to allow users to change the land cover and management practice within the model (Stage 5: Alter land cover (Figure 5-11)). The full list of land cover and management options can be found in Appendix G.

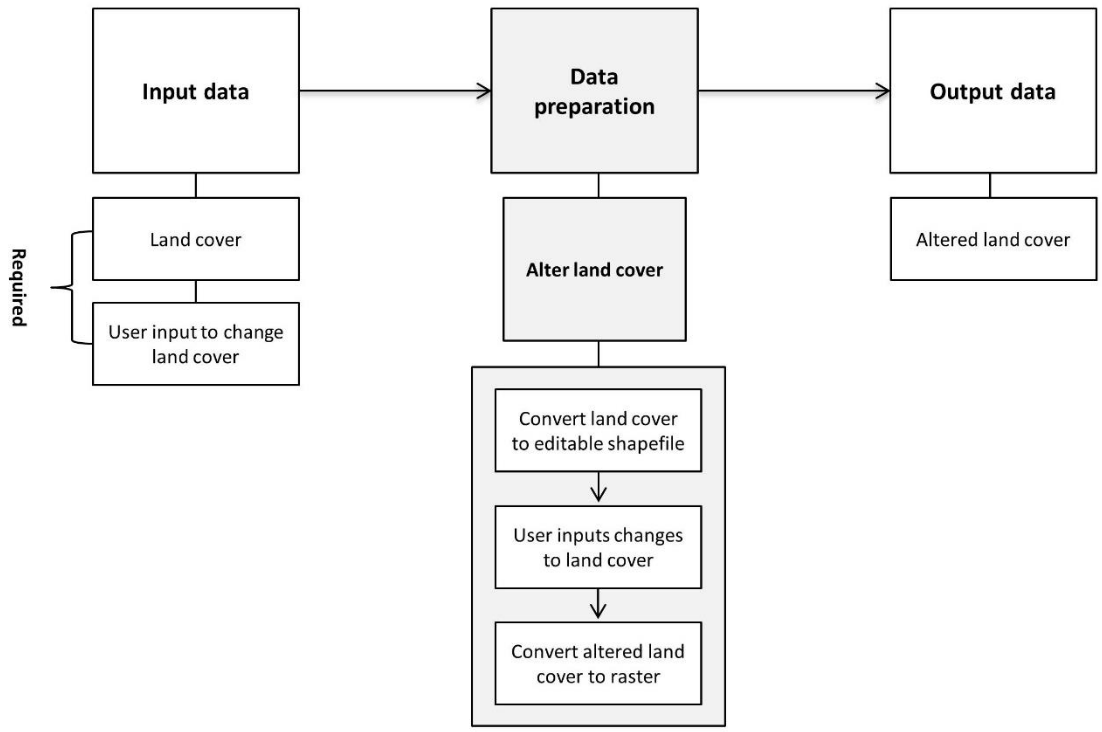


FIGURE 5-11: SCHEMATIC REPRESENTATION OF THE ALTER LAND COVER ASPECT OF THE DATA PREPARATION STAGE.

The importance of river baseflow was articulated by stakeholders in the requirement analysis sessions. A daily value for baseflow at the river gauge can be calculated in ENGAGE using a tool (Stage 5: Baseflow calculation (Figure 5-12)) developed by Arnold and Allen (1999) which extracts river baseflow from streamflow records. This method uses an algorithm based on the Rorabaugh hydrograph recession curve, daily streamflow, and the baseflow index (optional) to automatically determine baseflow. The study by Arnold and Allen (1999) found a predictive efficiency of 71 percent when compared to measured data from 6 river catchments in the United States.

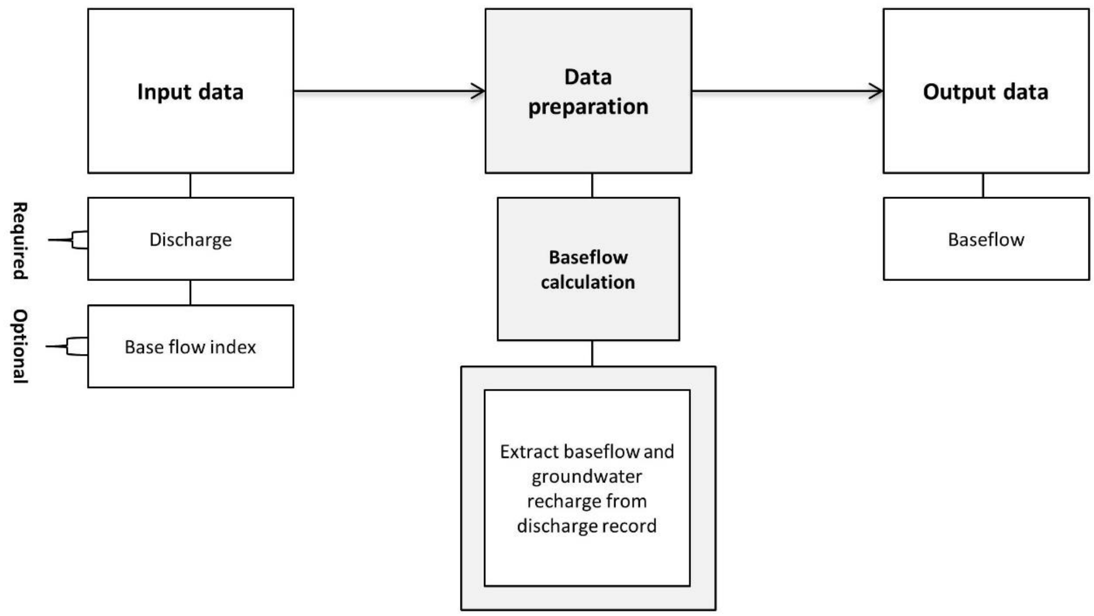


FIGURE 5-12: SCHEMATIC REPRESENTATION OF THE BASEFLOW CALCULATION ASPECT OF THE DATA PREPARATION STAGE.

5.1.3. Hydrology

The hydrology is based upon several of the hydrological processes used in SWAT (Soil and Water Assessment Tool (for a review see: Neitsch *et al.*, 2011)). This allowed for the influence of different land uses on surface runoff, the effect of elevation on precipitation, and baseflow to be incorporated. Additionally, the hydrological approaches used in SWAT have previously been peer-reviewed and could be easily integrated with the other model components. The remainder of this section will describe each of the hydrology stages shown in Figure 5-13.

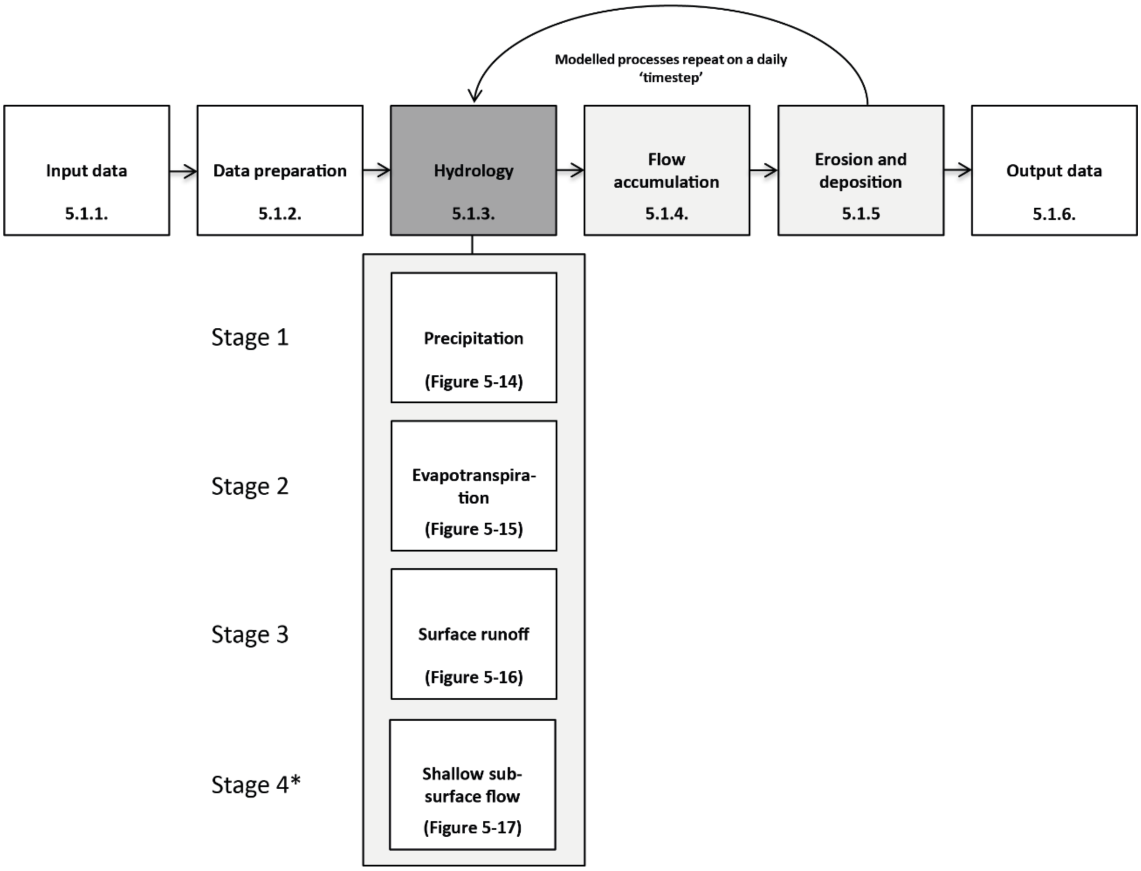


FIGURE 5-13: HYDROLOGY PROCESSES IN ENGAGE MODEL AND THE ORDER IN WHICH THEY ARE RUN. *NOTE THAT STAGE 4 IS AN OPTIONAL REQUIREMENT.

To calculate the spatially distributed precipitation, an important aspect described by stakeholders, ENGAGE uses a simplistic method adapted from the elevation bands methodology used in the Soil & Water Assessment Tool (SWAT) (see: Neitsch *et al.*, 2011) (Stage 1: Precipitation (Figure 5-14)). In SWAT the user defines up to 10 elevation bands within a sub–basin, for which values of precipitation are calculated using Equation 5-2 (Neitsch *et al.*, 2011):

$$R_{band} = R_{day} + \left(EL_{band} - EL_{gauge}\right).\frac{plaps}{days_{pcp,yr}.1000} \text{ when } R_{day} > 0.01$$

EQUATION 5-2

Where:

R_{band} = amount of precipitation falling in the rain band (mm), R_{day} = amount of precipitation falling at the rain gauge (mm), EL_{band}= mean elevation of the rain band (m), EL_{gauge} = elevation of rain gauge (m), $plaps$ = precipitation lapse rate (mm H_20/km), $days_{pcp,yr}$ = average number of days of precipitation per year.

In ENGAGE this method was slightly adapted to use the elevation of each cell to generate a value for precipitation, rather than at predetermined elevation 'bands'. Therefore, every grid cell within the model has a unique precipitation value based on its elevation difference to the rainfall gauge, this been achieved by adapting Equation 5-2 to:

$$R_{cell} = R_{day} + \left(EL_{cell} - EL_{gauge}\right) . \frac{plaps}{days_{pcp,yr} . 1000} \text{ when } R_{day} > 0.01$$

EQUATION 5-3

Where:

R_{cell} = amount of precipitation falling in the cell (mm), R_{day} = amount of precipitation falling at the rain gauge (mm), EL_{cell} = elevation of the cell (m), EL_{gauge} = elevation of rain gauge (m), $plaps$ = precipitation lapse rate (mm H_20/km) (default value set at 5.8, as suggested by Rahman *et al.* (2013), user calibration needed for greater accuracy), $days_{pcp,yr}$ = average number of days of precipitation per year.

There are a number of limitations with this approach; in particular, a number of studies have questioned the accuracy (see: Masih *et al.*, 2011; Ly *et al.*, 2013; Galván *et al.*, 2014). Despite this, the precipitation bands method was selected in recognition of the significantly lower data requirements compared to the method used in CAESAR-Lisflood. However, a new easy to use dataset has been released by CEH since this part of the model was developed, referred to as CEH-GEAR (Tanguy *et al.,* 2016). This dataset provides historic estimates of spatially distributed rainfall data for Great-Britain and Northern Ireland at a 1km resolution. This would provide a higher level of accuracy for spatial precipitation than the method presented here.

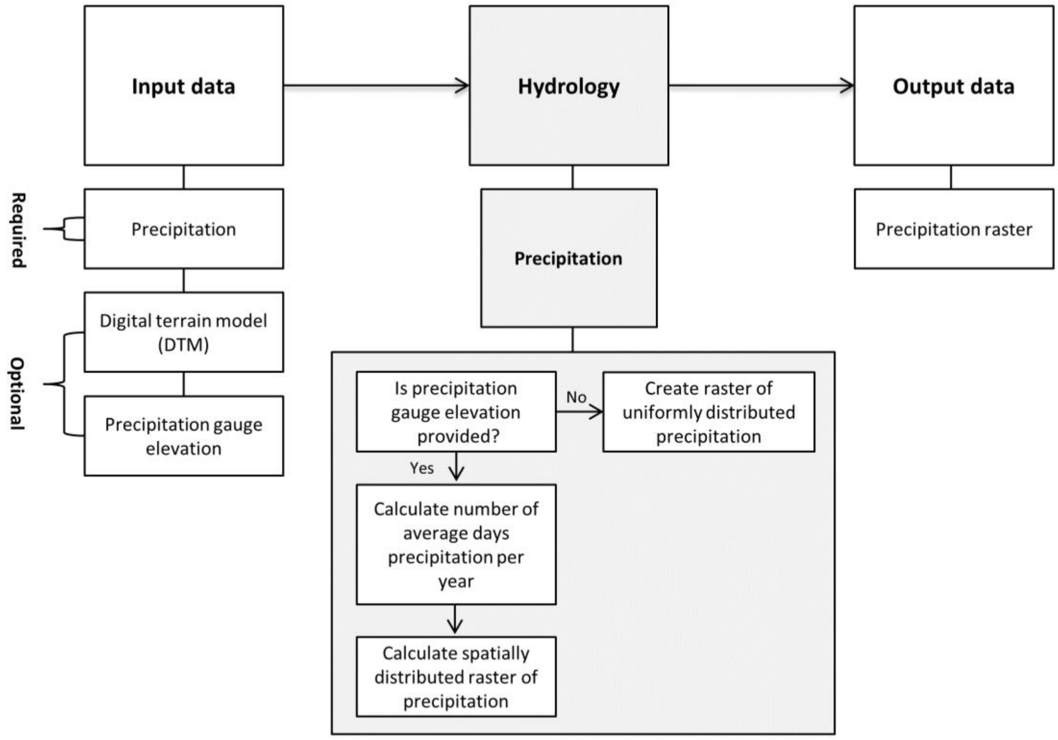


FIGURE 5-14: SCHEMATIC REPRESENTATION OF THE PROCESS FOR CALCULATING PRECIPITATION IN THE HYDROLOGY STAGE.

To reproduce the effect of evapotranspiration (Stage 2: Evapotranspiration (Figure 5-15)), ENGAGE utilises the updated 1985 Hargreaves equation for calculating reference crop evapotranspiration (ETo) (described by Reed *et al.*, 2008). The 1985 Hargreaves equation requires only measured temperature data, is easy to implement, and produces favourable results compared to other methods such as the FAO Penman-Monteith method (Reed *et al.*, 2006). The 1985 Hargreaves equation is:

$$ET_O = 0.0023 \cdot R_a \cdot (TC + 17.8) \cdot TR^{0.5}$$

EQUATION 5-4

Where:

ET_O = reference crop evapotranspiration (mm), R_a = extraterrestrial radiation (MJ/m^2), TR = daily temperature range ($T_{max} - T_{min}$, where T_{max} is the maximum temperature and T_{min} is the daily minimum temperature (^{O}C)), and TC = the mean air temperature (^{O}C).

Extraterrestrial radiation (R_a) is calculated using the method proposed by Allen *et al.* (1998):

$$R_a = \frac{24(60)}{\pi} \cdot G_{sc} \cdot d_r \cdot [\omega_s \cdot \sin(\varphi) \cdot \sin(\delta) + \cos(\varphi) \cdot \cos(\delta) \sin(\omega_s)]$$

EQUATION 5-5

Where:

G_{sc} = solar constant (0.0820 MJ/m^2/min), φ = latitude (radians) ($radians = \frac{\pi}{180}[decimaldegrees]$), dr = inverse relative distance ($d_r = 1 + 0.033 \cdot \cos\left(\frac{2\pi}{365} \cdot J\right)$), δ = solar decimation (radians) ($\delta = 0.409 \sin\left(\frac{2\pi}{365} \cdot J - 1.39\right)$ (J is the number of the day in the year between 1 and 365 (or 366)), and ω_s = sunset hour angle (radians) ($\omega_s = \arccos(-\tan(\varphi) \cdot \tan(\delta))$).

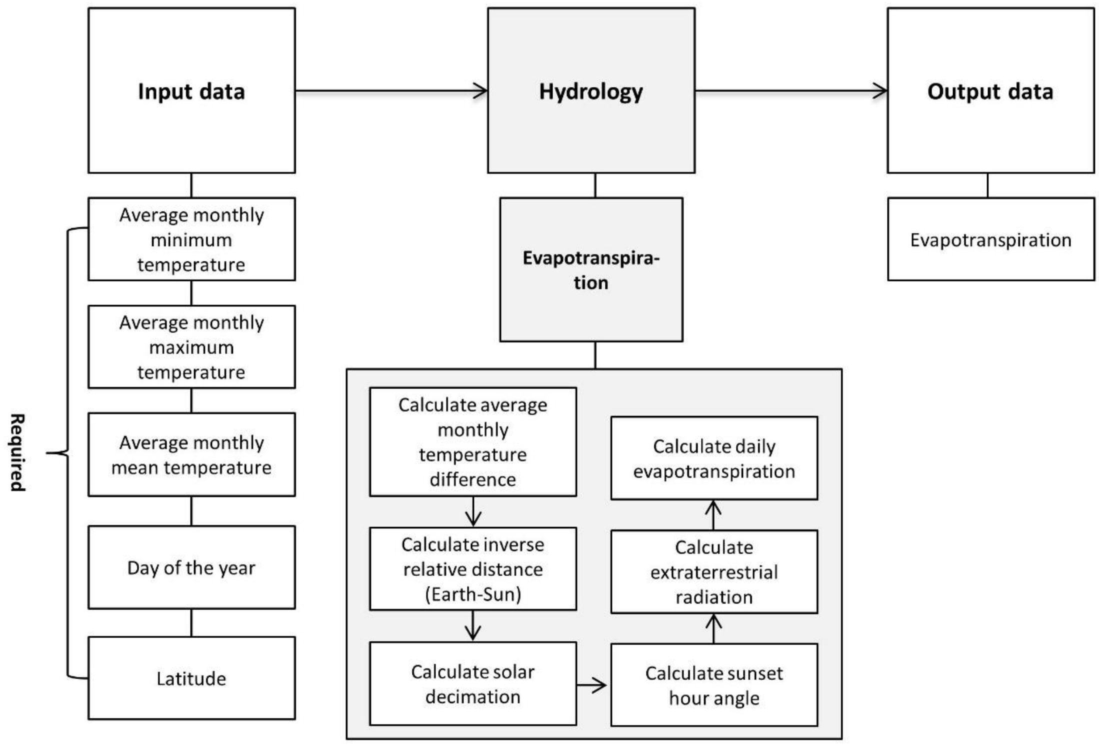


FIGURE 5-15: SCHEMATIC REPRESENTATION OF THE PROCESS FOR CALCULATING EVAPOTRANSPIRATION IN THE HYDROLOGY STAGE.

A unique value of surface runoff is calculated for each cell using an adapted version of the SCS curve number procedure (Stage 3: Surface runoff (Figure 5-16)). The SCS-CN curve number procedure was selected to provide a consistent method for calculating runoff under differing land use and soil type scenarios, an important factor raised by stakeholders throughout the PM process. This allows the stakeholders to input values not only for the type of land cover, but also the hydrological condition. In order to incorporate this into a cellular model, the SCS-CN curve number was adapted in a similar manner to precipitation and operates on individual cells rather than 'hydrological areas'. There is a wealth of literature reviewing the strengths and weaknesses of the SCS-CN curve number procedure (e.g. Mishra and Singh, 2003; Gao *et al.*, 2012). A full description and review of the SCS curve number procedure can be found in Neitsch *et al.* (2011). These methods were chosen for use in ENGAGE, based on the simplicity and ability to be easily integrated into the model. The fundamental SCS curve number equation is:

$$Q_{surf} = \frac{\left(R_{day} - I_a\right)^2}{\left(R_{day} - I_a + S\right)}$$

EQUATION 5-6

Where:

Q_{surf} = amount of surface runoff (mm), R_{day} = amount of precipitation (mm), I_a = initial abstractions and infiltration prior to runoff (mm), and S = retention parameter (mm).

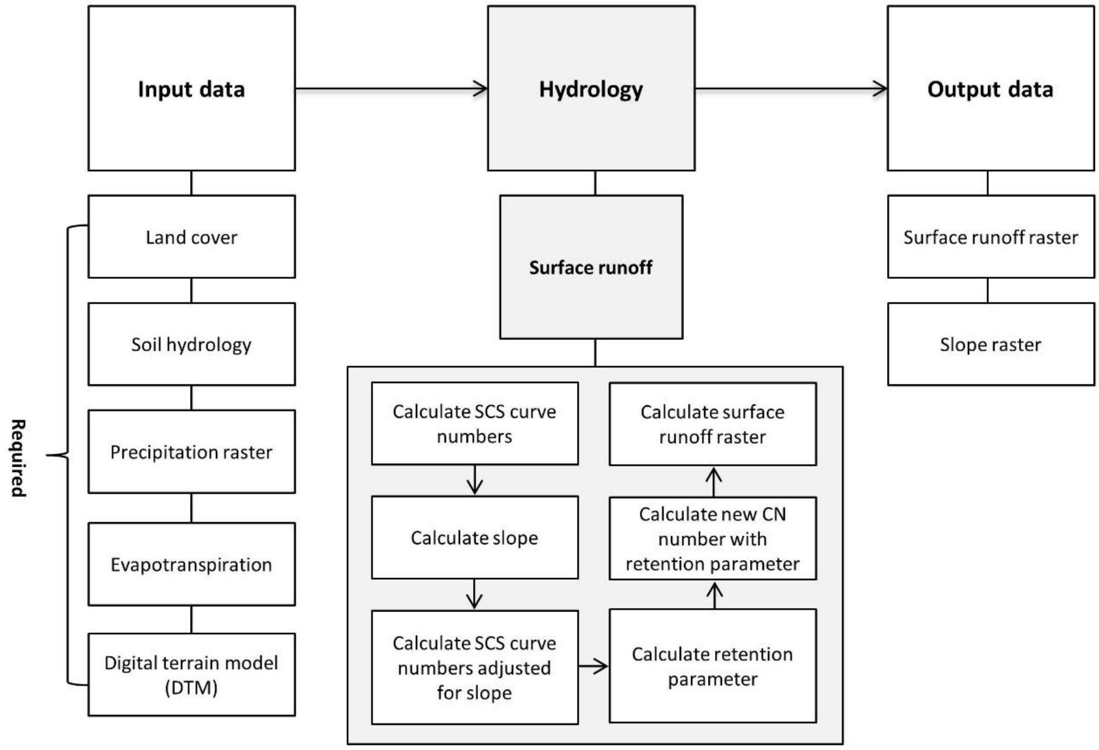


FIGURE 5-16: SCHEMATIC REPRESENTATION OF THE PROCESS FOR CALCULATING SURFACE RUNOFF IN THE HYDROLOGY STAGE.

The retention parameter (S) varies spatially based upon changes in antecedent soil water conditions, slope, soils, land cover and management. The retention parameter can be calculated using:

$$S = 25.4\left(\frac{1000}{CN} - 10\right)$$

EQUATION 5-7

Where:

S = retention parameter (mm), and CN = curve number for the day.

Initial abstractions (I_a) is usually assumed to be 0.2S, therefore Equation 5-6 becomes:

$$Q_{surf} = \frac{\left(R_{day} - 0.2S\right)^2}{\left(R_{day} + 0.8S\right)}$$

EQUATION 5-8

Where:

Q_{surf} = amount of surface runoff (mm), R_{day} = amount of precipitation (mm), and S = retention parameter (mm).

The SCS curve number is a function of the soil's permeability, land use and antecedent soil water conditions. Curve numbers for the United Kingdom can be found in Table 5-2. Soil is split into four hydrological groups (A, B, C and D) based on the infiltration characteristics of the soil (Neitsch *et al.*, 2011):

A. (Low runoff potential). The soils have a high infiltration rate even when thoroughly wetted.

B. The soils have a moderate infiltration rate when thoroughly wetted.

C. The soils have a slow infiltration rate when thoroughly wetted.

D. (High runoff potential). The soils have a very slow infiltration rate when thoroughly wetted.

The conversion of the US hydrological soil groups/classes to those used in the UK HOST dataset is shown in Table 5-3.

TABLE 5-2: ASSIGNMENT OF SCS RUNOFF CURVE NUMBERS FOR THE UNITED KINGDOM BASED ON LCM2000 AND LCM2007 CODE. ADAPTED FROM: (SEPA, 2011)

LCM2000 code	LCM description	LCM2007 code	LCM description	Soil A	Soil B	Soil C	Soil D	SCS description
11	Broad leaf woodland	1	Broad leaf woodland	36	60	73	79	Fair, woods (assumption of storm in winter)
21	Coniferous woodland	2	Coniferous woodland	36	60	73	79	Fair, woods
41	Arable	3	Arable and horticulture	74	83	88	90	Good, fallow ground (assumption of storm in winter)
42	Horticulture	3	Horticulture	74	83	88	90	Good, fallow ground (assumption of storm in winter)
51	Improved grassland	4	Improved grassland	68	79	86	89	Poor, pasture
52	Set-a-side grassland	5	Rough grassland	30	58	71	78	Meadow
61	Neutral grassland	6	Neutral grassland	39	61	74	80	Good, pasture
71	Calcareous grassland	7	Calcareous grassland	39	61	74	80	Good, pasture
81	Acid grassland	8	Acid grassland	39	61	74	80	Good, pasture
91	Bracken	8	Incorporated into acid grassland	35	56	70	77	Fair, brush
101	Dense dwarf shrub heath	10	Heather	30	48	65	73	Good, brush
102	Open dwarf shrub heath	11	Heather grassland	48	67	77	83	Poor, brush (muirburn)
121	Bog	12	Bog	85	85	85	85	Bespoke
131	Inland water	15 and 16	Saltwater and Freshwater	100	100	100	100	Open water
161	Bare ground	N/A	N/A	77	86	91	94	Fallow, bare soil
171	Suburban	23	Suburban	61	75	83	87	Residential, 1/4 acre plots
172	Urban	22	Urban	89	92	94	95	Urban- Commercial and business
201	Littoral rock	19	Littoral rock	98	98	98	98	Paved parking lots, roofs and driveways
111	Fen, Marsh and Swamp	9	Fen, Marsh and Swamp	85	85	85	85	Bespoke
151	Montane habitats	13	Montane habitats	35	56	70	77	Bespoke

(USED WITH PERMISSION OF SEPA)

TABLE 5-3: SUMMARY OF CONVERSION OF HOST SOIL CLASSES TO SCS SOIL CLASSES. SOURCE: (SEPA, 2011)

Stand Percentage Runoff (HOST)	SCS Soil Class	HOST soil classes
<10%	A	1, 2, 13
10-20%	B	3, 4, 5, 7, 11
20-40%	C	6, 8, 9, 16, 17, 18, 20, 28
>40%	D	10, 12, 14, 15, 19, 21, 22, 23, 24, 25, 26, 27, 29

(USED WITH PERMISSION OF SEPA)

The SCS curve number procedure incorporates antecedent soil moisture by defining three conditions: 1 – dry (wilting point), 2 – average moisture and 3 – wet (field capacity). These can be calculated using the following equations:

$$CN_1 = CN_2 - \frac{20 \cdot (100 - CN_2)}{(100 - CN_2 + \exp[2.533 - 0.0636 \cdot (100 - CN_2)])}$$

Equation 5-9

$$CN_3 = CN_2 \cdot \exp[0.00673 \cdot (100 - CN_2)]$$

Equation 5-10

Where: CN_1 = moisture condition 1 curve number, CN_2 = moisture condition 2 curve number (default 5% slope), CN_3 = moisture condition 3 curve number (default 5% slope).

The moisture condition 2 curve numbers provided in Table 5-2 are appropriate for a 5% slope. To adjust this value for different slopes Williams (1995) developed an equation to adjust the curve number:

$$CN_{2s} = \frac{(CN_3 - CN_2)}{3} \cdot [1 - 2 \cdot \exp(-13.86 \cdot slp)] + CN_2$$

Equation 5-11

Where: CN_{2s} = moisture condition 2 curve number adjusted for slope, CN_2 = moisture condition 2 curve number (default 5% slope), CN_3 = moisture condition 3 curve number (default 5% slope), slp = slope.

The final adjustment to the retention parameter incorporates the influence of evapotranspiration using Equation 5-12:

$$S = S_{prev} + E_o \cdot \exp\left(\frac{-cncoef * S_{prev}}{S_{max}}\right) - R_{day} + Q_{surf}$$

EQUATION 5-12

Where: S = retention parameter (mm), S_{prev} = the retention parameter from the previous day (mm), S_{max} = maximum value that the retention parameter can achieve on a given day ($S_{max} = 25.4\left(\frac{1000}{\mathrm{CN}_1} - 10\right)$), E_o = potential evapotranspiration for the day (mm), $cncoef$ = a weighting coefficient (default -1), R_{day} = amount of precipitation (mm), and Q_{surf} = amount of surface runoff (mm).

This adjusted retention parameter for antecedent soil water conditions, slope, soils, and land cover and management is then used to calculate the surface runoff in each cell for the day using Equation 5-8.

The final part of the hydrology process in ENAGE is to calculate a daily shallow sub-surface flow value in each cell (Stage 4: Shallow sub-surface flow (Figure 5-17)). This is scaled from the baseflow value calculated in the data preparation stage:

$$SSf = (FA/MFA) * Bf$$

EQUATION 5-13

Where: SSf = shallow sub-surface flow in each cell (m^3/s), FA = flow accumulation in each cell, MFA = flow accumulation at outlet, and Bf = baseflow at the gauge (m^3/s).

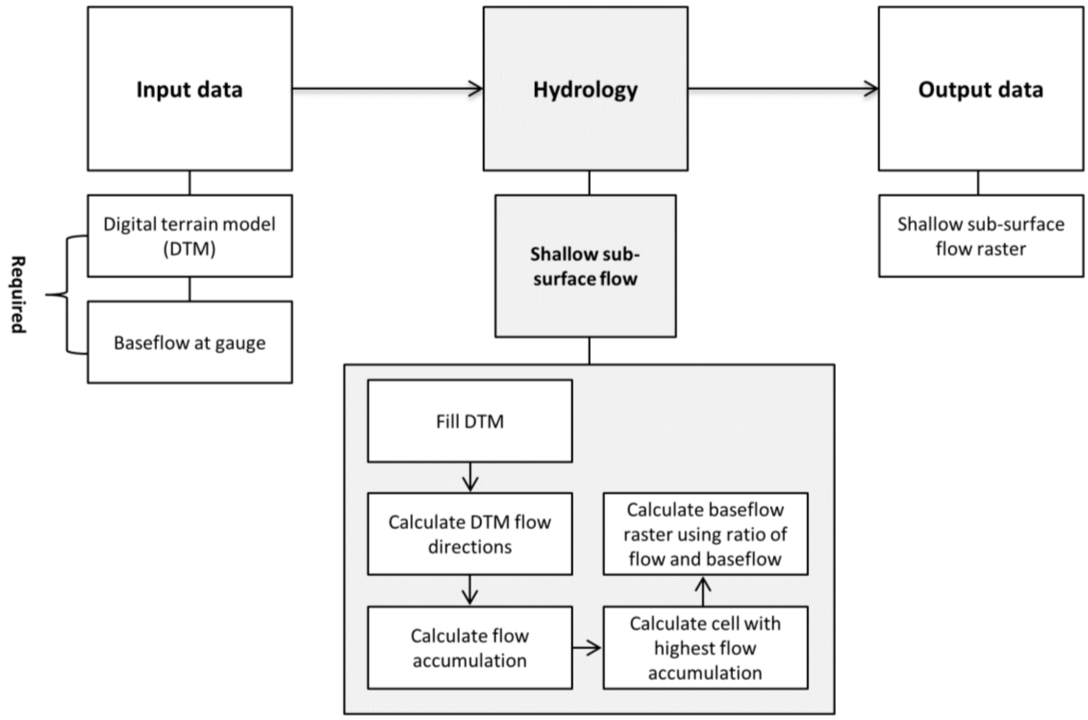


FIGURE 5-17: SCHEMATIC REPRESENTATION OF THE PROCESS FOR CALCULATING BASEFLOW IN THE HYDROLOGY STAGE.

5.1.4. Flow accumulation

A unique daily discharge value in each cell (Figure 5-18 and Figure 5-19) is calculated using the surface runoff and ArcGIS's Weighted Flow Accumulation Tool (see: ESRI, 2014). If shallow sub-surface flow is calculated, this is added to the discharge value to give a total discharge value in each cell. This method for representation of flow limits the model's applicability to 200km^2 catchments (for a review see: Keesstra *et al.*, 2014).

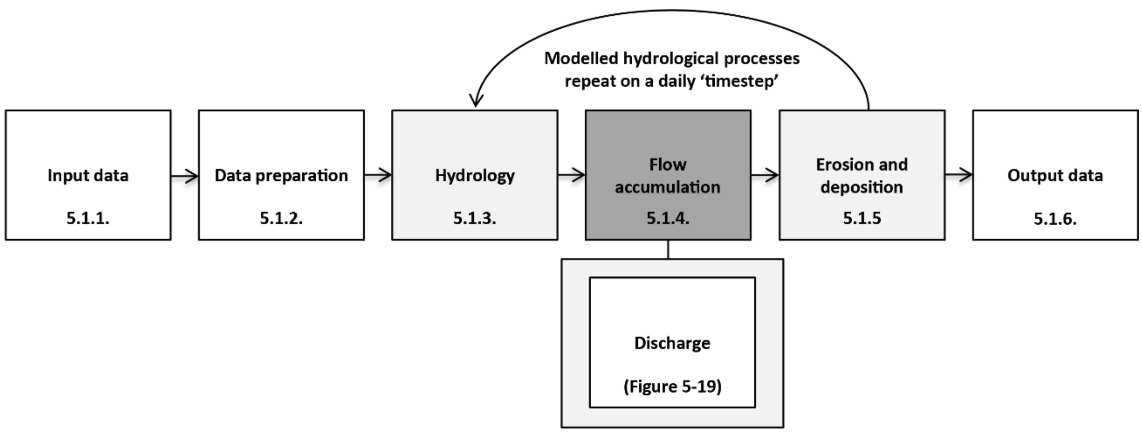


FIGURE 5-18: FLOW ACCUMULATION PROCESSES IN THE ENGAGE MODEL.

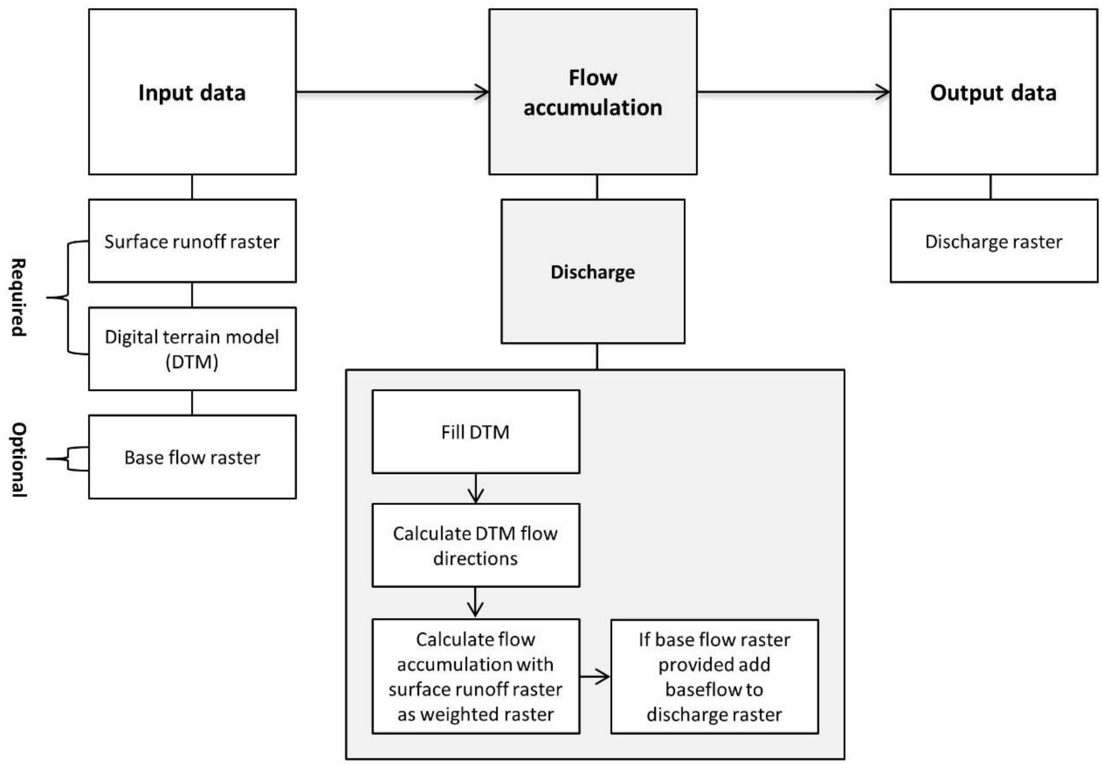


FIGURE 5-19: SCHEMATIC REPRESENTATION OF THE PROCESS FOR CALCULATING DISCHARGE IN THE FLOW ACCUMULATION STAGE.

5.1.5. Erosion and deposition

The erosion and deposition component of the ENGAGE model (Figure 5-20) is based upon those in CAESAR-Lisflood (Coulthard *et al.*, 2002; Coulthard *et al.*, 2007; Van De Wiel *et al.*, 2007) for in-channel processes and mass-wasting, and SWAT (Neitsch *et al.*, 2011) for other hillslope processes. Some of these have been modified or simplified in ENGAGE such that the model can operate using software, hardware, and data available to typical river management practitioners.

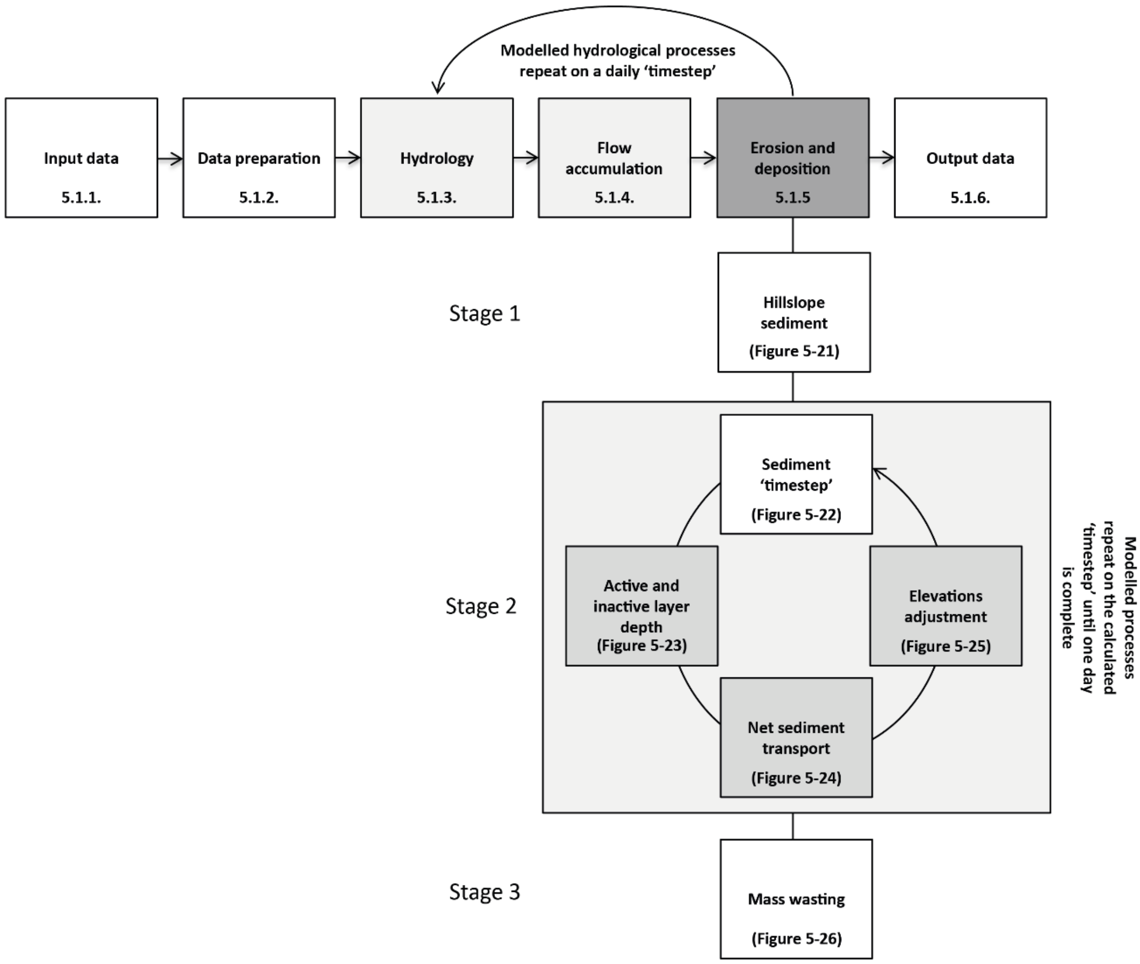


FIGURE 5-20: EROSION AND DEPOSITION PROCESSES IN ENGAGE MODEL AND THE ORDER IN WHICH THEY ARE RUN.

In the PM sessions, stakeholders described the importance of both in channel and hillslope erosion. Hillslope sediment erosion is calculated in ENGAGE using the Modified Universal Soil Loss Equation (MUSLE) (Figure 5-21) (Williams, 1975; 1995):

$$sed = 11.8 \cdot (Q_{surf} \cdot q_{peak} \cdot area_{hru})^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG$$

EQUATION 5-14

Where:

sed = sediment yield (metric tons), Q_{surf}= surface runoff value (mm/ha), q_{peak} = peak runoff rate (mm/ha), $area_{hru}$ = area of the sub-basin (ha), K_{USLE} = soil erodibility factor (metric ton m^2 hr / (m^3 – metric ton cm)), C_{USLE} = cover and management factor, L_{USLE} = topographic factor, $CFRG$ = coarse fragment factor.

KUSLE is calculated using the equation proposed by Williams (1995):

$$K_{USLE} = f_{csand} \cdot f_{cl-si} \cdot f_{orgc} \cdot f_{hisand}$$

EQUATION 5-15

Where: f_{csand}, f_{cl-si}, f_{orgc} and f_{hisand} are factors used to determine the soil erodibility based on the content of sand, clay to silt ratio, organic carbon content, and extremely high sand content. The equations for calculating these factors can be found in Neitsch *et al.* (2011, p. 256).

To convert the sediment yield from metric tons to cubic meters, the following equation is used:

$$v = \frac{m}{(1-n)p}$$

EQUATION 5-16

Where: v = volume (m^3), m = mass (kg), n = in-situ porosity of deposited sediment (a value of 0.39 is used based on porosity data presented in Bunte and Abt (2001)), p = particle density (2650 kg/m^3).

The calculated sediment volume is carried to the river channel with the surface runoff (as in SWAT, see: Neitsch *et al.*, 2011) and then incorporated within the active layer size distribution within the channel. There are a number of weaknesses associated with using the MULSE approach, such as, low levels of accuracy compared to physically-based models, and a tendency to under-predict sediment yields during large events (e.g. Zhang *et al.*, 2009; Chandramohan *et al.*, 2015). Despite this, the MULSE approach to represent the sediment runoff on the hillslopes based on land cover, soil, and topographic conditions was selected given the minimal data and computation requirements.

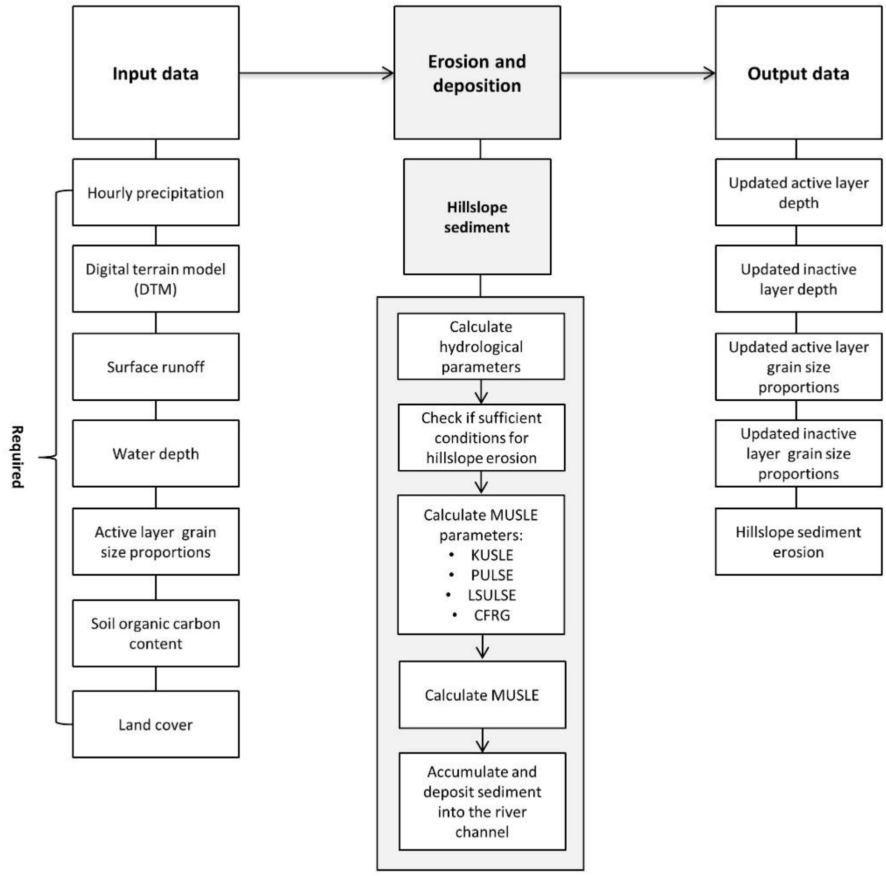


FIGURE 5-21: SCHEMATIC REPRESENTATION OF THE PROCESS FOR CALCULATING HILLSLOPE SEDIMENT USING THE MULSE.

ENGAGE uses variable time steps for calculating sediment transport in a similar manner to CAESAR, such that the model operates at a higher temporal resolution during periods of intense geomorphological change, and lower temporal resolution during periods of stability (Stage 1: Sediment 'timestep' (Figure 5-22)). The length of each 'timestep' is calculated at the beginning of the day using Equation 5-17 (described in Van De Wiel *et al.*, 2007):

$$dt = \frac{\Delta Z_{max} c_w^2}{q_{max}}$$

EQUATION 5-17

Where: dt = timestep of iteration (s), ΔZ_{max} = 0.1 * Lh (default Lh = 0.2m), c_w = cell width (m) and q_{max} = maximum calculated rate of sediment entrainment within catchment (m^3/s) (this is calculated using a mixed-size formula described later in this section).

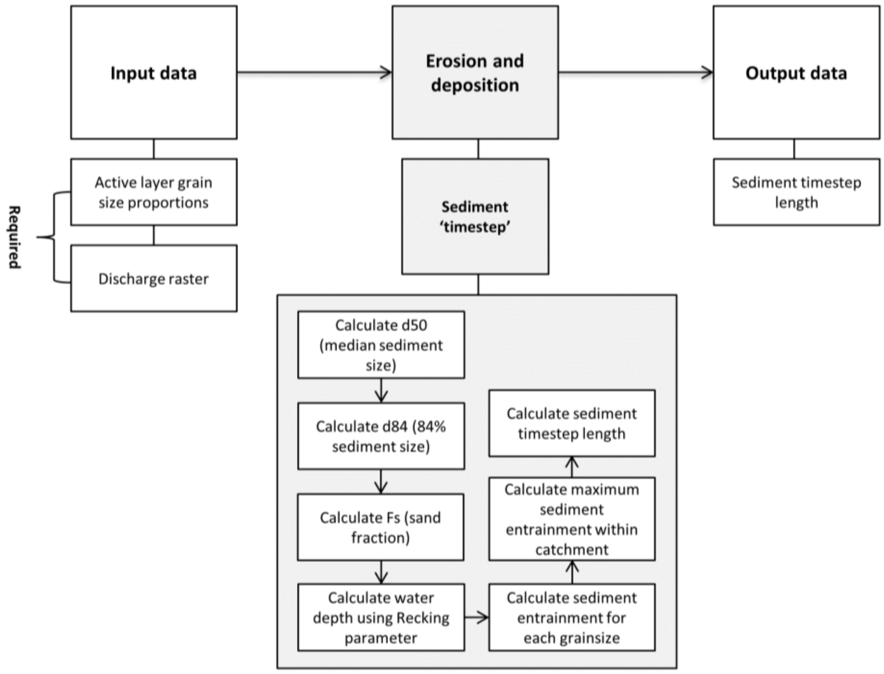


FIGURE 5-22: SCHEMATIC REPRESENTATION OF THE PROCESS FOR CALCULATING THE SEDIMENT TIMESTEP IN THE EROSION AND DEPOSITION STAGE.

ENGAGE operates with two sediment layers, referred to as the active layer and inactive layer. This simplified version of sediment layering compared to CAESAR (see: Van De Wiel *et al.*, 2007) was chosen due to computational requirements. As in CAESAR, the active layer has a variable cell by cell thickness of between 5cm and 30cm, depending on erosion and deposition processes. If the value of the active layer exceeds 30cm, sediment is transferred from the active layer to the inactive layer. Conversely, if the active layer depth becomes less than 5cm, then sediment is added to the active layer, these values are checked at the end of every loop (Stage 2: Active and inactive layer depth (Figure 5-23)).

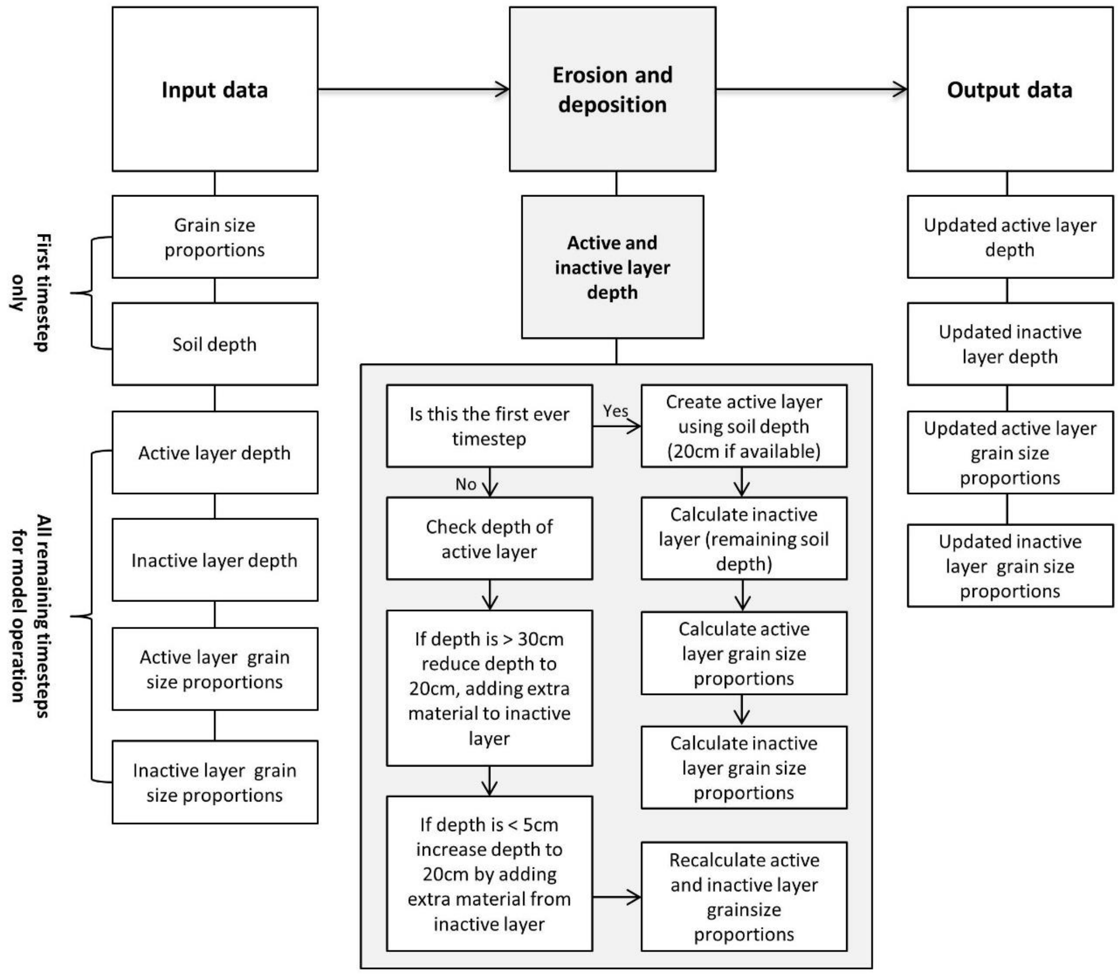


FIGURE 5-23: SCHEMATIC REPRESENTATION OF THE PROCESS FOR CALCULATING THE ACTIVE AND INACTIVE LAYER DEPTH IN THE EROSION AND DEPOSITION STAGE.

The net sediment transported in and out of each cell (Stage 3 (Figure 5-24)) is calculated firstly by multiplying the volumetric rate of transport by the ‘timestep’ of the iteration for each grainsize, and secondly, using the flow directions calculated in 4.6.4 to move the sediment downstream to the next cell. As in CAESAR, instream sediment transport is only calculated in cells with a depth of water greater than 0.01m.

The volumetric transport rate is calculated using a mixed-sized formula (Wilcock and Crowe, 2003):

$$q_{bi} = \frac{F_i U_i^3 W_i^*}{(s-1)g}$$

EQUATION 5-18

Where: q_{bi} = volumetric transport rate (m^3/s), F_i = the fractional volume of that grainsize sediment in the active layer, U^*= shear velocity (m/s), W_i^* = function that relates transport rate to the total transport rate (see: Wilcock and Crowe, 2003), s = sediment to water density, and g = gravity (m/s^2).

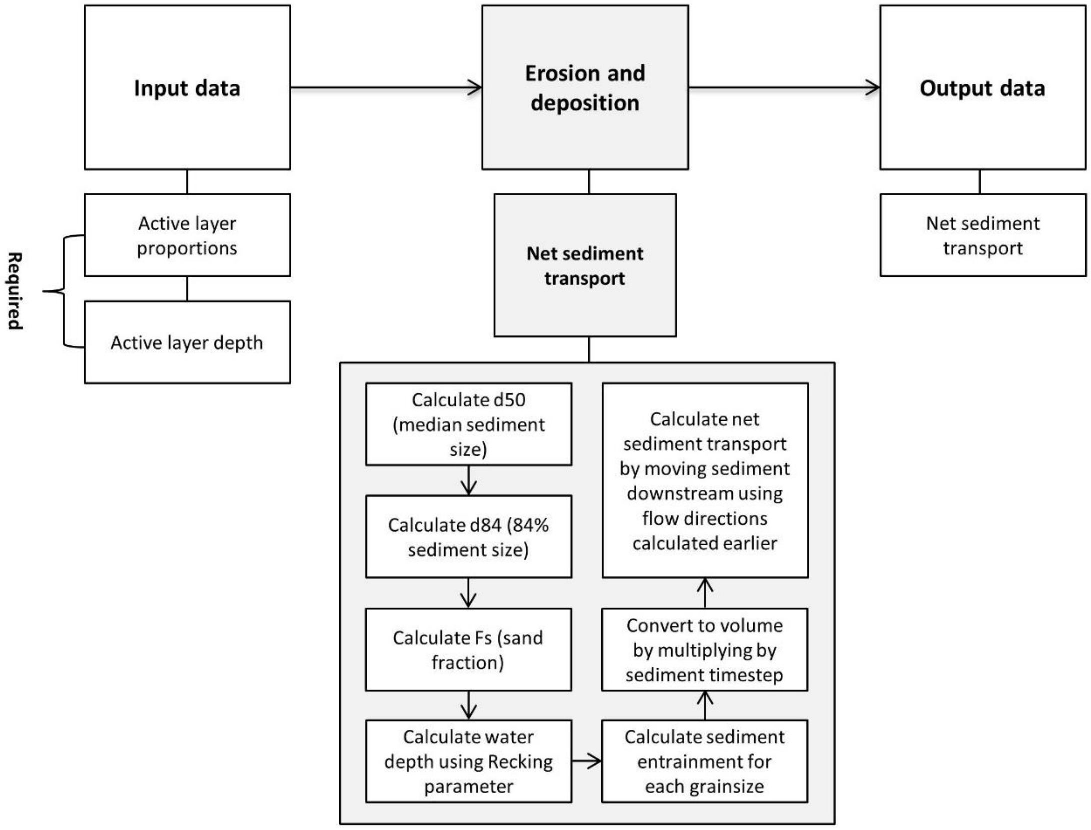


FIGURE 5-24: SCHEMATIC REPRESENTATION OF THE PROCESS FOR CALCULATING NET SEDIMENT TRANSPORT IN THE EROSION AND DEPOSITION STAGE.

At the end of each iteration, the active layer volumes are adjusted and the elevations of cells updated. If any of the cell elevations change by more than 0.05m then the slopes and flow directions are recalculated (Stage 4: Elevation adjustment (Figure 5-25)).

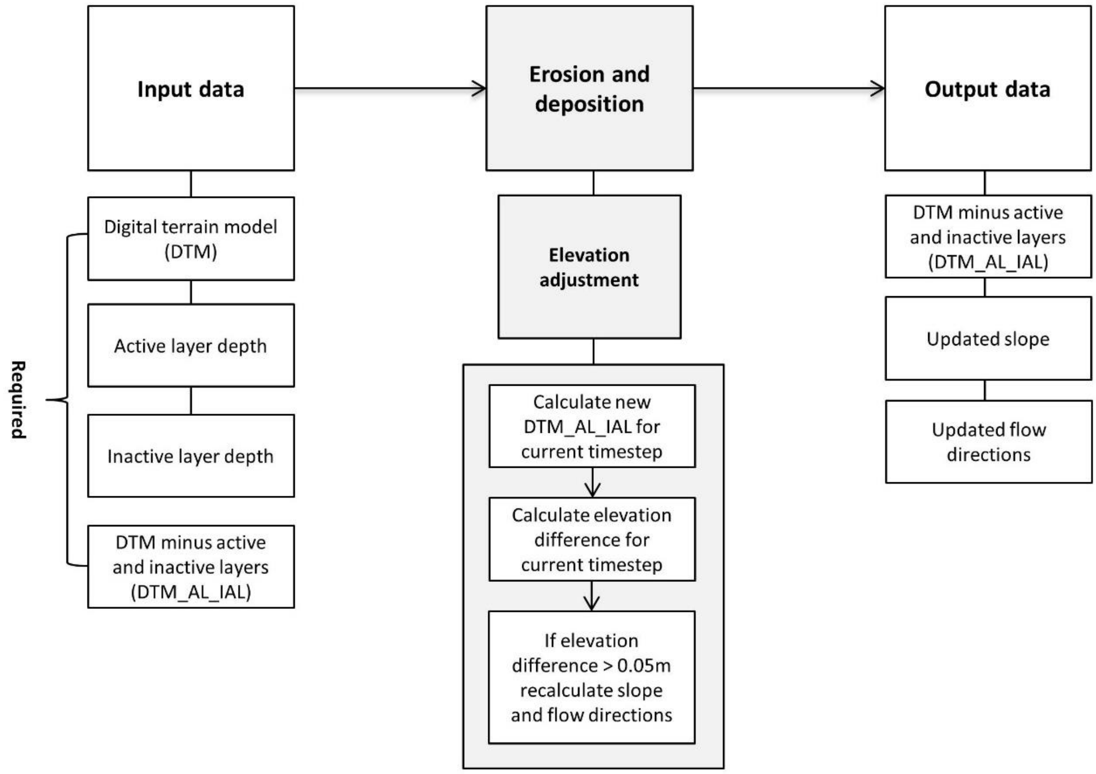


FIGURE 5-25: SCHEMATIC REPRESENTATION OF THE PROCESS FOR CALCULATING ELEVATION ADJUSTMENT IN THE EROSION AND DEPOSITION STAGE.

Mass wasting is conducted at the end of a daily 'timestep' and occurs when the slope between two cells exceeds 45 degrees (Stage 5: Mass wasting (Figure 5-26)). Material is moved from the uphill cell to the lower cell until the angle is lower than 45 degrees (Coulthard, 1999). This movement can trigger other cells to exceed 45 degrees, therefore the process repeats until no more mass wasting is required.

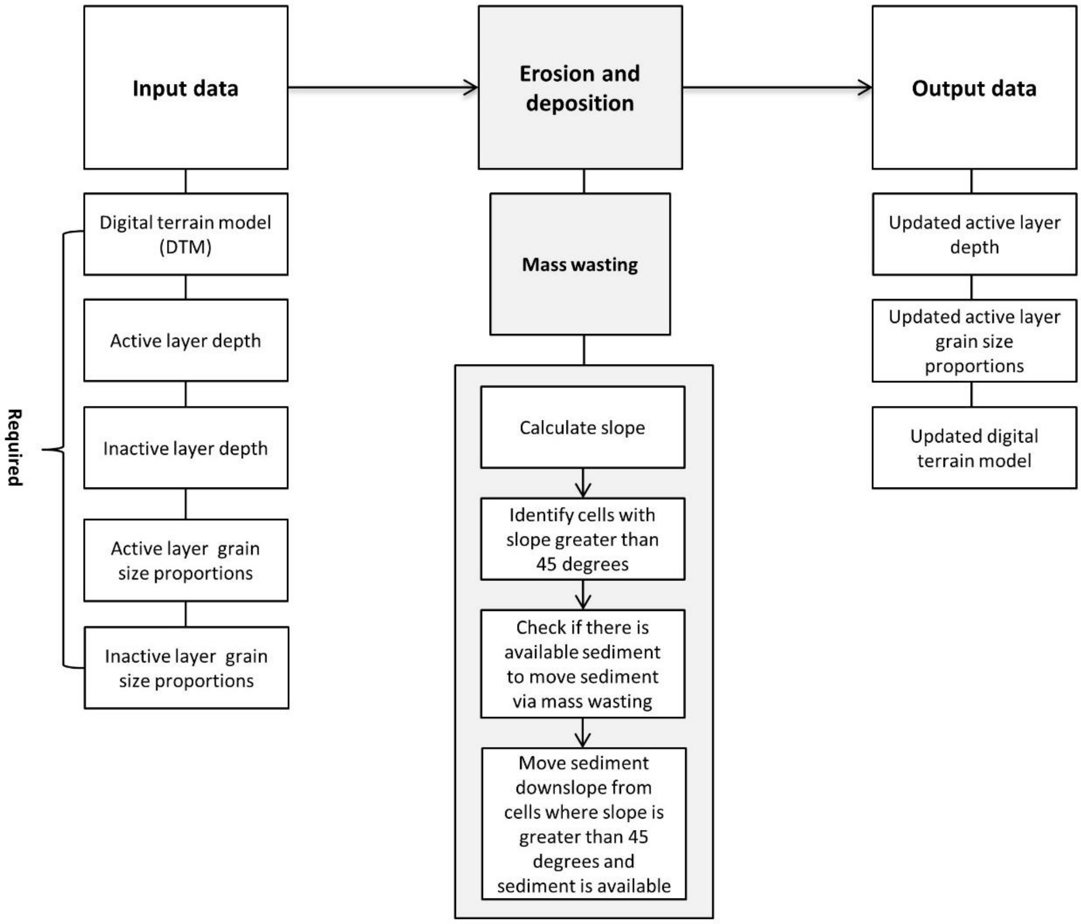


FIGURE 5-26: SCHEMATIC REPRESENTATION OF THE PROCESS FOR CALCULATING MASS WASTING.

5.1.6. Output data

In the model demonstration sessions, stakeholders provided feedback on the original outputs generated by the model. Figure 5-27 shows the output data generated by the model based on this feedback. In particular, the model is able to generate daily, weekly, monthly, yearly averages or totals for each of the outputs.

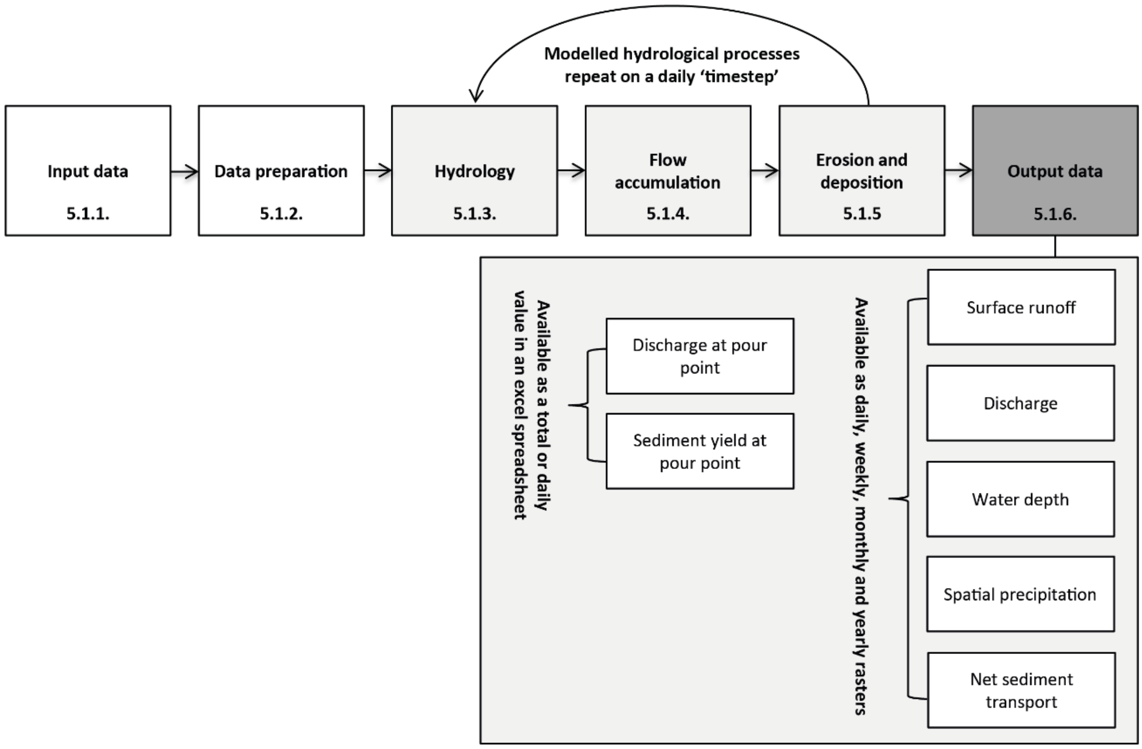


FIGURE 5-27: OUTPUT DATA FROM THE ENGAGE MODEL.

As described in Section 3.4, the developed model has not been 'validated' or assessed using traditional scientific methods. Therefore, the only presentable outputs from the model were generated for the hypothetical decision-making scenario in the model assessment. The hypothetical decision-making scenario used a small sub-catchment (21.5km^2) of the Camel called the De Lank. The datasets described in Table 5-1 were collated for the catchment for use by the stakeholders during the exercise (Appendix F). For speed, the model was ran for a single month (January 2012). Figure 5-28 shows some of the important input data used during the hypothetical decision-making scenario. Figure 5-29 and Figure 5-30 provide examples of the output data from the model after a month of operation prior to any land cover change taking place. Figure 5-31 highlights the parcel of land that was changed from pasture to broad leaf woodland. A comparison of the difference in the outputs after the change is displayed in Figure 5-32.

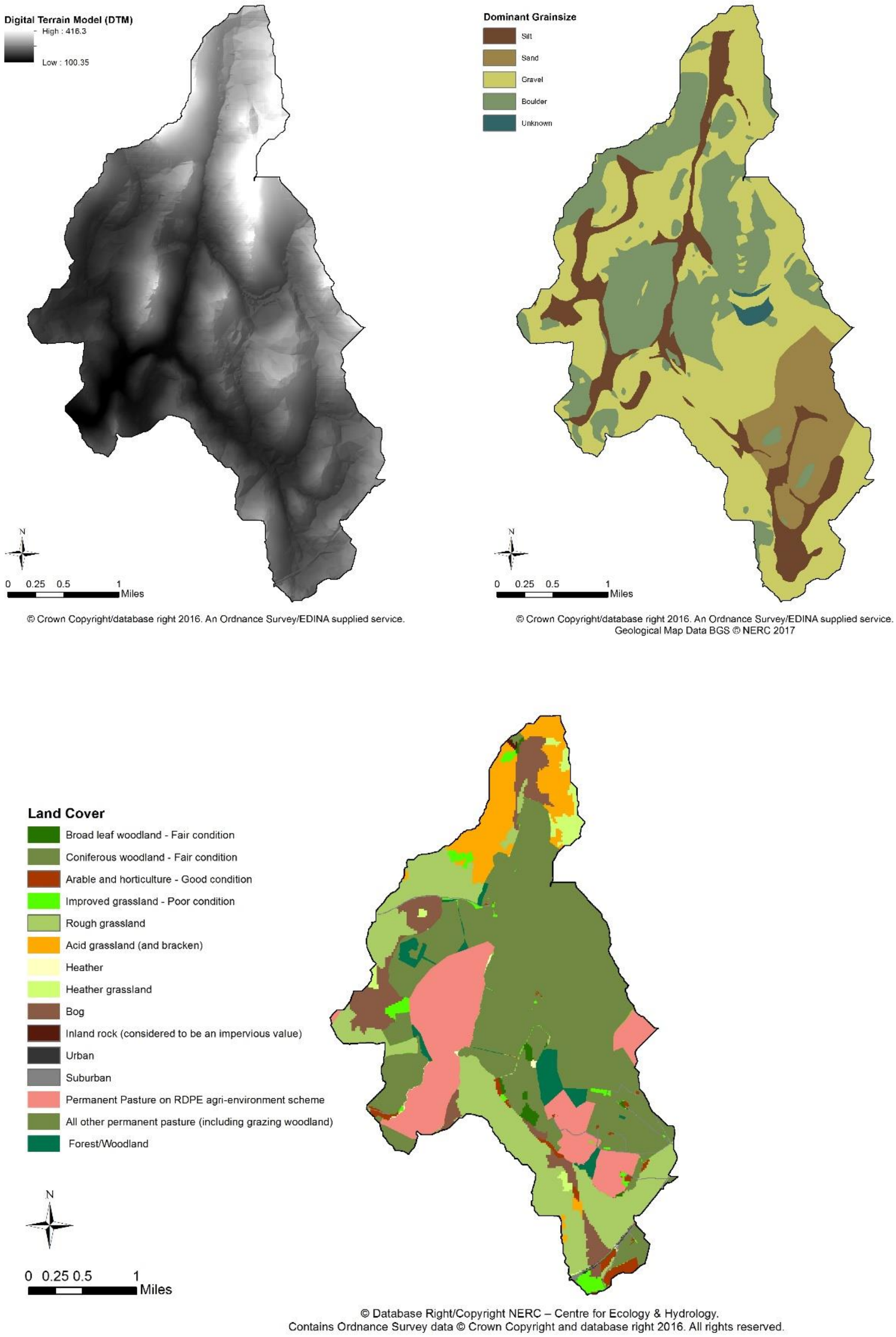


FIGURE 5-28: EXAMPLE INPUT DATA FOR THE HYPOTHETICAL DECISION-MAKING SCENARIO

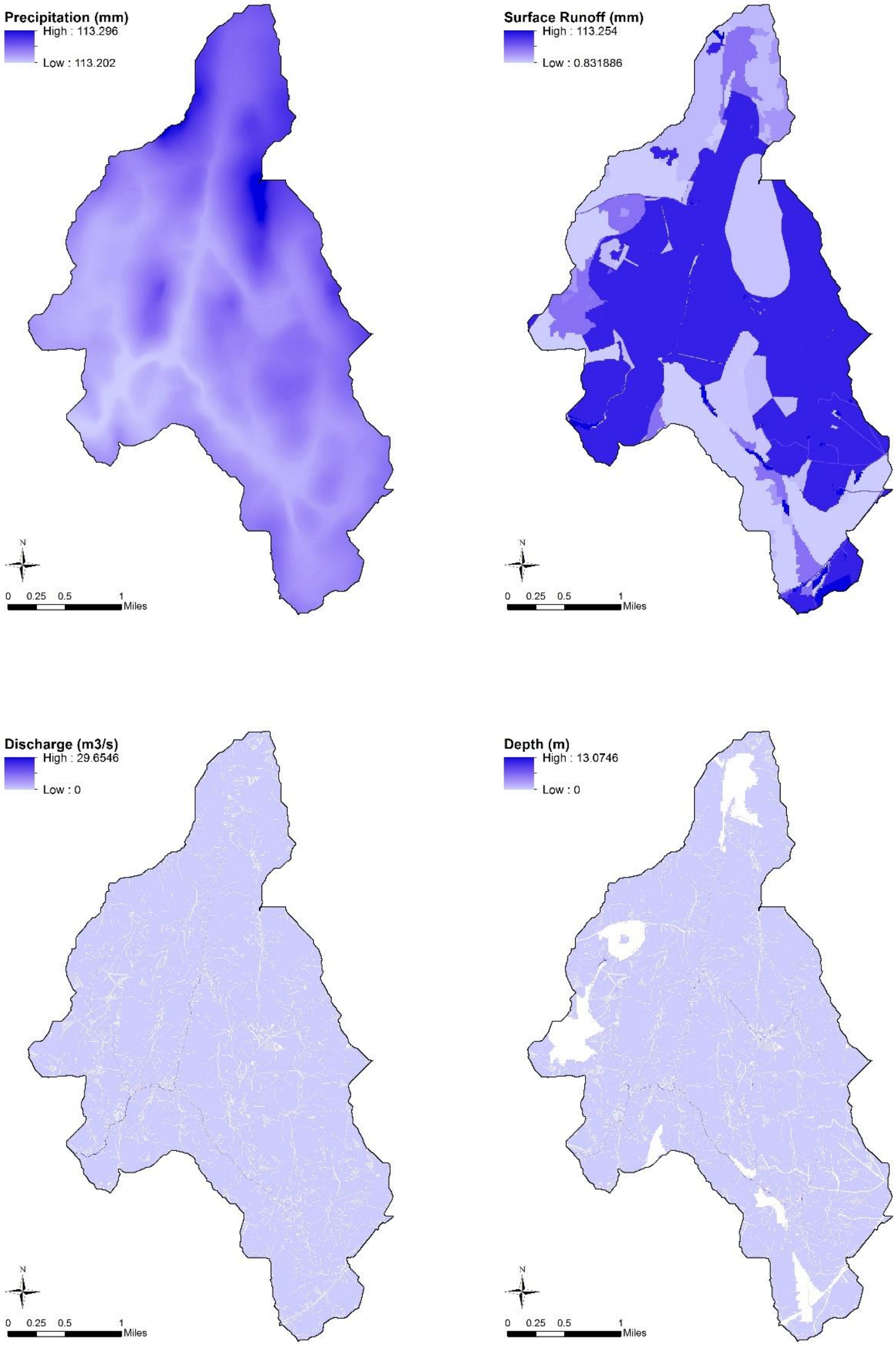


FIGURE 5-29: EXAMPLE HYDROLOGY MONTHLY TOTAL OUTPUTS FROM THE HYPOTHETICAL DECISION-MAKING SCENARIO PRIOR TO LAND COVER CHANGES BEING MADE

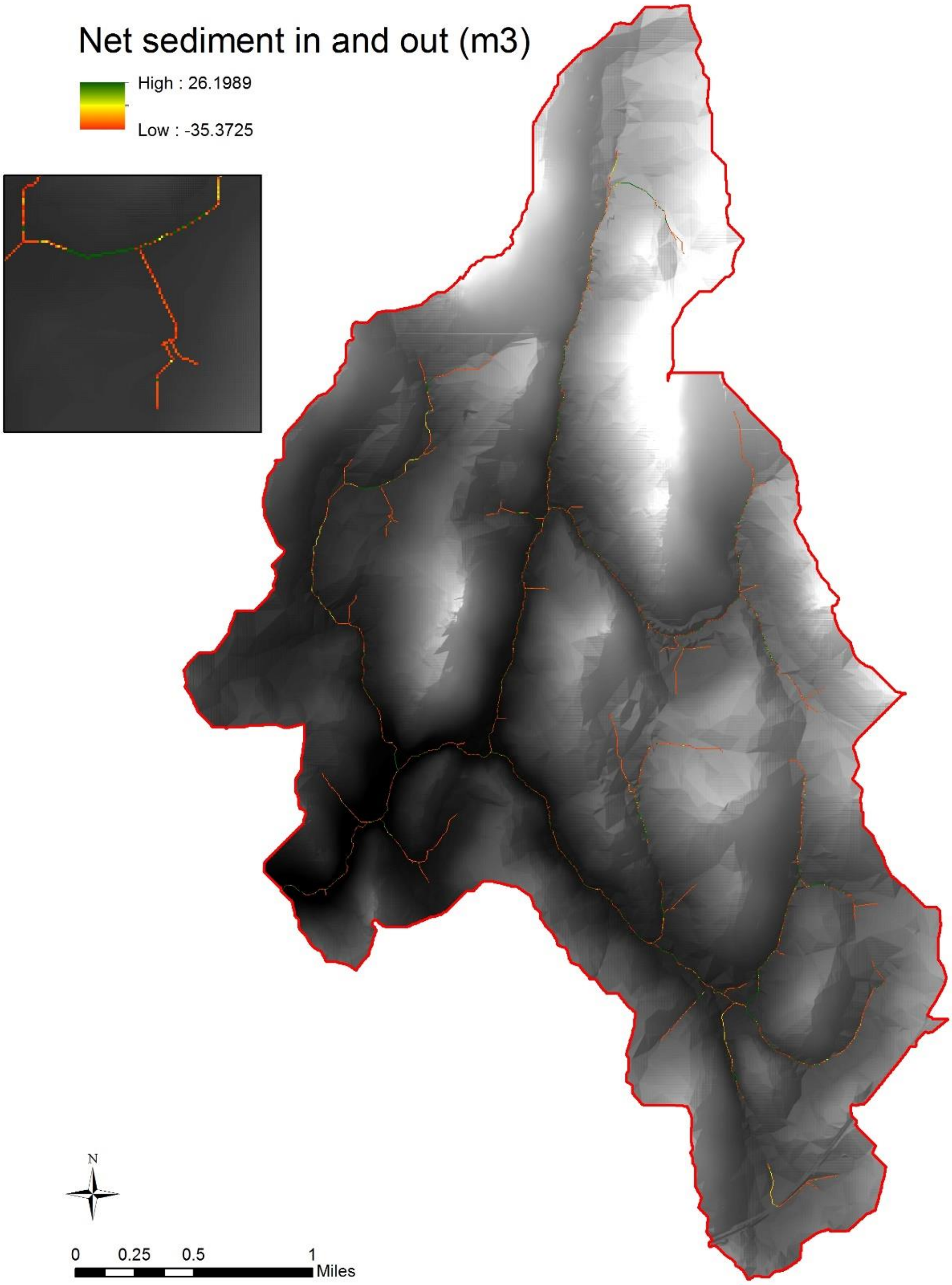


FIGURE 5-30: EXAMPLE IN-CHANNEL NET SEDIMENT TRANSPORT MONTHLY TOTAL FROM THE HYPOTHETICAL DECISION-MAKING SCENARIO PRIOR TO LAND COVER CHANGES BEING MADE

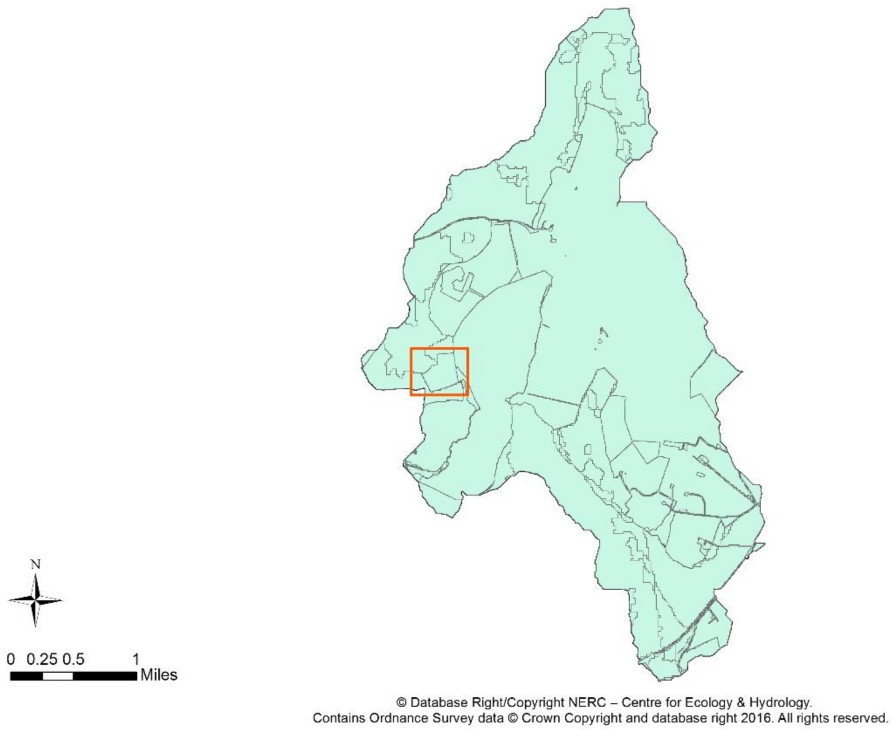


FIGURE 5-31: PARCEL OF LAND COVER CHANGED FROM PASTURE TO BROADLEAF WOODLAND DURING THE HYPOTHETICAL DECISION-MAKING SCENARIO

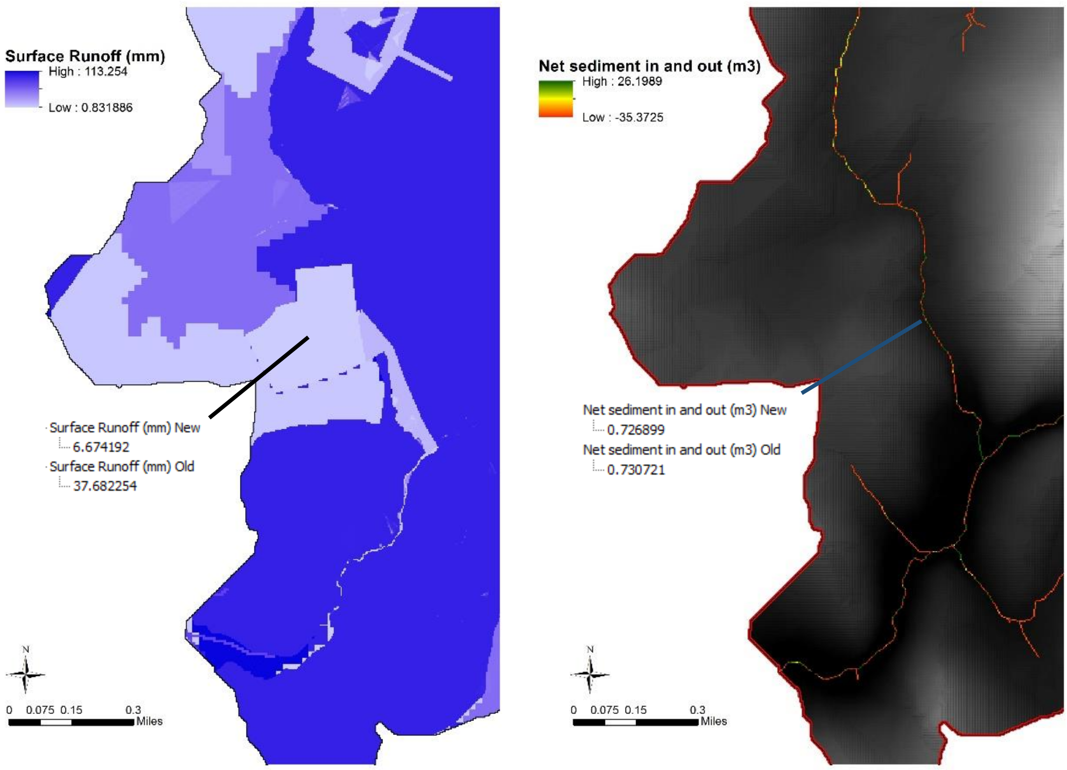


FIGURE 5-32: CHANGE IN SURFACE RUNOFF AND NET SEDIMENT TRANSPORT FOLLOWING THE CHANGE OF LAND COVER TYPE IN THE HYPOTHETICAL DECISION-MAKING SCENARIO.

5.2. Model assessment

This section of the chapter presents the results from the model assessment with the stakeholder groups. The model assessment focused on Objective 5.

5. Critically assess the new cellular model as a tool for use within river management.

5.2.1. Model use (hypothetical decision-making scenario)

The hypothetical decision making scenario activity was a key part of the model assessment as this was the first time the stakeholders had been able to use the model, the outputs of which were presented in the previous section. The activity was recorded and transcripts of these sessions produced and thematically analysed. Note that the Bristol Avon transcript is taken from the analysis of a one-on-one rather than a group exercise. Originally, the method was designed to be carried out with individuals. However, this was changed to entire groups in the recognition of the opportunity to use the exercise for knowledge exchange and social learning, as well as reducing the time intensive nature of conducting the activity with individuals. Figure 5-33 presents the thematic map generated from the analysis of these transcripts. Figure 5-34 shows a treemap of the themes and sub-themes. This was created based on the number of times a theme or sub-theme was coded within the transcripts, illustrating a relative importance of those themes. The remainder of this section describes each of these themes and sub-themes, supported by extracts from the transcripts.

Figure 5-33: Thematic map of themes and sub-themes identified through the coding of the hypothetical decision making scenario transcripts. The colours and thickness of the lines relate to the catchment and the number of catchments each code appears in.

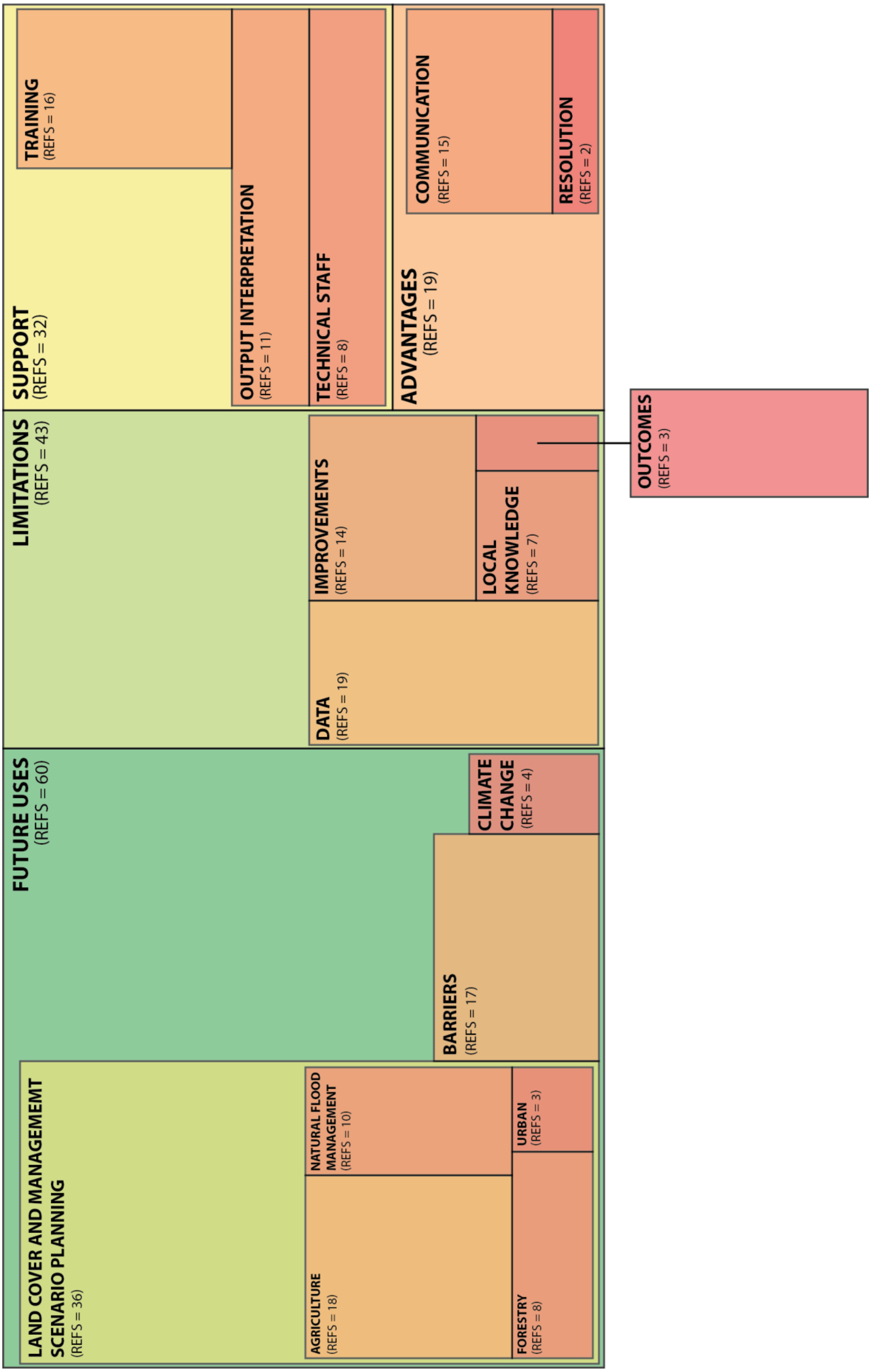


FIGURE 5-34: TREEMAP OF THEMES AND SUB-THEMES IDENTIFIED THROUGH THE CODING OF THE MODEL USE (HYPOTHETICAL DECISION MAKING SCENARIO) TRANSCRIPTS. 'REFS' REFERS TO THE TOTAL NUMBER OF TIMES A THEME WAS CODED.

The largest theme was **future uses** (refs = 60). This theme was then further divided into a number of sub-themes. In particular, stakeholders noted that it was no longer good enough that projects only dealt with flood risk or the WFD; instead they must achieve multiple benefits. The quotes below emphasise this.

'[There are many] *big issues with water management in the catchment, one of these being sediment and sediment management... we have got very limited funding available and we want to deliver projects with multiple benefits. So each project we're looking at has to have benefits at local level, whether that is flooding, sediment or biodiversity. This is a way of targeting and identifying areas within the catchment… at a field scale and I don't know any other models that do that.'* (Wessex Water, Bristol Avon)

'We can't just think of WFD and Natural Flood Management (NFM) in their silos. There is this concept of multiple drivers, multiple benefits and investing in works clear in people's minds. …we stand a good chance of success if you're looking to push this in house, and get some kind of project setup helps to break down the barriers between WFD and NFM.' (Scottish Environment Protection Agency, Spey)

The largest of the sub-themes under future uses was **land cover and management scenario planning** (refs = 36), suggested in all of the stakeholder groups. This sub-theme was then split into four areas, with the first and largest of these as **agriculture** (refs = 18). In particular, the stakeholders articulated how this model could be used to prioritise interventions in the catchment. The following quote emphasises this, with a stakeholder providing a real-world scenario of where this kind of model could be useful.

'A scenario that we've got is £6,000 to spend in that catchment on annual management options and we could use it to prioritise which options should go where to achieve the most benefit. One would be because you would know the number of hectares converted to potatoes from permanent pasture or grassland.' (Natural England, Camel)

The second split was into *'something everyone is talking about'*, **Natural Flood Management** (NFM) (refs = 10). The stakeholders articulated how this type of model would be useful to inform management interventions by showing *'how much the runoff will be reduced'*, and what happens if *'…we want to change this bit, this bit, this bit, and this bit'*. Another of the four areas was **forestry** (refs = 8); this was closely interlinked with NFM, as the quote below suggests the planting of trees was seen as an important method for reducing runoff.

> *'…100 hectares have been planted up in the last 2 years, that at the moment have no effect and instantly* [the model] *would tell you, down to the point how much the runoff could be reduced when those trees mature.' (Spey Catchment initiative, Spey)*

One of the aspects which was not the focus of the activity, but was raised in the Spey, was the use of the model to add and remove in-channel **barriers** (refs = 17). The particular interest of the Spey tended to focus on large hydropower dams which are influencing the natural system, and whether or not the model could be used to assess management solutions. The quotes below reflect some of these discussions.

> *'…assessing the cumulative effects of multiple reservoirs and dams, because from the agencies point of view how do you regulate them? At the moment we regulate those in almost a one hundred percent vacuum of information about what the impacts are, and this kind of approach is exactly the kind of thing that would be really helpful.'* (Scottish Environment Protection Agency, Spey)
>
> *'What I want to know is, if we put the barrier there what sediment we put in downstream is going to move. We want to start feeding the system again. How is it going to move down, so we don't cause any problems? Because we have to convince policymakers and landowners that we are improving the situation...'* (Spey Catchment Initiative, Spey)

The final sub-theme under future uses is **climate change** (refs = 4). This was not specifically covered in the activity and was raised in the Spey and Camel sessions. The code predominately related to how the model could be used to incorporate the effects of climate change, as articulated in the quote below.

‘The reason I asked is if we wanted to use this to incorporate a new hydrograph, say for climate change. Then we can see high areas which contribute much more sediment and do something to protect those areas from mass wasting i.e. plant some trees.’ (Scottish Environment Protection Agency, Spey)

Limitations (refs = 43) was the second largest theme covering the issues that the stakeholders raised on the model. The largest sub-theme under limitations was **data** (refs = 19). In particular, this refers to how some of the processes within the model would not be correct without the right data, as well as concerns on the accuracy of the data generated by the model. The quotes below provide an insight into this.

‘The complication with that [road runoff] *now is that they treat the run off. They attenuate what is coming off the road in suds ponds’* (Scottish Environment Protection Agency, Spey)

‘I guess that's another issue with taking things like that where you have too specific numbers. Take the value of changing 0.442 to 0.444 [displayed from the model on screen]*, at what point does that become a significant threshold, and we can ring a landowner and say we can reduce your sediment input if you plant some trees here by 0.002. I mean what is your confidence in that?’* (Scottish Environment Protection Agency, Spey)

The **improvements** (refs = 14) sub-theme, has overlap with the previous sub-theme as several of the improvements suggested, where the addition of new datasets would make the model ‘better’. The quotes below reflect this, with other changes that the stakeholders felt would improve the model.

‘So, could you have if this river cell has depth of more than 0.05, then it looks up a value from a lookup table with river widths, rather than taking the value from the cell width.’ (Scottish Environment Protection Agency, Spey)

‘So this is the interesting bit, how would the output change? Can you Program in 51 to equal arable for example?’ (Wessex Water, Bristol Avon)

The importance of **local knowledge** (refs= 7) came through in some of the stakeholder discussions of the outputs, as the stakeholder described that no matter how good the model was, there will always need to be an input of local knowledge to analyse and interpret the outputs of any modelling.

'The problem with that catchment is the majority of it is post-industrial china clay tips, and I don't know how the model would cope with that because it's not even natural, the topography completely changed so it's not stable rock and soil…' (West Country Rivers Trust, Taw)

The smallest sub-theme is **outcomes** (refs = 3), which refers to some of the transcripts where a couple of the stakeholders were not quite sure how this kind of modelling could be used in river management. The quotes below are part of an interaction between the stakeholders on the Camel, where after the initial comment by one stakeholder, other stakeholders challenged back, suggesting how this kind of modelling could be used as a tool to influence outcomes and decisions.

'…what I'm struggling with is to see how you can develop it in such a way that it can influence business outcomes outside, that's what I'm struggling with' (Environment Agency, Camel)

'It feeds the conversation, you can put a number of options to a catchment. Particularly, if you're trying to put CSF (Catchment Sensitive Farming) or any sort of grant scheme into a catchment. You can start to say what you would like, you can start to dictate a little bit more what you would like to happen and that is a tick in a box. You can be a little bit more focused with it.' (Environment Agency, Camel)

'Yeh it allows you to demonstrate.' (Natural England, Camel)

The **support** (refs = 32) theme has been used to code extracts of the transcripts where the stakeholders have described what they would need to operate the model. The largest sub-theme was **training** (refs =16), which referred to where stakeholders have made a reference to whether or not the tool will come with *'detailed instructions'* or *'instructional videos'*. The **output interpretation** (refs = 11) sub-theme relates to where the stakeholders described having issues understanding the difficulties in the outputs generated by the model. The two quotes below reflect two examples of this.

'…keys are really important, …this is where I'd fall down because I got an understanding but I want to double-check somewhere …in a really basic language this means lower sedimentation …this means higher sedimentation' (Wessex Water, Bristol Avon)

'So is that showing a difference of 0.002 cubic metres? So like that much (demonstrating with hands)*.'* (Spey Catchment Initiative, Spey)

The smallest sub-theme is **technical roles** (refs = 8) and came up in the Bristol Avon and Taw. This theme captured a concept conveyed by several stakeholders that they do not carry out modelling as they do not have the time or competencies to do modelling and instead this is left to *'technical'* people.

'So it would be great if I can follow this all the way through and do it. I think what you're trying to do in principal is really interesting. I think it's just that what you're trying to do through this study is a big leap… I don't have time to mess around with it…' (Wessex Water, Bristol Avon)

'Ideally I'd love to use this sort of thing because I do think it is a fantastic management tool …but sometimes it comes down to how many hours are in the day and if you don't use it all the time, then it does take a disproportionately large amount of time. But if you've got a team of GIS people then you're always going to ask them...' (West Country Rivers Trust, Taw)

The final and smallest theme is **advantages** (refs = 19). This theme relates to where stakeholders have picked out specifics of how the model will be useful, and has been split into two sub-themes: **communication** (refs = 15) and **resolution** (refs = 2). The communication sub theme relates to stakeholder comments on the visual outputs created by the model and how they could be useful to help communicate with other local stakeholders, such as farmers.

'…that visual tool to show the farmers …to be able to show hey this is where most of its coming from.' (Environment Agency, Camel)

'I was thinking, I wish we could do an intervention in here or if we did this bit of planting here what impact on sediment would that have. The potential to model in project and visual products could be awesome.' (Spey catchment Initiative, Spey)

'It is another thing to have in your arsenal. It's really to talk to farmers and be able to say ok, yes it's a model but this is just more evidence…' (West Country Rivers Trust, Taw)

The other theme of resolution reflects how stakeholders thought the model allowed them to operate at a much finer scale than had been possible before with other models.

5.2.2. Model comparison

The purpose of the model comparison part of the model assessment was to compare the developed tool with another existing model – CASEAR-Lisflood (described in Section 2.2.2). The comparison activity involved two key components. Firstly, the stakeholders were required to rank a series of model characteristics from 1 to 10 based on how important they thought they were, the results of which are shown in Figure 5-35 and Table 5-4. In the session, two of the stakeholders did not complete this activity; one of the stakeholders arrived late to the session and so did not have time, the other said that they did not understand the terminology being used in enough detail to provide a sufficient response (this stakeholder had not been involved in the process to date). Of the remaining 19 stakeholders, five filled in the questionnaire incorrectly (the researcher did not clearly explain they should not use the same rank twice) and so their responses have been removed from the quantitative results. However, as they provide valuable insight, their qualitative responses will be reviewed in the qualitative part of this section.

Figure 5-35 and Table 5-4 show that the most important factor was 'spatially distributed surface runoff and erosion based on rainfall, land cover, soil type and condition' (combined mean = 2.29) with 50% of the stakeholders ranking this number 1. The second most important factor was the ‘ability to change land cover type and management’ (combined mean = 3.29) with 50% of stakeholders giving a ranking of 1 or 2. The least important factor was the ‘ability to simulate the effect of tides and dunes’ (combined mean = 9.29) with 57% of stakeholders giving a ranking of 10. The ‘ability to simulate chemical and physical weathering’ within the model was the next least important factor (combined mean = 7.71) with 64% of stakeholders ranking this within the bottom three. This is followed by the ability to ‘output Google Earth animations’ (combined mean = 7.29) with 43% ranking this 8-10. The remaining model parameters are very closely distributed with means of 5.14 (2D flow model), 4.71 (automatic preparation of data), 5.21 (flexibility to select outputs), 5.21 (standalone tool) and 4.86 (detailed instructions).

A Kruskal-Wallis H test showed that there was a statistically significant difference ($p < 0.05$) in the ranking of ‘detailed instructions’ between the stakeholder groups, with a mean of 2.00 for the Bristol Avon, 6.33 for the Camel, 6.50 for the Taw, and 6.50 for the Spey (Table 5-7). Furthermore, a Kruskal-Wallis H test showed that there was a statistically significant difference ($p < 0.05$) in the ranking of ‘standalone tool’ between the stakeholder groups, with a mean of 3.00 for the Bristol Avon, 5.00 for the Camel, 5.00 for the Taw, and 8.25 for the Spey. Interestingly, there is also some variation between catchments for the ‘2D flow model (simulating flood plain flooding)’, with a mean of 2.75 on the Spey compared to 7.00 on the Bristol Avon. However, this was not statistically significant ($p > 0.05$). Overall, 4 of the top 5 ranked parameters were attributes from the ENGAGE model developed through this PM process.

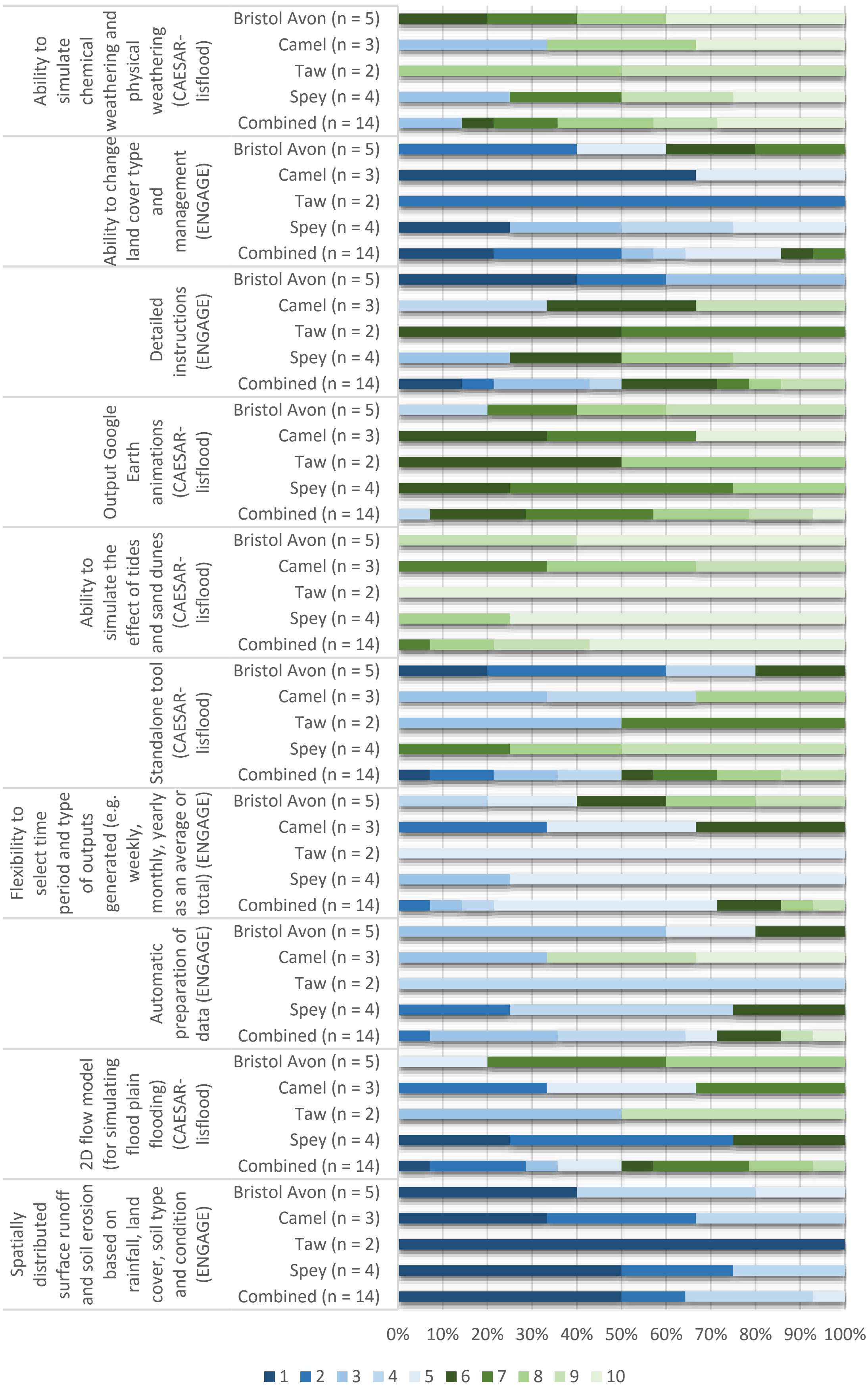


Figure 5-35: Ranking of factors in order of their importance when using a model (scale of 1 (most important) to 10 (least important)).

TABLE 5-4: DESCRIPTIVE AND STATISTICAL (KRUSKAL-WALLIS H TEST) ANALYSIS OF THE DATA COLLECTED IN THE MODEL COMPARISON EXERCISE WHERE STAKEHOLDERS WERE ASKED TO: 'PLEASE RANK THE FOLLOWING MODEL CHARACTERISTIC FROM THE MOST IMPORTANT (1) TO THE LEAST IMPORTANT (10)'.

Overall Rank	Model	Model Characteristic	Catchment	Mean	SE
1	ENGAGE	Spatially distributed surface runoff and soil erosion based on rainfall, land cover, soil type and condition	Bristol Avon (n = 5)	3.00	0.84
			Camel (n = 3)	2.33	0.88
			Taw (n = 2)	1.00	0.00
			Spey (n = 4)	2.00	0.71
			Combined (n = 14)	**2.29**	**0.41**
			$\chi^2(3)$	**2.51**	
			p =	**0.47**	
2	ENGAGE	Ability to change land cover type and management	Bristol Avon (n = 5)	4.40	1.03
			Camel (n = 3)	2.33	1.33
			Taw (n = 2)	2.00	0.00
			Spey (n = 4)	3.25	0.85
			Combined (n = 14)	**3.29**	**0.54**
			$\chi^2(3)$	**3.17**	
			p =	**0.37**	
3	ENGAGE	Automatic preparation of data	Bristol Avon (n = 5)	4.00	0.63
			Camel (n = 3)	7.33	2.19
			Taw (n = 2)	4.00	0.00
			Spey (n = 4)	4.00	0.82
			Combined (n = 14)	**4.71**	**0.62**
			$\chi^2(3)$	**1.73**	
			p =	**0.629**	
4	ENGAGE	Detailed instructions	Bristol Avon (n = 5)	2.00	0.45
			Camel (n = 3)	6.33	1.45
			Taw (n = 2)	6.50	0.50
			Spey (n = 4)	6.50	1.32
			Combined (n = 14)	**4.86**	**0.75**
			$\chi^2(3)$	**8.40**	
			p =	**0.038**	
5	CAESAR-Lisflood	2D flow model (for simulating flood plain flooding)	Bristol Avon (n = 5)	7.00	0.55
			Camel (n = 3)	4.67	1.45
			Taw (n = 2)	6.00	3.00
			Spey (n = 4)	2.75	1.11
			Combined (n = 14)	**5.14**	**0.72**
			$\chi^2(3)$	**6.22**	
			p =	**0.10**	
6 (joint)	ENGAGE	Flexibility to select time period and type of outputs generated (e.g. weekly, monthly, yearly as an average or total)	Bristol Avon (n = 5)	6.40	0.93
			Camel (n = 3)	4.33	1.20
			Taw (n = 2)	5.00	0.00
			Spey (n = 4)	4.50	0.50
			Combined (n = 14)	**5.21**	**0.47**
			$\chi^2(3)$	**2.61**	
			p =	**0.46**	
6 (joint)	CAESAR-Lisflood	Standalone tool	Bristol Avon (n = 5)	3.00	0.89
			Camel (n = 3)	5.00	1.53
			Taw (n = 2)	5.00	2.00
			Spey (n = 4)	8.25	0.48
			Combined (n = 14)	**5.21**	**0.75**
			$\chi^2(3)$	**8.07**	
			p =	**0.045**	
8	CAESAR-Lisflood	Output Google Earth animations	Bristol Avon (n = 5)	7.40	0.93
			Camel (n = 3)	7.67	1.20
			Taw (n = 2)	7.00	1.00
			Spey (n = 4)	7.00	0.41
			Combined (n = 14)	**7.29**	**0.41**
			$\chi^2(3)$	**0.68**	

			p =	**0.88**	
9	CAESAR-Lisflood	Ability to simulate chemical weathering and physical weathering	Bristol Avon (n = 5)	8.20	0.80
			Camel (n = 3)	7.00	2.08
			Taw (n = 2)	8.50	0.50
			Spey (n = 4)	7.25	1.55
			Combined (n = 14)	**7.71**	**0.63**
			$\chi^2(3)$	**0.22**	
			p =	**0.98**	
10	CAESAR-Lisflood	Ability to simulate the effect of tides and dunes	Bristol Avon (n = 5)	9.60	0.24
			Camel (n = 3)	8.00	0.58
			Taw (n = 2)	10.00	0.00
			Spey (n = 4)	9.50	0.50
			Combined (n = 14)	**9.29**	**0.27**
			$\chi^2(3)$	**6.43**	
			p =	**0.09**	

In addition to completing the ranking, the stakeholders were asked to provide a qualitative response for each. This created a large amount of data, which will not be presented in its entirety. Instead, themes from the responses have been identified and attributed to the ranking (in brackets) given by the stakeholders. From the responses to the highest ranked model parameter of ‘spatially distributed surface runoff and soil erosion based on rainfall, land cover, soil type and condition’, the most common response was that this was a *‘Key requirement’* (1), *‘Key piece of data’* (4), *’…key to what the model needs to show’* (4), *‘The crux and result of sediment runoff’* (1) and *‘Those are the key elements of the model.’* (1). Other responses included: *‘To reflect and tailor realistic land use’* (1), and *‘…this makes it more sensitive to changes in land cover and management’* (2).

The qualitative responses to the second highest model characteristic of the ‘ability to change land cover type and management’ related to stakeholders’ requirements in their day jobs. In particular, nine out of the 11 comments suggest this. For example, *‘To help us understand whether it’s worth paying farmers to change cover type is worthwhile’* (1), *‘It is vital to be able to do this to explore management scenarios, discuss with stakeholders and influence policy makers.’* (3), and *‘Impact (or potential) that changes to* [land management] *could have on rivers - informs decision making’* (4). One of the respondents did say that this model would be *‘more detailed than I would use’* (7).

The lowest ranked model parameter was the ‘ability to simulate the effect of tides and dunes’. Stakeholders’ responses tended to focus on two primary areas: (i) the local conditions within their catchment, and (ii) whether or not this was an important component in their day job. Many commented that this was *‘Not particularly relevant to the Camel’* (9), *‘Not relevant to Spey* *catchment'* (10) and *'No coastal areas / tidal in my area'* (10). In relation to their day job, stakeholders reflected on whether or not it was of interest, *'Only interested in inland surface waters. We do not want to regulate coastal waters or transitional zones'* (10), and *'Less important for me at this time'* (10). One of the hydromorphologists in the Spey commented that it would be a *'complex element to add with little in return'* (10).

In relation to the second lowest ranked element of the 'ability to simulate chemical weathering and physical weathering', seven of the nine stakeholders commented that these processes would have a *'small effect on morphology processes at the timescales we are looking at'* (9), *'Very slow process should be very minimal influence on results.'* (9), and the model was *'not really relevant to management timescales (decades), though more relevant if running a cellular model for centuries or millennia.'* (10). The two remaining stakeholders commented that this could be *'useful'* (6) or have the *'potential to highlight sites for interventions'* (3).

The ability to output Google Earth animations closely followed the previous parameter. Seven of the nine comments left by the stakeholders noted that this would be a useful output for communicating model results. All of these comments ranked the characteristic below 5 and included how this would be *'good for education'* (7), *'Important to present information to non-specialists'* (6), *'Visual outputs help immensely with audiences.'* (6) and *'sounds useful for demonstrating to others what the issues are'* (8). The one stakeholder who rated this 10, noted that they were *'not clear what this would entail'*.

The 'automatic preparation of data' had a mean of 4 in the Bristol Avon, Taw and Spey whereas in the Camel, the mean was lower at 7.33. Two stakeholders in the Camel who rated this as (9) and (10) did not provide any qualitative comment as to why they rated this as of low importance. In the other catchments, the stakeholders commented that this was important as the *'simpler the better'* (3), and *'reduces the time we spend on modelling'* (2). As mentioned earlier, there was some variation for a *'standalone tool'*. The stakeholder comments on the Spey suggest that although this could be useful, it was *'not essential'* (8) and *'has no real bearing on the quality of outputs'* (9). Whereas, in the other catchments, stakeholder comments focused on the availability of the software and the influence this has on the wider uptake of the developed tool or model. For example, *'Not all Natural England staff have access to GIS software'* (4), *'so can be used by all stakeholders'* (1) and *'…availability, especially if encouraging wider uptake, use and audiences.'* (3).

The characteristic of detailed instructions saw a split in responses between the Camel, Taw and Spey, (means = 6.33, 6.50, 6.50) and the Bristol Avon (mean = 2.00). The responses on the Bristol Avon indicated that detailed instructions were important as we *'must be able to explain what the model can do clearly'* (1), *'otherwise I won't use it'* (1) and '[I] *do not use and model typically'* (1). Whereas, comments from the other stakeholders indicated different ideas such as *'needs to be intuitive to use as people are reluctant to read instructions'* (6) and *'As long as everything is clear, we shouldn't be too prescriptive'* (9).

The 2D flow model characteristic had a mean of 2.75 on the Spey compared to means of 7.00, 4.67 and 6.00 for the Bristol Avon, Camel and Taw. Stakeholder responses to this question argued that this was important as *'if the basic model mechanics are not right the model is next to useless'* (1) and *'the key element of a model'* (2). Stakeholders in the other groups reflected that this characteristic was *'…less important…'* (9), *'…too detailed…'* (8) and *'would replicate existing work'* (7).

All of the above comments were included in the analysis of the data. This section now moves on to briefly present some of the results from those responses that were not included, as the stakeholders incorrectly completed the activity (e.g. multiple characteristics given the same rank). Table 5-5 presents these results. The overall rankings do not differ significantly, with the top two and bottom three remaining the same. The ranks and qualitative comments are shown to provide additional context. The same themes described earlier emerge for the top two parameters in that the stakeholders considered these to be *'essential to successfully simulating sediment transport'* (1) and *'very important to giving advice and showing the impact of land use'* (1). The lowest parameters were also similar, suggesting that these *'impact a relatively small part of the catchment'* (10), *'not required on my catchments'* (10) and *'too detailed'* (10).

TABLE 5-5: RESULTS FOR THE INCORRECTLY COMPLETED FORMS IN THE MODEL COMPARISON EXERCISE WHERE STAKEHOLDERS WERE ASKED TO 'PLEASE RANK THE FOLLOWING MODEL CHARACTERISTIC FROM THE MOST IMPORTANT (1) TO THE LEAST IMPORTANT (10)'.

	Overall rank									
	1	2	3	4 (Joint)	4 (Joint)	6	7	8	9	10
Model	ENGAGE	ENGAGE	ENGAGE	ENGAGE	ENGAGE	CAESAR-Lisflood	CAESAR-Lisflood	CAESAR-Lisflood	CAESAR-Lisflood	CAESAR-Lisflood
Model Characteristic	**Spatially distributed surface runoff and soil erosion based on rainfall, land cover, soil type and condition**	**Ability to change land cover type and management**	**Flexibility to select time period and type of outputs generated (e.g. weekly, monthly, yearly as an average or total)**	**Automatic preparation of data**	**Detailed instructions**	**Standalone tool**	**2D flow model (for simulating flood plain flooding)**	**Output Google Earth animations**	**Ability to simulate the effect of tides and dunes**	**Ability to simulate chemical weathering and physical weathering**
Rank and reason for selection	1 - understanding these indicators is very important	3	2	2 - Simplicity is the key for myself (non-technical specialist)	8	4 - Could be useful for practitioners in GIS or not	4	7	3 - Not relevant for our area but would be elsewhere	8
	1 -This data is essential to successfully simulating sediment transport	1 - This will allow managers to assess changing land uses and impacts on sediment transport	1 - This will increase the flexibility in how the model could be used	5 - I would expect some preparation of data prior to modelling but automatic could reduce error in input.	1 - This is essential for successful user / application of the model by non-technical specialists	7 - Not essential to be standalone, perhaps good to be linked to other modelling. Perhaps easier to be integrated into GIS	1 - Improve model accuracy and allow assessment of sediment transport	8 - Although perhaps useful for presenting the information to non-specialists, I don't think this is important	10 - This would only impact a relatively small part of the catchment	8 - Probably less important over short to medium timescales models likely to be run

	Overall rank									
	1	2	3	4 (Joint)	4 (Joint)	6	7	8	9	10
Model	ENGAGE	ENGAGE	ENGAGE	ENGAGE	ENGAGE	CAESAR-Lisflood	CAESAR-Lisflood	CAESAR-Lisflood	CAESAR-Lisflood	CAESAR-Lisflood
Model Characteristic	**Spatially distributed surface runoff and soil erosion based on rainfall, land cover, soil type and condition**	**Ability to change land cover type and management**	**Flexibility to select time period and type of outputs generated (e.g. weekly, monthly, yearly as an average or total)**	**Automatic preparation of data**	**Detailed instructions**	**Standalone tool**	**2D flow model (for simulating flood plain flooding)**	**Output Google Earth animations**	**Ability to simulate the effect of tides and dunes**	**Ability to simulate chemical weathering and physical weathering**
	2 - Depending on accuracy of model - spatial info is very important to targeting advice	1 - This would be very important to giving advice and showing impact of land use	2- Time period is critical to take advice and target at best time	2 - Outputs from the model need to be straight forward, therefore automated from raw data is important	3 - May be difficult to make instructions suitable for all levels	3 - More likely to be wider used if not need extra software	5	4 - This could be useful but more info needed	8 - Cannot comment	6 - More information needed
	8	9		6		6	8	6	7	8
	1 - Main concern	3 - Very important as want to see output change according to land use	? - Probably would want monthly	4 - This is at a premium so automatic data prep would be good	7 - As long as training is provided should not be a problem	1 - My company don't use ArcGIS and I don't have GIS experience	? (High) Not required for my work as not concerned with flood management	2 - Important for demonstration to stakeholders such as farmers	10 - Not required on my catchments	9 - Not important overall overtime Horizon we are concerned with as effect of land use on sediment use

	Overall rank									
	1	2	3	4 (Joint)	4 (Joint)	6	7	8	9	10
Model	ENGAGE	ENGAGE	ENGAGE	ENGAGE	ENGAGE	CAESAR-Lisflood	CAESAR-Lisflood	CAESAR-Lisflood	CAESAR-Lisflood	CAESAR-Lisflood
Model Characteristic	**Spatially distributed surface runoff and soil erosion based on rainfall, land cover, soil type and condition**	**Ability to change land cover type and management**	**Flexibility to select time period and type of outputs generated (e.g. weekly, monthly, yearly as an average or total)**	**Automatic preparation of data**	**Detailed instructions**	**Standalone tool**	**2D flow model (for simulating flood plain flooding)**	**Output Google Earth animations**	**Ability to simulate the effect of tides and dunes**	**Ability to simulate chemical weathering and physical weathering**
	1 - I assume this is the most important data for a sediment model, if getting the right data is paramount	2 - I assume this is the most important data for a sediment model, if getting the right data is paramount	5	7	6	9	8	10	3	1
	1- Critical for drinking water protected area models. Cost of data is a critical factor	1 - Essential to incorporate local knowledge	6 - We need relative risk at catchment-scale to target measures, but quantifying soil loss is useful.	1 - Casual users as tech skills are the limiting factor. 5 - for more technical users. As time saving is useful.	1	2 - Open source = important Web-based = better	5 - I'm not a flood modeller but think 3D modelling is far more useful for targeting natural flood risk Management Solutions.	10 - I can convert to kml so long as I have downloaded the data	8 - Currently low but we need to consider TRACs so that will become more important	10 - To detailed
Mean	2.14	2.86	3.20	4.33	4.33	4.57	5.17	6.71	7.00	7.14
SE	0.99	1.08	0.97	0.84	1.26	1.09	1.08	1.13	1.11	1.12

Model A vs Model B

The second activity required the stakeholders to compare two models: Model A (CAESAR-Lisflood), and Model B (ENGAGE). Table 5-6 presents the results by catchment when the stakeholders were asked to provide a rating out of 10 (High) to the likelihood that they would use each model. Overall, in every catchment the stakeholders gave Model B a higher rating (combined mean = 6.61) than Model A (combined mean = 4.22). The difference between the two is closest in Spey, where Model A has a rating of 5.4 compared to 6.8 for Model B. There is some variation between the groups as shown by the Min and Max ratings given to the two models. For example, the range in values for Model B ranged from 1 to 9, compared to 2 to 7 for Model A. However, Kruskal-Wallis H tests showed that these differences were not statistically significant ($p > 0.05$) (Table 5-6).

TABLE 5-6: RESULTS FROM THE MODEL COMPARISON EXERCISE WHERE STAKEHOLDERS WERE ASKED TO PROVIDE "A RATING OUT OF 10 (HIGH) BELOW FOR EACH MODEL IN RELATION TO THE LIKELIHOOD THAT YOU WOULD USE IN YOUR DAY JOB IF YOU HAD A NEED TO CONDUCT AN INVESTIGATION THAT REQUIRED THE USE OF A SEDIMENT DYNAMICS MODEL OR AS PART OF A DECISION MAKING PROCESS".

Model Parameter	Catchment	Min	Max	Mean	SE
Model A (CAESAR-Lisflood)	Bristol Avon (n = 7)	2	7	4.14	0.67
	Camel (n = 4)	2	3	2.50	0.29
	Taw (n = 2)	3	7	5.00	2.00
	Spey (n = 5)	4	7	5.40	0.51
	Combined (n = 19)	**2**	**7**	**4.22**	**0.42**
	$\chi2(3)$	6.79			
	p =	0.08			
Model B (ENGAGE)	Bristol Avon (n = 7)	4	9	7.14	0.70
	Camel (n = 4)	1	7	5.00	1.41
	Taw (n = 2)	7	8	7.50	0.50
	Spey (n = 5)	3	8	6.80	0.97
	Combined (n = 19)	**1**	**9**	**6.61**	**0.51**
	$\chi2(3)$	4.04			
	p =	0.26			

In addition to ranking the models, stakeholders were asked to provide a qualitative response. Several stakeholders who gave low ranks (less than 5) for Model A, suggested this was down to the practical application of the model in their day job, and how the model would be relevant to them.

'Too detailed for my role - may benefit flood roles more' (3) (Environment Agency, Camel)

'Uniform soil hydrology and land cover, too many input parameters, limited guidance' (2) (Natural England, Camel)

'More complex and detailed, perhaps more academic. Practical applications that would be useful in our work. This is perhaps a more research objectives model, peer reviewed is not necessarily our aim but can be part of other work. Useful for higher level research but not in everyday or average staff use application.' (3) (West Country Rivers Trust, Taw)

'This model appears too complex for me' (4) (Farming and Wildlife Advisory Group, Bristol Avon)

'Time consuming to prepare data. Probably very detailed but would require additional interpretations. Good for academic users, non-commercial' (2) (Wessex Water, Spey)

Three of the stakeholders ranked Model A higher. Two of the themes to come from this data were: (i) the validation and application of the model to some real catchments, and (ii) the perceived technical expertise required to operate the model.

'Gives a lot of flexibility in both model input and output and also been applied to a large range of catchments. It could also give a very detailed picture of sediment dynamics over a range of temporal scales. However, it would require quite a bit of expertise to use, particularly given the lack of detailed guidance. More useful for managers with experience in fluvial geomorphology...' (6) (Scottish Environment Protection Agency, Spey)

'2D hydrodynamic flow is useful and the interface looks simple. Not sure which gives me the most useful output, this is more flexible.' (7) (Environment Agency, Bristol Avon)

From the stakeholders who provided a higher rating for Model B (five or above), three themes were apparent in the data. The first of these was the **ease of use**, the second was the **spatially distribution of model variables,** and the third was the **ability to change and tailor the model inputs**. The quotes below move through these themes. The third quote refers to the target audience of the model, which was mentioned earlier.

'Better interface enabling visualisation to a broader audience, less technical input from user, detailed enough to inform area to focus on…' (7) (Environment Agency, Camel)

'Sounds like a much simpler model to set up and run so more likely that I want to spend time on it.' (7) (Scottish Environment Protection Agency, Spey)

'Links to GIS and automatic data preparation sound attractive' (8) (Spey Catchment Initiative, Spey)

'Relatively low level of data input as automatic data preparation means that less data input required, less need for expertise in the field, making it more usable by non-specialists …however, perhaps less flexibility in the model and not applicable to all catchments. Overall, a good model for use by managers rather than specialists!' (8) (Scottish Environment Protection Agency, Spey)

'Appears to allow more tailored, localised input and outputs. e.g. to change land use / cover types, trial in-channel barriers and outputs that allow temporal factors. Overall appears to be more localised and this is reflected in the scale of catchment i.e. less than 250 kilometres squared.' (8) (West Country Rivers Trust, Taw)

'This model seems to require less user input i.e. easier to use and less knowledge required. Also has the ability to change land cover types which is important when working with landowners.' (8) (Farming and Wildlife Advisory Group, Bristol Avon)

'Good spatial distribution land cover / use on surface runoff scale is appropriate to my work but limiting to others. Model prepares data, only a few variables required would prefer if it was standalone, ability to change land cover types' (9) (Bristol Water, Bristol Avon)

In addition to noting the positives of the model, four stakeholders noted some of the limitations with Model B. In particular, *'the only downside I can see is the limit on catchment area.'* (7), and *'good for sub-catchments but not suitable for whole Spey catchment (3000m^2)'* (8). Another issue noted was that a stakeholder would *'prefer if it was standalone'* (9).

Three stakeholders noted that they felt that they did not have the skillset required to understand or operate either of the models. For example one stakeholder said they were *'…not sure I am informed enough to say as I won't use these model myself in my role'* (8), whilst another commented *'I don't* *feel like I have a good enough understanding to score these models'* (did not rank). Lastly, the other commented saying '[I] *can't answer this as I don't model.'* (8).

5.3. Implications from the model assessment

The previous two sections have presented the developed model and the results from the model assessment. The purpose of the model assessment was to give ENGAGE a trial run with the stakeholders and measure stakeholders' opinions by comparing the developed model against an existing sediment dynamics model. This section moves on to discuss the implications from the model assessment for the developed model.

The results indicate that overall the stakeholders were impressed and positive towards the model developed through the PM process. In the model comparison, the model parameters for ENGAGE were found to rank higher than those selected from CAESAR-Lisflood. More specifically, four of the five model parameters were ranked higher, the only parameter ranked higher for CAESAR-Lisflood was the incorporation of the 2D flow model. Therefore, indicating that the stakeholders considered ENGAGE to have more important model characteristics than CAESAR-Lisflood. However, there is the possibility that these results only reflect a 'selection effect' as the model parameters for the exercise were selected by the researcher. Furthermore, CAESAR-Lisflood is a research developed model, and therefore has many characteristics that are targeted for use in research. As a result, CAESAR-Lisflood is not a completely satisfactory model to use for the comparison due to the different target audiences. Despite this, none of the models reviewed in Section 2.2 were considered to be a more suitable. This is important to recognise, as one observation from reviewing the literature is the potential of PM processes to reduce the number of unused research developed models (e.g. Bots and van Daalen, 2008; Hare, 2011).

Based on this premise, it is not surprising that four of the top five ranked model characteristics were from the ENGAGE model. Of these, the top two model characteristics were those that were articulated by the stakeholders throughout the process: (i) 'spatially distributed surface runoff and erosion based on rainfall, land cover, soil type and condition'; and (ii) 'the ability to change land cover type and management'. The stakeholders considered these to be critical aspects for a model to have in order to be useable in river management and articulated this throughout the PM process. The lowest ranked parameters from CAESAR-Lisflood were: (i) 'the ability to simulate the effect of tides and dunes', and (ii) 'the ability to simulate chemical and physical weathering'. The stakeholders suggested this was because they were processes that operated at timescales which were not relevant to river management. This finding supports and develops upon the recognition of Brasington and Richards (2007) and Keesstra *et al.* (2014) for the requirement to develop more intermediate-temporal and spatial-scale models relevant to river management practitioners. In particular, this research finds that the abilities and elements of these models is also important, such as the inclusion of different land cover types and the ability to manipulate model inputs to run river management scenarios.

These findings are further supported by the results of the second comparison activity where the stakeholders were asked to directly compare the two models, Model A and Model B. Model B (ENGAGE) was ranked higher overall (mean = 6.61/10) than Model A (CAESAR-Lisflood) (mean = 4.22/10). The stakeholders considered Model A to be too detailed and tailored to an academic audience, whereas Model B was more useful in management due to the ability to change and manipulate model inputs This was exemplified by the results from the hypothetical decision-making scenario, in which, the stakeholders suggested ways in which the ENGAGE could be used as a foundation to be developed further and applied to real scenarios. For example, the stakeholders described the potential for the model, given the ability to alter land cover at the field level, to be used for understanding the impact of multi-benefit outcome projects. This would involve using the model to assess the effect of changing land cover on the outputs generated by the model. Currently, this is predominately surface runoff and sediment dynamics, but this could be expanded to consider other factors, such as water quality, to make this a multidisciplinary multi-benefit model or tool.

On the other hand, some of the stakeholders did note the technical limitations of ENGAGE, such as the lack of validation, small catchment size, and situating the model in ArcGIS. A few stakeholders commented that they would not have the technical skills or time to operate either of the models. The researcher acknowledges this as a significant limitation of the model which was created through this process. Even with the simplifications and ease of use modifications made, there is a base level of technical expertise required beyond the capability of several of the stakeholders. In particular, the stakeholders would require a moderate understanding of Geographical Information Systems (GIS) and managing spatial data. Therefore, in the model's current form, it may not be a widely used tool by river management practitioners.

Interestingly, even without significant validation of the outputs of the model, the stakeholders stated that currently, they have limited suitable tools to identify specific areas for working with sediment dynamics. Therefore, a *'something is better than nothing'* approach was suggested. Some of the stakeholders also positively remarked on how detailed the model was in its representation, and how valuable the outputs would be *'powerful'* for communicating with farmers and other members of the public. This finding suggests that this type of modelling is a useful approach and has the potential value as a cutting edge technology to help in the management of the river catchments by treating the system as a whole, rather than individual components.

Three of the stakeholder groups mentioned Natural Flood Management (NFM) for the first time during this session. From the researcher's recent experience of working in the Environment Agency during and post the winter floods of 2015/16, this topic is quickly rising up the policy agenda in England. In the future, there will need to be models and tools developed to assist in the strategic planning and implementation of multi-benefit projects. This is supported by Wilkinson *et al.* (2014) who suggest that one of the unique selling points of NFM is that the solutions deliver multiple benefits; however, there need to be methods and tools to demonstrate them. In particular, this is important as the Environment Agency is an evidence-based decision-making organisation. The stakeholders also provided examples of how the model, even in its current form, would be useful to NFM by identifying areas of the catchment to focus work on.

To summarise, the research found that the stakeholders considered ENGAGE to be a more useful tool for river management practitioners, when compared to an existing cellular model of sediment dynamics, in this case CAESAR-Lisflood. However, at this point in the research, this can only be acknowledged in terms of its potential due to the lack of application in a real world decision-making scenario and further development required. Furthermore, there would need to be an assessment of the model's ability to accurately represent sediment dynamics before it could be used for regulatory purposes. At the time of writing this thesis several of the stakeholders have begun to try to use the model and have contacted the researcher to assist where possible (Environment Agency Camel, 2016). Potential uses of the model have also spread among river management practitioners who have not been involved in the PM process, and have heard about the model through 'word of mouth' (Environment Agency External, 2016).

Chapter Six: Evaluation of the participatory modelling process

The previous two chapters presented the results captured during the PM process, the ENGAGE model, and the assessment of the model. This chapter develops this further by presenting the results of the process evaluation, and discussing how these results relate to the research aim and objectives. Furthermore, the chapter considers how the knowledge generated is situated within the literature presented in Chapter Two. To achieve this, the chapter is split into four parts. The first section discusses the results generated from the PM process, and how at each stage these were integrated into the model's development. The second section presents the results from the evaluation of the PM process. The third section discusses the results from the process evaluation. Finally, the fourth section proposes and discusses a revised PM approach based on the results from the process evaluation.

6.1. The participatory modelling process and development of the model

This section discusses the results generated in the PM process, and how at each stage they were utilised in the model's development (Objectives 3.A and 3.B, and presented in Chapter Four). For ease of reference, the relevant objectives are restated:

3. Assemble and describe a new participatory modelling approach to developing a catchment-scale cellular model of sediment dynamics;
    A. Use the new participatory modelling approach to identify, refine and prioritise the requirements of management stakeholders when creating and using a catchment-scale sediment dynamics model in river catchment management;
    B. Use the new participatory modelling approach to assemble and describe a new model of river catchment sediment dynamics;

6.1.1. The requirements analysis and the conceptual model

In this section, the results from the requirements analysis (4.1), and their integration into the conceptual model (4.2) and co-designing sessions (4.3) are discussed. The purpose of these sessions was to identify the requirements of river management practitioners when creating and using a catchment-scale sediment dynamics model. This section also discusses these requirements in relation to the literature reviewed in Chapter Two. Importantly, this includes outlining the extent to which these requirements have been incorporated into existing reduced-complexity cellular models of sediment dynamics.

The requirements analysis resulted in the identification of human and natural influences on sediment dynamics (themes = 21), potential applications (themes = 13), and model characteristics (themes = 11). The results showed that the stakeholders were aware of the factors influencing the sediment dynamics within their respective catchments. One particularly interesting finding was that human influences (refs = 101) had over twice the number of references compared to natural influences (49). This was not surprising considering the recent suggestion by the scientific community of the Anthropocene (Smith and Zeder, 2013; Lewis and Maslin, 2015), whereby humans are the dominant force altering the earth's surface (e.g. Crutzen and Stoermer, 2000; Steffen *et al.*, 2007; Haff, 2010). Furthermore, the stakeholders involved in the PM process were members of management groups with a managerial or policy role at the river catchment-scale. Therefore, this activity would be expected to generate more references for the influence of humans than natural processes on sediment dynamics.

Table 6-1 profiles the human and natural influences described by the stakeholders in relation to three important aspects. Firstly, the table notes and discusses any differences between the catchments. Secondly, the table demonstrates how the literature, described in Chapter Two, relates to the influences articulated by the stakeholders. Thirdly, the table identifies and discusses the inclusion of these influences within the cellular models reviewed in Section 2.2.2. Importantly, Table 6-1 demonstrates that if the researcher had not engaged with the river management practitioners, a number of important influences from the stakeholders' perspective could have been omitted from the model development process.

TABLE 6-1: SUMMARY OF THE RELATIONSHIP BETWEEN THE LITERATURE, REDUCED-COMPLEXITY CELLULAR MODELS, AND THE HUMAN AND NATURAL INFLUENCES DESCRIBED BY THE STAKEHOLDERS IN THE REQUIREMENTS ANALYSIS SESSIONS.

PRINTED A3 EXPANDING TABLE GOES HERE: PART 1

PRINTED A3 EXPANDING TABLE GOES HERE: PART 2

The impacts sub-theme resulted from the discussions the stakeholders had during the requirements analysis sessions relating to the influences described above. The two dominant areas of focus were ecology and flooding (reviewed in Sections 2.1.2 and 2.1.3). Interestingly, the stakeholders also commented on the loss of sediment, through hillslope erosion, as a significant impact on agriculture within their catchments. Similarly to dredging, soil loss from agricultural land use has seen an increase in media and professional attention (e.g. ADAS, 2016; Monbiot, 2015).

The importance of incorporating hillslope soil erosion into intermediate-scale reduced-complexity cellular models of sediment dynamics has been recognised within academia. For example, Coulthard *et al.* (2012a) states there is considerable 'common ground' with Soil Erosion Models (SEMs), and to date, there has been limited collaborative cross-disciplinary research. Therefore, in the future it will be important for the two research communities, soil erosion and in-channel cellular dynamics modellers to *'continue to exchange ideas and compare and co-evaluate models'* (Coulthard *et al.*, 2012, p. 1054). This emphasises the importance of interdisciplinary and transdisciplinary research in encouraging the 'breakdown' of disciplinary 'barriers' in catchment science and thereby increasing the quality of the research produced. The final impact described the negative effect of fine sediment as a pollutant on riverine ecosystems. This supports the findings of several studies suggesting that increased fine sedimentation is degrading riverine habitats in the UK (see: Newson and Newson, 2000; Hendry *et al.*, 2003; Gido *et al.*, 2010).

The literature review identified that to date, there has been limited uptake or use of research developed cellular models of sediment dynamics by river management practitioners (Section 2.2.2). In the requirements analysis, a diverse range of potential applications were described by the stakeholders. For example, the stakeholders suggested that a reduced-complexity cellular model could assist with decision-making, cost-benefit analysis, scenario planning, understanding the natural processes, and stakeholder engagement and communication. The stakeholders articulated that the potential to understand natural processes was very important, as currently they have limited knowledge of the sediment dynamics within the rivers they manage. The stakeholders used phrases such as: *'we tend to look at sediment when it enters the watercourse, but we have no idea where it is going to end up'* and *'we need a model… to show how a whole catchment works'*. This important finding supports the identified knowledge exchange 'paradigm lock' described in Section 2.1.4, and the limited uptake of research-developed models by practitioners. Additionally, this suggests that the fundamental modelling approach adopted within this thesis was successful as the stakeholders identified a vast array of potential applications. Finally, as mentioned at the end of the previous Chapter, this supports the recognition of Brasington and Richards (2007) and Keesstra *et al.* (2014) for the requirement to develop more intermediate-temporal and spatial-scale models relevant to river management practitioners.

This is further supported by the other model applications identified by the stakeholders in decision—making and in communicating with stakeholders. For example, the stakeholders suggested the model could be used to inform where '*the best bang for your bucks is'*, as well as being able to communicate visually how these systems are changing through time. This finding is consistent with Tucker and Hancock's suggestion that these models can provide *'a powerful stimulus to the imagination and enhance our ability to interpret the landscape'* (Tucker and Hancock, 2010, p. 30). The stakeholders described the *'power'* of having visual modelled outcomes, which are *'engaging'* to bring other stakeholders on side. This was reinforced by the results to the questionnaire, in which all of the stakeholders involved in the study selected 'maps' as most useful output for river management. The raw output from the model in terms of 'figures' made up less than 1% of the combined total selections. Therefore, the visualisation and communication of the data generated by models should be an important consideration. Finally, the stakeholders suggested cellular models of sediment dynamics are a *'step up'* from current practice using *'tangible scientific output'*, further supporting the idea that this type of model is not currently widely used within river management.

These findings suggest cellular models of sediment dynamics could be a new method for promoting knowledge exchange, as they act as a 'delivery mechanism' for knowledge, ensuring that the best available science is used to inform the decisions made. This finding was reinforced by the results to the questionnaires, where the majority of stakeholders (60%) considered 'All stakeholders' to be the target audience for model outputs. Surprisingly, only 13% of selections were made for the general public. This could be a result of the definition of stakeholders used in this research, whereby members of the public who have a valid interest in an issue are considered to be stakeholders

(Section 2.3.1). This suggests that the use of modelling for general education of the public was not a priority for the stakeholders.

The third overarching theme was model characteristics and this was split into the two themes of usefulness and usability. The usefulness theme focussed on stakeholders' views on why models were not being used. One of the stakeholders suggested this was due to models tending to focus on *'theoretical'* and not *'relevant real world'* applications. This is a potentially important finding relating to why many research-developed models are not used by practitioners. This will be explored later in this chapter through a discussion of the importance of developing models or tools for a specific target audience. The sub-theme of usability refers to a number of 'critical' model considerations absent in the development of most research models; these include: data requirements, ease of use, user-interface, model flexibility and effective visualisation of outputs. These results support those considerations identified by Lynam *et al.* (2007) and reviewed in Section 2.2.

A surprising finding was the number of references for the importance of recognising and communicating the limitations of models (Refs = 29) compared to the ease of use (Refs = 27). This could explain a reluctance by stakeholders to use models, as one stakeholder reflected *'…you feel disingenuous if you are presenting something you do not understand completely'*. An aim of PM processes can be to break down this type of 'barrier' to model uptake, by encouraging a two-way process of knowledge exchange, as well as creating an environment for social learning to occur (Bots and van Daalen, 2008).

These results are supported by the questionnaire findings. For example, the ease of use and model abilities were the two highest ranked model factors. The questionnaire results also showed that despite the majority of the stakeholders not using a model within the past year (59%), 74% of stakeholders selected that either a 'Small selection of management stakeholders', 'Management stakeholders' or 'All stakeholders' should be responsible for running the model. This indicates that the stakeholders are open to using these types of models to help inform river management decisions. However, this will require a significant change in the culture and working practices of the stakeholders in order to see increased direct use of modelling and tools. The required changes will explored in Section 6.2.3.

This section has discussed the results generated in the requirements analysis sessions. These results have provided a number of useful insights into the requirements of river management practitioners. In particular, the requirements analysis has identified 21 human and natural influences on sediment dynamics, 13 potential applications, and 11 model characteristics. These results may help to target future priority areas for geomorphological research. Additionally, these findings support the decision to adopt a fundamental model structure as the stakeholders recognised the potential contribution of reduced-complexity cellular models of sediment dynamics to river management. As described earlier in Section 4.2, due to the number of influences and applications, a simplistic conceptual model was created. The conceptual model comprised of a few critical model components identified through the requirements analysis (Figure 4-14), and enabled the participants to feed into the development of the draft model. The methods selected for the co-designing sessions were designed to empower the stakeholders to make decisions through prioritising the influences and applications.

6.1.2. Co-designing and the draft model

This section briefly discusses the results from the co-designing session and how they were utilised in the development of the draft model. The purpose of these sessions was to refine and prioritise the requirements of river management practitioners when creating and using a cellular model of sediment dynamics; the second part of Objective 3.A.

Interestingly, the only influence that all stakeholder groups considered to be an intrinsic component in the model was 'spatially distributed precipitation'. This was in recognition that over entire catchments, precipitation can vary significantly and was an important 'trigger' in mobilising and transporting sediment. The second overall highest ranked influence was 'land cover – agriculture'. This again was not a surprising result and is likely due to the composition of the groups (e.g. the Environment Agency, Natural England and the Rivers Trusts) and their ability as river management practitioners to influence land management decisions through policy and schemes (e.g. Higher Level

Stewardship (HLS)). As mentioned in the previous section and in the literature review (Section 2.1.2), the influence of in-channel barriers on sediment dynamics is a critical issue for river management. Therefore, the ranking of in-channel barriers as the third most important influence is consistent with this body of research.

Soil characteristics and geology were the next two important model characteristics identified by the stakeholders. In the requirements analysis, these characteristics were only briefly referred to (Refs = 2 and 2). This finding emphasised the importance of recognising that in PM processes stakeholders may not refer to all the critical model componants. Therefore, in order for the developed model to be scientifically sound and defensible requires input from the researcher. This supports the recognition of Voinov and Bosquet (2010) that although the stakeholders may drive the participatory process, the model should be scientifically defensible if it is going to be used in decision-making. The lowest ranked parameters of 'snowmelt' and 'tourism' were excluded by all of the stakeholder groups. This was due, in part, to the stakeholders noting that these would be too difficult to include in the model based on their knowledge of the available data, or the impact on sediment dynamics would be lower than the other influences.

The second activity in the co-designing sessions required the stakeholders to prioritise the potential applications of the model. The top two ranked applications of 'understanding the impacts of management' and 'prioritisation of interventions and management options' were not surprising based on the composition of the stakeholder groups. In particular, as mentioned earlier, all of the groups comprised of stakeholders that have management or policy roles at the river catchment-scale. One of the additional applications suggested by the Camel group was 'ecosystem services'. This could suggest an increased awareness of its importance within governmental organisations (see: DEFRA, 2014a). However, the ecosystem services application was only mentioned in this catchment, and was ranked fourth overall. This could indicate that the ecosystem services approach to managing river systems has not yet been embedded within river management organisations. On the Spey, 'impact of abstractions' was added, as SEPA was experiencing an increase in the number of applications. Therefore, the stakeholders were interested in being able to model the impact of abstractions. This is an important finding as it suggests that local priorities can influence the prioritisation activities. More specifically, this supports the methodological decision to use multiple stakeholder groups, as to a degree, this can help mitigate this issue by allowing common priorities amongst all the groups to be identified.

The final activity was the presentation and discussion of the simplistic conceptual model. The stakeholder groups provided feedback under three themes: applications, processes, and data availability. The first theme focused on the potential applications of this type of model by identifying how it could be used to inform their work. In particular, the stakeholders recognised the potential to use the model to: (i) target interventions, (ii) provide a baseline, and (iii) understand the natural system. An important component to achieving this, was the ability to influence the type and condition of the land cover. These results further support the finding that these models could be a useful tool in river management.

The stakeholders discussed the incorporation of several other parameters, such as land drains, invasive species, and tides, which could all influence sediment dynamics. Interestingly, the stakeholders as a group debated these in the session, and decided that incorporating these processes in the model would be too difficult. For example, the stakeholders stated that currently there is insufficient data on the location and spread of invasive species, and that it would be difficult to incorporate this into a catchment-scale model. Similarly, on the Bristol Avon, when a stakeholder suggested the inclusion of the tidal influence, the group concluded that it was important to keep the model as simple as possible. This type of debate and discussion supports the hypothesis that social learning can be achieved through PM processes (Campo *et al.*, 2010). This was particularly interesting as during these sessions the decision-making power had been transferred from the researcher to the stakeholders. Therefore, the debates and exchange of knowledge during these sessions were particularly useful in shaping the developed model. For example, in the Camel catchment, when the stakeholders were shown the Land Cover Model (LCM) 2007 data being used in the conceptual model, a stakeholder from Natural England suggested they had access to more detailed land cover data, referred to as Single Farm Payment Scheme (SPS), which could be incorporated into the model. Subsequently, this was included in the model and provides a more accurate representation of the land cover. This important finding demonstrated a key type of knowledge held by stakeholders; an awareness of data resources.

Table 4-6 showed how the information gathered during the co-designing sessions was used to refine the conceptual model (Figure 4-16), and included all the material discussed in this section. Before moving onto the next section, it is important to note that the stakeholders did not directly choose the methods for incorporating the process in the draft model. These processes were selected by the researcher through a critical evaluation of existing methods. The key principle followed in the development of the model was to not create new methods for incorporating the processes and parameters in the model. Instead, processes from other models would be adapted to operate in the cellular model developed through the PM process. This principle was adopted to reduce the amount of time required to develop the cellular model. However, a new method was required to incorporate in-channel barriers as the researcher's search of the literature did not reveal any suitable approaches; this will be examined in the next section.

6.1.3. Model demonstration and the revised model

This section will discuss the results from the model demonstration session and reflect upon the processes used in the revised model (Objectives 3.A and 3.B). Some of the model parameters and characteristics described by the stakeholders earlier in the PM process were considered to be technically difficult, and therefore, inputs and processes such as groundwater and rainfall radar data were not incorporated. These decisions inevitably removed decision-making power from the stakeholders, and as a result, it could be argued that the developed participatory process does not achieve the higher rungs on Arstein's ladder of citizen participation. However, as Bailey and Grossart (2006) suggest the level of participation should dependent on the context of the situation. Consequently, it could be argued this is an acceptable decision by the researcher given these circumstances. Interestingly, a critical part of the process was the communication of the modelling decisions made by the researcher, rather than the direct decision-making, emphasising the importance of 'co-producing' the model.

Linked to this was the most important requirement from the stakeholders, the ability to 'easily' manipulate the model inputs beyond their 'baseline' conditions. As a result, the ability to change inputs was incorporated into the developed model through a variety of different methods. To change the land cover, two tools were created which allowed the user to change the input land cover and condition. The strength of this approach is that it allows the stakeholders to begin to 'play around' and understand through visuals, how changes to the land cover will influence the surface runoff, discharge, and sediment dynamics. Research-developed reduced-complexity models of sediment dynamics do not usually include this functionality.

At the time of these sessions, incorporating the impact of climate change became an important factor for some of the stakeholders (Refs = 5). This was surprising, given that 9 months earlier in the co-designing sessions, climate change had been one of the lower ranked influences (Rank = 5). Perhaps, this could be the result of the publication of the IPCC report (Intergovernmental Panel on Climate Change, 2014), and the ongoing media coverage of the Somerset Levels flooding (Schaller *et al.*, 2016) in the months leading up to these sessions. The stakeholders discussed modelling the effects of climate change within the model and concluded this would be difficult and time-consuming. Instead, the stakeholders identified a simplistic method could be to create a tool to scale up or down a historic precipitation record. This was a reflection of the stakeholders involved in the PM process, as they recognised models are imperfect and approximations of reality. Instead, the stakeholders were interested in being able to test the effect of increasing rainfall on the different modelled processes. As one stakeholder on the Taw commented *'the whole point is just having that ability to look at different scenarios'*.

In the co-designing sessions, the stakeholders prioritised the ability to add and remove in-channel structures. A review of literature did not reveal any suitable methods for simulating the impact of in-channel barriers within a cellular model of sediment dynamics. Therefore, the researcher developed a simplistic method, whereby the user could input an in-channel barrier in the model creating an area of 0^{o} slope and block the passage of sediment. This created a 'vacuum' at that point in the river withdrawing sediment from the system. The accuracy or validity of this approach has not been tested as a part of this thesis. However, as described above, the stakeholders appeared to be less concerned with model accuracy. Instead, the stakeholders focused on 'ease of use' and the potential to use the model to communicate visually and conceptually how sediment was moving within the system. Therefore, the developed approach could be considered a valid method to demonstrate visually the influence of an in-channel barrier. Unsurprisingly, the hydromorphologists within the groups were concerned with accuracy of the developed model if it was to be used for regulatory purposes. Therefore, the hydromorphologists suggested there would need to be a comprehensive evaluation conducted before they would consider using the model for this purpose.

The influence of groundwater was referenced only in the Bristol Avon catchment. A potential explanation could be the presence of a stakeholder from a water company or the physical characteristics of the catchment. This finding supports an important issue described in the literature that the composition of groups will influence the results generated (Broad *et al.*, 2007). Therefore, it is not surprising that the water company with groundwater interests questioned how this would be incorporated into the developed model. In the developed and implemented PM process, multiple stakeholder groups were used; this finding further supports this methodological decision in two ways. Firstly, the perspectives of a wide range of stakeholder groups was incorporated into the process, i.e. some stakeholders were present in only one or two of the groups. Secondly, this ensured that the views of unique stakeholders did not overpower the general requirements and priorities of the stakeholder groups. Consequently, the common themes emerging through this research could be reflective of the general requirements of river catchment management practitioners in the United Kingdom. However, it is important to recognise that there will be differences between most catchment stakeholder groups due to unique local challenges and the different organisations involved.

One significant limitation of the developed model and associated tools was that they were built within the popular commercial GIS package of ArcGIS (see: ESRI, 2014). The researcher had hoped that this would make the model significantly more useable for the stakeholders. The researcher had assumed at the start of the process that the stakeholders involved would have GIS skills and access to the required software. This was proved to be incorrect, and only became apparent in the model demonstration sessions with the stakeholders commenting *'it would be good if it was outside of*

ArcGIS' and *'output data that MapInfo could use'*. Due to the stage of the process at which this was discovered, there was no time to redevelop the model outside of ArcGIS. However, in hindsight, the prior knowledge, abilities, and access to tools should have been assessed during the requirements analysis at the start of the process.

The stakeholders also identified a need for instructions, and an *'idiot's guide'* on how to use the model. Neither of these had been built into the plan of the thesis, however, as the aim of the process was to develop a model that could be used by stakeholders, this was considered to be important. Therefore, basic instructions and instructional videos were created. At the time of writing this thesis, these will need to be revised given the iterative nature of the model's ongoing development.

The results from the PM process discussed in the last three sections support the acknowledgement that interdisciplinary and transdisciplinary research within fluvial geomorphology can result in the recognition of important relationships, connections, and gaps in knowledge that would have otherwise been missed (as recognised by Rice *et al.*, 2010; Meitzen *et al.*, 2013; Vugteveen *et al.*, 2014). This is reflected in this research by the diverse range of interests and knowledge the stakeholders brought to this PM process. Initially, the focus of the process was to create a cellular model focusing on in-channel sediment, but from the very start the stakeholders argued the model should consider aspects of the entire hydrological and sediment system. In the future, a more integrated approach across disciplines could focus on practical applications and result in innovative simplistic models or tools which begin to answer the 'interdisciplinary' questions of river management practitioners.

6.2. Participatory modelling process evaluation

This section presents the results from the PM process evaluation described in Section 3.3. The aim of this evaluation is to provide sufficient information to satisfy Objectives 4.A and 4.B. These are:

4. Critically evaluate the developed participatory modelling approach as a methodology for:

A. Engaging with stakeholders in model development to reduce unused research models, improve model quality, acceptance of the model, and integration of the model with stakeholder management processes;
B. Promoting knowledge exchange and social learning between fluvial geomorphologists and river management practitioners;

An important component of the evaluation was to assess the solutions implemented in the PM process to address the issues identified in the literature review (Table 3-3). In the following three sections, the results from the online questionnaire (Part one of the Protocol of Canberra (PoC)), follow-up telephone interviews (Part two of the PoC), and the researcher's reflections on the process (equivalent of the Designer's Questionnaire) will be presented.

6.2.1. Online questionnaire

The results from the online questionnaire are grouped into three parts: (i) reflections on the process; (ii) outcomes from the process; and (iii) improving the process. Table 6-2 presents the stakeholders' responses to a number of statements reflecting on the PM process. Overall, all the stakeholder groups enjoyed taking part in the process (combined mean = 3.81/5), although there is some variation between the groups with a mean of 3.5 for the Bristol Avon and the Taw. All of the stakeholder groups strongly agreed (combined mean = 4.44/5) that the collaborative approach, like the one undertaken in this thesis, was a better way to design a useful model than traditional approaches (e.g. Decide Announce Defend (DAD)). Additionally, stakeholders agreed that they felt comfortable interacting and exchanging their views in the participatory process (combined mean = 4.19/5), and that their input into the participatory process was valued by the research team (combined mean = 3.88/5). Of all of the responses, only one statement received a disagree value (< 3) from a stakeholder, this was on the Camel for the statement relating to whether or not they considered that their input to the process was valued. The catchment mean for the Camel was a higher value of 3.5. There were no statistically significant ($p > 0.05$) differences between the responses by catchment.

TABLE 6-2: RESULTS FROM THE: 'TO WHAT EXTENT DO YOU AGREE WITH THE FOLLOWING STATEMENTS' QUESTIONS. THESE QUESTIONS USED A SCALE OF 1 (STRONGLY DISAGREE) TO 5 (STRONGLY AGREE). SE IS THE STANDARD ERROR OF THE MEAN.

Statement	Catchment	Min	Max	Mean	SE
I found the participatory modelling process enjoyable.	Bristol Avon (n = 4)	3	4	3.50	0.29
	Camel (n = 4)	3	5	4.00	0.41
	Taw (n = 4)	3	4	3.50	0.29
	Spey (n = 4)	4	5	4.25	0.25
	Combined (n = 16)	**3**	**5**	**3.81**	**0.16**
	$\chi^2(3)$		3.90		
	p =		0.27		
This collaborative approach is a more effective way to design a useful model than having modellers design alone.	Bristol Avon (n = 4)	3	5	4.00	0.41
	Camel (n = 4)	3	5	4.25	0.48
	Taw (n = 4)	5	5	5.00	0.00
	Spey (n = 4)	4	5	4.50	0.29
	Combined (n = 16)	**3**	**5**	**4.44**	**0.18**
	$\chi^2(3)$		4.43		
	p =		0.22		
I felt comfortable interacting and exchanging my views in the participatory modelling process.	Bristol Avon (n = 4)	3	5	4.25	0.48
	Camel (n = 4)	3	5	4.00	0.41
	Taw (n = 4)	3	5	4.25	0.48
	Spey (n = 4)	4	5	4.25	0.25
	Combined (n = 16)	**3**	**5**	**4.19**	**0.19**
	$\chi^2(3)$		0.37		
	p =		0.95		
My input into the participatory process was valued by the research team.	Bristol Avon (n = 4)	3	5	3.50	0.50
	Camel (n = 4)	2	5	3.50	0.65
	Taw (n = 4)	4	5	4.50	0.29
	Spey (n = 4)	4	4	4.00	0.00
	Combined (n = 16)	**2**	**5**	**3.88**	**0.22**
	$\chi^2(3)$		3.60		
	p =		0.31		

For the last two statements, stakeholders were given the opportunity to provide a more detailed response through open ended questions. In the first, stakeholders were asked whether they felt this was, or was not, the case. Six of the 16 respondents provided a response to this question. Three of these commented that they felt comfortable because they were working with an existing group of stakeholders who had worked together before.

'Our working group has worked together for some time, so the discussions tend to be open anyway.'

'It was probably made easier for me as I knew most participants from previous contact over the last decade, and have spent quite some time working in the area in a related field of expertise – agronomy.'

'I found this a comfortable process because I was already familiar with participating in workshop type activities with this particular group of people.'

Of the three other responses, the first suggests that this was because *'…generally what was important was that Nick* [the researcher] *was very attentive to the views of the participants…'*. The second reflects on particular exercises, such as the bulls-eye prioritisation activity making it *'easier to express my views'* than the group discussions, which at times were dominated by the more *'knowledgeable stakeholders'*. The final response commented that despite enjoying the last session, they were disappointed with the *'engagement since the last meeting'*. The second open question reflected on how the stakeholders felt their input into the participatory process was valued by the research team. Two stakeholders stated that they did not feel they contributed as much to the process as others, but that their participation in the project was valued by the research team.

'I don't feel that I contributed as much as other more knowledgeable participants, and was unable to come to some of the sessions, but I always felt included by the research team.'

'I'm not sure how useful my own specific input was, but I believe that the research team appreciated me giving my time to the project.'

The way in which the researcher had *'…captured everyone's views from the previous sessions and incorporated them into the next iteration of the model…'* was highlighted in one of the other responses.

Figure 6-1 shows the activities the stakeholders enjoyed in the PM process. The combined results show that the most popular activities were the bulls-eye diagram (24%) and the group discussion (24%). There is some variation between catchments. For example, 27% of selections in the Taw catchment were for the video demonstration and discussion in the model demonstration, whereas in the Camel 27% selected the conceptual model discussion in the co-designing session. However, in all of the catchments the bulls-eye and group discussion activities retain a high percent of the total selections (17-36%). The least selected activity was the online engagement activities via the ENGAGE model website (7% - combined selections). In addition to being able to select which of the activities stakeholders enjoyed taking part in, there was an optional follow-up open question asking stakeholders to provide details of which particular activities they enjoyed. Stakeholders provided a range of responses, for which, three out of the five responses referred directly to the bulls-eye diagram. The quotes below provide context as to why stakeholders particularly enjoyed this activity.

‘Bullseye diagram - visual representation really clarified what was important.’

‘Prioritising model inputs using a bullseye diagram - good to have an input into model inputs and a simple effective way to prioritise them.’

‘Prioritising inputs; as we were a diverse group (all environmental but different focus) and this can raise awareness of other items.’

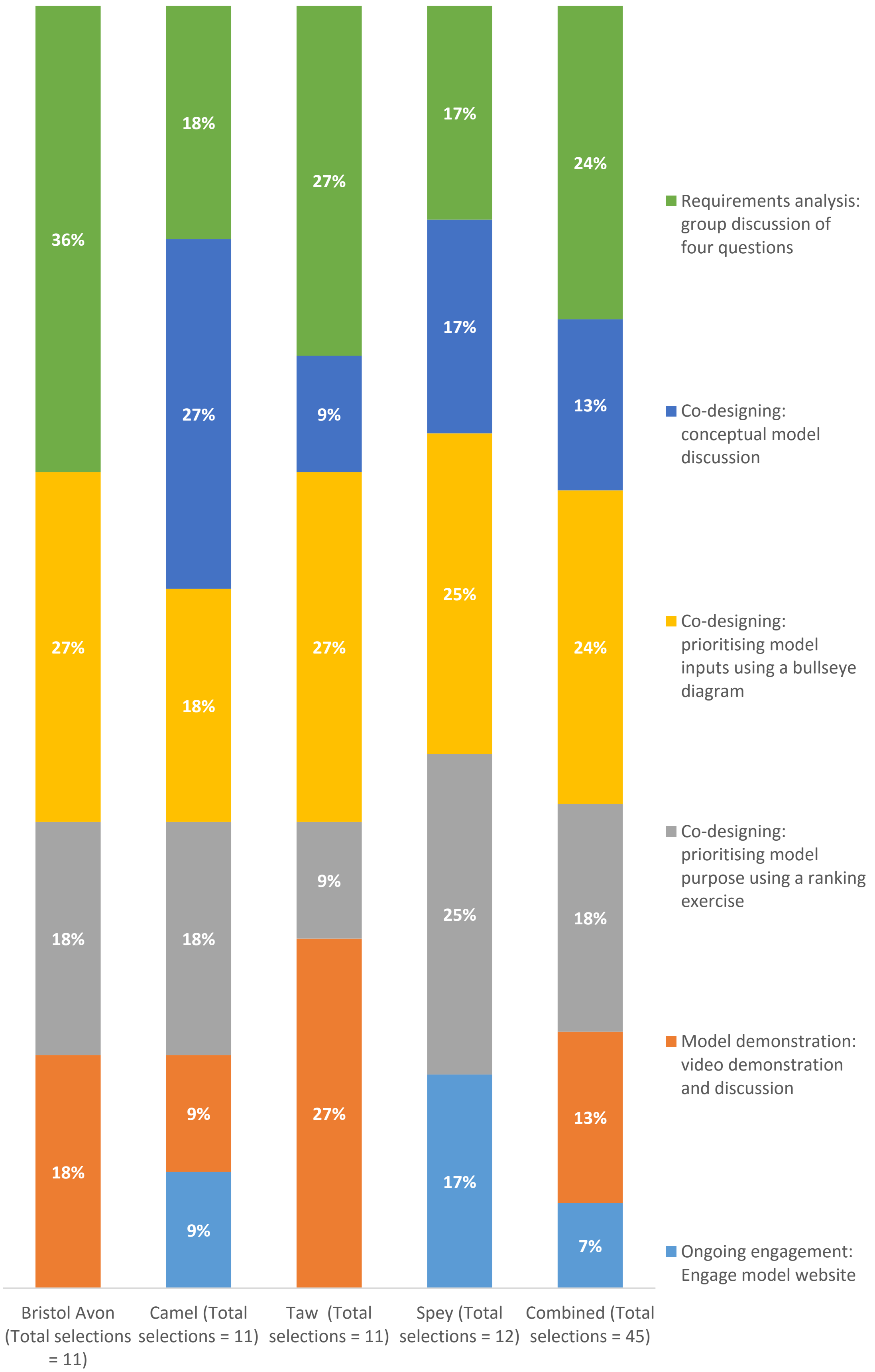


FIGURE 6-1: COMBINED AND INDIVIDUAL CATCHMENT RESULTS TO THE QUESTION: 'WHICH ACTIVITIES IN THE PARTICIPATORY MODELLING PROCESS DID YOU ENJOY?'. NOTE: STAKEHOLDERS WERE ABLE TO SELECT MORE THAN ONE OPTION.

The next part of the online questionnaire reflected on the outcomes of the PM process. In particular, this relates to whether or not stakeholders thought they had learnt anything through participating in this process, and if they felt the process was useful to their work. The combined results show that for each of the statements, stakeholders agreed that they felt their knowledge had increased in each of the areas (combined means = 3.5, 3.69 and 3.81/5). In some of the catchments the stakeholders disagreed, in particular this was the case in the Bristol Avon and the Camel, where a stakeholder selected a value of 2. However, there were no statistically significant ($p > 0.05$) differences in the responses between the catchments (Table 6-3). As with previous questions, there was an opportunity for stakeholders to provide more detailed feedback through an open question, one stakeholder provided a response:

> *'I think it was how the whole thing worked together rather than individual elements. I am fairly competent in soils, erosion, hydrology, etc so that was nothing new, but the way the model worked was new to me.'*

TABLE 6-3: RESULTS FROM THE: 'TO WHAT EXTENT DO YOU AGREE WITH THE FOLLOWING STATEMENTS' QUESTIONS. THESE USED A SCALE OF 1 (STRONGLY DISAGREE) TO 5 (STRONGLY AGREE). SE IS THE STANDARD ERROR OF THE MEAN.

Statement	Catchment	Min	Max	Mean	SE
My understanding of sediment dynamics has increased through my involvement in this process.	Bristol Avon (n = 4)	2	4	3.00	0.41
	Camel (n = 4)	2	4	3.25	0.48
	Taw (n = 4)	3	5	3.75	0.48
	Spey (n = 4)	3	5	4.00	0.41
	Combined (n = 16)	**2**	**5**	**3.50**	**0.22**
	$\chi^2(3)$		2.862		
	p =		0.413		
I have a better understanding of computer modelling through my involvement in this process.	Bristol Avon (n = 4)	3	4	3.25	0.25
	Camel (n = 4)	3	5	4.00	0.41
	Taw (n = 4)	3	4	3.50	0.29
	Spey (n = 4)	3	5	4.00	0.41
	Combined (n = 16)	**3**	**5**	**3.69**	**0.18**
	$\chi^2(3)$		3.30		
	p =		0.348		
My understanding of cellular models of sediment dynamics has increased through my involvement in this process.	Bristol Avon (n = 4)	2	5	3.75	0.63
	Camel (n = 4)	2	5	3.75	0.63
	Taw (n = 4)	3	5	4.00	0.41
	Spey (n = 4)	3	4	3.75	0.25
	Combined (n = 16)	**2**	**5**	**3.81**	**0.23**
	$\chi^2(3)$		0.257		
	p =		0.968		

Table 6-4 shows a large variation in the responses between stakeholders and catchments on whether they thought the process had been useful to their work (combined mean = 5.75/10). For example, the Spey has a higher mean of 7 compared to the Bristol Avon with a mean of 4.75. However, there were no statistically significant ($p > 0.05$) differences between catchments. As in previous questions, stakeholders were given the option to provide a qualitative response. In total, nine of the stakeholders provided a response. One explained how they felt that being involved in the process had improved their understanding of sediment dynamics in their catchment:

'…it aided my understanding of some similar sediment modelling work our catchment partnership had commissioned at around the same time, and how sediment transport in our catchment may function.'

The remaining responses referred to the difficulty in answering this question at this stage in the process as they had not yet used the model in their work. Below are some of the quotes that reflect this finding:

'Hard to say at this stage until the model is complete and we are using it.'

'Whilst I have not used this, it has made sure modelling is perhaps more in my thoughts than previously. It is a useful resource to inform future projects...'

'This model could be useful for my work in the future but so far it has not had an impact'

'I have a greater awareness of how models work and although I have not incorporated this into my work yet, I think it could be valuable in the future.'

'It is another example of how wider data and modelling can bring evidence to support current or future work.'

TABLE 6-4: COMBINED AND INDIVIDUAL CATCHMENT RESULTS TO THE QUESTION: 'HOW USEFUL TO YOUR WORK HAS YOUR PARTICIPATION IN THE PARTICIPATORY MODELLING PROCESS BEEN?'. THIS USED A SCALE OF 1 (NOT AT ALL USEFUL) TO 10 (VERY USEFUL). SE IS THE STANDARD ERROR OF THE MEAN.

Catchment	Min	Max	Mean	SE
Bristol Avon (n = 4)	3	7	4.75	0.85
Camel (n = 4)	2	7	5.25	1.11
Taw (n = 4)	2	9	6	1.47
Spey (n = 4)	3	10	7	1.47
Combined (n = 4)	**2**	**10**	**5.75**	**0.61**
	$\chi^2(3)$			2.417
	p =			0.49

The final part of the online questionnaire results relates to how the PM process could be improved (Figure 6-2). Respondents were able to select more than one answer in this part of the questionnaire, and therefore, the term selections is used. Interestingly, the total number of selections was low (total selections = 19) compared to the previous questions in this format (e.g. Figure 6-1, total selections = 45). Furthermore, the respondents were required to select an option in order to progress. The most combined popular selection was 'Other' (42%), followed by more sessions (26%). Increased communication and improved description of the process were the least selected (16%). There is some variation between the catchments, for example, in the Camel the most popular selection was increased communication (50%), whereas in the Spey the most popular was more sessions (50%). If stakeholders selected 'Other', then they were able to provide a qualitative response. Stakeholders suggested a broad array of things that could have improved the process, with no clear pattern emergent from the responses.

'I think if you work with EA and NE nationally, then you would have more chance of it becoming normal practice.'

'More local examples of how it can be used.'

'Clear identification of how the model can be used and who the possible users are'

'Results ground truthed and percentage reality stated [referring to the accuracy]*'*

'More feedback on progress'

'Perhaps an opportunity to contribute to the process through online tools.'

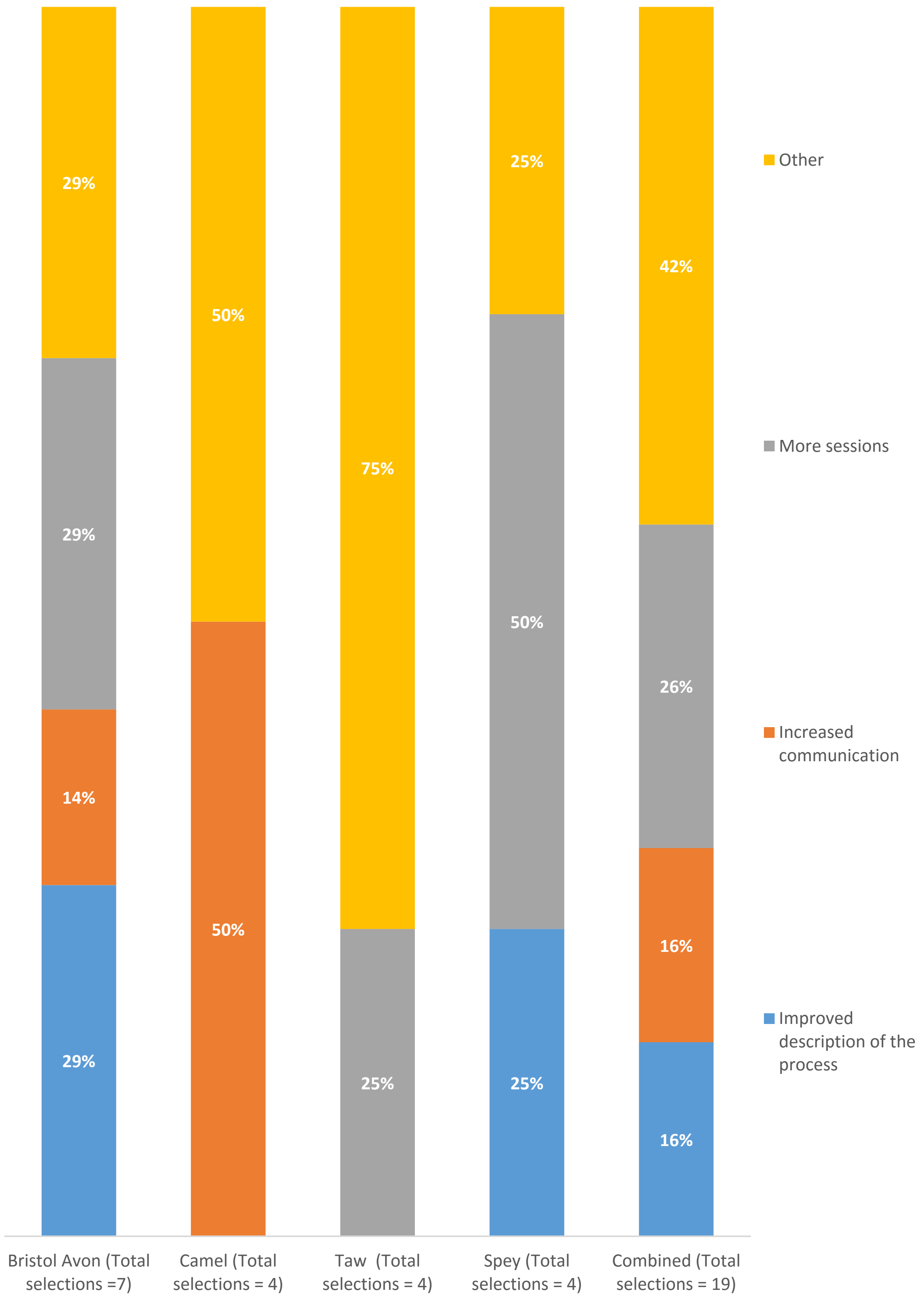


Figure 6-2: Combined and individual catchment results to the question: 'How do you think the participatory modelling process could be improved?'. Note that stakeholders were allowed to make more than one selection.

Figure 6-3 shows that some stakeholders thought that future exercises should include farmers (35% of selections) and flood risk practitioners (32% of selections). There is some variation between the catchments, for example, in the Bristol Avon and Camel, 44% of selections were farmers, compared to 27% and 20% on the Taw and Spey. The Camel is the only catchment to select the option that homeowners should have been included in the process (22%). As with the previous question, if stakeholders selected 'Other', there was a box for stakeholders to provide a qualitative response. The additional suggestions suggested by the stakeholders were:

- Ecologists
- Water companies
- Archaeologists
- All parties that are considered during planning permission
- Local authorities
- Geomorphologists
- Land managers
- None

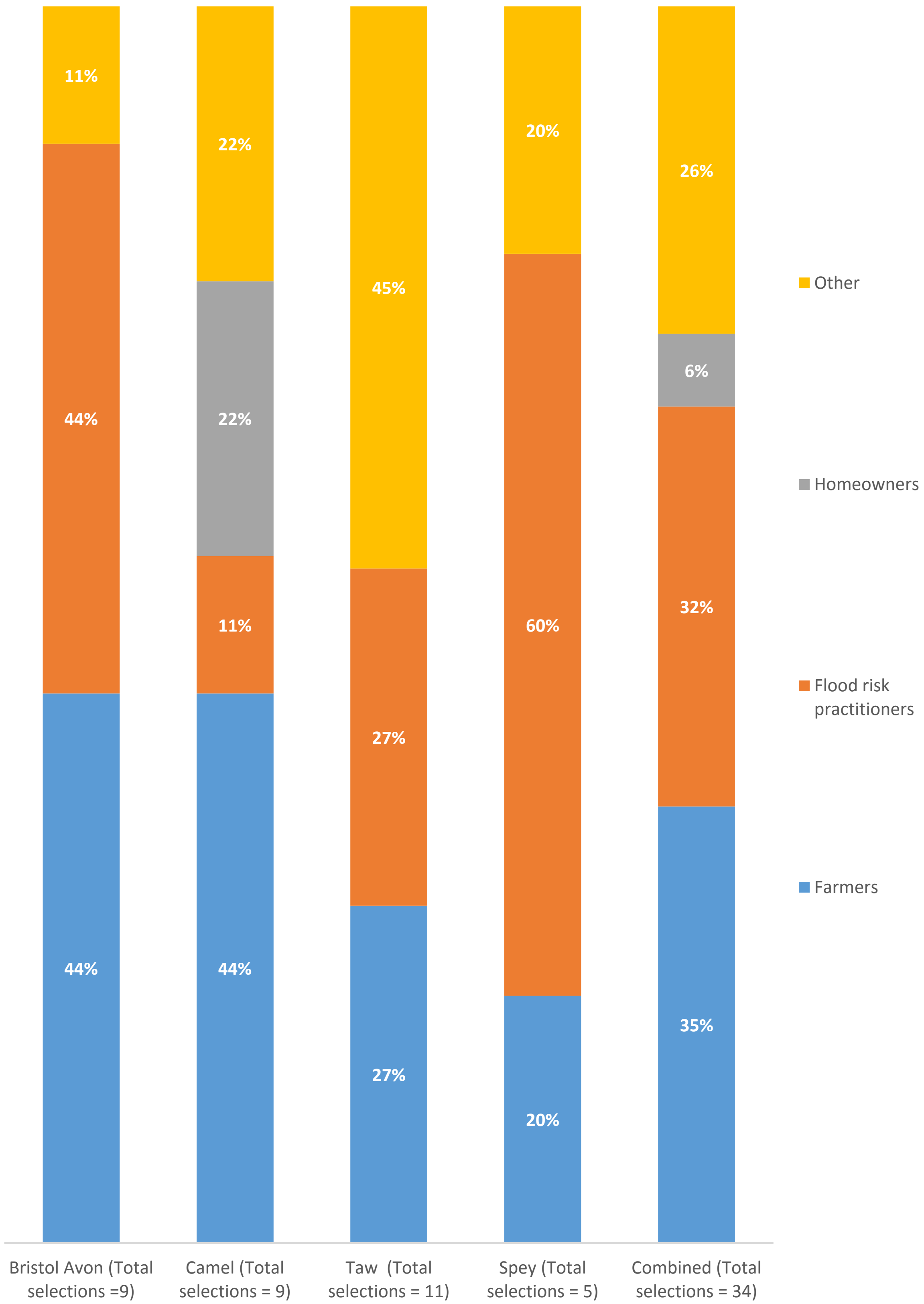


FIGURE 6-3: COMBINED AND INDIVIDUAL CATCHMENT RESULTS TO THE QUESTION: 'WHO ELSE DO YOU THINK SHOULD HAVE BEEN INVOLVED IN THE PARTICIPATORY MODELLING PROCESS?'. NOTE THAT STAKEHOLDERS WERE ALLOWED TO MAKE MORE THAN ONE SELECTION.

At the end of the questionnaire there was a space for stakeholders to add any other thoughts on their participation in the process. Some stakeholders suggested that the main obstacle to improving the process in their group was getting the group together to participate in the sessions.

> *'…I think the main barrier for our group was finding the time for people to get together to participate… We tried to incorporate sessions into our steering group meetings but often overran our agenda, and when we organised separate meetings, people sometimes found it difficult to justify the time, even though they thought it important to continue supporting the project.'*

Other responses indicated that there was some anxiety with regards to the future of the model and whether or not it will be used.

> *'I am still not sure how we will actually use this model and who will support us after the modeller moves on. I suspect the model will be very useful providing the right people are trained to use it. Perhaps the Rivers Trust could do this on our behalf.'*

The online survey generated a number of areas and topics for exploration in the follow-up interviews. The questions asked in these interviews were based upon the analysis of the online questionnaire (Appendix C).

6.2.2. Follow-up interviews

In total, eight stakeholders were interviewed, the results of the thematic analysis of the transcripts is presented in this section. Four overarching themes and sub-themes were generated from the analysis; these are shown in Figure 6-4. Figure 6-5 shows a treemap of the number of times each of the themes and sub-themes were referenced in the transcripts. As mentioned previously, the total number of references will not equal the total of the overarching theme as some of the references may have been coded under several sub-themes. This section will explore each of the themes and sub-themes as well as provide extracts from the transcripts to support the analysis.

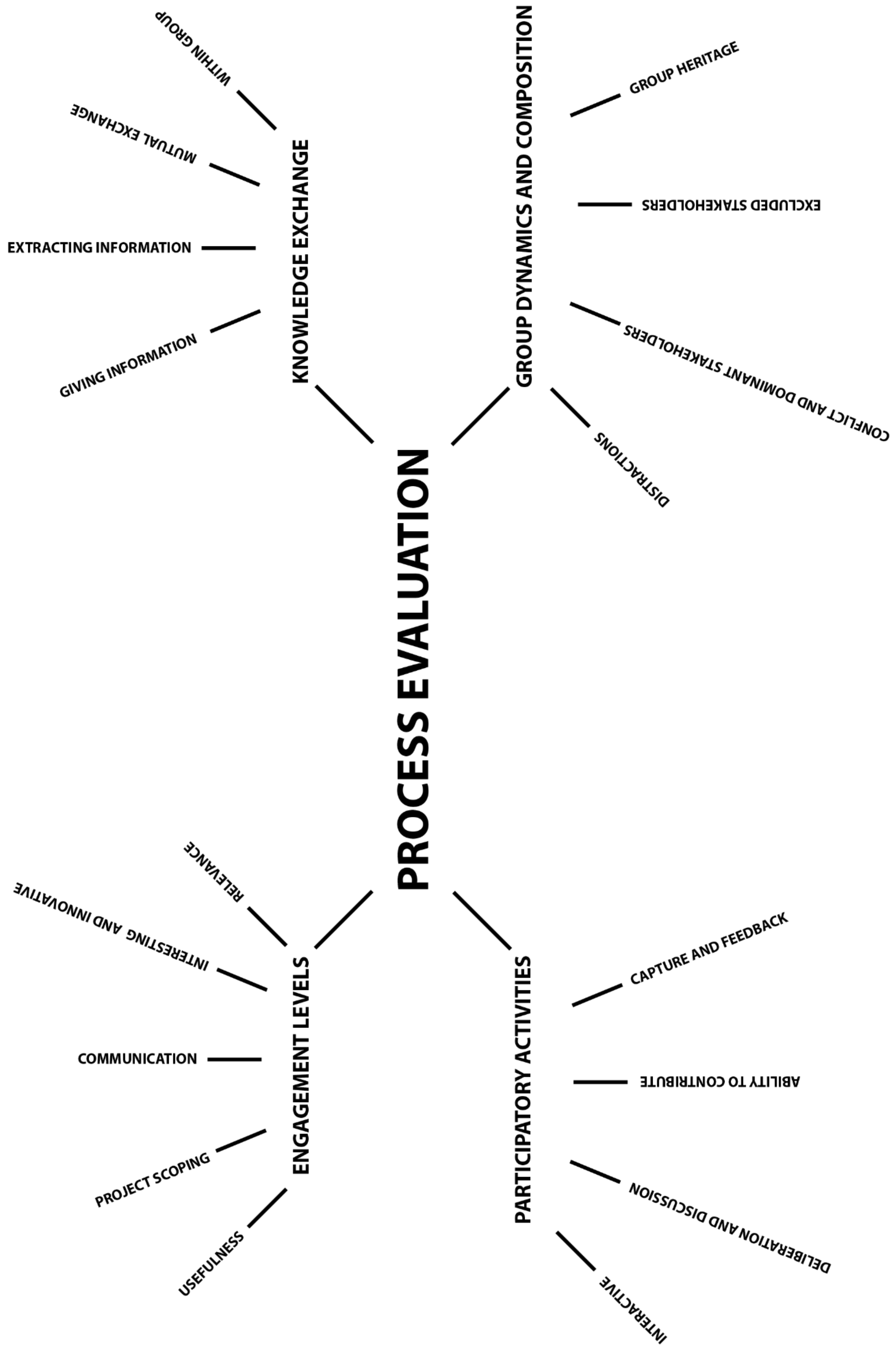


FIGURE 6-4: THEMATIC MAP OF THE PROCESS EVALUATION IDENTIFIED THROUGH THE CODING OF THE INTERVIEW TRANSCRIPTS.

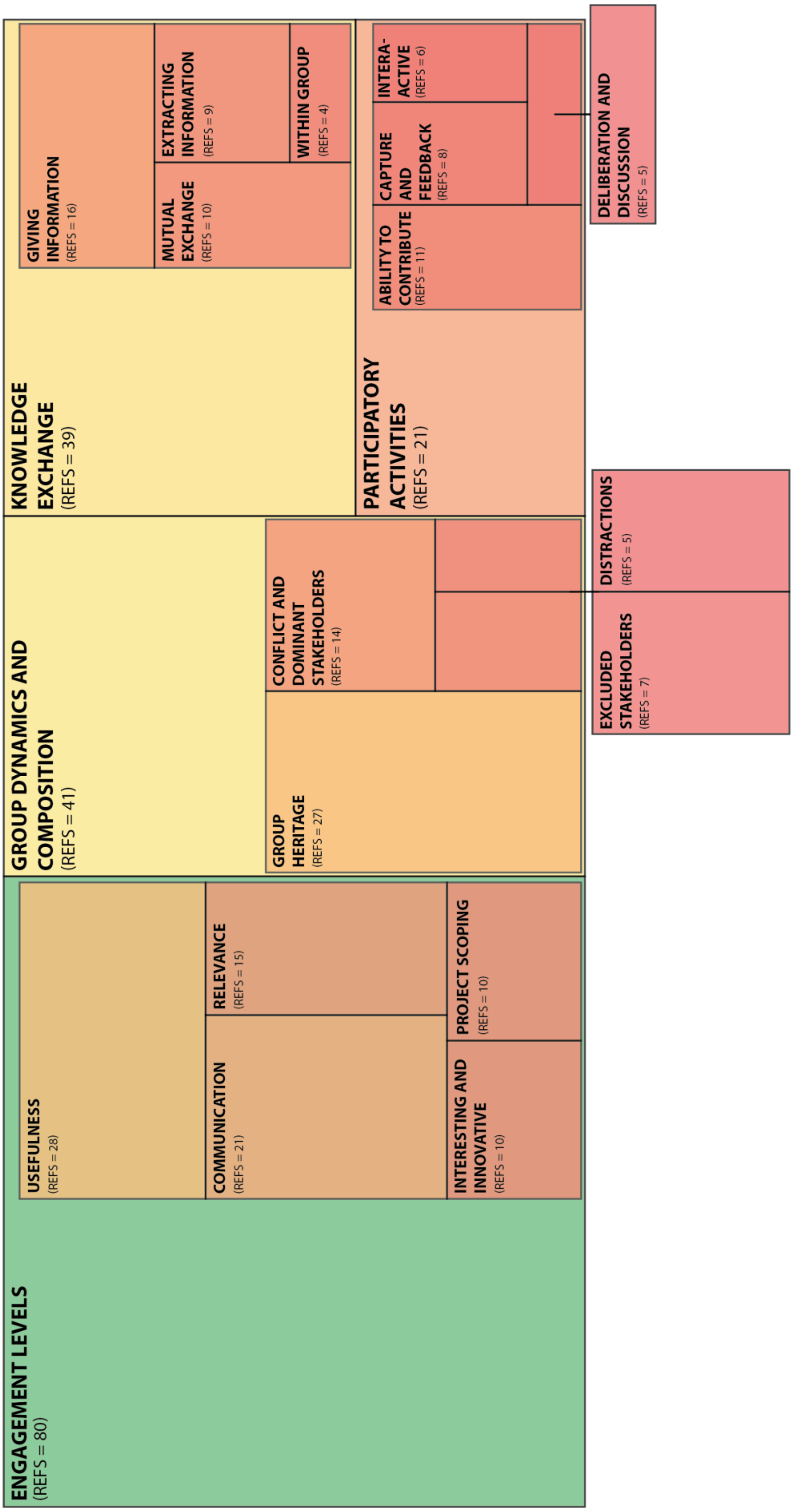


Figure 6-5: Treemap of the process evaluation theme and sub-themes from the thematic analysis of the process evaluation interviews. 'Refs' refers to the total number of coding references under each of the themes.

The engagement level theme reflects the stakeholders' opinions on the various factors that influenced their level of engagement in the PM process. The sub-themes reflect the mixed views of the stakeholders in relation to which aspects they felt went well, and what did not. Additionally, some of the stakeholders interviewed suggested methods to overcome some of the criticisms of the process.

One of the sub-themes related to stakeholders' opinions on the level of **communication** (Refs = 21) from the researcher throughout the process. None of the stakeholders interviewed believed that communication had been an issue. Many considered communication to have been at the right level and that the project could have over communicated, resulting in more stakeholders becoming disconnected from the process. In addition, several suggested that they thought it was more the other way around, and the researcher struggled to achieve the required engagement from them. The quotes below move through these points.

'I think the communication was maybe about right… you could have over communicated and put those people off more or you might have communicated more and got them on board more… You know there is nothing worse than communicating for the sake of communication. So I felt that when you did communicate with us, it was with some form of an update that was useful and you could see how you had moved on and where you were…' (Environment Agency, Bristol Avon)

'I thought it might have been an issue for you because we were not that easy to get responses out of. So I thought when you needed to and in the run up to giving a presentation there was good communication.' (Avon Frome Partnership, Bristol Avon)

'You have to develop the tool and unless you need input from us, apart from feeding back to us saying I am working on it, I am working on it. You know, there becomes a point at which there is only so much useful feedback you can give.' (Spey Catchment Initiative, Spey)

'You email from time to time and things are progressing. I have not really given it a second thought.' (West Country Rivers Trust, Taw)

Another of the sub-themes to come out of the analysis regarding engagement levels was the stakeholders' opinion of being involved in the process as being **interesting and innovative** (Refs = 10). This theme had two key aspects to it, the first, described below, relates to the stakeholders' opinion of the process and why they should be involved. The other important aspect relates to how the process is different to other types of work they are involved with, and how people within organisations tend to work in *'silos'*. This was an opportunity for stakeholders to work together on a problem.

'…the prospect of what you were doing was actually quite exciting. The potential benefits and information we could gleam from it. It was a no brainer to be involved.' (Spey Catchment Initiative, Spey)

'…they work on their own things a lot of the time. So they become a specialist and they build up a lot of knowledge, but I do not think we always get a chance to put that together in one overall picture, so perhaps that was one of those rare occasions where you actually have a chance to do that…' (Environment Agency, Camel)

A suggestion to improve the process came through under the sub-theme of **project scoping** (Refs = 10). This relates to the concept of a scoping session at the start of the process to:

- Set out the aims and objectives of the groups (i.e. what both sides want to get from being involved in the process);
- Lay out a project timeline, that works for both groups;
- Identify additional or more suitable stakeholders.

This was mentioned by several of the stakeholders as a way of improving engagement levels throughout the process.

'Goal setting and process setting. So that then we could have said every three months we are going to have a meeting from you or every four months and we would see your progress and you would see our progress.' (Bath and North East Somerset Council, Bristol Avon)

'If we had a really open session at the start, starting off with the group we had and saying who else would we need, and review that part way through.' (Environment Agency, Camel)

The **relevance** (Refs = 15) of the project to stakeholders' work was another of the sub-theme. Some of the stakeholders felt that the modelling was not that relevant to them. Therefore, some the stakeholders found their interest in the project was not as strong as others in the same group. This will be touched upon again later in this section.

'[I was] *not able to integrate it or apply it directly into my day to day work because I do not deal with sediment management.'* (Bath and North East Somerset Council, Bristol Avon)

Some of the stakeholders had the opposite opinion, whereby being involved in a PM process was, in their minds, linked to being beneficial to their work, and therefore engagement levels in the process increased.

'I think it is the enthusiasm of thinking 'oh wow' this could be really useful and it could really help. And as soon as you hit that target or that button. You will be engaged with people.' (Spey Catchment Initiative, Spey)

The stakeholders commented that the best way to use the model would be to have a 'host' organisation or person to be responsible for generating outputs for the group. This could be a result of the nature of the catchment partnership groups and the way they operate currently with a catchment 'host'. A catchment host is responsible for the ongoing administration of catchment based approach groups. This will be discussed at greater length in Section 6.3 in the discussion.

'I am slightly unsure at the moment how we will be able to use the tool… this could be actually something that [SEPA's Hydromorphology] *team that would almost take ownership of running it.'* (Spey Catchment Initiative, Spey)

The final sub-theme under engagement levels relates to the **usefulness** (Refs = 28) of taking part in the process. These quotes emphasise the importance of high levels of engagement in the process to create a useful model. Many of the stakeholders regarded this as an important incentive for their involvement in the process. The final quote below relates to the over use of consultants to do modelling work and that is why this stakeholder was interested in being involved in the process.

'I think it is probably a very simple answer really. You know you are just getting what people actually want out of the model from the start.' (Scottish Environment Protection Agency, Spey)

'…you could do an awful lot of work to get it to a stage where you're inputting a certain amount of data and then we come to application that is not the case or you have missed something quite important and you will have to backtrack or redo something that you have spent a lot of time on...' (West Country Rivers Trust, Taw)

'I think there are issues around people using consultants too much, because actually if you are really looking at what you are doing, you could probably do the work yourself.' (Environment Agency, Camel)

The theme of **group heritage** (Refs = 27) and composition was identified in the online survey as being an area of interest. This was followed-up in the interviews. This research finds a mixed message in the stakeholder opinions of whether or not pre-existing groups and meetings were beneficial to the process. Some stakeholders commented that they felt the use of pre-existing groups was beneficial to the process as they knew the people in those groups. Therefore, they felt comfortable interacting and providing their views in the process.

'It is a group of people that I have worked with in other projects over a long period of time. So coming together with those particular people in a workshop type setting felt quite natural and something I have done quite often.' (Avon Frome Partnership, Bristol Avon)

'You know the personalities involved as well, they are all very easy to work with, as we had an established group and then you are quite easy to work with.' (Scottish Environment Protection Agency, Spey)

Stakeholders were also asked if they felt this process would have worked with a new group of stakeholders who had not worked together previously. The stakeholders predominately agreed that it could have worked. However, they felt that *'knowing the people helped'* and that it would have taken longer for those involved to be comfortable exchanging and providing their views.

'I think either could work, but in that particular group we had worked together for more than a year and therefore we were quite happy to be relatively open. That is not to say it would not happen in a different group. It just takes a little bit longer for people to be more open just to contribute … and sometimes people are not always that confident in stating something if they are not particularly sure about their position.' (West Country Rivers Trust, Taw)

'I think if you are working with a new group of people, you know sometimes you go along to workshops and you have not met people before there is that element of 'I do not know'. If you are not quite so comfortable about the subject you are working on then you feel less comfortable about putting yourself out there.' (Avon Frome Partnership, Bristol Avon)

There was some divergence in opinion over whether or not the use of pre-existing meeting slots with the pre-existing groups was useful or not. On the Taw, the West Country River Trust suggested this was beneficial.

'… instead of creating a meeting for the sake of a meeting, unless you need quite a bit of time then actually piggybacking onto an existing meeting is quite a good idea. It is difficult enough getting everyone in one place at one time, sometimes even we didn't have all the partners in our existing meetings.' (West Country Rivers Trust, Taw)

Whereas on the Bristol Avon, the stakeholders suggested that it would have been better to have removed stakeholders who were not interested in the project and had a smaller, more focused group.

'Ideally, if you had some way of maybe getting those organisations, who the individuals sitting in on the group who were not particularly that fussed [i.e. remove them from the group]*. If you had a way of asking them to get someone from their organisation who would be better suited to input into the model.'* (Environment Agency, Bristol Avon)

'I think I might have alluded to this in the questionnaire in that we tried to fit our engagement with you into our regular steering group meetings which on reflection did not work and that was kind of a false pattern to try and fit in with.' (Avon Frome Partnership, Bristol Avon)

The stakeholders were asked if they felt there were any issues with **conflict and dominant stakeholders** (Refs = 14) in the discussion. This was a topic raised in the questionnaire. Those interviewed stated that either they did not feel that was the case, or that this was something they did not mind, as it was an opportunity for them to learn from other stakeholders.

'I don't recall that. So I probably wouldn't agree with that.' (Bath and North East Somerset Council, Bristol Avon)

'No I don't think so because I think everyone is knowledgeable in their own right.' (Spey Catchment Initiative, Spey)

'No I do not actually recall that being the case... from my own point of view I felt that [it] *was helpful because the points where I did not have any particular background, knowledge or expertise, I was actually learning at that point from other colleagues, so I found their expertise and questions were helpful to aiding my understanding.'* (Avon Frome Partnership, Bristol Avon)

Another of the sub-themes which links back to the online questionnaire is the idea of **excluded stakeholders** (Refs = 7). In particular, during the interviews, landowners were identified as not being part of the Spey catchment group. However, instead of helping the process, a stakeholder on the Spey suggested that having these types of stakeholders involved in the project might have hindered rather than helped, acting as a **distraction** (Refs = 5) from the goals of the process.

'I do not think so, maybe this is because of the organisation I work for, but I do not think it would have helped a lot. I think it might have hindered [the process]. *You might have got side-tracked.' (Scottish Environment Protection Agency, Spey)*

Excluded stakeholders (Refs = 7) relates to the earlier suggestion, in ensuring the 'correct' stakeholders are involved in the process by having some form of project scoping session at the start. In the transcripts, stakeholders suggested others who were not involved but could have been a part of the process, such as Munmurray Council (local government) was proposed by the Spey Fisheries Board stakeholder, as they are affected by flooding issues related to sediment.

The **knowledge exchange** (Refs = 39) theme relates to the different methods of information and understanding transfer through the process. The first of these themes draws out an aspect covered in the online survey, which related to whether or not stakeholders had acquired new knowledge from taking part in the project, more specifically, from the researcher – referred to as **giving information** (Refs = 16). The quote below from a stakeholder is an example from one of the presentations the researcher gave to the stakeholders at the start of the project, describing how cellular models use the equivalent of pixels in an image to break the landscape up, as well as the assumptions and resolution of data. There were two years between this interview and the first session.

'… you were also talking about the problems of resolution and I remember you were talking about the cells of the grid and you said you can have it at this scale or this scale and I remember something very strongly a visual in my mind of almost like pixels… that was quite a learning process that you could look at different scales …" (West Country Rivers Trust, Taw)

Another example of this type of exchange of information was when the researcher was presenting to stakeholders the ability to change the different input parameters to the model and how that would affect the outputs generated.

'It was like oh wow… my brain starts racing with the possibilities. Particularly, from my perspective of this is the baseline model of this is how it is. But that you can then change some of the parameters and see how that affects it.' (Spey Catchment Initiative, Spey)

One stakeholder also commented on how taking part in this process had changed their behaviour, in particular thinking about the different *influences* and the *physical processes* that drive how the catchment works. The opposite flow of information is the process of **extracting information** (Refs = 9) from the stakeholders. Many of the stakeholders in the interviews touched on how they felt it was important for there to be this capture of information from those involved in the practical application and local knowledge. Additionally, through this process, although the researcher may not be able to answer or implement the extracted information in the model, it could raise the importance of those issues within the relevant academic community. The quotes below demonstrate this idea.

'You should never go away from the practical and local knowledge of things when you are trying to do these types of projects. Whether it be somebody like myself or a farmer that has been there for 60 years. He will tell you when the river was at its highest, what day it was on if he has been a farmer there. So that is a key aspect of trying to fit into these models.' (Spey Fisheries Board, Spey)

'…it was good to be involved in trying to influence what went into the model and what it was designed to do.' (Environment Agency, Bristol Avon)

'Even just raising the fact that there are those other issues that were too big to tackle at this stage, is hugely important.' (Spey Catchment Initiative, Spey)

As well as having the flow of information from the researcher to the stakeholders and vice versa, stakeholders also articulated how the process encouraged a two-way **mutual exchange** (Refs = 10) of information. The quotes below emphasise how stakeholders felt this was achieved.

'I think through the sessions we had, we were able to raise things with you that we felt were important and should be included in the model and you kind of came along and told us how things were going with the model and what stage it was at and gave us the opportunity to feedback and add bits in.' (Environment Agency, Bristol Avon)

'I felt that maybe increasing my learning that I would become more helpful in the future. I guess that would be what I was hoping, if you see what I mean, so not just that I am taking everything from it but I would be able to put back more.' (Avon Frome Partnership, Bristol Avon)

The final sub-theme of the knowledge exchange theme relates to an idea that was touched upon earlier, that stakeholders felt that not only were they learning from the researcher but also from other stakeholders **within the group** (Refs = 4). One stakeholder described that they work in 'Silos' and this was an opportunity to come and work together to achieve a common goal. The two quotes below are just a few of the examples where stakeholders have commented on how they learnt from colleagues through the activities; an example of social learning.

'…because you are bringing in other opinions, and although you know we are all trying to achieve similar aspirations, people come from slightly different angles and get a little blinkered about a certain train of thought because that is what you do and that is your main objective. But it's not that you don't think about the other things, but you have a priority amongst those, so it is about getting everybody else to understand and come along with that…' (West Country Rivers Trust, Taw)

'I was actually learning at that point from other colleagues so I found their expertise and questions were helpful to aiding my understanding.' (Avon Frome Partnership, Bristol Avon)

The second of the themes under the process evaluation is **participatory activities** (Refs = 21). This theme focuses on the particular activities in the process and the stakeholders' opinions of which parts worked particularly well, and which did not. The first of these describes how many of the stakeholders enjoyed and found useful the activities that involved **interactivity** (Refs =6). Below are two of the stakeholders' responses on why they enjoyed the bulls-eye diagram activity.

'…it gets everybody involved, so we were all given the wee cards and then we had to shuffle them around and people could argue which bit to put where and it was quite a thing. It was easy to see what people were putting where and why.' (Spey Fisheries Board, Spey)

'… it is being able to interact with other people and work together with other people… and thinking about things enables you to bounce ideas off and lead you to think of things you maybe would not of thought of on your own… also having that visual element of being able to write things down and draw things out…' (Avon Frome Partnership, Bristol Avon)

One of the interviewed stakeholders did not enjoy the interactive exercises as much as other stakeholders. This was followed up in the interview and the stakeholder related this to similar activities they have been involved in the past *'I go to so many things and people ask you to stick bits of paper on it'*, arguing that often you *'never hear anything back'*, therefore suggesting *'I like a bit more meat on the bones'*. This stakeholder was not present at the next session. However, a stakeholder who was, commented on the importance of **capture and feedback** (Refs = 8).

'I feel like everything I contributed was captured and we saw that with the diagram you created with the words... it was obvious that you had captured everything I had contributed…' (Scottish Environment Protection Agency, Spey)

Deliberation and discussion (Refs = 5) is another sub-theme which is closely linked with interactivity and several of the extracts share the same codes. The stakeholders enjoyed these activities because they promoted and facilitated a discussion and debate on important aspects of managing sediment and modelling.

'I think it is quite interactive and that is a good way to engage people because there was a conversation going on between the groups of people that were there. You could suggest something, but then somebody else suggests something differently, so there is negotiation going on between the groups…' (West Country Rivers Trust, Taw)

The final sub-theme under the participatory activities is also related to several other sub-themes. The **ability to contribute** (Refs = 11) was mentioned as a reason why some of the stakeholders enjoyed the more interactive sessions in the process. A stakeholder suggested it was a positive experience to have *'a chance to contribute something, what things are important and what things are not'*.

6.2.3. Researcher's reflections on the process

This section presents the researcher's reflections on the PM process (equivalent of the Designer's Questionnaire) which are now apparent with the benefit of hindsight. These were noted down in a methodology reflective log throughout the process and are presented together here. These insights should be considered in any other PM approaches which use the combination of co-construction PM and computational modelling. These issues are complex and it was not possible to predict some of the issues that were encountered during the process.

Working with pre-existing groups of stakeholders

As discussed in Chapter Three, one of the methods adopted was to utilise pre-existing groups and run the sessions within scheduled group meetings (reviewed in Sections 3.2.1 and 3.2.2). Two issues arose from this choice of approach. Firstly, the groups only met on a handful of occasions throughout the year, which often meant that there were several months of waiting before the next PM session could be carried out. Secondly, these meetings were only scheduled to be a couple of hours at most and in the majority of cases the participatory sessions needed to be at least an hour to achieve their aims. The timings of meetings were something that could not be changed, and in one case a cancelled meeting meant that planned engagement with that group took place several months later. The amount of time the PM sessions took overall, did not pose a problem. Through negotiation with the stakeholder groups, they were willing to extend the length of meetings to accommodate the PM activities. An interesting reflection on these types of multiple year studies is that, in the case of pre-existing groups, regular changes in the political landscape (e.g. structure and funding) mean that these groups rarely remain static. For example, at the end of the process when carrying out the model assessment, some of these groups had undergone dramatic reform and the original meeting schedule of once a quarter had moved to once per annum. This is something that needs to be considered by studies taking place over several years, as with the Taw group it was only possible for the researcher to get a small number of the stakeholders together to complete the process.

Transcription of audio recording of groups discussion in the requirements analysis

One of the issues identified after the requirements analysis sessions was the difficulty in transcribing the audio recording from multiple group discussions. This made the transcription process difficult and time-consuming. This issue could have been resolved in other sessions through the use of multiple microphones. However, it was decided that in order to be time-effective, activities and discussions took place with the whole group, rather than in small break out groups.

Participatory processes are time (and resource) intensive

Participatory processes are often considered to be significantly time (and resource) intensive (e.g. Antrop and Rogge, 2006; Walz *et al.*, 2007). This was found to be particularly true in this PM process when it came to the qualitative analyses of the data. Working face-to-face with four groups of stakeholders and repeating the process each time, took a significant amount of time and resource. In total, each group engaged with approximately 7 hours of sessions, all of which were transcribed. In this project, due to the nature of the sessions taking place in groups and the researcher's familiarity with the process, an hour of audio took approximately 7-10 hours to transcribe and then at least 4 hours to code using thematic analysis. As a result, a few of the originally planned engagement sessions were scaled back or removed from the methodology. For example, the use of two PM model demonstration sessions was reduced to one with all of the stakeholders present.

The importance of having a flexible methodology

Throughout the process it was important to be flexible and adjust the methodology depending on how the methods worked with the stakeholders. For example in the model assessment session, the original approach split the activities into two separate sessions. The model comparison was to be carried out with the stakeholders as a group, and then on a one-on-one basis for the hypothetical decision-making scenario. However, after testing this structure with the Bristol Avon group, it became clear that it would be more beneficial to bring both activities together and completed as a group. There were three reasons behind this decision:

(i) the one or two volunteers stakeholders in the groups were unlikely to be the right individuals to operate the model;
(ii) debating and discussing how the model could be used as a group was more beneficial than individual perspectives at this stage in the process. In particular, this was identified as another opportunity for social learning and knowledge exchange to occur with the process;
(iii) the logistical requirements to conduct one-on-one's was significantly higher.

Therefore, future PM processes should not be overly concerned with adapting the process to allow for changes in conditions or identified improvements.

Encouraging continued interest over an extended study period

An early discovery in the research was that developing a numerical computational model (and learning to code) is also extremely time and resource intensive, and in this project it has taken around 18 months to date, and is still ongoing at the time of writing. This resulted in the need to engage with the stakeholder groups throughout this period in order to keep them engaged in the project. However, this led to another issue; there is a fine line to tread between over-burdening stakeholders with questions and information, and taking a less-involved approach. People can easily become frustrated if they receive too much communication, causing them to disengage or ignore the information. Taking a less involved approach, however, can have the opposite effect of making a group feel disconnected. Advice for future users of this approach would be to 'bank' model news and updates rather than sending out three or four pieces in one go and slowly trickle the information out to stakeholders. Stakeholders also fed back quickly that YouTube is blocked on some organisations' internal systems; therefore, hard copies of the videos were also provided.

Explanation of computational modelling to non-experts

One of the difficulties the researcher encountered, especially in the early sessions, was explaining to stakeholders how the model shown in conceptual model diagram would be translated into a computational model. A breakthrough in achieving clarity in this process was made in the final model demonstration sessions. This was achieved by showing the stakeholders extracts of the model code and providing a few examples of how the code translated into the conceptual model components and then into real life examples.

Translation and integration of qualitative outputs in numerical computational modelling

This issue was touched upon in the research literature as an issue when translating the outputs of participatory processes into model components or parameters (e.g. Walz *et al.*, 2007). In the methodology used here, this issue first became apparent during the coding of the transcripts, as through the qualitative thematic analysis and coding process the codes generated by the researcher became the model elements and features. For example, the quote below was interpreted by the researcher as the model parameter of spatially distributed precipitation.

> *'If you want your model to have credibility with stakeholders, they will say it always rains loads more here and it is always more intense here, compared to down there, so I think there would need to be some recognition of that.'* (Natural England, Camel).

One of the issues associated with this, is the process could be considered to be subjective and lack the rigour of quantitative methods. This is due to the researcher coding the transcripts and acting as the translator between the participatory and modelling components. However, despite the extensive documentation of the process, and the rigorous nature of capturing and refining this data with the stakeholders, subjectivity cannot be entirely removed from the PM process.

Challenges arising from the process evaluation and model assessment

The wording of some questions in the model assessment and in the process evaluation resulted in some difficulties in the PM process. For example, in the first part of the model comparison, five of 19 stakeholders incorrectly completed the exercise. This suggests that the wording and explanation of the task should have been more comprehensive. Whilst all of the stakeholders correctly completed the evaluation questionnaires, the questions asked could have been improved to focus not only on the process but also on the stakeholders. For instance, questions like 'Was the process a productive and effective use of your time?' and 'Do you feel like you were heard and your contributions reflected in the outcomes?' would have yielded additional beneficial data on the value of the PM process. Finally, there could have been more explanation and detail in the questions, especially in the online questionnaire. One example of this is question 9, where stakeholders are asked how the process could be improved. The available responses, such as 'more sessions', were vague and could have resulted in the lack of responses from the stakeholders.

Loss of participation due to timing of meetings

There was a loss of participation in the PM demonstration on the Bristol Avon and Taw, where due to the timing of the quarterly meeting a specific participatory modelling demonstration session was created. In these meetings, the attendance was lower than the existing quarterly meetings. In the Taw group, five of 14 stakeholders turned up to the session, whereas on Bristol Avon three of 12 attended. More specifically, on the Bristol Avon five people were expected to attend but due to unforeseen circumstances on the day two members had to cancel.

Ongoing support and development

Despite the positive comments towards the process and the model developed, one critical component is missing. Without continued support and development of the developed model, it is unlikely that the model will see adoption by stakeholders. CAESAR-Lisflood is an example of one of the most successful fluvial geomorphological models because Coulthard has dedicated much of his research career to developing the model (e.g. Coulthard, 1999; Coulthard *et al.*, 2002; Coulthard *et al.*, 2007; Coulthard *et al.*, 2013). Another example is SWAT (see: SWAT, 2015), which has regular developer conferences bringing together over 100 researchers to collaborate on enhancing the model. For the model to continue to develop and 'survive', more research projects will need to be instigated. One way in which it is hoped this model development might happen, was through making the model code and documentation available for free on the website. However, this has had limited impact to date. This need for continued support was also recognised by the stakeholders, suggesting there is a requirement for additional and updated training materials and instructional videos.

Shifting human capital

The observation of 'shifting human capital' originates from the assessment, the material covered in this chapter, and researcher's experience of conducting this PM process over several years. Shifting human capital refers to the consistent change associated with the stakeholders involved in this process. In particular, when considering this impact on Objectives 4 and 5, the ability for the stakeholders to use the knowledge they have gained is limited to the period of time they remain in a relevant position. This was exemplified in this study, as by the time the model assessment was carried out with the stakeholders over three years after the initial sessions. At this point, 49% of the stakeholders taking part had not been involved in the requirements analysis session (Table 3-2). Therefore, achieving effective long term knowledge exchange through this type of PM process is difficult.

Institutional barriers

The final observation relates to the some of the points above. More specifically, there are barriers beyond the control of researchers which would make the widespread adoption of models created through this type of PM process difficult. These include: (i) attitudes towards technology and models, (ii) access to data and technology (e.g. ArcGIS 10.2.2), and (iii) minimal internal expertise and increasing reliance on external specialists (e.g. consultants).

6.3. Implications from the participatory modelling process evaluation

This section presents an integrated discussion of the results from the evaluation of the PM process. A key component of the evaluation was to investigate the solutions implemented to address the common issues with participatory processes identified in the literature review (shown in Table 2-8). The discussion below moves through the key themes that emerged from the evaluation.

One of the issues identified in the literature was that bringing groups of stakeholders together for the first time can be 'uncomfortable' (Reed, 2008). Therefore, in this study pre-existing multi-professional groups were used. The responses to the questionnaire suggested that the stakeholders felt 'comfortable' interacting and exchanging their views, and therefore reinforced this as a valid methodological choice. Interestingly, one of the stakeholders commentated they felt this was because of the way in which the researcher facilitated the groups. This is consistent with the findings of Cornwall and Jewkes (1995), in that the researcher's attitude and ability to 'empower' the stakeholders is an important aspect in participatory processes. This is supported by Hare's (2011) emphasis on having the correct modelling, facilitation and knowledge acquisition skills required to conduct a PM process.

The advantages and disadvantages of using pre-existing groups was explored in greater depth in the follow-up interviews. The interviewed stakeholders' views were mixed. One of the stakeholders on the Bristol Avon recognised that the use of pre-existing groups was beneficial, as they were more comfortable working with people they had previously. The same stakeholder also suggested that newly created groups could have worked, but it would have taken longer for the stakeholders to feel able to freely contribute. This could be due to the initial time required for groups to trust each other and develop the feeling of a 'safe space'. These findings support the wealth of literature discussing the rationale for using pre-existing groups in research (e.g. Kitzinger, 1994; Bloor *et al.*, 2001; Videira *et al.*, 2009).

One area which saw contradictory views was over the use of pre-existing meeting slots. The original strategy was to use pre-existing meeting slots, however, due to the dynamic and diverse structure of the groups this was not always possible. One of the stakeholders on the Taw suggested it was beneficial for the PM process to *'piggyback'* onto existing meetings. Whereas, a stakeholder on the

Bristol Avon suggested some stakeholders should be *'swapped out'*, and the sessions conducted in separate focused meetings. However, other stakeholders either did not have an opinion or thought the process could work either way. Therefore, findings detailed in this thesis suggest that there was no clear consensus on the appropriate method from the perspective of the stakeholders. On the other hand, as described in Section 6.2.3, the researcher found the use of pre-existing groups to be useful in some respects, such as having pre-defined stakeholders, but troublesome in others, such as in the time constraints associated with using pre-existing meeting slots, as well as the constantly evolving and shifting political landscape and organisational change.

One of the most common criticisms of participatory processes is that the stakeholders become disengaged with the process. This is because they either feel their participation in the process is tokenism (Voinov and Bousquet, 2010), or they find the situation too scientifically complex to effectively contribute (Newig *et al.*, 2008). The online questionnaire results at the end of the process showed that all of the stakeholders enjoyed the process and they believed their input was valued. This finding suggests that the developed and implemented co-construction PM methodology was successful in achieving a 'meaningful' participatory approach. This was supported by the qualitative responses to the online questionnaire and interviews suggesting that this was due to the 'methodical' nature of the process, and the way in which the results from the previous session were incorporated into the following session. This could be argued to be the result of the researcher's positivist background and the influence this had on the design and implementation of the process. More specifically, the researcher's skillset influenced the fundamental model structure and the methods for incorporating and reporting on the modelling decisions. This finding and the framework developed can assist other researchers in the design of similar PM processes, in particular, by informing researchers how their processes could be adapted to demonstrate the capture and integration of the stakeholders' contributions.

In relation to the process being scientifically too complex to contribute, one of the stakeholders commented that they found it difficult to engage in the process due to the scientific complexity of cellular modelling. This finding is consistent with those of Newig *et al.* (2010), who identified that even within focused participatory groups there will be differences in knowledge and technical expertise. This is a limitation of the approach developed and implemented in this thesis. In particular, the use of pre-existing groups did not allow for targeting of stakeholders with similar skillsets. Some of the stakeholders suggested this could be addressed through project scoping and supplementing the existing groups with more suitable stakeholders. This is discussed in greater detail later in this section.

One of the notable results from the online questionnaire, was 'strongly agree' (mean = 4.44) to the statement 'the developed approach is a more effective way to design a useful model'. This encouraging result indicates that the stakeholders considered their participation in the process to be of value compared to traditional approaches to developing models. Therefore, with the push to achieve an impact on society from research (Harris and Lyon, 2013), there is potentially an opportunity for more of this type of PM research. However, as noted by Cooke and Kothari (2001), historically, a major significant issue with participatory approaches is that they become driven by an oversupply of resource to deliver them, rather than the demand. Therefore, academics should be careful to not 'overwhelm' stakeholders with these type of resource intensive exercises.

The recognition of the potential for conflict and dominant stakeholders in the process was identified in literature review (Bloor *et al.*, 2001). One stakeholder commented in the online questionnaire that in the requirements analysis, they found the more knowledgeable stakeholders tended to dominate the discussion. However, in the co-designing sessions, through activities such as the bulls-eye diagram, they were able to contribute. The importance of these types of activities for encouraging all stakeholders to participate, and promote social learning was supported by the qualitative responses. Stakeholders commented that in the discussion and debates, such as prioritising the inputs, they were able to appreciate and understand a number of new perspectives from the range of stakeholders present. This was reinforced by the results generated in the interviews. For example, one of the stakeholders describes how they *'had become a specialist'* and *'built up a lot of knowledge'*, and the PM sessions were one of those *'rare occasions'* where they could get together with other stakeholders to try to learn and understand the whole catchment system. None of the stakeholders interviewed felt that dominant stakeholders were an issue. Instead, they saw the process as an opportunity to learn from more knowledgeable stakeholders. These provide examples of where the stakeholders recognise the value of the PM process as a place to foster social learning (as suggested by Ridder *et al.*, 2006).

These results are in line with those of previous studies suggesting that carefully designed participatory approaches can create an environment for social learning to occur. This was achieved in this PM process by the stakeholders changing their perceptions through persuasive exchanges of ideas (as suggested by Blackstock *et al.*, 2007; Newig *et al.*, 2010; Reed *et al.*, 2010). Furthermore, this supports Voinov and Bousquet's (2010) suggestion that the end 'product' from the PM process is not as important as the process. Instead, they argue the value gained by participants in terms of understanding other viewpoints, and increased knowledge of the catchment system, is far greater than any product.

During the analysis, the knowledge exchanged between participants (social learning) was referred to as 'within group'. This is because social learning was not an initial objective of the PM process, but became part of Objective 4.A after the requirements analysis sessions, in recognition by the researcher that social learning was taking place. In the interviews, one of the stakeholders described how they felt the process was an opportunity to overcome an issue in river management of 'silo' working. More specifically, the stakeholder described how there is a requirement for catchment management practitioners to consider water quality, flood risk, ecology and hydromorphology. There is a desire to bring these different areas together to identify multi-benefit outcomes from restoration projects. This finding is supported by a developing body of academic research on taking an ecosystem services approach to river management (e.g. Bergeron and Eyquem, 2012; Iacob *et al.*, 2014; Everard and Quinn, 2015).

Interestingly, stakeholders enjoyed the bulls-eye diagram activity and the requirements analysis group discussion; as these are two of the most interactive exercises in the process, this was an unsurprising result. In these activities, the flow of knowledge is: (i) 'extracted' from the stakeholders to the research team, and (ii) transferred 'within the group' between stakeholders. This was explored in greater detail in the follow-up interviews, and from the responses, it is clear that as described in the literature (Section 2.3.4), these kinds of methods help to simulate discussion, social learning and knowledge exchange by involving all the stakeholders by *doing something* which is both *interactive* and *visual*. As a result, this allowed the stakeholders who found it difficult to contribute during the open discussions to participate.

A significant claim of participatory processes and PM, are that they promote knowledge exchange from the researcher to the stakeholders (e.g. Newig *et al.*, 2010; Laniak *et al.*, 2013). The results from the questionnaire indicated that the stakeholders felt that they learned about cellular modelling through taking part in the process. This was not surprising as the core modelling principles of cellular modelling were recapped at the start of each session. The responses to the open question further support this, with a stakeholder commenting *'the way the model worked was new to me'*. A limitation to the evaluation of knowledge exchange in this research is that it does not actually test the stakeholders' knowledge. Instead, the questionnaire and interview only reflect on whether the stakeholders felt they had learnt anything through their participation in the process. Therefore, further work would be required to sufficiently test this assertion in greater detail. This could be achieved through a longitudinal study testing the development of stakeholders' knowledge throughout the PM process. The opportunities for future research will be outlined in greater detail in Section 7.3.

The interviews provided the researcher with the opportunity to delve deeper into whether the stakeholders considered any knowledge exchange had occurred in the process. When asked if they felt like they learnt anything from the process, it was clear from the responses that some of the stakeholders were able to recall modelling concepts and ideas that the researcher had presented (e.g. cellular modelling). This could suggest that the aim of increasing knowledge exchange between fluvial geomorphologists and river management practitioners was achieved. The stakeholders also discussed how being involved in the process had changed their ways of working. An interesting piece of further research could be to investigate and analyse the changes to stakeholders' ways of working over an extended period. Conversely, when discussing the extraction of knowledge from the stakeholders, they commented that they felt a large number of topics for future research had been identified (outlined in Section 6.1), and that the model developed through the process would not be able to incorporate all of the issues. Instead, the stakeholders suggested the knowledge captured through the process could provide a vital first step to begin to develop a practical agenda of river catchment sediment management related research. Therefore, the PM process was found to be a useful tool for promoting knowledge exchange, enriching the professional practice of both the researcher and the river management practitioners.

The final part of the evaluation focused on how the process could be improved. Interestingly, the number of responses to this question were lower, by approximately 50%, than in any of the other questions, and no clear themes emerged from the qualitative responses. One of the stakeholders remarked that they felt the communication through the process could have been improved. This was explored in the follow-up interviews. However, when prompted on this topic, the majority of interviewees stated that they felt the communication through the process had been ‘about right’ and they recognised that developing a numerical model was a ‘time-consuming’ process, which the researcher had successfully conveyed to the stakeholders. Furthermore, a few of the stakeholders commented that they thought the reverse was the problem, as often they were difficult to get responses from.

Linked to this was the issue of declining participation over an extended time period. In this case, by the end of the three and a half year research period, 49% of the original stakeholders were no longer participating in the stakeholder groups (Table 3-2). This could support the observation of Cockerill *et al.* (2011) that participation should be expected to decrease, even within well designed and conducted participatory processes. However, in the case of this research, the cancelling of meetings was responsible for the decline in participation. One way of attempting to reduce declining participation during the time-consuming model coding was the use of online tools, such as the model blog and demonstration videos, described in Section 3.2.4. The results to the online questionnaire suggest these techniques were not successful, receiving only 7% of the total selections as an enjoyable part of the PM process and no mentions in the open questions. There are a few potential explanations for this. Firstly, although not specifically recorded, the older age demographic of the stakeholder groups could have had an influence on the willingness to interact with the online methods. Secondly, the online activities were an example of how one-way knowledge exchange methods can be used to update the stakeholders on the model’s development, but may not be particularly 'enjoyable'. Furthermore, as mentioned in the previous section, there was no direct measurement of the use of the online methods (e.g. blog hits). Therefore, future studies should look to incorporate this into the evaluation.

Similarly, one of the researcher's reflections on the process was that the methods used will not suit all stakeholders. For example, when discussing the highest overall rated activity, the bulls-eye diagram, one of the stakeholders interviewed did not enjoy this activity suggesting they *'like a bit more meat on the bones'*. This is a real challenge for PM processes which contain stakeholders with different knowledge and interests, which was found even within this thesis, using existing focused river management practitioner groups.

When asked on why they were interested in taking part in the PM process, the responses focused on the research being 'interesting' and 'innovative'. An implication of this could be that repetition of these types of process with the same groups of stakeholders will make it the *norm*, and the stakeholders become 'bored'. Therefore, as mentioned earlier, researchers will need to be careful that future PM processes are not being driven by an oversupply of resource (see: Cooke and Kothari, 2001; Stringer *et al.*, 2006; Reed, 2008). However, one of the stakeholders commented that the model would not be relevant to their work as *'they don't deal with sediment'* and so were not that interested in taking part in the process. This could be addressed in future studies through stakeholder analysis to establish more focused groups, as recognised by Videira *et al.* (2009). However, as pre-existing groups were used in this study, the removal or addition of stakeholders was not considered. To incorporate this into the process would increase the resource demand as a result of the time required to identify, consult and organise new stakeholder groups.

One of the ideas, suggested by one of the stakeholders in the online questionnaire and explored further in the telephone interview, was to have an initial project scoping session. The aim of this session would be to ensure the researcher and the stakeholders are able to achieve their requirements from the process. This supports the suggestion of Voinov and Bousquet (2010) that the stakeholders are crucial in defining the goals of the process. This session could clarify a defined structure for the process and timescales for the engagement sessions. The stakeholders suggested that having this upfront could avoid the issues with decreasing participation levels throughout the study.

The feasibility of adequately defining the structure of the PM process over a three-year period could be difficult. This is especially the case in this study where multiple stakeholder groups were used. For example, the process was refined throughout the three-year research period, resulting in the final structure presented at the start of the methodology chapter. The stakeholders were presented with initial timescales and structure in the requirements analysis session. However, these changed throughout the research processes (as recognised by Voinov and Bousquet, 2010). From the researcher's point of view, adopting a flexible approach was critical to the successful implementation of the framework developed (shown in Figure 3-2). For example, the time required to develop the numerical model was longer than expected, and therefore some sessions were removed or refined. One of the stakeholders suggested that one of the improvements might have been to update the stakeholders on how the structure of the PM process was evolving at the same time as the sessions were carried out.

Interestingly, when asked in the online questionnaire if there were any additional stakeholders that should have been involved in the process, the majority of those suggested, with the exception of homeowners, were active in other stakeholders groups (e.g. water companies or geomorphologists). Therefore, utilising a multiple case study approach ensured the views of these other stakeholders were incorporated into the process. This finding supports the critique of participatory processes from Etienne *et al.* (2011) who argue that using a single-case or single group can lead to artificial conditions. The results from the follow-up interviews suggested that any additional stakeholders should be carefully considered, as having the wrong mix of stakeholders could detract from the goals of the process, and become a 'distraction'. This supports the observation of Reed (2008) that not all stakeholders can be included in participatory process, and that clear criteria for those who are must be established.

The follow up interviews were conducted with the stakeholders who had volunteered to be interviewed in the online questionnaire. Therefore, it is important to acknowledge that the stakeholders interviewed are likely to be those highly engaged in the PM process. Furthermore, this is an important limitation to acknowledge for the wider PM process, as some of the sessions where conducted outside of the existing group slots, as a result the stakeholders present in these sessions were those most engaged in the process.

6.4. A revised participatory modelling approach

This section moves on to briefly present and discuss how the PM process developed, implemented and evaluated in this thesis, could be refined for future studies (Objective 6). The refined process is shown in Figure 6-6 and is based on the flows of information diagram presented in the methodology (Figure 3-2). Whilst this may appear to be a ridged structure, other PM studies which may wish to utilise this approach will need to adopt a flexible attitude, especially if the study takes place over several years.

Several parts of the PM process have not been changed; in particular, the requirements analysis, co-designing sessions, and model development stages. This was in recognition that these parts of the process produced useful results and were well received by the stakeholders. In particular, the group discussion in the requirements analysis promotes divergent thinking and social learning between participants at the start of the process. The use of interactive prioritisation activities (e.g. bulls-eye diagrams) in the co-designing sessions allows all the participants to move to convergent thinking and provide further opportunities for social learning.

Despite the challenges discussed in Section 6.3, the revised process maintains the use of pre-existing groups in recognition of their ability to allow the stakeholders to feel comfortable taking part in the process and reduce resource requirements. However, two changes would be required. Firstly, the number of groups would be reduced to three as having the extra catchment does increase the resource requirements significantly. Secondly, the three stakeholder groups should be geographically diverse as, in this study, the addition of the Spey has proven to provide a useful perspective on the management challenges within a different governance and physical catchment characteristics.

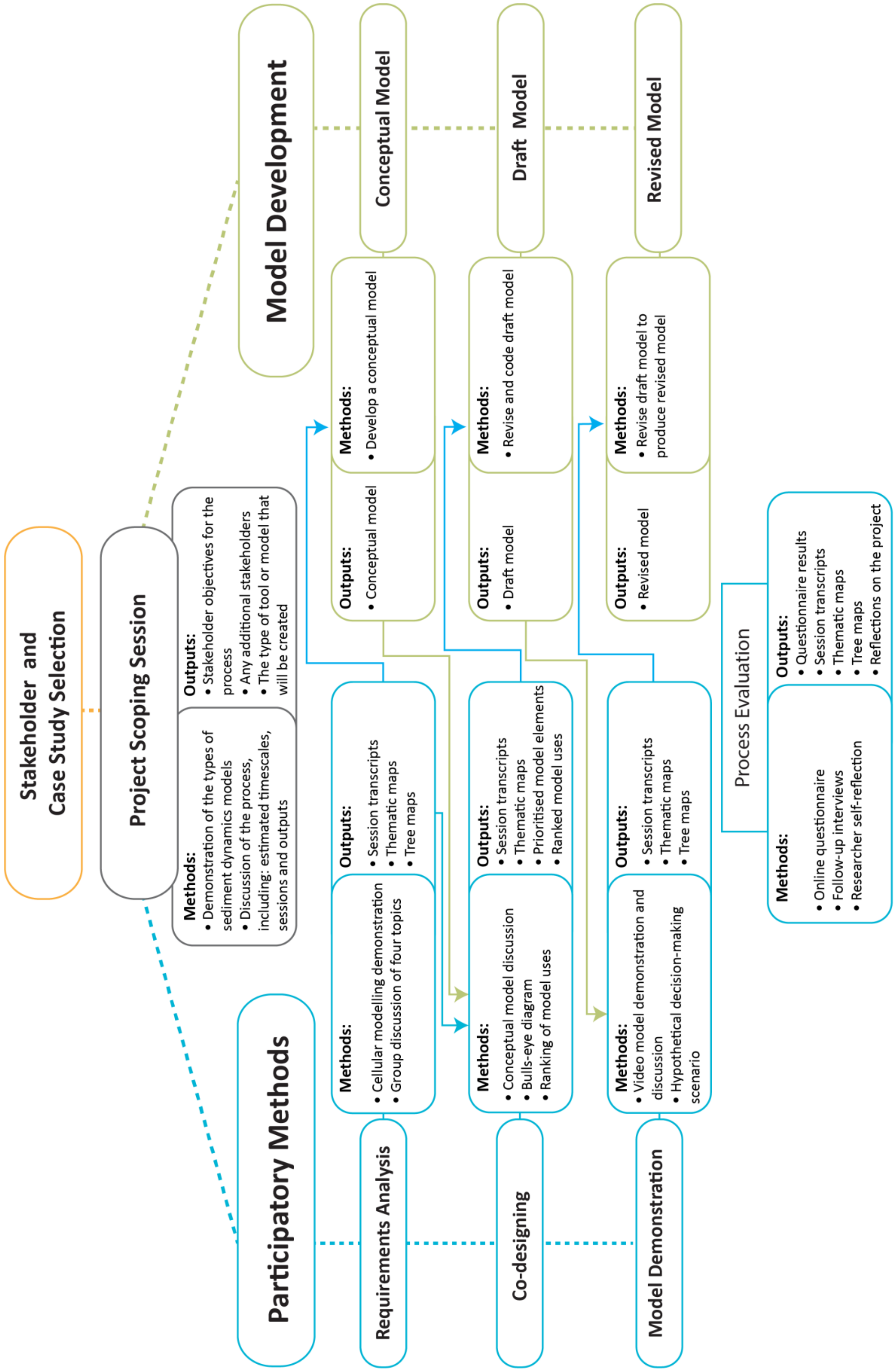


FIGURE 6-6: A REVISED PARTICIPATORY MODELLING PROCESS BASED ON THE FINDINGS FROM THE PROCESS EVALUATION AND MODEL ASSESSMENT.

One of the main changes to the process is the addition of a 'project scoping session' at the start. The idea of a project scoping session was discussed in the previous section. However, this session was added to the revised PM process in recognition that part of the time allocated in the requirements analysis was dedicated to outlining the process. Therefore, having a dedicated session to discuss the stakeholders' objectives, the structure and timing of process, and identify any missing important stakeholders could be beneficial. This would also allow the researcher to determine whether the stakeholder group would be suitable for engaging in the participatory modelling approach.

The model demonstration sessions have been revised slightly to include a hypothetical decision-making scenario. This was in recognition that this part of the model assessment would have been very useful to have earlier in the process. In particular, the hypothetical decision-making scenario generated a significant amount of feedback from the stakeholders that could not have been gathered through the existing methods. This session would follow the existing structure of presenting the model that had been created, and include the processes and methods used.

Ongoing engagement has been removed from the process; this was in recognition that the stakeholders did not actively engage with the online one-way methods of communication. This decision was taken based on the results from the stakeholder evaluation as there were no direct methods used to capture use of the online resources (e.g. blog hits). However, the researcher would still create a model website and keep a development blog up-to-date with tools to assess usage (e.g. page views and unique visitors). These two aspects were important as they provided a portal for the developed model to be viewed and downloaded. Furthermore, it is worth noting that the next generation of stakeholders could be more positive towards digital means of engagement. Therefore, a decision on the types of online methods used in the research could be informed through an assessment of stakeholder attitudes and capabilities, which could be carried out in the project scoping session.

The process evaluation appears unchanged in Figure 6-6, however, as noted in the previous section some minor changes will improve the evaluation of the process. In particular, the questions should involve examining what the stakeholders felt they gained from taking part in the process. The final change to the process is the removal of the assessment session. This was in recognition that the hypothetical decision-making scenario would be more useful earlier on in the process, and the results from the model comparison, whilst interesting, could be considered to be biased and targeted towards the model developed through the process.

Chapter Seven: Conclusions, implications, and future research

This chapter summarises the key contributions to knowledge discussed in the previous two chapters, highlights the key findings, considers the implications of these findings for future participatory modelling (PM) research, and identifies areas for future research.

7.1. Contributions to knowledge and key findings

The aim of this research was to *establish, implement and critically analyse a participatory modelling approach for developing and evaluating a catchment-scale cellular model of sediment dynamics; this model should be usable by management stakeholders engaging in decision-making processes of sustainable river catchment management*. To achieve this, a series of research objectives and sub-objectives were identified, refined, and completed. Objectives 1 and 2 required a systematic and critical review of the literature in order to identify the important existing knowledge and theories relevant to this research project. Two of the most important were: (i) the identification of the cellular models as a suitable approach to modelling sediment dynamics (2.2.2); and (ii) the recognition of the importance participatory processes (2.3), in particular, PM as a methodological approach to increase model quality, and promote knowledge exchange and social learning (2.4).

In the review of the literature, a number of frameworks and PM methodologies were identified (Table 2-9). However, approaches for developing the type of model required were rare or not well documented. Furthermore, the literature review identified a number of methodological issues associated with participatory processes, and some specifically to PM (Table 2-8). Therefore, the third objective of this research was to *assemble and describe a new participatory modelling approach to developing a catchment-scale cellular model of sediment dynamics.* This new approach was described in Chapter 3; this included a number of methodological solutions that were designed, implemented, and then evaluated (Table 3-3). Of particular note, this research used multiple pre-existing stakeholder groups to overcome fears of uniqueness (Broad *et al.*, 2007; Etienne *et al.*, 2011), and adopted a systematic mixture of qualitative and quantitative techniques to address concerns suggesting a lack of scientific rigour in participatory processes (Mendoza and Prabhu, 2005; Becu et *al.,* 2008).

The PM process had two sub-objectives: (3.A) *use the new participatory modelling approach to identify, refine and prioritise the requirements of management stakeholders when creating and using a catchment-scale sediment dynamics model in river catchment management*; and (3.B) *use the new participatory modelling approach to assemble and describe a new model of river catchment sediment dynamics*. Objective 3.A. was successfully completed and the results of the PM process were presented in Chapter Four, and then discussed in Chapter Six. The results indicated that the stakeholders need to be able to understand the sediment dynamics of the system, which was an important management challenge, and this was supported by the significant number of human and natural influences (21) described by the stakeholders (Section 4.1.1). Additionally, the stakeholders recognised the potential for cellular models of sediment dynamics to act as a tool to assist with several aspects of river management, including: decision-making and cost benefit analysis, understanding natural processes, scenario planning, and stakeholder engagement and communication (Section 4.1.2). As a result, this phase of the research has provided valuable insights for fluvial geomorphologists on the requirements of river management practitioners and identified a number of gaps in knowledge for future research (Table 6-1). For example, the importance of being able to model the influence of in-channel barriers and different types of land cover on the sediment dynamics of the system. In particular, the stakeholders articulated the need to be able to demonstrate the impact through engaging visuals that management changes will have on the catchment.

Due to the breadth of model parameters, applications and characteristics identified in the requirements analysis, the sessions that followed were designed to focus the stakeholder groups to debate, discuss and prioritise. The iterative and flexible PM process allowed for the development of a model through the various stages, from a conceptual model to the final model (Objective 4.B.). A detailed description of the model created through this process was presented in Chapter Five and discussed in Section 5.3. Therefore, this research successfully designed and implemented a PM approach to develop a cellular model of river sediment dynamics. However, crucially, this research included a critical evaluation of the process and an assessment of the model with the stakeholders.

The fourth objective of the research was *to critically evaluate the participatory modelling approach*. This objective addressed a criticism of participatory studies in that they often do not include a comprehensive evaluation of the process. This objective had two sub-objectives to evaluate the processes for: (4.A.) *engaging with stakeholders in model development to reduce unused research models, improve model quality, acceptance of the model, and integration of the model with stakeholder management processes*, and (4.B.) *promoting knowledge exchange and social learning between fluvial geomorphologists and river management practitioners*. There were two parts to the process evaluation: (i) an online questionnaire and follow-up interviews with the stakeholders (Sections 6.2.1 and 6.2.2), (ii) and the researcher's reflections (Section 6.2.3). A critical part of the evaluation was to assess and reflect on the solutions implemented to address the participatory process issues identified in the literature. Whilst doing so, this research makes a number of key methodological contributions to knowledge.

One of the issues with PM studies is that often the participation is 'merely tokenism' and that the stakeholders become disconnected from the process (Newig *et al.*, 2008). This research finds that combining an iterative and flexible PM process with a sufficiently documented analysis and reporting process achieves a meaningful level of participation (the higher rungs on Arnstein's ladder of participation). In particular, this was achieved by effectively communicating to the stakeholders the modelling decisions they have directly influenced. This was supported by the results to the questionnaires and the interviews, in which the stakeholders commented that they felt that their input into the process was valued (combined mean = 3.88/5). The stakeholders suggested this was the result of the clear demonstration at each stage of the process how their contributions had been captured and used.

This research found that issues of disillusionment when dealing with scientifically complex material reported in the literature did not occur. This result supports the growing body of research recognising the potential of this type of approach for engaging with stakeholders to promote knowledge exchange. This finding was supported by the results to the questionnaires and interviews as the majority of stakeholders stated they found the process an enjoyable experience (combined mean = 3.81/5) and strongly agreed that PM was a better way to develop models (combined mean = 4.44/5). However, this finding should be treated with some caution, as two of the stakeholders commented, they found the process scientifically challenging due to the content being covered and they did not feel they contributed as much as more knowledgeable participants.

This research suggests that, to a degree, some of the stakeholders became disillusioned with the output from the process, the developed model. This was the result of the model being relatively complex (compared to the tools they currently use (if any)) and beyond the technical capabilities of some of the stakeholders involved. This provides a valuable insight into the design and implementation of these processes. Importantly, researchers should recognise that PM will not be an effective solution for all participants, due to the diversity in technical skill and knowledge, even within pre-existing groups. This was a surprising finding in this PM process as focused management groups of stakeholders were used to reduce this impact. Therefore, this reinforced the need for a session early in the revised process (Section 6.4) to profile the stakeholder groups, referred to in this research as a project scoping session.

The developed PM process incorporated multiple pre-existing groups and meetings to prevent hijacking by special interest groups and unique results due to local catchment characteristics, two criticisms associated with participatory processes being based on a single case. Furthermore, pre-existing groups were used to ensure stakeholders were comfortable exchanging ideas. The results from the questionnaire and interviews indicate these methodological decisions were successful in addressing these issues. However, in doing so, created a number of methodological challenges for the researcher. Notably, the four groups' meeting schedules were often out of alignment with the PM process structure resulting in difficulties arranging sessions. This finding emphasised the importance of a flexible approach to allow the researcher to complete the research, as identified in the literature (Section 2.4). This enabled all of the groups to finish the process. Therefore, even though the project conducted approximately 7 hours of participatory activities per group, a critical part of the participatory process was to build relationships with the stakeholders outside of the sessions to get them to ‘buy in’ over the extended research period (3.5 years).

The research has also shown that external factors can influence the results from the PM process. In this study, real world events, such as the flooding on the Somerset Levels in the winter of 2013/14 resulted in the increased importance of understanding dredging for the river management practitioners. More recently, the flooding in Cumbria and Yorkshire in the winter of 2015/16 resulted in the recognition of the potential use of the model for Natural Flood Management, as traditional flood defences were overwhelmed. A strength of conducting this study over several years was the realisation of the important ongoing management challenges faced by practitioners rather than ‘topical’ issues. This new understanding should help to improve recognition that external influences can impact on PM processes, and could be used to help researchers identify the influence these events could have on their research.

In respect to the second objective (4.B), this research finds that the designed and implemented PM process successfully provided an environment for knowledge exchange and social learning to occur. In the questionnaires, the stakeholders agreed their knowledge of sediment dynamics, computer modelling and cellular modelling of sediment dynamics increased through taking part in the PM process (combined means = 3.5, 3.69 and 3.81/5). Importantly, the study also demonstrated that the most vital part of the process for this was the interactive activities. In particular, these occurred in the most enjoyable activities, the group discussions and bulls-eye prioritisation activity, where the stakeholders were required to discuss and work together in groups on a set task. The findings highlighted the importance of these interactive activities to provide opportunities for social learning and knowledge exchange between the stakeholders and the researcher. This is supported by the findings of the questionnaires, interviews, and the observations of the researcher throughout the process. However, one of the key factors to consider here, as mentioned above, is that although this research finds that knowledge exchange and social learning took place, the impacts that this has had on the knowledge bases of the stakeholders, and the perception of importance of fluvial geomorphology in river management, were not assessed. This could be another area for future research, which will be outlined in the final section of this thesis.

The fifth objective (5) *was to critically assess the new cellular model as a tool for use within river management.* From the model assessment, it is clear that ENGAGE (combined mean = 6.61) is the preferred choice for stakeholders over CAESAR-Lisflood (combined mean = 4.22), a specifically targeted research developed model. In the ranking of the model characteristics, the top four were from the ENGAGE model with 'Spatially distributed surface runoff and soil erosion based on rainfall, land cover, soil type and condition' and the 'Ability to change land cover type and management' ranked highest. However, the stakeholders also recognised the limitations with the model produced through the process. In particular, the lack of validation of the model's accuracy and level of support and skills required to operate.

This research recognises that, to a degree, this is an unfair comparison as CAESAR-Lisflood has been specifically developed for an academic audience. However, if there is a desire to demonstrate relevance beyond the academy and reduce the number of research developed models, then the importance of recognising the requirements of the target audience needs to be addressed. Therefore, the conclusion could be made that the desire for increased uptake of research developed models and increased knowledge exchange will not be achieved unless the developed models are targeted at the desired practitioner audience. For example, this research argues that even if reduced-complexity cellular models are developed at the temporal and spatial scales relevant to river management practitioners (as suggested by Brasington and Richards (2007) and Keestra *et al.* (2014)), the models will not be used, unless stakeholder priorities are incorporated. However, to achieve this will require a change in the way this type of academic research is conducted away from the traditional decide announce defend (DAD) approach, and as suggested in the literature, a change in the attitudes of some physical science researchers towards facilitating and analysing the results from participatory social science research (Section 2.3.3).

The final objective (6) was to *propose a refined participatory modelling approach based on the results from the process evaluation and model assessment.* Section 6.4 presented and discussed a number of revisions to the participatory modelling processed based on the lessons learnt, evaluation of the process and assessment of the model. Some aspects of the process, such as the requirements analysis and the co-designing sessions remained the same. However, some important refinements were suggested. For example, the addition of a project scoping session, a hypothetical decision-making scenario to the model demonstration sessions and the reduction of four to three catchments. These refinements were shown in Figure 6-6. If a future study adopts the revised structure, a comprehensive evaluation will be required to determine their effectiveness of these changes to improve the process.

7.2. Implications for transdisciplinary fluvial geomorphological research and river management practitioners

The main implication from this piece of research is that it demonstrates a successfully designed and implemented co-construction PM approach to develop a cellular model of sediment dynamics. This study could be considered a pioneering piece of participatory modelling research in fluvial geomorphology and provides a number of valuable methodological improvements, which should be considered in similar future studies. This research has demonstrated that, even though this type of approach has rarely been used for this type of modelling (Section 3.1.1), it has achieved the aim and objectives of the research. The methodology presented here can provide a framework for similar studies or even model development studies outside of academia wanting to combine PM with the development of a numerical model (Figure 6-6). However, this research also identified a number of issues with this type of approach which should be considered before conducting similar research.

The recent proliferation of participation and PM studies in the literature (described in Sections 2.3 and 2.4) suggests that there may have been a 'watershed' moment in the recognition of the value of interdisciplinary or transdisciplinary research, in particular, in the combination of social and physical sciences. This research identifies one major risk for future studies; the capacity and capabilities of the stakeholders to be involved in this type of research, which can be time-consuming. As more academics begin to increasingly use this type of approach, it is important that the common criticisms (Cooke and Kothari, 2001) of participatory approaches do not reappear. Importantly, these processes should be driven by demand from the stakeholders, and not the capacity of science or researchers to deliver. Even within this study, where none of the stakeholders were involved in other PM studies, the researcher had a limited amount of time to conduct activities. This problem could be amplified by an excessive number of researchers trying to engage with the same groups of stakeholders and organisations.

The approach developed in this research has demonstrated that unconventional methods of science communication can be used to promote knowledge exchange and begin to break down the 'paradigm lock' (Gregory *et al.*, 2008; Gregory *et al.*, 2014). Importantly, this research has demonstrated the important factors for river management practitioners when managing and modelling sediment within river catchments in the United Kingdom (Table 4-2). As a result, a number of new areas for future research have been identified through the exploratory and experimental nature of this participatory modelling process (Table 6-1).

Fluvial geomorphologists should continue to explore alternative methods to demonstrating the relevance of fluvial geomorphology to river management practitioners and the general public. Furthermore, fluvial geomorphology must also recognise its importance is not in isolation; instead, it is critical to become part of an interdisciplinary or transdisciplinary science, regularly crossing disciplinary boundaries to support the challenges faced by river management practitioners. Notably, this research demonstrated that the stakeholders were not interested in the impact that interventions will have solely on sediment, but also on the 'bigger picture' as the stakeholders are required to demonstrate multi-benefit outcome projects. Therefore, the recognition of fluvial geomorphology within society and the river management practitioner community will likely rise if fluvial geomorphology can demonstrate the importance of, and provide tools for river management practitioners to understand the important interrelationships between fluvial geomorphology, ecology and hydrology.

Finally, one of the most important contributions this research makes is that 'human capital', the stakeholders has a 'shelf-life'. This was experienced in this project as the stakeholders changed roles and positions within organisations. For example, by the end of this participatory process, only nine of the original 30 stakeholders were present in the final sessions. This is in part due to the way these groups and organisations operate with a continual change in personnel, and was exemplified by this study taking place over three and a half years. Furthermore, this research argues that it is too early to suggest whether or not ENGAGE will be 'taken up' by the stakeholders or become another unused research-developed model. Therefore, further research is required to better understand the relationship between the investment into these type of processes and the outputs generated (including the value of the knowledge exchanged).

7.3. Future research

A number of areas of future research have been identified and briefly referred to in the discussion in the previous chapter. The most crucial of these is the continued development and support of ENGAGE, as without this, it is unlikely that the model will enter wider use. This need to continue the development and research of the model became apparent in the final model assessment sessions, as the stakeholders identified some 'critical' areas for further development. Some of these areas were identified as being very important, such as the need to carry out a comprehensive assessment of the model's accuracy and further development work on the incorporation of in-channel barriers. CAESAR-Lisflood is an example of a successful research developed model which is now over 20 years old (e.g. Coulthard, 1999; Coulthard *et al.*, 2013). However, this has required a dedication to develop the model by its creator. This is supported by the recent requests from stakeholders, who have begun to try to use ENGAGE, but have come up with issues or errors with the model. Therefore, either further research time is required to develop and maintain the model, or an organisation such as the Environment Agency needs to take over the model and its application. This research therefore concludes that without this further investment, the future of models created from PM processes is far from certain. Furthermore, an important consideration before proceeding is that similar research projects should consider the management and long-term ownership arrangements, if any, for the outputs from the process.

There was also considerable interest from the stakeholders in the model assessment session to see whether this type of model, with further research, could be developed further into a multi-benefit decision-making tool. However, there are issues with adopting this approach as the model becomes more complex and more input data is required. However, as data availability increases and technology advances, this could potentially no longer be an issue. For example, at the time of starting this research the stakeholders only had access to 10m digital terrain model (DTM), whereas at the time of writing a 1-2m national composite is available. Furthermore, government agencies, such as the Environment Agency are adopting an 'open access by default' policy to their data, meaning that accessing data in the future should be become easier.

As described earlier, an issue with the assessment of knowledge exchange in this research was that it is the stakeholders' perception, rather than their knowledge. Another piece of research could involve acquiring a baseline knowledge, skills and attitudes for the stakeholders at the start of the process, and then retesting the stakeholders at different stages to assess the quantity and quality of knowledge being exchanged from the researcher to the stakeholders. This would be important, not only for testing the exchange of fluvial geomorphological concepts, but also to understand any change in working practices, such as the stakeholders' use of models. For example, has being involved in the process resulted in an increased awareness of the limitations of models, and therefore more criticality when using the outputs from models? Another interesting piece of further research would be to investigate the nature and types of knowledge exchanged from the stakeholders to the researcher. This would also involve capturing the researcher's understanding of the challenges and important factors for the stakeholders as these develop throughout the process.

One of the limitations of the evaluation and model assessments carried out within this PM process, was that these are a single snapshot taken at the end of the process. Therefore, this research was only able to draw limited conclusions as to how useful the model would be in the future and in 'real-world' decision-making scenarios. A further piece of research could assess whether or not, participation in the PM process resulted in the model being adopted and used by river management practitioners. This would require following the stakeholders involved in this process, and tracking the users of the developed model over several years after the end of the PM process.

References

The Assessment and Management of Flood Risks [online]. *Directive 2007/60/EC.* (2007) EUR-Lex. Available from: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32007L0060 [Accessed 14 June 2015].

The Quality of Fresh Waters Needing Protection or Improvement in Order to Support Fish Life [online]. *Directive 2006/44/EC.* (2006) EUR-Lex. Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:264:0020:0031:EN:PDF [Accessed 25 November 2015].

Establishing a Framework for Community Action in the Field of Water Policy [online]. *Directive 2000/60/EC.* (2000) EUR-Lex. Available from: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32000L0060 [Accessed 22 September 2016].

The Conservation of Natural Habitats and of Wild Fauna and Flora [online]. *Directive 92/43/EEC.* (1992) EUR-Lex. Available from: http://ec.europa.eu/environment/nature/legislation/habitatsdirective/index_en.html [Accessed 28 July 2016].

Endangered Species Act [online]. *93-205.* (1973) US Environment Protection Agency. Available from: http://www.epw.senate.gov/esa73.pdf [Accessed 24 September 2016].

Clean Water Act [online]. *92-500.* (1972) US Environmental Protection Agency. Available from: http://www.epw.senate.gov/water.pdf [Accessed 24 September 2016].

Abelson, J., Forest, P., Eyles, J., Smith, P., Martin, E. and Gauvin, F. (2003) Deliberations about deliberative methods: issues in the design and evaluation of public participation processes. *Social Science & Medicine.* 57 (2), pp. 239-251.

Adams, K. and Ian, B. (2006) *An Introduction to Market & Social Research: Planning & using Research Tools & Techniques.* London, UK: Kogan Page Publishers.

ADAS (2016) *Flood Related Soil Erosion - Impact of Farming Practices.* Available from: http://www.adas.uk/News/flood-related-soil-erosion-impact-of-farming-practices [Accessed 27 August 2016].

Ahilan, S., Wright, N.G., Sleigh, A., Too, S., Glenis, V., Chris, K. and Kutija, V. (2014) Flood risk management of a small urban river using a sustainable urban drainage system: Wortley Beck, Leeds, UK. In: *Proceedings of 11th International Conference on Hydroinformatics.* New York City, USA, 17-21 Aug 2014. City College of New York.

Allan, I.J., Vrana, B., Greenwood, R., Mills, G.A., Roig, B. and Gonzalez, C. (2006) A "toolbox" for biological and chemical monitoring requirements for the European Union's Water Framework Directive. *Talanta.* 69 (2), pp. 302-322.

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998) *Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements - FAO Irrigation and Drainage.* Available from: http://s3.amazonaws.com/academia.edu.documents/40878584/Allen_FAO1998.pdf?AWSAccessKeyId=AKIAJ56TQJRTWSMTNPEA&Expires=1474747977&Signature=iFpoOC8bqwD71zdDZa7Bv1uBuZw%3D&response-content-disposition=inline%3B%20filename%3DAllen_FAO1998.pdf [Accessed 23 July 2016].

Andersen, D.F. and Richardson, G.P. (1997) Scripts for group model building. *System Dynamics Review.* 13 (2), pp. 107-129.

Anon. (2016) Planting more trees can reduce UK's flood risk, research shows. *The Guardian* [online]. 11 March. Available from: http://www.theguardian.com/environment/2016/mar/11/planting-more-trees-can-reduce-uk-flooding-research-shows [Accessed 16 June 2016].

Anon. (2012) Wales floods: Environment Agency looks at defence failure. *BBC* [online]. 29 November. Available from: http://www.bbc.co.uk/news/uk-wales-north-east-wales-20533926 [Accessed 12 June 2016].

Anselme, B., Bousquet, F., Lyet, A., Etienne, M., Fady, B. and Le Page, C. (2010) Modelling of spatial dynamics and biodiversity conservation on Lure mountain (France). *Environmental Modelling & Software.* 25 (11), pp. 1385-1398.

Anthony, E.J. and Julian, M. (1999) Source-to-sink sediment transfers, environmental engineering and hazard mitigation in the steep Var River catchment, French Riviera, southeastern France. *Geomorphology.* 31 (1–4), pp. 337-354.

Antrop, M. and Rogge, E. (2006) Evaluation of the process of integration in a transdisciplinary landscape study in the Pajottenland (Flanders, Belgium). *Landscape and Urban Planning.* 77 (4), pp. 382-392.

Archer, M., Bhaskar, R., C., A., Lawson, T. and Norrie, A. (1998) *Critical Realism: Essential Readings.* London, UK: Routledge.

Arnaud-Fassetta, G., Astrade, L., Bardou, E., Corbonnois, J., Delahaye, D., Fort, M., Gautier, E., Jacob, N., Peiry, J. and Piégay, H. (2009) Fluvial geomorphology and flood-risk management. *Géomorphologie: Relief, Processus, Environnement.* (2), pp. 109-128.

Arnold, J.G. and Allen, P.M. (1999) Automated methods for estimating baseflow and ground water recharge from streamflow records. *Journal of the American Water Resources Association.* 35 (2), pp. 411-424.

Arnstein, S.R. (1969) A ladder of citizen participation. *Journal of the American Institute of Planners.* 35 (4), pp. 216-224.

Ashworth, P.J. and Ferguson, R.I. (1986) Interrelationships of Channel Processes, Changes and Sediments in a Proglacial Braided River. *Geografiska Annaler.Series A, Physical Geography.* 68 (4), pp. 361-371.

Baattrup-Pedersen, A., Friberg, N., Larsen, S.E. and Riis, T. (2005) The influence of channelisation on riparian plant assemblages. *Freshwater Biology.* 50 (7), pp. 1248-1261.

Bailey, K. and Grossardt, T. (2006) Addressing the Arnstein gap: improving public confidence in transportation planning and design through structured public involvement (SPI). *Kentucky Transportation Center Faculty and Researcher Publications.* Paper 3.

Bailey, K. and Grossardt, T. (2010) Toward Structured Public Involvement: Justice, Geography and Collaborative Geospatial/Geovisual Decision Support Systems. *Annals of the Association of American Geographers.* 100 (1), pp. 57-86.

Barnaud, C., Le Page, C., Dumrongrojwatthana, P. and Trébuil, G. (2013) Spatial representations are not neutral: Lessons from a participatory agent-based modelling process in a land-use conflict. *Environmental Modelling & Software.* 45, pp. 150-159.

Barnosky, A.D., Hadly, E.A., Dirzo, R., Fortelius, M. and Stenseth, N.C. (2014) Translating science for decision makers to help navigate the Anthropocene. *The Anthropocene Review.* 1 (2), pp. 160-170.

Barreteau, O., Bots, P. and Daniell, K. (2010) A framework for clarifying participation in participatory research to prevent its rejection for the wrong reasons. *Ecology and Society.* 15 (2), pp. 22.

Bauch, G.D. and Hickin, E.J. (2011) Rate of floodplain reworking in response to increasing storm-induced floods, Squamish River, south-western British Columbia, Canada. *Earth Surface Processes and Landforms.* 36 (7), pp. 872-884.

Becu, N., Neef, A., Schreinemachers, P. and Sangkapitux, C. (2008) Participatory computer simulation to support collective decision-making: Potential and limits of stakeholder involvement. *Land use Policy.* 25 (4), pp. 498-509.

Beierle, T.C. (2002) The Quality of Stakeholder-Based Decisions. *Risk Analysis.* 22 (4), pp. 739-749.

Benito, G. and Thorndycraft, V.R. (2004) *Systematic, Palaeoflood and Historical Data for the Improvement of Flood Risk Estimation: Methodological Guidelines.* Madrid, Spain: CSIC.

Berger, P. and Luckmann, T. (1966) *The Social Construction of Reality: A Treatise in the Sociology of Knowledge.* New York, USA: Pengiun Books.

Bergeron, N. and Eyquem, J. (2012) Geomorphology and Gravel-Bed River Ecosystem Services: Workshop Outcomes. In: Church, M., Biron, P.M. and Roy, A.G., eds. *Gravel-Bed Rivers.* Chichester, UK: John Wiley & Sons Ltd, pp. 242-257.

Berkes, F., Colding, J. and Folke, C. (2008) *Navigating Social-Ecological Systems: Building Resilience for Complexity and Change.* Cambridge, UK: Cambridge University Press.

Berry, K. and Mollard, E. (2010) *Social Participation in Water Governance and Management: Critical and Global Perspectives.* London, UK: Earthscan.

Bhaskar, R. (1975) *A Realist Theory of Science.* London, UK: Routledge.

Bhatnagar, B., James, K. and Sequeria, D. (1996) *The World Bank Participation Sourcebook.* Washington, DC: The World Bank.

Biggs, S.D., (1989) *Resource-Poor Farmer Participation in Research: A Synthesis of Experiences from Nine National Agricultural Research Systems* . Report number: On-Farm Client-Oriented Research (OFCOR) Comparative Study Paper No. 3.The Hague: International Service for National Agricultural Research (ISNAR).

Bizzi, S. and Lerner, D.N. (2015) The Use of Stream Power as an Indicator of Channel Sensitivity to Erosion and Deposition Processes. *River Research and Applications.* 31 (1), pp. 16-27.

Blackstock, K.L., Kelly, G.J. and Horsey, B.L. (2007) Developing and applying a framework to evaluate participatory research for sustainability. *Ecological Economics.* 60 (4), pp. 726-742.

Blench, T. (1957) *Regime Behaviour of Canals and Rivers.* London, UK: Butterworths Scientific Publications.

Bloor, M., Thomas, M., Robson, K. and Frankland, J. (2001) *Focus Groups in Social Research.* London, UK: SAGE Publications Ltd.

Blumenthal, D. and Jannink, J. (2000) A classification of collaborative management methods. *Conservation Ecology.* 4 (2), pp. 13.

Bommel, P., Dieguez, F., Bartaburu, D., Duarte, E., Montes, E., Machín, M.P., Corral, J., De Lucena, C.J.P. and Grosskopf, H.M. (2014) A further step towards participatory modelling. Fostering stakeholder involvement in designing models by using executable UML. *Journal of Artificial Societies and Social Simulation.* 17 (1), pp. 6.

Borja, A. and Elliott, M. (2007) What does 'good ecological potential' mean, within the European Water Framework Directive? *Marine Pollution Bulletin.* 54 (10), pp. 1559-1564.

Borowski, I. and Hare, M. (2007) Exploring the gap between water managers and researchers: difficulties of model-based tools to support practical water management. *Water Resources Management.* 21 (7), pp. 1049-1074.

Borrelli, P., Märker, M. and Schütt, B. (2015) Modelling Post-Tree-Harvesting Soil Erosion and Sediment Deposition Potential in the Turano River Basin (Italian Central Apennine). *Land Degradation & Development.* 26 (4), pp. 356-366.

Bots, P.W. and van Daalen, C.E. (2008) Participatory model construction and model use in natural resource management: a framework for reflection. *Systemic Practice and Action Research.* 21 (6), pp. 389-407.

Boulton, A., Piégay, H. and Sanders, M.D. (2008) Turbulence and train wrecks: using knowledge strategies to enhance the application of integrative river science in effective river management. In: Brierley, G.J. and Fryirs, K.A., eds. *River Futures: An Integrative Scientific Approach to River Repair.* Washington, DC: Island Press, pp. 28-39.

Bousquet, F., Barreteau, O., Le Page, C., Mullon, C. and Weber, J. (1999) An environmental modelling approach: the use of multi-agent simulations. In: Blasco, F. and Weill, A., eds. *Advances in Environmental and Ecological Modelling.* Paris, France: Elsevier, pp. 113-122.

Brasington, J. and Richards, K. (2007) Reduced-complexity, physically-based geomorphological modelling for catchment and river management. *Geomorphology.* 90 (3–4), pp. 171-177.

Braun, V. and Clarke, V. (2006) Using thematic analysis in psychology. *Qualitative Research in Psychology.* 3 (2), pp. 77-101.

Braun, J. and Sambridge, M. (1997) Modelling landscape evolution on geological time scales: a new method based on irregular spatial discretization. *Basin Research.* 9 (1), pp. 27-52.

Brierley, G.J. and Fryirs, K.A. (2005) *Geomorphology and River Management: Applications of the River Styles Framework.* Oxford, UK: Blackwell Publishing.

Broad, K., Pfaff, A., Taddei, R., Sankarasubramanian, A., Lall, U. and de Souza F., Franciso de Assis (2007) Climate, stream flow prediction and water management in northeast Brazil: societal trends and forecast value. *Climatic Change.* 84 (2), pp. 217-239.

Broekman, A. (2013) Reclaiming global citizenship: a perspective from Catalan water justice activists. In: Harris, L.M., Goldin, J.A. and Sneddon, C., eds. *Contemporary Water Governance in the Global South.* London, UK: Earthscan, pp. 233-241.

Brookes, A. (1985) Traditional engineering methods, physical consequences and alternative practices. *Progress in Physical Geography.* 9 (1), pp. 44-73.

Brookes, A., Chalmers, A. and Vivash, R. (2005) Solving an Urban River Erosion Problem on the Tilmore Brook, Hampshire (UK). *Water and Environment Journal.* 19 (3), pp. 199-206.

Brown, A.G., Tooth, S., Chiverrell, R.C., Rose, J., Thomas, D.S.G., Wainwright, J., Bullard, J.E., Thorndycraft, V.R., Aalto, R. and Downs, P. (2013) The Anthropocene: is there a geomorphological case? *Earth Surface Processes and Landforms.* 38 (4), pp. 431-434.

Brunner, G.W. (2010) *HEC-RAS, River Analysis System Hydraulic Reference Manual (Version 4.1).* Available from: http://www.hec.usace.army.mil/software/hec-ras/documents/HECRAS_4.1_Reference_Manual.pdf [Accessed 21 June 2015].

Bulcock, A., Whitfield, E., Lopez-Tarazon, J.A., Whitfield, R.G. and Byrne, P. (2016) The Impact of a Small Weir on Flood Risk Modelling and Management. *Geophysical Research Abstracts*.

Bulkeley, H. and Mol, A.P. (2003) Participation and environmental governance: consensus, ambivalence and debate. *Environmental Values.* 12 (2), pp. 143-154.

Bull, R., Petts, J. and Evans, J. (2008) Social learning from public engagement: dreaming the impossible? *Journal of Environmental Planning and Management.* 51 (5), pp. 701-716.

Bunte, K. and Abt, S.R., (2001) *Sampling Surface and Subsurface Particle-Size Distributions in Wadable Gravel-and Cobble-Bed Streams for Analyses in Sediment Transport, Hydraulics, and Streambed Monitoring* [online]. Report number: RMRS-GTR-74. Fort Collins, CO: United States Department of Agriculture. [Accessed 25 April 2015].

Campbell, L.M. (2005) Overcoming obstacles to interdisciplinary research. *Conservation Biology.* 19 (2), pp. 574-577.

Campbell, H. and Marshall, R. (2000) Public Involvement and Planning: Looking beyond the One to the Many. *International Planning Studies.* 5 (3), pp. 321-344.

Campo, P.C., Bousquet, F. and Villanueva, T.R. (2010) Modelling with stakeholders within a development project. *Environmental Modelling & Software.* 25 (11), pp. 1302-1321.

Carmona, G., Varela-Ortega, C. and Bromley, J. (2013) Participatory modelling to support decision making in water management under uncertainty: Two comparative case studies in the Guadiana river basin, Spain. *Journal of Environmental Management.* 128, pp. 400-412.

Castelletti, A. and Soncini-Sessa, R. (2007) Bayesian Networks and participatory modelling in water resource management. *Environmental Modelling & Software.* 22 (8), pp. 1075-1088.

Chambers, R. (1994a) The origins and practice of participatory rural appraisal. *World Development.* 22 (7), pp. 953-969.

Chambers, R. (1994b) Participatory rural appraisal (PRA): Analysis of experience. *World Development.* 22 (9), pp. 1253-1268.

Chandramohan, T., Venkatesh, B. and Balchand, A.N. (2015) Evaluation of three soil erosion models for small watersheds. *Aquatic Procedia.* 4, pp. 1227-1234.

Chen, S., Chen, B. and Fath, B.D. (2015) Assessing the cumulative environmental impact of hydropower construction on river systems based on energy network model. *Renewable and Sustainable Energy Reviews.* 42, pp. 78-92.

Chorley, R.J., Beckinsale, R.P. and Dunn, A.J. (1973) *History of the Study of Landforms: Or the Development of Geomorphology: The Life and Work of William Morris Davis.* London, UK: Routledge.

Chorley, R.J., Dunn, A.J. and Beckinsale, R.P. (1964) *The History of the Study of Landforms, Or the Development of Geomorphology. Vol. 1, Geomorphology before Davis.* London, UK: Methuen.

Chorley, R.J. (1962) *Geomorphology and General Systems Theory.* Washington, DC: United States government printing office.

Chorley, R.J. and Kennedy, B.A. (1971) *Physical Geography: A Systems Approach.* London, UK: Prentice-Hall International.

Church, M. (2010) The trajectory of geomorphology. *Progress in Physical Geography.* 34 (3), pp. 265-286.

CIWEM, (2014) *Floods and Dredging – a Reality Check* [online]. Avaliable from: http://www.wcl.org.uk/docs/Floods_and_Dredging_a_reality_check.pdf [Accessed 17 June 2015].

Cleaver, F. (2001) Institutions, agency and the limitations of participatory approaches to development. In: Cooke, B. and Kothari, U., eds. *Participation: The New Tyranny?* London, UK: Zed Books, pp. 36-55.

Clifford, N.J. (2008) River channel processes and forms. In: Burt, T.P., Chorley, R.J., Brunsden, D., Cox, N.J. and Goudie, A.S., eds. *The History of the Study of Landforms. Volume 4: Quaternary and Recent Processes and Forms (1890-1965) and the Mid-Century Revolutions.* London, UK: The Geological Society, pp. 217-312.

Cockerill, K., Tidwell, V., Daniel, L. and Sun, A. (2011) Environmental Reviews & Case Studies: Engaging the Public and Decision Makers in Cooperative Modeling for Regional Water Management. *Environmental Practice.* 12 (4), pp. 316-327.

Colfer, C., (1995) *Who Counts most in Sustainable Forest Management. Working Paper no. 7*. Jakarta, Indonesia: Center for International Forestry Research.

Colfer, C., Prabhu, R., Gunter, M., McDougall, C., Porro, N.M. and Porro, R. (1999) *Who counts most? Assessing human well-being in sustainable forest management.* Jakarta, Indonesia: Center for International Forestry Research.

Collins, A.L. and Anthony, S.G. (2008) Assessing the likelihood of catchments across England and Wales meeting ‘good ecological status’ due to sediment contributions from agricultural sources. *Environmental Science & Policy.* 11 (2), pp. 163-170.

Comte, A. (1868) *The Positive Philosophy of Auguste Comte.* New York, USA: William Gowans.

Considine, M. (2005) *Making Public Policy: Institutions, Actors, Strategies.* London, UK: Polity Press.

Cook, B.R., Atkinson, M., Chalmers, H., Comins, L., Cooksley, S., Deans, N., Fazey, I., Fenemor, A., Kesby, M., Litke, S., Marshall, D. and Spray, C. (2013) Interrogating participatory catchment organisations: cases from Canada, New Zealand, Scotland and the Scottish?English Borderlands. *The Geographical Journal.* 179 (3), pp. 234-247.

Cooke, B. (2004) Rules of thumb for participatory change agents. In: Hickey, S. and Mohan, G., eds. *Participation: From Tyranny to Transformation.* London, UK: Zed Books, pp. 42-55.

Cooke, B. (2001) The social psychological limits of participation? In: Cooke, B. and Kothari, U., eds. *Participation: The New Tyranny?* London, UK: Zed Books, pp. 102-121.

Cooke, B. and Kothari, U. (2001) *Participation: The New Tyranny?* London, UK: Zed Books.

Corbelli, D. and Conlan, K., (2012) *Evaluation of the Catchment-Based Approach – Pilot Stage (Baseline Characterisation of the Pilot Catchments)*. Report number: CC472.Manchester: Cascade Consulting.

Cornwall, A. and Jewkes, R. (1995) What is participatory research? *Social Science & Medicine.* 41 (12), pp. 1667-1676.

Costa, A., Molnar, P., Lane, S.N. and Bakker, M. (2015) Impact of River Regulation on Potential Sediment Mobilization and Transport in an Alpine Catchment. *EGU General Assembly Conference Abstracts*.

Coulthard, T.J. (1999) Unpublished PhD, School of Geography, University of Leeds.

Coulthard, T.J. (2001) Landscape evolution models: a software review. *Hydrological Processes.* 15 (1), pp. 165-173.

Coulthard, T.J., Hancock, G.R. and Lowry, J.B.C. (2012b) Modelling soil erosion with a downscaled landscape evolution model. *Earth Surface Processes and Landforms.* 37 (10), pp. 1046-1055.

Coulthard, T.J., Hicks, D.M. and Van De Wiel, M.J. (2007) Cellular modelling of river catchments and reaches: Advantages, limitations and prospects. *Geomorphology.* 90 (3–4), pp. 192-207.

Coulthard, T.J., Macklin, M.G. and Kirkby, M.J. (2002) A cellular model of Holocene upland river basin and alluvial fan evolution. *Earth Surface Processes and Landforms.* 27 (3), pp. 269-288.

Coulthard, T.J., Neal, J.C., Bates, P.D., Ramirez, J., de Almeida, G.A.M. and Hancock, G.R. (2013) Integrating the LISFLOOD-FP 2D hydrodynamic model with the CAESAR model: implications for modelling landscape evolution. *Earth Surface Processes and Landforms.* 38 (15), pp. 1897-1906.

Coulthard, T.J., Ramirez, J., Fowler, H.J. and Glenis, V. (2012a) Using the UKCP09 probabilistic scenarios to model the amplified impact of climate change on drainage basin sediment yield. *Hydrology and Earth System Sciences.* 16 (11), pp. 4401-4416.

Coulthard, T.J. and Van De Wiel, M.J. (2007) Quantifying fluvial non linearity and finding self organized criticality? Insights from simulations of river basin evolution. *Geomorphology.* 91 (3–4), pp. 216-235.

Coulthard, T.J. and Van de Wiel, M.J. (2012) Modelling river history and evolution. *Philosophical Transactions.Series A, Mathematical, Physical, and Engineering Sciences.* 370 (1966), pp. 2123-2142.

Croke, J., Fryirs, K. and Thompson, C. (2013) Channel–floodplain connectivity during an extreme flood event: implications for sediment erosion, deposition, and delivery. *Earth Surface Processes and Landforms.* 38 (12), pp. 1444-1456.

Cross, K. (1981) *Adults as Learners. Increasing Participation and Facilitating Learning.* San Francisco, USA: Jossey-Bass Publishers.

Crutzen, P.J. and Stoermer, E.F. (2000) The “anthropocene”. *Global Change Newsletter.* 41 pp. 17-18.

Cundill, G. and Rodela, R. (2012) A review of assertions about the processes and outcomes of social learning in natural resource management. *Journal of Environmental Management.* 113, pp. 7-14.

Daniell, K., White, I., Ferrand, N., Ribarova, I., Coad, P., Rougier, J., Hare, M., Jones, N., Popova, A. and Rollin, D. (2010) Co-engineering participatory water management processes: theory and insights from Australian and Bulgarian interventions. *Ecology and Society.* 15 (4), pp. 11.

Darby, S.E. and Thorne, C.R. (1992) Impact of channelization on the mimmshall brook, Hertfordshire, UK. *Regulated Rivers: Research & Management.* 7 (2), pp. 193-204.

Darch, G.J.C., McSweeney, R.T., Kilsby, C.G., Jones, P.D., Osborn, T.J. and Tomlinson, J.E. (2016) Analysing changes in short-duration extreme rainfall events. *Proceedings of the Institution of Civil Engineers - Water Management.* 169 (5), pp. 201-211.

Davidson, S. (1998) Spinning the wheel of participation. *Planning.* 1262, pp. 14-15.

Davis, W. (1902) Baselevel, grade and peneplain. *The Journal of Geology.* 10 (1), pp. 77-111.

De Stefano, L. (2010) Facing the water framework directive challenges: A baseline of stakeholder participation in the European Union. *Journal of Environmental Management.* 91 (6), pp. 1332-1340.

De Vente, J. and Poesen, J. (2005) Predicting soil erosion and sediment yield at the basin scale: scale issues and semi-quantitative models. *Earth-Science Reviews.* 71 (1), pp. 95-125.

Death, R.G., Fuller, I.C. and Macklin, M.G. (2015) Resetting the river template: the potential for climate-related extreme floods to transform river geomorphology and ecology. *Freshwater Biology.* 60 (12), pp. 2477-2496.

DEFRA (2013) *Catchment Based Approach: Improving the Quality of our Water Environment.* Available from: https://www.gov.uk/government/publications/catchment-based-approach-improving-the-quality-of-our-water-environment [Accessed 11 March 2014].

DEFRA (2014a) *Environmental Management – Guidance, Ecosystem Services.* Available from: https://www.gov.uk/guidance/ecosystems-services [Accessed 6 July 2015].

DEFRA (2014b) *Flood Risk Management Plans (FRMPs): How to Prepare Them.* Available from: https://www.gov.uk/guidance/flood-risk-management-plans-frmps-how-to-prepare-them [Accessed 15 June 2014].

DEFRA (2009) *Soil Strategy for England Supporting Evidence Paper.* Available from: http://webarchive.nationalarchives.gov.uk/20130402151656/http://archive.defra.gov.uk/environment/quality/land/soil/documents/evidence-paper.pdf [Accessed 6 June 2016].

Delli Priscoli, J. (1995) Twelve challenges for public participation. *Interact - the Journal of Public Participation.* 1 (1), pp. 77-93.

den Exter, K. and Specht, A. (2003) Assisting stakeholder decision making using system dynamics group model-building. *Extending Extension: Beyond Traditional Boundaries, Methods and Ways of Thinking.*

Diaw, M.C. and Kusumanto, T. (2005) Scientists in social encounters: the case for an engaged practice of science. In: Colfer, C.J.P., ed. *The Equitable Forest: Diversity, Community and Resource Management.* Washington: Resources for the Future and CIFOR, pp. 72-109.

Dougill, A., Fraser, E., Holden, J., Hubacek, K., Prell, C., Reed, M., Stagl, S. and Stringer, L. (2006) Learning from doing participatory rural research: lessons from the Peak District National Park. *Journal of Agricultural Economics.* 57 (2), pp. 259-275.

Downs, P.W. and Gregory, K.J. (2004) *River Channel Management: Towards Sustainable Catchment Hydrosystems.* London, UK: Routledge.

Dransfield, L. (2015) *Government Criticised Over Flood Defence 'Failure'.* Available from: http://www.building.co.uk/government-criticised-over-flood-defence-failure/5079103.article [Accessed 12 June 2016].

Dunn, C.E. (2007) Participatory GIS—a people's GIS? *Progress in Human Geography.* 31 (5), pp. 616-637.

Egunyu, F. and Reed, M. (2015) Social learning by whom? Assessing gendered opportunities for participation and social learning in collaborative forest governance. *Ecology and Society.* 20 (4), pp. 13.

Endreny, T.A. (2001) A global impact for hydro-socio-ecological watershed research. *Water Resources Impact.* 3, pp. 20-25.

Environment Agency (2012) *Catchment Based Approach for a Healthier Water Environment.* Available from: https://www.gov.uk/government/publications/catchment-based-approach-improving-the-quality-of-our-water-environment [Accessed 11 May 2013].

Environment Agency (2014) *Rivers and Coastal Maintenance Programmes 2013-14.* Available from: https://www.gov.uk/government/publications/river-and-coastal-maintenance-programme [Accessed 28 March 2015].

Environment Agency (2015) *Water for Life and Livelihoods. A Strategy for River Basin Management.* Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/500573/Part_2_River_basin_management_planning_process_overview_and_additional_information.pdf [Accessed 9 May 2016].

Environment Agency Camel (2016) Email to Nick Jones, 18 May.

Environment Agency External (2016) Email to Nick Jones, 12 May.

Erskine, W.D. (1998) Environmental impacts of extractive industries on the Hawkesbury-Nepean river, NSW. In: Powell, J., ed. *The Improvers Legacy: Environmental Studies of the Hawkesbury.* Berowra Heights, USA: Deerubbin Press, pp. 49-79.

ESRI (2014) *ArcGIS Help, 10.2, 10.2.1, and 10.2.2.* Available from: http://resources.arcgis.com/en/help/main/10.2/ [Accessed 11 November 2015].

Etienne, M., Du Toit, D.R. and Pollard, S. (2011) ARDI: a co-construction method for participatory modeling in natural resources management. *Ecology and Society.* 16 (1), pp. 44.

Evans, E., Ashley, R., Hall, J., Penning-Rowsell, E., Saul, A., Sayers, P., Thorne, C. and Watkinson, A. (2004) *Foresight: Future Flooding: Scientific Summary: Volume I: Future Risks and their Drivers.* London: DTI, Office of Science and Technology.

Evans, E.P., Ramsbottom, D.M., Wicks, J.M., Packman, J.C. and Penning-Rowsell, E.C. (2002) Catchment flood management plans and the modelling and decision support framework. *Proceedings of the Institution of Civil Engineers - Civil Engineering.* 150 (5), pp. 43-48.

Evans, K.G., Saynor, M.J., House, T. and Willgoose, G. (1998) *Effect of Vegetation and Surface Amelioration on Simulated Landform Evolution of the Post-Mining Landscape at ERA Ranger Mine, Northern Territory. Supervising Scientist Report 134.* Australia: Supervising Scientis.

Everard, M. and Quinn, N. (2015) Realizing the value of fluvial geomorphology. *International Journal of River Basin Management.* 13 (4), pp. 487-500.

Eyquem, J. (2007) Using fluvial geomorphology to inform integrated river basin management. *Water and Environment Journal.* 21 (1), pp. 54-60.

Farrington, J. (1998) Organisational roles in farmer participatory research and extension: lessons from the last decade. *Natural Resource Perspectives.* 27, pp. 1-4.

Fielding, N.G. and Lee, R.M. (1998) *Computer Analysis and Qualitative Research.* London, UK: SAGE Publications Ltd.

Fischer, F. (2000) *Citizens, Experts, and the Environment: The Politics of Local Knowledge.* Durham, USA: Duke University Press.

Flyvbjerg, B. (2001) *Making Social Science Matter: Why Social Inquiry Fails and how it can Succeed Again.* Cambridge, UK: Cambridge University Press.

Fookes, P.G. (2005) *Geomorphology for Engineers.* Dunbeath, UK: Whittles Publisher.

Foulds, S.A., Griffiths, H.M., Macklin, M.G. and Brewer, P.A. (2014) Geomorphological records of extreme floods and their relationship to decadal-scale climate change. *Geomorphology.* 216, pp. 193-207.

Freeman, R.E. (1984) *Strategic Management: A Stakeholder Approach.* Cambridge, UK: Cambridge University Press.

Freidman, B.L., Freidman, B.L. and Fryirs, K.A. (2014) Rehabilitating Upland Swamps Using Environmental Histories: A Case Study of the Blue Mountains Peat Swamps, Eastern Australia. *Geografiska Annaler: Series A, Physical Geography.* 97 (2), pp. 337-353.

Freire, P. (1970) *Pedagogy of the Oppressed.* New York, USA: Continuum.

Fritsch, O. and Newig, J. (2009) Participatory governance and sustainability. Early findings of a meta-analysis of stakeholder involvement in environmental decision-making. In: Brousseau, E., Dedeurwaerdere, T. and Siebenhüner, B., eds. *Reflexive Governance for Global Public Goods.* Cambridge, Mass, USA: MIT Press.

Funtowicz, S.O. and Ravetz, J.R. (2003) Post-normal science. In: *International Society for Ecological Economics.* http://www.ecoeco.org/publica/encyc.htm. Online Encyclopedia of Ecological Economics, [Accessed 12 June 2015].

Funtowicz, S.O. and Ravetz, J.R. (1995) Science for the post normal age. In: Westra, L. and Lemons, J., eds. *Perspectives on Ecological Integrity.* Netherlands: Springer, pp. 146-161.

Gaddis, E.J.B., Falk, H.H., Ginger, C. and Voinov, A. (2010) Effectiveness of a participatory modeling effort to identify and advance community water resource goals in St. Albans, Vermont. *Environmental Modelling & Software.* 25 (11), pp. 1428-1438.

Galván, L., Olías, M., Izquierdo, T., Cerón, J. and de Villarán, R.F. (2014) Rainfall estimation in SWAT: An alternative method to simulate orographic precipitation. *Journal of Hydrology.* 509, pp. 257-265.

Gamvroudis, C., Nikolaidis, N., Tzoraki, O., Papadoulakis, V. and Karalemas, N. (2015) Water and sediment transport modeling of a large temporary river basin in Greece. *Science of the Total Environment.* 508, pp. 354-365.

Gao, G.Y., Fu, B.J., Lü, Y.H., Liu, Y., Wang, S. and Zhou, J. (2012) Coupling the modified SCS-CN and RUSLE models to simulate hydrological effects of restoring vegetation in the Loess Plateau of China. *Hydrology and Earth System Sciences.* 16 (7), pp. 2347-2364.

Garrett, A.H. (1909)
Hydraulic Tables and Diagrams for Practical Engineers. New York, USA: Longmas, Green and Co.

Gibbs, G.R. (2008) *Analysing Qualitative Data.* London, UK: SAGE Publications Ltd.

Gibson, S.A. and Little, C.D. (2006) Implementation of the sediment impact assessment model (SIAM) in HEC-RAS. In: *8th Federal Interagency Sedimentation Conference.* Reno, NV, USA, 2-6 April 2006.

Gido, K.B., Dodds, W.K. and Eberle, M.E. (2010) Retrospective analysis of fish community change during a half-century of landuse and streamflow changes. *Journal of the North American Benthological Society.* 29 (3), pp. 970-987.

Gilbert, G.K. (1917) Hydraulic-mining debris in the Sierra Nevada. *United States Geological Survey Professional Paper.*

Gilbert, G.K. and Murphy, E.C. (1914) The transportation of debris by running water. *United States Geological Survey Professional Paper.* 86.

Gillham, B. (2008) *Developing a Questionnaire.* 2nd ed. London, UK: Continuum.

Gilvear, D.J. (1999) Fluvial geomorphology and river engineering: future roles utilizing a fluvial hydrosystems framework. *Geomorphology.* 31 (1–4), pp. 229-245.

Goetz, A.M. and Gaventa, J. (2001) Bringing citizen voice and client focus into service delivery. *Institute of Development Studies,.* Working Paper No. 138 .

Goldin, J.A. (2010) Water policy in South Africa: trust and knowledge as obstacles to reform. *Review of Radical Political Economics.* 42 (2), pp. 195-212.

Goldin, J. (2003) Washing away the sins of the past. *International Journal of Public Administration.* 26 (6), pp. 711-730.

Gottesfeld, A.S., Hassan, M.A., Tunnicliffe, J.F. and Poirier, R.W. (2004) Sediment dispersion in salmon spawning streams: the influence of floods and salmon redd construction. *JAWRA Journal of the American Water Resources Association.* 40 (4), pp. 1071-1086.

Graf, W.L. (1996) Transport and deposition of plutonium-contaminated sediments by fluvial processes, Los Alamos Canyon, New Mexico. *Geological Society of America Bulletin.* 108 (10), pp. 1342-1355.

Gray, D.E. (2009) *Doing Research in the Real World.* London, UK: SAGE Publications Ltd.

Greco, M., Iervolino, M., Leopardi, A. and Vacca, A. (2012) A two-phase model for fast geomorphic shallow flows. *International Journal of Sediment Research.* 27 (4), pp. 409-425.

Greenwood, P. and Kuhn, N.J. (2014) Does the invasive plant, Impatiens glandulifera, promote soil erosion along the riparian zone? An investigation on a small watercourse in northwest Switzerland. *Journal of Soils and Sediments.* 14 (3), pp. 637-650.

Gregory, K.J. (2002) Urban channel adjustments in a management context: an Australian example. *Environmental Management.* 29 (5), pp. 620-633.

Gregory, K.J. (2004) Human activity transforming and designing river landscapes: a review perspective. *Geographica Polonica.* 77, pp. 5-20.

Gregory, K.J. and Goudie, A.S. (2011) *The SAGE Handbook of Geomorphology.* London, UK: SAGE Publications Ltd.

Gregory, K.J., Benito, G. and Downs, P.W. (2008) Applying fluvial geomorphology to river channel management: Background for progress towards a palaeohydrology protocol. *Geomorphology.* 98 (1–2), pp. 153-172.

Gregory, K.J., Lane, S.N., Lewin, J., Ashworth, P.J., Downs, P.W., Kirkby, M.J. and Viles, H.A. (2014) Communicating geomorphology: global challenges for the twenty-first century. *Earth Surface Processes and Landforms.* 39 (4), pp. 476-486.

Grüne-Yanoff, T. and Weirich, P. (2010) The philosophy and epistemology of simulation: a review. *Simulation & Gaming.* 41 (1), pp. 20-50.

Haase, D. (2013) Participatory modelling of vulnerability and adaptive capacity in flood risk management. *Natural Hazards.* 67 (1), pp. 77-97.

Hacking, I. (1983) *Representing and Intervening: Introductory Topics in the Philosophy of Natural Science.* Cambridge, UK: Cambridge University Press.

Haff, P.K. (2010) Hillslopes, rivers, plows, and trucks: mass transport on Earth's surface by natural and technological processes. *Earth Surface Processes and Landforms.* 35 (10), pp. 1157-1166.

Halfpenny, P. (2001) Positivism in the twentieth century. In: Ritzer, G. and Smart, G., eds. *Handbook of Social Theory.* London, UK: SAGE Publications Ltd, pp. 371-385.

Hammersley, M. (1995) *The Politics of Social Research.* London, UK: SAGE Publications Ltd.

Hammersley, M. (2000) *Taking Sides in Social Research: Essays on Partisanship and Bias.* London, UK: Routledge.

Hancock, G., Evans, K., Willgoose, G., Moliere, D., Saynor, M. and Loch, R. (2000) Medium-term erosion simulation of an abandoned mine site using the SIBERIA landscape evolution model. *Soil Research.* 38 (2), pp. 249-264.

Hancock, G., Willgoose, G. and Evans, K. (2002) Testing of the SIBERIA landscape evolution model using the Tin Camp Creek, Northern Territory, Australia, field catchment. *Earth Surface Processes and Landforms.* 27 (2), pp. 125-143.

Hancock, G.R., Lowry, J.B.C. and Coulthard, T.J. (2015) Catchment reconstruction — erosional stability at millennial time scales using landscape evolution models. *Geomorphology.* 231, pp. 15-27.

Hannaford, J., Muchan, K., Lewis, M. and Clemas, S. (2014) Hydrological summary for the United Kingdom: January 2014.

Hansen, B. (1994) Report on the Seminar on integration of indigenous peoples and their knowledge. *Reykjavik.Iceland.Ministry for the Environment (Iceland), Ministry of the Environment (Denmark), and the Home Rule of Greenland (Denmark Office) Copenhagen, Denmark.*

Hare, M. (2011) Forms of participatory modelling and its potential for widespread adoption in the water sector. *Environmental Policy and Governance.* 21 (6), pp. 386-402.

Hare, M., Letcher, R. and Jakeman, A. (2003) Participatory modelling in natural resource management: a comparison of four case studies. *Integrated Assessment.* 4 (2), pp. 62-72.

Hare, M. and Pahl-Wostl, C. (2002) Stakeholder categorisation in participatory integrated assessment processes. *Integrated Assessment.* 3 (1), pp. 50-62.

Harper, D. and Everard, M. (1998) Why should the habitat-level approach underpin holistic river survey and management? *Aquatic Conservation: Marine and Freshwater Ecosystems.* 8 (4), pp. 395-413.

Harrabin, R. (2015) River health revealed in 'shocking' figures. *BBC* [online]. 26 March. Available from: http://www.bbc.co.uk/news/uk-32074953 [Accessed 14 November 2015].

Harris, L.M., Goldin, J.A. and Sneddon, C. (2013) *Contemporary Water Governance in the Global South: Scarcity, Marketization and Participation.* London, UK: Routledge.

Harris, F. and Lyon, F. (2013) Transdisciplinary environmental research: Building trust across professional cultures. *Environmental Science & Policy.* 31, pp. 109-119.

Hartley, N. and Wood, C. (2005) Public participation in environmental impact assessment—implementing the Aarhus Convention. *Environmental Impact Assessment Review.* 25 (4), pp. 319-340.

Hartmann, S. (1996) The world as a process. In: *Modelling and Simulation in the Social Sciences from the Philosophy of Science Point of View.* Netherlands: Springer, pp. 77-100.

Harvey, G.L., Moorhouse, T.P., Clifford, N.J., Henshaw, A.J., Johnson, M.F., Macdonald, D.W., Reid, I. and Rice, S. (2011) Evaluating the role of invasive aquatic species as drivers of fine sediment-related river management problems: the case of the signal crayfish (Pacifastacus leniusculus). *Progress in Physical Geography.* 35 (4), pp. 517-533.

Hayes, T. and Persha, L. (2010) Nesting local forestry initiatives: Revisiting community forest management in a REDD+ world. *Forest Policy and Economics.* 12 (8), pp. 545-553.

HEFCE (2016) *REF Impact.* Available from: http://www.hefce.ac.uk/rsrch/REFimpact/ [Accessed 19 June 2016].

Hendry, K., Cragg-Hine, D., O'Grady, M., Sambrook, H. and Stephen, A. (2003) Management of habitat for rehabilitation and enhancement of salmonid stocks. *Fisheries Research.* 62 (2), pp. 171-192.

Heritage, Z. and Dooris, M. (2009) Community participation and empowerment in Healthy Cities. *Health Promotion International.* 24 (1), pp. 45-55.

Herriott, R.E. and Firestone, W.A. (1983) Multisite qualitative policy research: Optimizing description and generalizability. *Educational Researcher.* 12 (2), pp. 14-19.

Hickey, S. and Mohan, G. (2004) *Participation - from Tyranny to Transformation?: Exploring New Approaches to Participation in Development.* London, UK: Zed books.

Hildyard, N., Hegde, P., Wolvekamp, P. and Reddy, S. (2001) Pluralism, participation and power: joint forest management in India. In: Cooke, B. and Kothari, U., eds. *Participation: The New Tyranny?* London, UK: Zed Books, pp. 56-71.

Hillman, M. (2009) Integrating knowledge: the key challenge for a new paradigm in river management. *Geography Compass.* 3 (6), pp. 1988-2010.

Hisschemöller, M., Tol, R.S. and Vellinga, P. (2001) The relevance of participatory approaches in integrated environmental assessment. *Integrated Assessment.* 2 (2), pp. 57-72.

Hodgson, A.M. (1992) Hexagons for systems thinking. *European Journal of Operational Research.* 59 (1), pp. 220-230.

Hoffmann, T., Penny, D., Stinchcomb, G. and Lu, X.X. (2015) Global Soil and Sediment transfers in the Anthropocene. *PAGES Magazine.* 23 (1), pp. 37.

Hooke, J.M. (2015) Variations in flood magnitude–effect relations and the implications for flood risk assessment and river management. *Geomorphology.* 251, pp. 91-107.

Howarth, W. (2009) Aspirations and realities under the water framework directive: proceduralisation, participation and practicalities. *Journal of Environmental Law.* 21, pp. 391-417.

Hudson, P.F. and Middelkoop, H. (2015) *Geomorphic Approaches to Integrated Floodplain Management of Lowland Fluvial Systems in North America and Europe.* New York, USA: Springer.

Hulme, M. (2007) The appliance of science. *The Guardian* [online]. 14 March. Available from: https://www.theguardian.com/society/2007/mar/14/scienceofclimatechange.climatechange [Accessed 3 June 2015].

Iacob, O., Rowan, J.S., Brown, I. and Ellis, C. (2014) Evaluating wider benefits of natural flood management strategies: an ecosystem-based adaptation perspective. *Hydrology Research.* 45 (6), pp. 774-787.

Inglis, C.C. (1949) *The Behaviour and Control of Rivers and Canals (with the Aid of Models).* Yeravda, USA: Yeravda Prison Press.

Intergovernmental Panel on Climate Change (2014) *Fifth Assessment Report (AR5).* Available from: https://www.ipcc.ch/report/ar5/ [Accessed 12 June 2016].

Intergovernmental Panel on Climate Change (2007) *Erosion and Sediment Transport. in Climate Change 2007: Working Group II: Impacts, Adaptation and Vulnerability, IPCC.* Available from: http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch3s3-4-5.html [Accessed 24 May 2013].

ISIS (2006) *ISIS Flow/Hydrology.* Wallingford: Wallingford Software Ltd. and Halcrow.

Ison, R. and Watson, D. (2007) Illuminating the possibilities for social learning in the management of Scotland's water. *Ecology and Society.* 12 (1), pp. 21.

Jessel, B. and Jacobs, J. (2005) Land use scenario development and stakeholder involvement as tools for watershed management within the Havel River Basin. *Limnologica - Ecology and Management of Inland Waters.* 35 (3), pp. 220-233.

Johnson, M.F., Reid, I., Rice, S.P. and Wood, P.J. (2009) Stabilization of fine gravels by net-spinning caddisfly larvae. *Earth Surface Processes and Landforms.* 34 (3), pp. 413-423.

Jones, N. and Parker, C. (2015) Water quality in two Icelandic rivers: the influence of impoundment, agriculture, glaciation and permafrost. *Hydrology Research.* 46 (3), pp. 429-445.

Jones, N.A., Perez, P., Measham, T.G., Kelly, G.J., d'Aquino, P., Daniell, K.A., Dray, A. and Ferrand, N. (2009) Evaluating participatory modeling: developing a framework for cross-case analysis. *Environmental Management.* 44 (6), pp. 1180-1195.

Jones, M.R., Fowler, H.J., Kilsby, C.G. and Blenkinsop, S. (2013) An assessment of changes in seasonal and annual extreme rainfall in the UK between 1961 and 2009. *International Journal of Climatology.* 33 (5), pp. 1178-1194.

Kadirbeyoğlu, Z. and Kurtiç, E. (2013) Problems and prospects for genuine participation in water governance in Turkey. In: Harris, L.M., Goldin, J., A. and Sneddon, C., eds. *Contemporary Water Governance in the Global South.* Abingdon, UK: Earthscan, pp. 199-215.

Kail, J., McKie, B., Verdonschot, P.F. and Hering, D. (2016) Preface: Effects of hydromorphological river restoration—a comprehensive field investigation of 20 European projects. *Hydrobiologia.* 769 (1), pp. 1-2.

Keen, M., Brown, V.A. and Dyball, R. (2005) *Social Learning in Environmental Management: Towards a Sustainable Future.* Abingdon, UK: Earthscan.

Keesstra, S., Temme, A., Wittenberg, L. and Greenbaum, N. (2011) LAPSUS-D: Testing a New Daily Sediment Delivery Model in a Meso-Scale Mediterranean Catchment in Northern Israel. *AGU Fall Meeting Abstracts* [online]. 1, pp.625.

Keesstra, S.D., Temme, A.J.A.M., Schoorl, J.M. and Visser, S.M. (2014) Evaluating the hydrological component of the new catchment-scale sediment delivery model LAPSUS-D. *Geomorphology.* 212, pp. 97-107.

Kennedy, R.G. (1895) The prevention of silting in irrigation canals. (including appendix). *Minutes of the Proceedings of the Institution of Civil Engineers.* 119 (1895), pp. 281-290.

Kesby, M. (2014) Retheorizing empowerment-through-participation as a performance in space: Beyond tyranny to transformation. *Signs.* 40 (4), pp. 2037-2065.

Kitzinger, J. (1994) The methodology of Focus Groups: the importance of interaction between research participants. *Sociology of Health & Illness.* 16 (1), pp. 103-121.

Kohlhagen, T., Fryirs, K. and Semple, A. (2013) Highlighting the need and potential for use of interdisciplinary science in adaptive environmental management: the case of endangered upland swamps in the Blue Mountains, NSW, Australia. *Geographical Research.* 51 (4), pp. 439-453.

Kondolf, G.M. and Piegay, H. (2016) *Tools in Fluvial Geomorphology.* 2nd ed .Chichester, UK: John Wiley & Sons Ltd

Kondolf, G.M., Piegay, H. and Sear, D. (2003) Integrating geomorphological tools in ecological and management studies. In: Kondolf, G.M. and Piegay, H., eds. *Tools in Fluvial Geomorphology.* 1st ed. Chichester, UK: John Wiley & Sons Ltd, pp. 633-660.

Koontz, T.M. and Thomas, C.W. (2006) What do we know and need to know about the environmental outcomes of collaborative management? *Public Administration Review.* 66, (1), pp. 111-121.

Kvale, S. (2008) *Doing Interviews.* London, UK.: SAGE Publications Ltd.

Lacey, G. (1939) *Regime Flow in Incoherent Alluvium.* India: Central Board of Irrigation and Power.

Lacey, G. (1934) Uniform flow in alluvial rivers and canals. *Minutes of Proceedings of the Institution of Civil Engineers, London.* 237 (1), pp. 421-453.

Lane, E.W. (1955) The importance of fluvial morphology in hydraulic engineering. *Proceedings of the American Society of Civil Engineers.* 81 (1-17).

Lane, S.N. (2011) Making mathematical models perform in geographical space (s). In: Agnew, J.A. and Livingstone, D.N., eds. *The SAGE Handbook of Geographical Knowledge.* London, UK: SAGE Publications Ltd, pp. 228-245.

Lane, S.N. (2012) 21st century climate change: where has all the geomorphology gone? *Earth Surface Processes and Landforms.* 38 (1), pp. 106-110.

Lane, S.N. and Richards, K.S. (1997) Linking River Channel Form and Process: Time, Space and Causality Revisited. *Earth Surface Processes and Landforms.* 22 (3), pp. 249-260.

Lane, S.N. and Richards, K.S. (2001) The 'validation'of hydrodynamic models: some critical perspectives. *Model Validation: Perspectives in Hydrological Science.* 413, pp. 439.

Lane, S.N., Bradbrook, K.F., Richards, K.S., Biron, P.A. and Roy, A.G. (1999) The application of computational fluid dynamics to natural river channels: three-dimensional versus two-dimensional approaches. *Geomorphology.* 29 (1–2), pp. 1-20.

Lane, S.N., Tayefi, V., Reid, S.C., Yu, D. and Hardy, R.J. (2007) Interactions between sediment delivery, channel change, climate change and flood risk in a temperate upland environment. *Earth Surface Processes and Landforms.* 32 (3), pp. 429-446.

Lane, S.N. and Thorne, C.R. (2006) River Processes. In: Thorne, C.R., Evans, E.P. and Penning-Rowsell, E., eds. *Future Flooding and Coastal Erosion Risks.* London, UK: Thomas Telford, pp. 82-99.

Lane, S. N., Odoni, N., Landström, C., Whatmore, S. J., Ward, N. and Bradley, S. (2011) Doing flood risk science differently: an experiment in radical scientific method. *Transactions of the Institute of British Geographers*. 36, pp. 15–36.

Laniak, G.F., Olchin, G., Goodall, J., Voinov, A., Hill, M., Glynn, P., Whelan, G., Geller, G., Quinn, N., Blind, M., Peckham, S., Reaney, S., Gaber, N., Kennedy, R. and Hughes, A. (2013) Integrated environmental modeling: A vision and roadmap for the future. *Environmental Modelling & Software.* 39, pp. 3-23.

Latour, B. (1999) *Pandora's Hope: Essays on the Reality of Science Studies.* Cambridge, MA: Harvard University Press.

Lawrence, A. (2006) 'No personal motive?'Volunteers, biodiversity, and the false dichotomies of participation. *Ethics Place and Environment.* 9 (3), pp. 279-298.

Lean, G. (2016) UK flooding: How a Yorkshire town worked with nature to stay dry. *Independant* [online]. 2 January. Available from: http://www.independent.co.uk/news/uk/home-news/uk-flooding-how-a-yorkshire-flood-blackspot-worked-with-nature-to-stay-dry-a6794286.html [Accessed 6 May 2016].

Lebel, L., Grothmann, T. and Siebenhüner, B. (2010) The role of social learning in adaptiveness: insights from water management. *International Environmental Agreements: Politics, Law and Economics.* 10 (4), pp. 333-353.

Leopold, L.B. (2004) Geomorphology: a sliver off the corpus of science. *Annual Review of Earth and Planetary Sciences.* 32, pp. 1-12.

Leopold, L.B. and Maddock, T. (1953) *The Hydraulic Geometry of Stream Channels and some Physiographic Implications.* Professional Paper 252, United States Geological Survey.

Lewin, J. and Macklin, M.G. (2014) Marking time in Geomorphology: should we try to formalise an Anthropocene definition? *Earth Surface Processes and Landforms.* 39 (1), pp. 133-137.

Lewis, S.L. and Maslin, M.A. (2015) Defining the Anthropocene. *Nature.* 519, pp. 171-180.

Lindley, E. (1919) Regime channels. *Proceedings of Punjab Engineering Congress.* 7, pp. 63-74.

Lindsay, J. (2014) The whitebox geospatial analysis tools project and open-access GIS. In: *Proceedings of the GIS Research UK 22nd Annual Conference.*

Lu, X.X., Zhang, S. and Xu, J. (2010) Climate change and sediment flux from the Roof of the World. *Earth Surface Processes and Landforms.* 35 (6), pp. 732-735.

Ly, S., Charles, C. and Degré, A. (2013) Different methods for spatial interpolation of rainfall data for operational hydrology and hydrological modeling at watershed scale. A review. *Biotechnologie, Agronomie, Société Et Environnement.* 17 (2), pp. 392.

Lynam, T., De Jong, W., Sheil, D., Kusumanto, T. and Evans, K. (2007) A review of tools for incorporating community knowledge, preferences, and values into decision making in natural resources management. *Ecology and Society.* 12 (1), pp. 5.

Macnaghten, P. and Jacobs, M. (1997) Public identification with sustainable development: Investigating cultural barriers to participation. *Global Environmental Change.* 7 (1), pp. 5-24.

Mapinduzi, A.L., Oba, G., Weladji, R.B. and Colman, J.E. (2003) Use of indigenous ecological knowledge of the Maasai pastoralists for assessing rangeland biodiversity in Tanzania. *African Journal of Ecology.* 41 (4), pp. 329-336.

Martin, A. and Sherington, J. (1997) Participatory research methods—Implementation, effectiveness and institutional context. *Agricultural Systems.* 55 (2), pp. 195-216.

Masih, I., Maskey, S., Uhlenbrook, S. and Smakhtin, V. (2011) Assessing the Impact of Areal Precipitation Input on Streamflow Simulations Using the SWAT Model. *Journal of the American Water Resources Association.* 47 (1), pp. 179-195.

Maskrey, S.A., Mount, N.J., Thorne, C.R. and Dryden, I. (2016) Participatory modelling for stakeholder involvement in the development of flood risk management intervention options. *Environmental Modelling & Software.* 82, pp. 275-294.

Maxwell, J.A. (2012) *A Realist Approach for Qualitative Research.* London, UK: SAGE Publications Ltd.

May, R.W.P., Ackers, J.C. and Kirby, A.M. (2002) *Manual on Scour at Bridges and Other Hydraulic Structures.* London, UK: Construction Industry Research and Information Association (CIRIA).

McDermott, M.H. (2009) Locating benefits: Decision-spaces, resource access and equity in US community-based forestry. *Geoforum.* 40 (2), pp. 249-259.

McDougall, C., Jiggins, J., Pandit, B.H., Thapa Magar Rana, Sushila K and Leeuwis, C. (2013) Does adaptive collaborative forest governance affect poverty? Participatory action research in Nepal's community forests. *Society & Natural Resources.* 26 (11), pp. 1235-1251.

McEwen, L., Jones, O. and Robertson, I. (2014) 'A glorious time?' Some reflections on flooding in the Somerset Levels. *The Geographical Journal.* 180 (4), pp. 326-337.

McIntyre, N. and Thorne, C. (2013) *Land use Management Effects on Flood Flows and Sediments - Guidance on Prediction.* London, UK: Construction Industry Research and Information Association (CIRIA).

Meadows, D.L., Fiddaman, T. and Shannon, D. (1986) Fish Banks, Ltd. A Microcomputer Assisted Group Simulation That Teaches Principles of Sustainable Management of Renewable Natural Resources. In: *Laboratory for Interactive Learning.* Durham, USA: University of New Hampshire.

Meitzen, K.M., Doyle, M.W., Thoms, M.C. and Burns, C.E. (2013) Geomorphology within the interdisciplinary science of environmental flows. *Geomorphology.* 200, pp. 143-154.

Mendoza, G.A. and Prabhu, R. (2005) Combining participatory modeling and multi-criteria analysis for community-based forest management. *Forest Ecology and Management.* 207 (1–2), pp. 145-156.

Metcalf, S.S., Wheeler, E., BenDor, T.K., Lubinski, K.S. and Hannon, B.M. (2010) Sharing the floodplain: Mediated modeling for environmental management. *Environmental Modelling & Software.* 25 (11), pp. 1282-1290.

Michener, V.J. (1998) The participatory approach: contradiction and co-option in Burkina Faso. *World Development.* 26 (12), pp. 2105-2118.

Mikuś, P., Wyżga, B., Radecki-Pawlik, A., Zawiejska, J., Amirowicz, A. and Oglęcki, P. (In Press) Environment-friendly reduction of flood risk and infrastructure damage in a mountain river: Case study of the Czarny Dunajec. *Geomorphology.*

Miller, T.R., Baird, T.D., Littlefield, C.M., Kofinas, G., Chapin III, F.S. and Redman, C.L. (2008) Epistemological pluralism: reorganizing interdisciplinary research. *Ecology and Society.* 13 (2), pp. 46.

Mingers, J., Mutch, A. and Willcocks, L. (2013) Critical realism in information systems research. *MIS Quarterly.* 37 (3), pp. 795-802.

Mishra, S.K. and Singh, V. (2003) *Soil Conservation Service Curve Number (SCS-CN) Methodology.* Baton Rouge, USA: Springer Science & Business Media.

Moir, H.J., Soulsby, C. and Youngson, N.A. (1998) Hydraulic and sedimentary characteristics of habitat utilized by Atlantic salmon for spawning in the Girnock Burn, Scotland. *Fisheries Management and Ecology.* 5 (3), pp. 241-254.

Mollinga, P.P. (2009) Towards the transdisciplinary engineer: Incorporating ecology, equity and democracy concerns into water professionals' attitudes, skills and knowledge. *Irrigation and Drainage.* 58, pp. 195-204.

Monbiot, G. (2015) We're treating soil like dirt. It's a fatal mistake, as our lives depend on it. *The Guardian* [online]. 25 March. Available from: https://www.theguardian.com/commentisfree/2015/mar/25/treating-soil-like-dirt-fatal-mistake-human-life [Accessed 15 May 2016].

Montané, A., Vinet, F., Buffin-Béranger, T., Vento, O. and Masson, M. (2015) Cartographie hydrogéomorphologique: émergence d'utilisations règlementaires en France. *Physio-Géo.Géographie, Physique, Et Environnement.* 9, pp. 37-60.

Montgomery, D.R. (2007) Soil Erosion and Agricultural Sustainability. *Proceedings of the National Academy of Sciences of the United States of America.* 104 (33), pp. 13268-13272.

Morris, S. (2014) Somerset Levels river dredging begins after flood-hit winter. *The Guardian* [online]. 31 March. Available from: https://www.theguardian.com/environment/2014/mar/31/somerset-levels-river-dredging-begins-floods [Accessed 14 December 2015].

Munn, P. and Drever, E. (1990) *Using Questionnaires in Small-Scale Research. A Teachers' Guide.* Edinburgh, UK: Scottish Council for Research in Education.

Murray, A.B. and Paola, C. (1994) A cellular model of braided rivers. *Nature.* 371, pp. 54-57.

Mychajliw, A.M., Kemp, M.E. and Hadly, E.A. (2015) Using the Anthropocene as a teaching, communication and community engagement opportunity. *The Anthropocene Review.* 2 (3), pp. 267-278.

Naiman, R.J. (1999) A perspective on interdisciplinary science. *Ecosystems.* 2 (4), pp. 292-295.

Nardi, F., Annis, A. and Biscarini, C. (2015) On the impact of urbanization on flood hydrology of small ungauged basins: the case study of the Tiber river tributary network within the city of Rome. *Journal of Flood Risk Management.*

Neitsch, S.L., Arnold, J.G., Kiniry, J.R. and Williams, J.R. (2011) *Soil and Water Assessment Tool Theoretical Documentation Version 2009.* Texas Water Resources Institute.

NetLogo (2015) *NetLogo.* Available from: https://ccl.northwestern.edu/netlogo/index.shtml [Accessed 28 March 2015].

Newig, J., Gaube, V., Berkhoff, K., Kaldrack, K., Kastens, B., Lutz, J., Schlußmeier, B., Adensam, H. and Haberl, H. (2008) The role of formalisation, participation and context in the success of public involvement mechanisms in resource management. *Systemic Practice and Action Research.* 21 (6), pp. 423-441.

Newig, J., Günther, D. and Pahl-Wostl, C. (2010) Synapses in the network: learning in governance networks in the context of environmental management. *Ecology and Society.* 15 (4), pp. 24.

Newson, M. and Newson, C. (2000) Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. *Progress in Physical Geography.* 24 (2), pp. 195-217.

Newson, M.D. and Large, A.R.G. (2006) 'Natural' rivers, 'hydromorphological quality' and river restoration: a challenging new agenda for applied fluvial geomorphology. *Earth Surface Processes and Landforms.* 31 (13), pp. 1606-1624.

Nicholas, A.P. and Quine, T.A. (2007) Crossing the divide: Representation of channels and processes in reduced-complexity river models at reach and landscape scales. *Geomorphology.* 90 (3–4), pp. 318-339.

Nicholas, A.P. (2005) Cellular modelling in fluvial geomorphology. *Earth Surface Processes and Landforms.* 30 (5), pp. 645-649.

Ockenden, M.C., Deasy, C., Quinton, J.N., Surridge, B. and Stoate, C. (2014) Keeping agricultural soil out of rivers: evidence of sediment and nutrient accumulation within field wetlands in the UK. *Journal of Environmental Management.* 135, pp. 54-62.

Okali, C., Sumberg, J. and Farrington, J. (1994) *Farmer Participatory Research: Rhetoric and Reality.* Bradford, UK: Intermediate Technology Publications Ltd.

Oswalt, S.N. and King, S.L. (2005) Channelization and floodplain forests: Impacts of accelerated sedimentation and valley plug formation on floodplain forests of the Middle Fork Forked Deer River, Tennessee, USA. *Forest Ecology and Management.* 215 (1–3), pp. 69-83.

Owens, P.N., Batalla, R.J., Collins, A.J., Gomez, B., Hicks, D.M., Horowitz, A.J., Kondolf, G.M., Marden, M., Page, M.J., Peacock, D.H., Petticrew, E.L., Salomons, W. and Trustrum, N.A. (2005) Fine-grained sediment in river systems: environmental significance and management issues. *River Research and Applications.* 21 (7), pp. 693-717.

Pahl-Wostl, C., Kabat, P. and Möltgen, J. (2008) *Adaptive and Integrated Water Management.* Berlin, Germany: Springer.

Pahl-Wostl, C., Craps, M., Dewulf, A., Mostert, E., Tabara, D. and Taillieu, T. (2007) Social learning and water resources management. *Ecology and Society.* 12 (2), pp. 5.

Palmer, M., Covich, A., Finlay, B., Gilbert, J., Hyde, K., Johnson, R., Kairesala, T., Lake, P., Lovell, C. and Naiman, R. (1997) Biodiversity and ecosystem processes in freshwater sediments. *Ambio.* pp. 571-577.

Palmer, R.N., Werick, W.J., MacEwan, A. and Woods, A.W. (1999) Modeling water resources opportunities, challenges and trade-offs: The use of shared vision modeling for negotiation and conflict resolution. In:
Proceedings of the ASCE 's 26th Annual Conference on Water Resources Planning andManagement. Tempe, AZ, 6-9 June 1999. Virgina, USA: American Society of Civil Engineers.

Palmer, M.A. and Bernhardt, E.S. (2006) Hydroecology and river restoration: Ripe for research and synthesis. *Water Resources Research.* 42 (3), pp. 1-4.

Parker, C. (2010) *Quantifying Catchment-Scale Coarse Sediment Dynamics in British Rivers*. Unpublished PhD, The University of Nottingham.

Parker, C., Thorne, C.R. and Clifford, N.J. (2015) Development of ST:REAM: a reach-based stream power balance approach for predicting alluvial river channel adjustment. *Earth Surface Processes and Landforms.* 40 (3), pp. 403-413.

Patton, M.Q. (1990) *Qualitative Evaluation and Research Methods.* 2nd ed. London, UK: SAGE Publications Ltd.

Pearson, C., Reaney, S., Bracken, L. and Butler, L. (2015) Investigating the potential to reduce flood risk through catchment-based land management techniques and interventions in the River Roe catchment, Cumbria, UK. In: *EGU General Assembly Conference Abstracts.* Vienna, Austria, 12-12 April 2015. Copernicus.

Piégay, H. and Gregory, K. (2005) Large wood in European Rivers: dynamics, human perception, challenge for restoration and application to other areas. In: *ESF LESC Exploratory Workshop, European Science Foundation.*

Pohjola, M.V. and Tuomisto, J.T. (2011) Openness in participation, assessment, and policy making upon issues of environment and environmental health: a review of literature and recent project results. *Environmental Health.* 10, pp. 1-13.

Pohl, C. and Hadorn, G.H. (2007) *Principles for Designing Transdisciplinary Research.* Munich, Germany: oekom.

Praskievicz, S. (2015) A coupled hierarchical modeling approach to simulating the geomorphic response of river systems to anthropogenic climate change. *Earth Surface Processes and Landforms.* 40 (12), pp. 1616-1630.

Prell, C., Hubacek, K., Reed, M., Quinn, C., Jin, N., Holden, J., Burt, T., Kirby, M. and Sendzimir, J. (2007) If you have a hammer everything looks like a nail: traditional versus participatory model building. *Interdisciplinary Science Reviews.* 32 (3), pp. 263-282.

Pretty, J.N. (1995) Participatory learning for sustainable agriculture. *World Development.* 23 (8), pp. 1247-1263.

Pretty, J.N., Guijt, I., Thompson, J. and Scoones, I. (1995) *Participatory Learning and Action: A Trainer's Guide.* London, UK: IIED.

Rahman, K., Maringanti, C., Beniston, M., Widmer, F., Abbaspour, K. and Lehmann, A. (2013) Streamflow modeling in a highly managed mountainous glacier watershed using SWAT: the Upper Rhone River watershed case in Switzerland. *Water Resources Management.* 27 (2), pp. 323-339.

Ramanath, A.M. and Gilbert, N. (2004) The design of participatory agent-based social simulations. *Journal of Artificial Societies and Social Simulation.* 7 (4), pp. 1.

Ramirez, R. (1999) Participatory learning and communication approaches for managing pluralism: Implications for sustainable forestry, agriculture and rural development. In: *Pluralism and Sustainable Forestry and Rural Development: Proceedings of the International Workshop on Pluralism and Sustainable Forestry and Rural Development.* Rome, Italy, 19-12 December 1997. FAO.

Reed, M., Evely, A.C., Cundill, G., Fazey, I.R.A., Glass, J., Laing, A., Newig, J., Parrish, B., Prell, C. and Raymond, C. (2010) What is social learning? *Ecology and Society.* 14 (4), pp. 1-10.

Reed, M. (2007) Participatory technology development for agroforestry extension: an innovation-decision approach. *African Journal of Agricultural Research.* 2 (8), pp. 334-341.

Reed, M.S. (2008) Stakeholder participation for environmental management: A literature review. *Biological Conservation.* 141 (10), pp. 2417-2431.

Reed, M.S. and Dougill, A.J. (2010) Linking degradation assessment to sustainable land management: A decision support system for Kalahari pastoralists. *Journal of Arid Environments.* 74 (1), pp. 149-155.

Reed, M.S., Dougill, A.J. and Baker, T.R. (2008) Participatory Indicator Development: What Can Ecologists and Local Communities Learn from Each Other? *Ecological Applications.* 18 (5), pp. 1253-1269.

Reed, M.S., Fraser, E.D.G. and Dougill, A.J. (2006) An adaptive learning process for developing and applying sustainability indicators with local communities. *Ecological Economics.* 59 (4), pp. 406-418.

Repko, A.F., Szostak, R. and Buchberger, M.P. (2013) *Introduction to Interdisciplinary Studies.* London, UK: Sage Publications Ltd.

Rice, S.P., Lancaster, J. and Kemp, P. (2010) Experimentation at the interface of fluvial geomorphology, stream ecology and hydraulic engineering and the development of an effective, interdisciplinary river science. *Earth Surface Processes and Landforms.* 35 (1), pp. 64-77.

Richards, C., Blackstock, K.L. and Carter, C.E. (2004) *Practical Approaches to Participation.* 1st ed. Aberdeen, UK: Macaulay Institute.

Richards, K. (2009) Geography and the physical sciences tradition. In: Clifford, N.J., Holloway, S.L., Rice, S.P. and Valentine, G., eds. *Key Concepts in Geography.* London, UK: SAGE Publications Ltd, pp. 21-45.

Richardson, G.P. and Andersen, D.F. (1995) Teamwork in group model building. *System Dynamics Review.* 11 (2), pp. 113-137.

Ridder, D., Mostert, E. and Wolters, H.A. (2006) *Learning Together to Manage Together: Improving Participation in Water Management.* Osnabruck, Germany: University of Osnabruck, Institute of Environmental Systems Research.

Rinaldi, M., Surian, N., Comiti, F. and Bussettini, M. (2013) A method for the assessment and analysis of the hydromorphological condition of Italian streams: The Morphological Quality Index (MQI). *Geomorphology.* 180–181, pp. 96-108.

Rinaldi, M., Wyga, B. and Surian, N. (2005) Sediment mining in alluvial channels: physical effects and management perspectives. *River Research and Applications.* 21 (7), pp. 805-828.

Rinaldi, M., Simoncini, C. and Piégay, H. (2009) Scientific design strategy for promoting sustainable sediment management: the case of the Magra River (Central-Northern Italy). *River Research and Applications.* 25 (5), pp. 607-625.

Rist, S., Chidambaranathan, M., Escobar, C., Wiesmann, U. and Zimmermann, A. (2007) Moving from sustainable management to sustainable governance of natural resources: The role of social learning processes in rural India, Bolivia and Mali. *Journal of Rural Studies.* 23 (1), pp. 23-37.

Ritchie, J. and Lewis, J. (2003) *Qualitative Research Practice: A Guide for Social Science Students and Researchers.* 1st ed. London, UK: SAGE Publications Ltd.

Robson, C. (2002) *Real World Research: A Resource for Social Scientists and Practitioners-Researchers.* 2nd ed. Oxford, UK: Blackwell.

Rollet, A.J., Piégay, H., Dufour, S., Bornette, G. and Persat, H. (2014) Assessment of consequences of sediment deficit on a gravel river bed downstream of dams in restoration perspectives: application of a multicriteria, hierarchical and spatially explicit diagnosis. *River Research and Applications.* 30 (8), pp. 939-953.

Rosgen, D.L. and Silvey, H.L. (1996) *Applied River Morphology.* Pagosa Springs, CO, USA: Wildland Hydrology.

Rouillard, J.J., Reeves, A.D., Heal, K.V. and Ball, T. (2014) The role of public participation in encouraging changes in rural land use to reduce flood risk. *Land use Policy.* 38, pp. 637-645.

Rowan, J., Carwardine, J., Duck, R., Bragg, O., Black, A., Cutler, M., Soutar, I. and Boon, P. (2006) Development of a technique for lake habitat survey (LHS) with applications for the European Union Water Framework Directive. *Aquatic Conservation: Marine and Freshwater Ecosystems.* 16 (6), pp. 637-657.

Rowe, G. and Frewer, L.J. (2000) Public participation methods: A framework for evaluation. *Science, Technology & Human Values.* 25 (1), pp. 3-29.

Rugg, G. and McGeorge, P. (2005) The sorting techniques: a tutorial paper on card sorts, picture sorts and item sorts. *Expert Systems.* 22 (3), pp. 94-107.

Russell, A., Perks, M., Large, A., Dunning, S. and Warburton, J. (2016) Fluvial geomorphological response along the upland sediment cascade during the record-breaking December 2015 floods, Cumbria, UK. In: *EGU General Assembly Conference Abstracts.* Vienna, Austria, 17-22 April 2016.

Sample, J.E., Duncan, N., Ferguson, M. and Cooksley, S. (2015) Scotland׳s hydropower: Current capacity, future potential and the possible impacts of climate change. *Renewable and Sustainable Energy Reviews.* 52, pp. 111-122.

Savin-Baden, M. and Major, C.H. (2013) *Qualitative Research: The Essential Guide to Theory and Practice.* London, UK: Routledge.

Sayer, A. (2000) *Realism and Social Science.* London, UK: SAGE Publications Ltd.

Schaller, N., Kay, A.L., Lamb, R., Massey, N.R., Van Oldenborgh, G.J., Otto, F.E.L., Sparrow, S.N., Vautard, R.t., Yiou, P.l. and Ashpole, I. (2016) Human influence on climate in the 2014 southern England winter floods and their impacts. *Nature Climate Change.* 6 (6), pp. 627-634.

Schoorl, J.M., Sonneveld, M.P.W. and Veldkamp, A. (2000) Three-dimensional landscape process modelling: the effect of DEM resolution. *Earth Surface Processes and Landforms.* 25 (9), pp. 1025-1034.

Schumm, S. (1973) Geomorphic thresholds and complex response of drainage systems. In: Morisawa, M., ed. *Fluvial Geomorphology.* New York, USA: Binghamton, pp. 299-309.

Schumm, S.A. (1969) River metamorphosis. *Journal of the Hydraulics Division.* ASCE 95 (HY1), pp. 255-273.

Schumm, S.A. (1977) *The Fluvial System.* New York, USA: Wiley.

Sear, D.A., Newson, M.D. and Thorne, R. (2004) *Guidebook of Applied Fluvial Geomorphology: Defra/Environment Agency Flood and Coastal Defence R&D Programme.* London, UK: Defra Flood Management Division.

Sear, D.A., Darby, S.E., Thorne, C.R. and Brookes, A.B. (1994) Geomorphological approach to stream stabilization and restoration: Case study of the Mimmshall brook, hertfordshire, UK. *Regulated Rivers: Research & Management.* 9 (4), pp. 205-223.

Senecah, S.L. (2004) The trinity of voice: The role of practical theory in planning and evaluating the effectiveness of environmental participatory processes. In: *Communication and Public Participation in Environmental Decision Making.* New York, USA: State University of New York Press, pp. 13-33.

SEPA (2011) *Allan Water Natural Flood Management Techniques and Scoping Study. Appendix A.* Available from: http://docplayer.net/5909057-Allan-water-natural-flood-management-techniques-and-scoping-study.html [Accessed 14 March 2013].

Shipman, M.D. (1997) *The Limitations of Social Research.* 4th ed. London, UK: Routledge.

Shuker, J.L., Moggridge, H.L. and Gurnell, A.M. (2015) Assessment of hydromorphology following restoration measures in heavily modified rivers: illustrating the potential contribution of the Urban River Survey to Water Framework Directive investigations. *Area.* 47 (4), pp. 396-407.

Siebenhüner, B. and Barth, V. (2005) The role of computer modelling in participatory integrated assessments. *Environmental Impact Assessment Review.* 25 (4), pp. 367-389.

Sievanen, L., Campbell, L.M. and Leslie, H.M. (2012) Challenges to Interdisciplinary Research in Ecosystem-Based Management; Retos para la Investigación Interdisciplinaria en el Manejo Basado en Ecosistemas. *Conservation Biology.* 26 (2), pp. 315-323.

Simon, C. and Etienne, M. (2010) A companion modelling approach applied to forest management planning. *Environmental Modelling & Software.* 25 (11), pp. 1371-1384.

Slater, L.J., Singer, M.B. and Kirchner, J.W. (2015) Hydrologic versus geomorphic drivers of trends in flood hazard. *Geophysical Research Letters.* 42 (2), pp. 370-376.

Slingo, J., Belcher, S., Scaife, A., McCarthy, M., Saulter, A., McBeath, K., Jenkins, A., Huntingford, C., Marsh, T. and Hannaford, J. (2014) *The Recent Storms and Floods in the UK.* Available from:

http://www.metoffice.gov.uk/media/pdf/1/2/Recent_Storms_Briefing_Final_SLR_20140211.pdf [Accessed 25 March 2014].

Smith, B.D. and Zeder, M.A. (2013) The onset of the Anthropocene. *Anthropocene.* 4, pp. 8-13.

Smolders, A., Lock, R., Van der Velde, G., Hoyos, R.M. and Roelofs, J. (2003) Effects of mining activities on heavy metal concentrations in water, sediment, and macroinvertebrates in different reaches of the Pilcomayo River, South America. *Archives of Environmental Contamination and Toxicology.* 44 (3), pp. 314-323.

Soulsby, C., Youngson, A.F., Moir, H.J. and Malcolm, I.A. (2001) Fine sediment influence on salmonid spawning habitat in a lowland agricultural stream: a preliminary assessment. *Science of the Total Environment.* 265 (1–3), pp. 295-307.

Squires, H. and Renn, O. (2011) Can participatory modelling support social learning in marine fisheries? Reflections from the invest in Fish South West Project. *Environmental Policy and Governance.* 21 (6), pp. 403-416.

Staddon, C. (2010a) In: *Public Participation in Water Management: Comparative Implementations of the Water Framework Directive in the UK, France & Bulgaria.* Institute for Geography and Geophysics, Bulgarian Academy of Sciences, 14 October 2010.

Staddon, C. (2010b) *Managing Europe's Water Resources: Twenty-First Century Challenges.* Farnham, UK: Ashgate Publishing Ltd.

StarLogo (2015) *StarLogo TNG.* Available from: http://education.mit.edu/portfolio_page/starlogo-tng/ [Accessed 14 March 2015].

Steffen, W., Crutzen, P.J. and McNeill, J.R. (2007) The Anthropocene: are humans now overwhelming the great forces of nature. *AMBIO: A Journal of the Human Environment.* 36 (8), pp. 614-621.

Stewart, D.W. and Shamdasani, P.N. (2006) *Focus Groups: Theory and Practice.* 3rd ed. London, UK: SAGE Publications Ltd.

Stringer, L.C., Dougill, A.J., Fraser, E., Hubacek, K., Prell, C. and Reed, M.S. (2006) Unpacking “participation” in the adaptive management of social–ecological systems: a critical review. *Ecology and Society.* 11 (2), pp. 39.

SWAT (2015) *Soil & Water Assessment Tool.* Available from: http://swat.tamu.edu/ [Accessed 26 August 2015].

Syvitski, J.P., Vorosmarty, C.J., Kettner, A.J. and Green, P. (2005) Impact of humans on the flux of terrestrial sediment to the global coastal ocean. *Science.* 308 (5720), pp. 376-380.

Tanguy, M., Dixon, H., Prosdocimi, I., Morris, D. G. and Keller, V. D. J. (2016) Gridded estimates of daily and monthly areal rainfall for the United Kingdom (1890-2015) [CEH-GEAR]. NERC Environmental Information Data Centre.

The National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine (2005) *Facilitating Interdisciplinary Research.* Washington, DC: The National Academies Press.

Thomas, J.C. (1993) Public involvement and governmental effectiveness a decision-making model for public managers. *Administration & Society.* 24 (4), pp. 444-469.

Thomas, R. and Nicholas, A.P. (2002) Simulation of braided river flow using a new cellular routing scheme. *Geomorphology.* 43 (3–4), pp. 179-195.

Thompson, A. and Clayton, J. (2002) The role of geomorphology in flood risk assessment. *Proceedings of ICE.* 150 (5), pp. 25-29.

Thorne, C.R., Hey, R.D. and Newson, M.D. (1997) *Applied Fluvial Geomorphology for River Engineering and Management.* Chichester, UK: John Wiley & Sons Ltd.

Thorne, C. (2014) Geographies of UK flooding in 2013/4. *The Geographical Journal.* 180 (4), pp. 297-309.

Tippett, J., Handley, J.F. and Ravetz, J. (2007) Meeting the challenges of sustainable development—A conceptual appraisal of a new methodology for participatory ecological planning. *Progress in Planning.* 67 (1), pp. 9-98.

Tippett, J., Searle, B., Pahl-Wostl, C. and Rees, Y. (2005) Social learning in public participation in river basin management—early findings from HarmoniCOP European case studies. *Environmental Science & Policy.* 8 (3), pp. 287-299.

Tress, B., Tress, G. and Fry, G. (2005) Defining concepts and the process of knowledge production in integrative research. In: Tress, B., Tress, G., Fry, G. and Opdan, P., eds. *From Landscape Research to Landscape Planning.* Dordrecht, Netherlands: Springer, pp. 13-26.

Tucker, G., Lancaster, S., Gasparini, N. and Bras, R. (2001) The channel-hillslope integrated landscape development model (CHILD). In: Harmon, R.S. and Doe III, W.W., eds. *Landscape Erosion and Evolution Modeling.* New York, USA: Kluwer Academic/Plenum Publishers, pp. 349-388.

Tucker, G.E. and Bras, R.L. (1998) Hillslope processes, drainage density, and landscape morphology. *Water Resources Research.* 34 (10), pp. 2751-2764.

Tucker, G.E. and Hancock, G.R. (2010) Modelling landscape evolution. *Earth Surface Processes and Landforms.* 35 (1), pp. 28-50.

Uehlinger, U., Naegeli, M. and Fisher, S.G. (2002) A heterotrophic desert stream? The role of sediment stability. *Western North American Naturalist.* 62 (4), pp. 466-473.

Van De Wiel, M.J., Coulthard, T.J., Macklin, M.G. and Lewin, J. (2007) Embedding reach-scale fluvial dynamics within the CAESAR cellular automaton landscape evolution model. *Geomorphology.* 90 (3), pp. 283-301.

van den Belt, M. (2004) *Mediated Modeling: A System Dynamics Approach to Environmental Consensus Building.* Washington, DC: Island press.

Van den Hove, S. (2000) Participatory approaches to environmental policy-making: the European Commission Climate Policy Process as a case study. *Ecological Economics.* 33 (3), pp. 457-472.

Van Tatenhove, J.P. and Leroy, P. (2003) Environment and participation in a context of political modernisation. *Environmental Values.* 12 (2), pp. 155-174.

Vaughan, I.P., Diamond, M., Gurnell, A.M., Hall, K.A., Jenkins, A., Milner, N.J., Naylor, L.A., Sear, D.A., Woodward, G. and Ormerod, S.J. (2009) Integrating ecology with hydromorphology: a priority for river science and management. *Aquatic Conservation: Marine and Freshwater Ecosystems.* 19 (1), pp. 113-125.

Vennix, J.A.M. (1996) *Group Model Building: Facilitating Team Learning using System Dynamics.* Chichester, UK: John Wiley and Sons.

Videira, N., Antunes, P. and Santos, R. (2009) Scoping river basin management issues with participatory modelling: The Baixo Guadiana experience. *Ecological Economics.* 68 (4), pp. 965-978.

Voinov, A. and Bousquet, F. (2010) Modelling with stakeholders. *Environmental Modelling & Software.* 25 (11), pp. 1268-1281.

Vugteveen, P., Besselaar, P.V.d. and Lenders, H.J.R. (2014) The dynamics of interdisciplinary research fields: The case of river research. *Scientometrics.* 100 (1), pp. 73-96.

Waddington, M. and Mohan, G. (2004) Failing forward: going beyond PRA and imposed forms of participation. In: Hickey, S. and Mohan, G., eds. *Participation: From Tyranny to Transformation?* London, UK: Zed Books, pp. 219-234.

Wainwright, J. and Mulligan, M. (2005) *Environmental Modelling: Finding Simplicity in Complexity.* Chichester, UK: John Wiley & Sons Ltd.

Wallerstein, N.P., Soar, P.J. and Thorne, C.R. (2006) River Energy Auditing Scheme (REAS) for catchment flood management planning. In: *International Conference on Fluvial Hydraulics.* Lisbon, Portugal, 6-8 September 2006.

Walz, A., Lardelli, C., Behrendt, H., Grêt-Regamey, A., Lundström, C., Kytzia, S. and Bebi, P. (2007) Participatory scenario analysis for integrated regional modelling. *Landscape and Urban Planning.* 81 (1–2), pp. 114-131.

Wantzen, K.M. and Mol, J.H. (2013) Soil erosion from agriculture and mining: a threat to tropical stream ecosystems. *Agriculture.* 3 (4), pp. 660-683.

Warner, M. (1997) 'Consensus' participation: an example for protected areas planning. *Public Administration and Development.* 17 (4), pp. 413-432.

Webler, T. (1999) The craft and theory of public participation: a dialectical process. *Journal of Risk Research.* 2 (1), pp. 55-71.

Webler, T., Kastenholz, H. and Renn, O. (1995) Public participation in impact assessment: a social learning perspective. *Environmental Impact Assessment Review.* 15 (5), pp. 443-463.

Wehn, U., Rusca, M., Evers, J. and Lanfranchi, V. (2015) Participation in flood risk management and the potential of citizen observatories: A governance analysis. *Environmental Science & Policy.* 48, pp. 225-236.

Whitney, J.W., Glancy, P.A., Buckingham, S.E. and Ehrenberg, A.C. (2015) Effects of rapid urbanization on streamflow, erosion, and sedimentation in a desert stream in the American Southwest. *Anthropocene.* 10, pp. 29-42.

Wilby, R.L., Orr, H.G., Hedger, M., Forrow, D. and Blackmore, M. (2006) Risks posed by climate change to the delivery of Water Framework Directive objectives in the UK. *Environment International.* 32 (8), pp. 1043-1055.

Wilcock, P.R. and Crowe, J.C. (2003) Surface-based transport model for mixed-size sediment. *Journal of Hydraulic Engineering.* 129 (2), pp. 120-128.

Wilensky, U. and Stroup, W. (2002) Participatory Simulations: Envisioning the networked classroom as a way to support systems learning for all. In: *Annual Meeting of the American Educational Research Association.* New Orleans, LA, April 2002.

Wilensky, U. and Stroup, W. (1999) Learning through participatory simulations: Network-based design for systems learning in classrooms. In: *Proceedings of the Computer Support for Collaborative Learning (CSCL) 1999 Conference.* Stanford University, CA, 12-15 December 1999.

Wilkinson, M., Quinn, P., Ghimire, S., Nicholson, A. and Addy, S. (2014) The use of Natural Flood Management to mitigate local flooding in the rural landscape. In: *EGU General Assembly Conference Abstracts.* Vienna, Austra, 27 April - 2 May 2014. Copernicus.

Williams, J.R. (1995) Chapter 25: The EPIC model. In: Singh, V.P., ed. *Computer Models of Watershed Hydrology.* Highlands Ranch, CO: Water Resources Publications, pp. 909-1000.

Williams, J.R. (1975) Sediment-yield prediction with universal equation using runoff energy factor. In: *Sediment-Yield Prediction with Universal Equation using Runoff Energy Factor. .* 28-30 November 1975. Washington, DC: USDA-ARS.

Williams, P.B. (2001) River engineering versus river restoration. In: *ASCE Wetlands Engineering & River Restoration Conference.* Reno, Nevada, 28 August 2001. San Francisco, USA: Philip Williams & Associates Ltd.

Woodward, J. and Foster, I. (1997) Erosion and suspended sediment transfer in river catchments: environmental controls, processes and problems. *Geography.* 82 (4), pp. 353-376.

Wyzga, B.J. (1996) Changes in the magnitude and transformation of flood waves subsequent to the channelization of the Raba River, Polish Carpathians. *Earth Surface Processes and Landforms.* 21 (8), pp. 749-763.

Yin, R.K. (2011) *Applications of Case Study Research.* London, UK: SAGE Publications Ltd.

Yin, R.K. (2008) *Case Study Research: Design and Methods.* London, UK: SAGE Publications Ltd.

Yuen, E., Jovicich, S.S. and Preston, B.L. (2013) Climate change vulnerability assessments as catalysts for social learning: four case studies in south-eastern Australia. *Mitigation and Adaptation Strategies for Global Change.* 18 (5), pp. 567-590.

Zhang, Y., Degroote, J., Wolter, C. and Sugumaran, R. (2009) Integration of Modified Universal Soil Loss Equation (MUSLE) into a GIS framework to assess soil erosion risk. *Land Degradation & Development.* 20 (1), pp. 84-91.

Zhao, Y., Zou, X., Gao, J., Xu, X., Wang, C., Tang, D., Wang, T. and Wu, X. (2015) Quantifying the anthropogenic and climatic contributions to changes in water discharge and sediment load into the sea: A case study of the Yangtze River, China. *Science of the Total Environment.* 536 pp. 803-812.

Ziliani, L., Surian, N., Coulthard, T.J. and Tarantola, S. (2013) Reduced-complexity modeling of braided rivers: Assessing model performance by sensitivity analysis, calibration, and validation. *Journal of Geophysical Research: Earth Surface.* 118 (4), pp. 2243-2262.

Glossary of terms

ArcGIS

ArcGIS is a geographic information system (GIS) for working with maps and geographic information. It is used for: (i) creating and using maps; (ii) compiling geographic data; (iii) analysing mapped information; (iv) sharing and discovering geographic information; (v) using maps and geographic information in a range of applications; and (vi) managing geographic information in a database. Accessible online from www.arcgis.com/

Catchment

This is an area of land where surface water from rain and melting snow or ice converges to a single point at a lower elevation, usually where the river meets the sea or a lake.

Cellular model

A cellular model works by representing the world as a grid of cells (1m to 50m2). Each cell contains values which interact with neighbouring cells as time passes. The cells interact based upon laws, which are represented through mathematical equations.

Discharge

The volume of water passing a certain point, over a set time period e.g. a day or hour.

Deposition

This is the process where materials like mud, sand, pebbles and silt are transported by the river and are eventually dropped. The process of deposition is linked to how much energy a river has. This is determined by how much water there is in the river channel and how fast it is flowing.

Ease of use

This relates to how easy to use the model is to use, and involves factors such as complexity, interface and training required.

Erosion

Erosion involves the wearing away of rock and soil found along the river bed and hill slopes. Erosion also involves the breaking down of the rock particles being carried downstream by the river.

Input

The data that goes into the model e.g. elevation.

Mass-wasting

The process by which soil, sand regolith, and rock move downslope.

Model speed or run-time

The amount of time the model takes to complete a simulation.

Neocorporatism

A united and hierarchical society where the government is the key player in all sectors of society, in which those sectors are required to work for the public interest.

Open source

This type of development model promotes universal access via free license to a product.

Output

The result that is produced after the model has completed a simulation.

Paradigm

A distinct concept or thought pattern, which can often be referred to the set of practices that define a scientific discipline at any particular period of time.

Parameter

A variable that sets the conditions of a model's operation, for example land use or rainfall.

Sediment dynamics

The processes of erosion, transportation, and deposition of sediment within a river catchment.

Sediment yield

The total amount of sediment that exits a catchment or past a certain point over a set time period.

Uncertainty

The estimated amount by which an observed or calculated value may differ from the true value.

Appendices

Appendix A – Requirements analysis post-session questionnaire

University of the West of England
BRISTOL

ENGAGE

Post-session questionnaire

Name: ______________________________

Organisation: ______________________________ Role: ______________________________

Section A: Modelling Usability

1. Who do you think should be responsible for running the model?

☐ *Technical modellers* ☐ *Management stakeholders* ☐ *Small selection of management stakeholders*
☐ *All stakeholders* ☐*Other (please specify):* ____________________

2. Who would you consider to be the target audience for the model outputs?

(Please tick all that apply) ☐ *Management stakeholders* ☐ *All stakeholders* ☐ *General public*
☐*Other (please specify):* ____________________

3. How many times have you used a model in your current role in the past year?

☐ *Once* ☐ *Twice* ☐ *Three times* ☐ *More than three times* ☐ *Never* ☐ *Don't know / Not sure*

4. In your current role how important is it for you to understand how a model works and generates outputs?

☐ *Not at all important* ☐ *Slightly important* ☐ *Moderately important* ☐ *Very important* ☐ *Extremely important*

5. Rank the following six issues in order of their importance when using a model (1 = most important and 6 = least important).

Model speed - *how quickly does the model run a simulation*	
Data requirements- *the amount and availability of data going into the model*	
Ease of use- *how easy is the model to use*	
Accuracy- *how close the values predicted are to the actual*	
Model abilities - *what the model can do e.g. simulate land cover*	
Outputs generated- *what the model creates e.g. erosion maps*	

Section B: Model Application

6. When using a model to representing catchment scale sediment dynamics, based on today's discussion what would you consider to be the most important ability, e.g. simulate land cover change?

____

7. The model is primarily concerned with representing the movement of sediment within a river catchment. Is there another important factor from a management perspective that would useful to simulate?

____

8. Which of these outputs would you consider to be useful in aiding sediment management in river catchments?

(Please tick all that apply) ☐ *Maps* ☐ *Animations* ☐ *Tables* ☐ *Graphs* ☐ *Interactive visuals*
☐*Other (please specify):* ____________________

Appendix B - Participatory modelling process evaluation online questionnaire

ENGAGE - Online Questionnaire

Your responses to this questionnaire are completely anonymous. However, you will be asked if you are willing to take part in a short follow-up telephone interview (under 30 minutes), in which case you will be asked to provide your contact information.

The questionnaire comprises of 10 questions and will take up to 15 minutes to complete. Not all questions are compulsory, where they are it will be indicated on the page. Please ensure you click submit on the final page, otherwise your responses will not be recorded!

All information will be treated confidentially and stored securely.

In the name of the research team, I declare that we will adhere to the principles set out in the information sheet for the purpose of this research.

Nick Jones - 21/05/2015

You can get in touch by email nick7.jones@uwe.ac.uk or by phone 0117 32 87144.

Supervisor - Professor Lindsey McEwen, Professor in Environmental Management, UWE. Email: Lindsey.McEwen@uwe.ac.uk or by phone 0117 32 83383.

* Required

RESEARCH PARTICIPANT – PLEASE TICK THE BOXES TO INDICATE YOU AGREE TO THE FOLLOWING STATEMENTS *

All participants in this research study were required to read the Project Information Sheet at the start of the project. If you have lost or need a new copy, they are located on the Engage website: http://www.engage-rivers.org.uk/downloads.html

☐ I have read and understood the Project Information Sheet related to this project.

*

☐ I agree that the information I provide may be used for the purpose of this piece of research and only by the members of the project team.

*

☐ If I choose to withdraw from the project, on request prior to publication of the research, any information I have provided will be returned or destroyed.

*

☐ I agree that the information I provide may be used for journal publications and presentations at conferences.

Are you willing to take part in a follow-up telephone interview based on your answers to this questionnaire?

If so please provide your name and email in the box below.

Continue »

11% completed

ENGAGE - Online Questionnaire

* Required

Question 1 - Which group of river catchment stakeholders do you belong to? *

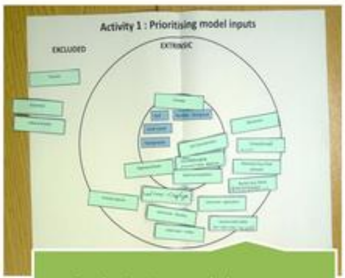
- ◯ Taw (TRIP)
- ◯ Camel
- ◯ Bristol Avon
- ◯ Spey

Question 2 - Which of the participatory modelling sessions were you present at? *

Please tick all those that apply. A description and image of each session is shown below.

- ☐ Requirements analysis
- ☐ Co-designing workshop
- ☐ Participatory model demonstration and discussion

Requirements analysis: group discussion of four questions



Co-designing workshop: two activities – bullseye and ranking

Participatory model demonstration and discussion: a series of video demonstrations and discussions

« Back   Continue »

22% completed

ENGAGE - Online Questionnaire

* Required

Question 3 - to what extent do you agree with the following statements: *

I found the participatory modelling process enjoyable.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

*

This collaborative approach is a more effective way to design a useful model than having modellers design alone.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

Question 4 - Which activities in the participatory modelling process did you enjoy? *

Please tick all that apply. A description and image of each activity can be found at the bottom of the page.

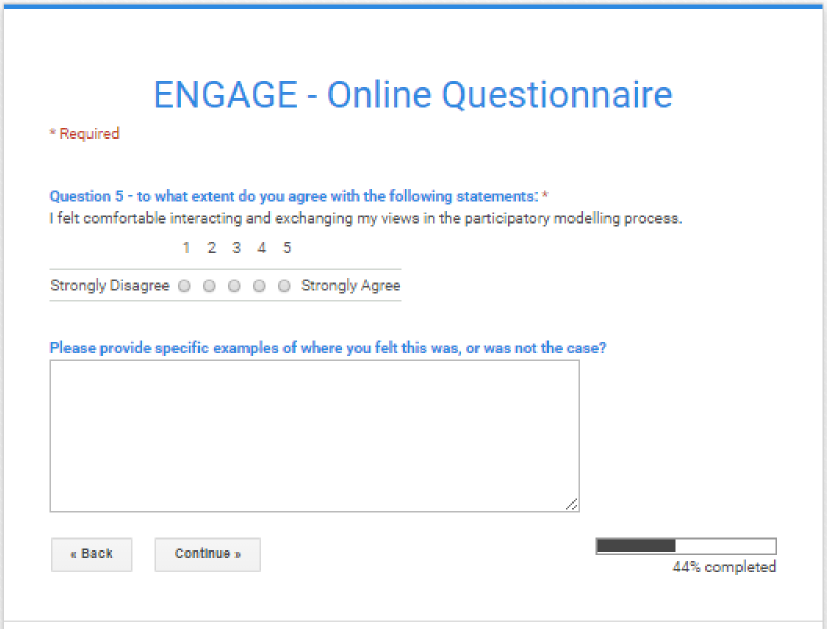
- ☐ Requirements analysis: group discussion of four questions
- ☐ Co-design workshop: conceptual model discussion
- ☐ Co-design workshop: prioritising model inputs using a bullseye diagram
- ☐ Co-design workshop: prioritising model inputs using a ranking exercise
- ☐ Model demonstration and discussion: video demonstration and discussion
- ☐ Ongoing engagement: Engage model website
- ☐ Other: ______

Is there one activity which you found particularly enjoyable? If so why?

Requirements analysis: group discussion of four questions	Co-design workshop: conceptual model discussion	Co-design workshop: prioritising model inputs using a bullseye diagram	Co-design workshop: prioritising model inputs using a ranking exercise	Model demonstration and discussion: video demonstration and discussion	Ongoing engagement: Engage model website

« Back | Continue »

33% completed



ENGAGE - Online Questionnaire

* Required

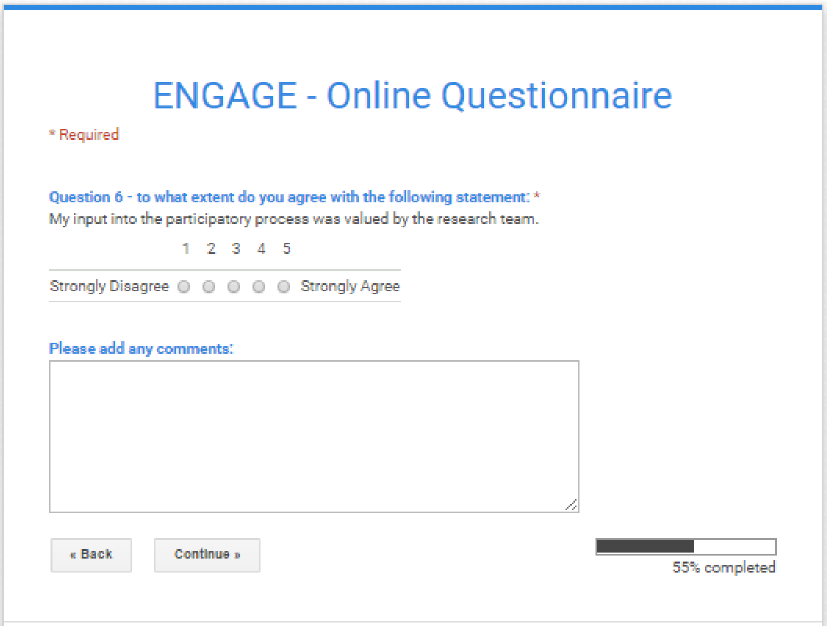
Question 5 - to what extent do you agree with the following statements: *
I felt comfortable interacting and exchanging my views in the participatory modelling process.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

Please provide specific examples of where you felt this was, or was not the case?

« Back   Continue »

44% completed



ENGAGE - Online Questionnaire

* Required

Question 6 - to what extent do you agree with the following statement: *
My input into the participatory process was valued by the research team.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

Please add any comments:

« Back   Continue »

55% completed

ENGAGE - Online Questionnaire

* Required

Questions 7 - to what extent do you agree with the following statements: *

My understanding of sediment dynamics has increased through this my involvement in this process.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

*

I have a better understanding of computer modelling through my involvement in this process.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

*

My understanding of cellular models of sediment dynamics increased through my involvement in this process.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

Please provide any specific examples of this, and how this was, or was not achieved.

« Back   Continue »

66% completed

ENGAGE - Online Questionnaire

* Required

Question 8 - How useful to your work has your participation in the participatory modelling process been? *

	1	2	3	4	5	6	7	8	9	10	
Not at all useful	○	○	○	○	○	○	○	○	○	○	Very useful

Please provide an example of how it has been useful or how it could be useful in the future.

« Back   Continue »

77% completed

ENGAGE - Online Questionnaire

* Required

Question 9 - How do you think the participatory modelling process could be improved? *

Please tick all that apply.

- ☐ Increased communication
- ☐ More sessions
- ☐ Improved description of the process
- ☐ Other: ______

Question 10 - Who else do you think should have been involved in the participatory modelling process? *

Please tick all that apply.

- ☐ Flood risk practitioners
- ☐ Farmers
- ☐ Homeowners
- ☐ Other: ______

Please add any additional comments you have about the participatory modelling process:

« Back | Continue »

88% completed

ENGAGE - Online Questionnaire

Please click submit to send your responses to the questionnaire.

« Back | Submit

Never submit passwords through Google Forms.

100%: You made it.

Appendix C - Participatory modelling process evaluation interview topic guide

Introduction:

- Purpose of this semi-structured interview – to go into more detail about the results of the online survey and explore some of the themes arising.
- The interview will last approximately 30-45 minutes
- I will be recording it to keep a record of the discussion and ensures I do not miss anything important we discuss. The material generated may be used in my thesis and subsequent publications (go through informed consent form with stakeholder).
- No right or wrong answers – just want thoughts and opinions. You do not have to answer every question.
- This is an opportunity to expand upon what was covered in the online survey. Please feel free to diverge from the questions ask as the purpose of this interview is to be semi-structured and pick out anything you may think is relevant.

Warm-up questions:

These questions are intended to be quick and easy to answer, allowing for some contextual information about the interviewee to be acquired.

1. Please tell me a little about yourself in relation to your role and the organisation you work for.
    a. What are your primary responsibilities?

Section A: Participatory modelling process (10-15 minutes)

The aim of this section is to examine the interviewees view on the process

1. You said that you enjoyed "X, Y and Z" could you expand on why you felt this to be enjoyable?
    a. The most popular response from the groups was the "Bulls-eye prioritisation activity", why do you think this is?
    b. Another popular choice is the group discussion right at the start around the 4 questions. Why do you think this was?
2. Stakeholders agreed that *"This collaborative approach is a more effective way to design a useful model than having modellers design alone".* Why do you think this is the case?
3. You said "X" in regard to *"I felt comfortable interacting and exchanging my views in the participatory modelling process".* Add question around response. If no response ask why.
    a. Do you think using pre-existing groups was beneficial to the process?
    b. Do you think discussions were dominated by more knowledgeable stakeholders?
4. In the question "My input into the participatory process was valued by the research team." You said "X", how do you think this was achieved?

Section B: Outcomes from the participatory modelling process (10-15 minutes)

1. You said "X, Y, Z" to whether or not you felt the process increased your knowledge of sediment dynamics. Why do you think this? *If they provided a response in the comments box then refer to this.*

    a. If you feel you learnt anything new, what was it and which part of this process developed this for you?
2. You said “X” for whether or not this process was useful to your work. Why was this?
    a. Several stakeholders suggested this is difficult to say until the model is released. Is this something you agree with? Why?

Section C: Improving the participatory modelling process (10-15 minutes)

1. Some stakeholders suggested that they had been disappointed with the lack of communication at times during the process. Do you think this was an issue?
    a. What types of communication do you think would have been beneficial to have throughout the process?
2. You commented that you though the process could be improved by “X” could you expand upon this?
3. Final question: Would you do it again?
    a. How about if the suggested improvements above were implemented?

Closing the interview

- That is the end of the interview
- Is there anything else you would like to add?
- Thank you for your time and responses

Appendix D – Model assessment of usability and usefulness. Activity 1: Questionnaire

Name: ____

Organisation: ______________________________ Role: __________________________________

1. How many times have you used (i.e. operated – not commissioned) a model in your current role in the past year?

☐ *Once* ☐ *Twice* ☐ *Three times* ☐ *More than three times* ☐ *I haven't* ☐ *Don't know / Not sure*

2. In your current role how important is it for you to understand how a model works and generates outputs?

☐ *Not at all important* ☐ *Slightly important* ☐ *Moderately important* ☐ *Very important* ☐ *Extremely important*

3. Who do you think should be responsible for using (i.e. operating) a model?

☐ *Technical modellers* ☐ *Management stakeholders* ☐ *Small selection of management stakeholders* ☐ *All stakeholders* ☐*Other (please specify):* _______________________

4. Who would you consider to be the target audience for this type of model outputs?

(Please tick all that apply) ☐ *Management stakeholders* ☐ *All stakeholders* ☐ *General public* ☐*Other (please specify):* _______________________

P.T.O

5. Please rank the following model criteria from the **most important (1)** to the **least important (10)** and importantly provide your reasons for making that selection.

Model Criteria	**Rank (1 – 10)**	**Reasons for selection**
Spatially distributed surface runoff and soil erosion based on rainfall, land cover, soil type and condition		
2D flow model (for simulating flood plain flooding)		
Automatic preparation of data (i.e. takes the data in its raw form and prepares it for use in the model)		
Flexibility to select time period and type of outputs generated (e.g. weekly, monthly, yearly as an average or total)		
Standalone tool (does not require any other software e.g. ArcGIS or QGIS)		
Ability to simulate the effect of tides and sand dunes		
Output Google Earth animations		
Detailed instructions for all levels of users (beginner to expert)		
Ability to change land cover type and management		
Ability to simulate chemical weathering and physical weathering (e.g. breakdown of rocks etc)		

Appendix E - Model assessment of usability and usefulness. Activity 2: Model A or Model B

Participant Instructions

Read the two cellular models of sediment dynamics (Model A and Model B) provided on the large A3 table. Take a couple of minutes to consider the advantages and negatives of each model. Then, please provide a rating out of 10 below for each model in relation to the likelihood that you would use in your day job if you had a need to conduct an investigation that required the use of a sediment dynamics model or as part of a decision making process. Note that you would be carrying out the modelling work yourself, and not using a consultancy on your behalf. If you are unsure of any of the terminology used, please do not hesitate to ask. Please do not confer with colleagues.

Model A

1 2 3 4 5 6 7 8 9 10

(Least likely) **(Most likely)**

Please provide the reasons for your score in the space below:

Model B

1 2 3 4 5 6 7 8 9 10

(Least likely) (Most likely)

Please provide the reasons for your selection in the space below:

Blank Page - A3 Model table goes here

Appendix F - Using ENGAGE to assist in a hypothetical decision-making process

The scenario

The Environment Agency has announced a pot of money for planting broad leaf woodland. The catchment you are responsible for is eligible to receive this funding. The criteria for this funding are:

- *The areas of tree planting must demonstrate **multi-benefit outcomes** for both reducing surface runoff, sediment erosion on fields and deposition downstream.*
- *The area for planting must be **strategically** placed in areas that contribute the greatest runoff and sediment erosion.*
- *Your decision must be backed up by evidence.*

By following this set of instructions for using ENGAGE, can you identify and model the effects of planting an area of broadleaf woodland in your catchment?

All of the resources for this exercise can be found on the Desktop in the Example Catchment folder.

Tutorial Key:

Action the user needs to complete **(Text in blue)**

An action already complete (usually manual task that is time consuming) **(Text in red)**

Step 1: Download Catchment Boundary and Flow Gauge Data.

Located at http://nrfa.ceh.ac.uk/data/station/meanflow/49003

To save time this has been downloaded and is located in the CEH Catchment Boundary folder located here:

"\Example Catchment\49003 - De Lank at De Lank\CEH Catchment Boundry"

Step 2: Source and download GIS data.

To save time this is located in the Raw GIS Data folder. The data is located in this folder:

"\Example Catchment\49003 - De Lank at De Lank\Raw GIS Data"

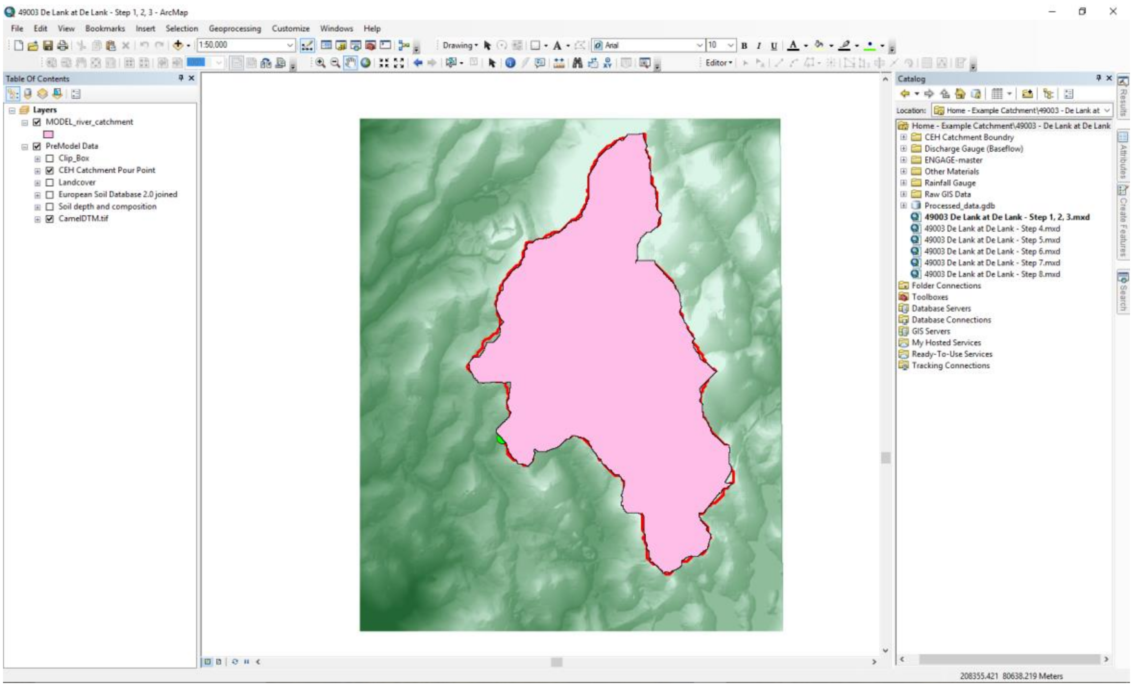
Step 3: Download Engage and extract it to your working folder

ENGAGE can be downloaded from www.engage-rivers.org.uk as a zip file and then extracted into the folder you are working in. ENGAGE has been download and extracted into the working folder.

Step 4: Create a pour point at the mouth of the river and create a river catchment specific to the ENGAGE model.

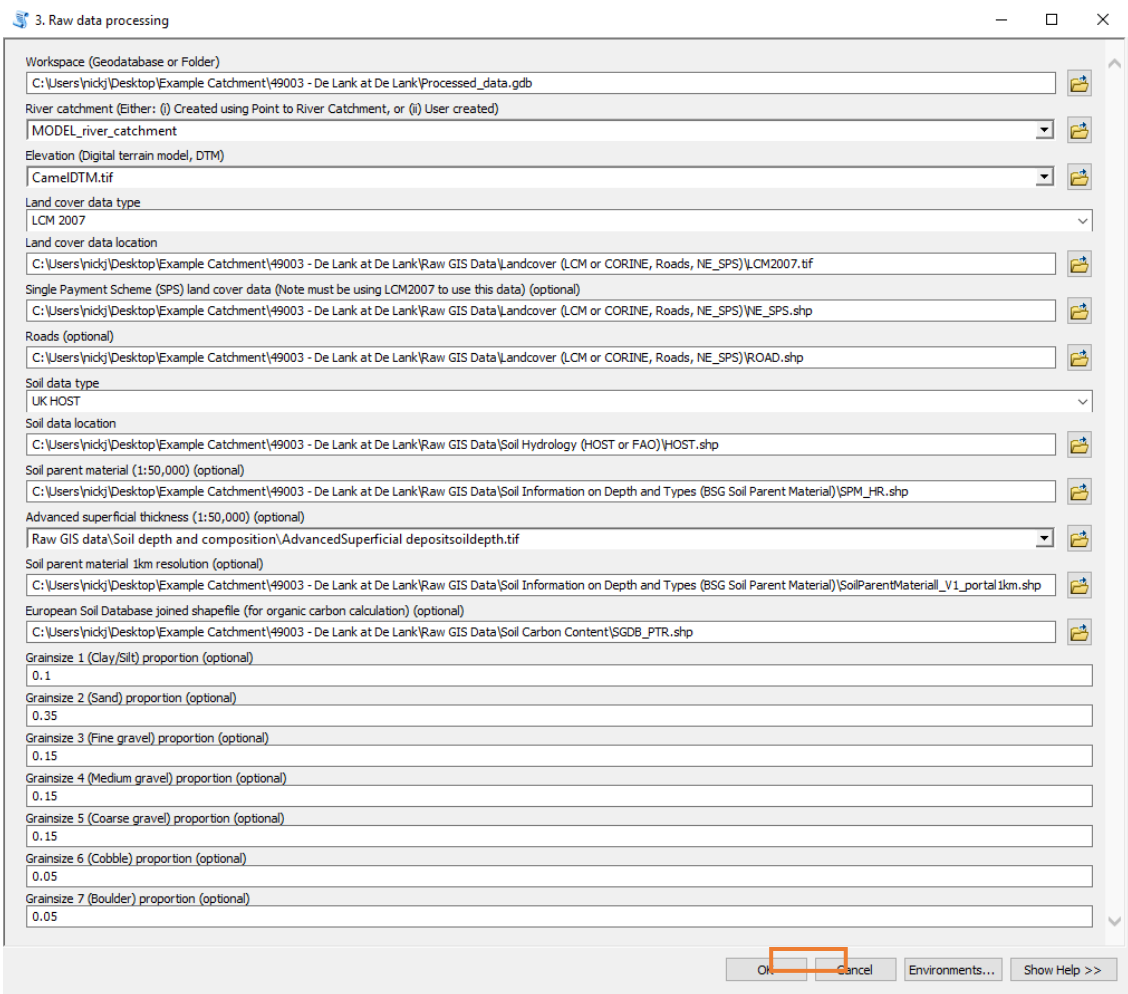
A pour point (river mouth/outlet for area of interest) has been created for you. The pour point and the elevation data were then used to create a river catchment for use in ENGAGE. Open the ArcMap Document *"49003 De Lank at De Lank - Step 1, 2, 3"* located here: *"\Example Catchment\49003 - De Lank at De Lank"*

1. Take a minute to explore the ArcMap Document in front of you containing the information from the steps described above. Take note of the different layers in the **Table of Contents** on the left hand side of the screen. We are going to need this map document for the next step so leave the map document open and progress to the next step.

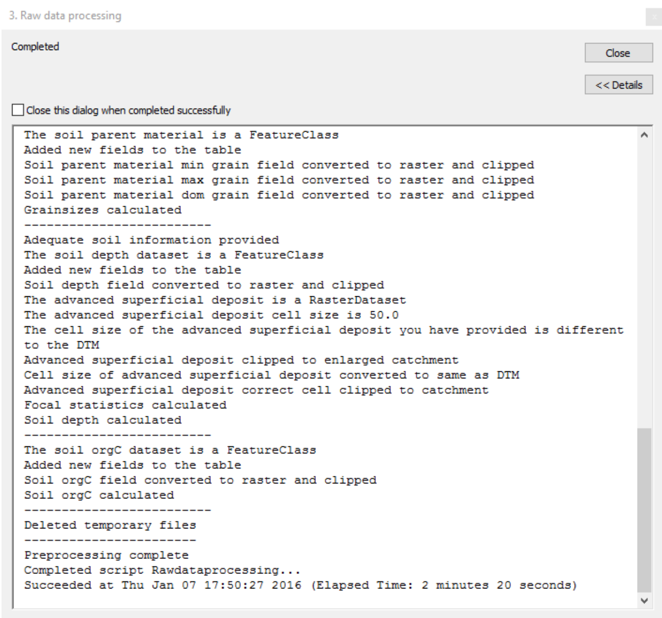


Step 5: Prepare the Raw GIS data ready to use in ENGAGE.

1. Using the **Catalog** window on the right hand side open **ENGAGE-master > ArcGIS Toolbox > ENAGE.tbx > Data Preparation (shown below)** and double click on **3. Raw data processing.**
2. A dialog box will appear. Fill the boxes in using the data shown below (using the folder explorer or drop downs), when complete **click ok as shown below.**



3. The model will now process the data getting it ready for the ENGAGE model to use. When the process is completed the following window will appear. **Click Close.**



4. View your new created data by opening the **Catalog** window on the right hand side. Navigating to the *"Processed_data"* geodatabase **expand it by clicking the +**. Your display should look like this:

Processed_data.gdb	Simplified Description
MODEL_ASD_soil_depth	Depth of river soil
MODEL_BGS_SOIL_DEPTH	Depth of soil in the rest of the catchment
MODEL_COMBINE_LC	Land cover combined (inc roads etc)
MODEL_DOM_GRAIN	Dominant soil type
MODEL_DTM	Elevation (DTM)
MODEL_GS1	Proportion of sediment grain size 1
MODEL_GS2	Proportion of sediment grain size 2
MODEL_GS3	Proportion of sediment grain size 3
MODEL_GS4	Proportion of sediment grain size 4
MODEL_GS5	Proportion of sediment grain size 5
MODEL_GS6	Proportion of sediment grain size 6
MODEL_GS7	Proportion of sediment grain size 7
MODEL_MAX_GRAIN	Maximum grain size present
MODEL_MIN_GRAIN	Minimum grain size present
MODEL_orgC	Proportion of organic carbon in the soil
MODEL_river_catchment	River catchment
MODEL_Soil_HOST	Hydrological condition of the soil

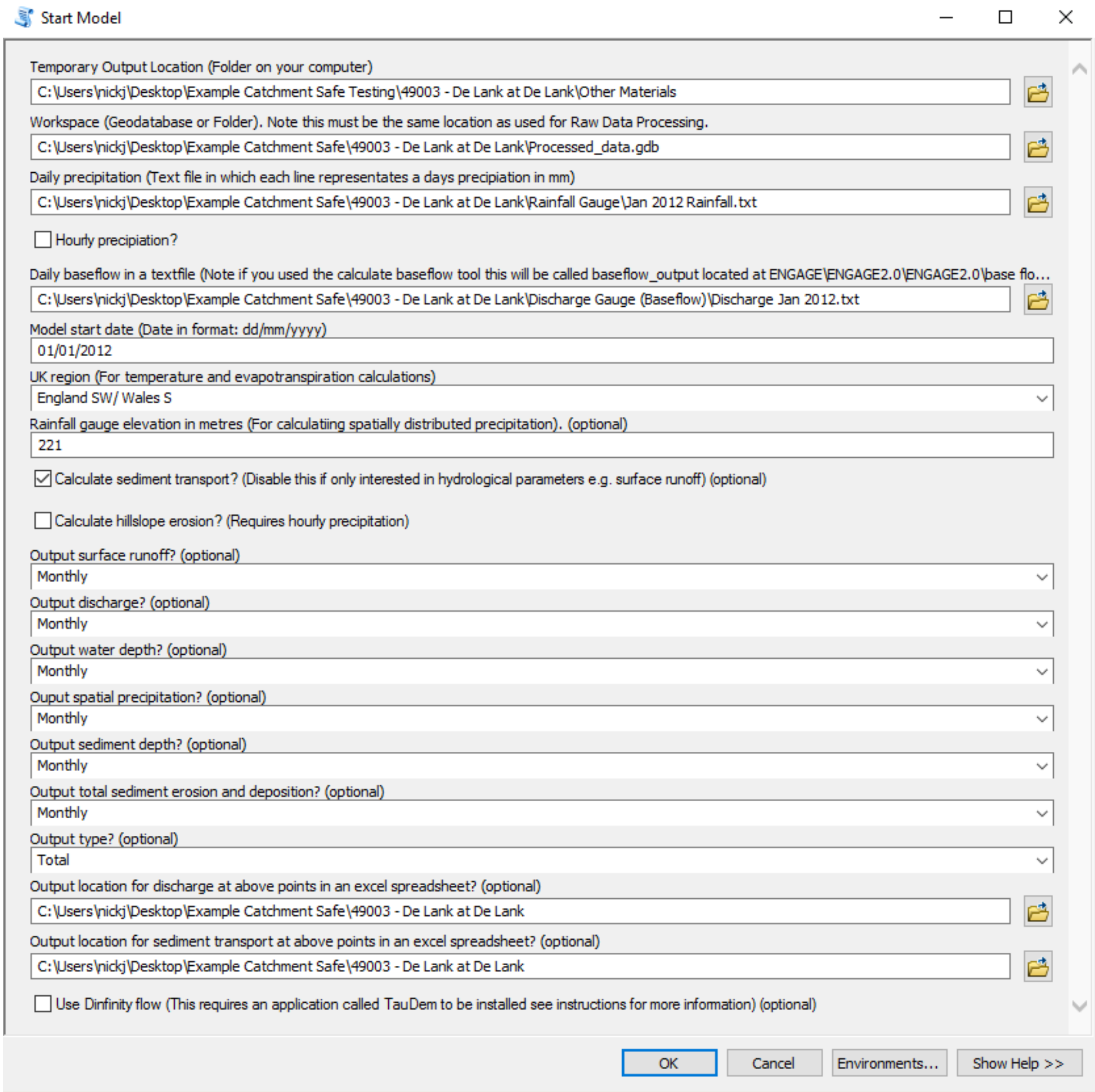
Add the created layers to your display using the add data button . Navigate to the created geodatabase *"Processed_data.gdb"* and selected all the layers using the **shift key**, **click Add**. If the create pyramids box appears, **tick the box at the bottom to remember your decision and click yes**. If the spatial reference box appears click **close**.

You have now added the base data to your map. Close the mxd file, **do not save**.

To save time the data has been organised ready for the next step.

Step 6 – Run the model with default starting conditions

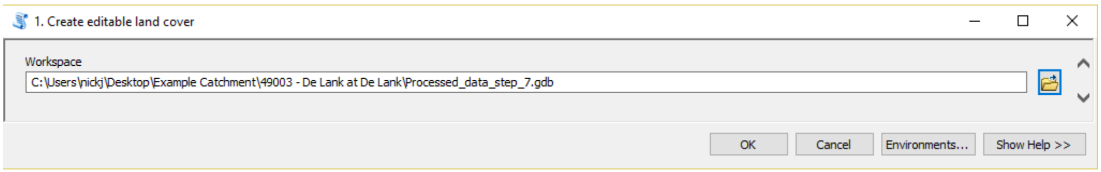
1. Open the "**49003 De Lank at De Lank – Step 6.mxd"** located here: *"\Example Catchment\49003 - De Lank at De Lank"*. Note that the Processed GIS data has been sorted for you, have a quick look through this data.
2. Using the **Catalog** window on the right hand side open **ENGAGE-master > ArcGIS Toolbox > ENGAGE.tbx** and **double click** on **Start Model.**
5. A dialog box will appear. Note how the boxes are filled in below using the data we created. Note the different options that you can use. **Do not fill in the data or click OK, to save time this has been completed for you. Clicking Ok would** initiate the model running which would take around an hour and a half to complete 30 days of simulation for a catchment of this size.



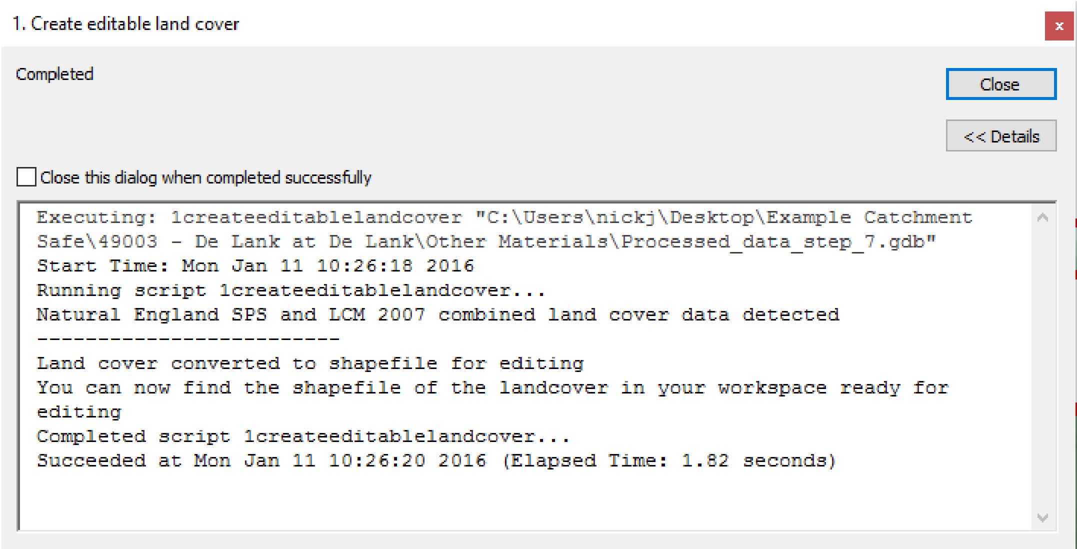
6. **Close** the ArcMap document. Not saving any changes.

Step 7 – Investigate the data generated and make a change to the input conditions by planting some woodland.

1. Open the "**49003 De Lank at De Lank – Step 7.mxd**" file located here: *"\Example Catchment\49003 - De Lank at De Lank".* Note that the output GIS data has been sorted for you.
2. Have a browse the different GIS layers that been created (Under Original Outputs) can you see any opportunities for tree planting to reduce surface runoff and sediment erosion?
3. Now it is time to change some land cover to woodland to do this we first need to create a shapefile we can edit. Using the **Catalog** window on the right hand side open **ENGAGE-master > ArcGIS Toolbox > ENGAGE.tbx > Alter land cover** and double click on **1. Create editable land cover**
4. A dialog box will appear. Fill the box in using the data shown below and then **click ok**. Note to select the Processed data step 7 database, as a copy has been created for you (we do not want to overwrite the default starting conditions).



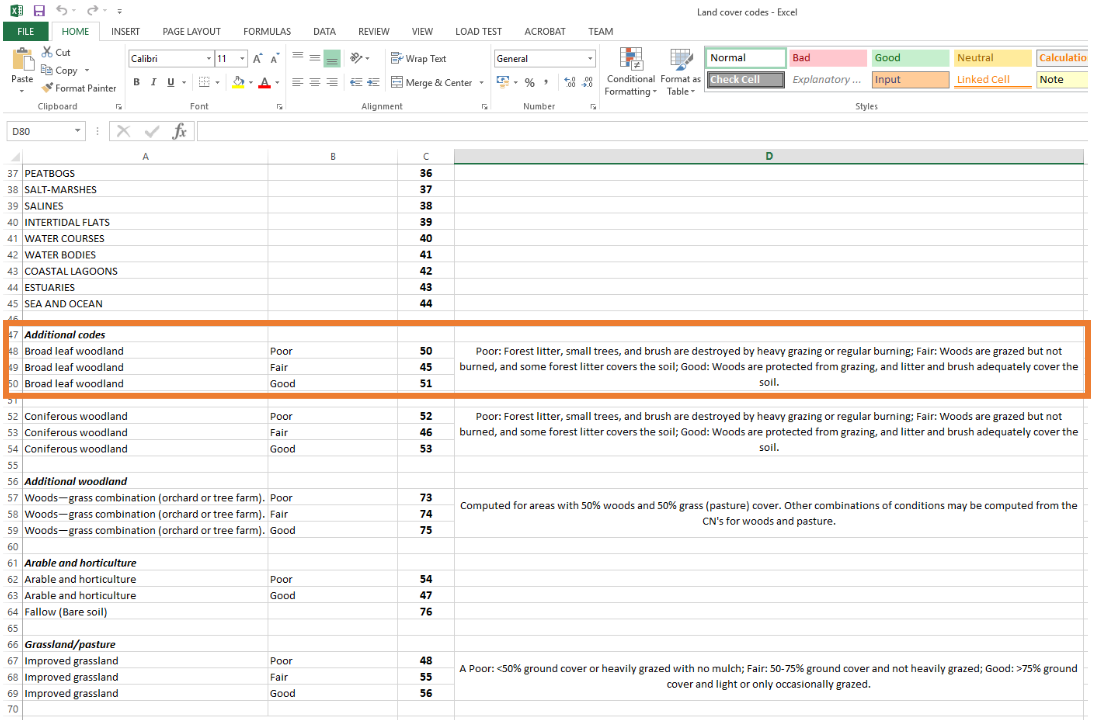
5. When the process is completed the following window will appear. **Click Close.**



6. A new shapefile of the land cover will now have been added to your display (shown below). This is the version we are going to change. The orange square below, highlights a field we are going to change the land use type.

7. Now open the excel spreadsheet named **"Land cover codes"** located here: **"\Example Catchment Safe\49003 - De Lank at De Lank\ENGAGE-master"** using windows

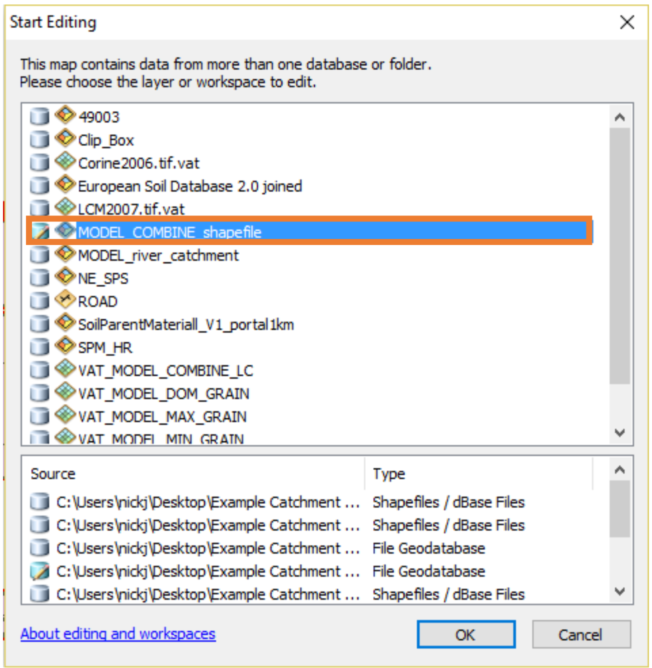
explorer. Within the spreadsheet locate the 3 numbers that correspond with Broad Leaf Woodland. On the next page you can check your answer.



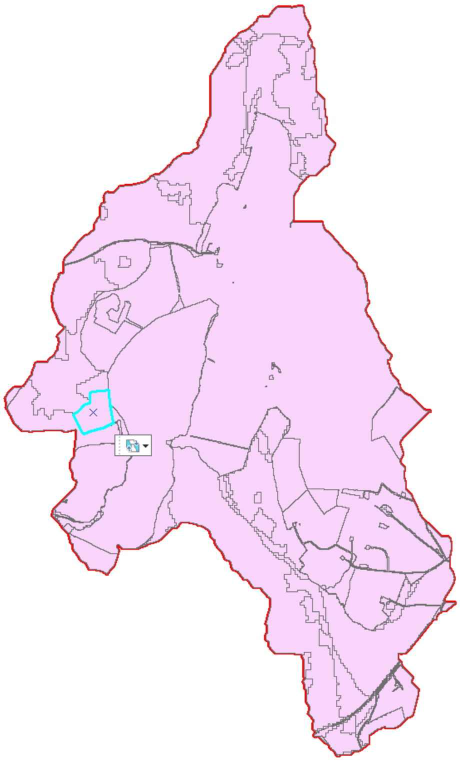
	A	B	C	D
37	PEATBOGS		36	
38	SALT-MARSHES		37	
39	SALINES		38	
40	INTERTIDAL FLATS		39	
41	WATER COURSES		40	
42	WATER BODIES		41	
43	COASTAL LAGOONS		42	
44	ESTUARIES		43	
45	SEA AND OCEAN		44	
47	*Additional codes*			
48	Broad leaf woodland	Poor	50	Poor: Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning; Fair: Woods are grazed but not burned, and some forest litter covers the soil; Good: Woods are protected from grazing, and litter and brush adequately cover the soil.
49	Broad leaf woodland	Fair	45	
50	Broad leaf woodland	Good	51	
52	Coniferous woodland	Poor	52	Poor: Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning; Fair: Woods are grazed but not burned, and some forest litter covers the soil; Good: Woods are protected from grazing, and litter and brush adequately cover the soil.
53	Coniferous woodland	Fair	46	
54	Coniferous woodland	Good	53	
55				
56	*Additional woodland*			
57	Woods—grass combination (orchard or tree farm).	Poor	73	Computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the CN's for woods and pasture.
58	Woods—grass combination (orchard or tree farm).	Fair	74	
59	Woods—grass combination (orchard or tree farm).	Good	75	
60				
61	*Arable and horticulture*			
62	Arable and horticulture	Poor	54	
63	Arable and horticulture	Good	47	
64	Fallow (Bare soil)		76	
65				
66	*Grassland/pasture*			
67	Improved grassland	Poor	48	A Poor: <50% ground cover or heavily grazed with no mulch; Fair: 50-75% ground cover and not heavily grazed; Good: >75% ground cover and light or only occasionally grazed.
68	Improved grassland	Fair	55	
69	Improved grassland	Good	56	
70				

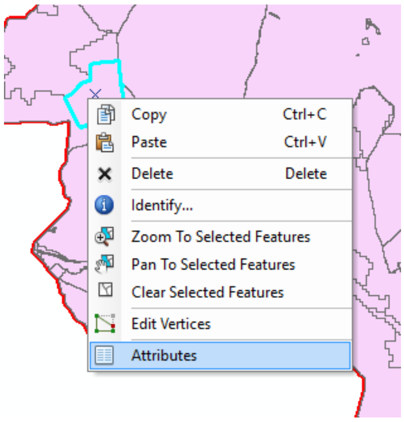
8. The next stage in the process is to change the field to woodland in ArcMap. **Select Editor** (located at the top of your screen). Then click **Start Editing.**

A dialog box will appear asking you which layer you would like to start editing. **Select the "MODEL_COMBINE_shapefile". Click OK.** An Error Message box may appear. **Click Continue.**

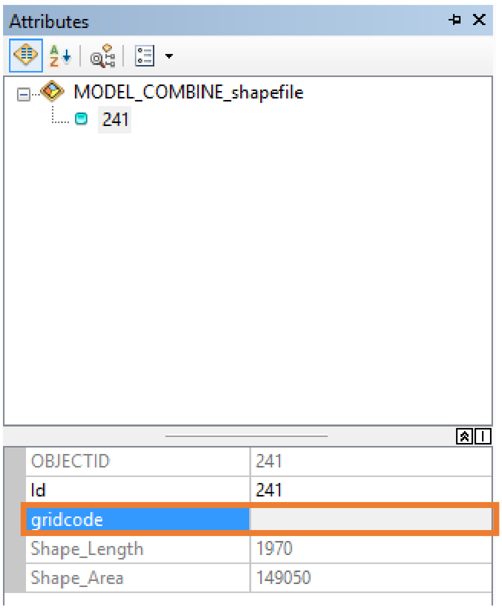


9. For speed an area of land for editing has been selected for you, this is highlighted in blue in the diagram. Next, Right click > Attributes. As shown below.





An attributes tab will appear on the right hand side. In the box next to grid code change the value in the box for the new woodland value (e.g. 51).



Finally, **click Editor > Save Edits > Editor > Stop Editing.**

10. Now it is time to change the land cover back to a version the model can use. Using the **Catalog** window on the right hand side open **ENGAGE-master > ArcGIS Toolbox > Alter land cover** and double click on **2. Save edited land cover**
11. A dialog box will appear. Fill the box in using the data shown below and then **click ok**. Note to select the *"Processed data step 7 database".*
12. When the process is completed the following window will appear. **Click Close.** Now the land cover is ready to be input into the model to re-run the scenario.

13. The final step in the process would be to re-run the model with the new conditions (described in Step 6). To save time this has been done for you.

Step 8 – Take a look at the new scenario vs the old.

1. Open the "**49003 De Lank at De Lank – Step 8.mxd"** file. Note that the output GIS data has been sorted for you.
2. Have a quick look at the data produced. In particular, compare the field you have changed to broadleaf woodland from grassland.

Appendix G – Land cover types and conditions that users can input into the model

Land cover	Hydrological Condition	Grid code	Additional Information
Continuous urban fabric	-	1	-
Discontinuous urban fabric	-	2	-
Industrial or commercial units	-	3	-
Road and rail networks and associated infrastructure	-	4	-
Port areas	-	5	-
Airports	-	6	-
Mineral extraction sites	-	7	-
Dump sites	-	8	-
Construction sites	-	9	-
Green urban areas	-	10	-
Sport and leisure facilities	-	11	-
Non-irrigated arable land	-	12	-
Permanently irrigated land	-	13	-
Rice fields	-	14	-
Vineyards	-	15	-
Fruit trees and berry plantations	-	16	-
Olive groves	-	17	-
Pastures	-	18	-
Annual crops associated with permanent crops	-	19	-
Complex cultivation patterns	-	20	-
Agriculture, with significant areas of nature vegetation	-	21	-
Agro-forestry areas	-	22	-
Broad-leaved forest	-	23	-
Coniferous forest	-	24	-
Mixed forest	-	25	-
Natural grassland	-	26	-
Moors and heathland	-	27	-
Sclerophyllous vegetation	-	28	-
Transitional woodland-shrub	-	29	-
Beaches, dunes, and sand plains	-	30	-
Bare rock	-	31	-
Sparsely vegetated areas	-	32	-
Burnt areas	-	33	-
Glaciers and perpetual snow	-	34	-
Inland marshes	-	35	-
Peatbogs	-	36	-
Salt-marshes	-	37	-
Salines	-	38	-
Intertidal flats	-	39	-
Water courses	-	40	-
Water bodies	-	41	-

Coastal lagoons	-	**42**	-
Estuaries	-	**43**	-
Sea and ocean	-	**44**	-
Additional codes			
Broad leaf woodland	Poor	**50**	Poor: Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning; Fair: Woods are grazed but not burned, and some forest litter covers the soil; Good: Woods are protected from grazing, and litter and brush adequately cover the soil.
Broad leaf woodland	Fair	**45**	
Broad leaf woodland	Good	**51**	
Coniferous woodland	Poor	**52**	Poor: Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning; Fair: Woods are grazed but not burned, and some forest litter covers the soil; Good: Woods are protected from grazing, and litter and brush adequately cover the soil.
Coniferous woodland	Fair	**46**	
Coniferous woodland	Good	**53**	
Additional woodland			
Woods—grass combination (orchard or tree farm).	Poor	**73**	Computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the CN's for woods and pasture.
Woods—grass combination (orchard or tree farm).	Fair	**74**	
Woods—grass combination (orchard or tree farm).	Good	**75**	
Arable and horticulture			
Arable and horticulture	Poor	**54**	-
Arable and horticulture	Good	**47**	-
Fallow (Bare soil)	-	**76**	-
Grassland/pasture			
Improved grassland	Poor	**48**	A Poor: <50% ground cover or heavily grazed with no mulch; Fair: 50-75% ground cover and not heavily grazed; Good: >75% ground cover and light or only occasionally grazed.
Improved grassland	Fair	**55**	
Improved grassland	Good	**56**	
Farmsteds - building, lanes, driveways and surrounding lots		**57**	
Additional urban land cover			
Open spaces (lawns, parks, golfcourses, cemeteries etc)	Poor	**58**	(grass cover <50%)
Open spaces (lawns, parks, golfcourses, cemeteries etc)	Fair	**59**	(grass cover 50 to 75%)
Open spaces (lawns, parks, golfcourses, cemeteries etc)	Good	**60**	(grass cover >75%)
Impervious areas			
Paved parking lots, roofs, driveways (Excl right of way)	-	**61**	-
Paved streets and roads: open ditches (Incl right of way)	-	**62**	-
Gravel streets and roads (including right of way)	-	**63**	-

Dirt streets and roads (including right of way)	-	**64**	-
Urban districts			
Commercial and business		**65**	
Industrial		**66**	
Residential districts by average size	***% impervious***		
1/8 acre or less (town houses)	65	**67**	
1/4 acre	38	**68**	
1/3 acre	30	**69**	
1/2 acre	25	**70**	
1 acre	20	**71**	
2 acres	12	**72**	