

1 **Development of ST:REAM: a reach-based stream power balance approach for**
2 **predicting alluvial river channel adjustment**

3
4 ***Chris Parker¹, Colin R Thorne² and Nicholas J Clifford³***

5
6 ¹Department of Geography and Environmental Management, Faculty of Environment
7 and Technology, University of the West of England, Bristol, BS16 1QY, UK. +44
8 (0)117 3282902. Chris2.Parker@uwe.ac.uk

9 ²School of Geography, University of Nottingham, University Park, Nottingham, NG7
10 2RD, UK

11 ³Department of Geography, King's College London, London, WC2R 2LS, UK
12
13

14 **Abstract**

15
16 River channel sediment dynamics are important in integrated catchment
17 management because changes in channel morphology resulting from sediment
18 transfer have important implications for many river functions. However, application of
19 existing approaches that account for catchment-scale sediment dynamics has been
20 limited, largely due to the difficulty in obtaining data necessary to support them. It is
21 within this context that this study develops a new, reach-based, stream power
22 balance approach for predicting river channel adjustment.

23
24 The new approach, named ST:REAM (Sediment Transport: Reach Equilibrium
25 Assessment Method), is based upon calculations of unit bed area stream power (ω)
26 derived from remotely sensed slope, width and discharge datasets. ST:REAM
27 applies a zonation algorithm to values of ω that are spaced every 50m along the
28 catchment network in order to divide the branches of the network up into relatively
29 homogenous reaches. ST:REAM then compares each reach's ω value with the ω of
30 its upstream neighbour in order to predict whether or not the reach is likely to be
31 either erosion dominated or deposition dominated.

32
33 The paper describes the application of ST:REAM to the River Taff in South Wales,
34 UK. This test study demonstrated that ST:REAM can be rapidly applied using

35 remotely sensed data that are available across many river catchments and that
36 ST:REAM correctly predicted the status of 87.5% of sites within the Taff catchment
37 that field observations had defined as being either erosion or deposition dominated.
38 However, there are currently a number of factors that limit the usefulness of
39 ST:REAM, including inconsistent performance and the need for additional, resource
40 intensive, data to be collected to both calibrate the model and aid interpretation of its
41 results.

42

43 **Introduction**

44

45 ***The importance of alluvial channel adjustment within river management***

46

47 Lane (1955) described alluvial river channels as tending towards a state of balance
48 using

49

$$Q \cdot S \propto Q_s \cdot D_{50}$$

50 *Equation 1*

51

52 where Q is water discharge (m^3/s), S is channel slope, Q_s is sediment supply rate
53 ($\text{kg}/\text{m}/\text{s}$), D_{50} is the median diameter of sediment supplied (m), the terms on the left
54 represent the sediment transport capacity of the flow, and the terms on the right
55 represent the sediment supply. Alluvial channel adjustments are driven by
56 imbalances in the transfer of channel-forming sediment through the fluvial system,
57 with marked and concerted changes in the morphology of a reach being associated
58 with a significant disparity between the quantity of sediment input to the reach
59 (supply) and the quantity that can be transferred downstream (capacity). These
60 imbalances can have important implications for the management of both flood risk
61 and ecological status.

62

63 Deposition dominated channels can experience increased probability of flooding due
64 to a reduction in channel conveyance capacity (Stover and Montgomery, 2001). This
65 reduces the standard of protection provided by defences, creates maintenance
66 issues (Sear, et al., 1995), and generates challenges for strategic planning (Lane, et

67 al., 2007). Conversely, erosion dominated reaches can have increased risk of flood
68 defence infrastructure failure or instability (Wallerstein, et al., 2006). As a result,
69 assessments of channel geomorphic processes have been applied within the design
70 of recent flood management schemes (Wallerstein, et al., 2006, Rinaldi, et al., 2009).

71

72 Whilst a complete understanding of how channel form influences in-stream biology
73 has not yet been achieved (Palmer, et al., 2010) the influence of channel
74 geomorphic processes and forms on freshwater biotic communities is well
75 recognized (Lorenz, et al., 2004). Excessive sediment delivery within deposition
76 dominated reaches can negatively impact salmonid spawning, with infiltration of fine
77 sediment into gravel matrices increasing spawned egg mortality rates (Soulsby, et
78 al., 2001). In addition, channel widening and incision within erosion dominated
79 reaches can greatly reduce the quality of the physical habitat necessary to sustain
80 healthy ecosystems (Shields, et al., 1998, Hendry, et al., 2003). As a result, the
81 importance of morphological adjustment to river channel ecological status is
82 recognised within a European Union directive that requires the evaluation of hydro-
83 morphological quality for all river networks in order to assess river ecological status
84 and to deliver catchment management plans (EU, 2000).

85

86 ***The need for resource-light approaches to predicting alluvial adjustment***

87

88 Whilst there have been substantial improvements to our understanding of river
89 channel morphological adjustment (Lane, 1955, Schumm, 1969, Ashworth and
90 Ferguson, 1986, Harvey, 1991, Coulthard and Van de Wiel, 2007) it is still rarely
91 taken into account within the management of river flood risk and ecological status
92 (Wallerstein, et al., 2006, Thorne, et al., 2010). This is partly due to the paucity of
93 practical tools available to the end user community that can be applied routinely at
94 the catchment scale (Bizzi and Lerner, 2013). Where channel adjustment is
95 considered within river management it is usually investigated by field-based fluvial
96 audits (Harvey, 2001, Rinaldi, et al., 2009, Sear, et al., 2010) and by hydrodynamic
97 models (ISIS, 1999, Olsen, 2003, Brunner, 2006). These latter approaches require
98 very detailed inputs on channel discharges, cross sections and grain-size
99 distributions which are not widely available. Methods which can be applied using
100 resources that are easily accessible would be of great value for catchment-scale

101 assessment at the regional and national level (Newson and Large, 2006, Wallerstein,
102 et al., 2006).

103

104 As an alternative to comparatively sophisticated hydrodynamic models, reach-based
105 sediment balance models such as RAT (Graf, 1996), SIAM (Gibson and Little, 2006)
106 and REAS (Wallerstein, et al., 2006) have been developed as a means of predicting
107 river channel status. This type of approach employs Exner's (1925) principle of the
108 conservation of mass and Lane's (1955) fluvial balance concept to define how the
109 amount of sediment stored in a reach changes in response to a net difference
110 between the incoming and outgoing rates of sediment transport. In disequilibrium
111 situations, the direction and degree of sediment imbalance indicates the potential for
112 erosion or deposition-led morphological adjustments. However, despite the
113 assumptions and simplifications made within these models, their widespread
114 applicability is limited by their data requirements because they require data
115 describing the flow regime, cross-sectional geometry, slope, roughness, and particle
116 size distributions (Wallerstein, et al., 2006). Much of this information is unavailable
117 without primary fieldwork that is seldom feasible at the catchment scale outside of
118 well-funded project-related or research studies. Methods that require fewer
119 resources than those described above would be of great value for regional or
120 national assessments (Wallerstein, et al., 2006, Newson and Large, 2006, Bizzi and
121 Lerner, 2013).

122

123 ***Predicting alluvial adjustment using catchment-scale representations of*** 124 ***stream power***

125

126 Stream power, a measure of the energy used to drive geomorphological change
127 (Bagnold, 1966), is a parameter that can be approximated using widely available
128 measurements of channel width, discharge and slope. For example, stream power
129 has been used extensively to explain sediment transport (Bagnold, 1966), bedrock
130 channel incision (Whipple and Tucker, 1999), and bank erosion (Lawler, et al.,
131 1999). To help explain such processes at basin scales, the downstream distribution
132 of stream power has been modelled conceptually (Lawler, 1992) and investigated
133 empirically (Bull, 1979, Graf, 1983, Magilligan, 1992, Lecce, 1997, Knighton, 1999,
134 Reinfelds, et al., 2004, Jain, et al., 2006, Barker, et al., 2009, Biron, et al., 2013).

135

136 More recently, the development of geo-spatial analysis software and the increased
137 availability and accuracy of spatial data (particularly digital elevation models) allow
138 the high resolution quantification of stream power throughout entire river catchment
139 networks (Barker, et al., 2009). Building upon this, recent studies have begun to
140 explore the opportunities for using this type of representation of stream power as a
141 stream assessment tool: Vocal Ferencevic and Ashmore (2012) calculated stream
142 power values across Highland Creek near Toronto in Canada and compared the
143 outputs against morphological changes observed during an extreme flood event;
144 Bizzi and Lerner (2013) calculated a range of stream power-based parameters for
145 the River Lune and the River Wye in England and compared the results against field-
146 based observations of erosional and depositional channel forms; and Biron et al.
147 (2013) calculated stream power values within two watersheds in Quebec and
148 compared the values against field evidence of bank erosion.

149

150 ***Study aims***

151

152 Recognising the need for a method of predicting river channel morphological status
153 that can be applied at the catchment-scale using readily available datasets, this
154 paper describes the development of a new reach-based, stream power balance
155 approach for predicting river channel adjustment: 'ST:REAM' (Sediment Transport:
156 Reach Equilibrium Assessment Method). This new approach aims to combine the
157 work of studies that have developed high resolution representations of stream power
158 across river catchment networks (Barker, et al., 2009, Vocal Ferencevic and
159 Ashmore, 2012, Bizzi and Lerner, 2013) with the work of studies that have
160 developed reach-based sediment balance models (Graf, 1996, Gibson and Little,
161 2006, Wallerstein, et al., 2006).

162

163 To achieve this aim this paper first describes the characteristics of the River Taff in
164 South Wales, which acts as a case study for the new method, along with the
165 datasets used within the study. Next, the paper describes the stages incorporated
166 within the new modelling approach, which include: calculation of stream power
167 across the catchment network; delineation of reach boundaries within the catchment
168 network; and calculation of reach stream power balances. The results are then

169 presented, which include the stream power values calculated across the catchment
170 network of the River Taff, the calibration of the reach boundary hunting algorithm and
171 the stream power balance thresholds, along with the final predictions of reach status
172 across the Taff catchment. Finally, the performance and potential applications of the
173 new approach are discussed.

174

175 **Method**

176

177 ***Case study and data sets: River Taff, South Wales, UK***

178

179 The River Taff in South Wales, UK, was selected as a case study for the
180 development of the new approach. The Taff was selected due to the availability of a
181 wide range of data that might have been useful to the study, although not all of the
182 data sources available were subsequently used in the production of this paper. In
183 addition, the River Taff is typical of many British rivers in that it is a steep, coarse-
184 bedded watercourse with a predominantly alluvial channel that is partially controlled
185 by bedrock outcrops and artificial structures.

186

187 The Taff catchment drains approximately 500km² of South Wales, including a
188 southern area of the Brecon Beacons National Park and the settlements of Merthyr
189 Tydfil, Aberdare, Mountain Ash, Treorchy, Abercynon, Porth, Pontypridd and Cardiff.
190 Its main stem rises in the Brecon Beacons south-west of Pen Y Fan and flows more
191 than 60km south to enter the Severn Estuary at Cardiff. Its major tributaries include
192 the Nant Ffrwd, Taff Fechan, Nant Morlais, Taff Bargoed, Cynon and Rhondda
193 (Figure 1). The geology of the catchment consists of mainly coal measures in the
194 south with carboniferous limestone and old red sandstone in the north, some peat on
195 the hills and boulder clay and alluvium in the valleys (CEH, 2014). Land use is
196 dominated by pasture, forestry and moorland in the headwaters with some urban
197 development in the lower valleys (CEH, 2014). Annual rainfall across the catchment
198 ranges from 950mm/year at Cardiff to 2400mm/year in the Brecon Beacons (CEH,
199 2014). At the flow gauge at Tongwynlais, near Cardiff, (drainage area of 486.9 km²)
200 the mean flow is 21.373 m³/s, with a median annual flood (Q_{med}) of 320.0m³/s (EA,
201 2014).

202

203 The method applied within this paper required the following datasets for the River
204 Taff catchment: a digital elevation model of the entire catchment; Q_{med} values from
205 flow gauges across the catchment; river channel width data for the catchment
206 network; and observations of river channel status at points across the catchment.

207

208 A representation of catchment elevation was obtained using a vector dataset
209 containing Ordnance Survey Land-form Profile contours and spot heights (Edina,
210 2014). The contours are generally at 5 metre vertical intervals but are at 10 metre
211 vertical intervals in some mountain and moorland areas. Contour accuracy values
212 are typically better than half the contour interval – ± 2.5 metres for areas with 5 metre
213 vertical intervals and ± 5 metres for areas with 10 metre vertical intervals (Edina,
214 2014).

215

216 Flow gauge Q_{med} values were obtained from the eight flow gauges within the CEH
217 National River Flow Archive database (CEH, 2014). River channel widths were
218 obtained from the water theme within the Ordnance Survey MasterMap Topography
219 Layer (Edina, 2014). Observations of channel status were recorded during field
220 reconnaissance of 152 points along the Taff catchment network in 2010.

221

222 *Figure 1. The River Taff, South Wales*

223

224 ***Classifying observed channel status***

225

226 The dominant process acting within a river channel can be qualitatively evaluated by
227 interpretation of field observations (Sear, et al., 2003). For instance, for single-
228 channel gravel-bed rivers, the extended presence of unvegetated gravel bars
229 indicates a rich sediment supply from upstream, which is partially stored in the reach
230 and constantly re-worked by periodic floods. Erosion features such as eroding cliffs
231 and vertical or undercut banks indicate processes of bank erosion and are an
232 indication of the degree of lateral mobility and of the amount of sediment mobilized
233 towards downstream (Osman and Thorne, 1988).

234

235 Based on the assumption that dominant channel processes can be identified based
236 on observed channel form, Table 1, adapted from Sear et al.'s (2003) Table 4.3,

237 presents form-based indicators that can be used to identify erosion or deposition
238 dominated channels. These indicators were used to define which of the 152 points
239 within the Taff catchment network visited during the 2010 field reconnaissance are
240 either erosion or deposition dominated: if a point has one or more indicators of a
241 particular channel status (erosion dominated or deposition dominated), without any
242 indicators of the other status, then its status was defined by those indicators. Points
243 without any indicators, or with a mixture of indicators from different status types were
244 not classified due a lack of confidence in whether they were either inactive (no
245 erosion or deposition), in steady-state equilibrium (a balance between erosion and
246 deposition), erosion dominated with some depositional features, or deposition
247 dominated with some erosional features.

248

249 The 152 locations at which channel observations were made during the 2010 field
250 reconnaissance were selected based on their accessibility and so, in general, are
251 where footpaths or roads run alongside or across the river channel. The length of
252 channel upon which observations of channel form were based was 100m, although
253 at several sites the length of channel visible was less than this. In order to encourage
254 consistency, the same geomorphologists were responsible for all of the 152 channel
255 observations but it is recognised that there is an element of subjectivity within this
256 method of defining channel status. This may result in inconsistencies between
257 different geomorphologists and also inconsistencies from an individual as their
258 perspective changes.

259

260 *Table 1. Criteria used for the definition of erosion dominated and deposition*
261 *dominated channels. Modified from Sear et al's (2003) Table 4.3.*

262

263 **Calculating unit bed area stream power across a river catchment network**

264

265 Unit bed area stream power (ω , Wm^{-2}) is defined as

266

$$\omega = \frac{\gamma \cdot Q \cdot S}{w}$$

267 *Equation 2*

268

269 where γ is the unit weight of water (9810N/m^3), Q is an indicative discharge (m^3/s),
270 slope is energy slope (m/m), which is often approximated by bed slope, and w is the
271 width of the flow (m), often approximated by channel bankfull width when using flood
272 flow discharges (Bagnold, 1966, Barker, et al., 2009).

273

274 The approach applied within this study involved calculating unit bed area stream
275 power across the river channel network at a series of separate points spaced 50m
276 apart along each of the branches of the river catchment network. To establish the
277 topology of the river catchment network and the location of the points along the
278 network it was necessary to apply a series of spatial analysis techniques (within
279 ESRI's ArcGIS software) on the Ordnance Survey Land-form Profile contour and
280 spot height data (Figure 2):

- 281 1. A digital elevation model (DEM) raster dataset (cells of $10\text{m} \times 10\text{m}$) was
282 interpolated from the Ordnance Survey Land-form Profile contour and spot height
283 data using the 'Topo to Raster' tool.
- 284 2. Any pits (local elevation minima) within the DEM raster dataset were filled in
285 order to prevent them obstructing the modelled progress of water flowing
286 downslope across the catchment surface. This was achieved using the 'Fill' tool.
- 287 3. The outgoing flow direction for each raster cell was established using the D8
288 algorithm available through the 'Flow Direction' tool.
- 289 4. For each raster cell, the total number of other cells that contribute flow into in was
290 calculated using the 'Flow Accumulation' tool.
- 291 5. The drainage area of each raster cell was calculated by multiplying the cell's flow
292 accumulation value by the area of each cell (0.0001km^2) using the 'Raster
293 Calculator' tool.
- 294 6. A raster representation of the predicted river catchment network was then
295 established by applying a drainage area threshold of 0.5km^2 using the 'Great
296 Than Equal' tool.
- 297 7. The raster representation of the predicted river catchment network was then
298 converted to a vector polyline representation using the 'Stream to Feature' tool.
- 299 8. A new DEM was interpolated from the original contour and spot height data and
300 the newly created polyline representation of the river catchment network. This
301 was to reduce the influence of any 'stair-step' artefacts that might have been

302 created as an artefact of the interpolation from the contour lines (Wobus, et al.,
303 2006).

304 9. Steps 2-7 were then repeated using the newly created DEM.

305 10. The vector polylines of the river network branches large enough to be included in
306 the model were then identified (based on them contributing at least 1% of the
307 total catchment drainage area).

308 11. Points spaced 50m apart along each of the river network branches included in
309 the model were then created.

310

311 *Figure 2. Flowchart of processes involved in creating a ST:REAM model*

312

313 In most recent studies involving high-resolution stream power calculations across
314 river catchment networks the median annual flood (Q_{med}) is used in the calculation of
315 ω (Jain, et al., 2006, Barker, 2008, Bizzi and Lerner, 2013). The Q_{med} , also known as
316 the 2-year flood (Q_2) was also selected as the representative flow discharge in this
317 study as it approximates the morphologically significant, bankfull condition in single-
318 thread, meandering rivers like the Taff (Wolman and Miller, 1960), confines fluvial
319 action to the channel (Wharton, 1995), and has sufficient energy to mobilise the bed
320 material (Ryan, et al., 2005). To estimate the Q_{med} values for each of the points
321 throughout the river catchment network Q_{med} was first identified for each of the eight
322 gauging stations in the catchment through analysis of their annual maxima series. A
323 power regression was then established between Q_{med} and drainage area (A , km^2)
324 across the eight gauging stations in a manner similar to that suggested by Knighton
325 (1999). The derived relationship for the flow gauges in the Taff catchment is $Q_{med} =$
326 $1.8632.A^{0.8422}$, with an r^2 value of 0.94. It was then possible to use this relationship,
327 along with the drainage area raster dataset, to predict the Q_{med} for each of the points
328 across the river catchment network.

329

330 The channel bed slope was approximated for each point by dividing the DEM-based
331 elevation drop between that point and its downstream neighbour by the downstream
332 distance between the two points (50m). In other stream power based approaches for
333 predicting channel adjustment slope measurements have been taken over longer
334 horizontal distances of 200m (Vocal Ferencevic and Ashmore, 2012), 1km (Bizzi and
335 Lerner, 2013), and 4km (Barker, et al., 2009). In these approaches lower resolution

336 slope measurements are justified on the basis of capturing reach-scale changes
337 relevant to sediment budgets rather than the breaks of slope associated with
338 morphological unit changes. However, the reach-averaging procedure applied within
339 this approach means that the final stream power balance calculations are based
340 upon reach-averaged slope measurements, not those taken over 50m. Therefore,
341 the purpose of these initial measurements of slope over 50m is to capture the local
342 breaks of slope within the reach boundary identification process rather than to
343 directly inform the reach-based stream power balances.

344

345 Unlike some other attempts to represent stream power across a river catchment
346 network, which estimate channel bankfull widths using empirical downstream
347 hydraulic geometry relationships (Knighton, 1999, Bizzi and Lerner, 2013), this study
348 measured bankfull width for each point within the river catchment network using the
349 Ordnance Survey MasterMap representation of the river channel in a manner similar
350 to that described by Barker et al. (2009). It is considered preferable to measure river
351 channel width as those predicted by empirically derived relationships will not
352 accurately represent local variation in channel form that could be responsible for
353 significant sediment erosion or deposition (Bizzi and Lerner, 2013).

354

355 Using the Q_{med} , slope and width measurements described above it was possible to
356 calculate the unit bed area stream power of the median annual flood (ω_{med}) for each
357 of the 4627 points within the Taff catchment network using Equation 2.

358

359 ***Defining reach boundaries within a river catchment network***

360

361 In a reach-based approach, the input variables are reach-averaged and so the
362 method used to identify reach boundaries is crucial as it affects the modelled
363 parameters and, consequently, its outcomes. In applying the reach-based, Riverine
364 Accounting and Transport (RAT) model, Graf (1996) sought to divide the system into
365 'functional' reaches where processes and forms were internally consistent and
366 noticeably different to those in neighbouring reaches. Graf was able to do this based
367 on his detailed a priori knowledge of the morphology of the fluvial system in question,
368 however this detailed knowledge is often unavailable and so an alternative method
369 has been applied in this study.

370

371 The approach applied here searches for 'functional' reach boundaries statistically
372 using Gill's (1970) global zonation algorithm, which was originally designed for
373 geological borehole zonation. Following a review of a number of alternatives, Parker
374 et al. (2011) identified Gill's global zonation algorithm as the most suitable statistical
375 means of identifying of reaches of channel with internally homogenous and
376 comparatively heterogenous characteristics. When applying the algorithm, which
377 uses an iterative analysis of variance approach, a data sequence begins as a single,
378 long zone (Figure 3A) and is temporarily divided into two zones, with the provisional
379 partition falling between the first and second points in the sequence. At this stage,
380 the sum of squares within the two temporary zones (SS_w) is calculated using:

381

$$SS_w = \sum_{j=1}^m \sum_{i=1}^{n_j} (x_{ij} - \bar{X}_{*j})^2 / \sum_{j=1}^m n_j - m$$

382 *Equation 3*

383

384 where, x_{ij} = the i th point within zone j , \bar{X}_{*j} = mean of the j th zone, n_j = number of
385 points in the j th zone, and m = number of zones. The partition between the two
386 zones is then moved along the sequence to successive positions and SS_w is
387 calculated for every possible position of the partition. The partition which results in
388 the lowest SS_w is selected as the first zonal boundary, forming two zones (Figure
389 3B). The procedure is then repeated, with the SS_w calculated for every possible
390 position of the second partition, the minimum of which is used to divide the sequence
391 into three zones (Figure 3C). In this manner, Gill's (1970) method finds the zonation
392 that minimises variance within each zone (reach) and maximises the difference
393 between the zones (reaches). The zonation procedure continues to insert new reach
394 boundaries until the proportion of total variance explained by the zonation ($R = \frac{SS_w}{SS_T}$)
395 reaches a specified level. As a result, with higher R values a greater number of
396 reaches (of shorter length) are identified by the algorithm.

397

398 In the method applied here, Gill's (1970) global zonation algorithm has been applied
399 to the sequence of ω_{med} values for the points spread 50m apart along each of the
400 branches of the River Taff catchment network. The method used to select an

401 appropriate R value when applying the zonation algorithm to the Taff catchment is
402 described at the end of the next section.

403

404 *Figure 3. Example of the reach boundary hunting process using Gill's (1970) global*
405 *zonation algorithm. The sequence of figures shows how the entire river branch starts*
406 *as one reach (A), then is divided into two reaches at the point that explains the most*
407 *amount of variation (B), and then again into three reaches (C), and so on until the*
408 *user-specified value of R is met – for example 0.01 (D).*

409

410 **Calculating reach stream power balances**

411

412 Following the calculation of ω_{med} values for the points spread 50m apart across the
413 river catchment network, and the aggregation of those points into reaches that are
414 relatively internally homogenous and comparatively heterogenous, the unit bed area
415 stream power balance ($\omega_{balance}$) for each reach was calculated (Figure 4). This was
416 achieved by dividing the ω_{med} value of the reach in question by the ω_{med} value of its
417 immediate upstream neighbour (or upstream neighbours if the reach was
418 immediately downstream of a confluence).

419

420 This method assumes that the ω_{med} value of the reach in question is an indicator of
421 the sediment transport capacity of the reach and that the ω_{med} value of its immediate
422 upstream neighbour is an indicator of the sediment transport supply that is delivered
423 from upstream. As a result, $\omega_{balance}$ values close to 1 should be indicative of reaches
424 that are in equilibrium, with $\omega_{balance}$ values significantly greater than 1 indicating
425 reaches that are likely to be erosion dominated and $\omega_{balance}$ values significantly less
426 than 1 indicating reaches that are likely to be deposition dominated.

427

428 In order to identify the most appropriate value of R to use within the zonation
429 algorithm, the impact that the assigned R value has on the accuracy of the stream
430 balance method was explored. To do this, 19 different models of the Taff catchment
431 were created with reach boundary configurations based on values of R ranging from
432 0.001 to 0.1. The $\omega_{balance}$ values for each version of the model were compared with
433 the status of the sites which had been observed as being either erosion or deposition

434 dominated and the proportion of sites that were correctly predicted ($\omega_{\text{balance}} > 1$
435 where channel is erosion dominated or $\omega_{\text{balance}} < 1$ where channel is deposition
436 dominated) was recorded. The R value that resulted in the highest proportion of
437 observed sites being predicted correctly was then used to produce the final version
438 of the model of the Taff.

439

440 After calculating the stream power balance values for each of the reaches across the
441 Taff catchment using the selected R value, the most appropriate ω_{balance} threshold
442 values for identifying deposition and erosion dominated reaches were explored.
443 Ideally, these thresholds would have been defined by the boundaries between the
444 ω_{balance} values of steady-state equilibrium sites and the ω_{balance} values of erosion
445 dominated and deposition dominated sites. However, this was not possible as
446 steady-state equilibrium sites could not be confidently identified using the channel
447 observations available. Instead, the threshold ω_{balance} values were defined using only
448 the ω_{balance} values of erosion dominated and deposition dominated sites. The
449 threshold for erosion dominated status was defined using the lower quartile
450 boundary of the ω_{balance} values of erosion dominated observed sites and the
451 threshold for deposition dominated status was defined using the upper quartile
452 boundary of ω_{balance} values of deposition dominated observed sites. These threshold
453 values were then used to identify the reaches with the Taff catchment that are
454 predicted as being either erosion or deposition dominated.

455

456 *Figure 4. Principles of reach-based stream power balance modelling applied in*
457 *ST:REAM*

458

459 **Results**

460

461 ***Classification of observed channel status***

462

463 Figure 5 displays the observed channel locations classified as either erosion or
464 deposition dominated using the criteria set out in Table 1. Of the 152 sites where
465 observations were made, 45 were classified as erosion dominated and 62 as
466 deposition dominated, with the remainder (45) not showing clear evidence of being
467 either erosion or deposition dominated.

468

469 *Figure 5. Observed channel locations classified as either erosion or deposition*
470 *dominated across the River Taff catchment, South Wales*

471

472 **Calculated unit bed area stream power values**

473

474 Figure 6 displays the calculated unit bed area stream power values (ω_{med}) for points
475 spaced every 50m along the catchment network of the River Taff. Measured ω_{med}
476 values range from $2 \times 10^{-8} \text{ W/m}^2$ to 10315 W/m^2 . In general, the highest ω_{med} values
477 are found in the first order, headwater channels where slopes are steepest and
478 channel widths are constrained by narrow valleys. The lowest ω_{med} values are
479 generally found in the sections of channel furthest downstream where the
480 topography is flatter. There are a large number of exceptions to this general trend,
481 with local variations driven by factors such as impoundment and geological
482 discontinuities.

483

484 *Figure 6. Calculated unit bed area stream power (ω_{med}) values for points spaced*
485 *every 50m across the channel network of the River Taff, South Wales*

486

487 **Calibration of reach boundary hunting algorithm**

488

489 Figure 7 illustrates the influence of the R value used within Gill's (1970) global
490 zonation algorithm on ST:REAM's ability to correctly identify the points along the
491 channel network that were observed as being either erosion or deposition
492 dominated. The percentage of points predicted correctly increases from 71% when
493 $R=0.001$ to 87% when $R=0.02$ before falling down to 55% when $R=0.08$. As a result,
494 a value of R of 0.02 was selected as being the most appropriate when applying
495 ST:REAM to the River Taff catchment.

496

497 *Figure 7. Proportion of observed erosion or deposition dominated sites predicted*
498 *correctly by ST:REAM for different boundary hunting algorithm 'R' values.*

499

500 **Calibration of stream power balance thresholds**

501

502 The spread of ω_{balance} values (when $R=0.02$) for points along the catchment network
503 of the Taff identified as being either erosion or deposition dominates is displayed in
504 Figure 8. As would be expected, the majority of sites identified as being erosion
505 dominated have ω_{balance} values greater than 1, with an interquartile range of 2.3-11.6.
506 The majority of sites identified as being deposition dominated have ω_{balance} values
507 less than 1, with an interquartile range of 0.27-0.59. However, there are also a
508 number of erosion and deposition dominated points that have values of ω_{balance} that
509 fall outside the ranges that would be expected – the minimum ω_{balance} value for
510 points identified as being erosion dominated is 0.4 and the maximum ω_{balance} value
511 for points identified as being deposition dominated is 339.7. The upper quartile
512 boundary of ω_{balance} values for deposition dominated points (0.59) has been selected
513 as the threshold for predicting reaches as being deposition dominated and the lower
514 quartile boundary of ω_{balance} values for erosion dominated points (2.3) has been
515 selected as the threshold for predicting reaches as being erosion dominated.

516

517 *Figure 8. Distribution of stream power balances for erosion dominated and*
518 *deposition dominated sites, using a boundary hunting algorithm 'R' value of 0.02.*

519

520 ***Predicted channel status***

521

522 The output from applying ST:REAM when $R=0.02$, the threshold ω_{balance} value for
523 deposition dominated reaches is 0.59, and the threshold ω_{balance} value for erosion
524 dominated reaches is 2.3 is displayed in Figure 9. The majority of the reaches within
525 the Taff catchment have been predicted as being either erosion or deposition
526 dominated. The majority of reaches predicted as being deposition dominated are
527 those where there has been a drop in the river slope, such as in the piedmont zone
528 downstream of the confluence between the Taff and the Rhondda. The majority of
529 reaches predicted as being erosion dominated are those with locally high slopes,
530 such as the final reach of the Cynon before it joins the Taff. Within the reaches
531 predicted as being either erosion or deposition dominated the status of 87.5% of the
532 observed sites were predicted correctly.

533

534 *Figure 9. Predicted location of erosion dominated and deposition dominated reaches*
535 *within the River Taff catchment, South Wales, using ST:REAM with a boundary*
536 *hunting algorithm 'R' value of 0.02 and deposition and erosion threshold values for*
537 *$\omega_{balance}$ of 0.59 and 2.3 respectively.*

538

539 **Discussion**

540

541 ***Model performance***

542

543 The results demonstrate that, when ST:REAM is applied to the Taff catchment, there
544 is a close correspondence between the calculated stream power balance of a reach
545 ($\omega_{balance}$) and the occurrence of features that are associated with erosion or
546 deposition dominated channels. This is as expected: reaches with a $\omega_{balance}$ value <
547 0.59 have ω_{med} values nearly half that of their upstream neighbour(s) and it is
548 therefore expected that their sediment supply exceeds their transport capacity –
549 leading to aggradation (Lane, 1955); reaches with a $\omega_{balance}$ value > 2.3 have ω_{med}
550 values more than double that of their upstream neighbour(s) and it is therefore
551 expected that their transport capacity exceeds their sediment supply – leading to
552 degradation (Lane, 1955).

553

554 However, it is evident that the method applied is not consistently accurate in its
555 prediction of channel status. Whilst Figure 8 demonstrated that the majority of
556 $\omega_{balance}$ values for sites observed as being erosion or deposition dominated fall within
557 the ranges that would be expected (>1 and <1 respectively), there are also some
558 values of $\omega_{balance}$ that fall well outside these expected ranges. Some of this error may
559 be due to uncertainties in the measurement of parameters used to calculate ω_{med} for
560 points across a catchment network (Bizzi and Lerner, 2013). There is significant
561 uncertainty regarding the most appropriate means of measuring channel slope from
562 digital elevation models (Vocal Ferencevic and Ashmore, 2012) and measurements
563 are very sensitive to errors in elevation data, particularly across shallow slopes (Lane
564 and Chandler, 2003). In addition, the method used to estimate the Q_{med} values for
565 points across the catchment is based upon an empirical relationship and will not
566 represent any local variability. An alternative would have been to use a physically-
567 based hydrological model (Barker et al., 2009).

568

569 As well as the uncertainty in the calculation of ω_{med} for points across a catchment
570 network (Bizzi and Lerner, 2013), error within the predictions made by ST:REAM
571 may derive from the simplifications made within the model. These simplifications
572 include: an assumption that the rate of sediment transport out of a reach is directly
573 related to its ω_{med} ; an assumption the supply of sediment into a reach is directly
574 related to the ω_{med} of its upstream neighbour(s); a static representation of a system
575 that evolves over time and is influenced by feedback; and a reach-based
576 representation of a system that varies continuously across space. Some of these
577 simplifications are explored in more detail in the paragraphs below.

578

579 In making its predictions of channel sediment dynamics, the reach-based stream
580 power balance approach assumes that each reach will be able to transport sediment
581 out of the reach at a rate that is directly proportional to the unit bed area stream
582 power of its median annual flood. Whilst it has been demonstrated both theoretically
583 and empirically that unit bed area stream power is closely associated with sediment
584 transport rates (Bagnold, 1966, Parker, et al., 2011), the entrainment threshold of the
585 channel boundary material (generally controlled by particle size/weight) is also
586 important (Bull, 1979). As a result, variations in the entrainment threshold of channel
587 boundaries between reaches can cause discrepancies in the application of ω_{med} as
588 an approximation of outgoing sediment transport rate. In addition, the relationship
589 between sediment transport rate and ω_{med} is assumed to be linear within ST:REAM
590 when it has been found to be non-linear (Bagnold, 1986). Therefore, ω_{med} is likely to
591 under represent the outgoing transport rate of high powered reaches and over
592 represent the outgoing transport rate of low powered reaches. A final simplification in
593 the representation of outgoing sediment transport within ST:REAM is that ω_{med} is an
594 indicator of transport capacity and does not take into consideration the availability of
595 sediment for transport. In reality, two reaches with similar values for ω_{med} will have
596 different influences on downstream reaches if they have different levels of sediment
597 availability but this is not reflected within ST:REAM.

598

599 These assumptions in the representation of outgoing sediment transport rate clearly
600 also have an impact on the representation of the incoming sediment supply to each
601 reach, as ST:REAM assumes that the supply of sediment into a reach is directly

602 related to the ω_{med} of its upstream neighbour(s). This assumption has a particularly
603 large impact on the predictions for a reach whose upstream neighbour has a high
604 stream power but has highly resistant channel boundaries (e.g. bedrock or artificial)
605 – in this scenario the upstream ω_{med} applied within ST:REAM will be high but the
606 actual incoming sediment supply will be limited to sediment that has been transferred
607 through the upstream neighbour from the next reach upstream. In addition,
608 ST:REAM assumes that the only sediment input into a reach is from its upstream
609 neighbour(s). Whilst this assumption may be reasonable within lowland channels, in
610 headwater streams hillslope-channel coupling can provide a significant proportion of
611 a channel's sediment input (Harvey, 2001, Michaelides and Wainwright, 2002) and
612 so ST:REAM may under-represent the incoming sediment supply.

613

614 The reach-based balance approach employed within ST:REAM allows for the
615 comparison of the stream power of a reach (and therefore its assumed outgoing
616 sediment transport rate) against the stream power of its upstream neighbours (and
617 therefore its assumed incoming sediment supply). However, the reach-based nature
618 of the approach may reduce its accuracy by exaggerating between reach differences
619 and not representing within reach differences. Re-examination of Figure 3D
620 illustrates that significant local variation in ω_{med} can exist within a reach – this might
621 be associated with local variation in channel sediment dynamics that are not
622 represented within ST:REAM. Figure 3D also demonstrates how the changes in ω_{med}
623 across reach boundaries are more sudden than the changes across the point-based
624 representation of ω_{med} . In addition, ST:REAM's reach-based nature also means that
625 its outputs are sensitive to the reach boundaries that are identified. Figure 7
626 demonstrates this sensitivity by illustrating how the accuracy with which $\omega_{balance}$
627 values can be associated with erosion or deposition dominated sites varies with the
628 number of reach boundaries identified. As a result of this sensitivity, ST:REAM is
629 limited in terms of consistency and therefore more research is necessary to improve
630 understanding of the influence of the location of reach boundaries on the model
631 outputs.

632

633 ***Model application***

634

635 Possible applications for an approach like ST:REAM within the contexts of integrated
636 catchment, river basin and flood risk management include planning actions for
637 sediment management performed as part of flood risk management. Currently,
638 locations where sediment must be managed are identified on the basis of
639 stakeholder pressure, experience and past practice, with little regard to whether the
640 cause of the problem is local or is a symptom of an imbalance in the sediment
641 transfer system and no consideration of the possible impacts of sediment
642 management for continuity and connectivity in the sediment transfer system (Thorne,
643 et al., 2010). An approach such as ST:REAM provides a science-base for examining
644 local sediment problems and the risks associated with different options for sediment
645 management, within the wider contexts of the catchment, fluvial and ecosystems.
646 For example, alongside local knowledge of the catchment system, Figure 9 could be
647 used to justify sediment extraction in the lower reaches of the main stem of the Taff
648 as it approaches and flows through Cardiff. Similarly, it could be used to help justify
649 spending on erosion protection on the lower reaches of the Cynon and Rhondda just
650 before their confluences with the main stem of the Taff.

651

652 In addition, an approach like ST:REAM could be used to link habitat degradation to
653 excessive sediment scour or accumulation when restoring rivers. It could provide a
654 means of rapidly relating system-scale sediment dynamics and local sediment
655 imbalances to reaches experiencing loss of habitat quality and/or diversity. This is
656 important as it allows river scientists and engineers charged with implementing
657 restorative or mitigating actions to account for sediment processes as well as
658 morphological forms in their designs. For example, where supported by local
659 observations, Figure 9 could be used to explain poor ecological status as a result of
660 excessive sediment deposition within the second order reaches of the Rhondda.

661

662 Specific applications like those above represent potentially valuable uses of the type
663 of approach developed herein, but perhaps the most useful contribution that an
664 approach like ST:REAM could make to river management is by providing a broad
665 understanding of catchment-scale sediment transfer systems nationally. The
666 importance of understanding the fluvial system when managing flood risk,
667 morphological adjustment and ecological status is emerging as the movement
668 towards integrated catchment management gains momentum. In this context, it will

669 no longer be sufficient to rely on qualitative description of sediment dynamics and
670 classification of sediment sources, transfers or sinks. Identification of causal links in
671 the sediment transfer system will be required to infer whether sediment imbalance in
672 a reach results from the natural operation of the sediment transfer system or is the
673 unintended consequence of a poorly designed management intervention, and to
674 predict the probable morphological responses to proposed mitigating or adaptive
675 actions – including that of ‘doing nothing’. The fact that climate and anthropogenic
676 pressures are likely to grow means that accounting for sediment status is central to
677 managing a catchment holistically and sustainably. This is evident in the
678 identification of geomorphology as a component of the English and Welsh
679 Environment Agency’s Catchment Flood Management Plans (CFMPs) and River
680 Basin Management Plans (RBMPs). However, there is currently no means of
681 considering sediment dynamics at the catchment scale due to data and operational
682 constraints. ST:REAM goes some way towards addressing this problem thanks to its
683 relatively low data requirements and ease of application. For example, Figure 9
684 indicates that whilst the entire length of the main stem of the Taff downstream of its
685 confluence with the Taff Bargoed is likely to be deposition dominated many of its
686 tributaries (notably the Rhondda, Cynon and Nant Morlais) are likely to be erosion
687 dominated just before their confluence with the main stem.

688

689 However, there are limitations on the suitability of ST:REAM to widespread
690 application within river management – the two most significant of which result from
691 uncertainty regarding its accuracy and its calibration requirements. Given that the
692 simplifications explored above limit the reliability of ST:REAM’s outputs, it is
693 important that the outputs from an approach like ST:REAM are not used in isolation
694 when making river management decisions. Instead, it is recommended that they are
695 considered in conjunction with field reconnaissance, desk-based and archival
696 investigations and careful examination of aerial photographs and satellite imagery, to
697 check whether the outputs of ST:REAM are supported by both historical records and
698 contemporary observations of sediment issues, channel forms and sedimentary
699 features. As a result, whilst the outputs from ST:REAM can be produced with
700 minimal resources, for them to be interpreted confidently at a local scale, it is
701 necessary for significant additional investment to be made.

702

703 As demonstrated in its application to the River Taff, when applying ST:REAM it is
704 necessary to select a value of R to control the number of reaches that a catchment
705 network is divided into. It is also necessary to select threshold values of ω_{balance} to
706 discriminate the reaches that are predicted to be either erosion or deposition
707 dominated. The most suitable values for these parameters have been established for
708 the Taff catchment but it is unknown whether these will be suitable for other river
709 catchments. Therefore, unless an alternative means of calibrating ST:REAM can be
710 identified it will be necessary to use the method applied here, which requires
711 significant investment of resources into recording observations of channel status.

712

713 **Conclusion**

714

715 This paper has described the application of a reach-based stream power balance
716 approach for predicting river channel adjustment within the River Taff catchment in
717 South Wales. The approach, named ST:REAM, can be rapidly applied using
718 datasets that are commonly available across river catchments. When applied to the
719 River Taff, ST:REAM correctly predicted the status of 87.5% of sites that field
720 observations had defined as being either erosion or deposition dominated. However,
721 whilst this demonstrates the potential that this type of approach has as a tool within
722 river catchment management there are currently a number of factors that limit its
723 usefulness. These limitations include the inconsistent performance that may result
724 from inaccuracies in the calculation of ω_{med} , or from simplifications made within the
725 reach-based stream power balance approach, or a combination of both of these.
726 Additionally, the approach is limited by the need to consider the outputs from
727 ST:REAM against the context of observations of channel status. A final limitation is
728 the current need to calibrate ST:REAM for each catchment against observations of
729 channel status.

730

731 These conclusions need to be considered in the context of the limitations of this
732 particular study, the most significant of which is that the reach-based stream power
733 balance approach has only been applied to one catchment. As a result, it is not
734 possible to confidently conclude whether or not the R value and ω_{balance} thresholds
735 selected or the level of accuracy observed within the Taff catchment will apply in

736 other catchments. Further testing of ST:REAM is planned across a wider range of
737 rivers to explore this.

738

739 Additional planned future work will involve investigation into alternative approaches
740 for predicting catchment-scale sediment dynamics using remotely sensed-based
741 calculations of stream power. Whilst there has already been a significant amount of
742 recent research into this area (Barker, et al., 2009, Vocal Ferencevic and Ashmore,
743 2012, Biron, et al., 2013, Bizzi and Lerner, 2013) there is an opportunity to not only
744 derive new approaches but also to compare the accuracy and utility of the
745 approaches that already exist.

746

747 **Acknowledgements**

748

749 The majority of the research for this paper was carried out as part of a Ph.D. thesis
750 funded by EPSRC doctoral training account EP/P502632 as part of the Flood Risk
751 Management Research Consortium, supervised at the University of Nottingham by
752 Professors Colin Thorne and Nicholas Clifford. The ST:REAM approach was based
753 on earlier work carried out by Philip Soar (University of Portsmouth) and Nick
754 Wallerstein (Heriot Watt University) in their development of REAS (River Energy
755 Audit Scheme). Ordnance Survey Land-form Profile and MasterMap data was
756 provided by Edina Digimap, catchment hydrology data was obtained from the Centre
757 for Ecology and Hydrology.

758

759 **References**

760 Ashworth PJ, Ferguson RI. 1986. Interrelationships of Channel Processes, Changes
761 and Sediments in a Proglacial Braided River. *Geografiska Annaler. Series A,*
762 *Physical Geography* **68** : 361-371.

763 Bagnold RA. 1986. Transport of solids by natural-water flow - evidence for a
764 worldwide correlation. In: Thorne CR, MacArthur RC, Bardley JB (eds). *The Physics*
765 *of Sediment Transport by Wind and Water*. American Society of Civil Engineers,
766 New York; 346-351.

767 Bagnold RA. 1966. An approach to the sediment transport problem from general
768 physics. In: Thorne CR, MacArthur RC, Bradley JB (eds). *The Physics of Sediment*
769 *Transport by Wind and Water*. American Society of Civil Engineers, New York; 231-
770 291.

771 Barker DM, Lawler DM, Knight DW, Morris DG, Davies HN, Stewart EJ. 2009.
772 Longitudinal distributions of river flood power: the combined automated flood,
773 elevation and stream power (CAFES) methodology. *Earth Surface Processes and*
774 *Landforms* **34** : 280-290.

775 Barker DM. 2008. A new approach for determining downstream change in river flood
776 power at a catchment scale based on the Flood Estimation Handbook and NextMap
777 Britain DEM. Ph.D. Dissertation. Department of Civil Engineering and School of
778 Geography, Earth and Environmental Sciences - University of Birmingham,
779 Birmingham.

780 Biron PM, Choné G, Buffin Bélanger T, Demers S, Olsen T. 2013. Improvement of
781 streams hydrogeomorphological assessment using LiDAR DEMs. *Earth Surface*
782 *Processes and Landforms* **38** : 1808-1821.

783 Bizzi S, Lerner DN. 2013. The use of stream power as an indicator of channel
784 sensitivity to erosion and deposition processes. *River Research and*
785 *Applications* DOI: 10.1002/rra.2717.

786 Brunner GW. 2006. HEC-RAS, River Analysis System Version 4.0 User's Manual.

787 Bull WB. 1979. Threshold of critical power in streams. *Geological Society of America*
788 *Bulletin* **90** : 453-464.

789 CEH. 2014. National River Flow Archive - 57003 Taff at Tongwynlais
790 <http://www.ceh.ac.uk/data/nrfa/data/station.html?57003>.

791 Coulthard TJ, Van de Wiel MJ. 2007. Quantifying fluvial non linearity and finding self
792 organized criticality? Insights from simulations of river basin evolution.
793 *Geomorphology* **91** : 216–235.

794 EA. 2014. Environment Agency HiFlows-UK - Taff at Tongwynlais (57003).
795 <http://www.environment-agency.gov.uk/hiflows/station.aspx?57003>.

796 Edina. 2014. Digimap Ordnance Survey Help.
797 http://digimap.edina.ac.uk/webhelp/os/osdigimaphelp.htm#data_information/os_products/.
798 [ucts/](http://digimap.edina.ac.uk/webhelp/os/osdigimaphelp.htm#data_information/os_products/).

799 EU. 2000. Directive 2000/60/EC of the European Parliament and of the Council
800 establishing a framework for the Community action in the field of water policy.

801 Exner FM. 1925. Uber die wechselwirkung zwischen wasser und geschiebe in
802 flussen. *Sitzungber der Akademie der Wissenschaften* : 165-180.

803 Gibson SA, Little CDJ. 2006. Implementation of the Sediment Impact Assessment
804 Model (SIAM) in HEC-RAS. Eighth Federal Interagency Sedimentation Conference.
805 Federal Interagency Subcommittee on Sedimentation. 65-72.

806 Gill D. 1970. Application of a Statistical Zonation Method to Reservoir Evaluation and
807 Digitized-Log Analysis. *Bulletin of the American Association of Petroleum Geologists*
808 **54** : 719-729.

809 Graf WL. 1996. Transport and deposition of plutonium-contaminated sediments by
810 fluvial processes, Los Alamos Canyon, New Mexico. *Geological Society of America*
811 *Bulletin* **108** : 1342-1355.

812 Graf WL. 1983. Downstream changes in stream power in the Henry Mountains,
813 Utah. *Annals of the Association of American Geographers* **73** : 373-387.

814 Harvey AM. 2001. Coupling between hillslopes and channels in upland fluvial
815 systems: implications for landscape sensitivity, illustrated from the Howgill Fells,
816 northwest England. *Catena* **42** : 225-250.

817 Harvey AM. 1991. The influence of sediment supply on the channel morphology of
818 upland streams: Howgill Fells, Northwest England. *Earth Surface Processes and*
819 *Landforms* **16** : 675-684.

820 Hendry K, Cragg-Hine D, O'Grady M, Sambrook-Smith H, Stephen A. 2003.
821 Management of habitat for rehabilitation and enhancement of salmonid stocks.
822 *Fisheries Research* **62** : 171-192.

823 ISIS. 1999. ISIS Sediment User Manual. Halcrow / HR Wallingford, Swindon.

824 Jain V, Preston N, Fryirs K, Brierley G. 2006. Comparative assessment of three
825 approaches for deriving stream power plots along long profiles in the upper Hunter
826 River catchment, New South Wales, Australia. *Geomorphology* **74** : 297-317.

827 Knighton AD. 1999. Downstream variation in stream power. *Geomorphology* **29** :
828 293-306.

829 Lane EW. 1955. Design of stable channels. *Transactions of the American Society of*
830 *Civil Engineers* **120** : 1234-1279.

831 Lane EW. 1955. The importance of fluvial morphology in hydraulic engineering.
832 *Proceedings of the American Society of Civil Engineers* **81**.

833 Lane SN, Tayefi V, Reid SC, Yu D, Hardy RJ. 2007. Interactions between sediment
834 delivery, channel change, climate change and flood risk in a temperate upland
835 environment. *Earth Surface Processes and Landforms* **32** : 429-446.

836 Lane SN, Chandler JH. 2003. Editorial: The generation of high quality topographic
837 data for hydrology and geomorphology: new data sources, new applications and new
838 problems. *Earth Surface Processes and Landforms* **28** : 229-230.

839 Lawler DM, Grove JR, Couperthwaite JS, Leeks GJL. 1999. Downstream change in
840 river bank erosion rates in the Swale-Ouse system, northern England. *Hydrological*
841 *Processes* **13** : 977-992.

842 Lawler DM. 1992. Process dominance in bank erosion systems. In: Carling PA (ed).
843 *Lowland Floodplain Rivers: Geomorphological Perspectives*. John Wiley & Sons Ltd;
844 117-143.

845 Lecce SA. 1997. Nonlinear downstream changes in stream power on Wisconsin's
846 Blue River. *Annals of the Association of American Geographers* **87** : 471-486.

847 Lorenz A, Hering D, Feld C, Rolaufts P. 2004. A new method for assessing the
848 impact of hydromorphological degradation on the macroinvertebrate fauna of five
849 German stream types. *Hydrobiologia* **516** : 107-127.

850 Magilligan FJ. 1992. Thresholds and the spatial variability of flood power during
851 extreme floods. *Geomorphology* **5** : 373-390.

852 Michaelides K, Wainwright J. 2002. Modelling the effects of hillslope–channel
853 coupling on catchment hydrological response. *Earth Surface Processes and*
854 *Landforms* **27** : 1441-1457.

855 Newson MD, Large ARG. 2006. 'Natural' rivers, 'hydromorphological quality' and
856 river restoration: a challenging new agenda for applied fluvial geomorphology. *Earth*
857 *Surface Processes and Landforms* **31** : 1606-1624.

858 Olsen NRB. 2003. 3D CFD Modeling of a Self-Forming Meandering Channel.
859 *Journal of Hydraulic Engineering - ASCE* **129** : 366-372.

860 Osman AM, Thorne CR. 1988. Riverbank stability analysis. I. Theory. *Journal of*
861 *Hydraulic Engineering - ASCE* **114** : 134-150.

862 Palmer MA, Menninger HL, Bernhardt E. 2010. River restoration, habitat
863 heterogeneity and biodiversity: a failure of theory or practice?. *Freshwater Biology* **55**
864 : 205-222.

865 Parker C, Clifford NJ, Thorne CR. 2011. Automatic delineation of functional river
866 reach boundaries for river research and applications. *River Research and*
867 *Applications* DOI: 10.1002/rra.1568.

868 Parker C, Clifford NJ, Thorne CR. 2011. Understanding the influence of slope on the
869 threshold of coarse grain motion: Revisiting critical stream power. *Geomorphology*
870 **126** : 51-65.

871 Reinfelds I, Cohen T, Batten P, Brierley G. 2004. Assessment of downstream trends
872 in channel gradient, total and specific stream power: a GIS approach.
873 *Geomorphology* **60** : 403-416.

874 Rinaldi M, Simoncini C, Piégay H. 2009. Scientific design strategy for promoting
875 sustainable sediment management: the case of the Magra River (Central-Northern
876 Italy). *River Research and Applications* **25** : 607-625.

877 Ryan SE, Porth LS, Troendle CA. 2005. Coarse sediment transport in mountain
878 streams in Colorado and Wyoming, USA. *Earth Surface Processes and Landforms*
879 **30** : 269-288.

880 Schumm SA. 1969. River metamorphosis. *Journal of the Hydraulics Division - ASCE*
881 **95** : 255-273.

882 Sear D, Newson MD, Thorne CR. 2010. Guidebook of Applied Fluvial
883 Geomorphology. Thomas Telford, London.

884 Sear DA, Newson MD, Thorne CR. 2003. Guidebook of Applied Fluvial
885 Geomorphology. Environment Agency R&D Dissemination Centre, Swindon.

886 Sear DA, Newson MD, Brookes A. 1995. Sediment-related river maintenance - the
887 role of fluvial geomorphology. *Earth Surface Processes and Landforms* **20** : 629-647.

888 Shields FD, Knight SS, Cooper CM. 1998. Rehabilitation of aquatic habitats in
889 warmwater streams damaged by channel incision in Mississippi. *Hydrobiologia* **382** :
890 63-86.

891 Soulsby C, Youngson AF, Moir HJ, Malcom IA. 2001. Fine sediment influence on
892 salmonid spawning habitat in a lowland agricultural stream: a preliminary
893 assessment. *The Science of The Total Environment* **265** : 295-307.

894 Stover SC, Montgomery DR. 2001. Channel change and flooding, Skokomish River,
895 Washington. *Journal of Hydrology* **243** : 272-286.

896 Thorne CR, Henshaw A, Bates P, Brown D, Coulthard TJ, Gurnell A, Lewin J,
897 Longfield S, Maas G, Macklin MG, Newson M, Nicholas AP, Parker C, Rees J, Sear
898 D, Surendran S, Walker J, Warburton J. 2010. Applied fluvial geomorphology for
899 sustainable flood risk management. DEFRA Annual Flood and Coastal Risk
900 Management Conference.

901 Thorne CR, Wallerstein NP, Soar P, Brookes A, Wishart D, Biedenharn DS, Gibson
902 SA, C.D. L,Jr, Watson CC, Coulthard TJ, Van de Wiel MJ. 2010. Accounting for
903 Sediment in Flood Risk Management. In: Pender G, Faulkner H (eds). *Flood Risk*
904 *Science and Management*. John Wiley & Sons, Chichester; 87-113.

905 Vocal Ferencevic M, Ashmore P. 2012. Creating and evaluating digital elevation
906 model-based stream-power map as a stream assessment tool. *River Research and*
907 *Applications* **28** : 1394–1416.

908 Wallerstein NP, Soar P, Thorne CR. 2006. River Energy Auditing Scheme (REAS)
909 for catchment flood management planning. In: Ferreira RML, Alves ECTL, Leal
910 JGAB, Cardoso AH (eds). *River Flow 2006*. Taylor & Francis, Lisbon, Portugal.

911 Wharton G. 1995. Information for channel geometry-discharge relations. In: Gurnell
912 A, Petts G (eds). *Changing River Channels*. John Wiley & Sons, Chichester; 442.

913 Whipple KX, Tucker GE. 1999. Dynamics of the stream-power river incision model:
914 Implications for height limits of mountain ranges, landscape response timescales,
915 and research needs. *Journal of Geophysical Research-Solid Earth* **104** : 17661-
916 17674.

917 Wobus C, Whipple KX, Kirby E, Snyder N, Johnson J, Spyropolou K, Crosby B,
918 Sheehan D. 2006. Tectonics from topography: Procedures, promise, and pitfalls.
919 *Special papers of the Geological Society of America* **398** : 55.

920 Wolman MG, Miller JP. 1960. Magnitude and frequency of forces in geomorphic
921 processes. *Journal of Geology* **68** : 54-74.

922

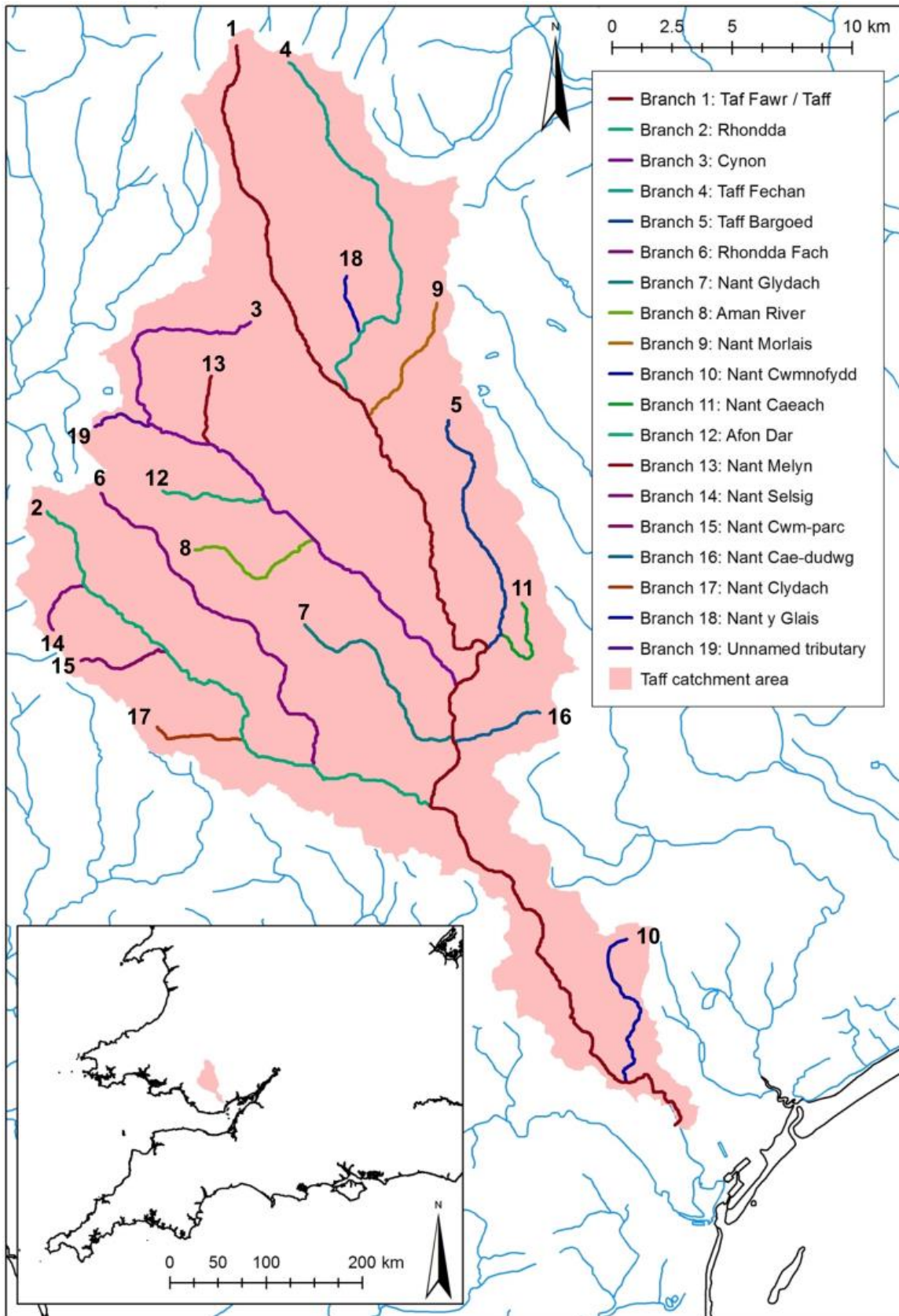
923

924 *Table 1. Criteria used for the definition of erosion dominated and deposition*
 925 *dominated channels. Modified from Sear et al's (2003) Table 4.3.*

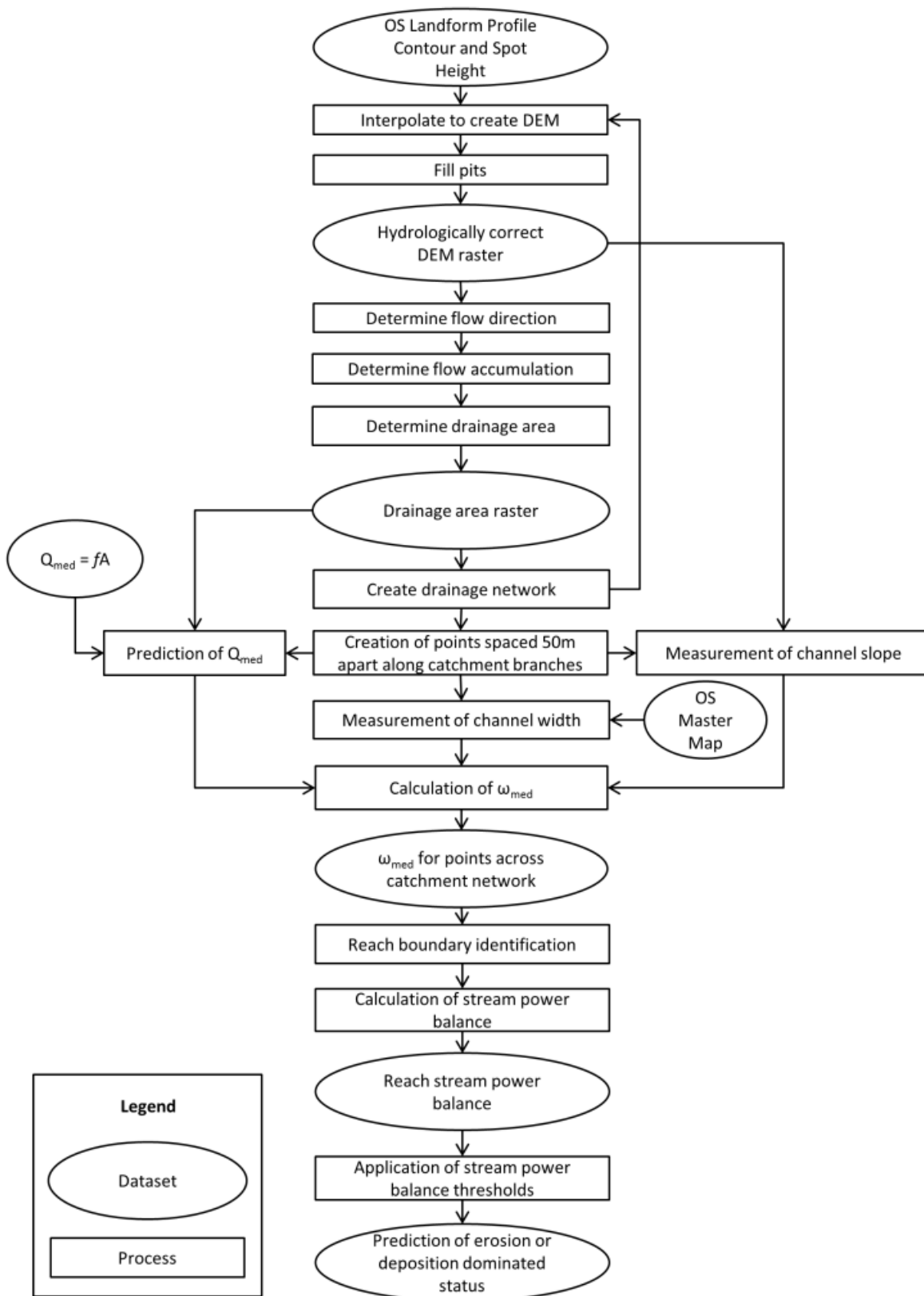
Chanel status	Indicators
Erosion dominated channels	Terraces Old channels in floodplain Undermined structures Exposed tree roots Tree collapse (both banks) Trees leaning towards channel (both banks) Downed trees in channel Narrow/deep channel Bank failures (both banks) Thick gravel exposure in the banks overlain by fines Armoured/compacted bed
Deposition dominated channels	Buried structures Buried soils Many uncompacted 'overloose' bars Eroding banks at shallows Contracting bridge openings Deep, fine sediment overlying coarse particles in bed/banks Many unvegetated bars

926

927



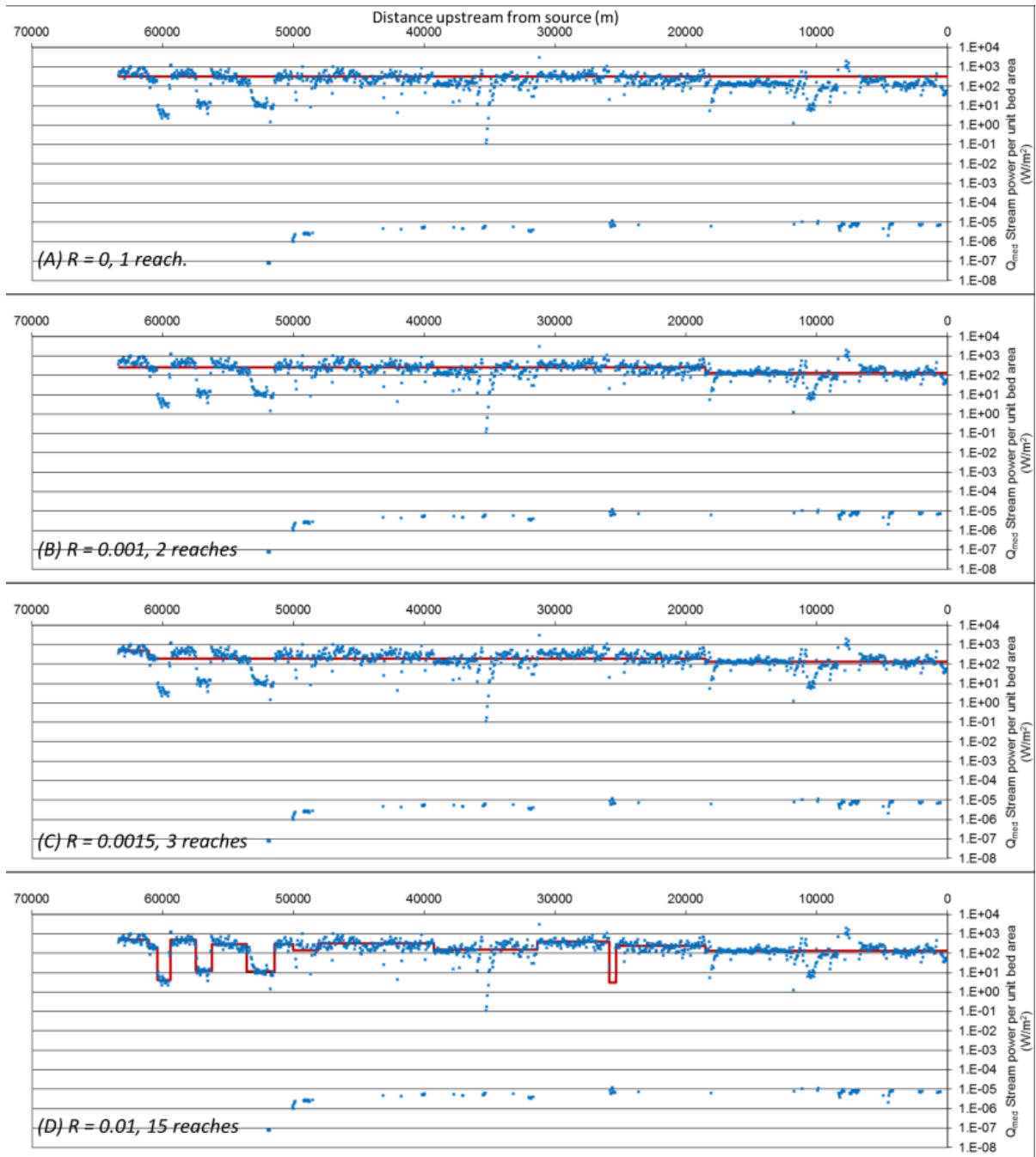
931 Figure 11. Flowchart of processes involved in creating a ST:REAM model



932

933

934 Figure 12. Example of the reach boundary hunting process using Gill's (1970) global
 935 zonation algorithm. The sequence of figures shows how the entire river branch starts
 936 as one reach (A), then is divided into two reaches at the point that explains the most
 937 amount of variation (B), and then again into three reaches (C), and so on until the
 938 user-specified value of R is met – for example 0.01 (D).

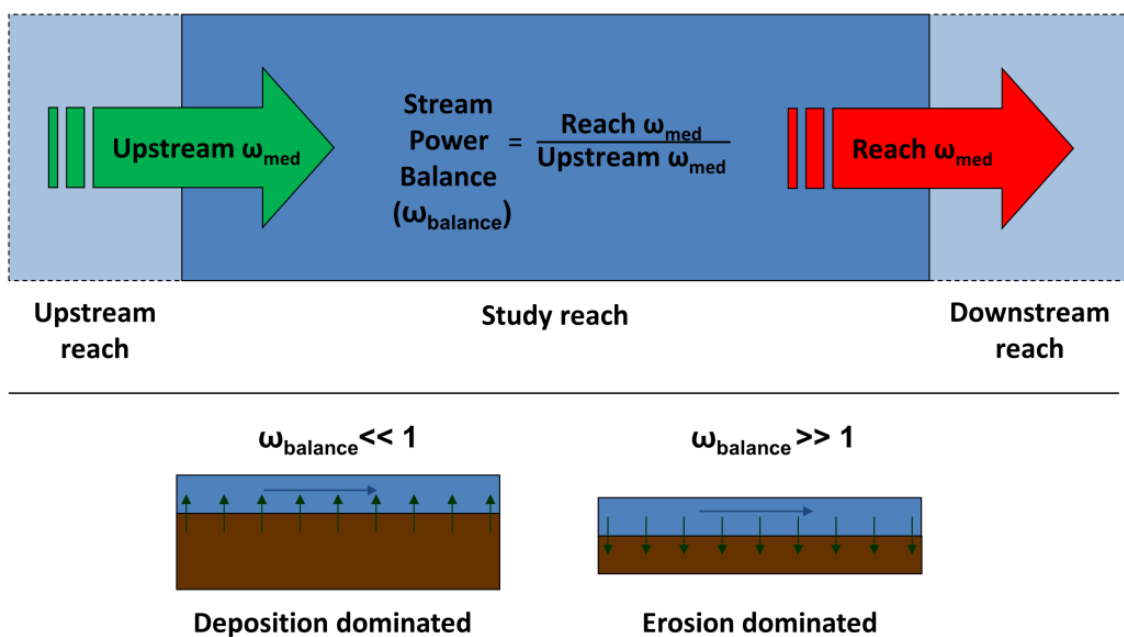


× Point ω_{med} values — Reach-averaged ω_{med} values

939

940

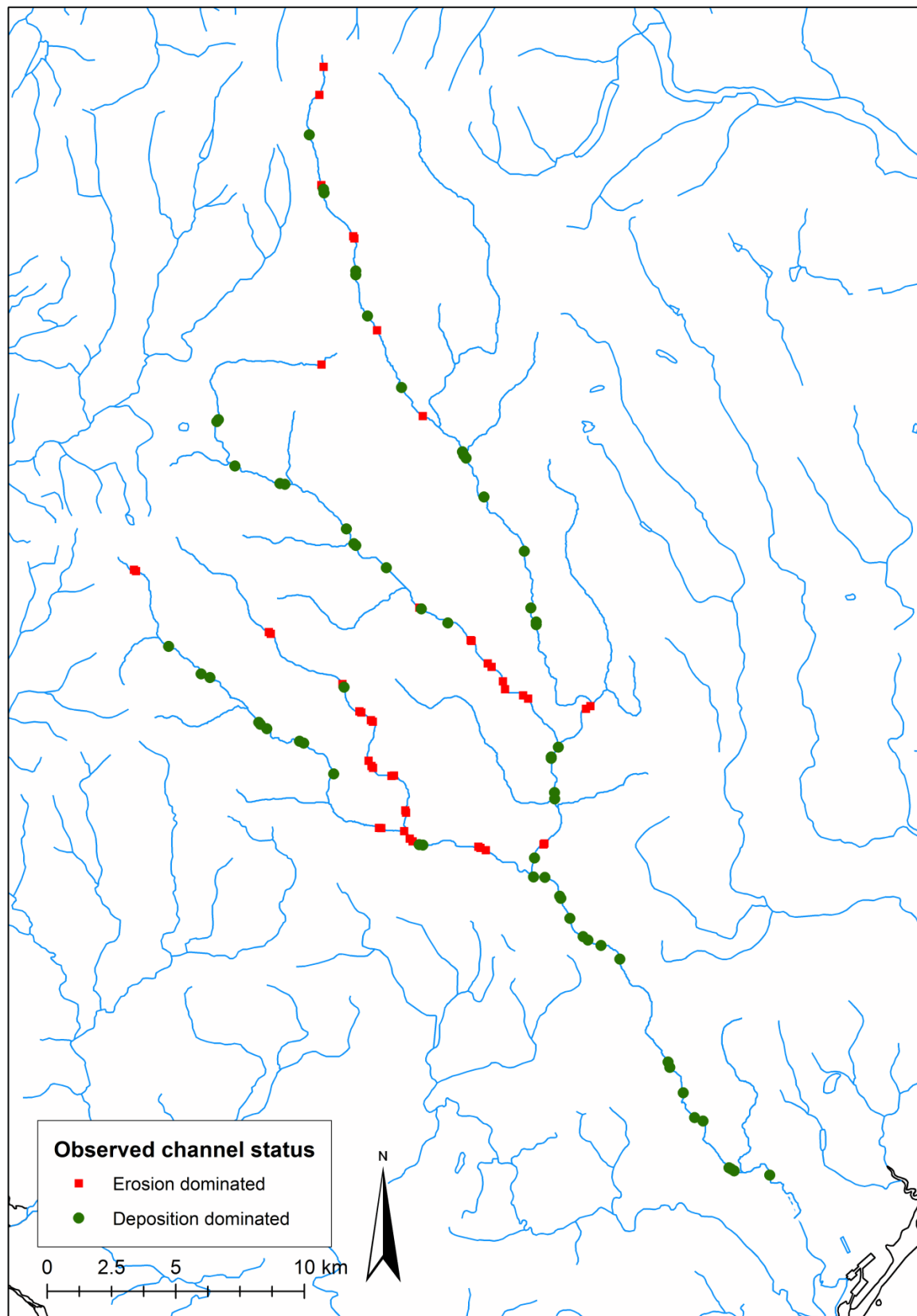
941 Figure 13. Principles of reach-based stream power balance modelling applied in
942 ST:REAM



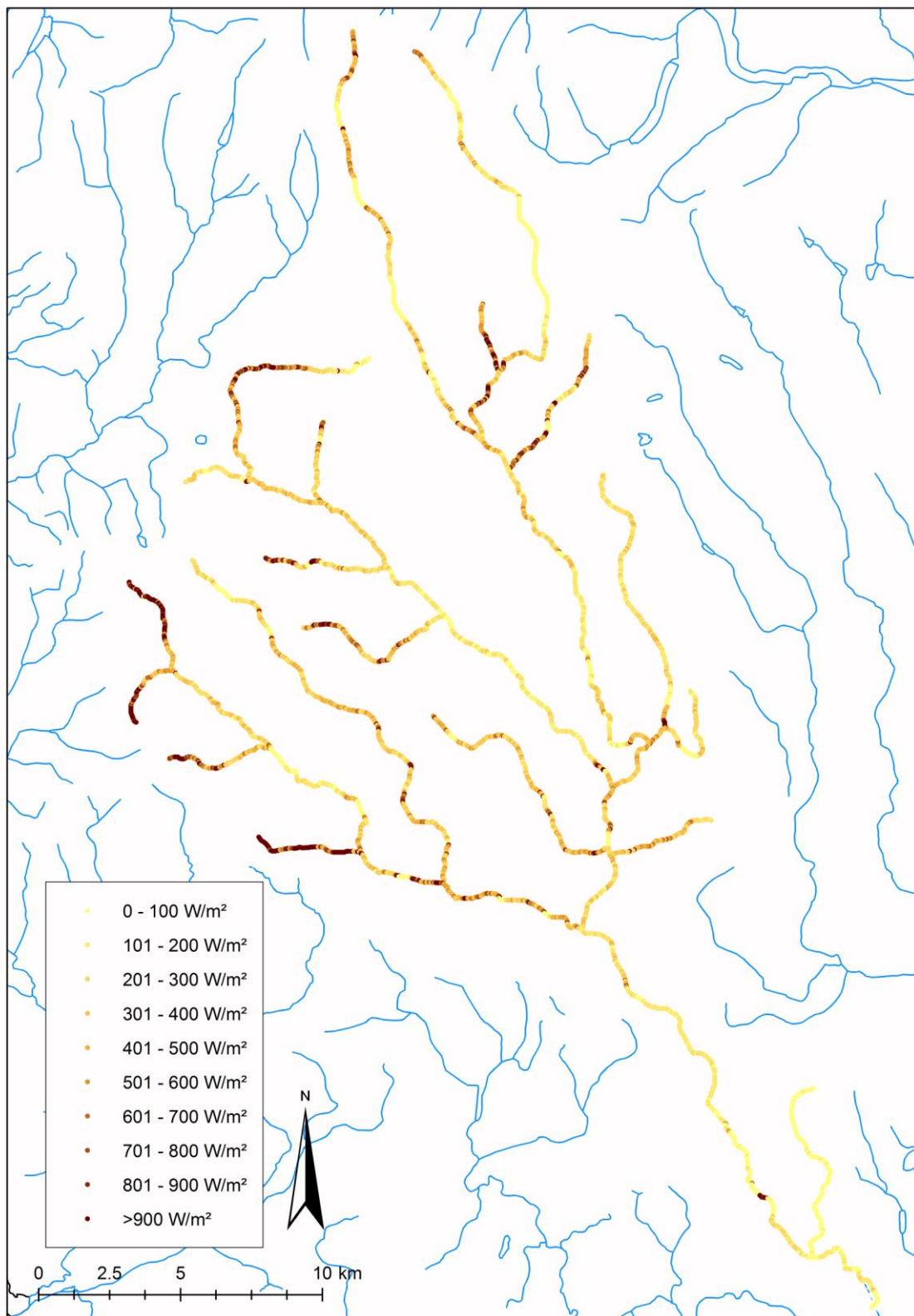
943

944

945 *Figure 14. Observed channel locations classified as either erosion or deposition*
946 *dominated across the River Taff catchment, South Wales*



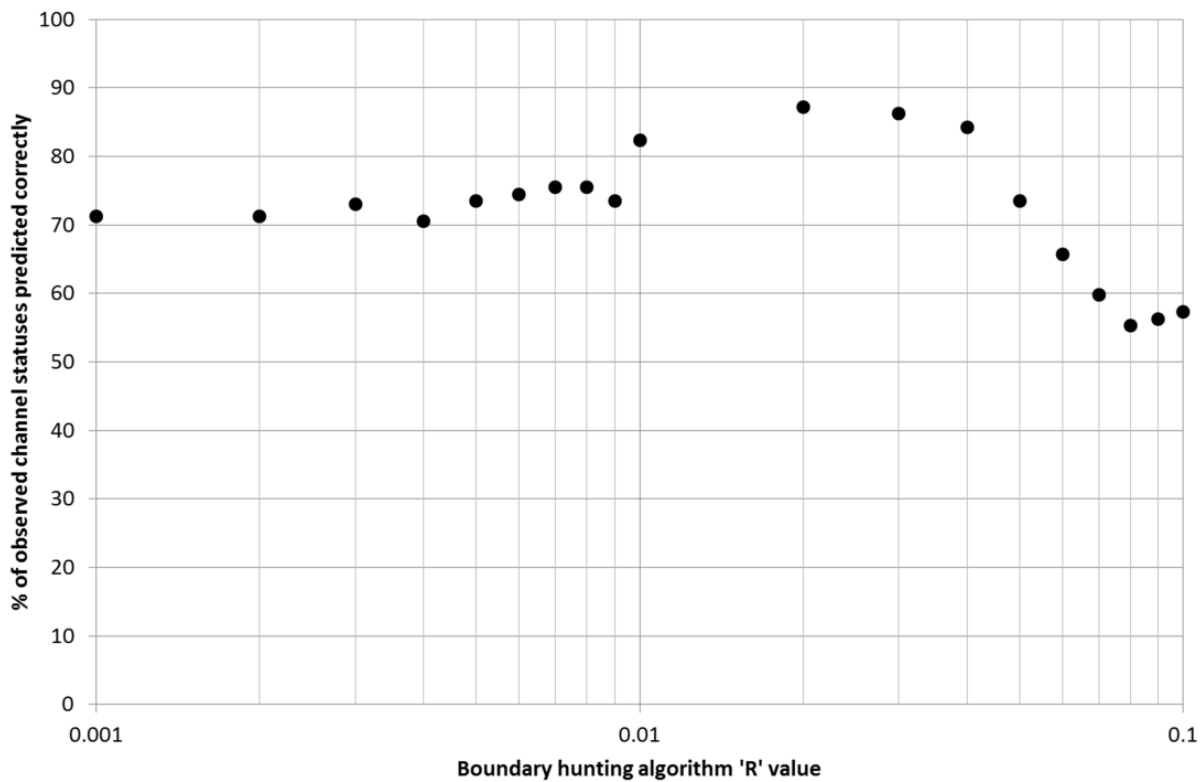
948 *Figure 15. Calculated unit bed area stream power (ω_{med}) values for points spaced*
949 *every 50m across the channel network of the River Taff, South Wales*



950

951

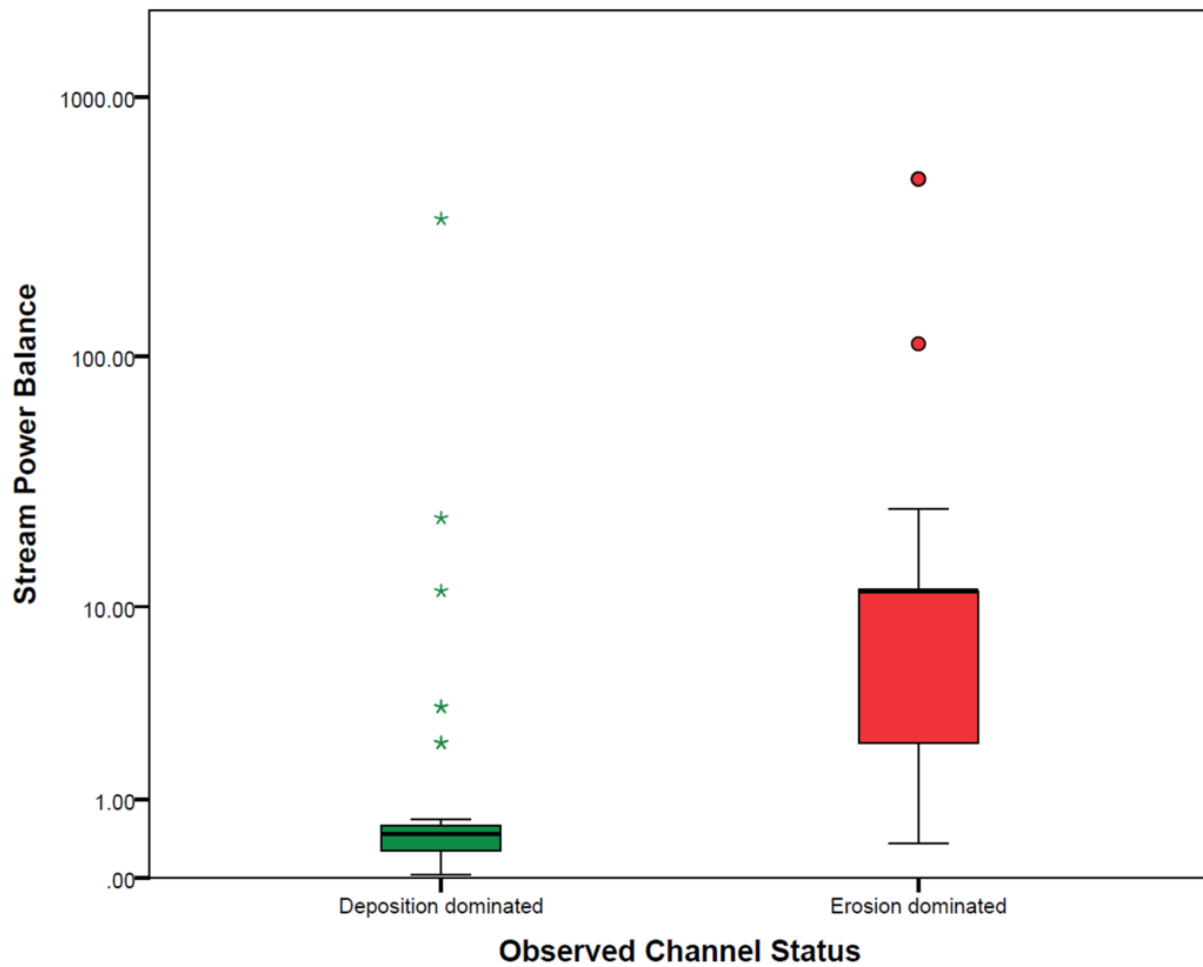
952 *Figure 16. Proportion of observed erosion or deposition dominated sites predicted*
953 *correctly by ST:REAM for different boundary hunting algorithm 'R' values.*



954

955

956 *Figure 17. Distribution of stream power balances for erosion dominated and*
957 *deposition dominated sites, using a boundary hunting algorithm 'R' value of 0.02.*



958

959

960 Figure 18. Predicted location of erosion dominated and deposition dominated
961 reaches within the River Taff catchment, South Wales, using ST:REAM with a
962 boundary hunting algorithm 'R' value of 0.02 and deposition and erosion threshold
963 values for $\omega_{balance}$ of 0.59 and 2.3 respectively.

