Flood resilience on the railways – solutions, appraisal and decision-making

Dr Ben Clark
Research Fellow, University of the West of England, Bristol.

Professor John Parkin
Professor of Transport Engineering, University of the West of England, Bristol.

Dr Mark Everard
Associate Professor of Ecosystem Services, University of the West of England, Bristol.

Dr Nevil Quinn
Associate Professor in Applied Hydrology, University of the West of England, Bristol.

Professor Graham Parkhurst
Professor of Sustainable Mobility, University of the West of England, Bristol.

Mr Rob McInnes
Director, RM Wetlands & Environment Ltd, Oxfordshire.

Abstract

The welfare costs of weather related disruption on the transport network have been estimated to be between £100m and £520m per day of disruption in England. This paper presents a case study of a mainline railway cutting and tunnel, which is situated in the catchment of a significant river and is susceptible to flooding. The project evaluated the benefits of using combined 'blue-green-grey infrastructure' schemes (respectively, use of floodplains and wetlands; use of sustainable drainage; and use of traditional drainage infrastructure) to increase the railway network's resilience to flooding events.

The policy perspective on valuing transport network resilience to extreme weather is briefly examined first. The wider economic costs of tunnel closure are then estimated using standard transport analysis guidance procedures. The calculation illustrates the potential magnitude of costs relating to rail network disruption at the tunnel (£264,000 per day of tunnel closure), and is used to frame a discussion of the limitations of current appraisal methodologies with respect to capturing the wider dis-benefits of inadequate network resilience.

The discussion is then broadened to critically examine the nature of the 'flooding problem'. Who are the stakeholders in the 'flooding problem' (Network Rail, landowners, housing developers, local authorities, the local community) and what are their vested interests in whether and how 'the problem' is solved? Example blue-green-grey schemes developed through the case study are used to identify how their collective interests might best be served through alternative approaches to flood risk management. Finally, the extent to which traditional approaches to transport option appraisals enable, or preclude, the delivery of such innovative schemes is discussed. Can collaborative approaches to decision-making be developed that lead to shared ownership of the 'flooding problem', and does consideration of ecosystem services offer greater potential for the development of innovative, multi-benefit and cost-effective schemes?

1. Introduction

The welfare costs of weather related disruption on the transport network have been estimated to be between £100m and £520m per day of disruption in England (in 2010 prices (DfT 2011)). In the Transport Resilience Review of 2014, the Department for Transport (2014a) acknowledged the scientific consensus that climate change will increase the likelihood of 'sustained' rainfall in UK winters and 'intense localised rain storms' in the summer months. They define transport resilience as "the ability of the transport network to withstand the impacts of extreme weather, to operate in the face of such weather and to recover promptly from its effects". It is recommended in the review that Network Rail should identify routes that are significantly at risk from future flooding and develop and apply solutions 'proactively rather than reactively'. The review also recognises that current appraisal methodologies are not well suited to valuing the costs of weather related disruption or the benefits of resilience schemes.

This sets the context for this paper which examines two principle issues:

1. The limitations of present transport appraisal methodologies in valuing the costs of absent resilience and the wider benefits of schemes designed to improve resilience; and

2. The different ways in which the 'flooding problem' on the rail network may be conceived (comparing narrow, single stakeholder conceptions, against holistic multi-stakeholder conceptions) and the implications of this for how solutions are designed, appraised and delivered.

These issues are addressed through a case study of a (real) mainline railway tunnel, which is situated in a river catchment and is susceptible to flooding. The case study involved the development of an economic model, which applied standard transport appraisal techniques to estimate the economic cost of tunnel closures over a period of one working day. This is presented in the next section and is used to illustrate some of the limitations of current appraisal methodologies when used to value the costs of disruption.

The discussion is then broadened in section three, to critically examine the nature of the 'flooding problem' on the rail network. This discussion addresses who the stakeholders are in the 'flooding problem' (Network Rail, landowners, housing developers, local authorities, the local community) and considers their vested interests in whether and how 'the problem' is solved. The concept of ecosystem services is then introduced in section four. This holistic approach to understanding the flooding problem was used in the case study to identify innovative blue-green-grey infrastructure flood resilience schemes (respectively, the combined use of floodplains and wetlands (blue); use of sustainable drainage (green); and use of traditional 'hard engineering' drainage infrastructure (grey). Finally, the paper concludes with some reflections on how the challenge of planning for flood resilience on the rail network (as posed in the Transport Resilience Review (DfT 2014a)) ought to be approached.

2. Railway tunnel case study: Valuing disruption

The case study examined flooding related disruption at a main railway line cutting and tunnel, which is utilised on weekdays by two high speed passenger services an hour in either direction between London and a number of major settlements. The tunnel was constructed in the early 1900s through an aquifer and the approaching cutting is also crossed by an aqueduct carrying a significant river overhead (see Figure 1). Consequently, the track is susceptible to flooding and in recent years the tunnel has been frequently closed during winter months.

The development of a model to estimate the wider economic costs of disruption during tunnel closures at the site involved three substantive tasks:

1. A supply-side calculation of the number of passenger seats potentially impacted by tunnel closures;

2. Identifying how passenger services are typically altered during tunnel closures; and

3. Defining the disruption cost components to be included in the model and how they ought to be monetised.

Disruption to freight operations was not considered and consequently the model results can be considered to be conservative estimates of the overall costs of tunnel closure.
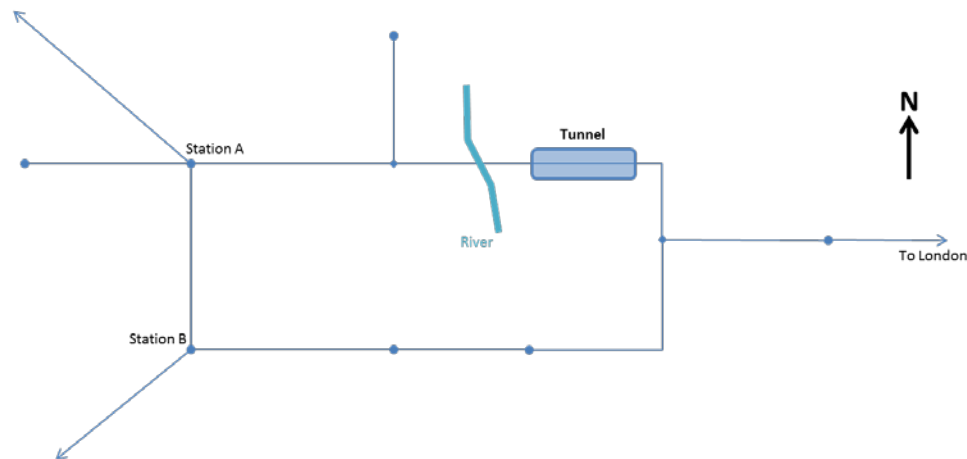

Fig 1: Schematic diagram of the railway network at the case study site

Passenger services under normal running

During tunnel closure events, passenger services calling through station A and then using the tunnel (referred to as tunnel services) are diverted via an alternative southern route, and call at an additional mainline station for the affected settlement (referred to as station B, see figure 1). Hence existing services at station B are also subject to delays. The weekday service patterns and capacities for tunnel and station B services are as follows:

Tunnel services:

- 60 high speed services travel through the tunnel in either direction on a weekday (30 in either direction)
- A typical service has a capacity of 558 seats.

Station B services:

- There are 62 services between station B and London on a typical weekday (31 in either direction).
- A typical service also has a capacity of 558 seats.

Alterations to passenger services during tunnel closures

The following assumptions were made in relation to the impact of tunnel closures on passenger service levels:

Tunnel services:

- All tunnel services are diverted via the southern line through station B. This implies that passengers are able to access the same number of daily services (as they call at the same stations), but will be subject to delays.
- All tunnel services are subject to a 20 minute delay.

Station B services:

- All station B services are subject to a five minute delay (as a consequence of additional traffic on the southern route).
- One station B service per day is cancelled to free-up capacity on the southern route for diverted tunnel services.

Disruption cost components considered in model development

The economic model was set up to estimate the *daily* cost of disruption due to closure of the tunnel. Weekday service patterns were used as these represent the worst case scenario. The model was developed using standard economic appraisal methods for rail infrastructure schemes, as set out in the Department for Transport's (DfT) Transport Analysis Guidance (TAG (DfT 2014b)). The following disruption cost components were considered in model development:

1. Network Rail 'track access contract' schedule eight compensation payments;

2. Costs of delays to rail passengers remaining on re-routed services;

3. Costs of rail passenger transfers to private car;

4. Indirect tax benefits of passenger transfers to private car; and

5. Wider welfare impacts.

Component one - Network Rail track access contract schedule 8 compensation payments

The rail industry was privatised in the UK through an initial franchising round from 1993-1997. Network Rail – a not-for-profit company limited by guarantee – owns and holds responsibility for the track, signals, tunnels, bridges, level crossings and viaducts. The DfT periodically awards franchises to run passenger services, on a competitive basis, to private sector Train Operating Companies (TOCs). The TOCs are allowed access to rail infrastructure through 'track access contracts' with Network Rail. In turn, Network Rail is obliged to pay compensation payments to the TOCs in circumstances during which access to track infrastructure is compromised and services are disrupted – for example during tunnel flooding events.

The level of compensation is set out under schedule eight of the track access contracts. These payments are assumed to 'fully compensate' a TOC for the loss of revenue owing to service disruptions (including the need, for instance, to lay on bus replacement services). Welfare impacts to rail and non-rail users (e.g. experience of rail service delays or additional road network congestion) are not captured within schedule eight payments (TAG Unit A5.3 – section 3.5.1 (DfT 2014c)). Hence these are dealt with separately in the model under cost components two and three (described below).

An average schedule eight compensation cost of £130 per minute of delay was estimated for use in the model, based on data from Network Rail on tunnel closure events occurring in 2013 and 2014. Compensation costs before this period were significantly lower and hence were no longer reliable estimates of the current costs to the rail industry.

The next two cost components deal with the welfare costs to rail passengers facing disruption to services. Three possible behavioural responses to disruption were considered in developing the model:

1. Remain on delayed services;

2. Transfer to private car; or

3. Choose not to travel (or postpone travel).

The model estimated costs for passengers remaining on delayed services and those choosing to transfer to private car. The effects of choosing not to travel were not quantified. This behavioural response was expected to apply to only a small number of passengers (given the relatively low level of disruption to services) and to have a negligible contribution to the overall economic cost of tunnel closure.

Component two - Costs of delays to rail passengers remaining on re-routed services

As is standard practice in UK transport appraisal, the benefits and dis-benefits accrued to passengers following improving or worsening transport service levels are calculated using monetised 'values of time'. 'Values of time' are set for three categories of transport system user: 'commuters', 'workers' and 'other' passengers. Workers are considered to have the

highest value of time, as their time in transit is considered to be unproductive, lost time to the UK economy.

The economic model applied 2010 'values of time' for rail commuters, workers and other passengers as specified in the latest TAG Data Book (table A1.3.2 (DfT 2014d)).

In the absence of data on passenger demand, it was necessary to make informed assumptions about passenger load factors and the proportions of passengers categorised as commuter, worker and other on affected services over the course of a typical weekday (reflecting typical peak and offpeak demand profiles).

Component three - Costs of rail passenger transfers to private car

To our knowledge, there is currently no robust data on how passengers respond to disruption on the rail network. This represents a clear evidential need in improving understanding of the impacts and hence costs of disruption. In the absence of data on observed behavioural responses to disruption, it was once again necessary to make assumptions on the proportion of passengers that may choose to transfer to private car when services are subject to delay. The following starting assumptions were used in developing the baseline scenario for the economic model:

• Two per cent of tunnel service passengers transfer to private car;

• None of the station B service passengers transfer to private car;

• Those that transfer are assumed to travel by single occupancy car and to travel the 160km along a motorway which runs parallel to the railway.

Given the relatively low levels of service disruption, a two per cent passenger transfer to single occupancy car, assuming a 160km motorway trip was considered to represent a worst case scenario.

TAG unit A5.4 (DfT 2014e) provides details on how to estimate the marginal external costs of congestion as a consequence of additional or removed car trips on different classes of road. The economic model applied the 2010 marginal external costs of congestion for motorways in the case study region disaggregated by morning, inter and evening peak periods (defined in the TAG Data Book table A5.4.4 (DfT 2014d)). These are specified in units of 'pence per km' of additional car trips transferring onto the motorway network.

Calculations performed on this basis indicated that the marginal external costs of congestion contribute to less than one per cent of the overall economic costs of disruption. Hence even a more accurate estimate of the passenger transfer to private car would have a negligible effect on the overall calculation. For this reason, the marginal external costs of other welfare factors including increased accident rates, air and noise pollution were not included in the calculation as these are of lower value than the marginal economic costs of congestion.

Component four - Indirect tax benefits of passenger transfers to private car

Where there is a switch between public transport and private car, TAG (unit A5.3 (DfT 2014c)) advises that the tax receipts accrued indirectly to government through fuel duty should be included as a benefit. In this case fuel duty would be subtracted from the costs of tunnel closures.

The TAG data handbook (DfT 2014d) provides a formula for calculating fuel consumption (table A1.3.8) and lists fuel duties per litre of fuel consumed (in table A1.3.7). On this basis and given the scenario of a two per cent level of passenger transfer to private car, the UK government would expect to accrue an additional £965 per day of tunnel closure in additional private car fuel duty. However, after adjusting for lost duty on passenger fares, this cost component can be considered to have a negligible effect on the overall cost of tunnel closures. For this reason indirect tax revenues were excluded from the model.

Component five – Wider economic impacts

As noted in the introduction, it is anticipated that extreme weather events will increase in frequency as a consequence of climate change and there is a recognised need to improve how the *wider* economic impacts associated with weather (or other forms of) disruption are

captured in economic evaluations of resilience schemes (Dft 2014a, Wardman et al 2014). Wider economic costs identified in the DfT's Transport Resilience Review (2014a) included reduced economic output from lost commuting (and hence lost business opportunities), lost output from working parents with dependent children not at school, lost hospital appointments, goods vehicles delays and wastage on food and perishables.

Within the scope of this limited case study it was not possible to estimate wider economic costs to the regions affected by tunnel closures, given a current lack of evidence, as well as uncertainty over appropriate methods of appraisal (Wardman et al 2014). The model results presented in the next section should therefore be considered as conservative estimates of the overall economic costs of disruption due to tunnel closure.

Model results - Estimated costs of tunnel closures

The economic cost of closing the tunnel for a full working day is estimated - based on summing the cost components considered above - to be of the order of £264,000 (see Table 1).

Table 1: Estimated week day economic costs of tunnel closure

COST COMPONENT	COST PER DAY OF TUNNEL CLOSURE
NETWORK RAIL SCHEDULE 8 COMPENSATION PAYMENTS	**£205,240.27**
Total weekday delay to tunnel services leaving London	£78,435.77
Total weekday delay to tunnel services towards London	£78,435.77
Total weekday delay to station B services leaving London	£20,262.57
Total weekday delay to station B services towards London	£20,262.57
Delay due to cancellation of 1 x station B to London service	£7,843.58
DELAYS TO TUNNEL SERVICES TOWARDS LONDON	**£24,562.82**
Delay to commuters remaining on tunnel services	£8,090.90
Delay to workers remaining on tunnel services	£11,097.53
Delay to other passengers remaining on tunnel services	£3,913.60
Marginal economic cost of additional road kms driven towards London	£1,460.80
DELAYS TO TUNNEL SERVICES FROM LONDON	**£19,724.58**
Delay to commuters remaining on tunnel services	£5,645.59
Delay to workers remaining on tunnel services	£10,188.76
Delay to other passengers remaining on tunnel services	£3,348.84
Marginal economic cost of additional road kms driven away from London	£541.39
DELAYS TO SERVICES FROM STATION B TO LONDON	**£9,543.04**
Delay to commuters remaining on delayed station B services	£3,361.99
Delay to workers remaining on delayed station B services	£4,808.61
Delay to other passengers remaining on delayed station B services	£1,372.44
DELAYS TO SERVICES FROM LONDON TO STATION B	**£4,989.95**
Delay to commuters remaining on delayed station B services	£1,521.41
Delay to workers remaining on delayed station B services	£2,622.88
Delay to other passengers remaining on delayed station B services	£845.67
TOTAL	**£264,060.66**

Network Rail compensation costs contribute the largest share at 78 per cent of this total. The remaining 22 per cent of costs are accrued through passenger delays and the scale of these costs is largely influenced by the proportion of 'workers' assumed to be travelling relative to 'commuters' and 'other' passengers. This is due to the much greater 'values of time' attributed to workers (over £25 per hour compared to £5 per hour for commuters and other

passengers). As noted before, the costs of passenger transfers to private car are negligible in comparison to schedule eight payments and passenger delays.

Forecasting under uncertainty

In economic appraisals of transport interventions, it is usual to estimate a Net Present Value (NPV) for the stream of costs and benefits that are expected to accrue over a 60 year appraisal period. To estimate a NPV for the future costs associated with flooding disruption at the case study site requires a prediction of the number and duration of tunnel closure events that are expected to occur over the 60 year appraisal period. This is clearly subject to a large degree of uncertainty, but could be approached in principle, by relating historic rainfall data to records of historic tunnel closures. This would allow categories of rainfall (defined by duration and rate of fall) that trigger tunnel closures to be identified. Established climate models, which incorporate predictions of local rainfall over (such as the Future Flows Climate and Hydrology models (Prudhomme et al 2013)) can then be used to predict the likely number of annual tunnel closure events under different climate scenarios.

Basic data on the number of tunnel flood events at the case study site in the period between 2011 and 2014 was available and this is summarised in Table 2. It can be seen that in 'normal' years (2011, 2013 and 2014), there may be three or four flood events during the winter months (usually the period between December and February). However, annual rainfalls vary significantly in the UK and the winter of 2012 was one of the wettest on record. This resulted in much longer periods of disruption, with 17 flood events being recorded during the winter of 2012.

Table 2: Number of tunnel closure events by year and month (2011 to 2014)

Month	2011	2012	2013	2014
Jan	3	1	2	2
Feb	0	0	0	2
Mar	0	0	0	0
Apr	0	2	0	0
May	0	0	0	0
Jun	0	0	0	0
Jul	0	0	0	0
Aug	0	0	0	0
Sep	0	2	0	0
Oct	0	0	0	0
Nov	0	10	0	0
Dec	1	2	1	0
Total	**4**	**17**	**3**	**4**

Attempts were made to 'calibrate' rainfall 'trigger events' against this data on historic tunnel closures, but it was not possible to achieve an accurate enough calibration for use in forecasting, owing to data constraints. Firstly, the disruption data did not indicate the duration of tunnel closure for each of the logged events or the specific reason for closure (e.g. landslip versus surface water flooding). Secondly, rainfall volumes were recorded over 24 hours giving limited insight into rainfall intensity. This would be required to identify the *likelihood* of different *types* of flooding occurring (e.g. flash flooding versus 'waterlogging' over a longer period of time). Hence it was not possible to accurately forecast a NPV over a 60 year appraisal period.

Given the inherent uncertainty in weather and disruption forecasting over the long term, NPVs when applied in this way cannot be treated in absolute terms. They can nevertheless be used as *comparators* to rank, for example, the performance of different flood mitigation measures (for varying climate scenarios) against a 'do nothing' scenario as is typical in

transport appraisal. A further consideration for the rail industry is the random nature of where extreme rainfall events will occur from year to year. Focussing investment on one location will be of no value if subsequent flooding events all occur in other locations over the next decade for example. This means that the resilience of the *entire network* to flooding ought to be appraised, rather than examining single locations in isolation. Investment can then be focussed on the nodes that are found to i. be subject to the greatest risk of flooding over the longer term and ii. which also have the greatest impact on service levels.

3. Ownership of the flood resilience problem

The discussion of the rail network's resilience to flooding is now broadened to critically examine the nature and ownership of the 'flooding problem'. Network Rail holds primary responsibility for the maintenance and resilience of the railway infrastructure. Network Rail's jurisdiction is also limited to a narrow corridor of land through which the rail network passes. These two factors in combination have the potential to limit the types of solution that might traditionally be developed in response to the flooding problem because: i) Network Rail has certain institutional competencies and perceptions that will generate particular styles of flood mitigation scheme (engineering measures for example); ii) the consultants often serving as solutions-providers may have established approaches, assumption and models favouring a traditional drainage approach; and iii) Network Rail has limited ability to develop solutions outside of their own land. We label this the 'narrow conception' of the flooding problem as it views the problem as being owned by Network Rail alone, as a single institution.

However, the railway clearly passes through a much broader landscape which incorporates built and natural environments that are owned, used and perceived very differently by many different social groups and institutions. This has implications for how the flooding problem *ought* to be addressed, in taking into consideration the wants and needs of *multiple* interested parties.

At the case study site, which is typical of many rail network contexts, these interested parties include: i) local land owners, in this case farmers who seek to maximise the economic value of their land through generally agricultural production shaped by the intrinsic properties of the landscape; ii) regulatory authorities and environmental Non-Governmental Organisations seeking effective environmental management of the watercourse, including responsibilities for flood management that include preventing the displacement of flood risk downstream; iii) local communities that may be subject to flood risk and who may also benefit from access to local green spaces around the rail network, as well as benefiting from a reliable local rail service; iv) local authorities who are accountable to their local communities and hold objectives to maintain and encourage economic activity within their jurisdiction and v) the travelling public. We label this wider viewpoint as the 'holistic conception' of the flooding problem.

These two differing conceptions of the flooding problem produce differing approaches to the development and delivery of solutions. For example, the 'narrow conception' potentially leads to a 'siloed' approach to decision-making, which proceeds through a neat, linear workflow as follows:

1. Network Rail identifies a localised flooding problem which requires investment at a specific location.

2. Engineering professionals are commissioned to develop solutions to the problem which fit within Network Rail's jurisdiction, vision of the problem and assumptions about solutions. Thinking may traditionally be limited to engineering solutions which are usually some form of detention dam, basin, pond, reservoir or tank. The aim is to increase the time of concentration, i.e. the time for water to flow from a point in the watershed to the outflow river. There may be a system of pipes, channels and pumps to operationalise the detention system.

3. Scheme options are appraised by transport economists through a cost benefit analysis. Benefits are limited to considerations of improved rail reliability (dominated by reduced compensation payments and journey time savings). A preferred option is selected given an assessment of value for money on this basis.

4. It is at this stage that officials from Network Rail approach land owners and other interested parties to open a consultation on the resilience scheme, though the traditional engineering paradigm has already shaped and sunk investment in a set of potential solutions that may therefore be inflexible.

A consequence of this approach is that potential multiple interested parties are engaged only *after* a preferred solution has been selected by the single problem owner, in this case Network Rail. Land owners and other interested parties may then perceive the official body, Network Rail, to be imposing their solution on the local community. Hence an unconstructive, adversarial relationship between Network Rail and other interested parties might emerge, hampering the delivery of effective solutions. This lock-in to an institutionally preferred technical approach has been characterised as a decide-announce-defend (DAD) approach, initially cheaper and quicker, but entailing substantial and unanticipated defensive costs to counter resistance from partners who may feel excluded from decision-making and that the scheme is imposed upon them.

By way of a contrast, the 'holistic perspective' on the flooding problem may lead to the adoption of a *collaborative approach* to finding solutions to broader objectives. The crucial difference is that interested parties are engaged *at the outset* of the decision making process, rather than after preferred scheme options have already been generated. In contrast to the DAD approach, this emerging engage-deliberate-decide (EDD) approach is gaining traction in planning for major investments in flood management and healthcare schemes; though initially entailing a longer pathway and associated costs, the more open EDD approach tends to result in lower life cycle costs and delays subsequent to decisions that, if not perfectly meeting the demands of all stakeholders, are at least better understood and accepted by them. Such a process may proceed as follows:

1. Network Rail convenes a group of interested parties at the outset, explaining the nature of their flooding problem but without suggesting a solution.

2. Interested parties then meet in an informal, local setting. The aim of the first meeting is to understand the nature of the flooding problem from the different perspectives of interested parties. An important objective of the meeting is to develop a positive relationship between Network Rail and other interested parties, so that ownership of the problem becomes shared.

3. Differing perspectives are documented and a set of shared objectives are defined and agreed through consultation. These may include aspirations to achieve wider benefits from possible interventions, for example the enhancement of green space for leisure activities.

4. Given that the objectives are now wider than singularly solving flooding on the rail network, a wider set of professional groups are engaged in developing solutions e.g. Network Rail engineers, river authorities, hydrologists, and land managers, as well as a broader set of value systems and ideas about how co-beneficial outcomes may be achieved.

The two key differences with this approach are first, acknowledgment of the *social* (as well as the technical) nature of the problem context and second, the development of scheme options that are *broader* than traditional engineering solutions to flooding on the rail network, both geographically and in terms of the ecosystem processes that can drive or regulate localised flooding problems, and which might therefore generate wider benefits.

4. Ecosystem services and flood resilience schemes

In relation to this, assessment of what are known as 'ecosystem services' offers potential to address the natural processes related to flooding and their ramifications for multiple dimensions of human interests. Ecosystem services are defined by the UN Millennium Ecosystem Assessment (2005, p.v) as "…*the benefits people obtain from ecosystems*". Using ecosystem services to shape decision-making helps with addressing the wider environmental, social and economic context of the perceived problem (in this case flooding of the rail network), and hence opens up thinking about optimal interventions in whatever element of the system they may lie.

As any intervention in a system has net impacts across all of its interconnected sub-systems, optimisation of societal benefits (including the avoidance of unintended negative outcomes) depends on addressing consequences for *all* related ecosystem services. Addressing a single service in isolation, for example erecting a flood wall for local regulation of flooding, can result in unintended negative externalities for linked services (aesthetic, habitat for wildlife and fishery potential as examples) as well as potentially exacerbating problems with the target service elsewhere (as has been a common consequence in the past of local flood protection schemes intensifying flood peaks downstream).

In practice, most management challenges are driven by a single perceived need. In the case of the railway tunnel example, the principal issue of concern is local flooding. However, this principal driver need not be addressed in isolation, but can instead be used as an 'anchor service' (Everard, 2014) that can form a central business case around which a more integrated approach can be taken to planning and identification of solutions of optimal societal benefit across the full spectrum of ecosystem services (including avoidance of unintended negative externalities).

Blue-green-grey infrastructure solutions at the case study site

Such an ecosystems services approach was adopted in identifying possible solutions to the flooding problem at the case study site. Flooding is inevitable here given that the tunnel is cut through an aquifer, seepage from which currently requires constant pumping from the one end of the tunnel. A further dimension to the problem is that an aqueduct carrying a significant river across the nearby cutting requires raising to accommodate line electrification. A fundamental solution to these problems would be to re-align the railway, but this is not economically viable. Various traditional engineering (drainage) solutions have been attempted over recent decades, but there is now acknowledgement that the only way in which to reduce tunnel closure is to increase pumping rates into the river. This is currently limited to 300 litres per second by an Environment Agency discharge consent, which also acknowledges flood risk to residential areas immediately downstream of the railway.

As part of the case study, the research team undertook site walkovers (January and March 2015) and extensive analysis of digital terrain, soil, geological and hydrological data to explore options for ecosystem-based solutions across the wider landscape. This included considering options to optimise benefits for all stakeholders whilst focussing on the most sustainable solutions for the 'anchor service' of tunnel and downstream property flooding. Solutions were sought that incorporated a combination of 'blue-green-grey' infrastructure where blue infrastructure refers to open waters and wetlands; green infrastructure refers to sustainable drainage (green); and grey infrastructure refers to traditional drainage (ducts and pumps).

The case study demonstrated that within the surrounding local catchment there were significant opportunities for holding back surface runoff in three watercourses through a number of variously sized runoff-attenuation features. These conceptual attenuation basins were located in currently farmed land in stream catchments upstream of the watercourses, and were designed to relieve pressure on peak flooding over and above that resulting from groundwater influx from the tunnel. The floodwater detention features release the water slowly back via the watercourses after rainfall ceases, doing so within a ten-hour period. The research project developed a procedure for siting and sizing appropriate landscape units for water storage, quantifying their hydrological impacts. Additional storage sites were also identified downstream of the railway to help attenuate flood peaks resulting from both groundwater pumping and surface run-off, relieving peak flood risk on both the railway and downstream properties via the river. Storage of water in this way would create opportunity for allowing Network Rail to increase its pumped discharge to the river, with some form of payment being made to landowners providing this water regulation service. In addition, to flood risk reduction, an *ecosystem services analysis* showed that significant co-benefits could be planned using this approach, delivering a wider range of and greater cumulative benefits relative to standard engineering design alternatives. As one example, the detention basins, wetlands and re-profiled watercourses could serve local amenity, nature reserve and recreational purposes. In contrast to the costs of disruption, costs for implementing these measures would be significantly less than £100 000.

5. Conclusion

In drawing on these various insights from the case study, the paper now concludes by summarising a general process for increasing the rail network's resilience to flooding and by identifying areas that would benefit from further research.

Increasing resilience on the rail network

As acknowledged in the Transport Resilience Review (DfT 2014), a first step is for Network Rail to conduct a network wide appraisal of flooding risk, drawing on the Environment Agency (2015) Flood Risk Maps for Great Britain as a starting point. The case study suggested further potential to develop a bespoke rail network flooding model, by calibrating historic flooding events against rainfall data and predicting future flooding risk at sensitive locations using climate and hydrology models (e.g. the Future Flows Climate and Hydrology models (Prudhomme et al 2013)). High risk locations can then be identified and investment prioritised accordingly.

This sets the foundation for the development of a programme of cost effective flood resilience schemes for high risk locations. In section three, we considered the implications of changing how the 'flooding problem' is conceived for the types of solution that are later developed. Narrow conceptions of the flooding problem, where Network Rail are seen to be singly responsible for designing and delivering solutions (a decide-announce-defend approach to problem solving), were contrasted against 'holistic conceptions', where multiple interested parties are engaged in solution design and delivery (an engage-deliberate-decide approach). Engaging multiple interested parties at the outset was shown to have the potential to broaden the objectives of interventions, leading to more effective intervention design and delivery. By developing collaborative relationships early on in the process, innovative solutions can be co-developed that are grounded in an understanding of inter-relationships between different ecosystem services and that also incorporate multiple benefits to multiple interested parties. An important first step in gaining institutional expertise and confidence in such engage-deliberate-decide approaches (which have not been widely applied in the UK) will be to trial the approach at a case study location and to conduct a thorough process evaluation to identify best practice.

Research needs

The development of the model to estimate the wider economic costs of disruption at the case study location served to illustrate that there are a number of uncertainties in current transport analysis guidance in relation to how to value disruption and resilience. Firstly, to our knowledge, there is little robust evidence on behavioural responses to disruption on the transport network, both in the short run and in the longer term. It will be necessary in enhancing transport analysis guidance, to establish evidence based estimates for instance, of the proportion of travellers that are likely to switch from rail to private car when facing different levels of delay. Estimates of how mode choices are influenced over the longer term are also required, in cases where services are subjected to regular disruptions relating to weather events. Secondly, within the scope of this project, it was not possible to consider the wider economic impacts of disruption to regional economies in the vicinity of affected rail links. In appraising resilience schemes, further guidance is also required on which of the costs associated with reduction in economic activity should be included in appraisals, how they should be valued and whether such values vary according to the type of journey being disrupted (e.g. long distance verses local). Such wider economic costs might include reduction in economic output relating to lost commuting (leading to missed business opportunities), lost output from working parents with dependent children not at school, lost hospital appointments, goods vehicles delays and wastage on food and perishables.

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