A whole catchment approach to improve flood resilience in the Eden

Defra set the following challenge for the Cumbrian Flood Competition:

"If you were responsible for managing the Eden catchment in Cumbria, what flood risk management approaches would you recommend, and why?"

Winning entry to the Defra Floods Competition 2016

January 2017

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Acknowledgements

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The assistance of staff from JBA Consulting in processing model results and also reviewing the report draft is also appreciated, in particular Marc Pinnell.

Front cover: Eden Catchment

Purpose

This document has been prepared as an entry to the Defra Cumbrian Floods Modelling Competition, 2016.

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A whole catchment approach to improve flood resilience in the Eden – Winning entry to Defra Floods Competition

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Executive Summary

In July 2016, after severe and extensive flooding during the preceding winters, the Department for Environment, Food and Rural Affairs (Defra) launched a competition to highlight imaginative approaches to flood risk management. The competition, which was open to anyone, asked "*If you were responsible for managing the Eden catchment in Cumbria, what flood risk management approaches would you recommend, and why?*". This question was accompanied by the release of new, open data sets to focus entries on innovative approaches alongside more established methods for reducing flood risk.

The winning entry was submitted by our inter-disciplinary team of experts and practitioners from JBA, a framework consultant for the Environment Agency's Water and Environmental Management services, and LEC, one of the country's leading environmental research and teaching centres. We assessed flood risk in the Eden using recent advances in whole-catchment modelling and recommended a range of measures to improve flood resilience. These focus on working with natural processes through distributed "natural" flood risk management (NFRM) in the headwaters, but also include large scale flood storage in the lower catchment and new, innovative non-structural measures emerging from national projects we designed. These include improved interpretations of flood warnings, interactive maps showing property-level impacts based on detailed models, and real-time event footprints.

We have put risk management measures to the test using newly-available data sets, both included in the Government's recent National Flood Resilience Review (NFRR), namely: (1) "worst credible case" extreme rainfall scenarios developed by the Met Office (MO), and (2) probabilistic spatial flood event scenarios produced using recent advances in spatial joint probability (SJP) modelling developed by Lancaster and JBA, as previously applied in the insurance sector and to underpin the latest National Risk Assessment inland flood scenarios. We have applied these data sets to demonstrate a step-change in the approach for testing resilience strategies rigorously by modelling catchment responses to events, with and without resilience measures, under a much wider range of realistic extreme event scenarios than would conventionally be applied. Our modelling approach here builds on ongoing work in the Eden, Derwent and Kent catchment for the Rivers Trust (RT), and uses a state of the art,

93,000,000-cell fully distributed two-dimensional (2d) flood flow model driven directly by rainfall as recommended in the NFRR. We argue that for catchments at this scale or larger, and with such distributed measures, we should test flood resilience measures using a wide range of plausible extreme events (plus historical events) rather than relying on only one or a handful of assumed scenarios, as with current practice.

There is no one solution to improving resilience in the Eden, where there has been repeated flooding of thousands of properties and hundreds of thousands of pounds of damages. It is important we recognise that with many people still continuing to suffer the distressing effects of the flooding in 2015 and 2016, the flood modelling competition is but one part of a very much bigger picture, and our entry responded to the particular challenge set by Defra. Our analysis concentrates on how the data and modelling innovations stimulated by Defra's competition could support catchment-based actions to reduce flood risk. Our modelling tells us that, *on average*, NFRM in the upper Eden would significantly reduce risks in the settlements around Appleby, but its influence would diminish downstream towards Carlisle, if all potential land use for tree-planting (65km^2) and distributed storage (22ha) is fully utilised. It also tells us that these measures would need to be balanced by similar interventions throughout the catchment so as to avoid synchronization issues, which could cause runoff in different streams to combine under some plausible rainfall patterns, resulting in the peak flows and damages for downstream communities being no better, and potentially even worse, than without the interventions. An initial cost-benefit analysis shows that the NFRM measures can be cost beneficial if implemented solely in the upper Eden, and this might well improve further with more widespread adoption, although more modelling would be needed to test this. However, the multiple benefits of such measures are many and include carbon storage, diffuse pollution and sediment regulation and habitat improvement. We conclude that effective NFRM needs to be widespread, but also combined with multiple larger scale interventions, improved uptake of property level protection (PLP) and improvements to flood warnings and forecasting.

This document is the winning submission by JBA and LEC, with minor edits and annotations to reflect updates since the submission in September 2016.

Contents

Introduction to our team

Or team is led by Dr Barry Hankin, and comprises flood risk management professionals from JBA and academic experts at LEC, bringing a rounded understanding of catchment processes and modelling expertise. Barry was consultant lead on the Environment Agency's research project "Modelling and Mapping Catchment Processes" (SC120015[1]), and is currently leading research funded through Life-IP for the RT on modelling, mapping and engagement investigation of NFRM in Cumbria. This involves whole-catchment modelling of the *Eden, Derwent and Kent catchments* by JBA and the team at LEC (Dr Trevor Page and Peter Metcalfe) incorporating measures identified in the *Cumbria Flood Plan*[2].

Our team is advised by Professor Rob Lamb, JBA's Chief Scientist and an honorary Professor at LEC, who's expertise in flooding and whole systems engineering helped us to integrate the interdisciplinary areas of catchment science with the focus on flood risk. Rob was a member of the Scientific Advisory Group for the recent National Flood Resilience Review (NFRR[3]), whose findings have informed our analysis. Professor Phil Haygarth (LEC) has been extensively involved in engagement with farmers and landowners within the Eden Demonstration Test Catchment (DTC) project, and his colleague Dr Nick Chappell (LEC) brings years of practical hydrological knowledge and field science to ensure our modelling assumptions are understood and realistic. Iain Craigen (JBA) is our lead modeller in the RT project, implemented recommendations of the NFRR by driving a detailed whole-catchment model of the Eden with the MO extreme event. Peter May (JBA) has advised the team, drawing on his flood resilience work in Cumbria, including work published recently by the JBA Trust in conjunction with Zurich Insurance Group[4], which uncovered different understandings of 'residual flood risk'.

Context

The Cumbria Flood Plan, released in June this year, identified 102 specific actions arranged within the five themes of: "Strengthening defences"; "Upstream management"; "Maintenance"; "Resilience"; and "Water Level Management Boards".

This briefing note is in response to a competition launched by Defra, the first of the five key actions in the Eden that relate to upstream management. Compared to key actions in the other four themes, the benefits and cost-effectiveness of upstream management strategies remain difficult to assess because of the considerable uncertainties in predicting the effects of catchment-wide flood and land/water management measures on local or downstream flood risk. This difficulty stems in part from scientific uncertainty about the net effects of catchment management measures, especially at broader scales, and in part from the relative immaturity of modelling and analytical tools for making the necessary predictions about the performance of distributed upstream management measures.

We believe that recent innovations in flood modelling can help to overcome some of the barriers to quantification of the flood risk management benefits that can be realised from upstream management. Scenario analysis is used

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[1] https://www.gov.uk/government/publications/how-to-model-and-map-catchment-processes-when-flood-risk-management-planning

[2] In agreement with the Rivers Trust we are incorporating some of the outputs and methodology

[3] https://www.gov.uk/government/publications/national-flood-resilience-review

[4] http://www.jbatrust.org/how-we-help/publications-resources/review-of-flood-response-in-cumbria-following-storm-desmond/

to begin assessing these benefits within the context of the scientific uncertainty, albeit acknowledging there is further work still to be done in this respect. Exploiting a combination of JBA's innovations in catchment scale flood modelling, with LEC's environmental science expertise and established community networks, we report here on initial modelling work to explore upstream management in the Eden catchment.

Whilst there are some specific upstream management actions for the Eden in the Cumbria Flood Plan (additional storage upstream of Gamblesby, Cumrew and Stockdalewath, planting in Mallerstang), here we go further with innovative modelling so that we can:

- consider opportunities and benefits throughout the whole catchment
- understand the resilience of different potential upstream management strategies under a wide range of flood event scenarios
- bring that understanding into a monetary cost/benefit framework
- use it also to support broad stakeholder and community engagement in the co-development of upstream management plans, which will align with other flood management actions and take account of the real-life, practical context for upstream management.

Other themes have specific, and in some cases monetised, actions which we assume are underway. We therefore focus on the potential to gain further mitigation of the residual risk through upstream management, targeting our efforts on this aspect because it is arguably the most uncertain with respect to scientific knowledge and evidence, and addresses many of the questions posed in your scope. We recognise also that upstream management must fit with other measures, and in particular we report on innovations in modelling and monitoring, already trialed by JBA and LEC, to support more effective local resilience through warnings. This is one of a number of components required to realise the potential for benefits from property-level and individual resilience measures.

Imaginative new approaches

Flood risk management requires an understanding of how water interacts with a complex landscape, containing different levels of productivity and husbandry, and a risk-based approach *needs to consider the whole spectrum of probabilities and consequences of flooding* for communities, infrastructure and individuals. At catchment scale, this perspective severely challenges the modelling methods that we rely on to provide evidence in deciding how best to improve resilience against flooding. Recognising there is also a complex funding landscape, with different tiers of governance, our approach for the Eden seeks to assess multiple and equitable benefits to people and the environment whilst remaining cost-effective. For a catchment on the scale of the Eden, nearly 2,300 km^2, and capable of generating over 1,700 tonnes of water every second in storm Desmond, it is vital that flood risk is appraised in the round, using new techniques that fully test the resilience of any management intervention, across all scales. So, we not only need a 'whole catchment model', but we also need to be able to test different measures across a large number of events that display the plausible spatial patterns, which in simple terms can be regarded as "different sorts" of rainfall extremes (Figure 1). Reducing risk means testing mitigation strategies not only against what *has* happened, but what *could* happen, including weather events of different shapes and sizes. Without this, we might not build in better resilience. NFRM in the headwaters (tree planting, soil structure improvements, distributed storage) needs to be delivered with engagement to understand what is feasible, and combined with larger measures such as FSAs funded through central government.

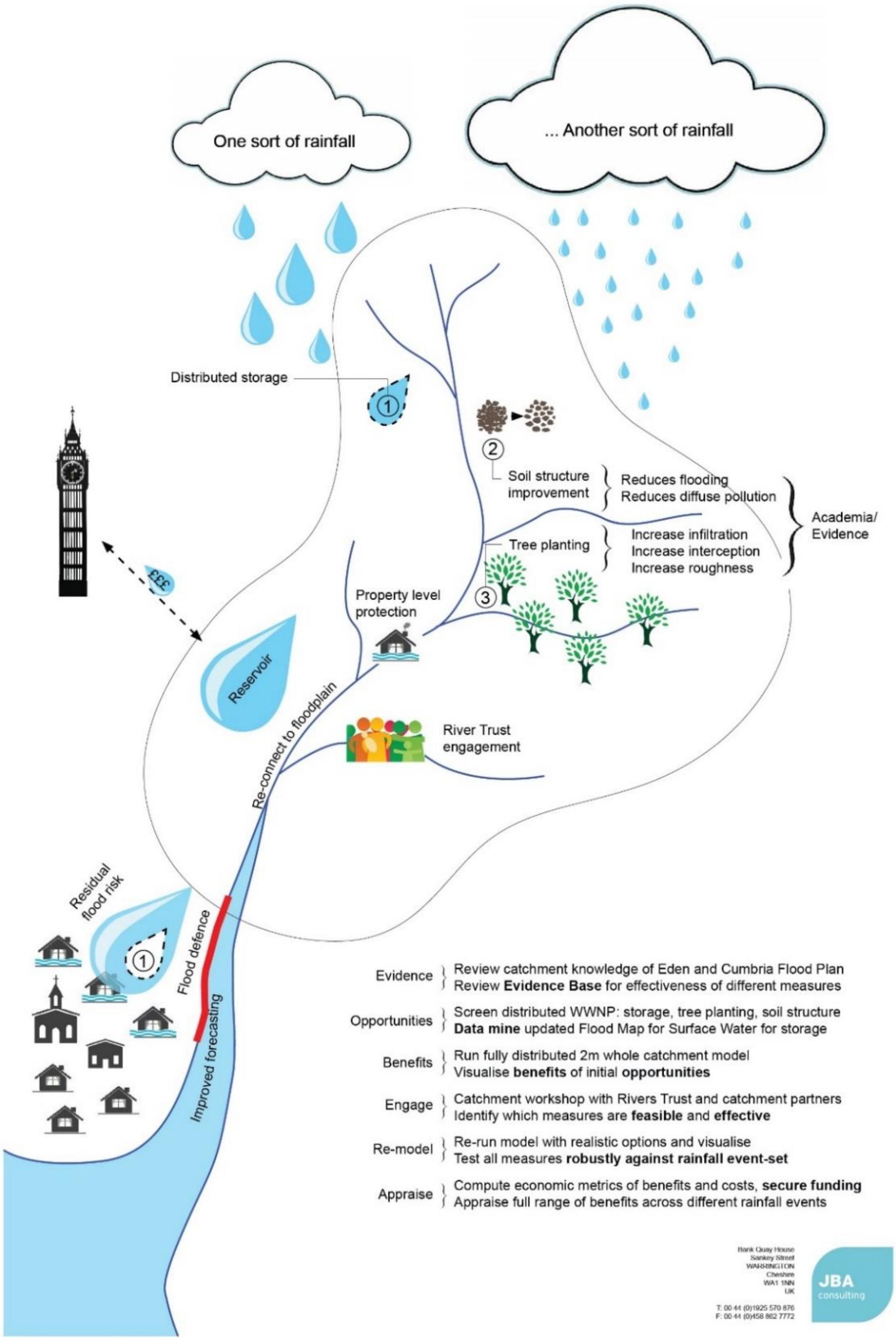


Figure 1: Whole catchment risk management

Methodology

Figure 2 encapsulates the process that we developed in working with the RT to investigate NFRM using a fully distributed 2d inundation model, combined with industry-standard hydrological modelling of runoff production in the upper Eden. This is an intermediate complexity model, having sufficient detail to reflect critical hydrological and hydraulic processes, but a faster simulation time than the 1d-2d linked models applied in the industry's current, more river-channel-centric approach. Our new approach can more readily be hooked up to multiple extreme weather scenarios, which can be generated statistically or through meteorological modelling. This has allowed us to explore more event scenarios, and test the resilience of a range of policy interventions robustly.

Our approach to modelling FRM measures is iterative, where we first map the opportunities for distributed storage and tree planting using available datasets plus those in the Cumbria Flood Plan, compute the benefits using the model, and then engage with catchment partners to test the feasibility of the opportunities, before amending and modelling again (Figure 2). For the Eden catchment, our innovative[5] flood modelling software allowed us to develop within weeks a 93 million cell[6], 5m resolution distributed runoff model, and show results later of testing this against the MO 'worst case' event. *We go further than this,* using a suite of 30 feasible events from our SJP work on extremes. <u>The aim of all this is to fully test how measures perform under a range of rainfall scenarios (Figure 1) so as to identify strategies that offer the best and most robust (under a range of scenarios) mitigation of flood risk.</u> These events have been generated based on the long-term time series of rainfall at 7 available raingauges around the Eden and make use of our SJP work.

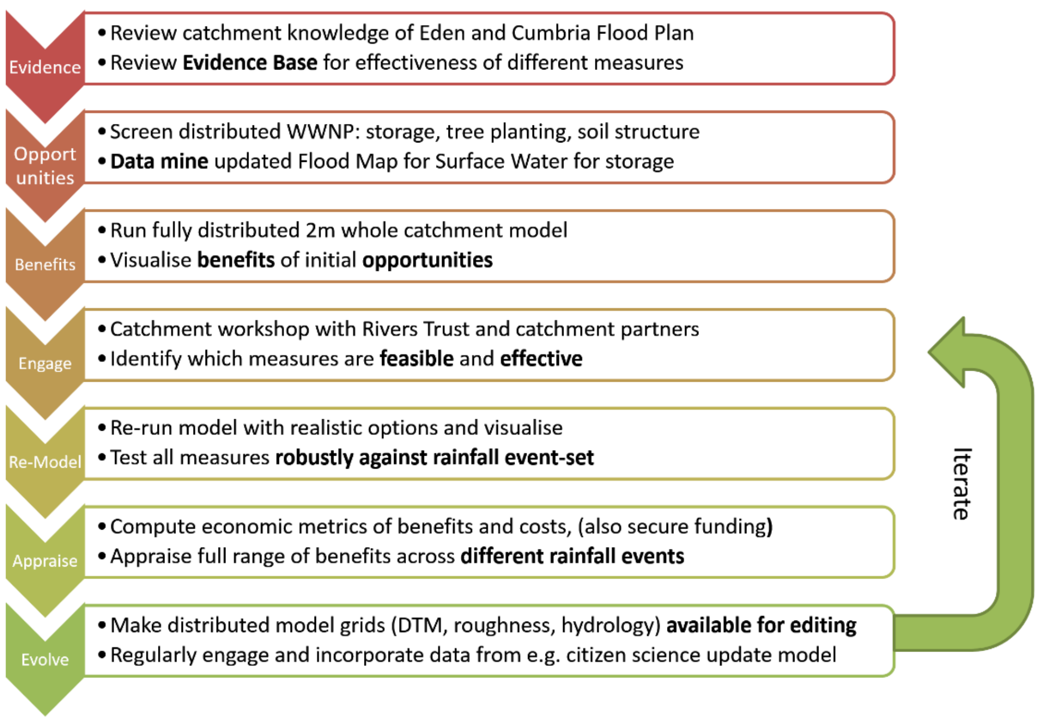


Figure 2: JBA and LEC methodology

[5] http://www.raeng.org.uk/news/news-releases/2012/May/three-finalists-shortlisted-for-uks-premier-prize

[6] It is possible to more than double this number of cells as technology has moved on since our entry

To help engagement, a series of interactive maps have been made (Figure 5) that will be enhanced by communities through a stakeholder workshop on October 7th, 2016[7]. This workshop will lead to co-production by our team, flood risk management stakeholders and communities in the catchment, of a final set of specific, realistic flood mitigation measures. In the meantime, in order to meet the timescale for Defra's competition, we have modelled a provisional set of mitigation measures and evaluated interim recommendations prior to gaining feedback at the workshop.

We will later model the feasible 'co-produced' NFRM measures to re-assess their benefits and provide updated maps of feasible opportunities and benefits. This will be undertaken using JFLOW plus a calibrated Dynamic TOPMODEL with Routing (DMTR) developed by a PhD student at LEC, Peter Metcalfe, who has been sponsored by the JBA Trust[8]. In November, Monte-Carlo simulations will be generated and the uncertainty analysis informed by Trevor Page (LEC) will be visualised using the UNCOVER software[9], developed by JBA under the EU funded SWITCH-ON[10] project.

All too often, models are 'parked' after one study, whereas in reality new information from monitoring and unstructured data sources appears all the time. Therefore, the model grids representing the terrain, land cover, woodland, soil condition, will be re-visited and soft information will be assimilated from time-to-time. The RT are well placed to help with this continual refinement from work with catchment partners (labelled 'Evolve' in Figure 2). The beauty of a whole-catchment, distributed model is that we can look at a range of measures anywhere in the catchment and test them against a large number of realistic events.

Modelling is merely one component in developing flood risk management strategies. It needs to be combined with other actions to improve resilience, especially in the light of climate change. Our recommended approach to managing flood risk in the Eden therefore includes providing people with access to some key advances that have been developed through work that we have been involved with in the areas of flood warning, PLP, flood forecasting and mapping impacts for communities at risk.

Getting flood risk management measures in proportion

There are a large range of possible management strategies which should all be considered in the round, and used in combination, to provide the most sustainable and equitable approach to risk management. These include flood forecasting and warning, PLP, distributed small scale NFRM, defence schemes and channel maintenance. Different measures make sense under different circumstances, which need detailed consultation and partnership working to agree, to overcome the many constraints. The schematic in Figure 1 illustrates how such measures operate at different scales, such that small scale interventions might provide multiple benefits, but cannot necessarily mitigate the 80 million m^3 of water that got around the new Carlisle defences after storm Desmond (Figure 1).

So, whilst distributed measures might provide part of the solution, it is important to quantify this with a distributed model, and combine in traditional approaches such as: flood storage areas (FSAs), a reconnection of any

[7] With thanks to all those who were involved, since the Defra competition submission the potential opportunities for flood management measures were modified and benefits re-computed, leading to a "user guide" issued to the Rivers Trust to help with their interpretation

[8] This work has now been undertaken and a Technical Report produced for the Rivers Trust

[9] http://shiny.jbahosting.com/uncover/

[10] http://www.water-switch-on.eu/

substantial, under developed floodplain that is not already active, or defence re-enforcements and channel conveyance management. During 2010/2011, the EA and Eden RT created the Thacka Beck nature reserve, as part of a wider alleviation scheme, storing ~76,000 m^3. To put this in context then, we would need ***one thousand Thacka-Beck*** schemes to contain the excess flood water estimated to have got around the defences in 2015. For this study we have incorporated a large FSA with a capacity of 5,000,0000 m^3 in our models to be representative of more conventional flood storage measures.

Property level protection (PLP) requires people dwelling in the catchment to confront what may technically be called "residual risk", in other words the risk of flooding that remains despite existing management measures. Through Peter May's resilience work in Cumbria, our team has seen how difficult it is to communicate this, and how small-scale measures such as PLP can help manage more frequent flooding, *if implemented properly,* and also offer greater resilience to a changing climate. Such measures may well not be of help for very large, rare events, and we have seen the consequences unfold three times in recent history in Carlisle (2005, 2009, 2015). It is therefore important to be honest and transparent, to estimate the best way to invest grants given for property resilience. For the Eden, we also need to improve existing non-structural measures to improve resilience, and we have proposed and costed a range of new advances that could be rolled out to help improve resilience in the Eden:

- Wider dissemination of more contextualized flood impacts warnings, for example tools such as the Forecasting Impacts Tool (FIT) spreadsheet we developed this year to support the EA's National Flood Forecasting team, which generates an electronic gauge board for over 2000 river gauges, and has added the contextual data from 17 EA Area teams (Figure 11).
- Production of the interactive maps (Figure 12), as under the EA's Communities at Risk theme, allowing a user to toggle the local gauge level and see maps of the flood hazard, view impacts at the individual property level, and help assess PLP needs.
- Systems such as Flood Foresight (www.floodforesight.com) that generate real-time flood footprints (Figures 13-14) to e.g. understand which communities might be isolated in an unfolding flood event.

A sandbox to test a range of measures

We have used JFLOW with the Flood Estimation Handbook ReFH losses model at 5m resolution for the whole of the Eden in one domain (Figure 3), as it provides a sandbox for testing the relative benefits of runoff attenuation interventions such as tree planting or in-stream dams over a whole catchment. The modelling stems from a proven approach developed to create the EA's Flood Map for Surface Water by accounting in an approximate way for infiltration and drainage of rainfall, whilst routing the remaining storm runoff over the terrain using a high resolution, physically detailed 2d hydraulic model. We are using the technique to model and consult on the upper Eden for the RT Life-IP funded work.

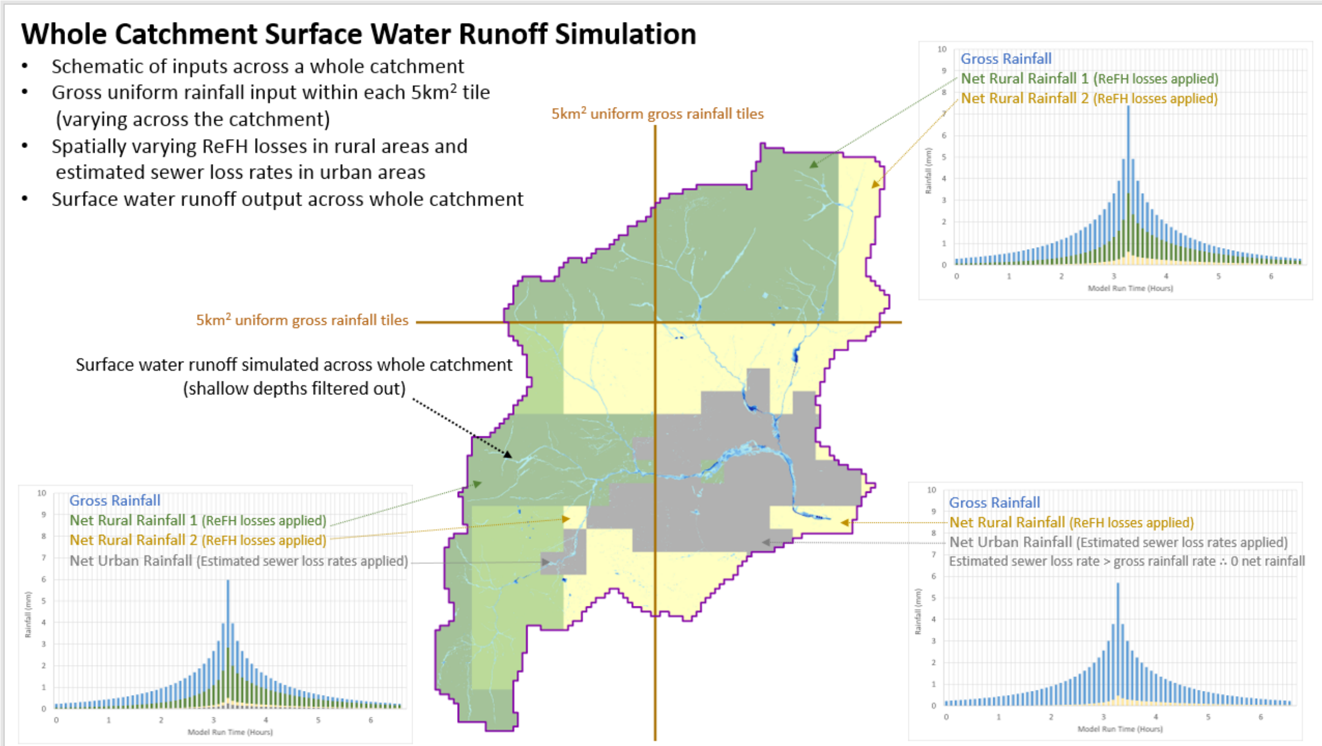


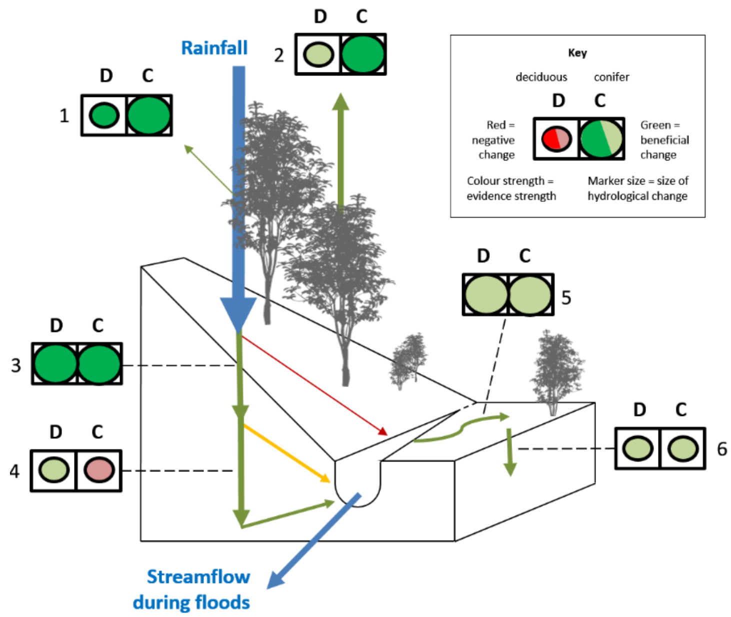
Figure 3: Whole catchment modelling with ReFH losses approach

With this approach we have modelled:

- Tree planting through increasing the distributed roughness and slowing the flow
- Distributed storage through altering the Digital Terrain Model (DTM)
- A Large FSA to represent more traditional risk management (Figure 6)

The tree planting opportunities are based on the EA/Forest Research 'Woodlands for Water' dataset, focusing on planting in riparian and high runoff areas, and avoiding existing woodland/peat, and modelled through increasing roughness[11]. The distributed storage measures (ponds, runoff attenuation features, re-connection of watercourses with floodplain) have been identified using a new tool (JRAFF) designed to data-mine locations where water is predicted to accumulate. A set of constraints are applied, such as a size range for potential new storage areas (100-5000m^2), the exclusion of urban areas or areas of high Agricultural Land Class, grades 1 and 2. The remaining locations are burnt deeper into the DTM model before re-modelling. How we model each measure has been closely informed by the evidence, including the work undertaken by Nick Chappell at LEC, summarised in Figure 4.

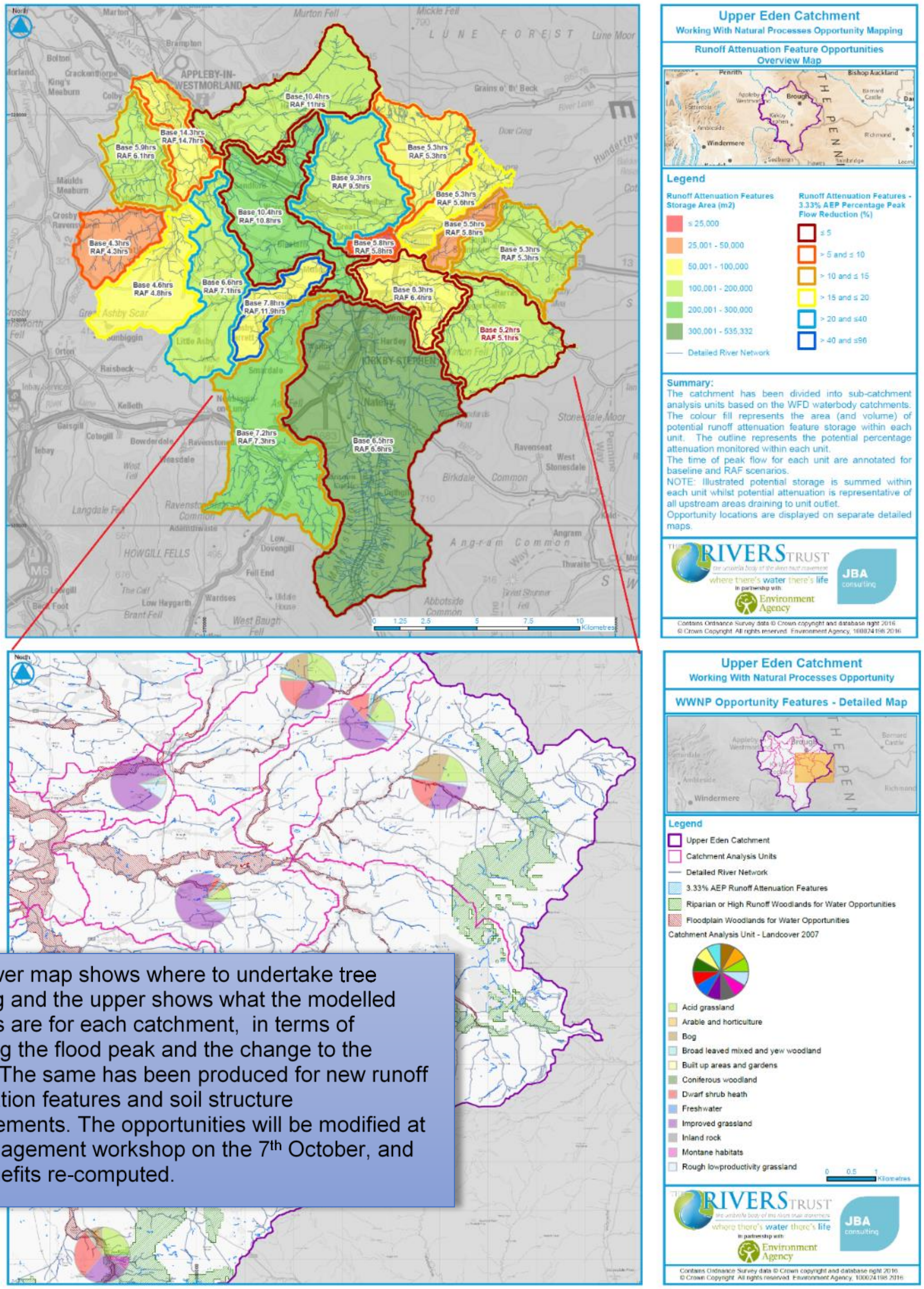
[11] For scrub, the roughness parameter Mannings' n was increased from a generic value of 0.1 for uplands to 0.125, and for woodlands 0.15



#	Hydrological function	Experimental evidence (examples only)
1	Enhanced wet-canopy evaporation	e.g., Komatsu et al (2011) etc...
2	Enhanced transpiration	e.g., Brown et al (2005) etc...
3	Enhanced infiltration	e.g., Chandler & Chappell (2008) etc...
4	Enhanced deep percolation	e.g., Chappell et al (1996) etc...
5	Enhanced floodplain roughness	e.g., Medeiros et al (2012) etc...
6	Enhanced floodplain infiltration	e.g., Heeren et al (2005) etc...

Figure 4: Presenting the evidence for trees as effective NFRM (after Nick Chappell/RAMSAR project)

Since we can undertake this modelling very rapidly, it is relatively straightforward to then create a set of interactive engagement maps (Figure 5) that show distributed opportunities and the modelled benefits of these have been computed based on the modelled percentage reduction in peak flow (i.e. overland runoff leading to high stream flows). Maps of this type will be used in the engagement process on October 7th. The colour-theming in the upper map shows areas of greater storage and the reduction in peak flow (defined over the time from the start of the simulation to the peak streamflow from the JFLOW modelling), such that for example sub-catchments with a blue perimeter have greater peak flow reduction. The sub-catchments are labelled with the time of the peak and adjusted time to peak for the NFRM. The tree planting scenario (not shown) can also increase the time of the peak substantially.



The lower map shows where to undertake tree planting and the upper shows what the modelled benefits are for each catchment, in terms of reducing the flood peak and the change to the timing. The same has been produced for new runoff attenuation features and soil structure improvements. The opportunities will be modified at the engagement workshop on the 7th October, and the benefits re-computed.

Figure 5: Upper Eden NFRM opportunities and benefits

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For the modelled measures we have used in this competition, the total surface area of distributed storage (which may already flood) corresponds to 22ha in the upper Eden, or a volume of 2.2 million m^3 (assuming water would be held back to a depth of one metre and could drain down slowly). This is about half the new storage volume in the proposed FSA that we modelled as an example 'established' FRM approach, alongside NFRM measures, and which is deeper (2.5m with 0.5m bund). This storage would not be appropriate if placed in the vicinity of an aquifer, but was added here to be representative of a more conventional flood reduction measure, and also as a location which would work in combination with a hypothesised gravity drain, which represents another engineered flood mitigation measure. This would remove water from a FSA upstream of Carlisle to the north-west, into a coastal-draining watercourse such as, for example, Rockliffe Beck and bypass Carlisle. We think a feasibility of this combined intervention is worth considering, but on the time frame of the competition we simply modelled the additional storage. We would also recommend more scenario runs where NFRM is implemented for the entire Eden, although if all the NFRM opportunities modelled (Figure 10) were scaled-up this could have large cost implications (Table 1).

Before discussing the results of modelling, we now focus on the rainfall events and methods for testing the measures robustly.

An Event-Set approach to truly testing NFRM measures

Many flood reduction measures are planned by computing the benefits in terms of a range of metrics, from percentage peak flow reductions through to economic damages, for particular design events. However, looking back at Figure 1, it is argued here, that we should be testing potential measures using a range of different types of extreme rainfall events, and also real events, since **some measures may work well for one weather event, but not for another**. This is closer to a fully risk-based analysis and shares some common ground with the approach taken by the insurance / re-insurance industry to build up damage distributions. **It leads to a more robust assessment of which measures work most of the time, and hence enhances understanding of resilience.**

Our approach is based on work on spatial joint probabilities (SJP) of extremes we have developed to model flood risk at large-scale (e.g. all property held by an insurer) or catchment scale, wherever flooding could be caused by a variety of spatial patterns of extreme events[12,13]. JBA has recently applied the same methods for the EA in generating plausible national inland flooding scenarios to support the new National Risk Assessment. Here, we have applied this approach to the rainfall record to 7 gauges around the Eden catchment, and interpolated the rainfall for a sample 30 events to provide gridded rainfall to replace the design event rainfall (Figure 6).

[12] Lamb, R., Keef, C., Tawn, J., Laeger, S., Meadowcroft, I., Surendran, S., Dunning, P. & Batstone, C. 2010 A new method to assess the risk of local and widespread flooding on rivers and coasts, Journal of Flood Risk Management. 3, 4, p. 323-336 14 p, DOI: 10.1111/j.1753-318X.2010.01081.x

[13] Keef, C., Tawn, J.A. and Lamb, R., 2013. Estimating the probability of widespread flood events. Environmetrics, vol 24, no. 1, pp. 13-21., 10.1002/env.2190

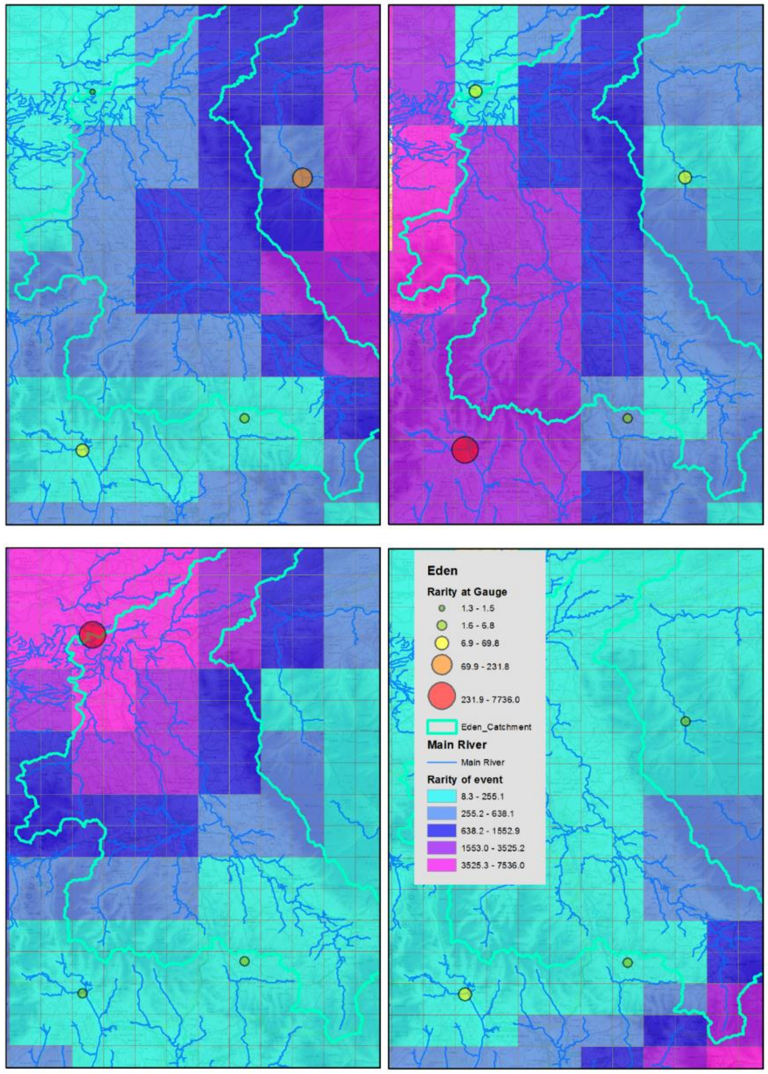

Figure 6 Subset of extreme, spatially coherent events based on long term raingauge records

The Met Office "Desmond+" Event

In addition to the probabilistic approach, it is informative to explore the modelled impacts for the so-called "Desmond+" event (or "maximum credible" event). This data was interpolated from the raw MO format into accumulations (15mins) over 5 km tiles (Figure 7) and used to drive the rainfall in the distributed JFLOW with ReFH losses model of the whole Eden for 15 minute time-steps for 24 hour hours on 5th December, 2015. We were unable to model the full event[14] in the time-scale, so we chose the worst period, and we must scale-up the impacts for this event[15].

[14] Nor the wetting up period, but have subsequently modelled this for the Rivers Trust using Dynamic TOPMODEL

[15] We had to assume that the extreme nature of the event meant that much of the event resulted in fast flow to the river network, although initial conditions have been underestimated and result in a smaller flow than measured

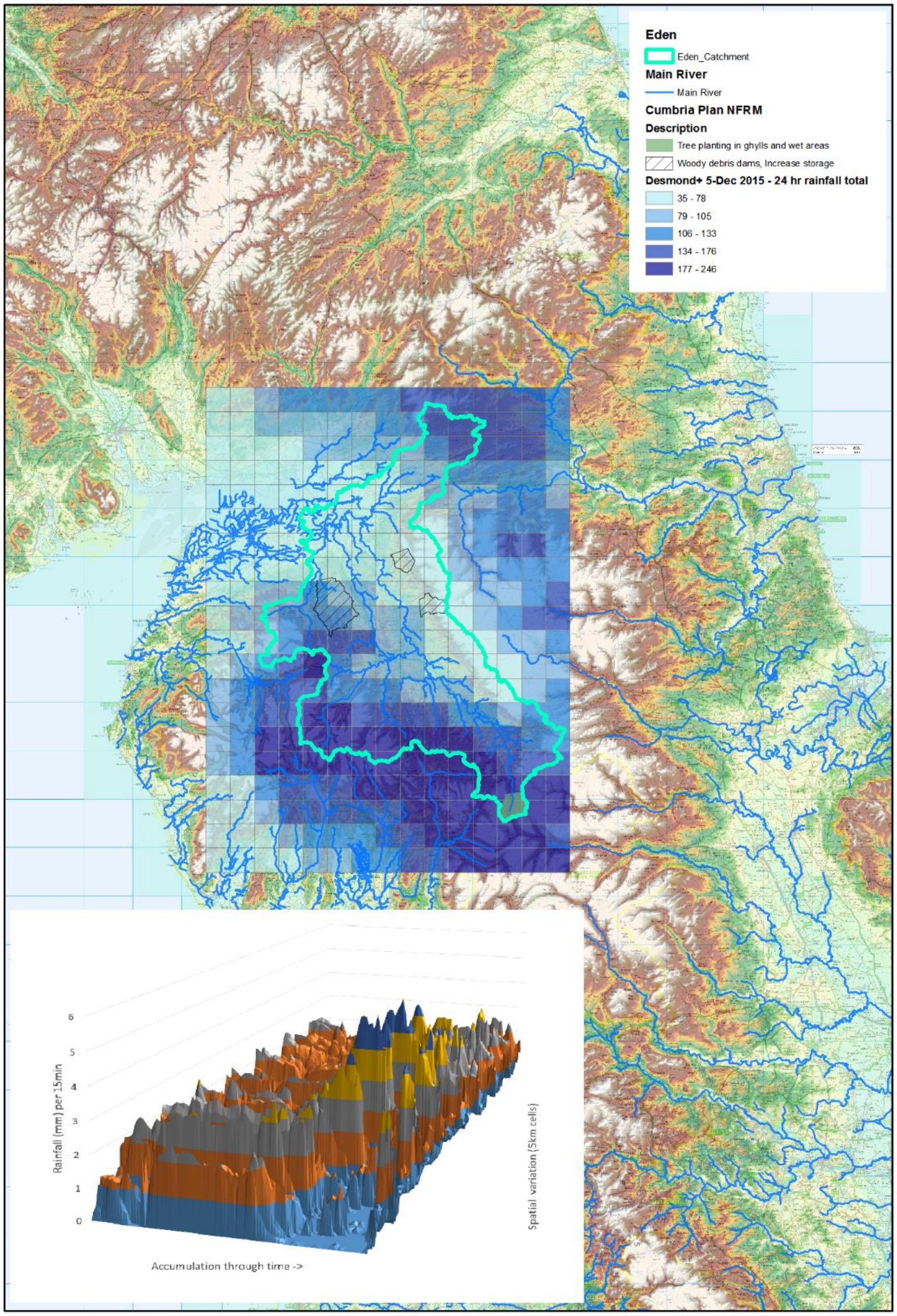

Figure 7 – The MO Desmond + event used as input for JFLOW.

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One issue with the MO event is that it is just that, a single event that does not in itself test different plausible extremes, and the nature of flooding is that it is very dependent on initial conditions both in terms of spatial distribution of rainfall, and also antecedent wetness. Testing flood reduction proposals against only a single event scenario may prove not to be a resilient approach because there may be a chance that other, plausible events could lead to flooding.

Results

We have focused on exploring the uncertainty to the loading and the distributed NFRM measures, rather than parameter uncertainty, but once the broad areas of policy and uncertainty in loading have been modelled, we will explore uncertainties in a more detailed hydrological model. Even by narrowing the combinations down, it leads to complex output (Figure 8), and we need to interpret this in a clear and concise way – which we have attempted in Figure 9 and Table 1 using averages.

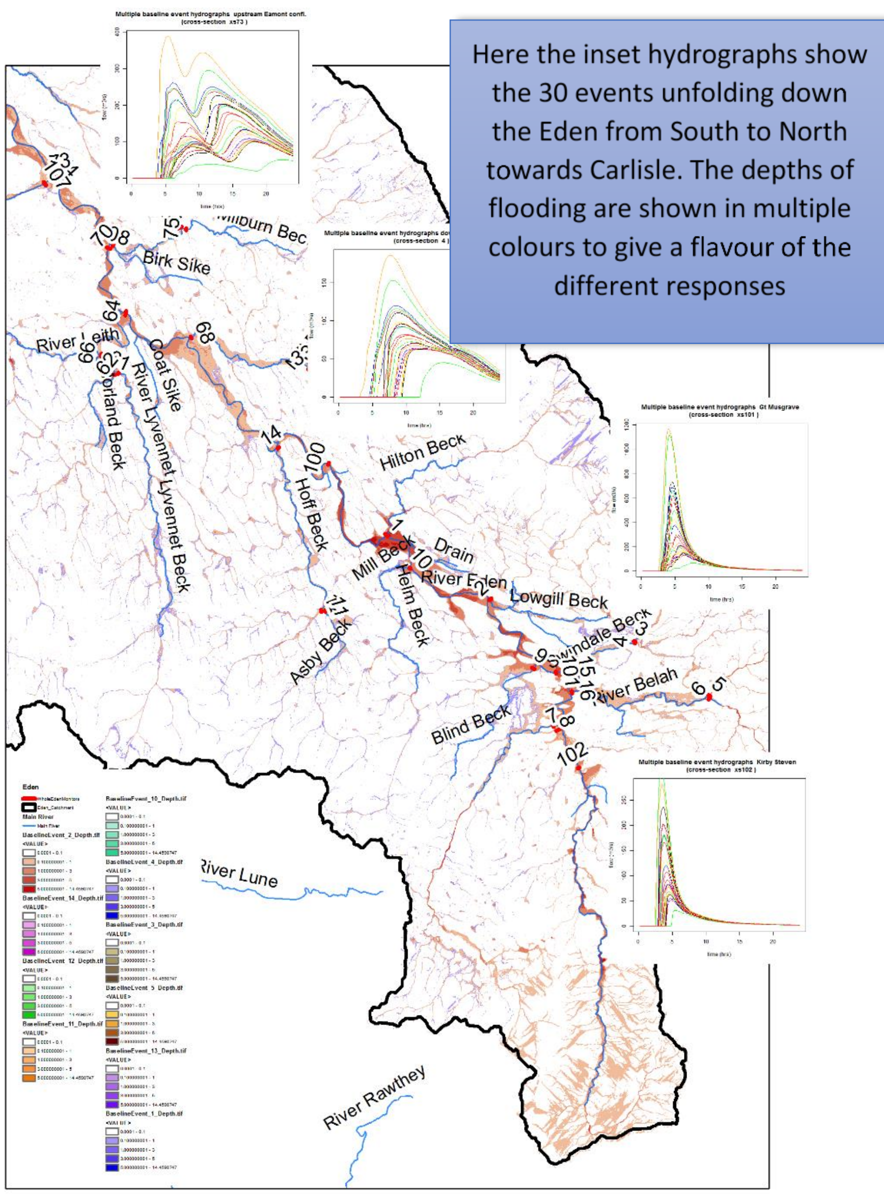

Figure 8: Results: ensemble feasible extreme events: multiple hydrographs and depth grids

What is clear from this, is that designing distributed solutions to manage risk further downstream needs to consider multiple events to locate areas that would be effective for as many of the events as possible. Figure 10 demonstrates how we can then select the measures which perform best under multiple extreme scenarios, by looking at the average peak flow[16] reduction when we apply the measures. We think this is more useful and robust than modelling a single extreme event.

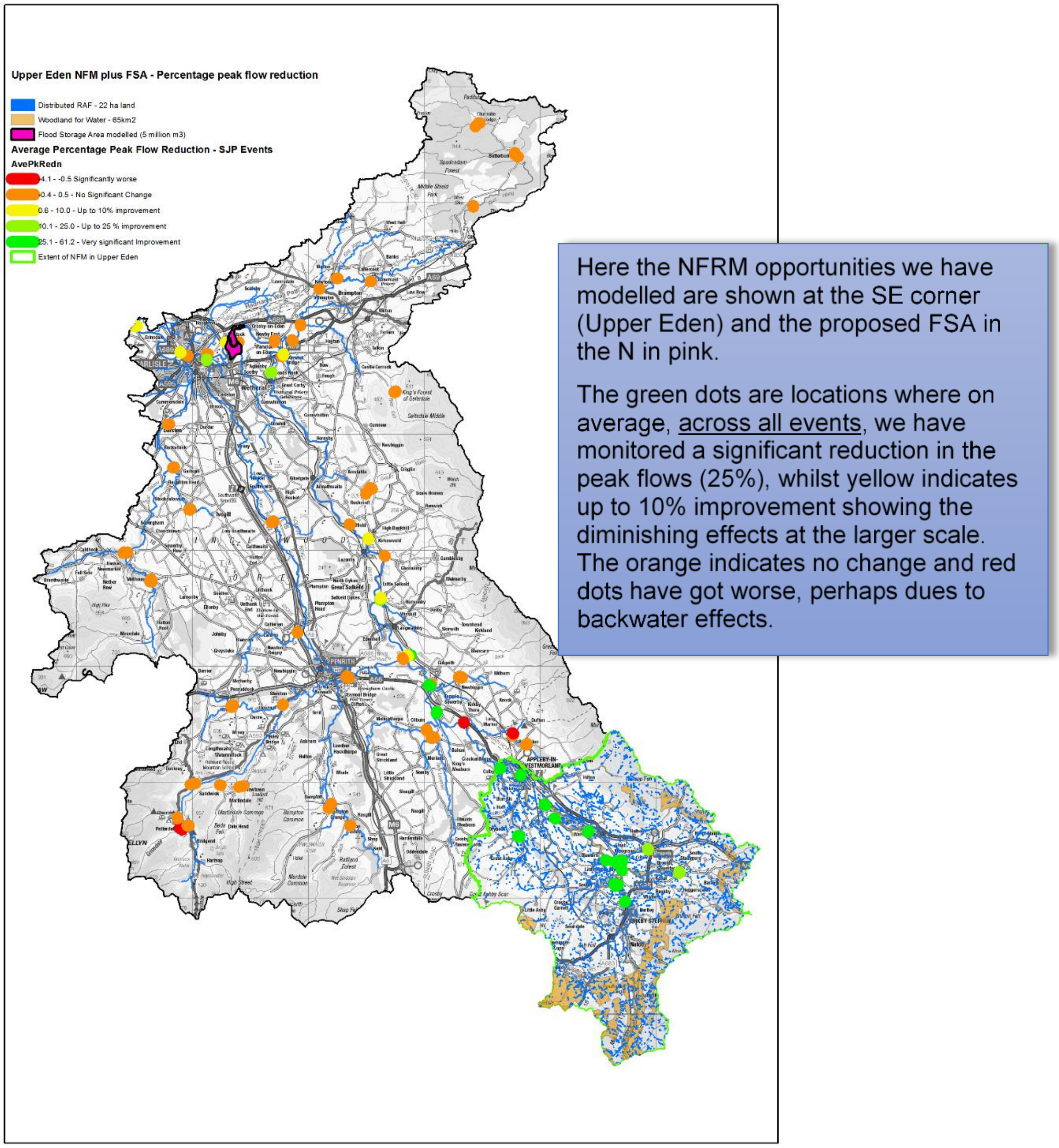

Figure 9: Comparing the average improvements of NFRM measures in the upper catchment

(Contains OS data © Crown copyright and database right 2016)

[16] Streamflow or overland / fast flow as modelled here and the dominant component in this extreme event

Figure 9 uses colour theming to show the average percentage reduction in the peak flow that has been directly modelled with the 93-million cell JFLOW model, with and without NFRM measures. There are some very interesting features, such as how we can see the average effect of the NFRM above Appleby is locally strong (green), but diminishes downstream as might be expected (yellow). For a lot of the Eden below this, there is relatively little change (orange). There is a red dot just to the NE where flooding is predicted to worsen, possibly due to re-synchronisation issues and a backwater effect. To counter this, it would be recommended that this area should also be targeted for NFRM. The MO event is more biased to higher rainfalls in the SW, so this has a different response than these averages.

For the MO event, we have also modelled a baseline, NFRM, and NFRM with the FSA (Figure 10). The FSA has been designed not to fill up until a certain peak flow through applying a 0.5m bund. The baseline peak falls short of the recorded peak on the Eden (1,700m^3/s) for the MO event because we were only able to model 24 hours of the event[17], but we note one of our SJP event peaks was well over 1,100m^3/s so more realistic when we come to computing damages (Table 1).

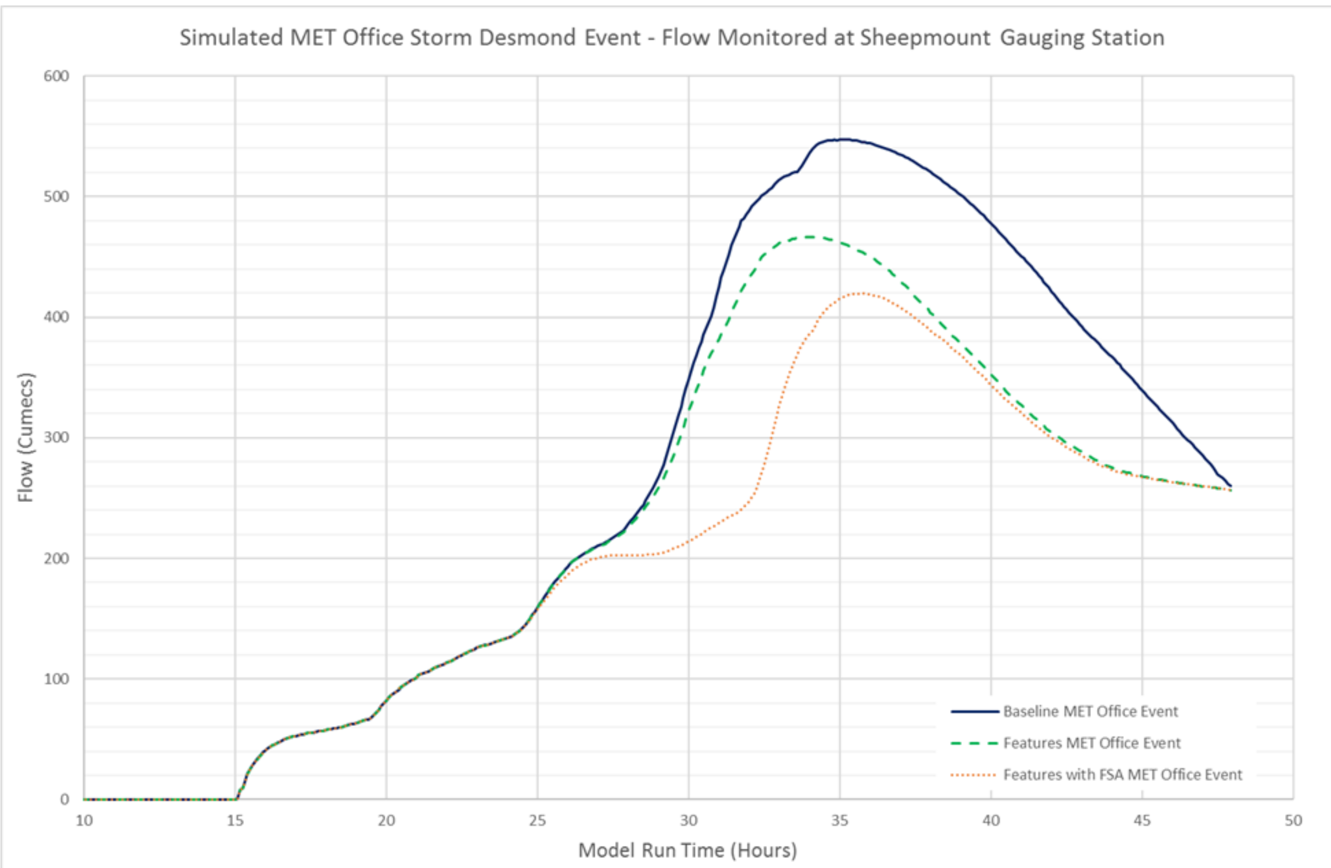

Figure 10: Compares baseline MO hydrograph just upstream of Carlisle with and without measures

[17] And as noted the wetting up was underestimated for this part of the event. Here we are primarily interested in the change that the distributed NFM and FSA can have on flow reduction and attenuation

Cost-Benefit analysis

We also undertook a basic cost-benefit analysis of the proposed NFRM using the NRD 2011 provided for the competition, plus our in-house FRISM software that implements the depth-damage curves in the Multi-Coloured-Manual[18]. We had time to work out the impacts for 3 of the worst SJP events and note that these are significantly higher than those for the MO event, which appears biased to large rainfall in the SW of the catchment, whereas the SJP events vary more widely. Although the two answers are similarly beneficial in terms of damages avoided, the SJP event damages are more realistic, and show a wide scatter[19].

Table 1: Costs and Benefits

Option	Residential and Non-Residential damages	Damages Saved	Estimated Cost (NFRM)	Multiple benefits
Average Baseline (across 3 SJP events)	£183,298,509			
NFRM in upper Eden only (across 3 SJP events)	£176,826,278	£6,472,231	£7,400,000	Reduction in diffuse pollution and sediment
Baseline (MO Event)	£66,872,604			
NFRM in upper Eden only (MO Event)	£58,989,494	£7,883,110	£7,400,000	Reduction in diffuse pollution and sediment

We have been unable to model additional scenarios, but would recommend modelling NFRM throughout the Eden, and a range of different scenarios that for example include the suggested gravity drain from an FSA to bypass Carlisle, draining into the sea. A feasibility study would be needed and around 4km pipe / canal, which could be simulated with the same model. Table 1 indicates that without community and voluntary involvement, the cost of NFRM measures can also be prohibitive on this scale, unless the wider benefits in terms of sediment removal and diffuse pollution mitigation are weighed-in.

Discussion

In addition to the direct measures discussed above we have made it clear that multiple improvements to resilience measures are needed in the Eden. Recently, JBA helped the national flood forecasting team to develop an interim database to hold and interpret the different threshold levels that are used around the country and display as a simple 'thermometer-plot'. We developed the Flood Impacts Tool (Figure 11), to add contextual information to gaugeboard plots. The simple spreadsheet contains the thresholds (warning, operational and information) for over 2000 gauges nationally, and also makes us of the API to import the current live levels from the internet. We witnessed people using 'River Levels On the Internet' to determine when to evacuate or not during storm Desmond on the River Lune. The publication of such information is invaluable to resilience, and we would take this forward by providing the greater richness of contextual information above, and add forecast levels on the internet, once available.

[18] http://www.mcm-online.co.uk/

[19] We also found that the tree-planting, if downstream of settlements can cause a backwater effect that increases flood risk, so we advise that backwater effects are considered in this situation before large scale floodplain planting downstream of settlements

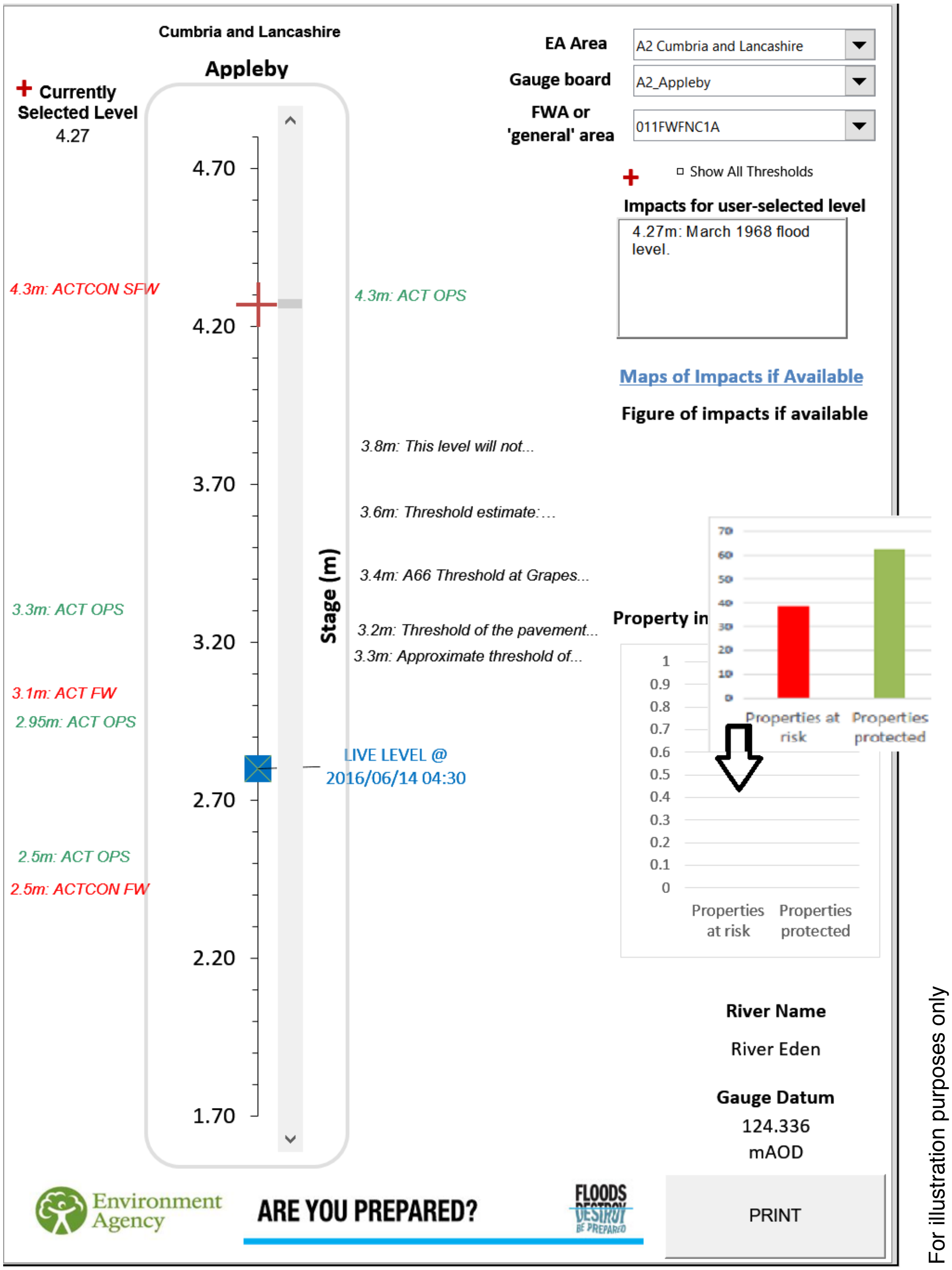

Figure 11: Adding context to flood warning with the Flooding Impacts Tool

In addition to this, the FIT tool has been linked to detailed spatial flood impact data. JBA derived a detailed approach[20] to map the impacts at communities at risk based on the current river level. The user can select from a

[20] http://www.floodandcoast.com/2speaker.php

drop-down on the Interactive PDF the current level and the property-level impacts are displayed on the map (Figure 12), so can help with assessing PLP needs or emergency planning.

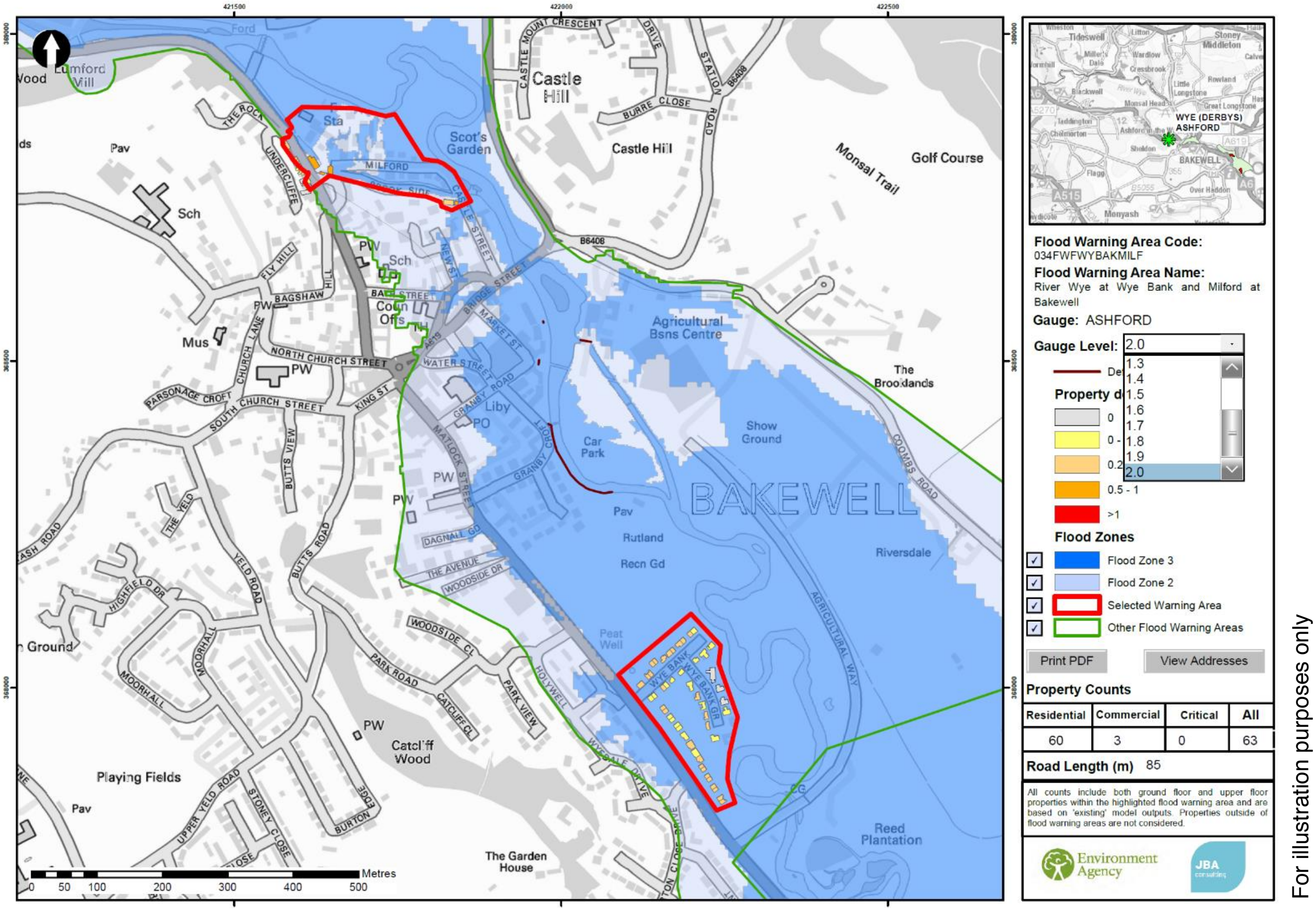

Figure 12: Interactive maps of spatial impacts of different river levels using the detailed model outputs

(Contains OS data © Crown copyright and database right 2016)

Improving forecasting: real-time event-footprints

We also recommend visualising the real-time flood footprint to understand interdependencies: are two places flooding at once? What are my evacuation routes? Here we demonstrate how this has been done, using software called Flood Foresight[21] developed by JBA and ImageCat with additional support of Innovate-UK grant (noting that other forecasting systems exist, and not all have the same capabilities). Figure 14 provides screenshots of the forecasts (up to 7-day lead-time) from the screening tool for the Desmond event, for which rainfall totals are accumulated over catchments (13a), and the rarity automatically assessed against re-analysis data for every modeled pixel (13b).

[21] www.floodforesight.com

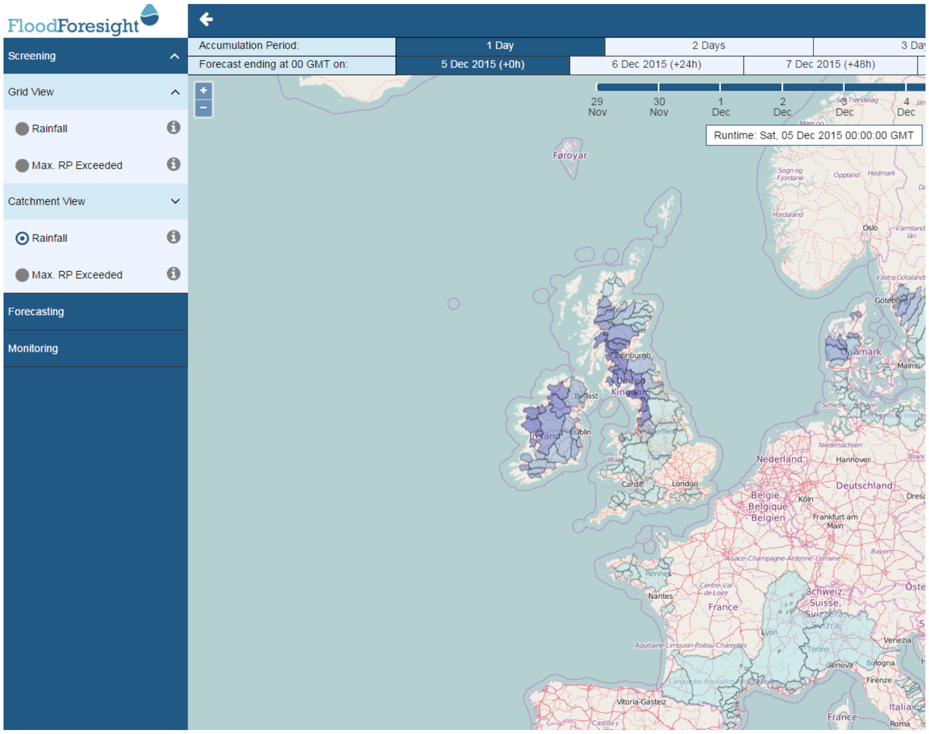

Figure 13a Flood Foresight Screening tool: significant rainfall accumulations

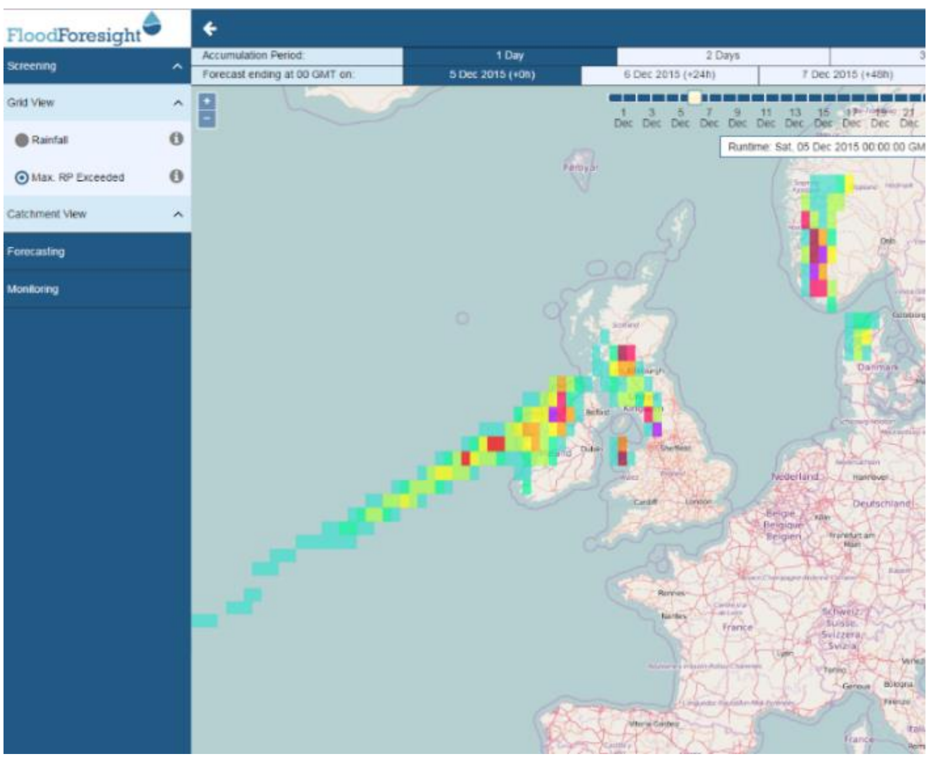

Figure 13b. Forecast rarity of Desmond – purple is >1000 year RP

Figure 14 shows output from the Monitoring Tool, whereby flood maps have been stitched together in near real-time to generate an event footprint. Such real-time and forecast footprints would be invaluable to promoting resilience at the local scale and help the assessment of interdependencies during an event.

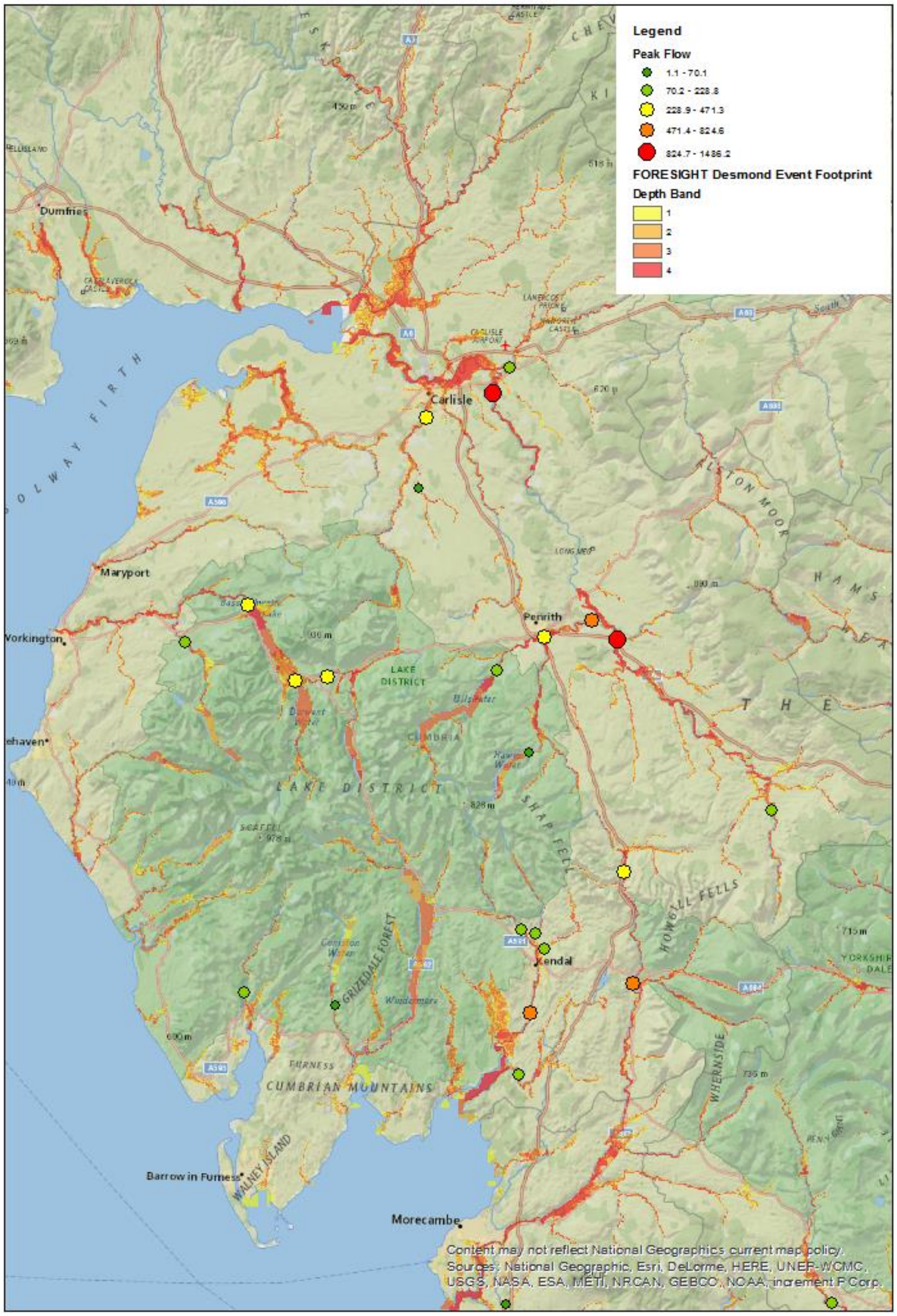

Figure 14: Real-time footprint for Desmond for Cumbria using Flood Foresight

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Summary

Through our whole-catchment modelling approach for the Eden we have sought to provide an advancement in understanding of how the whole catchment system responds to extreme rainfall events, and to provide a framework for evaluating nature-based flood risk management strategies at catchment scale. We think the approach leads to more robust analyses of policy decisions on NFRM and other measures, combining advances in hydrological science and catchment modelling with risk analytics more prevalent in the reinsurance sector. If combined with the iterative approach to engagement and refinement of the model, as we are doing for the Rivers Trust, this approach will help to deliver improved resilience against flooding. We have demonstrated how NFRM in the upper catchment can make a significant contribution, and whilst this provides multiple benefits for wildlife and diffuse pollution and sediment regulation, it can also have significant costs, which we have compared to the damages avoided. We believe NFRM can make a large contribution alongside traditional measures, such as the FSA we modelled and those programmed in the CFP. We have recommended additional scenario runs and feasibility investigations, and have a model ready to undertake these[22].

There are also many risk management measures that need to be taken on board from recent advancements across different areas of flood warning, PLP, property level hazard information, and real-time event footprints. We have provided recommendations based on our work for the EA on adding contextual information to real-time flood warnings using the Flooding Impacts Tool we developed, plus we recommend quickly assembling some interactive maps of the type developed for the Communities at Risk theme. The approach effectively links the local gauge level to expected levels at every individual property based on the detailed model outputs.

In summary, we do not think there is a single solution to improved flood risk management in the Eden, but we have demonstrated some advancements in whole catchment modelling in a framework that engages, and truly tests policy decisions on distributed measures in a large catchment. We have undertaken some benefit-cost estimates of proposed solutions showing that they are credible, but we also think multiple risk management measures including the advances above should be implemented.

[22] We have now also investigated the benefits using Dynamic TOPMODEL in an uncertainty framework for the upper Eden, in a technical report for the Rivers Trust, where we still predict benefits of RAFs and tree-planting even for extreme events such as Desmond.

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