

Integration of hillslope hydrology and 2D hydraulic modelling for natural flood management

Barry Hankin, Peter Metcalfe, Keith Beven and Nick A. Chappell

ABSTRACT

Natural flood management (NFM) has recently invigorated the hydrological community into redeploying its process understanding of hydrology and hydraulics to try to quantify the impacts of many distributed, 'nature-based' measures on the whole-catchment response. Advances in spatial data analysis, distributed hydrological modelling and fast numerical flow equation solvers mean that whole-catchment modelling including computationally intensive uncertainty analyses are now possible, although perhaps the community has not yet converged on the best overall parsimonious framework. To model the effects of tree-planting, we need to understand changes to wet canopy evaporation, surface roughness and infiltration rates; to model inline storage created by 'leaky barriers' or offline storage, we need accurate channel hydraulics to understand the changes to attenuation; to model the complex behaviour of the whole network of NFM measures, and the possibility of flood peak synchronisation effects, we need efficient realistic routing models, linked to key flow pathways that take into account the main physical processes in soils and the antecedent moisture conditions for a range of different rainfall events. This paper presents a new framework to achieve this, based on a cascade of the Dynamic Topmodel runoff generation model and the JFlow or HEC-RAS 2D hydraulic models, with an application to the Swindale Catchment in Cumbria, UK. We demonstrate the approach to quantify both the effectiveness of a relatively large 'runoff attenuation feature' in the landscape and the uncertainty in the calculation given model parameter uncertainty.

Key words | hydrology, hydraulics, NFM, topmodel, uncertainty

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INTRODUCTION

There has been a growing number of investigations attempting to model the effectiveness of NFM measures for flood risk reduction (Nicholson *et al.* 2012; Ghimire *et al.* 2015; Metcalfe *et al.* 2017, 2018), although relatively few have focussed on modelling strategy (Hankin *et al.* 2017a). Such measures comprise distributed changes in the landscape aiming to emulate natural processes to store, slow or infiltrate water to help reduce flooding and have been

collectively referred to as working with natural processes (Pitt 2008; Burgess-Gamble *et al.* 2017), natural flood management (UK and used hereinafter), Natural Water Retention Measures (Europe) and Nature-Based Approaches (international, e.g. World Wildlife Fund 2016). Such measures include in-stream leaky barriers (Metcalfe *et al.* 2017), engineered log jams (Addy & Wilkinson 2016), riparian or widespread tree-planting (Carrick *et al.* 2018), runoff attenuation features (RAFs) in the landscape (Nicholson *et al.* 2012; Metcalfe *et al.* 2018), peatland restoration to increase roughness (Holden *et al.* 2008; Shuttleworth *et al.* 2019), and river restoration including re-meandering and floodplain

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reconnection to hold back and temporarily store more water which has been popular across Europe (e.g. [Office International de l'Eau 2013](#)). They present a challenge to hydrologists and hydraulic modellers to first identify the catchment processes that might be altered, and then to justify changes or 'shifts' to effective parameter values controlling these processes in their models.

NFM has often been seen as a low-cost alternative to traditional flood risk management techniques and is being deployed by communities at risk unable to secure funding for measures such as hard flood defences. Many such examples are included within 65 UK case studies recently compiled in [Burgess-Gamble *et al.* \(2017\)](#), with online mapping (naturalprocesses.jbahosting.com/) and a dedicated European website (<http://nwrn.eu/>). The recent UK Evidence Directory ([Burgess-Gamble *et al.* 2017](#)) and review papers ([Dadson *et al.* 2017](#); [Lane 2017](#)) summarise the current state of knowledge, pointing to evidence at the small (10 km²) to medium (100 km²) scales and for small (<10% annual exceedance probability – AEP) to medium floods (1% < AEP < 10%), but indicate little direct evidence for effectiveness at larger scales (>100 km²) and major flood events (<1% AEP). European research ([Office International de l'Eau 2013](#)) and other international advice on nature-based methods ([World Wildlife Fund 2016](#)) provide much advice on incorporating risk reduction measures based on green engineering.

Strategies for distributed modelling of NFM (e.g. [Hankin *et al.* 2017a](#)) and testing the resilience against realistic spatial extremes ([Hankin *et al.* 2017b](#)) and synchronisation effects ([Pattison *et al.* 2014](#)) rely on modellers first being able to represent distributed hydrological responses accurately, and then represent the changes incurred to those processes as a result of small-scale distributed nature-based interventions realistically. Since the effective parameterisation of these processes and changes to processes are very uncertain, a framework for uncertainty analysis such as the generalised likelihood uncertainty estimation methodology ([Beven & Binley 1992](#); [Beven & Binley 2014](#)) becomes a necessity, and methods for detecting change in ensemble modelling results with and without nature-based measures important ([Hankin *et al.* 2017a](#)).

Physics-based models can offer a useful lens for upscaling small-scale distributed processes such as increases in friction, storage and infiltration to study their combined

effect at the catchment scale, yet also reveal a blurry image of our knowledge of exactly how to represent often variable and difficult-to-measure processes. The crux for modellers has therefore been how to represent very distributed and evidenced small-scale changes to hydraulic and hydrological processes, using efficient tools to capture the main interactions, whilst allowing for ensemble simulations and uncertainty estimation. Often a single type of model is used to represent the whole system, whereas using a combination of models (which are becoming more versatile to integrate) can improve the overall accuracy of process representation. The 'evidenced' changes to effective distributed parameters require further research, currently the focus of three ongoing UK Natural Environmental Research Council research projects (<https://nerc.ukri.org/research/funded/programmes/nfm/>).

This paper demonstrates a new integrated modelling framework, isolating one large runoff attenuation feature in a relatively small catchment, to test the effectiveness of a new modelling strategy to assess changes in catchment response whilst also quantifying uncertainty. The paper aims to assert the need for such a framework with the following three objectives:

- Bring together two fast technologies that improve integrated modelling of the distributed hydrology and hydrodynamics required to simulate small-scale NFM interventions and scale the effects up to the catchment scale, whilst allowing for ensemble simulations to explore uncertainties. Hillslope processes are modelled using the R version of Dynamic Topmodel ([Metcalf *et al.* 2016](#)) with channel and floodplain hydrodynamics modelled using JFlow ([Lamb *et al.* 2009](#)).
- Undertake cascade modelling of an ensemble of 'acceptable' model structures ([Beven 2006](#); [Blazkova & Beven 2009](#)) and define the modelling uncertainties in our estimates of the effectiveness of NFM. Many investigations are using modelling to scale up the effects of distributed catchment measures, to understand the change in response at the outlet, but few are attempting to *quantify uncertainties in their answers*.
- Use more of the 2D modelling outputs to drive a better understanding of processes having a strong influence on flooding and flood risk reduction – here we use 2D

depth and velocity data to estimate shear stresses and generate erodibility maps.

Study area and data

Swindale is a small, 15 km² upland valley near Shap in Cumbria, UK, with water draining from upland peatland cascading down to a valley with runoff characteristics dominated by impermeable glacial till. It has a high annual average rainfall (standard period annual average rainfall (SAAR) = 2,445 mm) and low baseflow index (BFIHOST = 0.29). Flows are gauged upstream of the United Utilities (UU) abstraction point (NY5146113169) that feeds water to Haweswater in the adjacent valley. The UU flow gauge (station 761113) has telemetry at 15 min 1997–2015; 2016 to present, with a gap whilst the intake and fish pass were upgraded. This unfortunately results in no data for the extreme event of Storm Desmond in winter 2015, so a large storm November 2009 is studied here with an estimated annual exceedance probability of between 50% and 20% of the scale where there is more evidence for NFM interventions being effective (Burgess-Gamble *et al.* 2017).

The Swindale catchment has been the subject of recent investigations by UU and the Royal Society for the Protection of Birds (RSPB) into land management and peatland restoration strategies, river restoration and riparian and upland tree-planting. The effects of these distributed NFM measures were previously modelled (RSPB 2017), identifying that the most effective single measure was a large RAF created by restricting flow out of a large storage area at Dodd Bottom (marked as blue in Figure 1). For the purposes of modelling at a fine temporal resolution, the closest 15-minute Tipping Bucket Rainfall gauge in the vicinity was Deeming Moss (NGR NY5545206553, SAAR = 1,982 mm), which was proportionately scaled using the annual average rainfall based on catchment descriptors, although there will be unknown local orographic and rain shadow effects. A digital terrain model (DTM) with detailed resolution (0.5 m) was available from the RSPB (collected by Glasgow University), in the vicinity of Dodd Bottom and the restored river meandering. This was resampled to 2 m resolution using bilinear interpolation, and feathered into coarser scale topography (2 m composite DTM based on LiDAR and where unavailable, Synthetic Aperture Radar) to increase the computational efficiency of the model calculations.

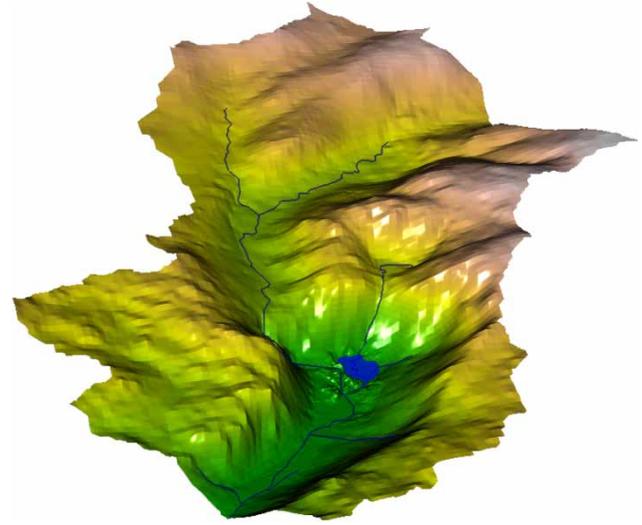


Figure 1 | Three-dimensional schematic of Swindale topography with greater detail in the valley bottom, and where the Dodd Bottom storage area is marked in blue context in Figure 2. Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/nh.2019.150>.

METHOD

We demonstrate a cascade modelling approach that couples Dynamic Topmodel (Beven & Freer 2001; Metcalfe *et al.* 2016) with JFlow (Lamb *et al.* 2009). It takes advantage of the computational efficiency and parsimonious parameterisation of hillslope hydrology in Dynamic Topmodel, coupled with the fast 2D hydrodynamic modelling offered by the graphics-card implementation of the Shallow Water Equations (SWE) in JFlow (for benchmarking study, see Hunter *et al.* 2008 and the updated speed testing for the SWE solver in Lamb *et al.* 2009). This highly efficient combination allows us to undertake ensemble simulations to explore uncertainties, whilst capturing essential surface/subsurface interactions in the wider catchment, *and* the complex channel–floodplain hydrodynamic interactions needed to understand the influence of in-channel NFM measures. Other rainfall runoff models could be used in a similar approach, but here Dynamic Topmodel has been used based on it having a low number of parameters, whilst being able to represent the key processes in a set of distributed hydrological response units (HRUs) which dynamically interact with one another. Many rainfall runoff models such as PDMs, hydrological predictions for the environment (HYPER) and SWAT similarly use efficient HRUs to generate responses reflective of local topography or soils, but few use

a flow distribution matrix to pass flows between the landscape units to more properly reflect celerities in the saturated zone responses. In the R version of Dynamic Topmodel (Metcalf *et al.* 2016), saturation excess overland flow can be generated in an upslope HRU and be passed downslope to an HRU with a deficit and re-infiltrate. Here, we require a general NFM modelling framework that can represent such processes since these are processes that we seek to influence through, for instance, tree-planting or reduced grazing intensity. In the discussion we also demonstrate a similar coupling between Dynamic Topmodel and HEC-RAS2D, giving similar results and highlighting the increasing versatility of 2D hydrodynamic packages.

The model cascade is a natural extension of the modelling in the Brompton catchment (Metcalf *et al.* 2017), in which the distributed runoff from Dynamic Topmodel was fed into a network solution of the 1D St Venant equations to explore leaky barriers, that were designed largely to store water in the channel. Here, we require that the general modelling framework is capable of representing the effects of NFM interventions that promote additional flood flow attenuation by encouraging water onto the floodplain where it was previously poorly connected. The method also builds upon the direct rainfall with losses 2D modelling approach (e.g. Hankin *et al.* 2017a) that use Revitalised Flood Hydrograph losses model (Kjeldsen *et al.* 2005) or approaches that simulate distributed infiltration using an effective hydraulic conductivity. None of these approaches are capable of modelling surface–subsurface interactions, such as saturation excess runoff flowing overland until it reaches an unsaturated area, whereupon it re-infiltrates (run-on). Such interactions can, however, be represented in Dynamic Topmodel, so here we combine this more realistic hillslope process representation with the 2D hydrodynamic routing to capture the complexity of flows over steep and diverse terrain and distributed interactions between channel and floodplain, where many NFM measures are currently being experimented with (for examples, see Office International de l'Eau 2013; Clilverd *et al.* 2013). The cascade of models, therefore, provides a useful compromise between detail in process representations and computational efficiency and a framework for exploring NFM and uncertainties.

Before Dynamic Topmodel is used to simulate a catchment, some preprocessing of the Digital Terrain Model (Figure 1) is required in order to divide the catchment

into areas that respond in a hydrologically similar way. These are the HRUs (shown in Figure 2) in Dynamic Topmodel and are typically based on accumulated upslope area, slope or distance to a channel. A flow connectivity matrix provides the relationship between the direct runoff between these HRUs and into the channel, represented initially through a time delay histogram in order to route the flows to the outlet, and permitting an assessment of performance at the UU flow gauge. Driven by rainfall and evapotranspiration for the winter storm modelled (November 2009), the different parameters controlling the runoff response in the HRUs were sampled from uniform random distributions between typical ranges expected for this upland catchment. Swindale has peat in the uplands and slowly permeable, shallow soils lower down dominated by glacial till deposits synonymous with slowly permeable soils. More details of the parameters in the Dynamic Topmodel model are provided in Beven & Freer (2001), but the most sensitive parameters include the saturated surface transmissivity, the exponential transmissivity shape parameter, m , the route zone storage coefficient and the vertical time delay parameter, T_d .

Solutions meeting a relatively high Nash–Sutcliffe efficiency (NSE) (>0.85) were classed as behavioural. The more stringent limits of acceptability approach (Beven 2006; Blazkova & Beven 2009; Liu *et al.* 2009; Hollaway *et al.* 2018) was not used at this stage, but the intention is to use this for new applications to larger catchments. Insisting on a relatively high performance (NSE > 0.85) resulted in 1,482 behavioural simulations out of the ten thousand Monte-Carlo simulations that were undertaken, and these were taken forward and fed into the 2 m resolution JFlow model. This was achieved by taking the simulated distributed runoff (subsurface and surface flows) and feeding the time series into along-reach internal flow boundaries in the 2 m resolution JFlow mesh, represented in Figure 2. Here, the colour shading represents the different HRUs where each produce similar surface and subsurface runoff responses based on the model of Metcalf *et al.* (2016). In this investigation, eight in-stream reaches were used, represented as HRUs that receive flows via the flow distribution matrix in Dynamic Topmodel. These time series are distributed over internal flow boundaries as through-time source terms in the SWE in JFlow.

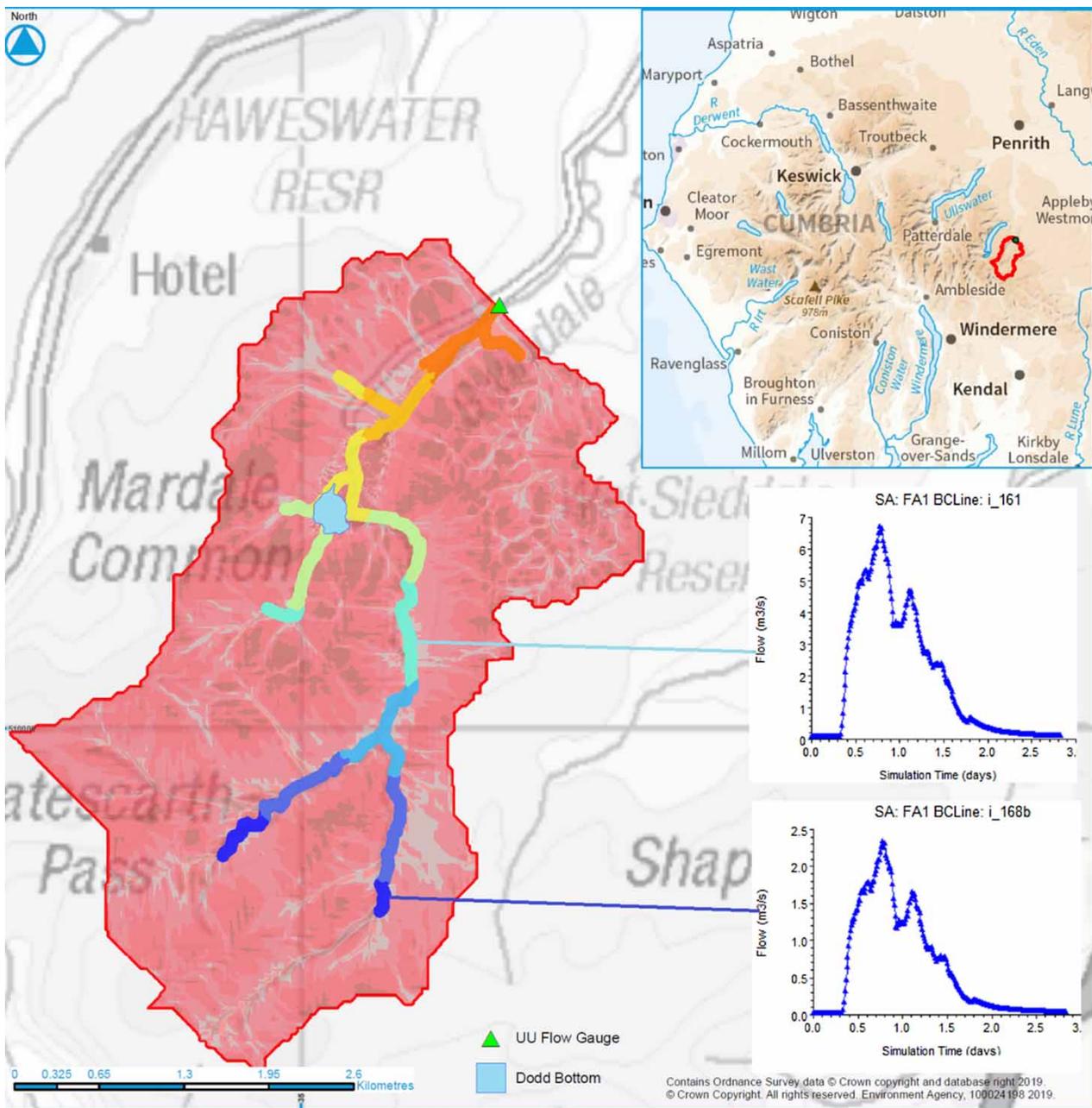


Figure 2 | Schematic of cascade modelling approach showing shading based on hillslope and channel-based hydrological response units and internal flow boundaries for the hydrodynamic model with example lateral inflows from Dynamic Topmodel. Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/nh.2019.150>.

In the discussion, we also compare the same approach to model integration using a combination of Dynamic Topmodel and HEC-RAS 2D (using a diffusion wave), using a much coarser resolution numeric grid (10 m). We discuss how this scheme is able to incorporate detailed subgrid topographic data (2 m) despite the coarse grid (10 m), and explore additional outputs from

the 2D hydrodynamic models, such as generating spatial distributions of shear stresses and erodibility maps. These outputs can help understand sediment processes that are also important to understanding risk reduction and the long-term performance of RAF-based NFM measures, which may, if designed incorrectly fill up with sediment.

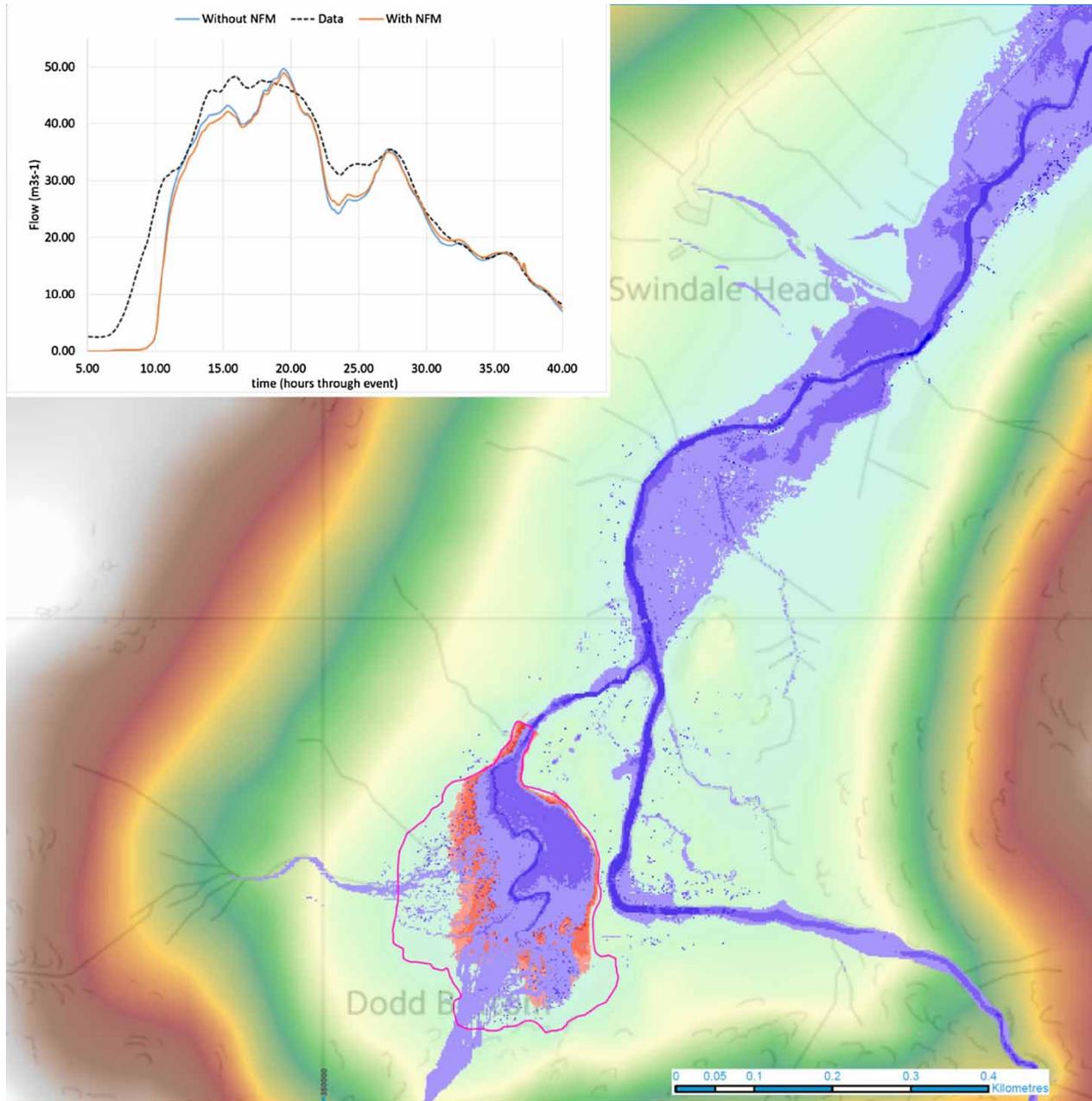


Figure 3 | Cascade modelling for the baseline modelling (blue) with a simulated NFM intervention (red) depth grids and hydrograph showing performance at UU flow gauge inset. Volume change 16,100 m³ to 51,700 m³ with NFM following the intervention. Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/nh.2019.150>.

RESULTS

Figure 3 shows the initial spatiotemporal results of a single coupled simulation, with and without an in-channel obstruction downstream of Dodd Bottom (Figure 1) to throttle flows using a reduced outflow width of 4 m so as to store more peak flows temporarily in the areas known as Dodd

Bottom labelled in the lower left. We focus effort here on this single large RAF and model it in isolation from other measures to test the framework. The re-meandering of the watercourse in the valley bottom undertaken to improve biodiversity is included in both scenarios and can be seen in darker blue (deeper) water in Figure 3 where it is evident that the floodplain in this area is inundated for the

November 2009 event. Critically, there is no evidence of unrealistic stepping in the predicted depths near the boundaries between the river reaches receiving different time series from Dynamic Topmodel, apart from close to the intervention, where the red shaded depth grid shows the additional storage due to constricting the width of the outlet to the RAF to 4 m. Use of Dynamic Topmodel alone would not have been able to accurately represent and show this level of important detail in the floodplain. The inset hydrograph shows a slight underprediction compared with the observed $48.3 \text{ m}^3 \text{ s}^{-1}$ peak flow at the UU river gauging station, although the ensemble results are analysed further below, showing a range of under- and overpredictions of the peak.

A sample of 120 of the 1,482 ensemble baseline behavioural simulations is shown in Figure 4 highlighting a range of peak flows in comparison with the gauged flow. The overall performance is strong ($\text{NSE} \sim 0.8\text{--}0.9$), although there is a delay in the early part of the rising limb for all the model runs and a slight difference in response near the peak with observations suggesting a broader peak.

Rather than plot the time series for the intervention scenario, it is more informative to look at the difference between baseline and intervention (following Metcalfe

et al. 2018). Figure 5 shows the ‘difference hydrograph’ between the baseline and the RAF intervention scenario for the sample of 120 simulations, for which positive values represent a reduction on the rising limb of the hydrograph, and negative values indicate successfully attenuated flows returning back to the watercourse. The maximum difference in the peak is $1.8 \text{ m}^3 \text{ s}^{-1} \pm 1.4 \text{ m}^3 \text{ s}^{-1}$, although the largest changes tend to occur in advance of the peak in the hydrograph that occurs around hour 20 at the UU flow gauge. This confirms what was suspected from observations of the basic geometry of the watercourse (see Figure 1), in that Dodd Bottom is on a faster-rising part of the catchment, and the additional attenuation tends to result in taking volumes from the rising limb of the hydrograph as considered at the UU flow gauge.

The reduction in the peak flow afforded by the additional temporary storage is not so pronounced by the time the flows reach the UU flow gauge (Figure 5). This indicates that the restriction applied (4 m) needs to be narrower, and that restricting flows in this area from what is a faster rising part of the catchment is not an effective strategy and to improve it further, flows from the main channel may also need to be diverted into Dodd Bottom and multiple interventions may be needed. However, this is a sensitive

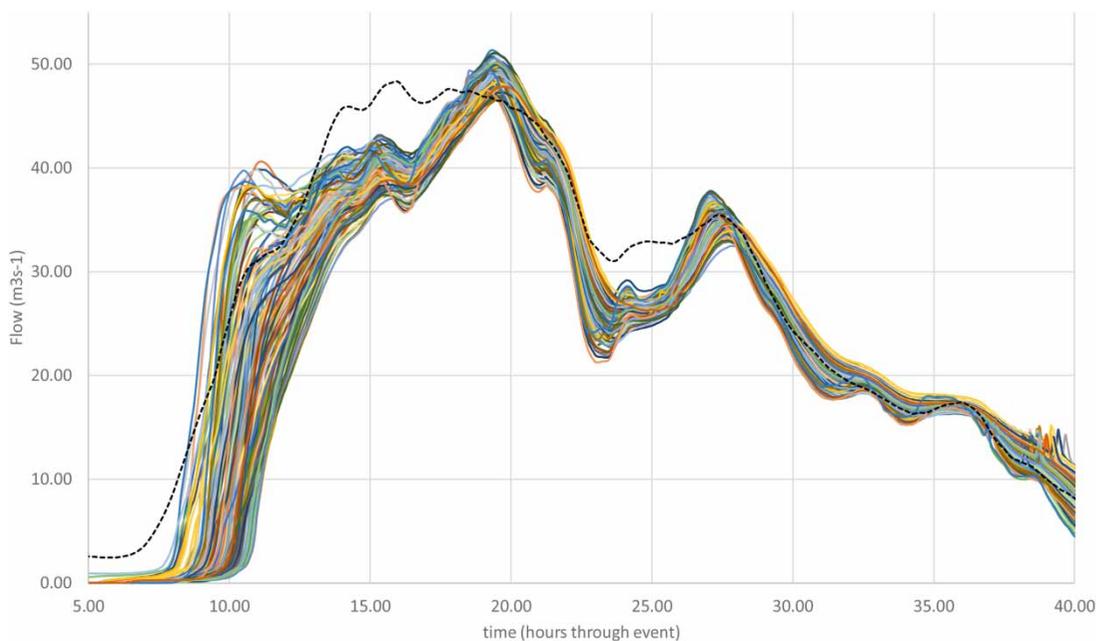


Figure 4 | Sample of 120 behavioural simulations for the baseline scenario at flow gauge. Observed flows in black-dashed. Simulations are randomly coloured to highlight variation within the ensemble of acceptable models.

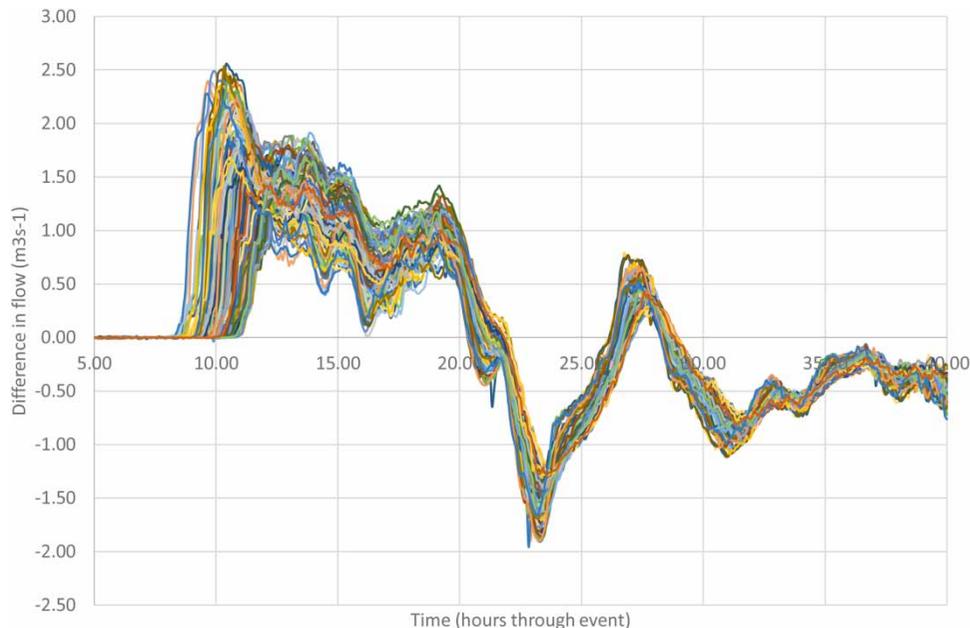


Figure 5 | Difference hydrograph: Baseline hydrograph minus the intervention hydrograph. Peak difference = $1.8 \text{ m}^3 \text{ s}^{-1} \pm 1.4 \text{ m}^3 \text{ s}^{-1}$. simulations randomly coloured to highlight variation in the ensemble of acceptable models. Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/nh.2019.150>.

site, and building bunds, structures and diversions across unique moraine formations is not likely to be acceptable, with the added constraint that the volume retained if impounded would come under the UK Reservoirs Act and thereby require regulation.

In addition to the spaghetti time series plots of the ensemble predictions in Figure 5, it is important to view the ensemble results spatially and develop methods for constraining model outputs which can also be helpful for expressing additional limits on the acceptability of model structures. An example of this can be found in Aronica *et al.* (1998) where the approximate timing of part of the flood wave exiting one area of the Imera flood basin was used as a fuzzy acceptability criteria, which if not simulated, was used to effectively reject models that might otherwise have generated an acceptable behaviour.

To understand the differences between Monte-Carlo simulations, it is once again more informative to look at the differences in predicted depths in this catchment, since the high performing simulations ($\text{NSE} > 0.85$) have similar extents. Figure 6 shows the performance-weighted depth grid in the central pane for the NFM scenario (6e—on scale of 0.0–3.0 m), with the eight outside panes showing the difference between this most likely depth grid and

eight other NFM Monte-Carlo simulations (panes 6a–6i *excluding* 6e on a scale of -0.1 to $+0.1$ m). Some of these show positive differences (6a, 6h, 6i), negative differences (6c, 6d, 6g), and some not much difference (6b, 6f), but the range of predicted depths is expected based on the range of differences in Figure 5. This example illustrates how there can be differences in spatial behaviour, including potentially flood pathways within our acceptable simulations, which may coincide with knowledge of flooding that can be used to constrain the model behaviour further and reject certain modes.

DISCUSSION

The key advantages of the new approach demonstrated here include efficient, distributed representation of hillslope processes using Dynamic Topmodel, combined with more accurate 2D hydraulics of flows over a complex terrain. The previous coupling of Dynamic Topmodel with 1D hydraulic routing has proven successful in a similar scale UK catchment (Metcalf *et al.* 2017), including representation of the hydraulics of in-stream leaky barriers. Such measures are also being designed to spill flows onto the

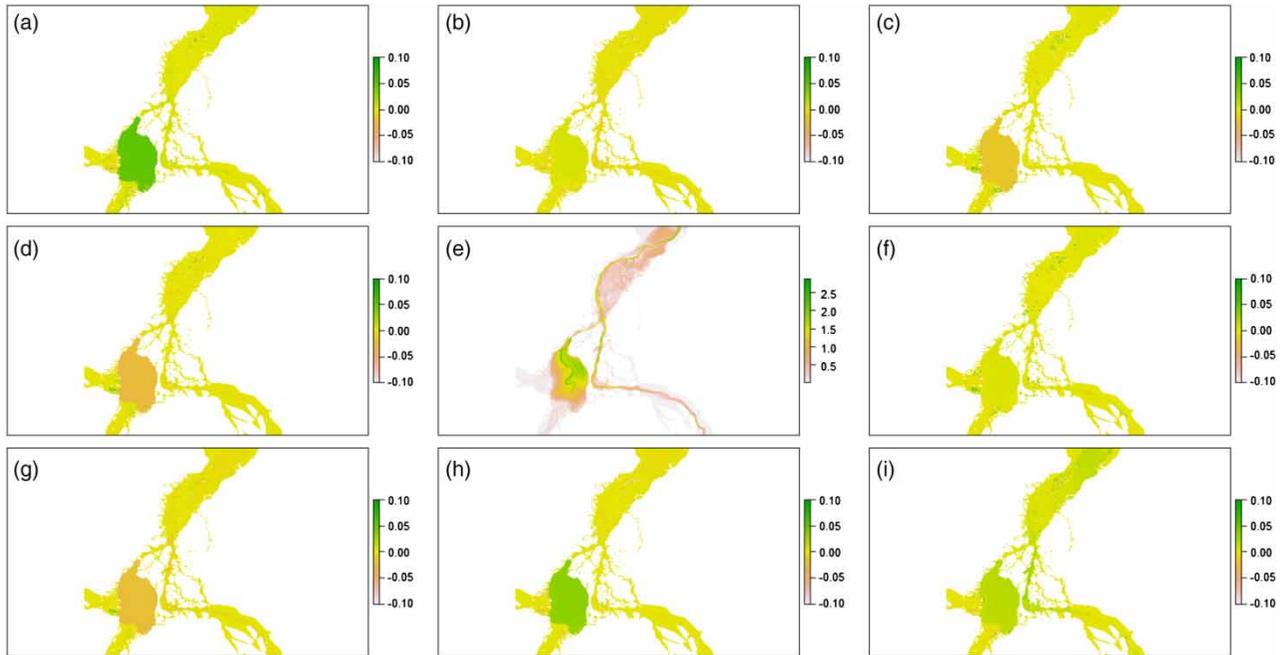


Figure 6 | Performance (NSE)-weighted depth grid (6e on a scale of 0.0 m to 3.0 m), surrounded by plots showing the depth differences (-0.1 m to $+0.1$ m) between weighted grid and eight other simulations.

floodplain to enhance flood attenuation, and so a 2D model becomes more desirable. The use of the fast 2D SWE model, JFlow, allows the impacts of in-channel modifications such as ‘leaky barriers’ and floodplain reconnection, and failures of these features, to be more adequately explored at larger scales. This includes assessing their positive and negative effects on sediment transport, in ways that take into account the large uncertainties inherent in the modelling process (including the parameters representing change within the models).

To show that the coupling Dynamic Topmodel with JFlow is a generic approach, we present a preliminary simulation of Dynamic Topmodel with an alternative 2D hydraulic model, namely, the licence-free HEC-RAS2D (<https://www.hec.usace.army.mil/software/hec-ras/downloads.aspx>). The HEC-RAS2D model has a new type of numerical scheme that permits efficiencies, whereby a relatively coarse numerical grid can be used (e.g. 10 m), for which the subgrid topography (2 m) is taken into account. This is achieved through precomputing hydraulic tables for each coarse numerical grid cell, comprising the conveyance across each face as a function of subgrid geometry, and then also a table of storage volume in the cell as a function of water elevation. This permits the

modelling of channels that pass through the numerical cells if they are represented in the subgrid topography. Figure 7 shows the results of using HEC-RAS2D with a 10 m numerical grid based on a 2 m resolution subgrid topography compared with JFlow. The solution shown is driven by 8 time series distributed along 8 inflow reaches that are identified as HRUs in the Dynamic Topmodel modelling scheme. The red-dashed HEC-RAS 2D output is compared with the gauged data (black dash) and one of the JFlow ensemble runs. The slight differences between JFlow and HEC-RAS2D are likely to stem from the different resolutions: JFlow uses a 2 m grid, HEC-RAS 2d uses a 10 m grid with hydraulic tables based on the 2 m sub-grid topography; and the equations: HEC-RAS 2D uses an implicit solution to the Diffusion Wave, whilst JFlow solves the full SWE using an explicit scheme.

The approach yields very similar behaviour and performance at the gauge, and this increases confidence in the outputs from both models that either could be used in this model cascade approach.

To further illustrate the advantages of using 2d hydraulic models to better represent channel/floodplain flows resulting from the hillslope outputs Dynamic Topmodel, we very

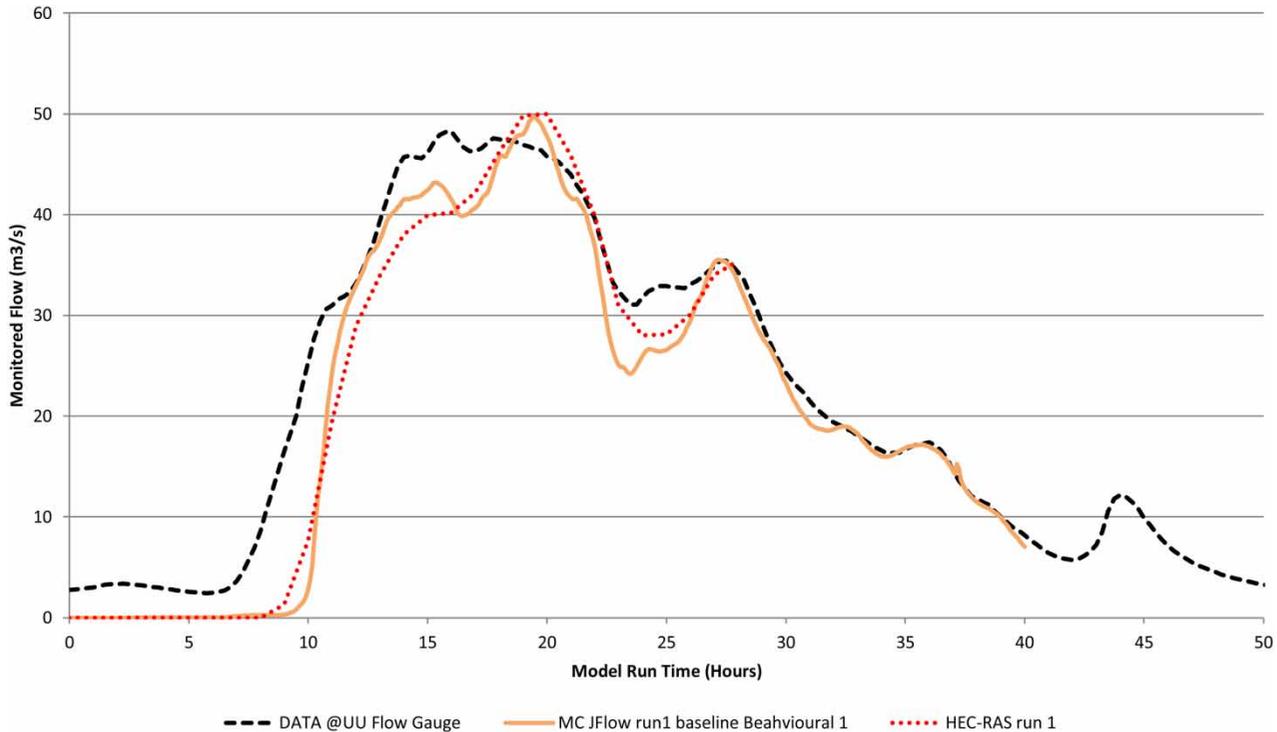


Figure 7 | Comparisons between two 2D hydraulic models for the baseline scenario. Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/nh.2019.150>.

briefly show the ease to which the hydraulic modelling could be extended to understand the spatial distribution of shear stresses and sediment erodibility, critical to understanding the performance of NFM measures longer term. A problem with RAF measures is the potential for reduction of flow velocities and subsequent sediment deposition within the temporary storage area, or localised increases in velocity at the outlet to the storage area, creating scour and unwanted bed erosion, which can both lead to a loss of performance in terms of flood risk reduction.

Given our framework uses 2D hydrodynamic modelling in areas of significant flow, this can be used to provide velocity and shear stress outputs that can help with the design of NFM to avoid in-filling. Here, we follow approaches discussed in Lane & Ferguson (2005), and more recently Reid *et al.* (2018), whereby we use the distributed depth and velocity information from JFlow or HEC-RAS2D, combined with Manning's roughness to estimate shear stress of the form

$$\tau = \frac{\rho g n^2 U^2}{d^{1/3}} \quad (1)$$

where U is the depth-averaged velocity, d is the depth, and n is Manning's roughness. This is dimensionally consistent with shear stress and produces a similar shear stress compared with assuming a logarithmic vertical velocity profile. In a comparative exercise, the distributed value of shear stress was then compared with the critical shear stress for movement of bed material, given an estimate of average grain size. The RSPB provided estimates of $D_{50} = 82$ mm in upper Swindale. Using a Shields constant of 0.06, the zones of likely erosion are developed, shown in red in Figure 8. A zone of deposition was also derived using a deposition coefficient multiplier of 0.3 to the critical shear stress for the bedload and shown in yellow in Figure 8. Areas between these values are assumed to be a zone of transition (in blue). Of note, is a large red patch of a zone of likely erosion at the start of where the channel re-meandering occurs (flows are from bottom to top of figure) which may require some consideration of the need to armour this part of the channel, although it may also be a facet of the digital terrain model, for which further analysis would be needed. The red areas above Dodd bottom are expected given the steep channel gradient

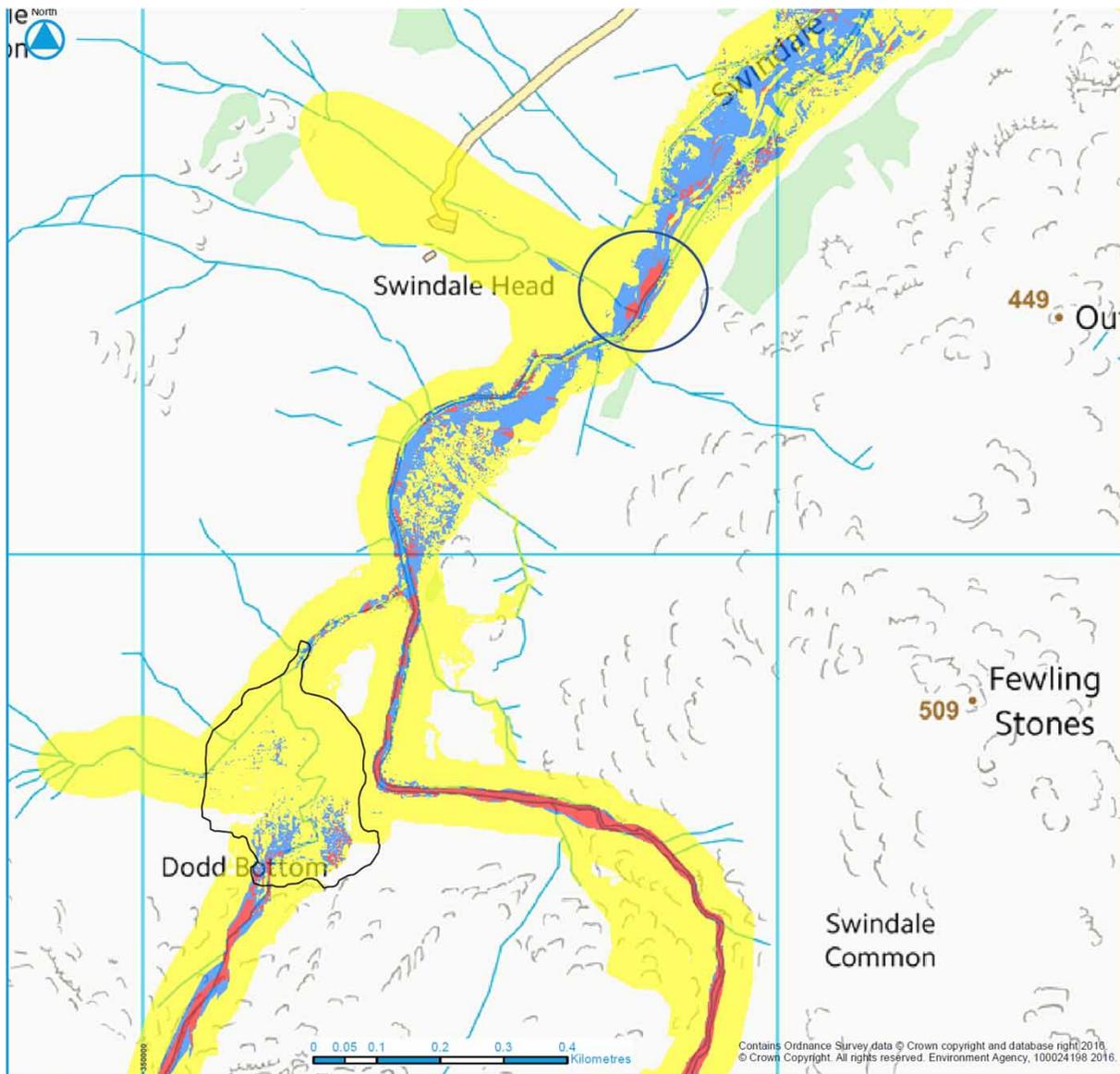


Figure 8 | Erodibility map based on shear stress analysis for the floodplain along Swindale beck, where erosion = red, deposition = yellow, and blue = transition. Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/nh.2019.150>.

and very rough bed. Identifying such issues is critical to the design of NFM schemes and their long-term performance.

CONCLUSIONS

The study demonstrates the feasibility of utilising the best aspects of two models, using Dynamic Topmodel for hillslope hydrology and JFlow or HEC-RAS2D for 2D channel–floodplain hydraulics, in order to simulate the

detail of the processes that need to be represented with uncertainty in an NFM scheme evaluation. The credibility of the simulations of subsurface flows beneath hillslopes is increased with the use of Dynamic Topmodel for this component, while the credibility of the 2D floodplain hydraulics increased with the use of JFlow (or alternative 2D hydraulic models such as HEC-RAS2D). We have demonstrated that the approach is capable of a detailed simulation of interventions applied to floodplains (e.g., storage impoundments or channel–floodplain reconnection).

The approach has successfully advanced the coupled distributed hydrology and 1D hydraulics approach taken by Metcalfe *et al.* (2017) to 2D, permitting investigation of the upscaled impact of very small-scale (2 m^2) NFM measures at the catchment scale (15 km^2), whilst accounting for dynamic interactions in the drainage network. We have made use of the increasing versatility of different 2D hydrodynamic software packages to incorporate lateral inflows and hydraulic structures directly into a 2D mesh and allowing flexible mesh around key floodplain features such as embankments. Whilst there are numerous examples of broadscale coupling of hydrology and hydraulics models (Nguyen *et al.* 2015; Cea & Rodriguez 2016), these recent developments make integration of distributed hillslope-hydrological processes with distributed 2D hydrodynamic modelling considerably more feasible for a range of catchment investigations.

We have demonstrated that the approach can be used for identifying the quantum of change due to an isolated runoff attenuation feature, and also the uncertainty associated with this, given as: $1.8 \text{ m}^3 \text{ s}^{-1} \pm 1.4 \text{ m}^3 \text{ s}^{-1}$. This represents a $4\% \pm 2\%$ change at the flow gauge, which can help decision makers understand whether the intervention is worth investing in or re-engineering as a risk reduction strategy. In reality, further scenarios can be investigated, some diverting more of the flow from the main channel into Dodd Bottom, or through adding multiple features.

The approach will next be scaled up to the 210 km^2 Kent catchment, with 5 flow gauges and 72 km of watercourse as part of the NERC-funded Q-NFM project (<https://www.lancaster.ac.uk/lec/sites/qnfm>), to investigate the wider applicability of the approach. This larger catchment poses a computational problem, whereby it will no longer be feasible to simulate all of the behavioural Dynamic Topmodel scenarios using 2D hydraulic modelling at 2 m resolution, and a further sampling strategy will need to be devised. Since many of the hydraulic outputs are similar, we intend to record statistics of each of the inflow time series from Dynamic Topmodel for each reach (such as peak, volume, time of peak) and use these to distinguish between scenarios likely to result in different spatial behaviours. These can then be further constrained with local knowledge of particular flooding pathways during recent flooding.

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REFERENCES

- Addy, S. & Wilkinson, M. 2016 An assessment of engineered log jam structures in response to a flood event in an upland gravel-bed river. *Earth Surface Processes and Landforms* **1**, 1658–1670. <https://onlinelibrary.wiley.com/doi/full/10.1002/esp.3936>
- Aronica, G., Hankin, B. G. & Beven, K. J. 1998 Uncertainty and equifinality in calibrating distributed roughness coefficients in a flood propagation model with limited data. *Advances in Water Resources* **22** (4), 349–365.
- Beven, K. J. 2006 A manifesto for the equifinality thesis. *Journal of Hydrology* **320** (1–2), 18–36.
- Beven, K. & Binley, A. 1992 The future of distributed models: model calibration and uncertainty prediction. *Hydrological Processes* **6**, 279–298.
- Beven, K. J. & Binley, A. 2014 GLUE: 20 years on. *Hydrological Processes* **28**, 5897–5918.
- Beven, K. J. & Freer, J. 2001 A dynamic TOPMODEL. *Hydrological Processes* **15** (10), 1993–2011.
- Blazkova, S. & Beven, K. J. 2009 A limits of acceptability approach to model evaluation and uncertainty estimation in flood frequency estimation by continuous simulation: Skalka catchment, Czech Republic. *Water Resources Research* **45**, W00B16.
- Burgess-Gamble, L., Ngai, R., Wilkinson, M., Nisbet, T., Pontee, N., Harvey, R., Kipling, K., Addy, S., Rose, S., Maslen, S., Jay, H., Nicholson, A., Page, T., Jonczyk, J. & Quin, P. 2017 Working with Natural Processes – Evidence Directory. Environment Agency Project SC150005. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/681411/Working_with_natural_processes_evidence_directory.pdf
- Carrick, J., Shaiful Azman Bin Abdul Rahim, M., Adjei, C., Habib Hassan Ashraa Kalee, H., James Banks, S., Bolam, F. C.,

- Campos Luna, I. M., Clark, B., Cowton, J., Freitas Nongando Domingos, I., Duba Golicha, D., Gupta, G., Grainger, M., Hasanaliyeva, G., Hodgson, D. J., Lopez-Capel, E., Magistrali, A. J., Merrell, I. G., Oikeh, I., Salim Othman, M., Kumari Ranathunga Ranathunga Mudiyansele, T., Warren, C., Samuel, C., Sufar, E. K. H., Watson, P. A., Azwanida Binti Zakaria, N. N. & Stewart, G. 2018 Is planting trees the solution to reducing flood risks? *Journal of Flood Risk Management* **2018**, 1–10. DOI: 10.1111/jfr3.12484.
- Cea, M. & Rodriguez, M. 2016 Two-dimensional coupled distributed hydrologic–hydraulic model simulation on watershed. *Pure and Applied Geophysics* **173**, 909. <https://doi.org/10.1007/s00024-015-1196-5>.
- Ciliverd, H. M., Thompson, J. R., Heppell, C. M., Sayer, C. D. & Axmacher, J. C. 2013 River-floodplain hydrology of an embanked lowland Chalk river and initial response to embankment removal. *Hydrological Sciences Journal* **58** (3), 1–24.
- Dadson, S., Hall, J. W., Murgatroyd, A., Acreman, M., Bates, P., Beven, K., Heathwaite, L., Holden, J., Holman, I. P., Lane, S. N., O'Connell, E., Penning-Rowsell, E., Reynard, N., Sear, D., Thorne, C. & Wilby, R. 2017 A restatement of the natural science evidence concerning catchment-based natural flood management in the UK. *Proceedings of the Royal Society A* **473**, 20160706. <http://dx.doi.org/10.1098/rspa.2016.0706>.
- Ghimire, S., Wilkinson, M. & Donaldson-Selby, G. 2015 Application of 1d and 2d Numerical Models For Assessing And Visualizing Effectiveness Of Natural Flood Management (NFM) Measures. In: *Proceedings of the International Conference on Hydroinformatics*.
- Hankin, B., Metcalfe, P., Craigen, I., Page, T., Chappell, N., Lamb, R., Beven, K. & Johnson, D. 2017a Strategies for testing the impact of natural flood risk management measures. In: *Flood Risk Management* (T. V. Hromadka II & P. Rao, eds). InTechOpen, London. Available from: <https://www.intechopen.com/books/flood-risk-management/strategies-for-testing-the-impact-of-natural-flood-risk-management-measures>.
- Hankin, B., Lamb, R., Craigen, I., Page, T., Chappell, N. & Metcalfe, P. 2017b A whole catchment approach to improve flood resilience in the Eden. *Winning entry to the Defra Flood Modelling Competition* 2016 [Internet]. 19-01-2017. Available from: https://consult.defra.gov.uk/water-and-flood-risk-management/flood-risk-management-modelling-competition/results/jba_defra_winning_entry_full_report.pdf
- Holden, J., Kirkby, M. J., Lane, S. N., Milledge, D. G., Brookes, C. J., Holden, V. & McDonald, A. T. 2008 Overland flow velocity and roughness properties in peatlands. *Water Resources Research* **44**. doi:10.1029/2007wr006052.
- Hollaway, M. J., Beven, K. J., Benskin, C. M. H., Collins, A. L., Evans, R., Falloon, P. D., Forber, K. J., Hiscock, K. M., Kahana, R., Macleod, C. J. A., Ockenden, M. C., Villamizar, M. L., Wearing, C., Withers, P. J. A., Zhou, J. G. & Haygarth, P. M. 2018 Evaluating a processed based water quality model on a UK headwater catchment: what can we learn from a 'limits of acceptability' uncertainty framework? *Journal of Hydrology* **558**, 607–624.
- Hunter, N. M., Bates, P. D., Neelz, S., Pender, G., Villanueva, I., Wright, N. G., Liang, D., Falconer, R. A., Lin, B., Waller, S., Crossley, A. J. & Mason, D. C. 2008 Benchmarking 2d hydraulic models for urban flooding. *Proceedings of the Institute of Civil Engineers, Water Management* **161** (1), 13–30, Issue WM1.
- Kjeldsen, T. R., Stewart, E. J., Packman, J. C., Folwell, S. & Bayliss, A. C. 2005 *Revitalisation of the FSR/FEH Rainfall-Runoff Method*. Defra R&D Technical Report FD1913/TR.
- Lamb, R., Crossley, A. & Waller, S. 2009 A fast 2d floodplain inundation model. *Proceedings of the Institution of Civil Engineers: Water Management* **162** (6), 363–370.
- Lane, S. N. 2017 *Natural flood management*. *Wiley Interdisciplinary Reviews: Water* **4** (3), e1211.
- Lane, S. N. & Ferguson, R. I. 2005 Modelling reach-scale fluvial flows. In: *Computational Fluid Dynamics: Applications in Environmental Hydraulics* (P. D. Bates, S. N. Lane & R. I. Ferguson, eds). John Wiley & Sons Ltd., Chapter 10, pp. 217–269. Available from: <https://onlinelibrary.wiley.com/doi/book/10.1002/0470015195>
- Liu, Y., Freer, J. E., Beven, K. J. & Matgen, P. 2009 Towards a limits of acceptability approach to the calibration of hydrological models: extending observation error. *Journal of Hydrology* **367**, 93–103. doi:10.1016/j.jhydrol.2009.01.016.
- Metcalfe, P., Beven, K. & Freer, J. 2016 *dynatopmodel: Implementation of the Dynamic TOPMODEL Hydrological Model*. R package version 1.1. <https://CRAN.R-project.org/package=dynatopmodel>
- Metcalfe, P., Beven, K., Hankin, B. & Lamb, R. 2017 A modelling framework for evaluation of the hydrological impacts of nature-based approaches to flood risk management, with application to in-channel interventions across a 29 km² scale catchment in the United Kingdom. *Hydrological Processes*. HYP-16-0365.R1. <https://doi.org/10.1002/hyp.11140>.
- Metcalfe, P., Beven, K., Hankin, B. & Lamb, R. 2018 Simplified representation of runoff attenuation features within analysis of the hydrological performance of a natural flood management scheme. *Hydrology and Earth System Sciences* **22**, 2589–2605. <https://doi.org/10.5194/hess-2017-398>.
- Nguyen, P., Thorstensen, A., Sorooshian, S., Hsu, K., AghaKouchak, A., Sanders, B., Koren, V., Cui, Z. & Smith, M. 2015 A high resolution coupled hydrologic–hydraulic model (HiResFlood-UCI) for flash flood modeling. *Journal of Hydrology* **541** (A), 401–420. <http://dx.doi.org/10.1016/j.jhydrol.2015.10.047>
- Nicholson, A. R., Wilkinson, M. E., O'Donnell, G. M. & Quinn, P. F. 2012 Runoff attenuation features: a sustainable flood mitigation strategy in the Belford catchment, UK. *Area* **44** (4), 463–469. doi: 10.1111/j.1475-4762.2012.01099.x.
- Office International de l'Eau 2013 Individual Natural Water Retention Measures: Floodplain Restoration and Management. 07.0330/2013/659147/SER/ENV.C1 for the Directorate General for Environment of the European

- Commission. http://nwrn.eu/sites/default/files/nwrn_ressources/n3_-_floodplain_restoration_and_management.pdf
- Pattison, I., Lane, S. N., Hardy, R. J. & Reaney, S. M. 2014 *The role of tributary relative timing and sequencing in controlling large floods*. *Water Resources Research* **50**, 5444–5458. doi:10.1002/2013WR014067.
- Pitt, M. 2008 *The Pitt Review, 2008. Learning Lessons From the 2007 Floods*. June 2008. http://archive.cabinetoffice.gov.uk/pittreview/thepittreview/final_report.html
- Reid, H. E., Williams, R. D., Brierley, G. J., Coleman, S. E., Lamb, R., Rennie, C. D. & Tancock, M. J. 2018 *Geomorphological effectiveness of floods to rework gravel bars: insight from hyperscale topography and hydraulic modelling*. *Earth Surface Processes and Landforms* <https://doi.org/10.1002/esp.4521>
- RSPB 2017 *Modelling Working with Natural Process in Swindale Beck*. JBA Final Report. REF 2017s5854.
- Shuttleworth, E. L., Evans, M. G., Pilkington, M., Spencer, T., Walker, J., Milledge, D. & Allott, T. E. H. 2019 *Restoration of blanket peat moorland delays stormflow from hillslopes and reduces peak discharge*. *Journal of Hydrology X* **2**, 100006. <https://doi.org/10.1016/j.hydroa.2018.100006>.
- World Wildlife Fund 2016 *The Flood Green Guide. Natural and Nature-Based Flood Management: A Green Guide*. https://c402277.ssl.cf1.rackcdn.com/publications/1058/files/original/WWF_Flood_Green_Guide_FINAL.pdf?1495628174

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