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Guidelines on the Eco:Actuary Policy Support System for understanding the role of Natural Flood Management (NFM) in flood mitigation

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Executive summary

This deliverable introduces the ‘Eco:Actuary Toolkit’ a suite of novel natural flood management decision support tools. The toolkit consists of three specific tools: Eco:Actuary Investment Planner, //Smart:, and Eco:Actuary Policy Support System. Each tool has a specific niche. Eco:Actuary Investment Planner is useful early on in the decision making process when investment in a range of natural flood management interventions is being considered and an evaluation of costs in relation to performance is required. It will calculate the financial cost required to achieve a specified flood mitigation goal. Once interventions are in place then the //Smart: tool is applicable. //Smart: is new, low-cost DIY monitoring equipment and associated software which is designed to evaluate the efficacy of existing natural flood management interventions. The //Smart: tool provides a real-time understanding of what effect a particular flood management intervention is having on flood risk. The third tool developed is the Eco:Actuary Policy Support System (PSS) which is designed to support high-level flood risk mitigation planning and decision making. It is a global flood catastrophe model designed to support catchment-scale (or larger) flood mitigation strategies. Eco:Actuary PSS is able to identify assets at risk of flood, how climate change and changes to land-use and land management can alter flood risk, and the optimal location within the catchment to place natural flood management interventions. The toolkit therefore provides support at multiple stages in the decision making process from planning, to monitoring and evaluation and for interventions from small to large-scale.

The creation of the Eco:Actuary Toolkit is an important step in creating the evidence base for natural flood management. The tools can also practically help organisations make informed decisions as to the suitability of natural flood management in general, or the suitability of specific types of interventions based on their individual circumstances. These tools show that area- based natural flood management interventions such as changes to land-use (i.e. reforestation) and land-management (i.e. conservation agriculture) are more effective than point-based natural flood management interventions such as leaky dams. Our field sites were located in the Thames catchment only. It is possible that point-based interventions elsewhere are more effective and have lower costs. As the tools are all open-access and the components for the monitoring equipment low-cost, the tool-kit can be deployed cheaply anywhere. The Eco:Actuary PSS has already been applied by users in many other national contexts as shown by our monitoring and evaluation data.

The deliverable is structured as follows. We first describe each tool - its purpose, how to use it (see Methods), before then applying each tool in a series of case studies (see Applications of the



Eco:Actuary toolkit within NAIAD) and then examine applications by other users outside of NAIAD. In the case of the Eco:Actuary Investment Planner, the tool is used to estimate the cost required to achieve an X% mitigation of flood peaks wherever there is available flow data. Data are supplied for UK and we apply for a selection of tributaries in the Thames River catchment. The costs of three natural flood management interventions were compared: leaky dams, retention ponds and conservation agriculture. In the case of //Smart, the tool is used to calculate how much water is stored by leaky dams, retention ponds and conservation agriculture for rainfall events at a range of sites within the Thames catchment. To complement the field monitoring we also undertook laboratory flume experiments to systematically investigate differences in performance between different dam designs. The results of these experiments are described at the end of the //Smart section. In the case of the Eco:Actuary PSS, three UK-centered applications are provided: a baseline assessment, flood risk under climate change and flood risk if protected areas are reforested. Applications outside UK are described in follow up publications (D2.6). The deliverable ends with a description of how the toolkit has been applied beyond NAIAD and links to live (i.e. constantly updated) training materials and guidance. We conclude with a discussion of the implications of our results for natural flood management use and policy.



Introduction

Aim of deliverable

This deliverable will provide examples and guidelines on the application of the various components of the Eco:Actuary policy support system. It will identify a series of use cases of relevance to NAIAD demos and the broader insurance industry and other user types identified in D2.4. The components described include the modules for: potential risk of hazard (the catastrophe model), asset inventory and value distribution, damage functions, mitigation by green and grey infrastructure and thus realized risk of hazard. The deliverable covers application of Eco:Actuary in both simulation model (for scenario analysis) and early warning mode (for near real time forecasting when coupled with deployed FreeStations as //Smart:River and //Smart:Soil.

The complementary D2.7 presents a variety of alternative approaches as developed and applied by the NAIAD project in the DEMOs. The approaches are compared **for their data requirements, applicability, level of detail and ease of application**. In each case **we do not focus on the detail of the method, nor on the results but on: (a) the nature of the hazard, (b) the scale and types of NFM proposed, (c) the data, scale and other constraints, and (d) the rationale for the application of this specific approach as most suitable under these conditions**. In this way, we compare and contrast the use of different approaches for different situations.

The Eco:Actuary toolkit

The Eco:Actuary toolkit is a suite of tools developed to support risk analysis for natural hazards, investment planning for **natural flood management (NFM)**, assessment of co-benefits and effectiveness monitoring for installed interventions. The toolkit comprises three key components:

1. The //Smart:River and //Smart:Soil systems for in field monitoring and web-based analysis of the effectiveness of specific interventions made.
2. The Eco:Actuary web-based Investment planner - which is an empirical spreadsheet based tool for understanding the magnitude and type of interventions necessary to make a significant difference to observed flood peaks. All data are provided for application in the UK through the Environment Agency real-time API, and can be sourced from national meteorological services for application elsewhere.



The Eco:Actuary web-based spatial policy support system - which maps risk, exposure, loss, mitigation and avoided loss for current natural capital and scenarios for climate and nature-based solution investments. Working with the Co\$tingNature Policy Support System, Eco:Actuary can also be used to assess co-benefits beyond hazard mitigation. All data are provided for application anywhere, globally.

Methods

The //Smart: tools for monitoring NFM effectiveness

Vision -

//Smart: is intended as a turnkey system for monitoring the effectiveness of specific in-place NFM accurately, at low cost and with ease. It comprises self-build open source hardware alongside on-device firmware and server-side software for near real-time monitoring and assessment of NFM including point source in-line storage (leaky dams, retention ponds) and non-point land management options such as conservation agriculture. //Smart: includes the following components.

Hardware -

//Smart hardware includes //Smart:Soil and //Smart:River systems. //Smart:Soil is near-real time monitoring of soil water storage using low cost sensors and internet-connected microcontrollers. The sensor design is at the FreeStation website [here](#). These sensors are connected to the [FreeStationLive](#) or [FreeStationLocal](#) stations. They can be used to monitor subsurface storage created by an inline storage intervention or soil storage resulting from a land management intervention. Two stations can be deployed to monitor the differential between two land management interventions (for example conservation agriculture vs. traditional tillage) or to monitor river stage on either side of an intervention such as a leaky dam.

Firmware -

The FreeStation firmware reads a variety of sensors and sends their data to the FreeStation servers at user-defined intervals in a variety of connectivity settings. The firmware performs basic troubleshooting and quality control for data.



Serverware -

The //Smart: serverware reads and stores FreeStation data in a database and provides a series of functions for filtering, checking, troubleshooting, download and analysis, including analyses specific to NFM.

The visualisation and control panel for the system is available at www.policysupport.org/smart and provides access to:

- Line and scatter charts for current and past data with visualisations covering a day, week, month or year. Data shown are automatically filtered to remove out-of-bounds data and data with more rapid than expected change (spikes). These filters can be disabled.
- Download as CSV, TSV.
- Tools to manage and troubleshoot the device.
- Analytical tools, both general and specific to the variables measured.
- Device monitoring.

The //Smart:River system -

//SmartRiver: is developed as a turnkey solution for monitoring and assessing the effectiveness of inline storage NFM such as retention ponds, leaky dams, Beaver dams etc. It combines the FreeStation stage gauge and subsurface (soil) storage (moisture) sensors with specific serverware for analysis of storage by such interventions.



An example //Smart:River sensor is shown and uses a low-cost sonar to measure distance from the sensor to the water surface and thus changing water stage. The solar powered device sends data in real time or once per day to the FreeStation servers. A //Smart:River device can be self built with components costing \$100-150.



The usual deployment for monitoring the effectiveness of inline storage is to have a device either side of the intervention (such as this leaky dam). Each device measures soil moisture and river stage. There is also a local measurement of rainfall, temperature, humidity and air pressure. These devices can be used:

- (a) to assess the differences in soil moisture and stage either side of the intervention as a measure of the behaviour of the intervention
- (b) to assess the volume of inline storage as a proportion of total flow at the downstream *asset of interest*.



A typical visualisation for FreeStage is shown in figure 1 with measured stage shown alongside rainfall for the nearest station as captured from the UKEA Live data API.



//Smart: [L10]

≤ 2019 Hour , Day , Week , Month , Year , ≤ ≥ ±	Download: CSV , TSV . Tools: Manage Config , Analyses (Refresh)	Options: Auto range , No-filter , No- remove , Scatter	Info: RE:159, D:24, M:6%, R:0%, F:0%, B:6%	Air temperature (deg. C) L / R	Humidity (%) L / R	Pressure (mb) L / R	Distance 1 (metres) L / R	Battery status (%) L / R
---	---	---	---	---	--	---	--	---

| L10 | Unum Pipp Brook | latest record: 2019-07-25 14:47:06 GMT, min: 0.57, max: 0.69 , Y2 min: 0.0, Y2 max: 4.6 |

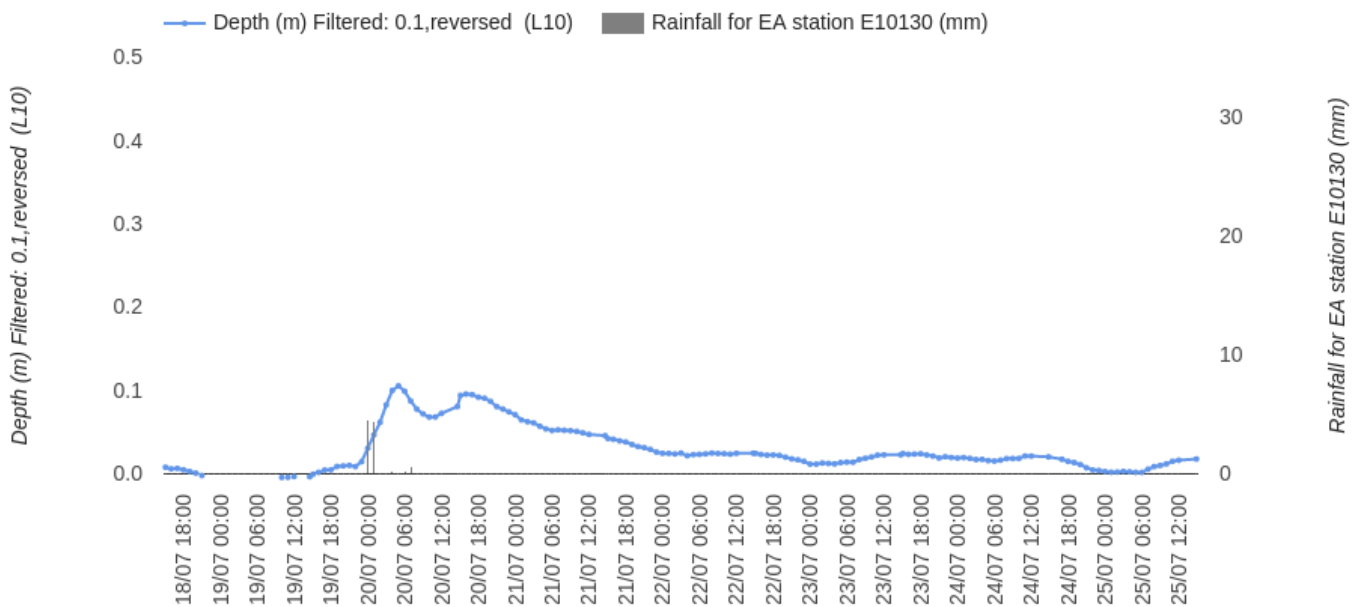


Figure 1 The //Smart: visualisation and control panel interface (see website for table options).

When used to assess the effectiveness of inline storage, two variable-specific functions for the stage variable can be used. The first of these can be used to calculate the difference in change of stage upstream and downstream of the intervention. The resulting time series is positive where the changes in stage above the dam are greater than those below the dam (as expected if the dam is effective) and negative if the changes in stage downstream are higher. The upstream and downstream devices should be located close to the dam and thus have similar channel cross-sectional geometry.



Variable-specific analyses based on //Smart: stage for L44								
Variable	Explanation	Calculate						
Difference in stage either side of dam	Examine difference in stage either side of leaky dam at this upstream sensor	<table border="1"><tr><td>Include drainage? (Y/N): N</td><td>L# of downstream FreeStation: -</td></tr><tr><td colspan="2">☒ Submit</td></tr></table>	Include drainage? (Y/N): N	L# of downstream FreeStation: -	☒ Submit			
Include drainage? (Y/N): N	L# of downstream FreeStation: -							
☒ Submit								
Mitigation of flood peak by inline storage intervention	Calculate mitigation of flood risk by inline storage intervention at this sensor. Can be calculated as a volume or percentage of flow (with downstream flow volume data)	<table border="1"><tr><td>Include drainage (Y/N): N</td><td>Area of water body (m²): 10</td><td>L# of FreeStation measuring flow at asset at risk: -</td></tr><tr><td colspan="3">☒ Submit</td></tr></table>	Include drainage (Y/N): N	Area of water body (m ²): 10	L# of FreeStation measuring flow at asset at risk: -	☒ Submit		
Include drainage (Y/N): N	Area of water body (m ²): 10	L# of FreeStation measuring flow at asset at risk: -						
☒ Submit								

Figure 2 Specific functions for the //Smart:River system.

The second can be used to calculate the storage behind the dam either as a volume or as a proportion of measured flow downstream, from another FreeStation. All that is required to access the data from FreeStations are their L number (known as FID, FreeStation ID). The storage can be calculated for rising limb only (excluding drainage) or both rising and falling limb. Since it is the volumetric storage during the rising limb that is critical to flood peak reduction we show this value in figure 3 for a week-long period in which some ~3m³ in total are captured during the rising limbs by a dam on this small stream.



//Smart:

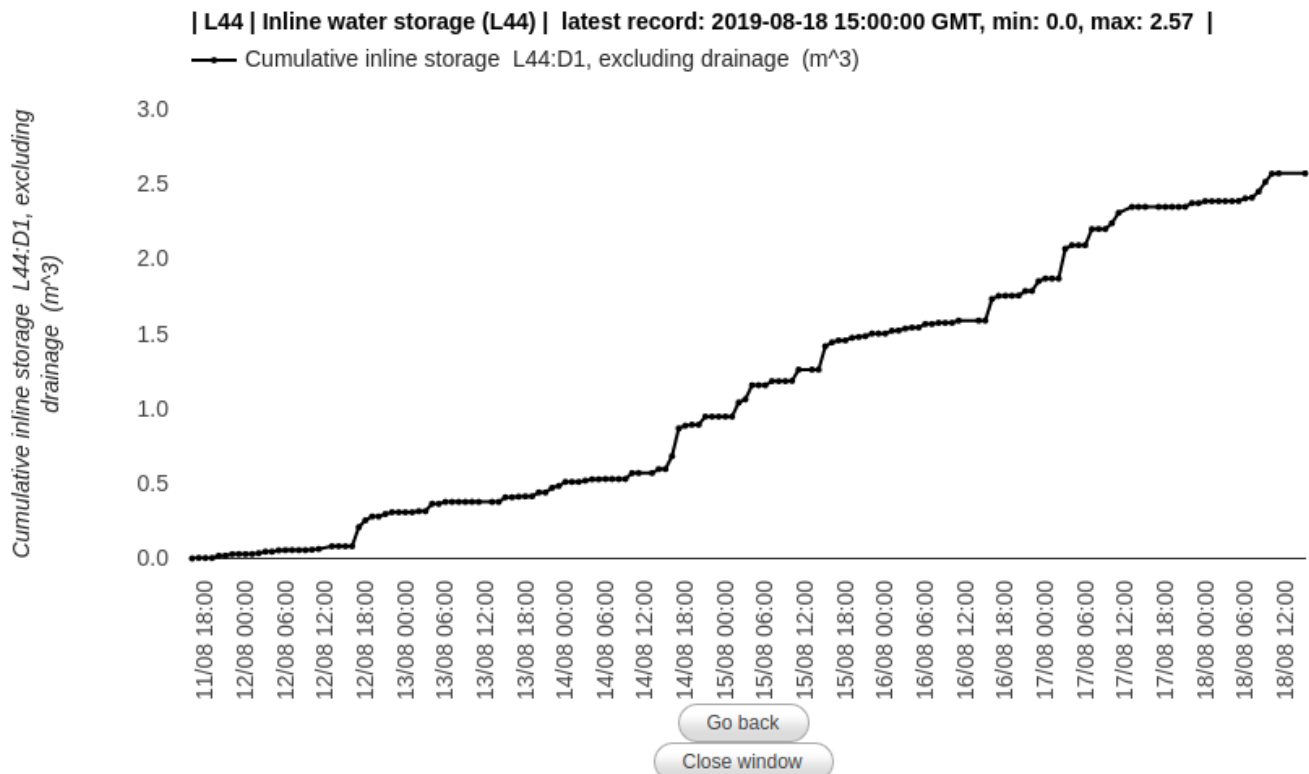


Figure 3 Inline water storage calculated by //Smart:River

The //Smart:Soil system

//SmartSoil: is developed as a turnkey solution for monitoring and assessing the effectiveness of soil storage. It combines the FreeStation subsurface (soil) storage (moisture) sensors with specific serverware for analysis of storage by soil and for measuring the impact of soil management interventions.



An example //Smart:Soil sensor is shown and uses a low-cost soil moisture probe to measure soil moisture. The solar powered device measures 6 times per hour, averages hourly and sends data in real time or once per day to the FreeStation servers. A //Smart:Soil device can be self built with components costing \$100-150.



The usual deployment for monitoring the effectiveness of soil storage is to have a device within the land use where the soil management intervention is practiced and another in the counterfactual (land use without intervention). Each device measures soil moisture at one or two depths (30cm,60cm). There is also a local measurement of rainfall, temperature, humidity and air pressure. These devices can be used:

- (a) to assess the mitigation of flood risk by a soil management intervention (relative to a counterfactual)
- (b) to assess the volume of soil storage or as a proportion of total flow at the downstream *asset of interest*.



Box 1 The //Smart Soil: system

A typical //Smart:Soil series is shown in figure 4, with soil moisture shown alongside rainfall from the nearest UKEA station.



//Smart: [L14]

≤ 2019 Hour, Day, Week, Month, Year, ≤ ≥ ±	Download: CSV, TSV. Tools: Manage Config. Analyses (Refresh)	Options: Auto range, No-filter, No- remove, Scatter	Info: RE:166, D:0, M:2%, R:0%, F:0%, B:84%	Air temperature (deg.C) L / R	Humidity (%) L / R	Pressure (mb) L / R	Soil moisture (%) (volumetric) L / R	Distance 1 (metres) L / R	Battery status (%) L / R
--	--	--	---	--	--	---	---	--	---

| L14 | Retention pond | latest record: 2019-08-18 15:02:04 GMT, min: 51.0, max: 108.0 , Y2 min: 0.0, Y2 max: 3.2 |

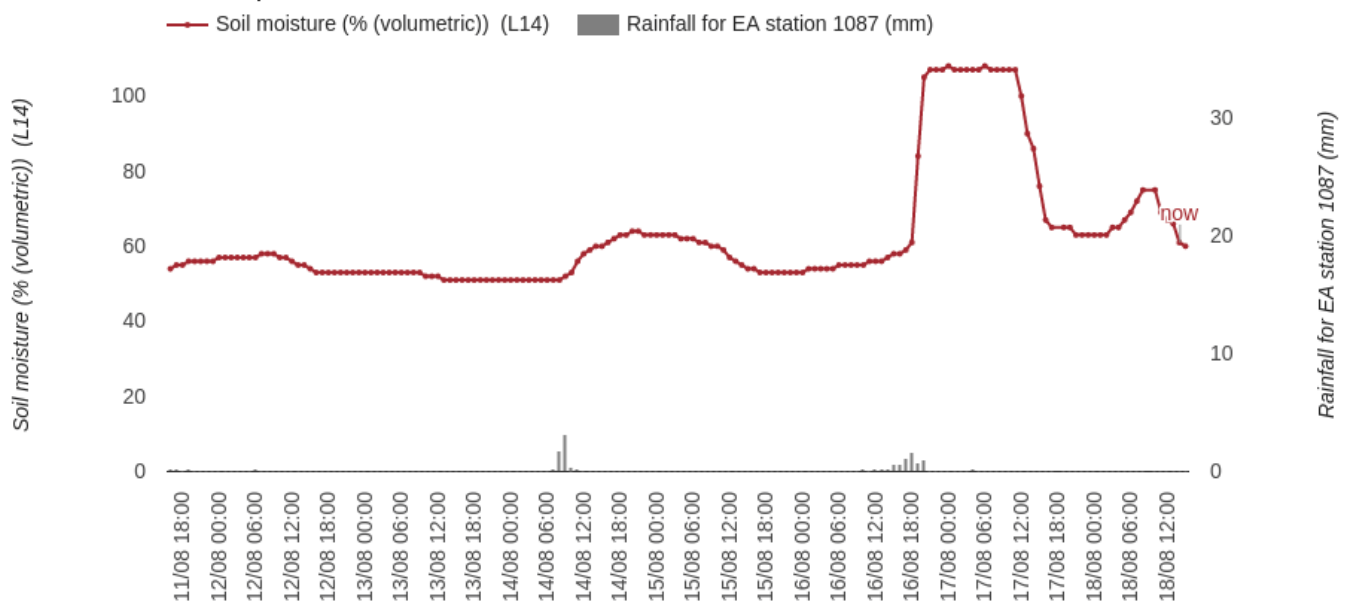


Figure 4 Typical //Smart:Soil data showing soil moisture response to rainfall

When used to assess the effectiveness of soil storage, two variable-specific functions for the soil moisture variable can be used. The first of these can be used to calculate mitigation of flood risk by the soil management intervention at this sensor, compared with a counterfactual under different management. The result can be calculated as a volume or percentage of flow (with downstream flow volume data), figure 5.



Variable-specific analyses based on //Smart: soil moisture for L20				
Variable	Explanation	Calculate		
Mitigation of flood risk by this soil management intervention	Calculate mitigation of flood risk by the soil management intervention at this sensor, compared with a counterfactual under different management. Can be calculated as a volume or percentage of flow (with downstream flow volume data).	Include drainage? (Y/N): N	Area of CA land (ha.): 10	Depth to sensor (m): 1
			L# of counterfactual FreeStation: -	L# of FreeStation measuring flow at asset at risk: -
		☒ Submit		
Mitigation of flood risk by this soil storage	Calculate mitigation of flood risk by soil storage at this sensor. Can be calculated as a volume or percentage of flow (with downstream flow volume data)	Include drainage (Y/N): N	Area of land (ha.): 10	Depth to sensor (m): 1
			L# of FreeStation measuring flow at asset at risk: -	
		☒ Submit		

Figure 5 variable-specific functions available for //Smart:Soil

The resulting time series is positive where the water taken up by the intervened soil is greater than that of the counterfactual (as to be expected if the intervention is effective) and negative if the changes in soil storage in the counterfactual is higher. Figure 6 shows an example where the intervention is conservation agriculture (CA, brown line) and storage under the intervention tends to be higher than for traditional tillage in which evaporation and drainage seems more rapid. Figure 7 shows the cumulative extent of this additional storage (max. 0.06 Mm3 over the period for this intervention).

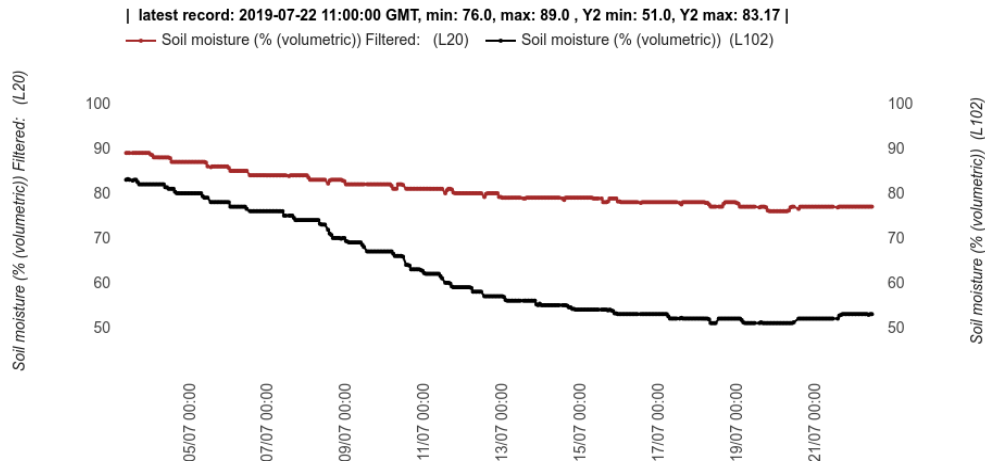


Figure 6 The positive effect of conservation agriculture in encouraging soil storage versus a counterfactual, as shown by //Smart:Soil. CA (brown) vs non CA soil moisture (CA retains more moisture).

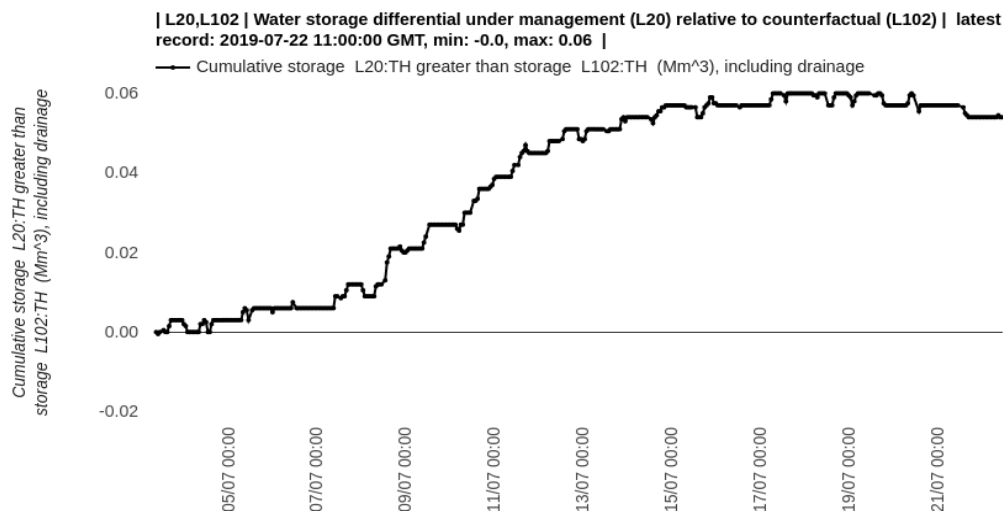


Figure 7 Cumulative additional storage under CA vs non-CA Mm³

Training for the //Smart:River and //Smart:Soil systems is available [here](#)



The Eco:Actuary Investment planner (EIP)

The Eco:Actuary Investment Planner (EIP) is designed as a simple, online spreadsheet-based tool that allows assessment of the scale and approximate cost of interventions of different types that would be required to reduce peak flows by a given proportion.

Purpose

It will be useful to those considering the type and scale of investment that will have impact on a stream for which there is available flow data and thus is only relevant for gauged catchments. The spreadsheet is [available here](#).

How it works

Environment Agency flow data is used to calculate the water volume represented by the rising limb of a flood hydrograph. The maximum of this volume (the largest flood) peak over the observation period is assumed to be volume required for 100% mitigation. The user enters what proportion of this volume (flood peak) they wish to mitigate and the tool calculates the volume of storage that NFM must hold back to achieve that mitigation.

Since the EA timeseries used are short, the difference between mean stage and highest observed stage at the nearest stage gauge is used to calculate a multiplier that better represents the longer term maximum flow. Users can enter the per-unit volume cost of different Natural Flood Management (NFM) techniques and the tool will estimate the budget required to mitigate at the level required.

EIP takes no account of how the placement of NFM in specific catchment positions can make a difference: a spatial model like Eco:Actuary is necessary for that. This tool uses data supplied by UK EA through DEFRA opendata and connects to this directly through a real time API (application protocol interface). The *non-UK* spreadsheet tab allows users to paste in their own flow timeseries data where this is not available through the UK EA.

How to use it

There are four stages to using EIP labelled 1-4 as taken from the interface (figure 8) and listed below:

1. Complete the fields indicating the location of assets at risk (the drop-down list on the right will then be populated with the nearest flow and stage stations). Also set the per cubic metre cost of each of the three types of intervention. Then set the flow mitigation requirement (the flood peak reduction target (%))



2. Read the code of the nearest station and other stations. Add station numbers (in brackets) where indicated and then choose a station from drop down lists above.
3. Choose the station IDs that you want to use in the drop down list (or leave blank for these to be chosen automatically below)
4. The results for your analysis will appear:

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q				
1	EcoActuary: Investment Planner-UK can be used to assess the scale of NFM investment necessary to make a difference How it works: Environment Agency flow data is used to calculate the water volume represented by the rising limb of a flood hydrograph. The maximum of this volume (the largest flood) peak over the observation period is assumed to be volume required for 100% mitigation. The user enters what proportion of this volume (flood peak) they wish to mitigate and the tool calculates the volume of storage that NFM must hold back to achieve that mitigation. Since the EA timeseries used are short, the difference between mean stage and highest observed stage at the nearest stage gauge is used to calculate a multiplier that better represents the longer term maximum flow. Users can enter the per unit volume cost of different NFM techniques and the tool will estimate the budget required to mitigate at the level required. EIP takes no account of how the placement of NFM in specific catchment positions can make a difference: a spatial model like EcoActuary is necessary for that. This tool uses data supplied by UK EA through DEFRA opendata.												3. Choose the station IDs that you want to use here (or leave blank for these to be chosen automatically below)								
2	1. Please complete the fields below indicating the location of assets at risk the drop-down list on the right will then be populated with the nearest flow and stage stations. Then set the mitigation requirement:							4. The results for your analysis will appear here:					Asset location map		Mole stage station map		Flow gauge location map				
3	River, catchment or station name	Latitude	Longitude	Flood peak reduction target (%)	Cost per m³ of mitigation (leaky dams) GBP/m³	Cost per m³ of mitigation (conservation agriculture) GBP/m³	Cost per m³ of mitigation (ponded surface storage) GBP/m³	Upstream storage volume required to meet flood risk reduction requirement (m³), for 100% mitigation	Upstream storage volume required per % of flood peak reduction (m³), for max. observed CIV	Cost of full mitigation (using leaky dams) GBP	Cost of full mitigation (using conservation agriculture) GBP	Cost of full mitigation (using ponded surface storage) GBP	Location of assets at risk (location)	Stage Stations	Flow Stations						
4	Stort	51.590927	0.346424	10	£500.00	£100.00	£600.00	439 m³ or 0.2 olympic swimming pools	44	£219,978	£43,996	£263,974	Brentwood	3280TH	3280TH						
5	Highest recorded level (m):	3.071	Max level over period shown (m):	1.536	Flood flow multiplier:	2.00	Change in max flow (%):	10	Change in min flow (%):	#DIV/0!	Change in total volume (%):	-11.11	Latitude:								
6													Longitude:								
7													Name (label):								
8													River name:								
9													Distance (km):								
10													2. Add station numbers here (in brackets) and then choose from drop down lists above.		(3280TH)		(3280TH)				
11													Other stations:		Shonks Mill Bridge (5442TH)		WRITTLE GS GSM (E21194)				
12															Mountnensing (E24899)		BEACHES MILL FGS GSM (E22890)				
13															Harold Park (5546TH)		SPRINGFIELD FGS AND RAINGAUGE				

Figure 8 The Eco:Actuary Investment Planner interface

The interface to the EIP is shown in figure 8. Grey cells contain information. Blue cells contain results. Red cells are calculated by the model. Green cells can be edited to apply the model to different intervention types and upstream of different flow gauges. The image shows recent



flow events (blue) and the required mitigation by this storage. The volume of storage required is calculated relative to the long term flow maxima and the typical flow dynamics as shown in the chart and a total volume of storage and approximate cost for the required mitigation is derived.

Stage and Flow stations in the UK are shown in the EIA and shown in figure 9. A Flow station must be present downstream in order to use the EIA, since EIA is an empirical tool.

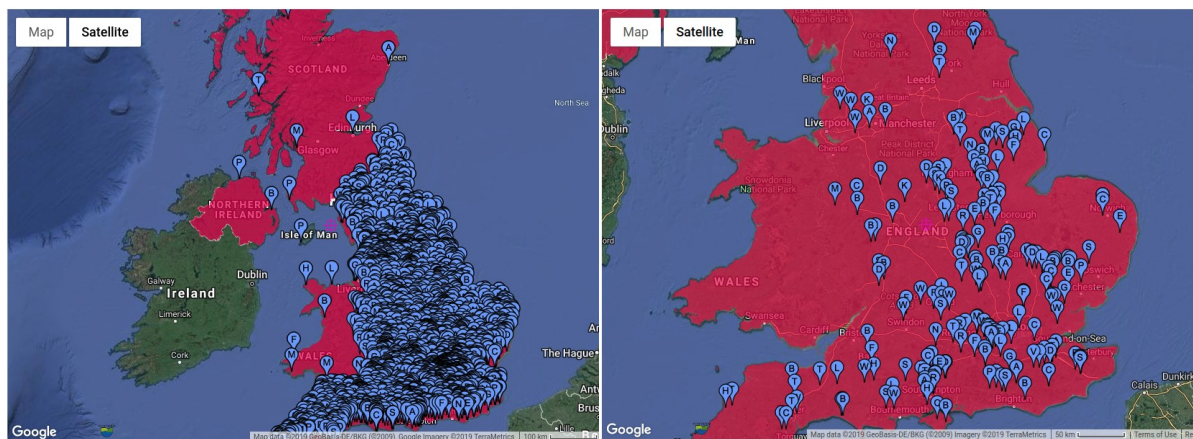


Figure 9 Stage and flow Stations available in the UK Environment Agency Real time API

The Eco:Actuary spatial policy support system (PSS)

Purpose

Eco:Actuary is a spatial policy support system (PSS) developed using the EcoEngine framework that also underpins WaterWorld, Co\$tingNature and a range of other PSS. Eco:Actuary is focused on assessing risks, exposure of multiple assets and their values and better understanding the mitigation of potential damage by existing green infrastructure and proposed green infrastructure interventions. It can do this for the current status of climate and land use and for scenarios of combined climate, land use, asset value and asset adaptation (damage function modification) change. Though intended to become multi-hazard in the long term, Eco:Actuary currently covers only flood. Like all policysupport.org PSS Eco:Actuary is freely available online



at www.policysupport.org/Eco:Actuary and applicable anywhere globally based on datasets provided with the model. As a physically based model the EcoActuary PSS can be used in gauged catchments or catchments without a flow gauge.

The needs of the insurance and reinsurance industries

The Eco:Actuary Policy Support System was co-developed with the UK (re)insurance industry through a series of interviews as well as through research into industry documents and events. Inspired by the catastrophe modelling approach currently used by the industry, and after identifying shortcomings in existing catastrophe models, we developed the Eco:Actuary Policy Support System. Catastrophe models are used by the (re)insurance industry to calculate the likelihood and severity of potential future natural hazards by considering the hazard itself, the vulnerability of assets to the hazard and an estimation of the financial losses caused by the hazard. The natural hazards covered by cat models include earthquakes, tropical cyclones, windstorms and floods (coastal, pluvial and fluvial).

The main strengths of catastrophe modelling are the detailed asset and insurance datasets (for modeled areas only) which allows a thorough assessment of asset exposure and vulnerability. However, not all parts of the world are covered by existing cat models, and the regions covered depend on the hazard. The regions and the resolution of coverage are decided based on numerous factors including the demand for insurance. This leaves much of the globe without robust assessments of both natural hazard risk and the assets vulnerable to such hazards. Furthermore, as cat models are proprietary black box systems there is very little information available about their assumptions and methods, which makes it difficult to evaluate the accuracy of the models. Indeed, the level of uncertainty in cat models is acknowledged to be high, particularly so for flood models (LMA 2013, Sampson et al. 2014, LMA 2017). Due to the differences in model construction, assumptions and data, comparing risk between different sites and different models is difficult. Finally, the fees payable to access these models limit the accessibility of these tools for less affluent users. There is a move within the industry, and pressure from outside the industry, to address some of these limitations of cat models. Notably the OASIS Loss Modelling Framework, a not-for-profit owned by members of the (re)insurance industry, aims to increase the transparency and collaboration within the industry (Arthur 2017). The Geneva Association think tank has called for more global coverage of cat models, enhanced transparency with regard to assumptions and uncertainty, incorporation of climate change science in cat models and scenario generation (Golnaraghi et al. 2018).



Flooding, and in particular inland flooding, is the most difficult of all the hazards to accurately model and predict due to the complexity of the processes and the way they interact (pers. comms, Oasis LMF 2019). A basic method to assess flood risk is through the use of static global flood maps showing the footprints of floods with different return intervals; i.e. Swiss Re's CatNet, Munich Re's NATHAN, FM Global Flood Map or Lloyd's City Risk Index. For a more thorough assessment, a cat model must be used. Unfortunately there is very little flood modelling capability outside of Europe, the USA and a few select other countries. Five companies produce flood cat models and only for select regions of the world: RMS (UK, Europe, USA, India, Philippines), AIR (Austria & Czech Republic, Japan), CoreLogic (Europe, USA), JBA (UK, Europe, Sierra Leone, Sri Lanka, Malaysia, Thailand, Vietnam) and AON (USA). The resolution and coverage across these models varies dramatically depending on the model and the study region. For example, the resolution varies from 2m in RMS' UK model to 125m in AIR's Japan model; and, the model does not always cover the entire country, as only selected cities may be covered eg. JBA's model in Sierra Leone only covers three cities.

There are two main types of modelling approach used in cat models; scenario and stochastic (Rimkus et al 2016). The former is a simple form of modelling which predicts the footprint of a specific flood event based on terrain height. In contrast stochastic models simulate many thousands of plausible events to create a probability based flood footprint, calculated from either return period-flow relationships based on observed flood data, or rainfall-runoff modelling based on historical rainfall. All other variables being equal, the accuracy of flood risk prediction is expected to increase as the spatial resolution of the model increases because the model better represents localised variation in elevation, and flood risk is highly dependent on elevation (Rimkus et al 2016). However, Sampson et al. (2014) found that flood maps are highly sensitive to the rainfall inputs; so the limiting variable preventing accurate flood prediction may be the model's ability to accurately simulate rainfall rather than elevation. Currently within cat models there is some capacity for modelling flood defences, but this functionality requires improvement and the inclusion of the role of other grey infrastructure (e.g. dams, reservoirs) (Oasis LMF 2019). There is no modelling of flood storage in the current models (pers. comms).

Based on our assessment of cat modelling we identified that both the (re)insurance industry and wider society would benefit from an improved flood model. Eco:Actuary is a global probabilistic fully distributed hydrological model that is capable of modelling the ability of landscapes to store water through natural (i.e. green) or human-made (i.e. grey) infrastructure. Another element of Eco:Actuary currently missing in cat models and desired (Oasis LMF 2019) is the ability for the user to easily change input data and to run scenario analyses. Currently the inputs to cat models



are only changed during major model updates which happen every few years (pers. comms). This means that changes to the climate, asset distribution and landscape in the intervening years are not taken into the assessment of flood risk. Scenario analysis allows the user to conduct sensitivity analyses as well as explore how changes to land-use or climate, or the presence of green and/or grey infrastructure may affect flood risk. The ability of the user to quickly create flood maps on demand based on user-defined parameters and conditions provides the user with more control and allows them to use the model to make decisions. This focus on risk mitigation and user empowerment are ways in which Eco:Actuary diverges from the currently available-flood risk tools of the (re)insurance industry. The ability of Eco:Actuary to run climate change scenarios, as well as alter flood parameters, as well as add/remove green and grey infrastructure, is a considerable contribution to cat modelling functionality. Although there is little remit at the moment for the UK (re)insurance industry to become directly involved in evaluating or providing hazard mitigation, the policy situation may change in the future. Currently in the UK, the government has the responsibility to build and maintain flood defences. However, the flood risk in some areas of the UK has become untenable for insurers, and insurance premiums unaffordable to consumers, and in response *Flood Re* has been launched. Flood Re is a joint initiative between the government and the insurance industry to act as a reinsurance scheme for residential properties at extremely high risk of flood, until the time when flood risk can be mitigated and/or there are sufficient data to predict flood risk more accurately. It is acknowledged that for the highest risk areas, insurance in the open-market will never be a solution: in these instances, relocation or compulsory insurance are more likely options (Bord, 2018). As the climate changes, flood risk may become too great, necessitating a greater alignment between the government and the insurance industry, as currently occurs in some other European countries. Although the role of cat modelling in flood risk mitigation has yet to be fully recognised, this is not the case for climate change mitigation (Golnaraghi et al. 2018). With growing support behind the Financial Stability Board's *Task Force on Climate-related Financial Disclosures (TCFD)* on the risks and opportunities presented by climate change, Eco:Actuary could be an important tool for assessing how the vulnerability of assets to flood risk may change in the future.

For the vulnerability and financial components of cat models, the insurance industry requires detailed information on asset vulnerability including information on claims history, individual building characteristics as well as the impact of various insurance coverage terms. Eco:Actuary has the capability to do a basic vulnerability assessment, but this functionality is not sufficient for industry assessment and pricing requirements (pers. comms) - and is not intended for this. A more detailed assessment is not possible with Eco:Actuary given its global reach, open-source



ethos and inability to access proprietary industry datasets. Within Eco:Actuary there is a damage function table which allows the user to define damage levels according to hazard intensity (flood height) for each asset class. This means that those users that have access to such data are able to populate the table with accurate figures for the study region.

The typical outputs of a cat model are average annual loss and the annual probability of occurrence: flood risk is typically expressed as return intervals (i.e. 1 in 200 year flood, 1 in 100 year flood). Eco:Actuary produces different outputs as it presents outputs spatially, in the form of maps.. For any given location specific values can be extracted from the maps: such as, the monetary value of assets at risk of flooding at any location. An advantage of displaying results in map form is that it is an accessible tool to communicate risk to a wide variety of stakeholders. The greatest contribution Eco:Actuary provides specifically to the (re)insurance industry are the global flood modelling capabilities and scenario analysis. There will however be numerous beneficiaries beyond insurance, as everyone will benefit from the model being open-access.

Eco:Actuary PSS Methods

Pre-calculation

The model first calculates the necessary derivatives of the 148 input maps including flow networks, catchments, topographic exposure. **Read parameters:** The catastrophe model parameters set at the *Prepare data* step are read. **Initial conditions** for key variables are set based on the 148 input maps. **Asset values** are calculated per pixel for each of 19 asset types as full replacement cost (FRP) and loss of function (LOF) cost (based on different loss of function periods and a loss of function fractions that vary with hazard type). Function *i.e.* business interruption is defined according to underlying GDP in the area of the asset. First, the frequency of each asset in each pixel is calculated.

Replacement values are calculated by scaling the min and max asset values in the study area by brightness of nighttime lights, multiplying by area and the fraction of all assets represented by this class. For cropland and pasture, agricultural suitability are used instead of nighttime lights and mapped crop or pasture fraction used instead of OSM tag frequency

Loss of function values are calculated as GDP multiplied by the per-asset-class LOF fraction and period and the fraction of all assets represented by that asset class. For cropland and pasture crop or pasture fraction are used instead of OSM tag frequency.

Asset type counts and per-pixel least and most valuable asset class for replacement value and loss of function value are written as maps. **Floodplains** are mapped topographically as low-lying areas next to rivers. Per-pixel asset values are calculated on these floodplains. A map of asset



values on **floodplains downstream** of each pixel is calculated as a measure of assets vulnerable to runoff from the pixel.

Generating rainfall events: The number of events requested is generated probabilistically from the parameters specified for the Pareto distribution. These exact events are used for every run of the baseline and for any scenario in which the Pareto distribution parameters do not change. Two independent series are generated: a series of rainfall intensities and a series of rainfall depths. The model now iterates for the set number of events with each event representing an event during a month of the year that is independent of all other iterations. Events are individual storm intensities (for infiltration excess) and monthly rainfall totals (for saturation excess)

During the first iteration

Data initialisation: monthly climate data are read for wind speed, direction and sea level pressure. Interpolated monthly rainfall are then corrected to produce wind-driven rain. Annual rainfall is calculated and each month of rain expressed as a fraction of the annual. A maximum potential infiltration rate is calculated from global permeability data, opportunity time, enhancement by tree cover and diminution by impermeable surfaces

Distribution of per-pixel, per-month mean(normal) potential infiltration excess: is calculated on the basis of soil, thickness (porosity), opportunity time (according to slope gradient), and rainfall normals, with infiltration decaying as the store fills. Soil thickness is calculated using a terrain accumulation index and set to zero for impermeable surfaces (roads,urban,bare,water). The number of rain days per month is calculated from annual rain days and monthly rainfall. Infiltration excess is then the rain per rain day minus the infiltration for each month of each event. This potential is cumulated down the flow networks.

Distribution of per-pixel, per month mean(normal) potential saturation excess: is calculated as difference between monthly rainfall and monthly soil saturation after infiltration. This potential is cumulated down the flow networks.

Flood mitigation by green infrastructure: is calculated by estimating the volume of each store in each pixel for soil, water bodies, wetlands, floodplains and canopies (using the WaterWorld algorithms published [here](#)) and depending on the input maps representing these systems and the depth parameters set at the *Prepare data* step.

- Soil storage capacity depends upon soil depth, soil organic matter/infiltrability (tree cover) and cover of impermeable surfaces,
- Canopy storage depends on tree cover and event size (since canopy drains by evaporation to the atmosphere after each event - i.e. is refillable without draining to rivers),



- All other stores are calculated according to aerial extent and the depth parameters set
- All stores are cumulated downstream to be comparable with accumulated runoff

For each iteration

Spatial rainfall events: For each simulated event two consistent (the same for the same iteration, baseline and scenario) random numbers between 0 and 1 are chosen. If the normalised monthly rainfall normal for a pixel is greater than the minimum and less than the maximum of these a rainfall event is supposed for that pixel. This way the spatial distribution of events is consistent with the spatial pattern of rainfall magnitudes in the mapped climatology.

Potential Flood Risk (before storage):

- **For each pixel in which it is raining** an intensity (mm/hr) and depth of rainfall (volume) is assigned from the *Pareto* distribution in proportion to the monthly rainfall **for that month**
- **Event potential infiltration** is calculated on the basis of the soil thickness, infiltration rate and decay considering a probabilistic antecedent soil moisture content
- **Event potential runoff from infiltration excess** is cumulated downstream on the basis of the per pixel intensity of the event relative to the per-pixel potential infiltration
- **Event potential infiltration excess flood ratio** is calculated as the infiltration excess for that runoff event versus the infiltration excess for the baseline monthly **runoff** for that month
- **Event potential runoff from saturation excess** is cumulated downstream on the basis of the per pixel volume of the event versus the baseline monthly potential infiltration at a probabilistically derived soil saturation
- **Event potential saturation excess flood ratio** is calculated as the excess for that runoff event versus the saturation excess for the baseline monthly **runoff** for that month
- The flood ratios are summed and (where >1) counted in order to derive all-event summaries

Realised Flood Risk (after storage):

- Uptake by green canopy stores is calculated on the basis of the store volume in relation to the event volume and by the store volume intensity equivalent in relation to the event intensity
- Runoff, net of this uptake, (on the basis of the intensity event and separately of the volume event) is calculated. Maximum potential runoff is the maximum of these two in



a given pixel.

- The combined saturation and infiltration excess ratios are used to determine the state of the land stores (*i.e.* fraction full). A high ratio means more full.
- Realised runoff is thus the runoff after accounting for canopy stores and minus the remaining capacity in the land stores
- The flood ratios are summed and (where >1) counted in order to derive all-event summaries

After the final iteration

Influential storage is calculated as the percentage green storage per unit runoff and percentage runoff per unit green storage, locally and downstream. Influential storage thus takes account of the volume of runoff that needs to be stored (managed) by the storage in question. Asset values per unit total storage and green (canopy, wetland, soil) storage, both locally and downstream, are also calculated as well as per-unit of influential storage and of green storage

Damage costs

Damage costs are calculated in a similar way to asset values on a per-pixel, per-asset-class basis. They are calculated against *full replacement value* and *loss of function value*. For *full replacement value* the loss is the proportion of the value for each asset class lost according to the flood ratio conditions in the pixel of interest and the damage function loss fraction at that flood ratio. For *loss of function value* different damage function loss fractions are specified by the user. Losses are summed across all asset classes in each pixel to arrive at total losses locally. The asset with greatest and least damage in each pixel is calculated for both replacement costs and loss of function costs. Finally, losses on floodplains and on floodplains downstream are calculated.

Training for the Eco:Actuary Policy Support System is available here:

<http://www.policysupport.org/ecoactuary>



Applications of the Eco:Actuary toolkit within NAIAD

NFM Effectiveness assessment

The Eco:Actuary Investment planner: scaling NFM investments for flood risk reduction

Description of tool

As part of a green Infrastructure planning process, it is imperative to know the capacity of the green infrastructure under consideration in order to ensure that it is large enough to mitigate the levels of peak flow at the asset at risk. This assessment is built into the design process for grey infrastructure which is built to an exact specification, however the capacity of nature-based solutions (NFM) are often more difficult to assess in a complex and changing landscape. The impact of NFM is also difficult to assess because of the rapid decay in influence downstream of the interventions, which are usually individually small stores. The NFM needs to be close upstream to the assets at risk and large enough to store significant volumes of the observed peak flow in order to make an impact on them, as discussed in D6.2 where the rapid downstream decay of hydrological influence of Lake Neusiedl, a large shallow lake in Danube basin 315 km² in area, was modelled using WaterWorld. Individual NFMs tend to have only a small impact on flood hazard mitigation, and therefore a large number may be needed. This tool is therefore designed to address the issues of how large combined storage interventions need to be in order to achieve a target reduction in flood peak downstream for a gauged catchment, -- and how much this volume of storage might cost. The tool takes no account of how the placement of NFM in specific catchment positions can make a difference: a spatial model like the Eco:Actuary PSS is necessary for that. The Eco:Actuary PSS can be used as a second step as a spatial tool to assess where in the landscape to place the intervention to be most cost-effective.

Application of EIP to Thames tributaries

The UK version of the EIP has been applied to Thames tributaries. We used the EIP to define costs and options for 15% mitigation of flood peaks in some of the tributaries of the Thames. The aim of this exercise was to assess how the best investment options vary with size of catchment and flow characteristics. Figure 10 shows the results for three areas where relatively large volumes of extra storage are needed and four where smaller volumes are needed.

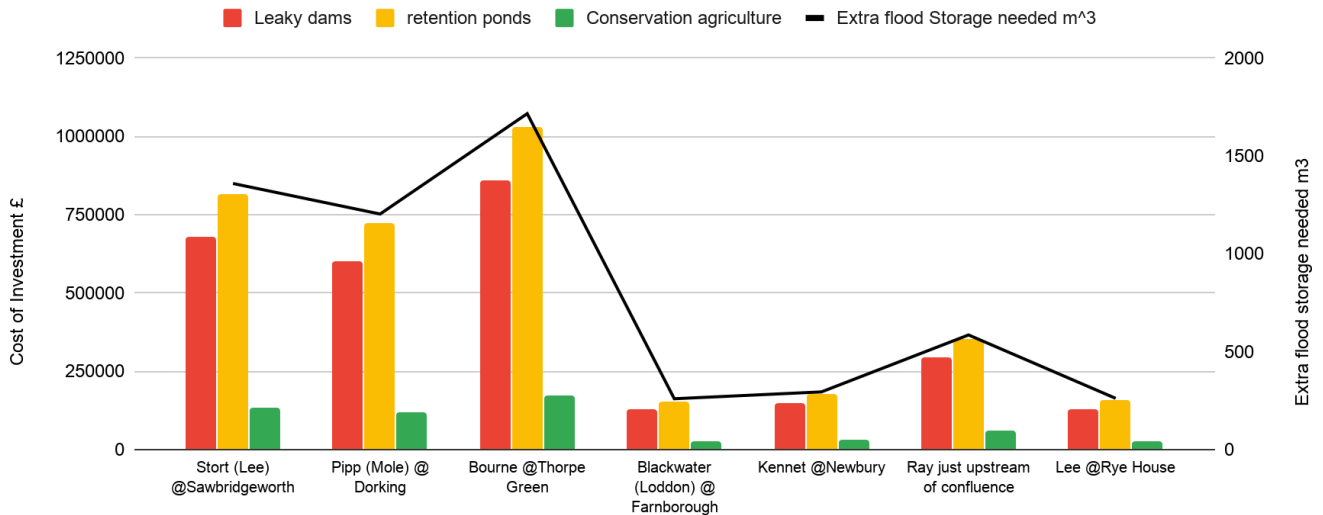


Figure 10 Estimates of extra storage and NFM investment options.

Here we assume 10% flow reduction target, cost per m³ leaky dams £500, CA £100, retention ponds £600. River names in brackets show the main watercourse downstream that flows to Thames. These prices reflect the investment involved per unit of storage for each of the storage types. Leaky dams and retention ponds require active engineering and store relatively little, conservation agriculture is more passive and can store much larger volumes in total since it can be applied over a much larger area.

The results show that each river requires a different volume of flood storage in order to mitigate peak flows by the required 15%. The costs of achieving this vary by intervention type and river at less than £250K for the Lee but up to £1million for the Bourne, depending on their different flow conditions. For the same extra volume of flood storage the most cost efficient method in all cases is Conservation Agriculture, where no tillage means that the natural structure of the soil is restored, there is more capacity within the soil to store rainwater, and runoff is reduced. Leaky dams and retention ponds are more expensive, and this differential is most marked for larger flood storage schemes. We can conclude that for all scales of investment, Conservation Agriculture has the greatest beneficial impact for cost. Conservation Agriculture has other co-benefits such as reduced farm fuel costs and improved soil biodiversity.

The EIP can be applied anywhere globally to quickly assess relative costs of different investment solutions even for small rivers, but demands historical peak flow data which can be sourced from



national hydro-meteorological services. Other DEMOs were encouraged to use the tool at the launch at the NAIAD session of the ECCA 2019 Lisbon Conference presentation “Nature-based climate change adaptation: open access tools for NBS investment strategy and effectiveness assessment” and again when presented at the following NAIAD internal general meeting in Copenhagen. The Slovenia DEMO was interested in the application of the tool, however there are no water level monitoring data for the Brdnikova reservoir, as confirmed by the Municipality of Ljubljana, hence the DEMO’s interest in installing a FreeStation water level sensor in Ljubljana.

Eco:Actuary://SmartRiver: real time understanding of contributions of NFM to flood risk reduction in the Thames using FreeStation

Introduction

Models can be used for large scale Natural Flood Management (NFM) strategy, but measurement is most appropriate for assessment of *in situ* NFM effectiveness because of the scale and nature of NFM and the cost of data for modelling at these scales (Burgess-Gamble et al, 2017). To date, much of the evidence regarding the impact of NFM interventions (e.g. leaky woody dams) is modelled rather than observed and there is therefore little information on the performance, longevity, and operation and maintenance of such structures to be able to effectively cost these (Burgess-Gamble et al., 2017; Dadson et al., 2017).

To address this gap, NAIAD has developed the //Smart: system for monitoring the effectiveness of specific in-place NFM accurately at low cost and with ease. The //Smart:River and //Smart:Soil systems (described in Methods) consists of a series of web connected sensors designed to monitor NFM effectiveness to assess the contribution of NFM to mitigate flooding in rivers throughout the southeast and midlands of the UK, monitoring the effectiveness of leaky dams, beaver dams, conservation agriculture, wetlands and retention ponds in reducing downstream flood peaks.

Monitoring the effectiveness of leaky dams

Leaky dams have gained considerable interest in the last few years. In particular, in the UK where they are being promoted by government and non-government organisations such as the Environment Agency, Woodland trusts and rivers trusts as low cost solutions to slow down flows and reducing flood risk without the need for further hard engineering or traditional flood defences. Leaky woody dams typically only cost between £175-£500 to install (Burgess-Gamble et al., 2017). They do need managing but the structures can be replaced or reinforced during



normal woodland or farm management practises using on site or nearby materials (Short et al., 2019).

Field sites

Under the NAIAD project, a total of 23 smart river monitoring stations have been installed at 8 sites in the UK throughout 2018 and 2019 to monitor the effectiveness of leaky dams. GPS and laser surveys were carried out to assess the dimensions of stream channels in order to calculate the potential volume of water that can be retained behind the leaky dams. For two monitoring sites in the Thames basin, results are described below. Since many of these stations have only been installed recently, data records are still very short therefore these results should be considered early results.

Brent river (Thames)

Thames21 has been funded by DEFRA to install, with the aid of volunteers and the local warden, two leaky dams in the upper part of the Silk Stream catchment of the River Brent at Stanmore Country Park. The water level behind one of these dams was monitored from June 2019. The storage volume behind the dam was calculated by interpolating laser survey points and creating a 3-D profile up to a natural higher point upstream in the channel. Figure 11 shows the water level sensor and the profile of the stream behind the dam.

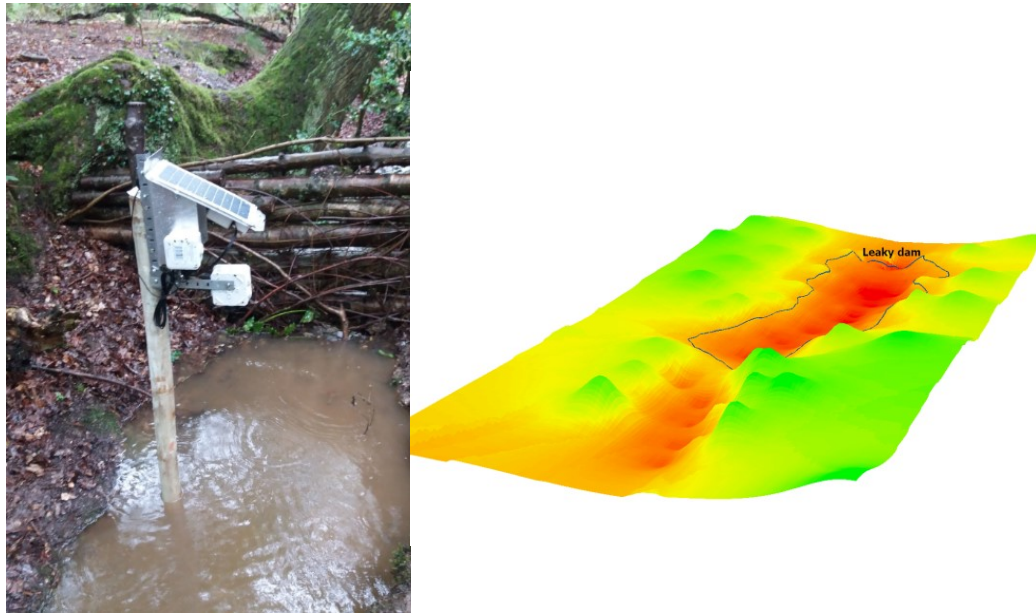


Figure 11 Leaky dam and water level sensor (left) and channel profile for Stanmore country park site

Figure 12 shows the water level upstream of the dam measured by the water level sensor for a week in June 2019 where water levels had a fluctuation of 8 cm. Using the *calculate volume* function on the //Smart: web interface with the measured surface area of 35 m² of the instream storage, the storage volume of water behind the dam was calculated. The volumetric storage during the rising limbs is critical to flood peak reduction and this is what is shown in figure 13 for the same week. During this period, the dam captured just over 8 m³ of water. As a leaky dam, this volume is likely greater than below the dam and should be assessed in relation to the volumes at the asset at risk downstream.

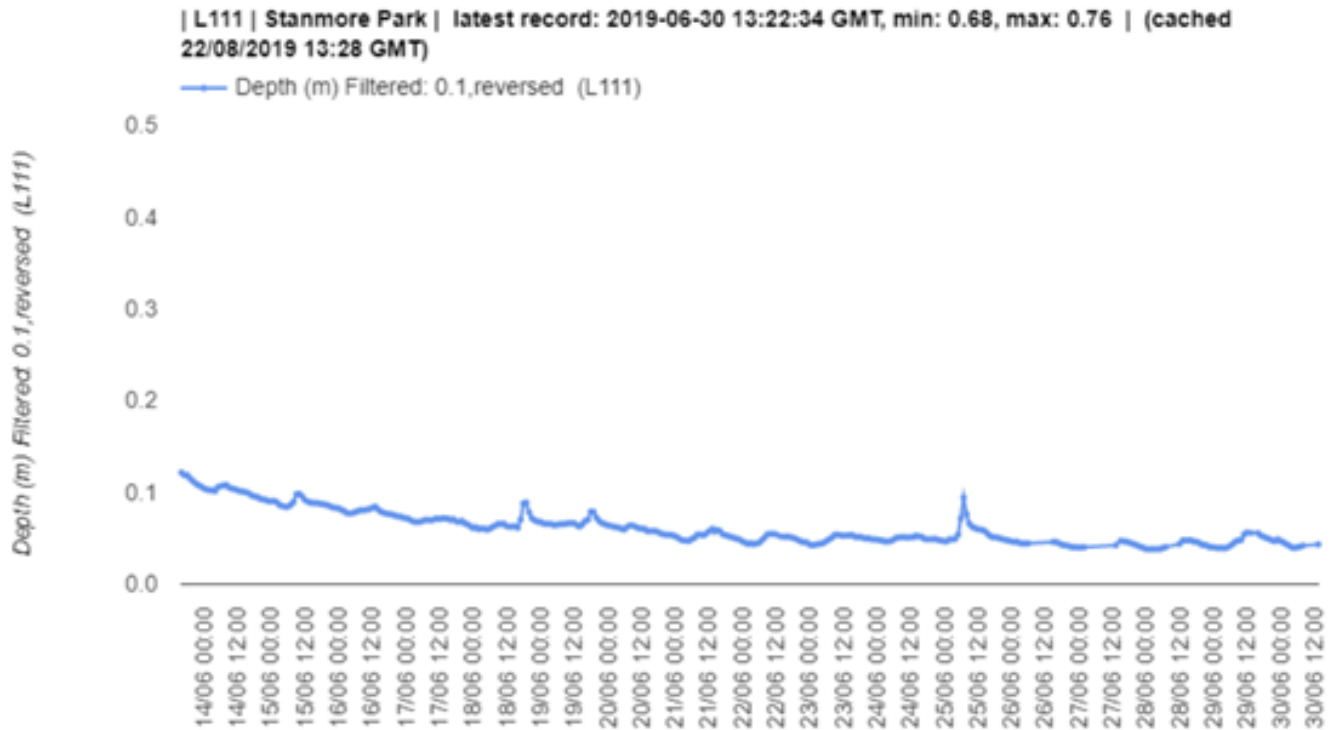


Figure 12 water level upstream of the dam at Stanmore park for a week in June 2019

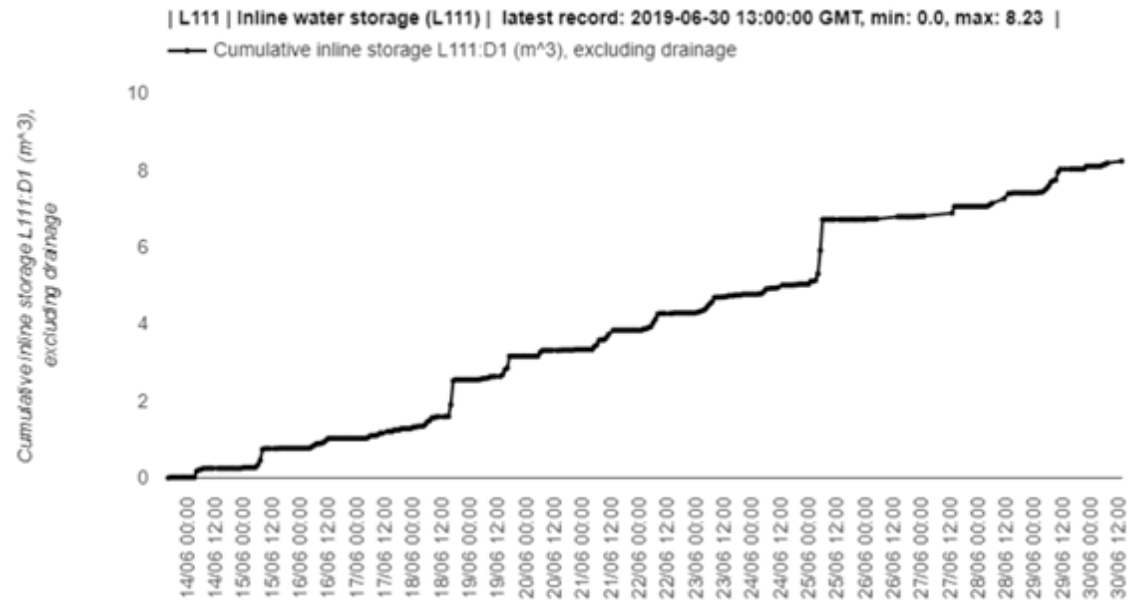


Figure 13 Inline cumulative water storage behind dam at Stanmore park for a week in June 2019. Calculated by //Smart:River

Salmons Brook (Thames)

Parts of the borough of Enfield, north London, have suffered from severe flooding. The Salmons Brook Flood Alleviation Scheme was completed in 2006 at a cost of £15.3 million and protects more than 2500 homes. However, some areas still remain at risk, and so Thames21, funded by DEFRA and in collaboration with the London Borough of Enfield Council, have constructed two leaky dams, with the aid of local volunteers, to slow the flow of Merryhills Brook. Flow levels above one of these leaky dams were monitored for the month of June 2019. Figure 14 shows the water level sensor and the profile of the stream behind the dam. Water enters the channel through a culvert under a concrete dam.

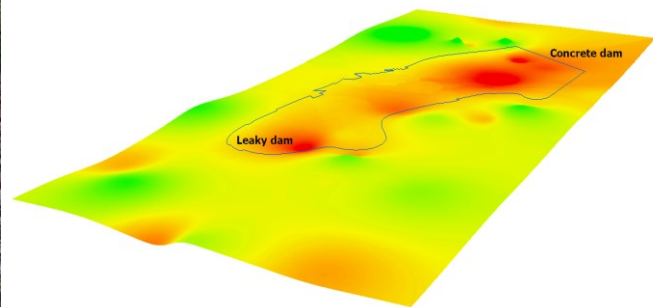


Figure 14 Water level sensor in stream channel and stream profile for Salmon's brook catchment, London

Figure 15 shows the water level upstream of the dam measured by the water level sensor for a week in June 2019 where water levels fluctuated 5.2 cm. Using the *calculate volume* function on the //Smart: web interface with the measured surface area of the instream storage, the storage volume of water behind the dam was calculated. The volumetric storage during the rising limbs is shown in figure 16 for the same week. During this period, the dam captured just over 30 m³ of water.

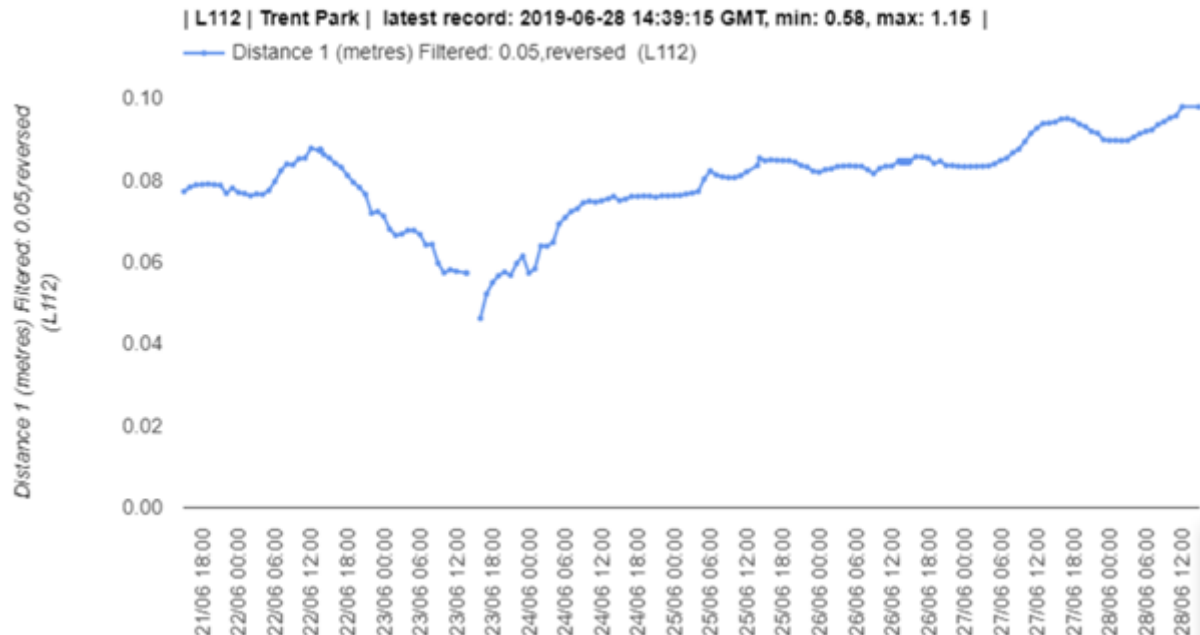


Figure 15 Water level upstream of dam at Trent park for a week in June 2019

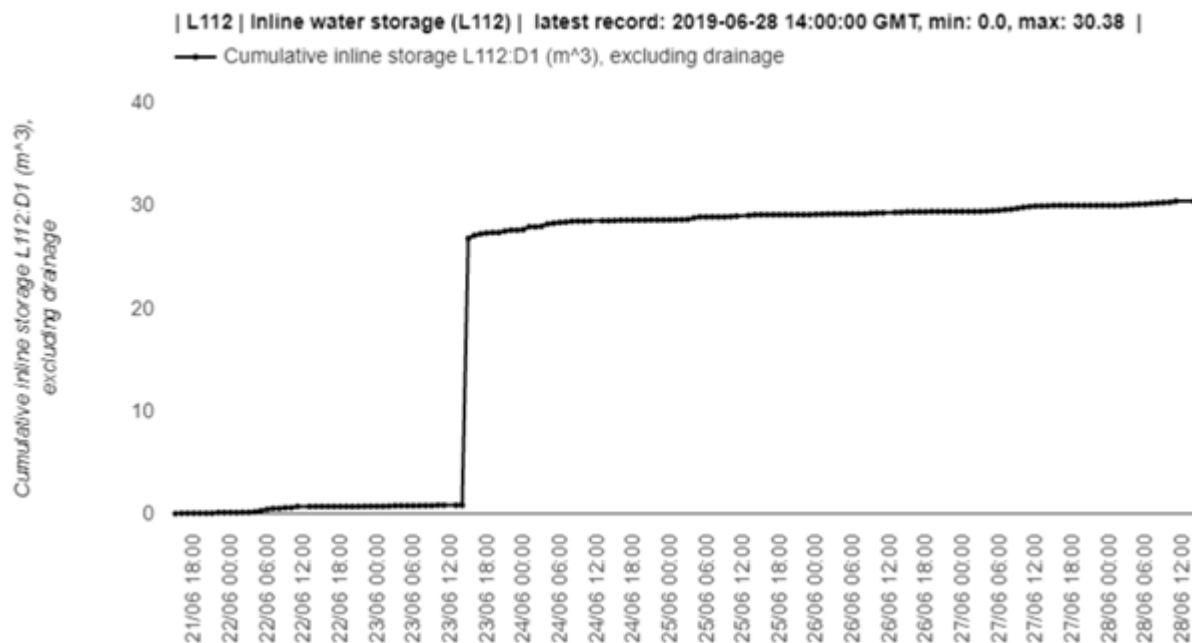


Figure 16 Inline cumulative water storage behind dam at Trent park for a week in June 2019. Calculated by //Smart:River.



Blackwater

Spains Hall Estate includes two tributaries on the Blackwater river upstream of Finchingfield, a village prone to flooding of roads and properties. Spains Hall, in partnership with the Environment Agency and DEFRA have installed one tributary with a series of leaky dams which allow floodwater onto water meadows to be slowly released after rainfall. Water level sensors and soil moisture sensors were installed above and below one of the dams and in the water meadow, to assess the operation of the dams and their contribution to mitigate the flooding downstream. The other tributary has an enclosure for recently introduced Eurasian beavers who have built leaky dams. To monitor the effectiveness of these, a water level gauge upstream of the dams, just inside the enclosure, and one downstream of the enclosure were installed. A third water level gauge just above the village downstream of the confluence of these two tributaries was installed to measure the flow behaviour at the location of flood risk in relation to the volume retained by the Natural Flood Management interventions upstream. The dam and sensors are shown in figure 17.



Figure 17 Leaky dam at Spains hall estate on Blackwater river with upstream and downstream water level sensors



To understand the storage and drainage dynamics of this leaky dam, the upstream (L93) and downstream (L48) water levels are plotted for a day in July 2019 following a rainfall event (figure 18,top). The blue line represents the upstream water level and black is the downstream level. Flows are very low and thus there is little impact from the leaky dam. However, the rate of change in stage upstream of the dam is higher during the rising limb event (figure 18,bottom) indicating water being held back by the dam.

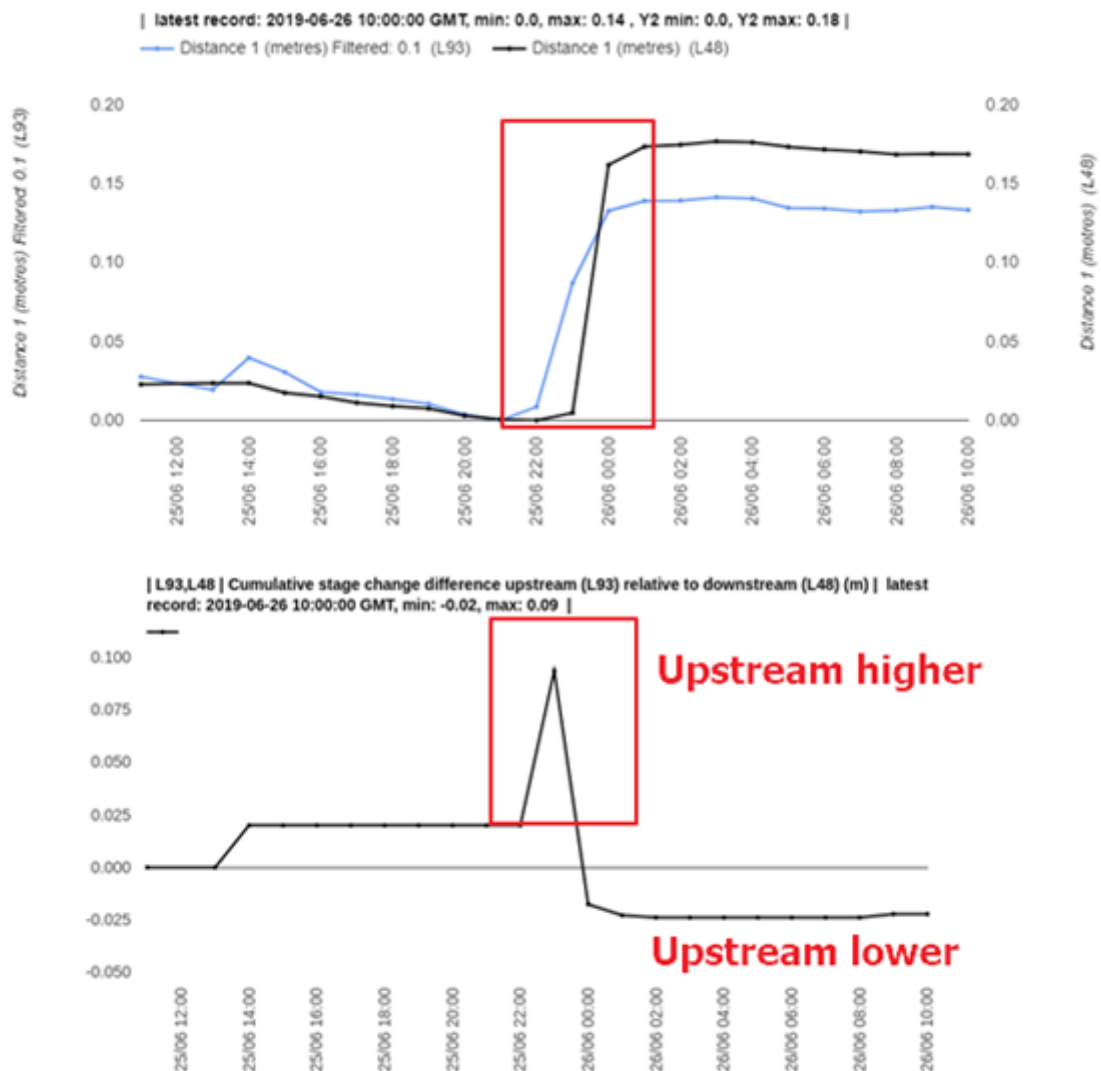




Figure 18 top: water level upstream and downstream of leaky dam for a day in June 2019 at Spains hall estate. Bottom: cumulative difference in stage between upstream and downstream of leaky dam for the same period.

Monitoring the effectiveness of retention ponds

Retention ponds tend to be slightly more expensive NFM solution compared to leaky dams but they are low in maintenance. They do however take up valuable land, for instance in the case of farm ponds taking out land suitable for agricultural production. Retention ponds on farms tend to encourage waterlogging in nearby field areas as water is backed up by them. A co-benefit of retention ponds, in particular larger ones is that they support aquatic biodiversity.

To monitor the effectiveness of retention ponds at sites in the UK, water level and soil moisture sensors were installed at different types of retention ponds, a small farm retention pond in an agricultural field in the catchment of the river Stour and a large retention pond at the bottom of a catchment close to the town of Dorking near the Mole river which is a tributary of the Thames.

Mole river (Thames)

As part of the Dorking Flood Alleviation Scheme, Unum, an insurance company, in partnership with the Environment Agency, maintain an online flood retention pond upstream of the town of Dorking, where the Pipp Brook recently flooded factories and properties. The Pipp brook drains an area of around 20km² and includes the town of Dorking and village of Westcott. The Pipp Brook is a tributary of the River Mole. A 2015 study carried out by the EA, found that at present 112 residential and 19 commercial properties are at risk of fluvial flooding for 1% Annual Exceedance Probability (AEP) event. Of those, 102 residential properties and 12 commercial properties are at 'Significant' risk or 'Very Significant' risk of flooding (up to a 1 in 75 year event). Estimates of economic damages indicate up to £2,398k in Present Value (PV) whole life benefits could potentially be achieved by implementing a range of different flood risk reduction measures.

Water level sensors were installed in the retention pond (figure 19) and downstream near a Dorking factory where flooding has recently occurred. The Environment Agency are planning a series of additional leaky dams in the upstream catchment to further alleviate flooding in the near future.



Figure 19 retention pond on Pipp Brook

Proportion of flow at assets at risk

To assess the potential reduction in flow at assets at risk, the WaterWorld model was used to calculate the downstream influence of flow from the retention pond (figure 20). This is a metric of the proportion of flow that reaches the assets at risk downstream from the point in the stream that is monitored (in this case the retention pond). It shows, that if all water from the upstream catchment were held back by the storage pond, around 80 percent of the Pipp brook flow would be reduced at the asset at risk.

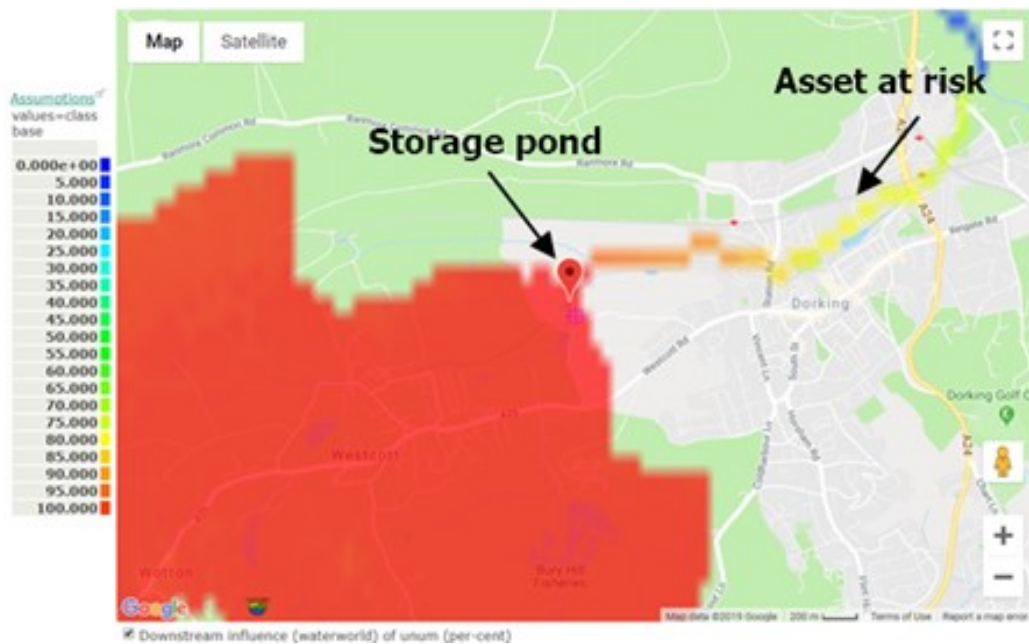


Figure 20 proportion of flow at assets at risk downstream of Pipp brook retention pond

Water levels

Figure 21 shows the retention pond water levels for a week in July 2019 and figure 22 shows the cumulative storage in the pond during that period based on an estimated surface area of the pond of 75 m². During this period, the pond captured over 164 m³ of water.

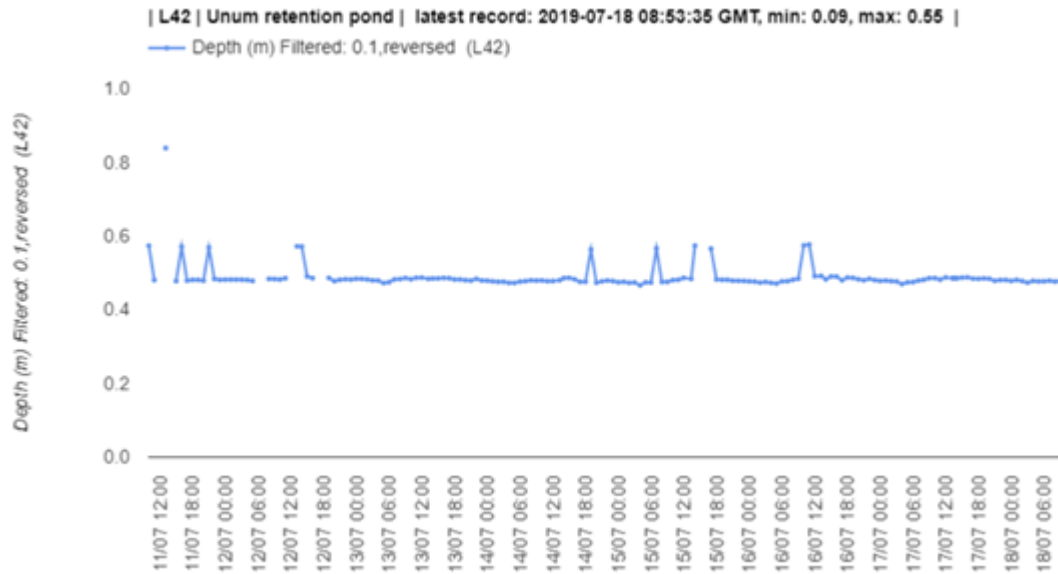


Figure 21 Water levels in retention pond during week in July 2019

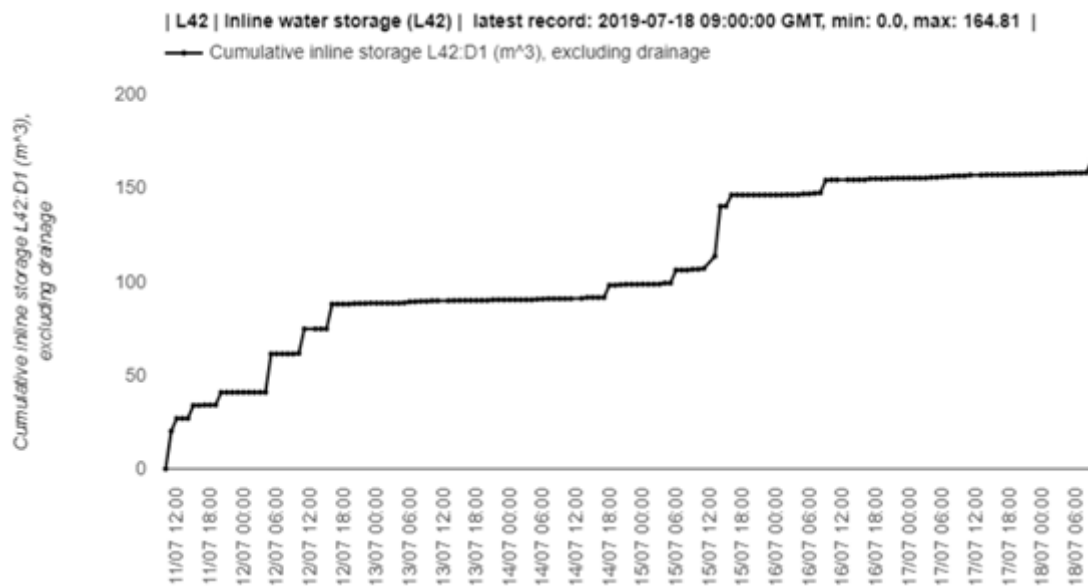


Figure 22 Cumulative water storage in retention pond at Dorking for a week in July 2019.
Calculated by //Smart:River



Stour river

SAFAG, the local Flood Action Group based in Shipston upon Stour is one of the UK's most prolific producers of Natural Flood Management. SAFAG have constructed hundreds of NFM interventions in the catchment above Shipston upon Stour and aim to complete 1000 NFM interventions in the next two years, if funding allows. One of the NFM interventions in the catchment is a retention pond (figure 23) where the fill and empty dynamics were monitored using a water level and soil moisture sensor.



Figure 23 Farm retention pond with drain in Stour river catchment with water level and soil moisture sensor.

Figure 24 (top) shows the water level and nearby rainfall in the retention pond and bottom figure shows the soil moisture for a week in July 2019. Both the water level and soil moisture respond to the rainfall with soil moisture returning to previous level about a day later (during this very hot period of the year) while water level in the retention pond remains high. Figure 25 shows the cumulative storage in the pond during that same week, storing a total volume of nearly 4.5 m³ of water over the pond surface area of 50 m². Given the very large increase in soil moisture, water storage in the soil was much higher however, storing around 6,000 m³ during this event based on a 1 ha area.

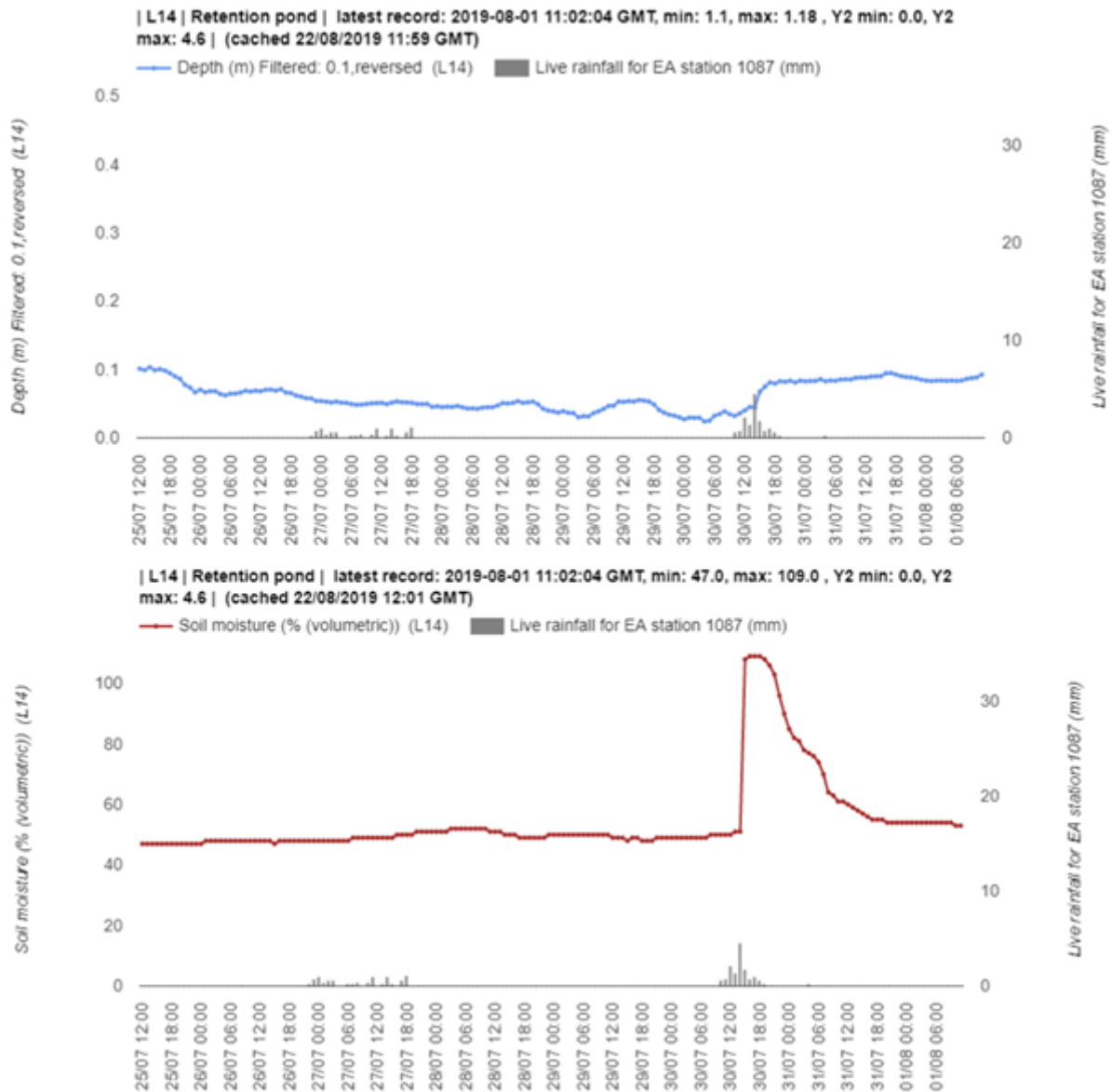


Figure 24 Top: Water level and nearby rainfall in the farm retention pond for a week in July 2019.
Bottom: Volumetric soil moisture of soil next to retention pond for the same week.

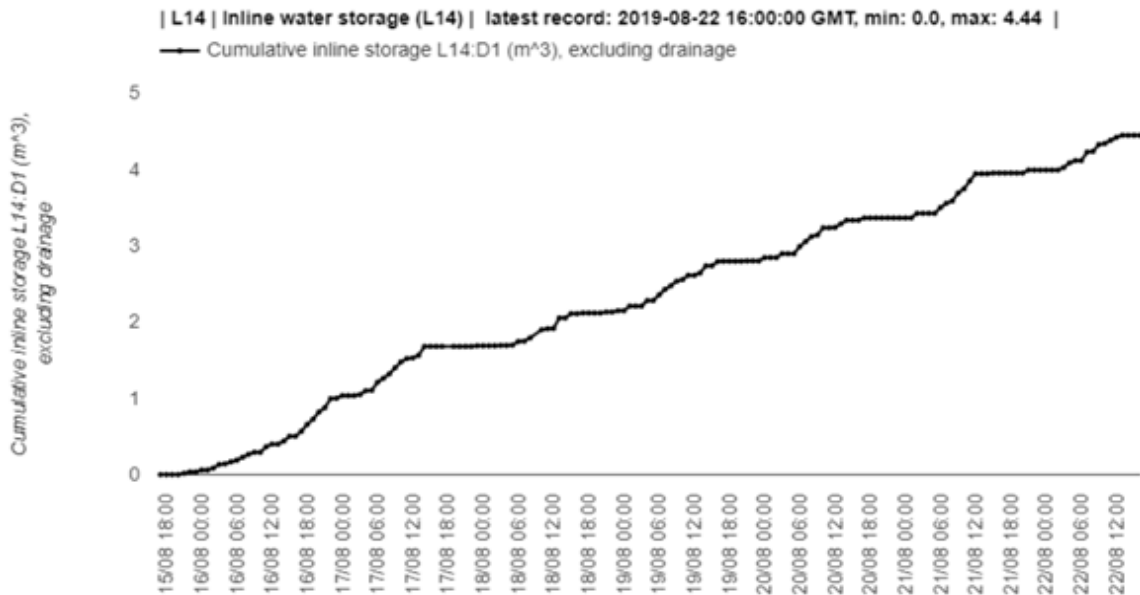


Figure 25 Cumulative water storage in farm retention pond in Stour catchment for a week in July 2019. Calculated by //Smart:River

Monitoring the effectiveness of conservation agriculture

Conservation agriculture (CA) is a non-point (areal) contribution to Natural Flood Management. It generally leads to a build-up of organic matter, improved soil condition, higher infiltration and drainage rates and as such it can help mitigate floods and increase dry season flows through more subsurface flow. Conservation agriculture also stores more (soil) carbon and hosts greater soil faunal abundances and biodiversity than fields under conventional agriculture (Hobbs et al., 2008).

To monitor the impact of conservation agriculture on overland flow generation and infiltration, soil moisture sensors were installed on fields under conservation agriculture and conventional tillage on four farms in the Thames and surrounding catchments to make sure that different soil types were reflected. At each site, soil samples were taken at different depths (0, 25, 50, 75cm) and tested in the KCL geography laboratory to assess the organic matter content and bulk densities. Lower bulk densities and higher organic matter content usually means that a soil has higher porosity and better water infiltration and retention and thus less surface runoff or quickflow. Early results for the monitoring on two farms are discussed below.



Hertfordshire (Thames)

This farm has been practising conservation agriculture for 9 years. Soil moisture sensors were installed on neighbouring fields, one under CA management and the other under non-CA management or conventional tillage. (figure 26). The two fields have the same soils, geology and climate.



Figure 26 Soil moisture monitoring station installed on non-CA field in Hertfordshire

Figure 27 shows the differences in bulk density and organic matter between the fields with the CA field showing lower bulk density and higher organic matter than the non-CA field and thus better water infiltration and retention.

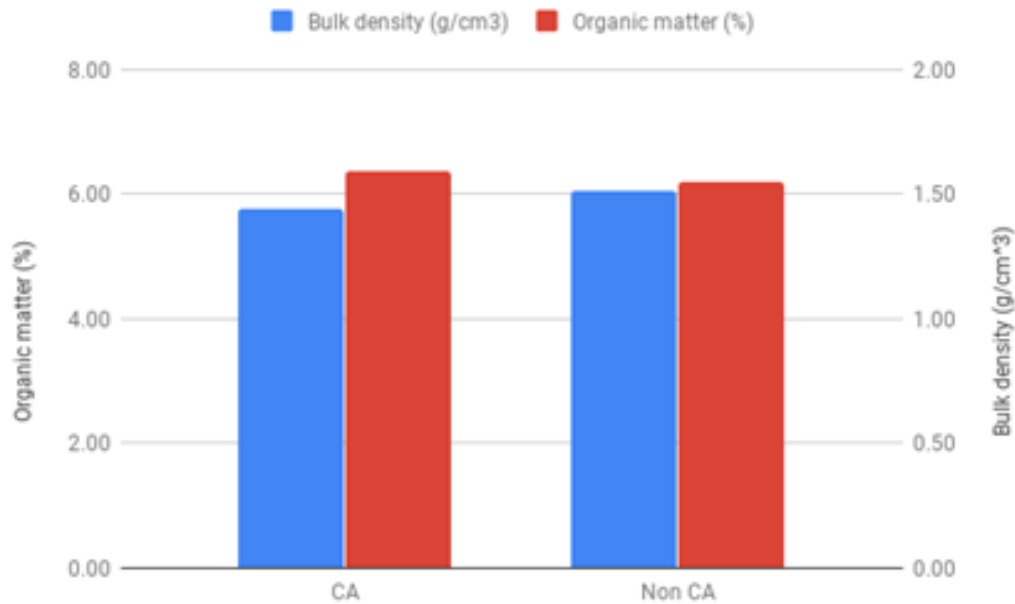


Figure 27 Bulk density and organic matter for field under CA management (left) and non-CA management (right).

Figure 28 shows the monitored response to a rainfall event (bars in bottom of graph) in the CA field (brown) and non-CA field (black) for a week in May 2019. Clearly, the CA field has much greater infiltration during rainfall whereas in the non-CA field (black) there is little infiltration and water ponding taking place which generates runoff. The CA field also drains more rapidly.

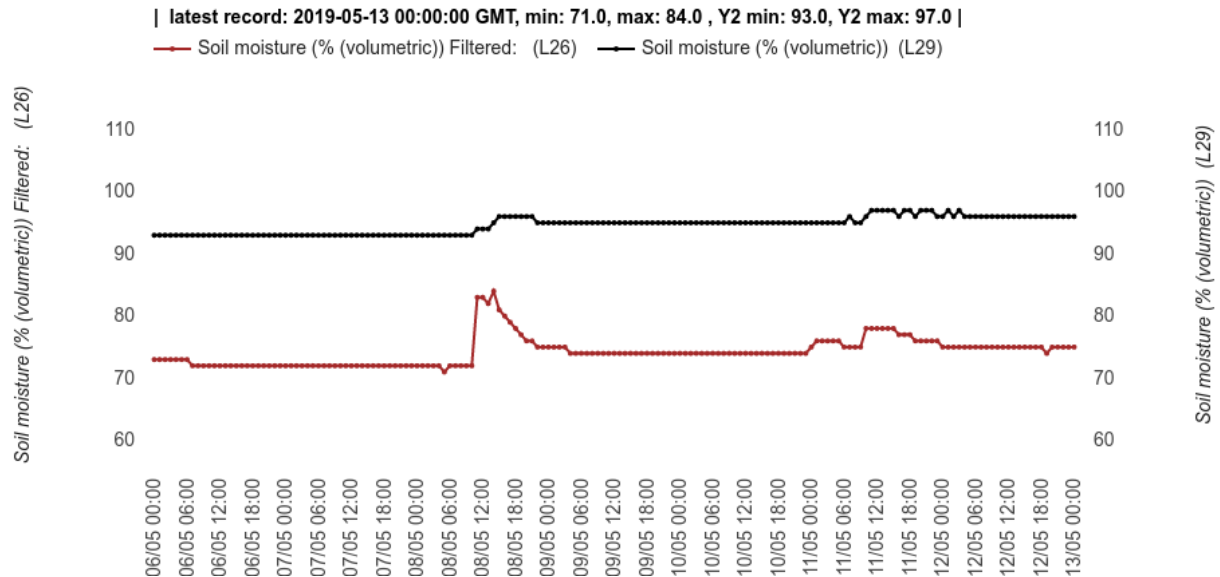


Figure 28 Measured soil moisture in the CA field (brown) and non-CA field (black) and measured nearby rainfall for a week in May 2019 at a farm in Hertfordshire, UK.

Suffolk (Great Ouse)

This farm has been practising conservation agriculture for 6 years. The two fields (CA and non CA) are next to each other and sit on identical slopes and on chalky boulder clay soil. The CA field (9.8ha) was last deep tilled in autumn 2013 (Figure 29). Since then it has been direct drilled with the exception of a very shallow cultivation in autumn 2017 to incorporate bio solids. The non-CA field (23.4 ha) has been in a normal non inversion heavy tillage programme for years. Both fields have received applications of bio solid and poultry manure since 2013. During the monitoring, both fields were planted with wheat crop which is harvested once a year. No cover crops have been grown on either field.



Figure 29 Soil moisture monitoring station installed on CA field in Suffolk

The results of the soil sampling (bulk density and organic matter) are shown in figure 30. Similar to the site in Hertfordshire, bulk density in the soil under CA management is lower while organic matter is higher than in the non-CA soil and thus likely better water infiltration and retention in this field.

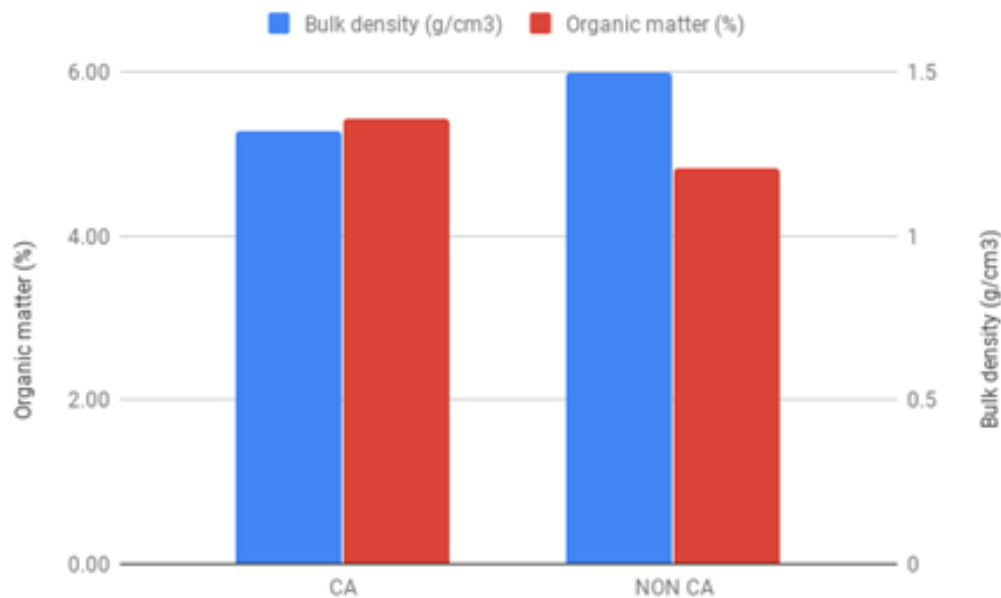


Figure 30 Bulk density and organic matter for field under CA management (left) and non-CA management (right).

Figure 31 (top) shows the soil moisture for the CA field (brown line) compared to the non CA soil (black line) for a period in July 2019. The CA soil has a much lower loss through evapotranspiration and drainage than the non CA soil so is capable of holding more moisture. Figure 31 (bottom) shows the cumulative additional storage in the CA field compared to the non CA field for the same period with a maximum of 0.02 Mm³ for this field of roughly 10 hectare.

To better understand the potential of this soil management intervention on reducing flood peaks downstream, the percentage flow reduction was calculated using the //Smart: web interface and setting a measured peak flow for the river Lark at Bury St Edmonds, around 10 miles downstream of the farm of 4 m³/s (based on Environment Agency data). The 10 hectare of land under CA would be capable of changing the flow of this river by a maximum of 1% over this period compared with the same land under conventional tillage. Increasing the area of soil under CA management would linearly increase this potential flow reduction, e.g. increasing this to 30 ha would result in a potential 3% reduction of peak flows downstream.

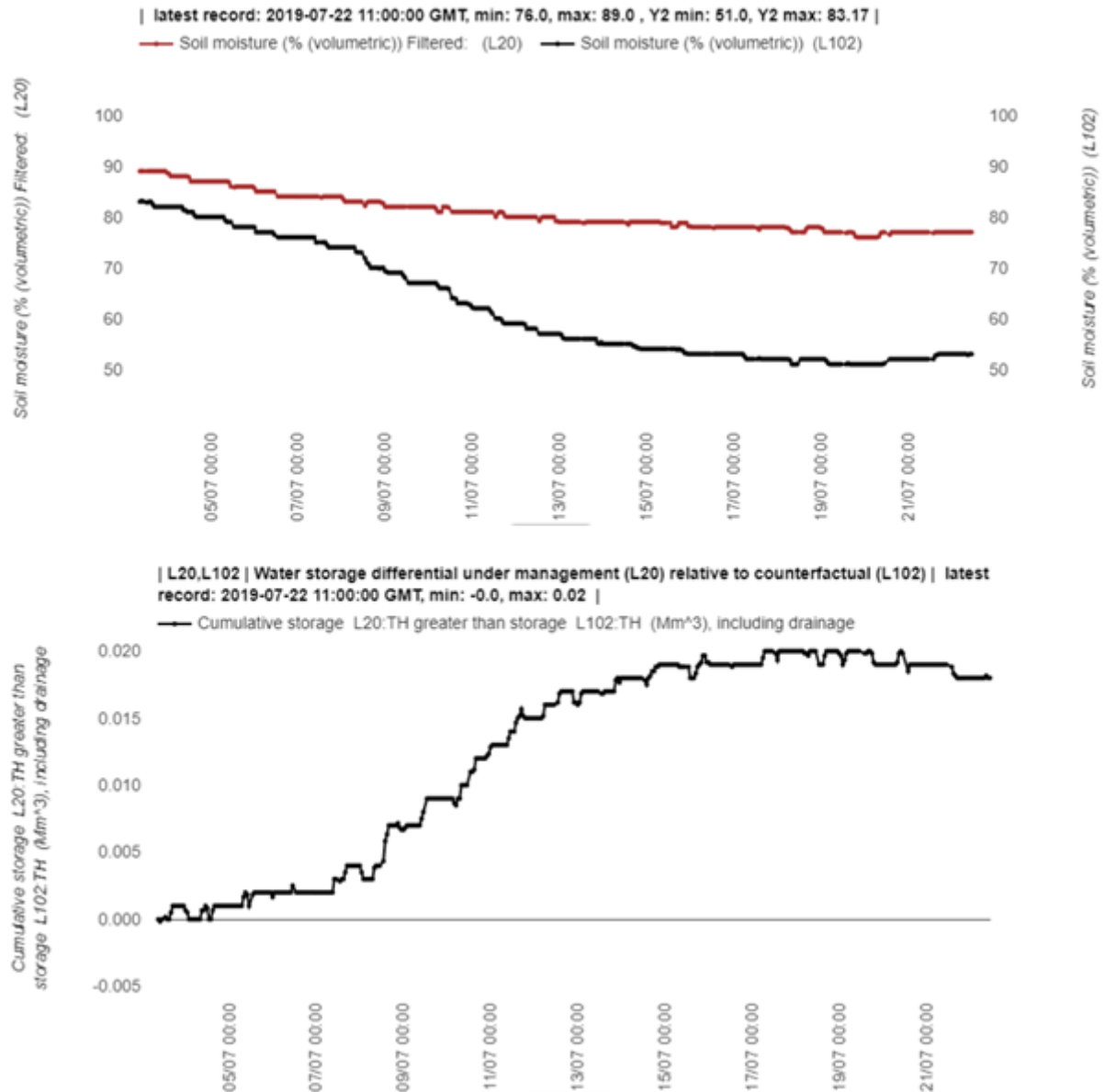


Figure 31 top: Soil moisture for CA field (brown line) and non CA field (black line) for 3 weeks in July 2019 for a farm in Suffolk. Bottom: cumulative soil storage for CA field compared to non CA field for the same period.



Conclusions

This section has shown the potential for the //Smart: system for monitoring the effectiveness of specific in-place NFM accurately at low cost and with ease. The different types of natural flood management such as leaky dams, storage ponds and agricultural management require different kinds of analyses to understand their impact and the best way to understand their full impact is to relate it to downstream flow. Large area interventions such as the soil storage under conservation agriculture tend to have much higher impact (and lower cost per m³) than smaller interventions such as leaky dams. They are capable of making more substantive percentage contributions to reducing downstream flow peaks compared with leaky dams.

Lab Experiments on optimal and sub optimal designs of leaky dams

To complement the field monitoring of leaky dams described above we undertook laboratory flume experiments to systematically investigate differences in performance between different dam designs, under controlled flow conditions.

Methods

The river was simulated using two aluminium troughs (14.5 cm wide, 5 cm high and 100 cm long). In one trough a beaver dam was constructed using clay, sand, plasticine and small twigs. In the second trough 0.6 cm diameter dowelling was used to simulate the logs used to build leaky dams. The dowels were slotted in between dowelling that had been glued to the base and sides of trough. The height of the dams were 8 dowels in height (i.e. 4.8 cm). The troughs were on a stream table and positioned under the water outflow pipe integrated with a water flow meter. The trough was positioned at a 24% incline on the table. Blue dye was used to improve the visibility of the water and the experiments were recorded so that data could be extracted from the footage.

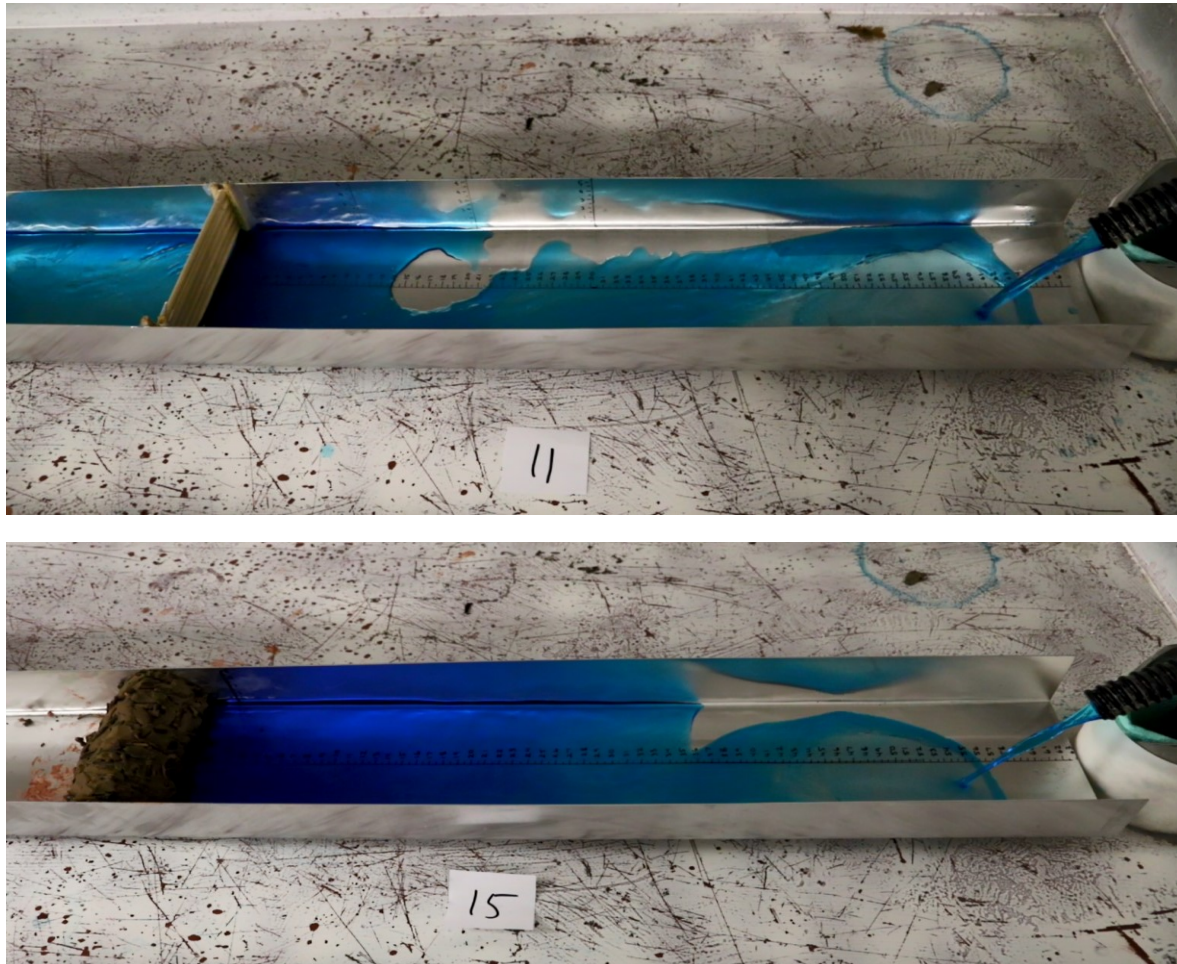


Figure 32 Experimental setup for testing leaky dam (top) and beaver dam (bottom)

Six different styles of NFM were tested: five leaky dams and a beaver dam. The designs were chosen based on popular designs and those being monitored as part of this study (Table 1). The performance of the dams were tested under low and high flood pulses: low defined at 100L/h for 30 seconds and high as 200L/h for 15 seconds. The performance of the dam was assessed using two indices: i) the volume of water held back by the dam and ii) the length of time it took the water held back by the dam to drain following the end of the flood pulse. To calculate the (i) volume of the wedge of water held back by the dam we used the formula $\frac{1}{2} \times \text{channel width} \times \text{height of water} \times \text{distance of water upstream}$ which represents half the volume of a rectangular prism (Fig 32a). We therefore needed to record the height of the water behind the dam (height) and the distance behind the dam the water accumulated (distance); the width of the trough



(width) is constant. The first two measurements were taken at the end of the flow pulse using rulers on the side and bottom of the trough. In order to calculate (ii) the length of time it took the water held behind the dam to empty we also used a stopwatch. We timed for a maximum of 10 minutes, at which point if water still remained behind the dam we stopped the experiment and recorded the height and distance measurements required to calculate the volume of the water still remaining behind the dam after 10 minutes. Two replicates of each design were run and the average values across the replicates calculated and used in the analysis.

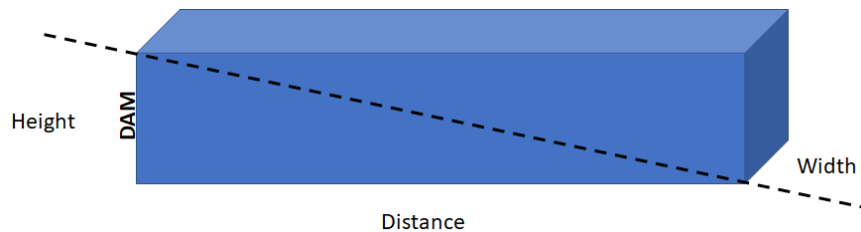


Figure 32a. Visualization of the measurements required to calculate the volume of water held back by the dam. The volume held back the dam represents a half of the volume of a rectangular prism (the dotted line). $V = \frac{1}{2} (\text{height of water at the dam})(\text{distance of water behind the dam})(\text{width of the trough})$.

Description	Gap percentages	Acronym
Single layer of logs with No Gaps 	0%	SNG
Single layer of logs with a Gap at the Bottom 	Total: 13% 13% at the bottom; 0% between logs	SGB
Single layer of logs with Gaps between logs but No Gap at the Bottom	Total: 50%	SGNGB



	0% at the bottom; 13% between each log	
Single layer of logs with Gaps between the logs and at the bottom 	Total: 50% 13% at the bottom; 13% between logs	SG
Double layer of logs with No Gaps 	0%	DNG
Beaver dam analogue 	NA	B

Table 1. Summary of the different designs of NFM solutions tested with flume experiments

Results

The beaver dam performed the best, as indexed by the volume of water held back by the dam and the length of time required for the water to recede from behind the dam. For both low and high flows, water still remained behind the dam when the experiment ended 10 minutes after the pulse ended. The beaver dams were the only type of NFM to not have fully drained; approximately half of the original volume of water still remained after 10 minutes (initial volume held back, low: 891 cm³/high: 769 cm³ vs. volume held back after 10 minutes, low 473 cm³/high 425 cm³).



The leaky dam designs with the gaps at the bottom performed the worst in that water did not accumulate behind for both the low and high flows. Both the single and double layered designs with no gaps trapped more water under high flows than low flows (single layer, low vs high flow: 234 vs 529 cm³; double layer, low vs high flow: 390 vs 612 cm³), but the high flows did not take too much longer to empty than the single layer (single layer, low vs high flow: 28 vs 32 seconds; double layer low vs high flow: 34 vs 41 seconds).

The leaky dam style with gaps between the logs but no gap at the bottom trapped some water behind the dam but the volume accumulated did not differ between the low and high flows and there was little difference in the amount of time taken to empty (Figure 33). Although this style of leaky dam did not hold back much water it did slow the flow of water (Figure 33).

Based on the experimental evidence, beaver dams (or non-leaky dams) provide the best performance in regards to retaining water and slowing its flow, followed by double layer with no gaps, single layer with no gaps, and single layer with gaps between the logs but no gap at the bottom. The two styles of leaky dams with gaps at the bottom did not hold any water back.

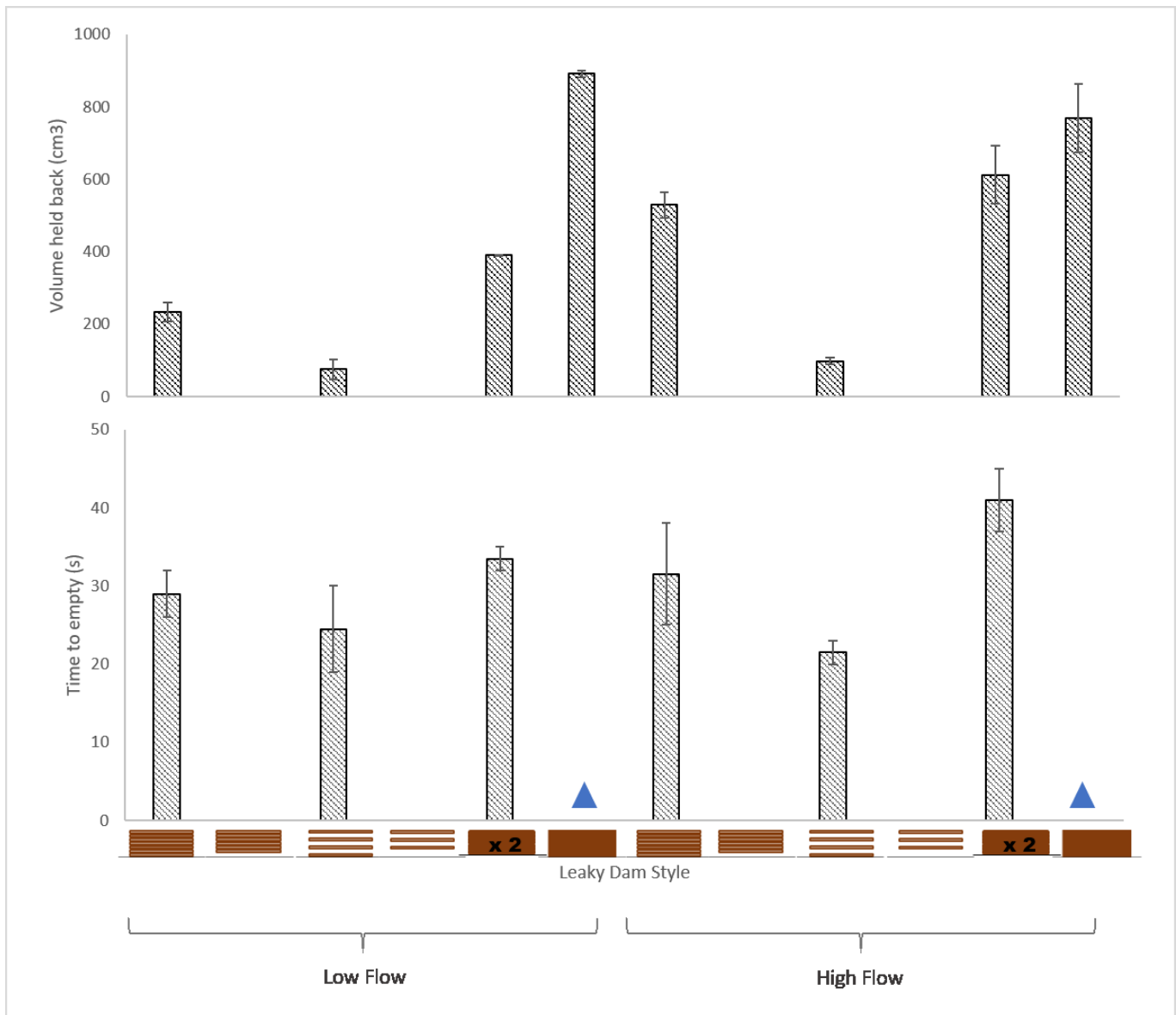


Figure 33. Performance of different leaky dam designs under low (100 m/s, 30 seconds) and high (200 m/s, 15 seconds) flow conditions. The volume of water held back by the dams (top) and the amount of time required for the water to empty after the flood pulse (bottom). The bars represent the average value of two replicates and the error bars show the minimum and maximum value. The triangles indicate that water still remained behind the dam after 10 minutes. Designs with gaps at the bottom did not hold water back; the beaver dam held back



the most water and took the longest to drain. Of the leaky dam designs tested, the double layer of logs with no gaps between them held the most water back and took the longest to drain. Five dam styles from left to right: Single layer of logs No Gaps; Single layer of logs with a Gap at the Bottom; Single layer of logs with Gaps between logs but No Gap at the Bottom; Single layer of logs with gaps between the logs and at the bottom; Double layer of logs with No Gaps; Beaver dam analogue.

Application of Eco:Actuary Policy Support System to the UK

Introduction

In this section we apply the Eco:Actuary Spatial Policy Support System to the UK. The system can be applied anywhere globally, by anyone, on the basis of the data that we provide.

Eco:Actuary is:

- A portfolio catastrophe model (estimates losses from catastrophic events)
- A portfolio catastrophe mitigation model (helps understand the mitigation of losses by nature and investment in (nature-based) interventions)
- A portfolio catastrophe avoidance model (helps understand the avoidance of losses through investment in adaptation measures)
- Suitable for sub-national and international analyses/portfolios
- Focused on NFM, climate & land use change, land management
- Very much a first step, single hazard (flooding) probabilistic model
- To be further developed over time, including water quality impacts, other hazards

Eco:Actuary is not:

- A detailed local scale flood-water inundation model
- Suitable for individual local (property scale) risk analyses
- Suitable for designing engineered (grey infrastructure) mitigation & adaptation



Applying the Eco:Actuary Policy Support System

For this application we will use the Eco:Actuary Flood risk model to assess current damage costs in UK and future damages under a climate change scenario before examining a scenario for mitigating damage through reforestation of protected areas. Note that Eco:Actuary is a probabilistic model so each run will provide different numbers depending on the exact portfolio of intensity and size of events generated. Since nobody can predict the magnitude and location of future events, it is the patterns and lessons, not the exact numbers that we need to focus on. Figure 34 shows the Eco:Actuary interface available at www.policysupport.org/Eco:Actuary. The five steps, Define Area, Prepare data, Start Simulation, Results Maps and Policy exercises are used to run a baseline simulation and a scenario. The user documentation and online training provide details on how this is done. A key part is to complete the Catastrophe model parameters (figure 35) in which the hazard ensemble, asset inventory, damage function and mitigation infrastructure may need to be adapted to suit the local conditions in the area the model is being applied. These can also be edited to simulate a hazard scenario or adaptation measures that affect asset values, loss of function periods and fractions or damage functions. Eco:Actuary recognises - and maps the distribution of - 19 different asset types: Commercial, Residential, Industrial, Cropland, Pasture, Airport, Bridge, Highway/road, Hospital, Hydropower plant, Pipeline, Power utility, Railway, Retail, School, Telecoms, University, Waste water plant, Water treatment plant.



D2.5 Guidelines on the Eco:Actuary Policy Support System NAIAD GA n° 730497



The screenshot displays the Eco:Actuary Policy Support System (PSS) interface. At the top, a red banner indicates the user is signed in as 'hyperuser' and provides a license expiration date of 01/01/2020. Below this, a status bar shows system metrics: 'ecoengine for: ecoactuary v.2 [0beta] [non-commercial use]', 'Disk: 55 | d: 156 GB', 'Mem: 17 %', and 'Load: 60%'. The main interface features a sidebar on the left with navigation links for 'Further credits', 'Report problem', 'Logout', 'Control panel', 'explore:', 'set-up: Step 2. Prepare data', 'simulation: Step 3. Start simulation, Step 4. Policy exercises, Manage simulations', 'results: Step 5. Results: maps', and 'help: System documentation, FAQ, Change log, Model documentation'. The main area shows a map of South Asia with a blue box highlighting Bhutan and India. The map includes labels for various countries and regions, such as China, Nepal, India, Bangladesh, Myanmar (Burma), and Laos. A search bar at the top of the map area shows coordinates 'lat: 27.479 lon: 90.441' and a 'Run name' of 'Bhutan [Country, 1km]'. A 'View in Earth' button is located at the bottom of the map area.

Figure 34 Eco:Actuary PSS interface



D2.5 Guidelines on the Eco:Actuary Policy Support System NAIAD GA n° 730497



Edit flood model parameters:

Use this function to activate the flood model and edit the parameters for potential and realized hazards, asset and other values, damage functions and insurance conditions. First edit the rainfall intensity and depth distributions which will be used to generate an ensemble of events. Second edit the asset and asset class valuation matrix. FRC = Full replacement cost of asset. LOFP = Loss of function period for asset. LOF = Loss of function cost of asset (e.g. business interruption) as a fraction of local GDP. [FSC = Function substitution cost for asset (e.g. rehousing during construction), not available yet]

HAZARD ENSEMBLE

☒ Check this box to use the flood model

Number of events to simulate: 1200 ?

Max. ever rainfall intensity: 120 ? Intensity Pareto scale: 1 ? Prob. of zero rainfall intensity: 0.9 ?

Max. ever monthly rainfall in wettest area: 1000 ? Monthly totals Pareto scale: 1 ? Prob. of zero monthly rainfall: 0.9 ?

If you wish to define a smaller analysis area, please create a ZOI for the area and refresh this page. If not, the values below must refer to the whole current analysis area. Please ensure that this area includes the entire upstream catchment and the areas downstream to all affected populations.

ASSET INVENTORY

	Lowest FRC (MUSD/ha)	Highest FRC (MUSD/ha)	Max LOFP (days)	Max. Fractional LOF	Calculate?
Commercial	14.7	20	90	1	Yes ?
Residential	10	20	30	0.25	Yes ?
Industrial	3.2	26	60	1	Yes ?
Cropland	0.0076	0.01	10	1	Yes ?
Pasture	0.00988	0.02	1	1	Yes ?
Airport	5	5	100	0.25	Yes ?
Bridge	1	10	300	0.25	Yes ?
Highway/road	0.2	2	30	0.25	Yes ?
Hospital	20	20	100	0.25	Yes ?
Hydropower plant	4	10	300	0.25	Yes ?
Pipeline	0.00776	0.07768	30	0.5	Yes ?
Power utility	0.06213	50	5	0.75	Yes ?
Railway	1	23.4	60	0.75	Yes ?
Retail	7	35.7	90	1	Yes ?
School	14	14	90	0.25	Yes ?
Telecoms	0.27	0.54	10	0.25	Yes ?
University	14	14	90	0.25	Yes ?
Waste water plant	30	90	10	0.75	Yes ?
Water treatment plant	0.14	267	10	0.75	Yes ?



DAMAGE FUNCTIONS.

Damage functions are expressed as the fractions of full replacement cost and full loss of function period affected per asset class for different mean water excess over available storage (i.e. for different multiples of bankfull or soil-profile full storage). Parameters should be provided for mean excess between 0 and 5 times storage, 5 and 10 times storage and greater than 10 times storage, representing short return period to very long return period events.

	<5x FRC (fraction)	5x-10x FRC (fraction)	>10x FRC (fraction)	<5x LOFP (fraction)	5x-10x LOFP (fraction)	>10x LOFP (fraction)
Commercial	0.25	0.5	0.9	0.5	0.75	1.0 ?
Residential	0.5	0.75	1.0	0.1	0.5	1.0 ?
Industrial	0.5	0.75	1.0	0.5	0.75	1.0 ?
Cropland	1.0	1.0	1.0	1.0	1.0	1.0 ?
Pasture	0.1	0.25	0.5	0.1	0.5	0.75 ?
Airport	0.5	0.75	0.75	0.75	0.75	1.0 ?
Bridge	0.25	0.5	1.0	0.25	0.5	1.0 ?
Highway/road	0.1	0.1	0.1	0.5	0.75	1.0 ?
Hospital	0.75	0.9	1.0	0.75	0.9	1.0 ?
Hydropower plant	0.25	0.5	1.0	0.25	0.5	1.0 ?
Pipeline	0.1	0.5	0.9	0.5	0.75	1.0 ?
Power utility	0.1	0.25	0.5	0.5	0.75	1.0 ?
Railway	0.1	0.25	0.5	0.5	0.75	1.0 ?
Retail	0.1	0.5	0.75	0.5	0.75	1.0 ?
School	0.1	0.5	0.75	0.5	0.75	1.0 ?
Telecoms	0.25	0.5	0.75	0.5	0.75	1.0 ?
University	0.1	0.25	0.5	0.1	0.5	1.0 ?
Waste water plant	0.1	0.15	0.25	0.1	0.5	1.0 ?
Water treatment plant	0.1	0.15	0.25	0.1	0.5	1.0 ?

MITIGATION INFRASTRUCTURE.

	Associated parameters		
Flood storage			
Floodplain storage capacity	FP Max. height from river (m): 5.0	Floodplain depth (m): 0.5	Weight in total: 1.0
Water body storage capacity	WB volume intercept: 30.684 WB volume slope: 0.9578 Weight in total: 1.0		
Wetland storage capacity	Wetland depth(m): 5.0 Weight in total: 1.0		
Canopy storage capacity	100% tree canopy store depth per rainday (mm): 5.0 Weight in total: 1.0		
Soil storage capacity	Maximum soil store depth(m): 2.0	Soil added per per-cent of tree cover (mm): 1.0	Weight in total: 1.0

☒ Check and Submit

Figure 35 Catastrophe model parameters interface in Eco:Actuary

Hazard ensemble

The hazard ensemble defines the number and characteristics of the probabilistic rainfall intensity and rainfall volume events that will be applied across the study area (with modification to fit with the spatial distribution of long term monthly and annual rainfall volumes from a global climatology). The user specifies the number of events and parameters for a Pareto distribution of rainfall intensity and of rainfall volume. Maximum rainfall intensity and maximum monthly rainfall anywhere in the region are specified alongside the probability of zero rainfall and a scale parameter for each of intensity and rainfall volume. The Pareto parameter determines the shape file distribution (eg fraction of more extreme events). Typical produced distributions for the UK are shown in figure 36.

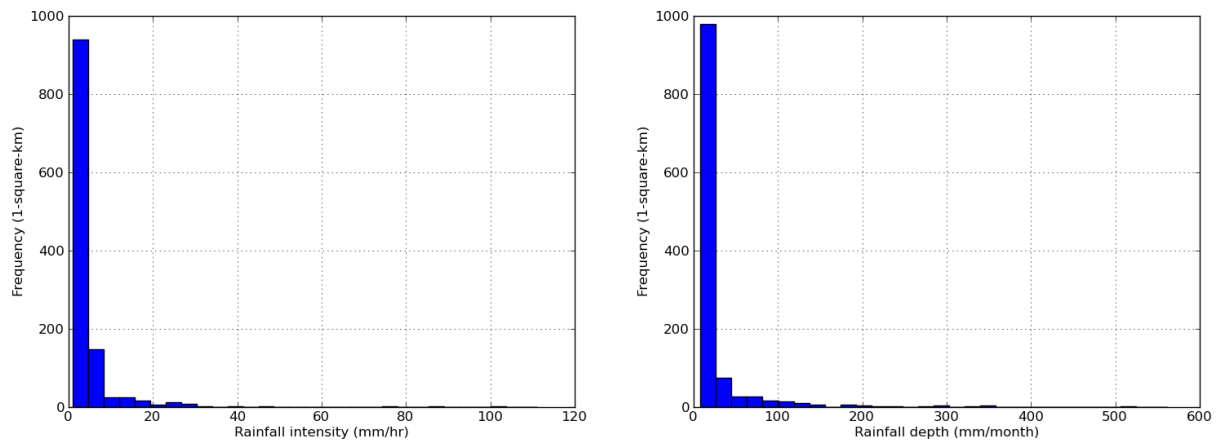


Figure 36 Eco:Actuary Pareto distributions for rainfall intensity (left) and volume (right)

Asset inventory

The asset inventory requires specification of Min and Max full replacement cost (FRC) in the region per asset class. These have to be estimated based on the most expensive and cheapest FRC in the study area per asset and asset class. Also required is Max. loss of function period (LOFP). These have to be estimated based on the interaction of type of hazard and the asset or asset class. Finally Max. fraction of function lost (business interruption) needs to be specified, again estimated on the basis of the interaction between the type of hazard and the asset type.

Damage function

Both damage to FRC (full replacement cost) and LOFP (loss of function period) are affected by the magnitude of the flood event and the impact varies from asset type to asset type. In each case the fraction of FRC or LOFP at three levels of water excess over storage capacity (i.e. flood ratio) are given: <5 times, 5-10 times and >10 times the storage capacity. These have to be estimated based on the type of asset and the impact of the type of hazard.

Mitigation infrastructure

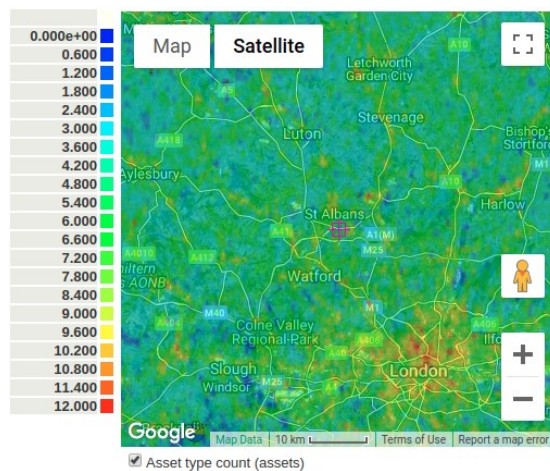
Mitigation infrastructure is mapped on the basis of remote sensing. For each of floodplain, water body, wetland, canopy and soil, parameters are given that combine with remote sensing distributions of these stores to estimate the volumes of natural flood storage. These spatial distributions and volumes will be affected by land use change or land management interventions. For most situation the global default values can remain as set.



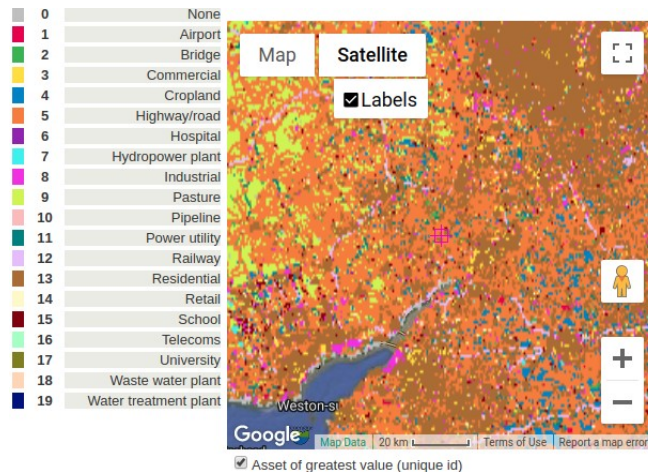
Baseline results for UK

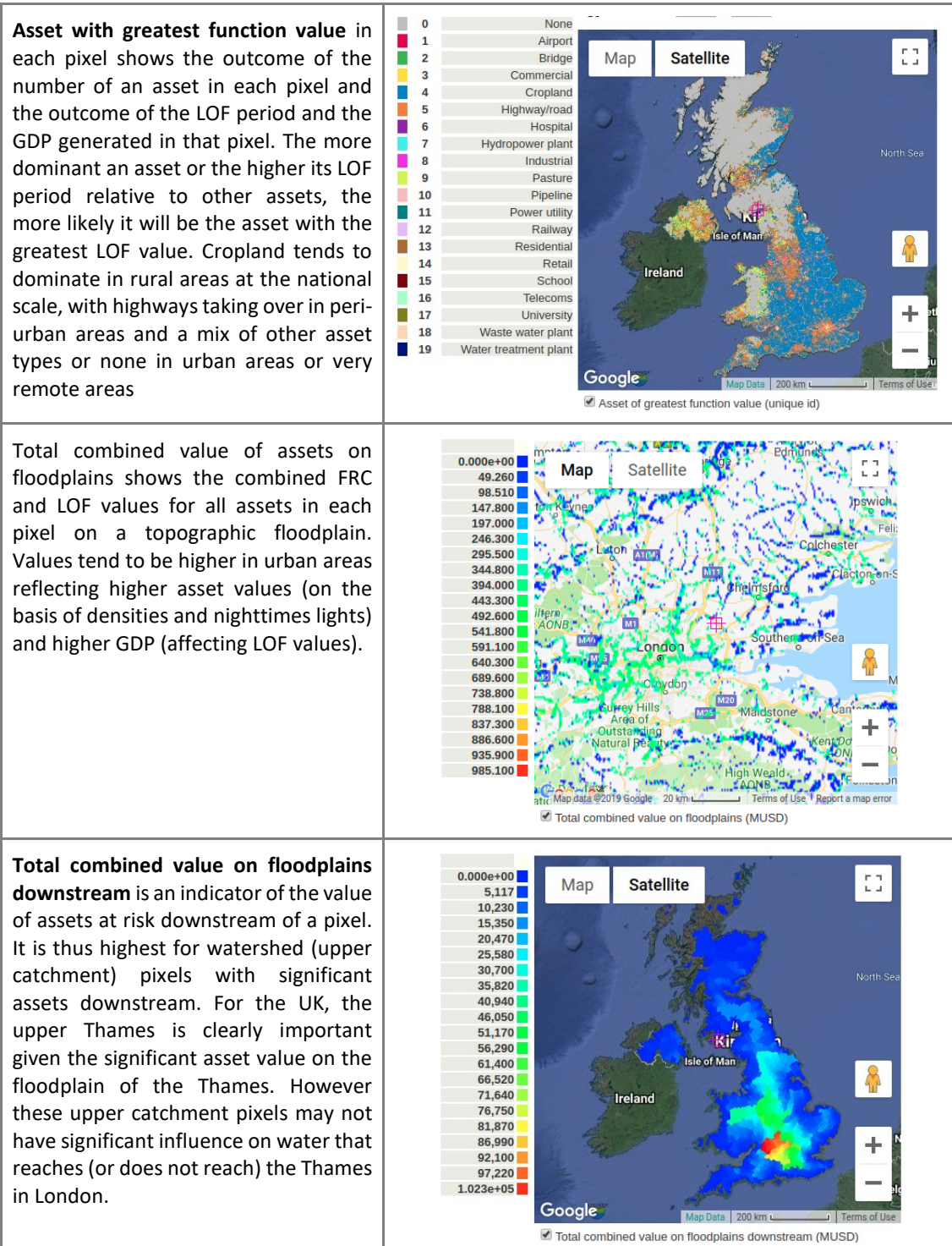
Once the *Define Area* and *Prepare data* steps are complete (including setting the catastrophe model parameters) the simulation can be run with Start Simulation. Once the simulation is complete (around 30mins for 1200 events over an area the size of UK), the *Results maps* link can be used to examine the model results. A variety of outputs are written including those summarised below

Asset type count - the number of asset types in each pixel. The more asset types the greater complexity of the asset valuation and damage or disruption analysis. Rural areas can to have few asset types, urban and peri-urban areas many asset types. Asset data are taken from open street map (OSM)



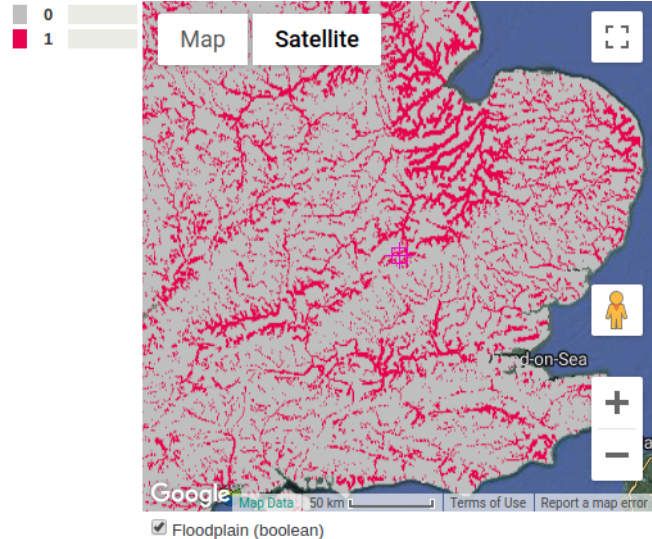
Asset with greatest replacement value in each pixel shows the outcome of the number of an asset in each pixel and the max FRC value. The more dominant an asset and/or the highest its FRC relative to other assets, the more likely it will be the asset with the greatest FRC. Highways tend to dominate at the national scale, with agriculture taking over in rural areas and a mix of other asset types in urban areas



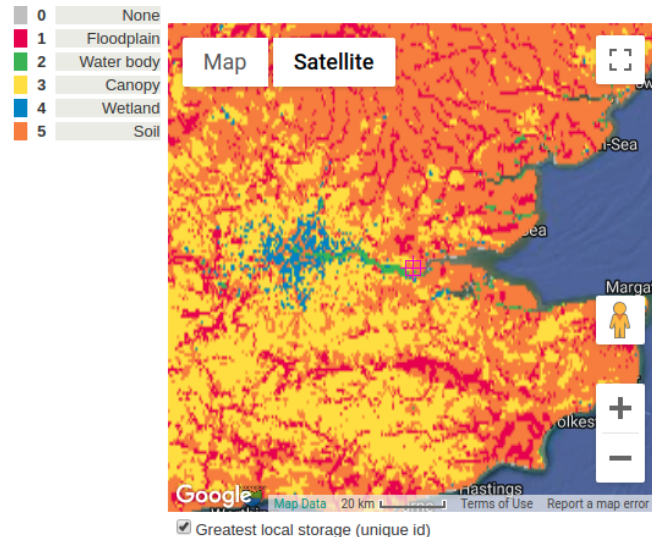




Floodplains are defined as areas close to rivers and topographically similar (i.e. within a given elevation of the river, defined according to the pixel resolution).



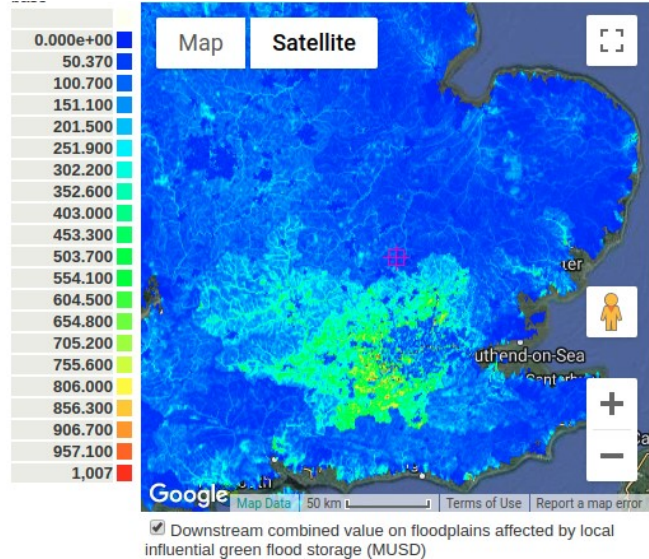
Greatest local storage capacity - mitigation of floods is assisted by flood storage in the form of canopy, soil, wetland, water body and floodplain storage. These are mapped from remote sensing and the greatest store (in terms of size) shown in each pixel. On floodplains this store dominates, in forested areas, canopy store dominates, elsewhere soil stores dominate. In urban areas canopy and soil stores are small so the greatest is often wetlands (ponds, rivers)



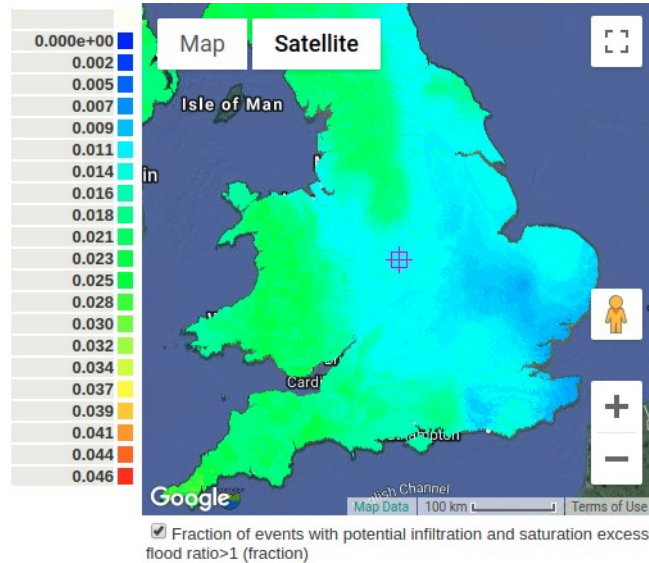


Downstream combined value on floodplains affected by local influential green flood storage. This map combines the asset value on downstream floodplains with an indication of whether storage is influential or not (depending on its size relative to the green **storage downstream**).

It shows that even though the upper catchments have most exposed assets downstream they may not be the most influential in mitigation of flows. The most influential are closer to London. These are the most in need of careful management.

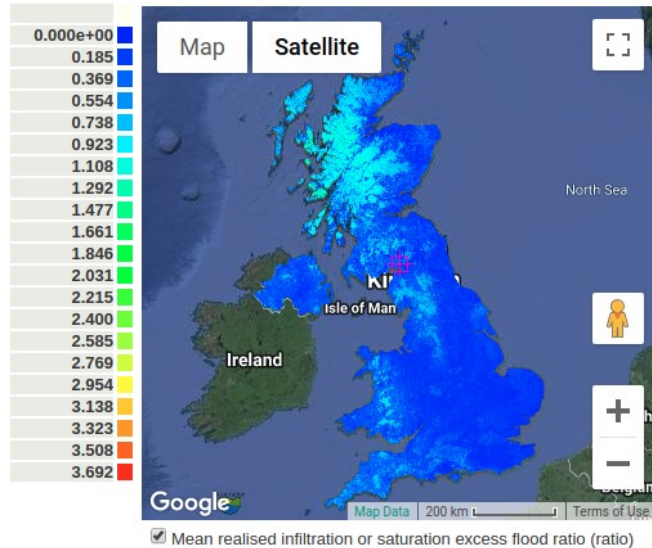


Fraction of events with potential infiltration and saturation excess flood ratio >1 - is essentially the fraction of events leading to saturation runoff (on the basis of event size) or Hortonian runoff (on the basis of event intensity) runoff, in excess of local storage. This fraction is affected by distribution of rainfall, soil infiltration properties. It is a potential that does not take into account water storage by the various stores.

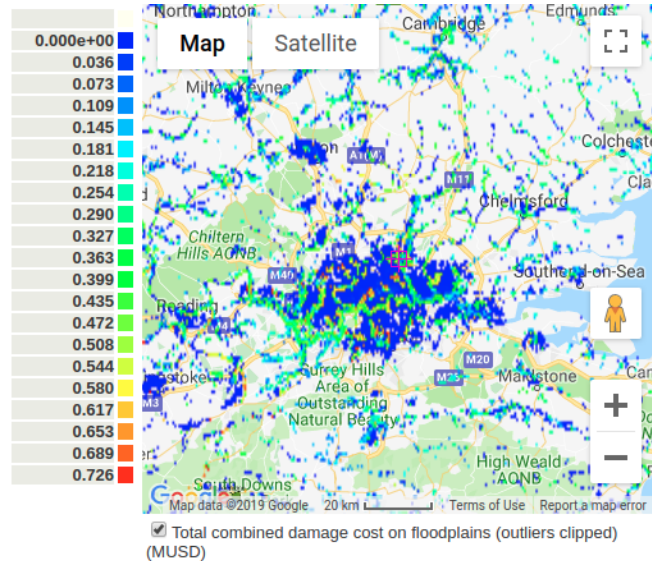


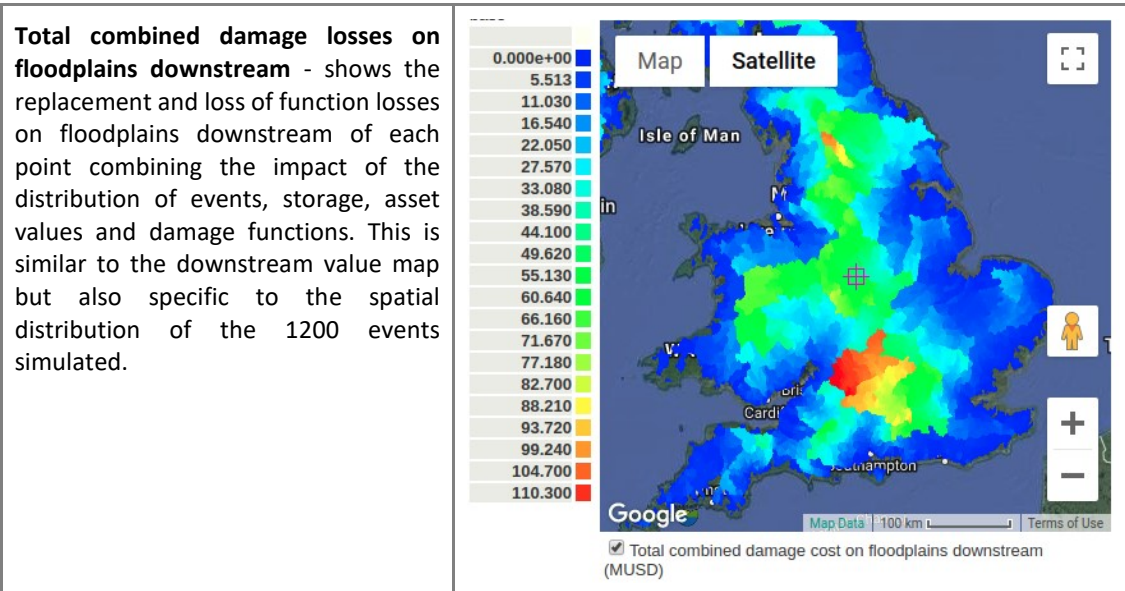


Mean realised flood ratio - this is essentially the magnitude of excess of Hortonian and Saturated runoff over the flood storage volume available. It is thus the realised flood risk. It is expressed as a ratio of the mean of the events generated relative to the background climate normals and shows (values >1) areas at risk of surface runoff and river levels > bankfull for the events simulated.



Total combined damage losses on floodplains - represent the results of the damage function calculation. Assets on the floodplain are exposed to the modelled flood ratio and both FRC and LOF thus affected through the asset-specific damage functions set. The map shows this for London for 1200 simulated baseline intensity and volume events.





Box 2 Baseline eco:Actuary PSS results for UK

Implementing a climate change scenario

Climate change scenarios are accessed through the *Step 4: Policy exercises* option. This allows us to apply a stacked scenario combining changing extremes through the Pareto event generator and changing spatial and seasonal distribution through downscaled IPCC GCM scenarios. 17 GCMs are available alongside multiple climate scenarios/emissions pathways, periods (2050s, 2080s) as well as multimodel ensembles. We will change the **Intensity pareto scale** and the **Monthly totals Pareto scale** to 3 to reflect the larger, more intense rainfall events under climate change. On top of this we apply different climate normals in terms of seasonal and spatial distribution by applying a downscaled GCM scenario to the spatial climate data. We apply CMIP5, RCP60, HADGEM2-ES Met Office Hadley Centre, 2041-2060. The model generates a new set of 1200 rainfall events (intensity and depth) based on the new parameters set for the Pareto distribution (i.e. higher volumes and intensities per event). The model extracts monthly and annual maps for rainfall and mean temperature from the downscaled GCM scenarios. These are expressed as differences from the WorldClim 50 year baseline used by Eco:Actuary. The parameters and new maps are copied over to a scenario directory. The model runs exactly the same algorithms as the baseline but on these new data. If the Pareto parameters had not changed exactly the same intensity and depth samples would be used (such that differences only represent the scenario characteristics chosen, not probabilistic differences in the events). Since the Pareto parameters have changed, the new rainfall events are used. The model outputs



are expressed as differences from the baseline enabling an understanding of the impact of the scenario of each of the model outputs. Example outputs for monthly temperature and precipitation for this scenario are shown in figure 37.

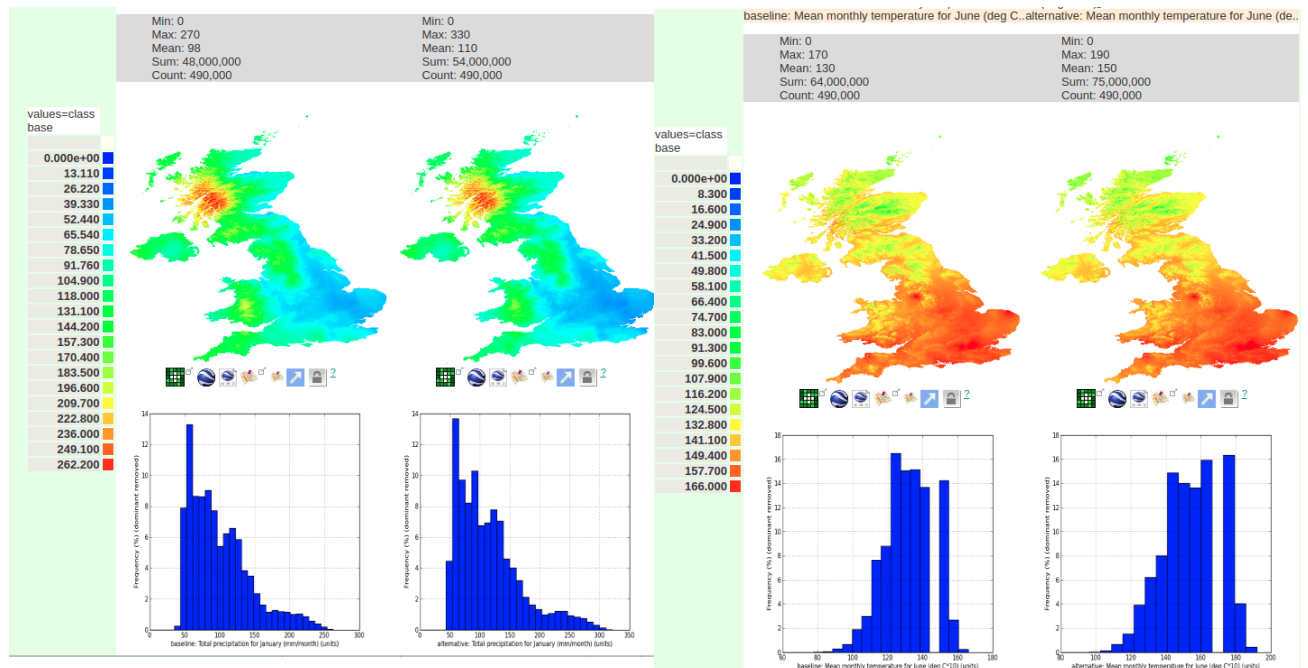
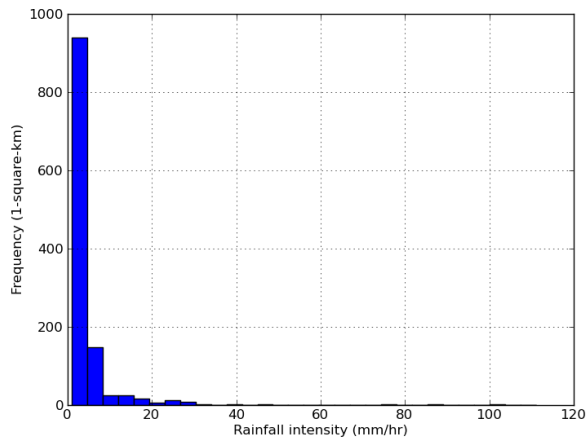
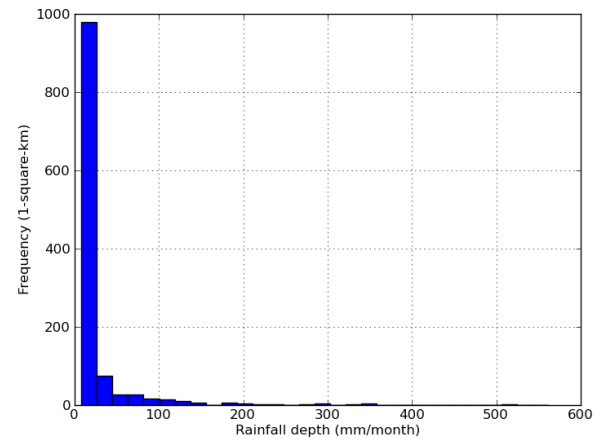


Figure 37 Rainfall (left) and temperature (right) change under CMIP5, RCP60, HADGEM2-ES Met Office Hadley Centre, 2041-2060.

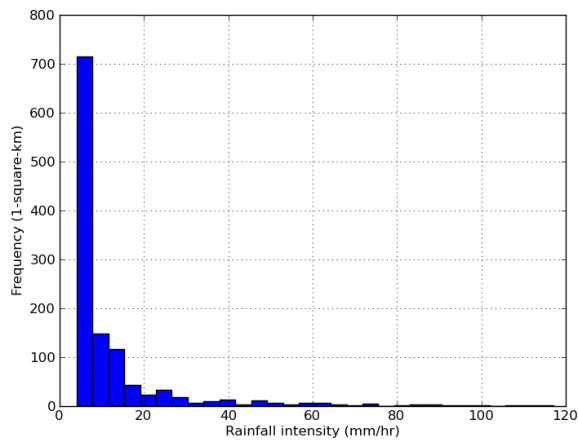
The significant impacts of changing the Pareto scale parameter from 1 to 3 are shown in fig 38. Between baseline and scenario the distributions shift significantly to the right (higher intensities, higher volumes). Mean intensity changes from 7.15mm/hr to 14.8mm/hr and mean depth 42.8 mm/hr to 71.3 mm/hr



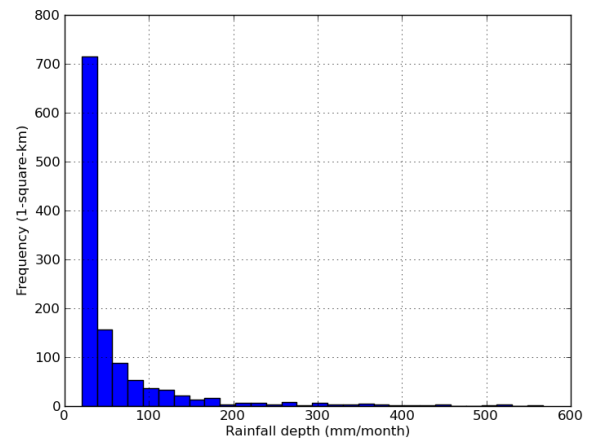
Baseline rainfall intensity PDF mean:7.15 mm/hr



Baseline rainfall depth PDF Mean:42.8 mm/month



Scenario rainfall intensity PDF mean:14.8mm/hr



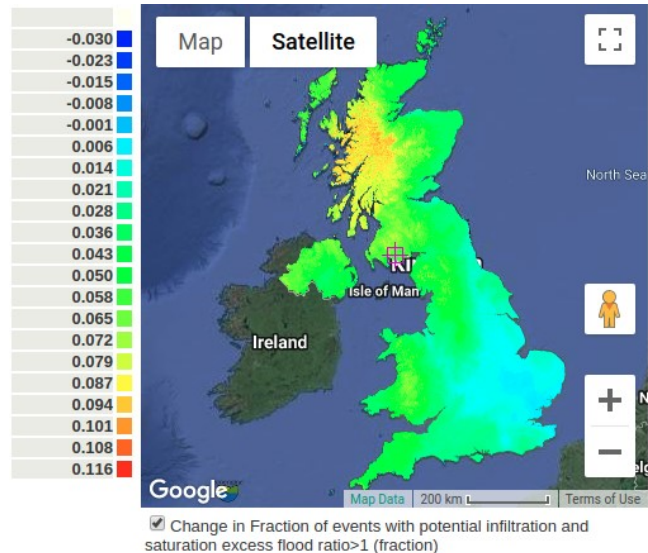
Scenario rainfall depth PDF mean: 71.3 mm/month

Figure 38 Pareto distributions for the baseline and climate change scenario

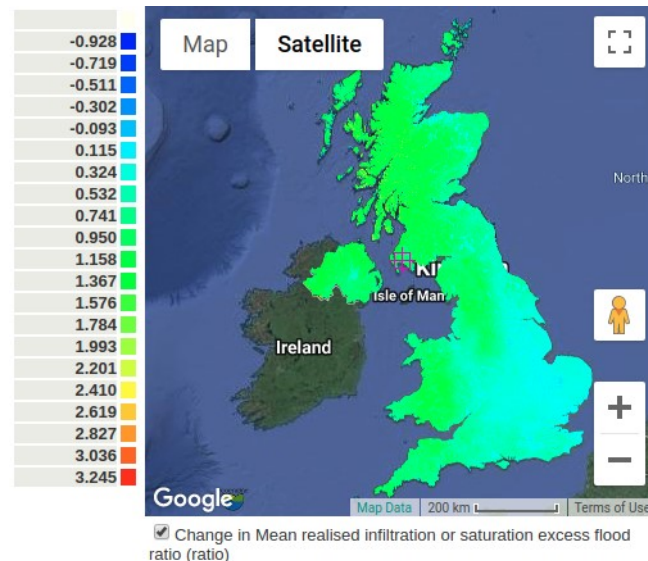
The key outputs of the climate change scenario (all expressed as difference from baseline values) are shown below, with explanations.

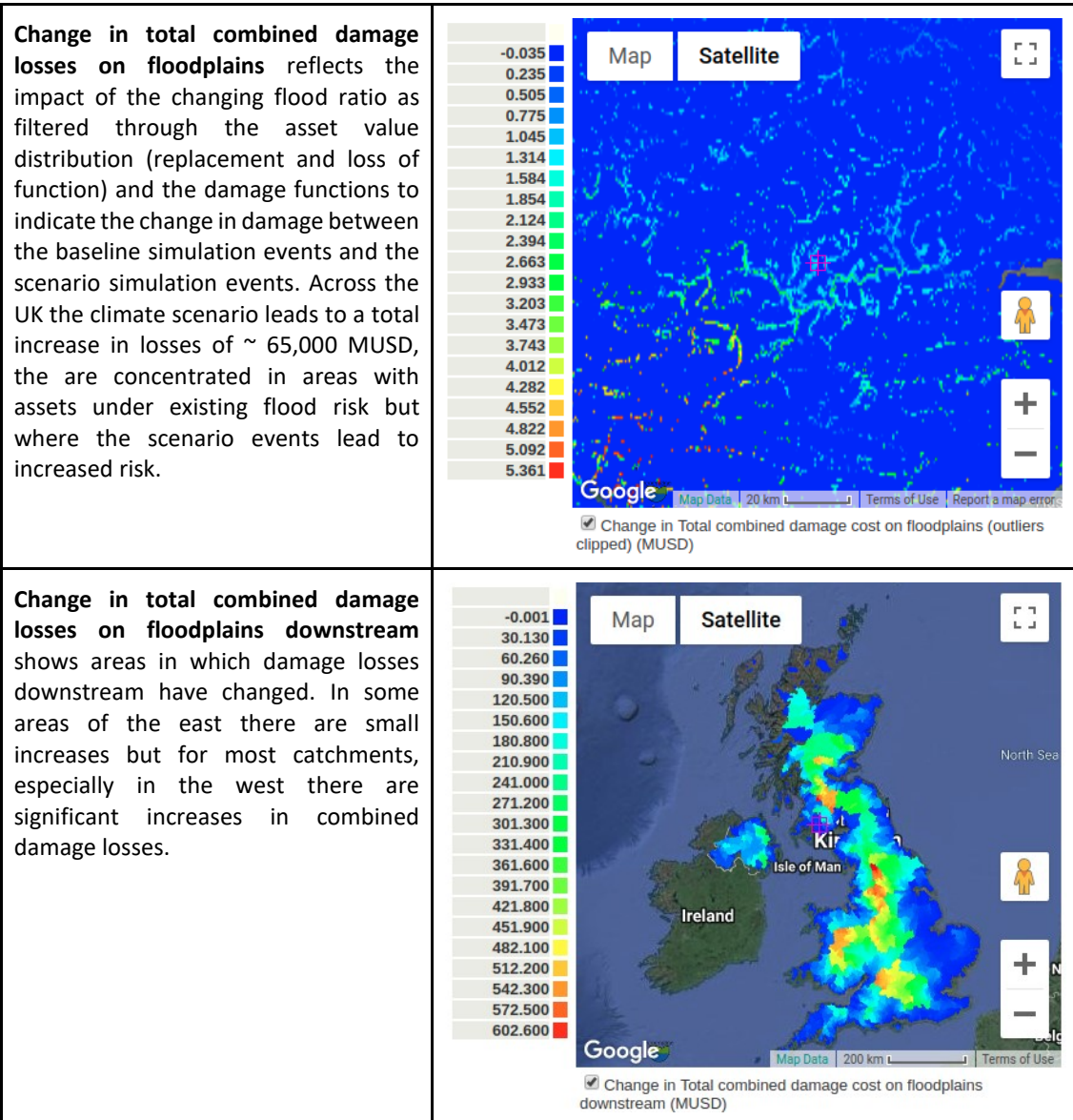


Change in fraction of events with potential saturation or infiltration excess. This is the key outcome of the spatial and temporal scenario applied and indicates, for each pixel, the fraction of events generating runoff in excess of those for the climate normals. The map indicates that for this scenario there is a general increase in such events towards the west and a small decrease (with climate drying) towards the east.



Change in mean realised flood ratio. The realised flood ratio is the ratio of realised runoff from infiltration-excess and saturation-excess (after inclusion of green infrastructure stores) relative to those for the climate normals. Again there is an east to west pattern to result from the scenario with the flood ratio decreasing in the east and increasing in the west.





Box 3 Results of Eco:Actuary climate change scenario for UK

Implementing a land management scenario

We will now implement a land use change intervention targeted at increasing flood storage to reduce damages downstream. Like all scenarios, this is implemented relative to the baseline. This is achieved through **Step 4: Policy options**, then choosing **Land use and cover change**. Under **CREATE LAND COVER TYPE** cwe choose ...or define your own rule and use the form to



generate a scenario of our choice. We will reforest within protected areas with low bare cover (i.e. not rocky slopes). This is done by completing the interface as in figure 39 below.

...or define your own rule:

Name for my scenario: refor

Set/change tree, herb, bare covers: +100 % 0 % 0 % for approx: 100 per-cent of land, cluster, ☒ pixels:

where: Protected areas (UNEP-WCMC WCPA) June 2019 is > this value: 0

other rules: -

... and where: Cover of bare ground (Copernicus 2015) is < this value: 50

Define converted areas as: All Natural (non-human) Fraction of water exposed to contamination: 1 or: ☒ scale the default for land use.

Total change in population for changed land uses (persons per sq. km.): 0

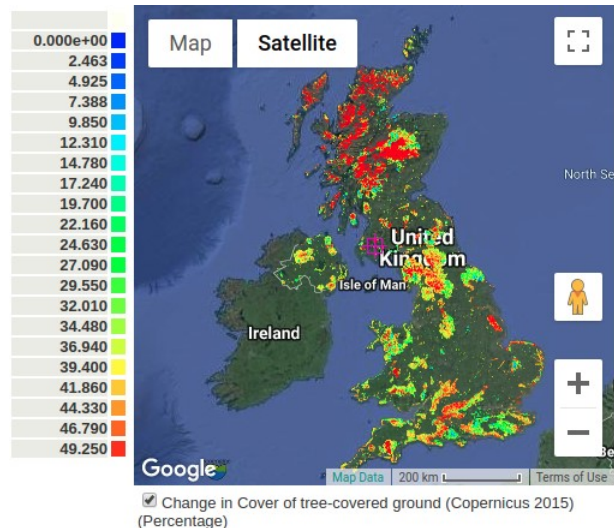
Mean conversion cost (USD per ha.): 100

☒ Check and Submit

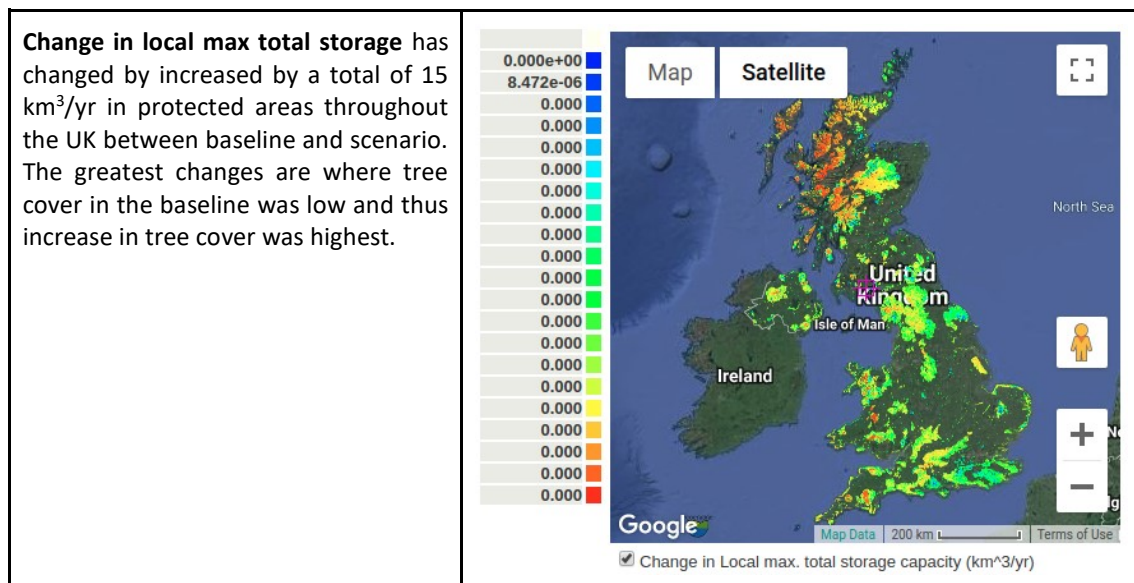
Figure 39 Land use change scenario interface

Which will increase tree cover up to 100% from its existing values holding the ratio of herb and bare cover to their current values, for areas that are protected and have a low bare fraction (i.e. are not rocky outcrops or water bodies), The model generates a new set of land use and land cover maps based on the scenario required. Tree cover is increased up to 100% from its baseline value, for all pixels which are in a protected area and for which land cover is <50% bare (i.e. not rocky or water).

This produces the increase in tree cover shown right with already forested areas changing less than unforested protected areas. Land use is changed to natural (affecting water quality). Tree, herb, bare, protected, croplands, pasture, grazing, wetlands and other land use maps are all affected by this change. The new maps are copied over to a scenario directory. The model runs exactly the same algorithms as the baseline but on these new data.

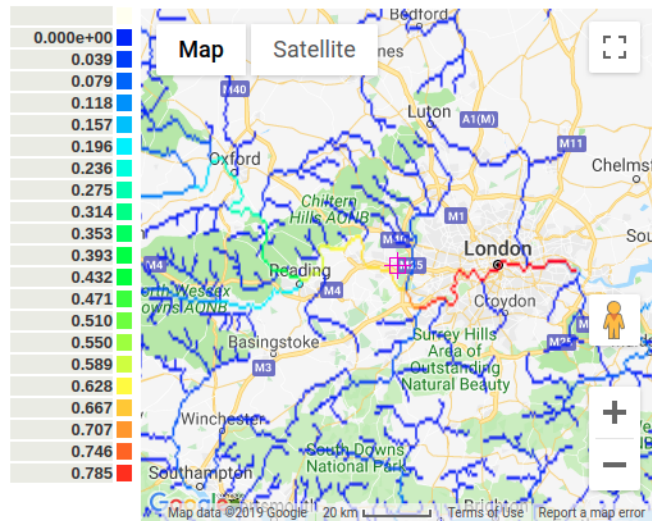


Tree cover, wetland and soil stores are affected (increasing storage). The model outputs are expressed as differences from the baseline enabling an understanding of the impact of the scenario of each of the model outputs. This is a very significant scenario which would be very challenging to implement and have significant impacts on other properties, including agriculture and water resources. Its impacts are summarised below.

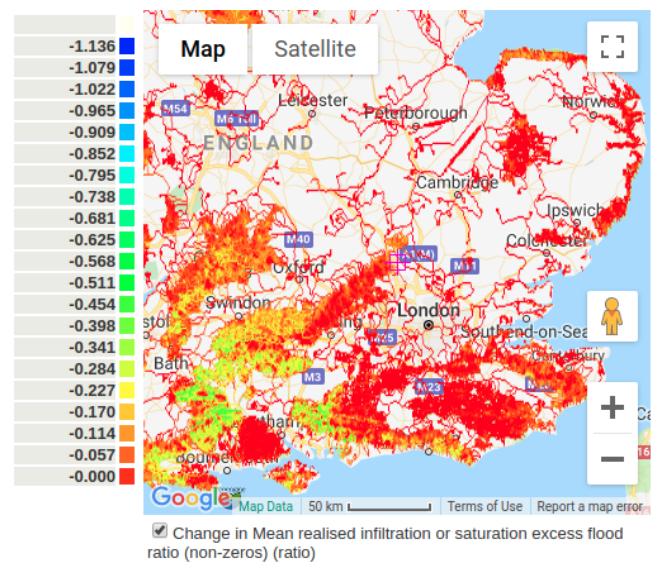




Change in Accumulated max. total flood storage capacity increases for rivers throughout the UK. The change is greatest for the Thames, which being a catchment with many protected areas and little tree cover reaches an increase of 0.81 km³/yr.



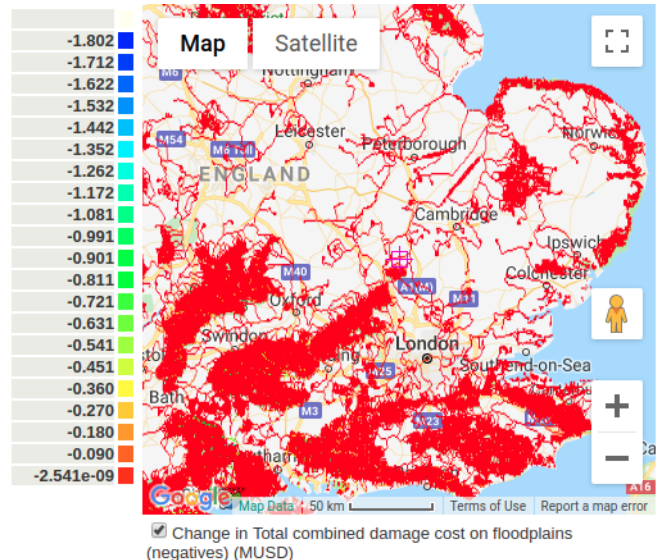
Change in Mean realised flood ratio (i.e. the outcome of this increased storage) as a result of this scenario show a decrease for most areas in which tree cover changes, through this decrease does not permeate significantly downstream since these areas are still small relative to the total catchment size and the change in ratio is small over the majority of areas,





Change in total combined damage losses on floodplains. The intervention leads to -1,700 MUSD reduction in losses (i.e. avoided loss). Even for this very significant scenario, this is very small compared with the increases associated with significant climate change (65,000 MUSD) so adaptation will also be important as well as mitigation. Nevertheless it is a significant proportion of current losses (£1.4 billion per year replacement cost damage only) and likely in excess of the cost of the intervention and co-benefits for other ecosystem services.

-0.13 MUSD of losses/km² are mitigated at the Thames at Teddington.



Box 3 results of Eco:Actuary land use change scenario for UK

Applications of Eco:Actuary://SmartRiver to other NAIAD DEMOs

The uptake of Eco:Actuary and //Smart: by other DEMOs within NAIAD was low. A FreeStation was installed on the Danube main river by GEOECOMAR as a demonstrator for local NBS planners, but was not used directly for assessing the impact of NBS as there is no existing nearby NBS. Subsequently, discussions were held between the GEOECOMAR and WWF Romania on using //Smart: to measure the changing volume of wetland at Gârla Mare while it is being restored, and to assess its hydrological function. Gârla Mare is an ecologically important wetland that was previously disconnected from the main Danube river, but will now flood at high flows. However the stakeholders did not take up the offer. Secondly, the Slovenia DEMO installed a FreeStation river level sensor to measure the water level for the Berdnikova reservoir, supported by the local stakeholders in the Municipality of Ljubljana. This FreeStation continues to be the only gauge measuring the water levels of this NBS, and is still in place and functioning after the end of the project as local capacity building. Further stations are being built by a Slovenian company.



The Eco:Actuary model was not used by other DEMOs as there were no DEMOS with large scale surface water NBS planned which would be suitable to model. Eco:Actuary is not suitable for groundwater modelling or small scale NBS within the urban fabric. It is a catchment scale model for larger scale application. Discussions were held with the MEDINA DEMO on how Eco:Actuary could be used to assess the impact of land use change in Medina. However, there is already a substantial modelling effort in the MEDINA using multiple models that covered a number of aspects already, so this DEMO did not go ahead with using Eco:Actuary. As shown below there have been significant applications outside the UK by external users.

Applications of this toolkit beyond NAIAD

A number of organisations have carried out independent applications of this toolkit. Monitoring and evaluation of use is built in to each tool. All those building FreeStations must register their intentions to access documentation. All those using the //Smart: tools are registered users.

The Eco:Actuary PSS

EcoActuary uses and usage is tracked and users are requested to register their intentions. In 2020 the Eco:Actuary PSS has been used by 249 organisations in 35 countries (see figure 40) with most users in Europe (UK: 34%, US 19%, NL 5%, BE 4%, ES 4%). There are Eco:Actuary users from all EU countries. This is rapid uptake for the first year with only occasional dissemination efforts.

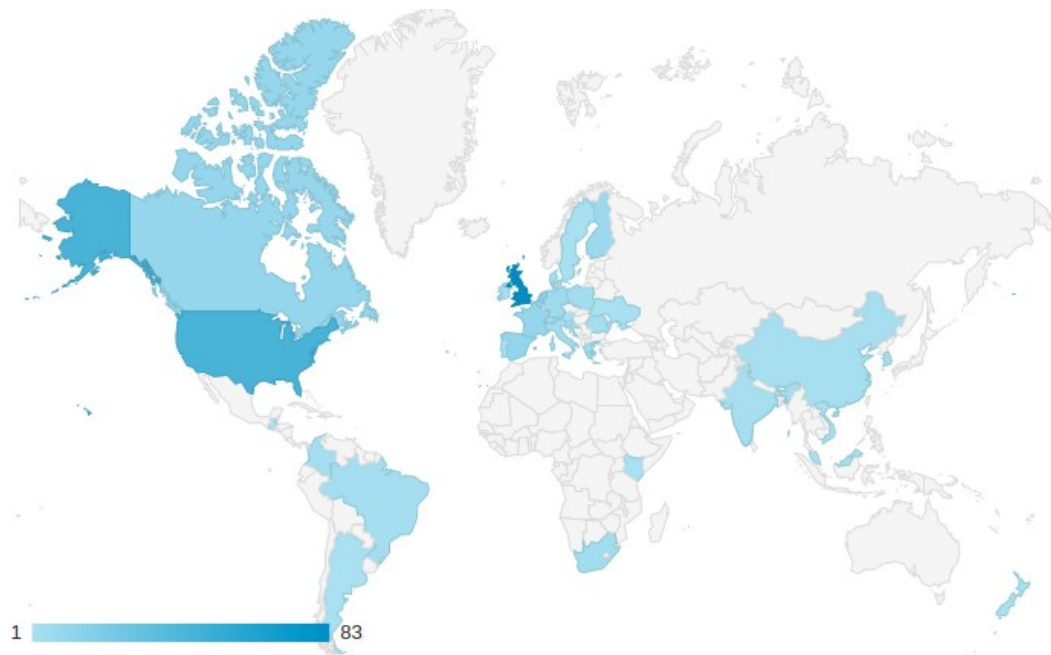


Figure 40 Distribution of organisations using Eco:Actuary in 2020

//Smart: has some 520 users from 37 countries in 2020 with top countries including UK (60%), India (7%), NL (4%), Spain (3%), US (3%), Finland (2%), Slovenia (2%) and Belgium (1.7%), see figure 41.

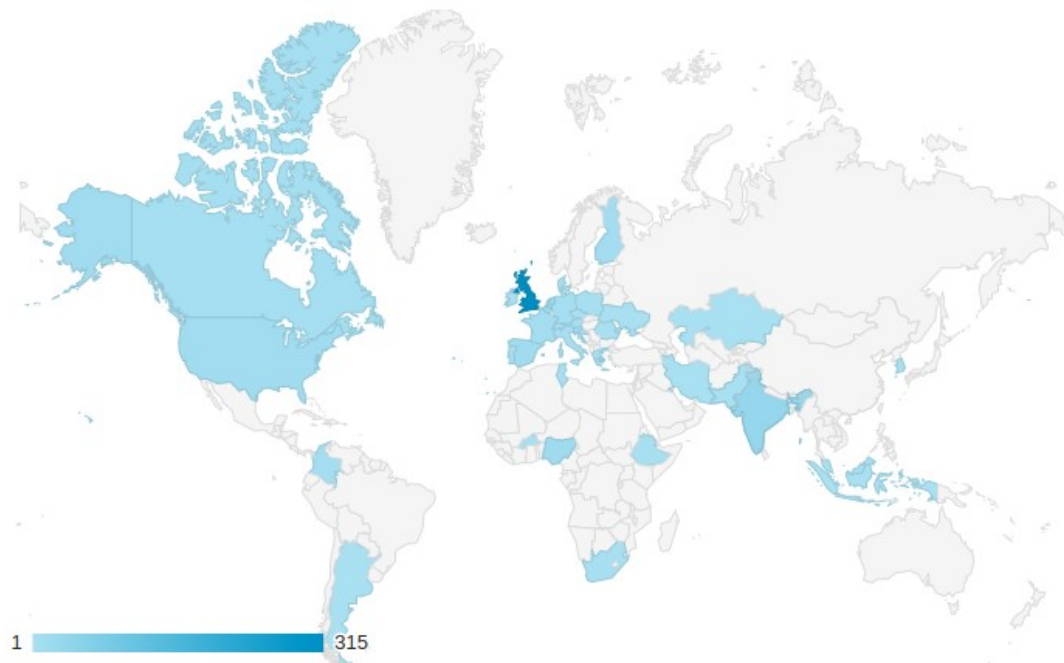


Figure 41 Distribution of organisations using //Smart: in 2020

Eco:Actuary PSS users have applied the tool in **26 countries** (Turkey, Sierra Leone, Belgium, Dem People's Rep of Korea, West Bank, Uruguay, India, Madagascar, Nepal, France, Bhutan, United Republic of Tanzania, Hungary, Colombia, Uganda, Pakistan, Malawi, Ecuador, Peru, Mozambique, Costa Rica, Brazil, Ghana, Thailand, U.K.), **22 major global basins** (Sulawesi, Spain South and East, Douro, Cauvery, Sri Lanka, India West Coast, Volta, Sumatra, Ganges Bramaputra, Yangtze, India South Coast, Danube, India East Coast, France South Coast, Magdalena, Mexico Northwest, Nile, Spain Portugal Atlantic, Colorado, England and Wales, Philippines), **15 1ha** tiles and **36 1km** tiles around the world as shown in Figure 42.

Insurers have been involved in the development of Eco:Actuary from the start with our 11 January 2019 **Eco:Actuary co-development workshop** attended by AIG, Jetram partnership, AON Benfield, Willis Towers Watson, Bank of England, FloodRe, Barbican Insurance Group, National Association of Insurance and Reinsurance Companies, Romania (UNSAR), Allianz-Tiriac Asigurari SA, Romania. Our first Eco:Actuary training event was in the General Assembly in Ljubljana in January 2019 where the entire NAIAD participants were invited to a hands-on demonstration of the Eco:Actuary Beta version. We followed up with an indexed video so that

participants could try again at their own pace, and the DEMOs were encouraged to apply Eco:Actuary where appropriate.

Our **Eco:Actuary official launch and training workshop** on Sep 11 2019 in London included participants from AXA, AIG, RSA Group, LV, Capita, DirectLine, UNSAR, Willis Towers Watson NPX-NPQ, Moodys, CCR, Affinity Water, Thames21 and Ocaso. 100% of responses rated the workshop excellent and indicated that Eco:Actuary was relevant to them professionally. Some requested additional functionality for example for calculating AAL and return period losses. Particularly positive responses were around the ability to adjust model parameters in Eco:Actuary "This type of adjustment is very limited in existing commercially available models". Also the possibility of "providing NBS functionality to existing flood 'cat models'" is "valuable in a variety of ways" and "The temporal/antecedent condition aspect is an interesting one – not considered explicitly by cat models". The recognition that land condition as well as climate is a key factor for flood insurance risk was definitely the key learning outcome of the day.

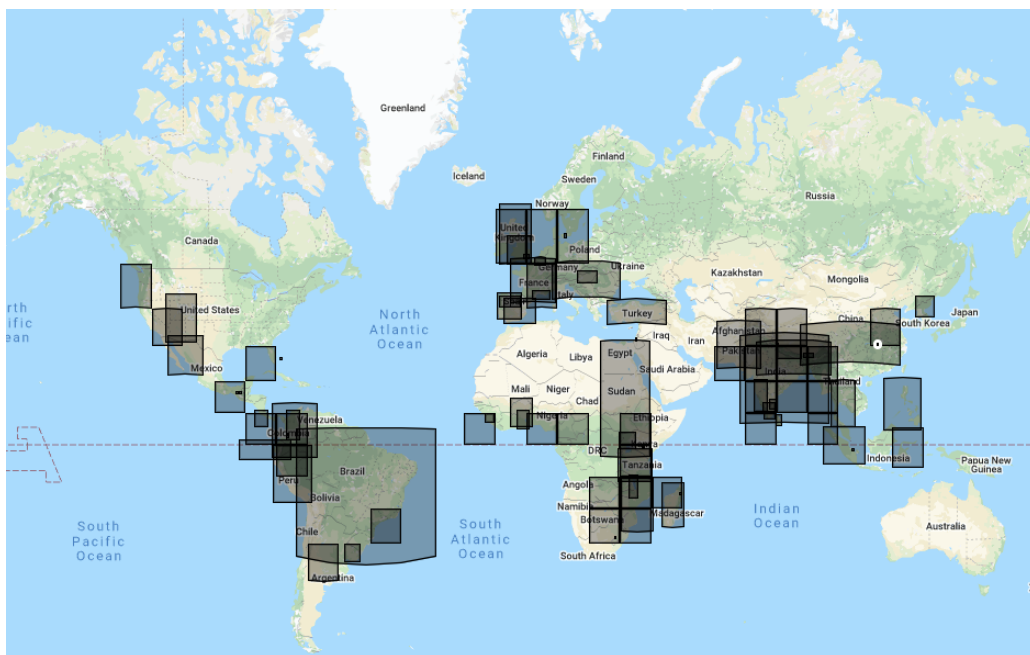


Figure 42 Applications of the Eco:Actuary PSS in 2020

In June 2019, Eco:Actuary and the NAIAD project has also been presented to KPMG in a half-day private meeting with Space4Climate on ways to accelerate private investment in the UK



Government's Clean Growth Strategy. We presented "Tools for prioritising investments to mitigate impacts of climate change".

In July 2019, Eco:Actuary and the NAIAD project was presented to FloodRe, a UK government backed flood reinsurance scheme.

In November 2019, Eco:Actuary and the NAIAD project were presented to the Natural Capital Coalition at the Institute of Chartered Accountants in England and Wales. Also in November 2019, Eco:Actuary was presented to an "Insurance Round Table" of representatives from the Insurance industry, hosted by the EU H2020 project "We Value Nature" called "Climate Change related Financial Risks and natural capital". This was also hosted at the Institute of Chartered Accountants in England and Wales.

In December 2019, Eco:Actuary and the NAIAD project was presented to the Chair of the Actuarial Association of Europe and the Lead for the European Actuaries Climate Index Working Group, with other European Actuaries including Aegon. The actuaries were very interested in the use of Eco:Actuary in developing their European Climate Risk Index and a further more technical discussion was held by Skype in February 2020.

FreeStation and //Smart:

Our three FreeStation training courses took place in London on 2nd April 2019 and 29th May 2019 (as part of London Rivers week) and in Durham on 6 June 2019. The first was for a professional audience and was attended by 35 from Environment agency, local and county councils, rivers trusts, flood action groups, other NGOs and universities. Their key interests are shown in figure 43



Figure 43 Key interest of attendees at FreeStation //Smart: training

Most attendees were interested in application in Natural Flood management (Figure 44a) and would either build FreeStations themselves or wish to engage volunteers to build them (Figure 44b). The workshop was for those from London and the South East and the projects in which participants wished to use the technology are mapped in Figure 44c

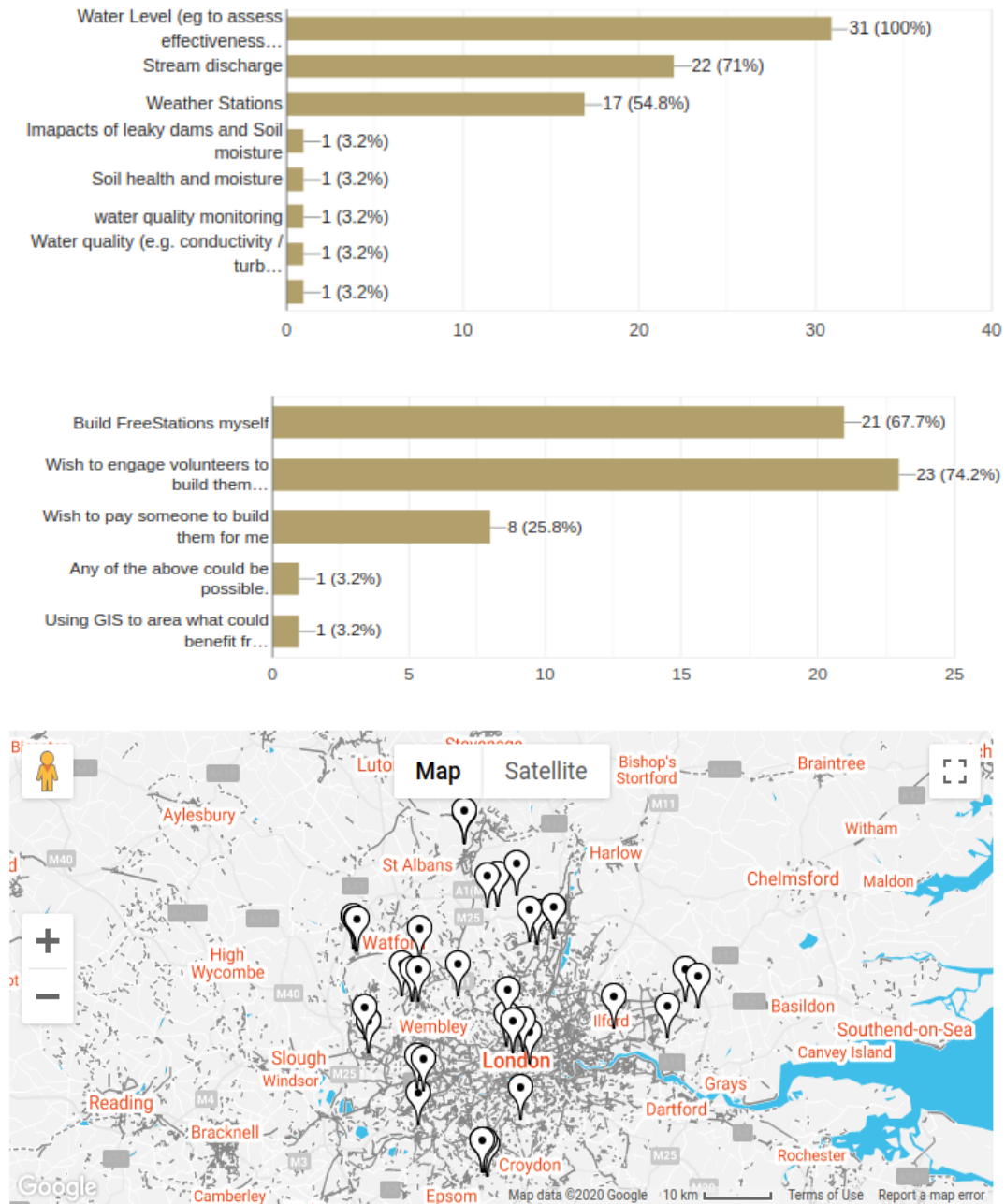


Figure 44 Declared interests and intentions of attendees at NAIAD FreeStation training course



The second training was for the general public as part of London rivers week and was attended by 43. The third (in Durham) was for a professional audience and was attended by 11 from the Yorkshire Dales, Eden, Trent and Wear Rivers Trusts.

Two organisations have independently built and registered FreeStations in 2020 for NFM related projects: Thames21 with 17 stations and Niko Petelin s.p.(a Slovenian company) with 2 devices. Many more have expressed their interest to do so as below.

Thames 21: "We are using FreeStations to monitor water level and build evidence for natural flood management (NFM) approaches in four headwater catchments at locations in Hillingdon, Harrow, Enfield and Havering. The projects, funded by Defra, require monitoring to assess the contribution of NFM interventions to reducing flood peaks during storm events. We are keen to build more FreeStation equipment with volunteer citizen scientists."

SE Rivers Trust: "We are using it to monitor effectiveness of leaky debris dams but also hope it will provide baseline data for water levels for modelling. The data will contribute towards our reporting requirements as a DEFRA funded community NFM programme."

Lune Rivers Trust: "Aim to use it to measure water depths in relation to NFM interventions"

West Country Water Trust: "Amazing project and perfect for river monitoring."

UrbanWise, London: I think this is a wonderful idea. We are an environmental education charity and would love to do this with some of the schools we work with. It is super useful.

Surrey County Council: "I want to develop an understanding of the resources and build capability to share with our schools."

FreeStations have also been taken up in follow up projects by: The Environment Agency (River Brain, 2 stations), Hertfordshire County Council (River Colne, 4 stations), Buckinghamshire County Council (River Leck, 5 stations), Essex County Council (West Horndon, 5 stations), SAFAG, the local Flood Action Group based in Shipston upon Stour (River Stour, 6 stations), Lannock Manor Farm, Hertfordshire (5 stations, conservation agriculture), Affinity Water (crop cover trials, 6 stations, and comparing cultivation practices under oil seed rape, 3 stations).



Training and guidelines

Training materials are provided online as live documents that can be updated as the systems are updated rather than as a static document here. Links to training materials are provided below.

EcoActuary Policy Support System

Key training materials for the E:A PSS are delivered at www.policysupport.org/ecoactuary and include:

- (a) A powerpoint presentation
- (b) A training video demonstration of baseline and scenario functionality
- (c) Links to model and data documentation as well as system (interface and functionality documentation)
- (d) Links to the step by step training course delivered to insurance companies, risk managers, credit rating agencies and others on 11 Sep 2019

Our training programme is outlined below and provides a step by step training in use of Eco:Actuary and //Smart:

<i>Objective: to introduce and provide training in the Eco:Actuary tools for risk assessment, mitigation planning and and natural flood management</i>
NAIAD results and an introduction to the Eco:Actuary catastrophe and catastrophe mitigation model
EcoActuary to map mitigation of flood damage by nature & NFM

The //EcoActuary: training video (211 views) has the following sections:

[What is The Eco:Actuary PSS?](#) (0m0s)

[Accessing and logging in](#) (1m45s)

[Define area](#) (2m55s)

[Prepare data](#) (3m41s)

[Edit catastrophe model parameters](#) (5m10s)



[Start simulation](#) (12m6s)

[Results maps](#) (14m17s)

[Catastrophe model statistics](#) (15m4s)

[Floodplains](#) (16m41s)

[Assets](#) (17m25s)

[Flood storage](#) (20m55s)

[Influential flood storage](#) (28m49s)

[Testing interventions](#) (33m40s)

[Hydrological footprint of protected areas](#) (37m40s)

[Downstream inflence of point interventions \(eg leaky dams\)](#) (40m30s)

FreeStation and //Smart:

Key training materials for FreeStation and //Smart: are delivered at www.freestation.org and www.policysupport.org/smart and include:

- (a) Detailed information on building, troubleshooting and using FreeStations
- (b) A training video demonstration of //Smart: concepts and functionality including:
- (c) Links to the step by step training course delivered to insurance companies, risk managers, credit rating agencies and others on 11 Sep 2019

Our training programme is outlined below and provides a step by step training in use of and //Smart:

Objective: to introduce and provide training in the //Smart:River natural flood management effectiveness assessment tools



[An introduction to FreeStation and //Smart: sensing for real time monitoring, early warning and mitigation effectiveness assessment](#)

[//Smart: training: how to build and use FreeStation //Smart: tools for understanding the effectiveness of \(NFM\) interventions.](#)

The //Smart: training video (48 views) has the following sections:

[What is FreeStation?](#) (0m21s)

[Types of FreeStation](#) (3m5s)

[What is //Smart:?](#) (4m7s)

[How does //Smart: work?](#) (6m10s)

[Smart demo: basics](#) (7m27s)

[Smart demo: analysis: comparison of stage either side of an intervention](#) (9m32s)

[How do I start building?](#) (12m5s)

Conclusions

Natural Flood Management interventions are widely touted as a nature-based solution to mitigating flooding under current and future conditions, to help adapt to climate change and as a means of reducing current flood risk cheaply and effectively. Flooding is a complex phenomenon and the behaviour of NFM interventions such as afforestation, leaky dams, retention ponds and low till or conservation agriculture are poorly known.

We have developed and applied the Eco:Actuary toolkit to better understand current and future risk and the mitigation potential for current green infrastructure and for interventions made towards Natural Flood Management. The toolkit has components for effectiveness assessment



of existing interventions (//SmartRiver: and //SmartSoil), investment planning for the scale of new interventions required (the EcoActuary Investment Planner) and spatial policy support for where and how-many interventions of different types are required to reduce flood losses under current and climate change scenarios.

We find from field, laboratory and modelling studies that the most popular interventions (leaky dams) have a high cost per unit of water stored, require significant maintenance and have low impact on most river systems unless very large scale replication is possible. Different designs of dam have different efficiencies of retention, but the most popular designs (the most leaky) are ineffective for most events and may be subject to damage under extreme events. Leaky dams have few to no co-benefits.

Retention ponds are similarly expensive per unit storage and have little impact at the catchment scale but have an opportunity cost of productivity or other uses on the land which they take up. Retention ponds do have co-benefits for aquatic life, recreation and aesthetics. Retention ponds are expensive to build but low maintenance, though they are subject to sedimentation in the long term and - depending on construction methods - their walls may be subject to breach and damage under extreme events.

Conservation agriculture or other sensitive agricultural land management practices can be much more effective and lower cost. The conservation agriculture trials undertaken here show that land under low tillage has lower soil bulk density, higher soil organic matter, improved infiltration during rain and improved drainage following rain compared with neighbouring fields under conventional tillage. Conservation agriculture is low-cost since it requires less fuel, machinery and effort than conventional tillage, though there may be an opportunity cost for productivity in the short term and weed control can require higher herbicide inputs. Nevertheless CA can be applied over large areas and thus make very significant contributions to reducing flow downstream. The Eco:Actuary Investment Planner shows CA to be a scalable and effective approach, capable of reducing peak flows on most of the Thames gauged tributaries by 15% for an investment of <£250,000 per tributary. CA also has co-benefits for soil carbon sequestration, biodiversity, water resources (though there may also be risks) and sediment retention.

Since agriculture covers some 72% of UK land area, improved management of this land is the only effective way to reduce flooding downstream. The 192,000 farms in the UK need a well designed incentive scheme that prioritises public money for public goods and services such as



flood mitigation. The UK 25 year Environment Plan and new UK Farm Bill show some progress in this area. The EU CAP is moving in similar directions.

However, there need to be clear mechanisms for identifying the marginal benefit of different management strategies, relative to the counterfactual, in a spatially explicit way that takes account of the distribution of assets at risk downstream of farms. Payments for ecosystem services need to be robust and parametric to the services provided. Tools are needed that can measure these services *in situ* in real time and connect to turnkey systems for calculation of parametric payments.

The Eco:Actuary PSS provides an accessible and open platform for mapping flood risk under current and future (climate and land use) conditions and understanding the impact of these floods on damage to a range of asset classes. Eco:Actuary also indicates the role of current green infrastructure in mitigating losses and the potential of specific intervention scenarios to reduce them. Eco:Actuary can be applied anywhere in the world, by anyone to examine flood risk and estimate damage costs, with very little need for additional data. There may be issues with variable Open Street Map (OSM) coverage in some parts of the world but the user can rectify those by doing some asset mapping at OSM. The application is rapid, though the parameterisation of the hazard ensemble, asset inventory values, damage functions and mitigation infrastructure may need editing from place to place.

The tool provides data on (natural) flood storage, flood risk, damage costs for the current baseline and a range of possible user scenarios representing climate change, land use change/management and asset adaptation. The tool may be useful to insurers alongside traditional CAT models but will also have broader applications in the design and effectiveness assessment of NFM solutions in relation to local and downstream assets at risk. In combination with the empirical Eco:Actuary Investment planner and networks of //Smart: sensors, the Eco:Actuary PSS adds an element of strategic planning and scenario analysis.

Examining the impact of climate change scenarios on increasing flood risk and economic losses in the UK shows that a combination of increased storm size and intensity as well as changes in seasonal and spatial distribution of rainfall will likely lead to significant increases in flood damages over the next 30 years. These are shown to be far in excess of the mitigation potential of even a very large scale NFM strategy (converting most protected areas to forested). Protected areas are simply too far from the majority of assets at risk to make much difference and any increase in intensity or size of storms relative to the current provide much greater volumes of saturation and infiltration-excess runoff than can be effectively managed through mitigation. In



the UK setting the improved management of agricultural land will be key to mitigating the impacts of climate change. This land is generally much closer to assets at risk (and thus more influential on them) and provides a much greater storage capacity through improved soil management aerally than other aerial interventions like afforestation or point interventions such as leaky dams and retention ponds. This situation is likely similar in direction if not magnitude across the EU and the world (though should be tested through baseline and scenario applications of Eco:Actuary in these settings). A variety of mitigation options may still be important for localised small scale flooding but, at the basin scale, adaptation will also be important. Mitigation can never reduce risks to zero and even significant mitigation efforts may not keep up with the impacts of climate change. Thus assets and their functions need to be adapted to cope with flooding and, in extreme cases, be rebuilt away from flood plains. Nature-based solutions are still required for their contribution locally and for the co-benefits that they provide but we cannot rely on NBS alone to protect us from current floods not from those that are to come.

References

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