A cloud based tool for knowledge exchange on local scale flood risk using land management scenarios

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Research highlights

- An Environmental Virtual Observatory forms the basis for catchment management.
- A cloud based stakeholder tool was created to explore and manage local flood risk.
- Data, models and local knowledge were integrated into the problem solving tool.
- An agile iterative development process was used incorporating stakeholder feedback.
- Bespoke visualisations allow users to explore future scenarios and model outputs.

Abstract

There is an emerging and urgent need for new approaches for the management of environmental challenges such as flood hazard in the broad context of sustainability. This requires a new way of working which bridges disciplines and organisations, and that breaks down science-culture boundaries. With this, there is growing recognition that the appropriate involvement of local communities in catchment management decisions can result in multiple benefits. However, new tools are required to connect organisations and communities. The growth of cloud based technologies offers a novel way to facilitate this process of exchange of information in environmental science and management; however, stakeholders need to be engaged with as part of the development process from the beginning rather than being presented with a final product at the end.

Here we present the development of a pilot Local Environmental Virtual Observatory Flooding Tool. The aim was to develop a cloud based learning platform for stakeholders, bringing together fragmented data, models and visualisation tools that will enable these stakeholders to make scientifically informed environmental management decisions at the local scale. It has been developed by engaging with different stakeholder groups in three catchment case studies in the UK and a panel of national experts in relevant topic areas. However, these case study catchments are typical of many northern latitude catchments. The tool was designed to communicate flood risk in locally impacted communities whilst engaging with landowners/farmers about the risk of runoff from the farmed landscape. It has been developed iteratively to reflect the needs, interests and capabilities of a wide range of stakeholders. The pilot tool combines cloud based services, local catchment datasets, a hydrological model and bespoke visualisation tools to explore real time hydrometric data and the impact of flood risk caused by future land use changes. The novel aspects of the pilot tool are; the co-evolution of tools on a cloud based platform with stakeholders, policy and scientists; encouraging different science disciplines to work together; a wealth of information that is accessible and understandable to a range of stakeholders; and provides a framework for how to approach the development of such a cloud based tool in the future. Above all, stakeholders saw the tool and the potential of cloud technologies as an effective means to taking a whole systems approach to solving environmental issues. This sense of community ownership is essential in order to facilitate future appropriate and acceptable land use management decisions to be co-developed by local catchment communities. The development processes and the resulting pilot tool could be applied to local catchments globally to facilitate bottom up catchment management approaches.

1 Introduction

Europe is currently experiencing a relatively flood-rich period with a spate of major floods across the continent over the last decade (Macklin and Rumsby 2007, Wilby and Keenan 2012). UK agriculture has experienced significant intensification over the past 70 years as a direct result of national government and European incentives to increase productivity (O'Connell *et al.* 2007, Marshall *et al.* 2013). Agricultural land use management is known to have an influence on downstream flood risk in the UK (Burton *et al.* 2003, O'Connell *et al.* 2007, Wilby *et al.* 2008, Hess *et al.* 2010, McIntyre and Marshall 2010, Wilkinson *et al.* 2013b). Instead of fighting and controlling flood hazards with only traditional engineered solutions (e.g. higher dikes, flood walls), new management styles focus on ‘‘understanding and managing the flood risk’’ (Samuels *et al.* 2006, de Groot 2014). Farmers and land managers are increasingly targeted by scientists to help inform research and policy tools (Nettle *et al.* 2010, Vignola *et al.* 2010, Winsten *et al.* 2010, Oliver *et al.* 2012). There is growing recognition that the appropriate involvement of local communities in land and water management decisions can result in multiple environmental, economic and social benefits. Therefore, local stakeholder groups are increasingly being asked to participate in decision making alongside policy makers, government agencies and scientists (see Lane et al. 2011 which illustrate a way of working with experts, both certified [academic natural and social scientists] and non-certified [local people affected by flooding], for whom flooding is a matter of concern). As such, addressing issues such as flooding requires new ways of learning about the catchment, by engaging with local communities for better mutual understanding. There is a need for a catchment based, community led initiative to understand and respond to flood hazards, using a bottom up approach. Tools are required which are developed through a behaviour driven design process. The communities at risk of flooding, the landowners who manage the land which generate the runoff and the organisations who manage catchments need to be part of the development process from the beginning rather than being presented with a final product at the end.

Recent advances in the area of computing and cyber infrastructure have provided computing platforms to enhance the management of data resources, using services which bring together people and tools, facilitating information sharing for science or other data rich applications (Yang *et al.* 2010, Fox and Hendler 2011, Huang *et al.* 2013). In short this means that we can now compute, model, share information and therefore, potentially, achieve higher levels of insight, and make better decisions than before. A problem today is not so much that we can visualise a virtual reality that has the appearance of being more and more realistic; it is much more the evaluation of the models on which that representation of reality is based. Models can be misleading in the detail, even if they provide some broad resemblance to observations of real variables. An important concept in this respect is treating models as tools for learning about places (the "models of everywhere" concept of Beven (2007) and Beven and Alcock (2012)), whereby models become repositories of knowledge that can assimilate data, integrate information about places from local stakeholders, and be interrogated to guide management and policy decisions, or to inform the requirements for new data to constrain uncertainties.

This type of learning process about places will be similar regardless of discipline, process, users and uses. Detailed visualisation changes the focus from the concepts and issues about how to represent the system to the idiosyncrasies of places; to learn in depth about a particular reach of river, a soil profile or a field. This will require making all the data available about that place on a shared platform; being able to access a collection of models and choose those that are appropriate to understand the complexities that exist; and, allowing that the information collected by communities of volunteers (such as farmers, catchment managers or members of the public) might be valuable in constraining the virtual view of a place. This sense of place can be particularly useful in engaging local communities with processes in familiar contexts to them (Lane *et al.* 2011). If all of these opportunities can be truly managed and brought together, this is the vision and the possibility of what we see as a great new way of doing hydrology and earth science and is what we describe the start of here – an environmental virtual observatory.

New and specific computational opportunities that can contribute to this vision include: (i) the use of cloud computing techniques to allow disparate databases to be readily available to inform the representation of a complex sequence of processes and forcing boundary conditions for a particular application and scale, (ii) the choice and the linking-in of the relevant process representations in a complex system in a way that allows those representations to be easily modified in an open source, user-driven, future-proofed way, (iii) the means of evaluating and managing uncertainty by conditioning against past and new future observations at different scales in space and time, and (iv) ways of presenting complex interpretative and predictive model results to different groups of users using effective visualisation methods. A particularly difficult issue is how to convey the assumptions on which such results are based, and record the audit trail of the decisions that lead to them, in a way that is accessible to users if required (e.g. Kloprogge *et al.* 2011, Beven and Alcock 2012). Accountability should be an important part of the process (e.g. Stirling 2010).

The Environmental Virtual Observatory Pilot project (EVOp) was a proof of concept project to develop new cloud based applications for accessing, interrogating, modelling and visualising environmental data by developing a series of exemplars at the local, national and international scale (in this paper we focus on the local scale exemplar). The long term vision of the Environmental Virtual Observatory concept is to (http://www.evo-uk.org):

1. Make environmental data more visible and accessible to a wide range of potential users including public good applications;
2. Provide tools to facilitate the integrated analysis of data, greater access to added knowledge and expert analysis and visualisation of the results;
3. Develop new, added-value knowledge from public and private sector data assets to help tackle environmental challenges.

The aim of this work was to develop a cloud based learning platform for stakeholders, bringing together fragmented data, models and visualisation tools that will enable these stakeholders to make scientifically informed environmental management decisions at the local scale. This novel cloud based tool was developed through an evolutionary iterative development process involving active local stakeholder engagement. In particular we focussed on communicating the management implications related to flooding, which was identified as a key environmental issue with stakeholders in three focus areas across the UK. More specifically, the objectives were to (1) Develop a framework for creating the cloud based learning platform using stakeholder engagement to identify the crucial components for the end-users, (2) Based on outcomes from (1), build and evaluate the cloud based tool utilising further stakeholder feedback, and (3) Explore how complex hydrological processes (e.g. concepts of hydrological modelling) can be effectively communicated to all stakeholders using cloud based tools to increase understanding of environmental management decisions.

2 Study Areas

The development of the local EVOp cloud based tool was undertaken in three dominantly rural river systems in the UK; the Dyfi (Wales), Dee (Scotland) and Eden (England) (Figure 1). Focus subcatchments of Leri (47 km^2; Dyfi), Tarland (80 km^2; Dee) and Morland (15 km^2; Eden) were chosen based on provision of knowledge from existing research into land, water and stakeholder interactions, coupled with a good network of hydrological sensing. All sites commonly have mixed land use, a range of water quality issues, with small population centres that have suffered recent flooding.

The River Dyfi is located north of Aberystwyth in mid-Wales and its catchment drains an area of 671 km^2. The Dyfi and its tributaries form a dense, dendritic drainage network with a total channel length of over 1,500 km. Rainfall in the upland areas is on average 2000 mm per annum, falling to c. 1000 mm on the coast. Land use in the catchment is dominated by agricultural activity, whereas slate quarrying and metal mining were historically prevalent. The Dyfi catchment has been designated as a UNESCO Biosphere reserve, with 23 designated Sites of Special Scientific Interest (SSSI) and parts of the Snowdonia National Park lying within the catchment boundary. The Leri is a tributary of the Dyfi to the northwest, near the coast. Stakeholders include farming interests and residents of Tal-y-Bont village (population 660) which had severe flooding in June 2012, including damage to local housing and businesses (Foulds *et al.* 2014a, Foulds *et al.* 2014b).

The River Dee in northeast Scotland has multiple European habitat designations (Natura 2000, SAC) for species such as Freshwater Pearl Mussel and economically-important Salmonid fish species. Tarland Burn, situated centrally in the Dee catchment, is the first tributary with intensive land use and first point of nutrient-impacted waters entering the oligotrophic main river (Stutter and Lumsdon 2008). Rainfall is approximately 1000 mm per year with long periods of winter snow. Stakeholders include farming interests, local residents and businesses in both the village of Tarland and town of Aboyne (populations 600 and several thousands, respectively). The Tarland Burn suffers diffuse pollution and morphology issues with pressures from farming, urbanization and septic tanks. It is currently Poor-Moderate under the European Union Water Framework Directive (WFD) and is a Priority Catchment for the national regulator, Scottish Environment Protection Agency (SEPA). The community suffered a large flood in 2002, with minor ones since. In response to these pressures excellent examples of community led initiatives in natural flood management and riparian habitat improvement have occurred (Bergfur *et al.* 2012).

The Eden catchment in northwest England is a mixed grassland area of 2398 km^2, with a main channel length of 130 km. Average rainfall is 1700 mm per year, with higher rainfall on the uplands of the Lake District and Pennine fells on the catchment boundaries to east and west (Mayes *et al.* 2006). The catchment has several sites designated as SSSI and Special Areas of Conservation (SAC) status, for the range of habitats and species it supports and the river passes through two National Parks, two Areas of Outstanding Natural Beauty (AONBs) and a World Heritage Site. Agriculture in the catchment is characterised by mixed dairy and livestock farming, and comprises both rough grazing and improved grazing with some arable land use towards the north and on the richer soils of the River Eden floodplain. Diffuse pollution and flooding are key water pressures across the Eden, including the Morland subcatchment, in the southwest of the main catchment (Owen *et al.* 2012). Stakeholders in this area represent farmers and residents of Morland village (population 380).

3 Iterative Framework Development Process

This section describes the methodology by which the Local EVOp Flooding Tool (LEFT) was created following the agile development cycle presented in Figure 2. The tool was created by a multidisciplinary working group composed of hydrological, environmental modelling, social science, distributed computing and programming specialists. Agile development allows adaptive planning through evolutionary steps and with continued collaboration with stakeholders, facilitating rapid and flexible response to change. Fundamental steps in the process were the discussions with stakeholders at the beginning and in a number of iterations throughout the project cycle to ensure the tool meets the needs of its users.

3.1 Stakeholder Engagement

A fundamental objective was to design, develop and test a cloud based tool with local catchment stakeholders based around the environmental issues of interest to the community; for this a development cycle was proposed (Figure 2). Morland catchment stakeholders were residents of the village of Morland, farmers and catchment managers from the Environment Agency and Natural England. Dyfi catchment stakeholders were villagers who live close to the Dyfi (e.g. Tal-y-bont village), farmers, and local environmental and catchment groups. In the Tarland catchment, stakeholders included farmers, local village residents, SEPA and the local council. These stakeholders were engaged throughout the life of the project. However, it was acknowledged that stakeholders should not be just those who reside within or have a vested interest in the named catchment but also external stakeholders who are interested in the process. These could include, for example, national environmental policy officers or other scientists (including members of the EVOp). The EVOp had a Project Advisory Group (PAG) who offered guidance on the scientific, political and technical development aspects of the project and tool development. This group of eight members consisted of national level representatives from the water and IT industry, regulatory bodies, government, and academia who were technical and scientific experts in the fields of cloud computing and environmental sciences.

Development and feedback meetings (Figure 2) and an evaluation workshop were held in the Dyfi, Tarland and Morland catchments over the two year lifespan of the pilot project. In most cases, these took the form of evening meetings with farmers and local residents, where informal dialogue was engendered to gain their local knowledge and opinions. Alongside this there were meetings with the PAG and other scientific stakeholder groups. The start-up community stakeholder meeting began by introducing the concept of the EVOp, followed by a workshop session to discover relevant environmental issues to both the farming and local village communities. The knowledge exchange exercise during the first workshops identified flooding as a shared and important issue in all three catchments (Mackay *et al.* 2012, Wilkinson *et al.* 2013a). Local flood risk and management became the primary focus of the pilot tool. Development suggestions for the tool were then presented for the next stages with further discussions between the project team and the local stakeholders. The two contrasting stakeholder groups were used to validate the tool throughout the process.

3.2 Storyboard Development

Based on initial stakeholder discussions, there was a requirement for communities to be better informed about flooding in relation to environmental aspects of change in climate, land use and management. A novel aspect of the project was to use a storyboard to ensure the tool development was grounded in real questions and challenges of the end-users. A storyboard was developed for each catchment that reflected the needs of the different stakeholders based around the theme of flooding. This was used to engage and commence design of the data needs and the prototype cloud based tool. This approach allowed the tool to be developed efficiently through stakeholder consultation. With direction from the local communities, the local flooding communities storyboard was created (Table 1). The generic aspects of the combined storyboard process are presented in Table 1b with examples of the specific needs to be addressed by individual communities (Table 1a). The storyboard sets a series of technical and scientific questions. The spatial scale of the tool was reduced to research case studies and the flooding processes were focused primarily on flash flooding arising from rural land management. Other flooding processes were discussed and acknowledge at the first stakeholder workshops (e.g. surface water flooding), however, the stakeholder focus remained on rural land use management. The storyboard provided a mechanism to create a focused tool, which incorporated stakeholder feedback. Before the prototype tool was developed an exercise to understand what cloud resources were available was conducted (Vitolo *et al.* accepted).

3.3 Development Phases

3.3.1 First Development Phase

For the first stage of prototype testing, the format of local community workshops followed a structure of presenting the prototype concepts of the LEFT (see Appendix 1 for an overview of the cloud technologies used in development of the prototypes), obtaining initial feedback, followed by structured discussion on how to move to the next step (following the principles of the LEFT storyboard; Table 1). The main feedback points at this stage from the community meetings were:

- The choice of the LEFT mapping tool technology was accepted (Appendix 1), Google was familiar to them and the use of overlaying colour-coded markers on the map to indicate the availability of additional data sets such as rainfall time series and telemetered imagery was considered intuitive by the stakeholders.
- Many of the technical complexities were not appreciated or even noticed (Appendix 1). For example, in the Morland workshop, real time (telemetry) feeds of rainfall, river level and webcams were accepted as being normal.
- There was more interest in a discussion of the point of the science and modelling and less in the detail of the science and the models. The end users wanted simple messages in a simple format.

The spatial and temporal web interface and the early form of the modelling widget were approved subject to improvements.

3.3.2 Prototype 1

Feedback from the previous step was interpreted by the development team and incorporated into the LEFT. In essence, the need for validation through the agile development process was embraced as the prime methodology for evolving the tool. The development cycle (Figure 2) highlights the agile development steps. This showed that validation is needed at the technical verification stage and at the stakeholder validation stages (Figure 2). Independent testing of each cycle of the design was carried out with stakeholders. This included both a critical assessment of the technical development (e.g. the tools and data – where limitations were acknowledged by the user groups, for example farmers understood the rainfall variations across their catchment) and validation of the conceptual modelling approach (e.g. acknowledging the limitations in conceptualising how the catchment system works and the impact of change). The repetition of the development cycle to produce new prototype versions resulted in the formation of a development matrix (Appendix 2), which indicates the refinement steps of the LEFT and the key improvements made as feedback was assimilated. This allowed stakeholder knowledge to be directly incorporated into the tool. Prototype 1 was able to choose tools that could reflect time series (Flot) and Graphical User Interface (GUI) options such as parameter sliders (which were implemented using HTML5) (see Appendix 1). At this stage, the creation of parameter sliders allowed instantaneous visualisation of the impact of “what-if” decisions on flow and on flood level. Hence land use change and sensitivity of parameter changes could be shown simplistically (although deterministically).

During community workshops, the need to articulate the message of how flooding occurs and the meaning of scenarios became the main focus. An important part of this exercise was to determine what land use change scenarios the stakeholders (both villagers as the receptors and landowners at the source) would prefer to see implemented in the catchment to illustrate how changes to land use and management practices are likely to impact on flood risk at the catchment outlet. The meeting in Morland village attended by local farmers and villagers looked to identify some common land use change scenarios. Alongside the 'current' scenario, three other conceptual scenarios were discussed; increased and intensified farming activities (which would not take on best farming practices), sustainable runoff management with current farming practices (i.e. using agri-environment schemes) and increased woodland. The communities did understand the hydrological concepts and were able to comprehend the danger and possible benefits arising from land management options upstream. It became very clear that 'simple informative descriptions' of processes and scenarios were needed. The PAG largely approved of the tool, however, they were enthusiastic that the tool should be able to run as a self-contained package on the cloud. There was a need to show both sets of stakeholders a comparison of cloud based modelling and desktop based modelling in order to demonstrate computational speed and elasticity differences between both systems.

3.3.3 Prototype 2

The final prototype LEFT was created with a mixture of spatial and temporal tools for the impacts of land use change on flooding. Help and guidance was supplied as part of the LEFT in the form of on-screen help balloons and explanatory illustrations. It was agreed that series of 'talking head' videos would be needed to act as a walkthrough of the tool that would clearly show the generic and bespoke aspects. It was vital to end users that the capability of the modelling tool be explained to all stakeholders with detailed worked examples. Prototype 2 was achieved at the final point of the EVOp project (however, the development group still work to continue its legacy - see discussions). The next section will present the outputs from prototype 2.

4 Results from the Local EVO Flooding Tool

By following the agile development process described in the previous section it has been possible to create a pilot LEFT designed for community needs and to demonstrate the future potential of a full EVO (beyond the pilot). The methodology of using a frequent feedback loop with many user groups was an important development aspect. Hence an agile development approach using active feedback to evolve the tool rapidly was embraced by the stakeholders. Through this development the unique parts of the overall tool are:

- A dynamic mapping interface
- Viewing different sources of live and historical data
- Combining different data sets (mashup)
- Dynamic and elastic cloud modelling
- Learning and explanatory material

A multimedia video demonstration of the pilot LEFT tool can be viewed at http://vimeo.com/103323374 (accessed August 2014).

4.1 Mapping and Data Visualisations

The first prototype responded to the catchment stakeholder desire to view local environmental data relevant to flooding. It was identified during stakeholder meetings with villagers in Morland, Tarland and Tal-y-bont that access to live data can allow communities to make self-informed decisions. This data can be either quantitative (such as rainfall and river level data) or qualitative (e.g. webcam imagery). For example, farmers in the Morland catchment were interested to view live rainfall data across the Eden catchment to compare rainfall totals during storm events. In the Eden catchment, three different sources of time series of hydrometric data visualisations were discovered and linked to (Environment Agency for England and Wales, UK Meteorological Office, and Eden DTC), one of these allowed access to live rainfall dataset visualisations (EdenDTC; see Owen *et al.* 2012, Outram *et al.* 2014). This process indicated the potential to access data from different sources within the Virtual Observatory framework. A customized interactive mapping interface was developed which the user experiences first on entry to the LEFT. Live and static datasets from hydrometric sensors were overlaid on the map as geotagged markers. This provides users with the ability to instantly identify assets of interest based on geographical location. For most users, this entails exploring their local catchment and gathering information from various data sources. The interactive nature of the geospatial layers provides the ability to reveal new interfaces to the user.

This led to the development of bespoke visualisation widgets whereby quantitative and qualitative data could be assessed together using data mashup principles. For example, turbidity data (units NTU) were not widely known by the local community. This useful dataset can communicate the amount of suspended sediment being carried in the channel, an indication of both flow levels and potential diffuse pollution. Combining this dataset with webcam imagery taken at the site of the turbidity measurement allows the user to examine the colour of the water, or how ‘cloudy’ the stream looks. The Flot web library allowed datasets to be combined on the Google Map tool (Figure 3). This LEFT widget was integrated into a georeferenced pin allowing the user to locate the source of the information.

The mapping tool allowed users to explore and discover live data from within their catchments and to potentially use this data to make decisions regarding flooding (however, the river level data only indicate the stage at a fix point). Offline tools have also been developed through a complementary project (the Flood Risk Management Research Consortium) to map flooding and uncertainty in areas at risk of flooding (see Leedal *et al.* 2010, Beven *et al.* 2014a). These were demonstrated in Eden workshops. Integrating these mapping tools into a cloud-based tool would be an ambition of a full EVO. However, for the pilot project, simple cloud based tools and models were investigated (see Appendix 1) to show the potential of a cloud based system. It became apparent during the first prototype workshops with the communities that there was a desire to understand why flooding was occurring and whether could it get potentially worse or improve in the future. Therefore using the interactive mapping tool where assets are laid on a map and widgets opened upon interaction, a LEFT modelling widget was created.

4.2 Cloud Modelling Widget and Communication

This widget contains a number of different options for the user to choose from: the datasets available at this location (for the LEFT this was a recent flood event that the communities in the case study catchments were familiar with), a cloud based hydrologic model, and the model's parameters (using pre-set parameterised scenario buttons or sliders). The LEFT modelling widget was able to model these events and then the user could adjust the parameters accordingly to get a deterministic conceptual understanding of different land use change scenarios impact on the flood hydrograph. A cloud implementation of TOPMODEL (Beven and Kirkby 1979, Beven 2012) was used within the rainfall-runoff modelling widget. TOPMODEL was selected as it is: (1) one of only a few cloud enabled hydrological models available during the development of prototype 1; (2) a simple hydrological model which is widely applicable; and therefore (3) frequently used in the hydrological sciences community; and (4) its concepts and results are easily communicated to stakeholders. During development, model setup was carried out offline to ensure that the input datasets were in the correct format and the model calibrated and validated to adequately simulate the observed discharge. Once all selections were performed by the user, the model was run instantly on demand in the cloud and the returned results were rendered as a hydrograph plotted using Flot (Figure 4, right). Changes in the flood hydrograph could be examined by running the model under different conceptual scenarios and/or parameter combinations to allow comparison between model runs and provide an understanding of the stream's response at the catchment outlet to changes to land use and management. Changes in land use and management in a catchment should be expected to have an impact on flood runoff generation even without any future climate change (Di Baldassarre *et al.* 2010a, Di Baldassarre *et al.* 2010b, de Moel and Aerts 2011, Beven *et al.* 2014b). Figure 4, right, highlights the outputs from the LEFT modelling widget graphical interface. These outputs give a conceptual understanding that if farming was to intensify then flood peaks could increase in magnitude and the time of peak decrease (e.g. O'Connell *et al.* 2004). By implementing runoff management, peak discharges could decrease and the time of peak increase (e.g. O'Connell *et al.* 2007, Deasy *et al.* 2014, Wilkinson *et al.* 2014). Large scale woodland planting could increase this effect (e.g. Robinson *et al.* 1998, Wahren *et al.* 2012, Wheater *et al.* 2012). Owing to the uncertainties in applying the scientific knowledge behind the scenarios at particular sites, it was made clear that they are not meant to specify accurately how much change in flooding would actually take place. However, the educational value of the scenarios and the ensuing debate are indicative of how the community can comprehend and rationalise the scenarios for their own circumstances. The debate on the uncertainties in the approach was discussed. Stakeholders were therefore encouraged to explore the sensitivity to the magnitude of those changes (as represented by the sliders) regardless of how those changes might be implemented in practice. Again the broader understanding of the benefits of flood management and land use management are conveyed to the users in terms of relative risk and not as absolute values.

Users can explore model parameter sensitivity through HTML sliders included in the widget. TOPMODEL parameters m, VR and SRmax were the most sensitive parameters and were implemented as sliders. However, when these parameters were discussed with stakeholders, m was referred to a “land use change” parameter (i.e. the rate of change of the runoff leaving the catchment - the recession rate), VR was referred to the “ditch network” parameter (which relates to the connectivity of the flow) and SRmax referred to as “the vegetation parameter” (which is the rooting depth of the crop or tree species). These sliders default to the settings for each scenario to allow a user to compare how changes to these values alter the model outputs. This expands functionality of the widget, allowing the user to manually parameterise the model, and explore changes in the parameterisation of the model and associated outputs. The derivation of the ‘current’ scenario outputs are based on the calibration of the model to observed flow data.

The uncertainties of this calibration process were discussed and were acknowledged by the stakeholders during workshops. The conceptual ‘change’ scenarios (Figure 4, left) were developed based on a large range of scientific publications that an increase in intensive farming practices increase runoff generation (e.g. O'Connell *et al.* 2004, O'Connell *et al.* 2007), runoff management can reduce the flood peak and afforestation can reduce this further if implemented on a large scale (e.g. McIntyre and Thorne 2013). However, with measures such as woodland planting, there were both synergy and conflict of interest amongst flood storage, environment and farming objectives. Similar findings were concluded in Morris *et al.* (2008) for washland creation in S. England. None of the stakeholders in the Morland catchment wanted to see a substantial increase in woodland. Both villagers and farmers thought this would alter how the community currently functions (i.e. the landscape is a farming environment and that is an important part of the local economy). This highlights that if substantial woodland was desired to meet policy requirements, a sustainable payment mechanism would be required to ensure the rural economy is supported and supportive (e.g. payment for ecosystem services Prager *et al.* 2012).

It should be noted that the evidence behind these flood mitigation impacts are based on this broad knowledge only and it is still subject to current debate. For example, in the Leri catchment (tributary of the Dyfi), given both the size of the storm and the nature of the catchment, the land management scenarios would have had very little impact on the extreme flood event. The key issues were floodplain encroachment and the local Agency’s under-estimation of the flood risk because of the use of short instrumental records (see Foulds *et al.* 2014a). This highlights how land use management change can have little effect on extreme flood events. Catchment stakeholders did comprehend and generally agreed with these scenarios and the discussion about the uncertainties ensured the stakeholders were aware of the limitations of the assumptions. Uncertainty analysis and its communication was highlighted as a key addition to any future tool in a full EVO project. In discussing some of the sources of uncertainty with the local community, further local knowledge can be gathered that could help to minimise some of these uncertainties (e.g. Lane et al. 2011, Beven and Alcock, 2012).

A requirement from stakeholder testing was to create help tools to allow the user to learn about different parts of the modelling widget. These were incorporated as a result of discussions during prototype 1 testing phase. For example, users in Tarland were unfamiliar with how land use scenarios would look for their catchment. By using outputs from a virtual reality theatre, these scenarios could be visualised for their catchment. One of the most important help tools developed (based on feedback from prototype 1) was the TOPMODEL help tool. Using expert knowledge combined with stakeholder feedback, a dynamic help tool was created that allows the user to highlight certain parts of a flood hydrograph and conceptually understand the catchment and model state at that point in time (Figure 5). Figure 5 also allows stakeholders to understand the significance of the model parameters required to run TOPMODEL.

4.3 Stakeholder Evaluation of the Cloud Tool

At the end of the project (whilst demonstrating the final pilot prototype), evaluation events were held in the Morland catchment (local community and landowners/farmers), in Tal-y-bont (local community), the Tarland catchment (with local advisory groups and scientists) and with the wider PAG and scientific groups. After demonstration or use of the final version of the pilot LEFT, attendees were asked to fill in a brief questionnaire. Appendix 3 summarises responses to the main questions on the likely usage, ease of use and appearance of the local EVOp demo. The results from the questionnaire data suggest that the respondents have a mixed perception of the LEFT demo. Although the total number of responses does not represent a large sample size, there are a greater number of positive than negative responses to questions about interest in using the demo and its appearance. Particularly strong positive responses were elicited from questions about frequency of use, ease of use, presentation/layout, usefulness and help and information resources (Appendix 3). A citizen of Tal-y-bont summed up the demonstration saying '*potentially, all of the internet resources* *demonstrated could be very useful to a range of different users*'. Another participant said '*there is a need for internet resources that brings the various strands of data and information together on a particular topic/for an individual or group in one location*'. The large number of neutral responses perhaps reflects that the LEFT does not currently meet the needs of those users, which as a pilot might be expected. However, one participant commented that '*although the EVO portal was interesting, more time would be needed to adequately assess its usefulness*'. The potential use of the LEFT demo was seen more for 'work' as opposed to 'personal' purposes, indicating how stakeholders currently view its likely utility. This highlights the need to develop further versions of the tool based on a wider stakeholder community to capture the needs of the users. The majority of participants would recommend the LEFT to a friend and some people commented that the web tools discussed (especially webcams) '*are a very positive development*'. Stakeholders raised a wide range of issues that should be tackled by a full EVO; for example, biodiversity and habitat conservation, climate change and energy security; food security; droughts; water quality; health of fisheries were all mentioned alongside flood risk.

5 Discussion and Lessons Learned

5.1 Development Framework and Tool outputs

The LEFT has been through three development cycles (Appendix 2) during the life of the project. This agile development approach has allowed stakeholders to input into the design of the tool throughout the pilot project. The key features of the LEFT is that it has a dynamic mapping interface, a user can view live data from different sources, it combines different data sets (using mashup methods), it uses dynamic and elastic cloud modelling, and it engages at all levels of prior knowledge through learning and explanatory material. Stakeholder evaluation has been an important process throughout the development of the tool. The first engagement events led to the focus of developing a flooding tool, whilst later events helped develop the functionality for local stakeholders, local policy makers and scientists. The second meeting (during prototype 1) focused more on the exploration of data, understanding of water processes in the landscape, and the initial development of model scenarios. A discussion of flooding in Morland village using the Environment Agency for England and Wales flood inundation predictions highlighted that the local knowledge of the residents could be used to 'ground truth' these model predictions and help to improve the way the model is set up to run. It was suggested the LEFT modelling widget could be developed into a farmer engagement tool. Further development of the LEFT modelling widget would probably need to focus on the needs of a few regular end-users, such as Catchment Sensitive Farming Officers and the River Trusts, with the prospect for widening this audience over time. A clear message from the evaluation with catchment stakeholders was that the concept of the cloud was not important to them; there was an expectation that this information should be available via the internet already regardless of the employed technical concepts. The real interest was in how it could help their particular problem or the way information was combined, modelled and presented using tools that they do not usually have on their own computers.

Many suggestions were made in the final evaluation workshops to progress the LEFT and the wider EVO concept further. In particular, it was felt the tools needed a clearer focus and applicability to land management scale decision making rather than the catchment scale. This could be a farm scale tool or more defined implications of the impacts of decisions made at the farm level in terms of economic cost or practical changes needed. This would require more existing (or new) models to be developed for use on cloud computing platforms. Stakeholders saw the LEFT and the EVOp concept as an effective means to taking a whole systems approach to solving environmental issues. These findings are similar to de Groot (2014) who concluded that by including both experts and citizens in the development of specific measures, cultural elements such as meanings, values and visions on human/nature relationships can be taken into account in reaching safety and ecological goals. Feedback also identified other ways to take the LEFT forward, for example, by creating flood maps which relate to the modelled hydrographs (see for example Leedal *et al.* 2010, Beven *et al.* 2014b). By linking flood maps to socio-economic data, assessments of the costs and benefits of options could be made, providing the community with information with which to make decisions. Where it was worth the investment a local real-time forecasting could be developed to provide warnings to local people based on local sensors (e.g. Smith *et al.* 2012, Smith *et al.* 2014).

5.2 Future Directions

The modelling widget highlights how elasticity in a cloud computing environment can significantly speed up modelling simulations. The use of cloud computing to run environmental models has great potential. There is no up-front investment, it has lower operating costs, it outsources demanding issues such as scalability, and it has the potential for green IT (El-khatib *et al.* 2014). However, some issues do need to be resolved such as knowing where your data resides, risks of cloud companies closing down and running costs/funding (highlighting sustainability and maintenance issues; who would keep the site up and running and solve technical problems). Legal issues also need to be explored, for example, by mashing two different datasets together it may be possible to create new data (for example, which could identify a regulatory breach) which could identify an individual that could subsequently be used for a prosecution.

The EVOp uses a hybrid approach to take advantage of both types of cloud server (public and private) (El-khatib *et al.* 2012, El-khatib *et al.* 2013). The pilot tool uses flood events which were known by the local community and these events were pre-calibrated within the modelling tool environment, therefore the user could click ‘current conditions’ (Figure 4, left) and the best fitting model output would be applied. This was identified using a random search approach, based on an offline Monte Carlo simulation with 5000 realisations. An automated Monte-Carlo script could be integrated into the modelling widget, but for the purpose of demonstrating the tool, the user is able to use parameter sliders to manually calibrate the model. However, calibrating the tool does require expert hydrological knowledge in the modelling process or it can form part of the learning process for other end users. The pilot LEFT has highlighted there is potential for users to pre-select their desired time period. This was something that could not be actioned in the pilot, however, should be considered in a full EVO. It was found that if complex tools are being communicated to non-specialists, the help material needs to be clear and to the point. An example of how the LEFT has taken this forward is with ‘talking head’ video demonstrations (see weblink at the beginning of the results section).

As the focus of the pilot project was to demonstrate the potential to connect data, models and visualisation tools in the cloud, the model outputs are conceptual. Uncertainty surrounding the outputs was discussed with stakeholders during trialling prototype 2 (when the pilot project ended). The next step would take on board this feedback and consider model uncertainty and communication of this uncertainty. The communication of uncertainty in modelling results was explored in the National Hydrology EVO tool (this shows uncertainty bounds calculated offline). The flood hazard maps used for illustration in the project also included uncertainty estimates (Beven et al., 2014a,b). There is potential to link these types of maps with the outputs from the European Flood Risk Management Directive, allowing flood risk and hazard maps developed in those plans to be linked with similar flood mapping tools (though cloud technologies). There was also an attempt (after the final evaluation) to generate 'live' the uncertainty bounds for the LEFT tool using a Taverna workflow based on the generalized likelihood uncertainty estimation (GLUE) methodology. This was not pursued due to limited time frame of the project. Figure 6 highlights just one option as to how the uncertainty could be visualised in the modelling using only the sliders and multiple simulations. There is a need for future development of the LEFT to include a tool/function to communicate the nature of uncertainties that might result in decisions being made in different ways (see Prudhomme *et al.* 2010, Wilby and Dessai 2010, Beven and Alcock 2012, Beven *et al.* 2014b).

The LEFT is one of four pilot tools developed within the wider EVOp project, focusing on the local scale. National (UK) tools were developed looking at diffuse pollution exports (Greene *et al.* 2015) and water resources modelling (Odoni and the NERC EVOp team 2012). An international scale tool explored soil carbon fluxes (Emmett *et al.* 2014). These tools use the same cloud principles of linking cloud models, data and visualisation tools. However, the fundamental difference is they exist at different scales and engage with different stakeholders. There is a need to link up these tools to allow knowledge from each to be either upscaled or downscaled. For example, some farmers in the Eden catchment were interested to learn more and discover how diffuse pollution levels vary across the UK.

The development of the LEFT (and also the wider EVO tools) raised issues about data availability and sharing. There is a need for all stakeholders to become better at data sharing. Coupled with this, many spatial datasets within the case study catchments are restricted (e.g. land use) and cannot be made public (however, some can be made public at a cost). Therefore if a full EVO were to include real time models, issues regarding the acquisition of real time data would need to be resolved in order for the full potential of an EVO to be realised. Combining live data and environmental models in a cloud environment would allow for more accurate predictions (e.g. local flood warning systems). There is also a need to address compatibility issues; for example some visualisation tools did not perform properly in Internet Explorer prior to version 9.

6 Conclusions

The pilot LEFT tool has been created and tested using an agile development approach. It has brought scientists (from different disciplines), communities and catchment managers together to identify common environmental issues and to look forward at ways to manage these. It provides data visualisations, modelling capability and interpretative information, which can build a greater understanding of the environment and facilitate the exchange of ideas between different interest groups. Overall, there was universal stakeholder agreement that EVOp has the potential to provide a tool that holds both educational and scientific value. The novel aspects of the LEFT are: the co-evolution of tools on a cloud based platform with stakeholders (communities), policy makers and scientists; encouraging sciences to work together (this pilot brought together environmental, computing and social disciplines together); a wealth of information that is accessible and understandable to a range of stakeholders; and provides a framework for how to approach the development of such a cloud based tool in the future. The framework and resulting tool could be applied to similar catchments globablly and applied to other environmental issues. The concept of deploying data, models and tools as services in the cloud was demonstrated to be an effective way forward.

Flooding was highlighted as a key environmental issue in all three study catchments. Other catchment issues were also identified but all the stakeholders involved explored the cloud based tools provided to understand and manage flood risk at a local level. The iterative development process allowed the LEFT tool to be adapted to the users' needs and allowed the development team to efficiently design the functions of the tool that the stakeholders requested. In particular, to make the outputs from modelling more accessable to catchment stakeholders, the results from the hydrological model could be fed into a hydraulic model to allow the effects of different land management scenarios to be tested in terms of predicted inundation maps. The development of the pilot LEFT highlighted issues that should be resolved when developing the next stage of the EVO process. Owing to the limited timeframe of the project (a two year pilot project) the LEFT was unable to explore uncertainty of model outputs in detail. Therefore uncertainties were discussed in final stakeholder workshops.

There is a great deal of potential to further develop the LEFT and incorporate some of the additional features illustrated by the storyboard. It is essential that additional functionality within EVOp is matched by the careful development of supporting material and help features to empower and educate users in how to carry out analyses in a considered way. The addition of more data and sensors from within the study catchments or across more locations would be a simple step to expand the geographical range of EVOp. In terms of tools, the ability to import and manipulate data, rather than stream an image, would allow more options for how the user can view data at sites and compare data between sites. Creating a greater sense of ownership of EVOp by the wider community is important for its continuation and future success; this may partly be achieved by the development of crowdsourcing tools to enable a wide range of people to contribute to tackling science problems. This supports statements that catchment science and management should follow bottom-up working principles (Fraser *et al.* 2006, McGonigle *et al.* 2014, Watson 2014) whereby stakeholders on the ground need to be engaged and involved in catchment management and restoration projects. Local catchment stakeholders identified important merits of using the LEFT (and cloud based tools in general), for example, being able to access data and tools remotely that are normally not available to them. Above all, stakeholders saw EVOp as an effective means to taking a whole systems approach to solving environmental issues.

Already, nationally and internationally there is an appetite for the creation of a full EVO. By using findings from this study and other pilot tools, new initiatives have already been proposed (for example the Belmont Forum [see http://igfagcr.org/ - accessed August 2014]). The EVO concept highlights the ambition for holistic thinking between scientists, policy, practitioners and the general public in order to solve environmental issues. By bringing together our fragmented environmental datasets, models and tools using a cloud infrastructure, these issues can be resolved more efficiently and cost effectively. The EVO offers the realisation of a new type of catchment science and the ‘models of everywhere’ concept.

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Table 1. Migration of (a) one of the community led storyboards (Tarland example) into (b) the conceptual framework storyboard for the interactions of a user with a set of processes for querying a web tool interface.

(a)

1) A local resident asks "how do I decide when my property is at risk from flooding?" and looks at home location on basemap.	2) What data can be accessed that will help me understand the current state of the river and flood risk?	3) User selects link to historical data of where has flooded in the past (includes webcam time lapse analysis)
4) What factors influence flooding? Can we do anything proactive as a community? How may things be different in the future?	5) What does this data mean for the future? User then feeds in model inputs (mitigation, climate, runoff) to give future predictions.	6) So how should I act given all this information? Can I get an SMS text alert at higher risk times? Is all this data really necessary?

(b)

1) **POINT OF ENTRY WITH THE TOOL, MODEL OR DATABASE:** A user has a question, data or interpretation need and arrives at a web portal	2) **SELECTING AN AREA OF INTEREST:** Areas of interest are selected by location of interest, topic or user type (and/or level).	3) **BROWSING AND EXPLORING:** The user can explore environmental data in their catchment including archived and live data feeds with some interpretative levels.
4) **SELECTING AND UNDERSTANDING THE BASIS FOR SCENARIOS**: The user can select a historic flood and a catchment gauging station and run 'what if' land use scenarios for that flood. User selects land use scenario modelling pin.	5) **EXPLORING AND TESTING SCENARIOS:** User can run a hydrological model for different land use scenarios for their local catchment. User selects model (TOPMODEL) and the choice of four land use scenarios.	**6) EXPLAINING FINDINGS:** User can explore outputs and help material about the model. Uncertainty on the conceptual outputs can be assessed using parameter sliders. Help material is available to guide user about interpretation of results.

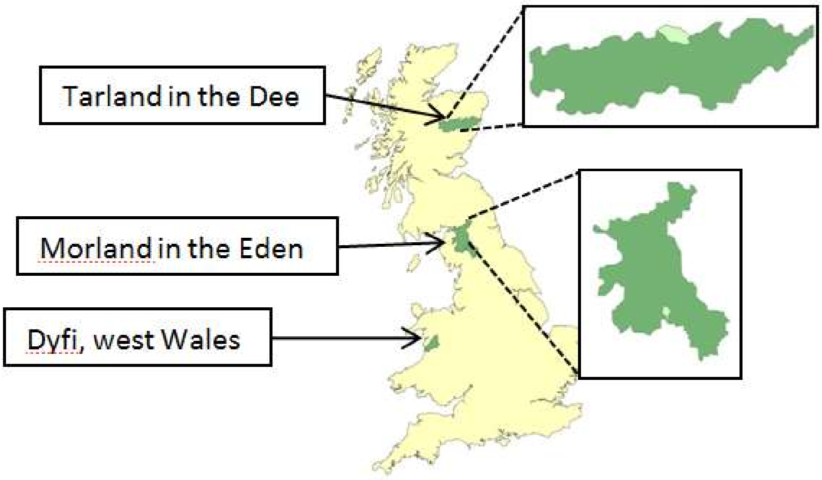


Figure 1: The three UK catchments in which testing and evaluation occurred. The Morland and Tarland (light green) catchments are located within the larger Eden and Dee catchments (dark green) respectively.

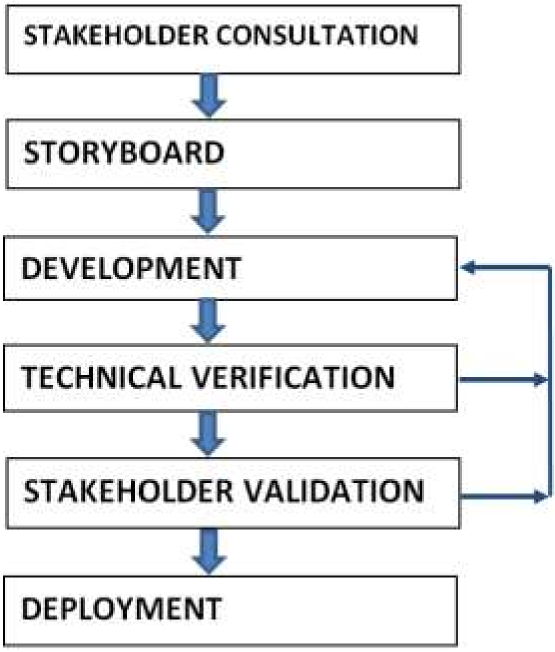
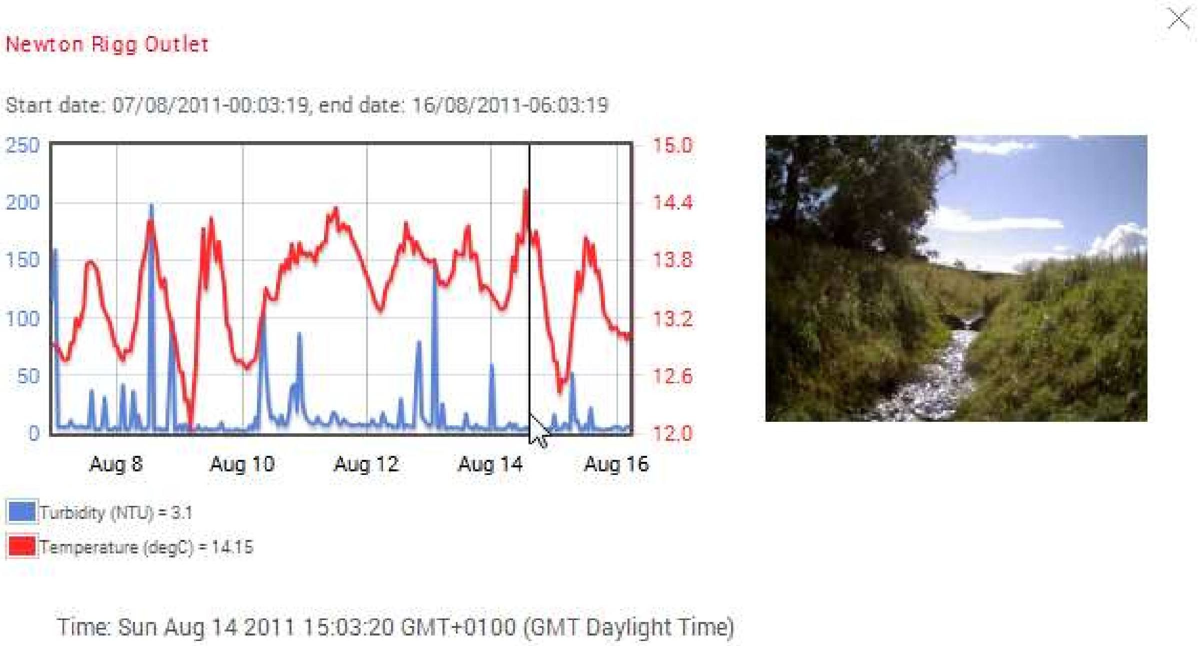


Figure 2: LEFT development cycle



Newton Rigg Outlet

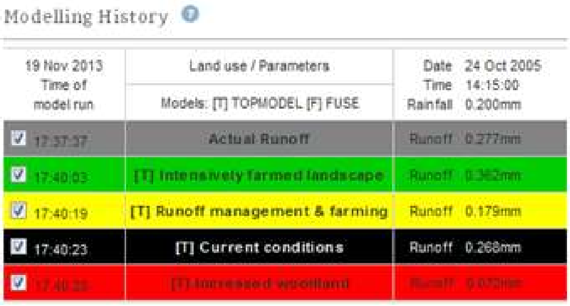
Start date: 07/08/2011-00:03:19, end date: 16/08/2011-06:03:19

🟦 Turbidity (NTU) = 3.1

🟥 Temperature (degC) = 14.15

Time: Sun Aug 14 2011 15:03:20 GMT+0100 (GMT Daylight Time)

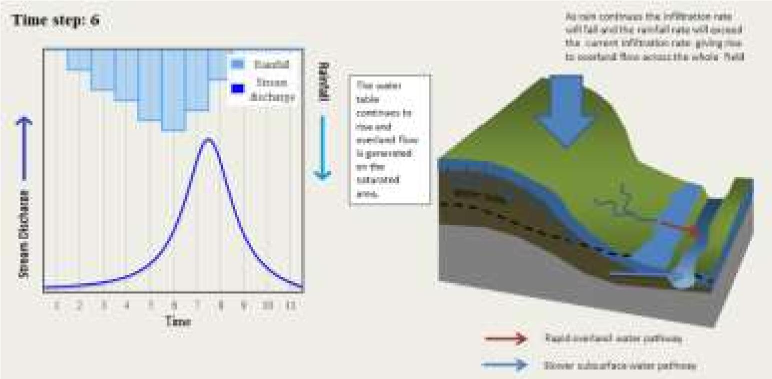
Figure 3: A widget linking turbidity and temperature time series with a webcam image at a selected point in time.



Modelling History

19 Nov 2013 Time of model run	Land use / Parameters Models: [T] TOPMODEL [F] FUSE	Date 24 Oct 2005 Time 14:15:00 Rainfall 0.200mm
☑ 17:37:37	Actual Runoff	Runoff 0.277mm
☑ 17:40:03	[T] Intensively farmed landscape	Runoff 0.362mm
☑ 17:40:19	[T] Runoff management & farming	Runoff 0.179mm
☑ 17:40:23	[T] Current conditions	Runoff 0.268mm
☑ 17:40:28	[T] Increased woodland	Runoff 0.072mm

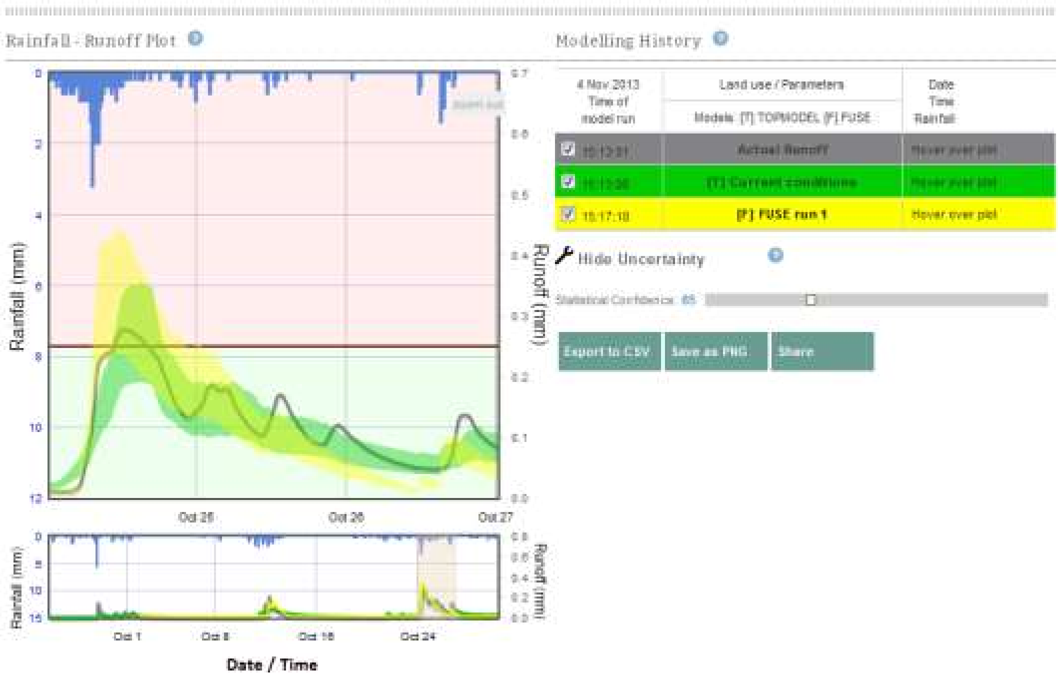
Figure 4: ***Left***; **Conceptual scenarios used in the LEFT modelling widget.** ***Right***; **Outputs from the LEFT modelling widget relating to the selected conceptual scenarios.**



The water table continues to rise and overland flow is generated on the saturated area.

As rain continues the infiltration rate will fall and the rainfall rate will exceed the current infiltration rate giving rise to overland flow across the whole field

Figure 5: Output from an interactive help tool – "what is a hydrograph and how does this relate to TOPMODEL?"



4 Nov 2013 Time of model run	Land use / Parameters Models: [T] TOPMODEL [F] FUSE	Date Time Rainfall
☑ 15:13:31	Actual Runoff	Hover over plot
☑ 15:13:26	[T] Current conditions	Hover over plot
☑ 15:17:10	[F] FUSE run 1	Hover over plot

Figure 6: An example interface (using Flot) that could be used in future tools to explore uncertainties