AGU PUBLICATIONS

Water Resources Research

COMMENTARY

10.1002/2014WR016824

**Key Points:**
- Digital observatories in catchment science can aid stakeholder involvement
- Digital catchment observatories enable new engagement between user groups
- Stakeholders can participate in science and cocreate tools for communication

**Correspondence to:**
E. B. Mackay,
ellcka@ceh.ac.uk

**Citation:**
Mackay, E. B., M. E. Wilkinson, C. J. A. Macleod, K. Beven, B. J. Percy, M. G. Macklin, P. F. Quinn, M. Stutter, and P. M. Haygarth (2015), Digital catchment observatories: A platform for engagement and knowledge exchange between catchment scientists, policy makers, and local communities, *Water Resour. Res.*, *51*, 4815–4822, doi:10.1002/2014WR016824.

Received 6 JAN 2015
Accepted 1 MAY 2015
Accepted article online 5 MAY 2015
Published online 7 JUN 2015

# Digital catchment observatories: A platform for engagement and knowledge exchange between catchment scientists, policy makers, and local communities

**E. B. Mackay[1], M. E. Wilkinson[2], C. J. A. Macleod[2], K. Beven[3], B. J. Percy[4], M. G. Macklin[5], P. F. Quinn[6], M. Stutter[2], and P. M. Haygarth[3]**

[1]Lake Ecosystems Group, Centre for Ecology & Hydrology, Lancaster, UK, [2]The James Hutton Institute, Craigiebuckler, Aberdeen, UK, [3]Lancaster Environment Centre, Lancaster University, Lancaster, UK, [4]Department of Meteorology, University of Reading, Reading, UK, [5]Department of Geography and Earth Sciences, Aberystwyth University, Aberystwyth, UK, [6]School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, UK

**Abstract** Increasing pressures on the hydrological cycle from our changing planet have led to calls for a refocus of research in the sciences of hydrology and water resources. Opportunities for new and innovative research into these areas are being facilitated by advances in the use of cyberinfrastructure, such as the development of digital catchment observatories. This is enabling research into hydrological issues such as flooding to be approached differently. The ability to combine different sources of data, knowledge, and modeling capabilities from different groups such as scientists, policy makers, and the general public has the potential to provide novel insights into the way individual catchments respond at different temporal and spatial scales. While the potential benefits of the digital catchment observatory are large, this new way of carrying out research into hydrological sciences is likely to prove challenging on many levels. Along with the obvious technical and infrastructural challenges to this work, an important area for consideration is how to enable a digital observatory to work for a range of potential end-users, paving the way for new areas of research through developing a platform effective for engagement and knowledge exchange. Using examples from the recent local-scale hydrological exemplar in the Environmental Virtual Observatory pilot project (http://www.evo-uk.org), this commentary considers a number of issues around the communication between and engagement of different users, the use of local knowledge and uncertainty with cloud-based models, and the potential for decision support and directions for future research.

## 1. Introduction

Addressing the hydrological and water resource challenges of the 21st century has led to calls for a change of focus within the research community [*Wagener et al.*, 2010; *Lall*, 2014]. The growing recognition of the complex interconnections between natural and human systems across the water cycle and the unprecedented levels of hydrological and societal change being observed around the world have been identified by the International Association of Hydrological Sciences (IAHS) as the driver for their new Scientific Decade of research challenges [*Montanari et al.*, 2013]. These changes and challenges require new ways of working across national, disciplinary, and societal boundaries, to deliver the research outcomes that will better meet the needs of society. The need for new approaches to research comes at a time when there is a parallel expansion in the capabilities of computing power and cyberinfrastructure, offering new opportunities for research and collaboration [*Montanari et al.*, 2013; *Macleod*, 2015].

At a broad level, community-based geospatial cyberinfrastructure (GCI) is improving people's access to data and information [*De Longueville*, 2010]. This new cyberinfrastructure is facilitating the collection, discovery, and use of data and knowledge, allowing us to do science differently [*Beven*, 2007; *Yang et al.*, 2010]. An example of a GCI is the concept of a digital observatory [*Muste*, 2014], a collection of interoperating data archives and software tools which utilize the internet to form a scientific research environment, with the potential to carry out large and diverse research programs. There are currently initiatives to develop the infrastructure and science base needed for functional digital environmental observatories underway at national and international levels e.g., EarthCube (http://earthcube.org/), TERENO (http://teodoor.icg.kfa-juelich.de/overview-de), and

NEON (http://www.neoninc.org/). In the hydrological sciences, interest is growing in the use of digital catchment observatories, such as the CUAHSI Hydrologic Information System [*Horsburgh et al*., 2011], to improve our spatial and temporal understanding of hydrological processes and how they are modeled and managed [*Beven et al*., 2012; *Muste et al*., 2013]. At the same time, national and international monitoring networks and collaborations among researchers are also providing opportunities for analysis of a wide range of data at high resolutions, such as the lake networks of UKLEON (http://www.ceh.ac.uk/sci_programmes/water/uk-lake-ecological-observatory-network.html) and GLEON (http://www.gleon.org/) and the comparative hydrology project SWITCH-ON (www.water-switch-on.eu) [*Ceola et al*., 2014].

Alongside these technological and scientific developments in hydrology, there is also a recognition that addressing hydrological problems like flooding requires new ways of engaging with the catchment and associated inhabitants at a local level [*Tompkins et al*., 2008; *Krueger et al*., 2012; *Evers et al*., 2012]. Key to the success of these initiatives will be to ensure that the science being carried out within catchments to address these problems allows a dialog focussed on providing solutions to be developed between stakeholders [*Macleod et al*., 2007; *Lane et al*., 2011]. This necessitates the communication of issues from the physical principles of hillslope hydrology to local knowledge of flow paths in a way that is understood by all.

While the technical challenges and potential of these large and global science projects are often highlighted [e.g., *Goodall et al*., 2008; *Wood et al*., 2011; *Laniak et al*., 2013], it is also necessary to consider broader issues surrounding engagement with the potential end-users of the science. Here we discuss and reflect on some of these broader issues, highlighting areas for future research, which were raised during the demonstration and evaluation of the hydrological local-scale exemplar in the Environmental Virtual Observatory (EVO) pilot project [*Emmett et al*., 2014] in three catchments in the UK. The purpose of the EVO pilot project was to use cloud computing technologies to develop novel pilot online applications capable of bringing together data, models, tools, and knowledge for use by a wide range of potential end-users to improve the understanding and management of catchments. The local-scale exemplar, working in river catchments 10–100 km$^2$, developed tools for communicating the topic of flood hazards with a range of stakeholders. Case studies focussed on three catchments in the UK; the Afon Dyfi in Wales (http://www.dyfivo.org.uk/), the River Tarland in Scotland (http://yourcatchment.hutton.ac.uk/), and the River Eden in England (http://www.edendtc.org.uk/). Using our experiences during the project, we provide a brief overview of our pilot digital observatory and then highlight five areas associated with the development of a platform for engagement in a digital catchment observatory, highlighting the potential for future research. These areas relate to opportunities for engagement with stakeholders, the encouragement, and sustainability of participation in science, the communication of hydrological concepts and uncertainties, reconciling different users' demands, and the need to move toward decision support.

## 2. The Pilot Observatory (EVO) and Its Stakeholder Interactions

The Local EVO Flooding Tool (LEFT) was developed as part of an iterative process of stakeholder consultation, storyboard design, web services development, and technical verification (for more detail see M. Wilkinson et al., A cloud based tool for knowledge exchange on local scale flood risk, in review in *Journal of Environmental Management*, 2015). It is a "cloud computing" based tool because it implements internet-based workflows as web services to direct the storage and access of distributed computer resources [*Vitolo et al*., 2015]. The structure of the LEFT was devised using a storyboard approach where a user such as a local resident or farmer wants to find out about current flooding risks and the relationship between land use and flooding in their locality, starting with live data and going on to use model predictions based on land use change scenarios. It is based around a map interface that can be used to identify data visualization and modeling tools at specific locations, providing information on, for example, current river levels and through on-demand modeling, potential influences of land use change on flooding (Figure 1). Using the familiar and freely available Google Maps API as the main interface, data sources and models were linked through location pins accessing external web-based data, databases, and hydrological models (TOPMODEL [*Beven and Kirkby*, 1979] and the framework FUSE [*Clark et al*., 2008]) deployed as web processes [*Vitolo et al*., 2015]. In total, nine workshops and meetings were held with stakeholders at various stages of the LEFT development to discuss hydrological concepts, information needs, display preferences, and opinions on the utility of the tool [*Emmett et al*., 2014]. Feedback was gained through open structured discussion and more formally

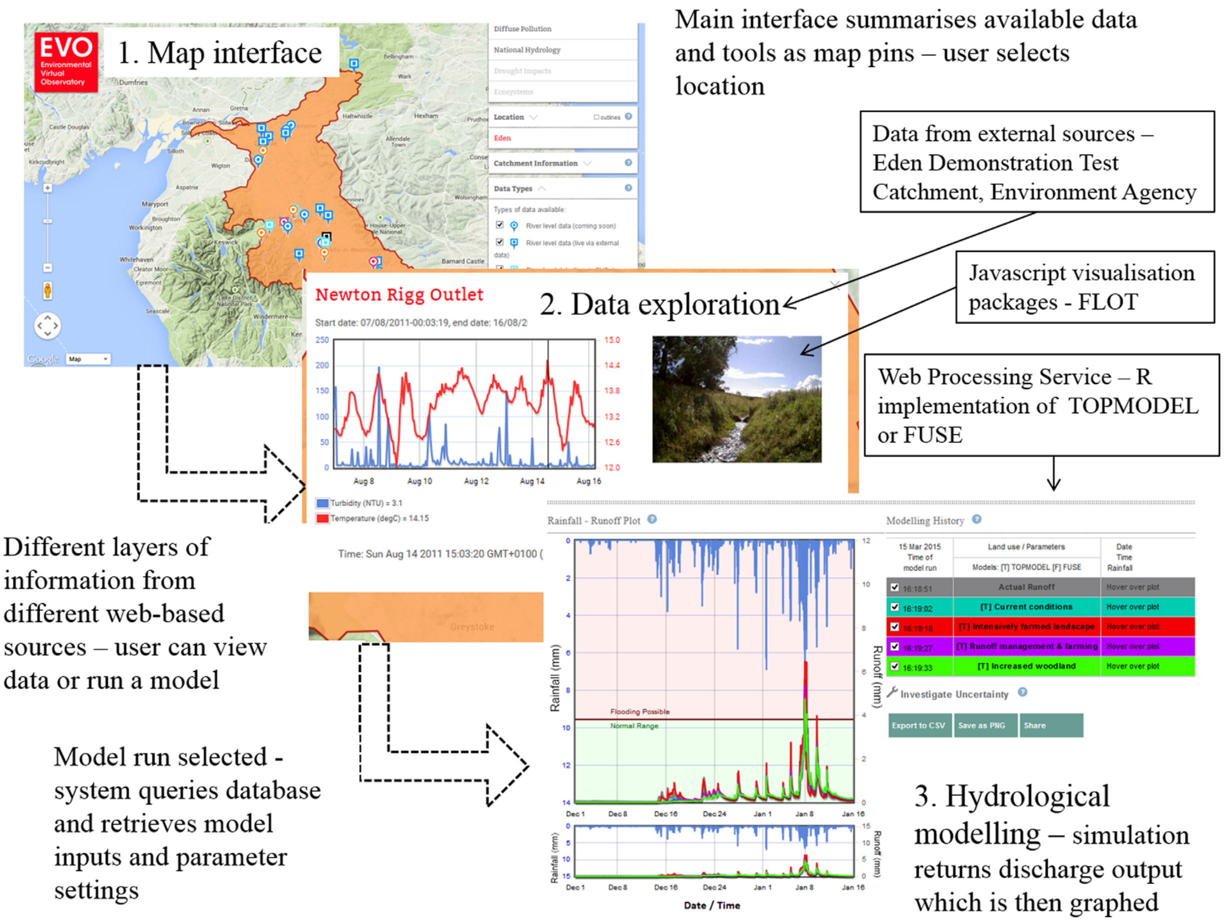

**Figure 1.** Conceptual diagram of the Local EVO Flooding Tool (LEFT) interface showing data sources and land use change hydrological modeling workflow.

through questionnaire responses. Various interest groups were involved in this process including local residents, farmers, catchment managers, policy makers, environmental groups, and scientists. In the following sections, we set out the main benefits we think digital catchment observatories could bring to researchers, policy makers, and local communities based on our experiences of developing and testing LEFT.

## 3. Engagement With Stakeholders

Identified both nationally and internationally as a critical environmental problem, the impacts of flooding become most tangible at a catchment scale, where measures to mitigate the problem are implemented [*Olsson and Berg*, 2005; *Wilkinson et al*., 2010; *CIRIA*, 2013, 2014; *Wilkinson et al*., 2014]. This importance of the catchment scale has been recognized by policy initiatives such as the European Union's Water Framework and Floods Directives, which have sought to decentralize power, through a move toward greater subsidiarity in decisions at regional and local levels and a recognition of the need for the engagement of stakeholders in the process [*Jonsson*, 2005; *Olsson and Berg*, 2005; *Macleod et al*., 2007; *Krueger et al*., 2012]. Addressing complex problems such as flooding and using a digital observatory approach, necessitates collaboration between a wide range of different interest groups from land owners to scientists to policy makers. However, initiating engagement of these stakeholder groups is often not an easy process. This collaborative effort between the different groups requires a long-term commitment focused on finding solutions to clearly defined problems [*Quinn et al*., 2010]. Within the digital catchment observatory, there is a clear opportunity to develop problem-oriented linkages between researchers in different locations and non-research stakeholders linked to locations through land management or habitation. All parties can contribute data, knowledge, and understanding of an issue to a common platform that could be used as the basis for trying out potential solutions on the ground. In the pilot implementation of the LEFT, providing access to linked visualizations of live data such as rainfall, hydrographs, and river webcam images and modeled river flow based on land use scenarios with interpretative help features gave important context and background information to stakeholders to assist in the facilitation of discussions around flooding. Providing visualizations of local rivers and streams and modeled outputs of flood events which the participants were familiar with helped to engage people in discussions through bringing in their own understanding or memories of places and events. In the context of the digital catchment observatory, every locality can potentially be represented by data and models [*Beven*, 2007], which can in turn, be linked into national and international networks of other locations to exchange information on common problems such as reducing flood hazards.

The key benefits of the interaction of local communities and local knowledge within these observatories are that it may allow us to collectively learn more about specific places [*Beven*, 2007] and take more workable decisions at an appropriate scale to address these problems. The digital catchment observatory approach should make moving between scales easier, through the development of user-friendly interfaces, help features, and the combination of multiple scales of observation and modeling within one platform. This could facilitate the work of scientists and policy makers through the transfer of scientific understanding gained about local catchment-scale processes and decision making to national and international-scale projects and vice versa. Beyond the individual national and international exemplars developed as part of the pilot EVO project [*Emmett et al*., 2014], there is now a need to carry out cross scale and interdisciplinary analysis, linking local to global to address some of the global-scale pressures on water resources, and engage more widely with stakeholders [*Lall*, 2014].

In addition, digital catchment observatories potentially offer the opportunity to provide a “voice” for local communities, providing them with access to the same data, information, and models as other stakeholder groups. *Lane et al*. [2011] suggests that this parity of information could lead to a radical change in the hierarchy of decision making for issues such as flood risk management. New collaborations could also be facilitated such as those between scientists, farmers, and environmental economists for the economic justification of payments for flood prevention services in headwater catchments. However, finding ways to facilitate a dialog and the engagement of these different groups, who often use different vocabularies and have different perspectives, experiences of a problem and different drivers for finding a solution is unlikely to be a simple process [*Olsson and Andersson*, 2007; *Savenije and Van der Zaag*, 2008; *Lane et al*., 2011]. The use of cloud-based environmental management tools, which provide greater access to data and models from different disciplines and can facilitate the development of tools to make better use of the information, may create the impetus for new ways to communicate and form consensus around decisions. A key advance of the digital observatory in this context is that the same set of data is used by all stakeholders, creating a shared understanding of an issue, facilitating a more transparent process of engagement, and participation for all users. Operationalizing digital catchment observatory projects that can take account of both the global scale of hydrological challenges and create tangible dialogs for action at appropriate national, regional, and local scales represents a key task for the future.

## 4. Encouraging Participation in Science

Democratization of participation in science and decision making to the scale of local stakeholders could represent an important use for the digital catchment observatory, enabling new science questions to be posed and answered, and engaging the public in their local environment on a platform that is accessible to a range of users [e.g., *Newman et al*., 2012; *Tweddle et al*., 2012]. The stakeholders in our case study catchments had a wide range of environmental questions that they were interested in from flooding and diffuse pollution problems to wildlife conservation and energy supplies. Within the hydrological context, encouraging participation is important for the development of “crowd” validation techniques for model outputs by real people in real places [*Beven et al*., 2012]. This includes both the generation of new data and a review of scientific understanding in the local context such as the use of photos of flooding to map flood extents. Within our local catchments, many participants already collected potentially useful data on rainfall or had qualitative wider knowledge about fields, roads, or properties vulnerable to flooding that could be used alongside model predictions of flood extents.

The benefits of encouraging the participation in science through crowd validation for model outputs and the generation of new data are that they should assist scientists in the improvement of model implementations for specific localities and facilitate engagement between scientists and local communities in addressing local environmental issues and potentially in the wider discussion of scientific research between different groups. Developing tools to capture and integrate this more qualitative information into our model predictions represents an interesting challenge for future research. Maintaining data quality, common standards [e.g., *INSPIRE*, 2007; *Zaslavsky et al.*, 2012], and integrity within the digital catchment observatory is likely to be an essential part of user confidence and participation. To make effective use of these new sources of data and knowledge, rigorous methods are required to capture information with well-designed and standardized data collection, appropriate data verification, and validation techniques [*Silvertown*, 2009].

Sustained engagement of contributors and users of the digital catchment observatory beyond the scientific community is crucial, yet it may represent our greatest challenge in the rapidly evolving digital age [*Olsson and Berg*, 2005; *Cohn*, 2008; *Kim et al.*, 2011]. In addition to the importance of data integrity within the digital catchment observatory, there is a need to create a feeling of community and ownership amongst those participating. For those providing data and local knowledge, this could be through feedback of how results are being used [*Silvertown*, 2009] or how models are being improved in response to local feedback in a process of codevelopment of knowledge [*Lane et al.*, 2011; *Beven and Alcock*, 2012], while for data users, an appreciation of the wider metadata around data sets and tools should accompany their appropriate application.

## 5. Facilitating Communication Between Different Groups

The drive to increase engagement in flood hazard decision making requires effective communication of the problem to a wide range of end-users. Often this necessitates an increased understanding of the problem by decision makers and of the existing knowledge of decision makers by scientists and developers. The issue of communication is important to the development of the digital catchment observatory because of the need to simultaneously engage with different users groups in ways that everyone understands. This applies both to the science issue of focus and the best way to present information to different groups [*Arts et al.*, 2015]. Discussing the linkages between land use management, runoff generation, and flooding with local residents and farmers in our case study catchments highlighted their existing understanding of local hydrological processes, so called "local knowledge," and the need for simple ways to capture their complexity.

The benefit of a digital catchment observatory was that it enabled the "mashing-up" of different data sources into novel tools for communication of these concepts. This included the use of time-lapse images of the response of a nearby stream to a rainfall event and animations alongside hydrological model outputs of hydrograph peaks, making visual linkages between hillslope hydrology and flow levels in a river. These tools facilitated discussions around the local hydrological processes occurring and the viability and extent of land use change required to see a response in a flood peak on a hydrograph. However it was clear that taking this discussion further into making decisions around land use change such as a large-scale increase in woodland would be difficult and require the integration within the observatory of wider cultural, social, and economic data relating to the rural community and economy. The use and development of the visualization tools enabled an exchange of understanding and ideas in both directions during discussions, improving the way that flooding concepts were communicated [see also *Lane et al.*, 2011]. The discussions in our pilot project were face to face, but future development of a digital catchment observatory which might extend over larger scales would necessitate the integration of virtual discussion tools to allow the effective interrogation of modeled outputs. Facilitating dialog between users of a digital catchment observatory will be key to scaling up engagement.

A particularly interesting aspect of the process of developing a digital catchment observatory is the role of modeling uncertainties in the interaction and communication between scientists and stakeholders. Both groups will readily appreciate that model outputs are uncertain, especially when local results are visualized in their correct spatial context. This is, of course, for good epistemic reasons, given insufficient knowledge of local inputs, process representations, and local effective parameter values. In the LEFT tool, there was the possibility of exploring the sensitivity of ranges of model outputs to different assumptions about future change but not yet a full uncertainty analysis, which should form an integral part of further developments in cloud modeling capability. This sensitivity analysis is one way of conveying the potential uncertainty of outcomes to users in an honest and proportionate way (especially given the uncertainty about what type of uncertainty estimation should be used in different circumstances) [e.g., *Beven*, 2012]. Being honest about uncertainties is intended to build confidence in communicating between different groups [e.g., *Juston et al.*, 2013; *CIRIA*, 2014].

## 6. User Demands

Understanding and accommodating the demands of different users of the LEFT is a further challenge to producing an effective platform for dialog about environmental problems [*Yang et al*., 2010; *Macleod et al*., 2012]. Previous studies on model output acceptability have stressed the need for user relevance, transparency in models, data, and their uncertainties, appropriate ways to communicate model results and time for an appropriate dialog between model developers and stakeholder groups [*Olsson and Andersson*, 2007; *Faulkner et al*., 2007; *Beven and Alcock*, 2012]. Within our pilot project, the local-scale flooding tools evolved iteratively in response to a number of evaluation exercises with different user groups to provide a sense of ownership with stakeholders. This created the need to reconcile the competing demands of demonstrating the potential benefits of using the cloud by developers with high levels of model functionality and interactivity for scientists and policy makers and the need for straightforward messages for local residents and farmers.

The benefits of attempting to reconcile the different demands of users in the digital catchment observatory development process are that it challenges scientists and web developers to consider a hydrological problem from alternative perspectives and how to most effectively communicate potentially complex scientific results with other stakeholders. It also encourages other groups such as policy makers to define the information that they need to make decisions. For LEFT, the result is a tool that combines a simple interface with help features (codesigned with stakeholders) to assist with interpretation of modeled results and the additional ability to drill-down into the science behind the model. Several iterations of the development of the model interface were required to ensure functionality was available for all users without creating perceptions of "expert" and "beginner" between users. At the same time, it was important to prevent the interface being overcrowded with technical information relating to model parameterizations unless a user requested it. In general, feedback from the evaluation process was positive, although a key area for improvement was identified by just under half of respondents as the layout, organization, and navigation of the interface, highlighting the importance of considering this area when designing tools for multiple users. The creation of a multilayered interface is our approach to dealing with competing user demands, although this is an ongoing challenge to those seeking to develop digital catchment observatories for a wide range of users.

## 7. Moving Toward Decision Support

The digital catchment observatory pilot project has been a learning process; in terms of the technical challenges surrounding cloud computing and especially how we engage with, interest and develop an observatory which suits the needs of our local communities and wider users. We have developed tools to examine issues around land use management, runoff generation, and flooding. Our stakeholder communities understood and believed these concepts but have now set us the task to expand these tools into decision support mechanisms to offer solutions. The type of decisions discussed included changes to land use or farming practices at specific locations or times to reduce flood risk and local-scale real time warnings based on modeling and sensor networks of rain gauges and soil moisture sensors to highlight locations vulnerable to flooding or when trafficking on fields might lead to soil compaction. At a technical level, decision making could include the coproduction of models and their underlying assumptions between different stakeholders, providing new insights for adaptive management or the pursuit of "no regrets" approaches [*Olsson and Andersson*, 2007; *Lane et al*., 2011]. Using the digital catchment observatory, decisions could be based on site-specific information, making it more relevant and tangible for stakeholders working at the catchment scale. Coupling input data, model outputs, and decision support capability into a digital catchment observatory is an important next step in the development of this type of multiuser research platform, enabling the whole community to work together to tackle issues around flooding. Key to the success of this initiative will be the successful engagement of and communication of concepts between groups, such as the transparent use of uncertainties in model outputs, the appropriate integration of local knowledge and crowd sourced data, and an interface that meets the needs of a wide range of users. It is clear that the potential use of digital catchment observatories for catchment science is a new and evolving approach. The local-scale exemplar of the EVO pilot offers a contribution to these developments and highlights the future potential in this area of hydrological sciences.

## 8. Conclusions

Based on our experience, we argue that digital catchment observatories have a potential to:

1. Raise engagement with stakeholders by facilitating linkages between groups at a range of spatial scales which leads to the ability of scientists to learn more about specific locations and working with local communities and policy makers, pursue more workable decisions.
2. Encourage participation in science by engaging local communities in the collection and contribution of data and knowledge which leads to potential improvements in model implementation for scientists and facilitates engagement between scientists, policy makers, and communities.
3. Facilitate communication between different groups by bringing together different data sources, building on the consideration of uncertainties in science, and designing novel tools for communication which could lead to the exchange of perspectives between scientists and local communities, improving how scientific concepts are represented.
4. Make it easier to reconcile user demands by developing multilayered interfaces and novel visualizations which leads to greater accessibility of scientific understanding for all users and challenges scientists and policy makers to consider different perspectives and specific knowledge requirements.
5. Assist in decision support by bringing together common data and tools which can bring the whole community of scientists, policy makers, and local communities together to address a problem such as flooding.

**Acknowledgments**
To access the EVO portal, please contact pvo@ceh.ac.uk or the corresponding author. This work was supported by the Natural Environment Research Council pilot project, Environmental Virtual Observatory (NE/I002200/1). We are grateful for the helpful suggestions of Berit Arheimer and three anonymous reviewers, which substantially improved a previous version of the manuscript. We would like to thank the Eden Rivers Trust, Dee Catchment Partnership, the Talybont Floodees group, Simon Foulds, and Nicola Thomas for assistance with the project. We also acknowledge the wider contribution of the full EVO pilot project team: Lucy Ball (CEH), Gordon Blair (Lancaster University), John Bloomfield (BGS), Paul Brewer (Aberystwyth University), Wouter Buytaert (Imperial College London), Lucy Cullen (CEH), Julie Delve (CEH), Bridget Emmett (CEH), Jim Freer (Bristol University), Sheila Greene (CEH), Robert Gurney (University of Reading), Penny Johnes (Bristol University), Jane Lewis (University of Reading), Keith Marshall (James Hutton Institute), Adrian McDonald (Leeds University), Nick Odoni (Bristol University), Sim Reaney (Durham University), Gwyn Rees (CEH), Bholanath Surajbali (Lancaster University), Doerthe Tetzlaff (Aberdeen University), John Watkins (CEH), Bronwen Williams (CEH)—all based at UK universities and research institutes.

## References

Arts, K., A. A. R. Ioris, C. J. A. MacLeod, X. Han, S. Sripada, J. R. Z. Braga, and R. Van der Wal (2015), Supply of online environmental information to unknown demand: The importance of interpretation and liability related to a national network of river level data, *Scot. Geogr. J.*, doi:10.1080/14702541.2014.978809, in press.

Beven, K. (2007), Towards integrated environmental models of everywhere: Uncertainty, data and modelling as a learning process, *Hydrol. Earth Syst. Sci.*, *11*, 460–467.

Beven, K., and R. E. Alcock (2012) Modelling everything everywhere: A new approach to decision-making for water management under uncertainty, *Freshwater Biol.*, *57*, 124–132.

Beven, K., W. Buytaert, and L. A. Smith (2012), On virtual observatories and modelled realities (or why discharge must be treated as a virtual variable), *Hydrol. Processes*, *26*, 1905–1908.

Beven, K. J. (2012), Causal models as multiple working hypotheses about environmental processes, *C. R. Geosci.*, *344*, 77–88, doi:10.1016/j.crte.2012.01.005.

Beven, K. J., and M. J. Kirkby (1979), A physically based variable contributing area model of basin hydrology, *Hydrol. Sci. Bull.*, *24*, 43–69.

Clark, M. P., A. G. Slater, D. E. Rupp, R. A. Woods, J. A. Vrugt, H. V. Gupta, T. Wagener, and L. E. Hay (2008), Framework for understanding structural errors (FUSE): A modular framework to diagnose differences between hydrological models, *Water Resour. Res.*, *44*, W00B02, doi:10.1029/2007WR006735.

Ceola, S., et al. (2014), Virtual laboratories: New opportunities for collaborative water science, *Hydrol. Earth Syst. Sci. Discuss.*, *11*, 13,443–13,478, doi:10.5194/hessd-11–13443-2014.

CIRIA (2013), Land Use Management Effects on Flood Flows and Sediments: Guidance on Prediction, London, U. K.

CIRIA (2014), Framework for assessing uncertainty in fluvial flood risk mapping, *Rep. C721*, London, U. K. [Available at http://www.ciria.org/Resources/Free_publications/fluvial_flood_risk_mapping.aspx.]

Cohn, J. P. (2008), Citizen science: Can volunteers do real research?, *Bioscience*, *58*, 192–197.

De Longueville, B. (2010) Community-based geoportals: The next generation? Concepts and methods for the geospatial Web 2.0., *Comput. Environ. Urban*, *34*, 299–308.

Emmett, B., et al. (2014), NERC Environmental Virtual Observatory Pilot, *Final Rep. NE/I002200/1*, Nat. Environ. Res. Counc., U. K.

Evers, M., et al. (2012), Collaborative modelling for active involvement of stakeholders in urban flood risk management, *Nat. Hazards Earth Syst. Sci. 12*, 2821–2842.

Faulkner, H., D. Parker, C. Green, and K. Beven (2007), Developing a translational discourse to communicate uncertainty in flood risk between science and the practitioner, *Ambio*, *16*(7), 692–703.

Goodall, J. L., J. S. Horsburgh, T. L. Whiteaker, D. R. Maidment, and I. Zaslavsky (2008), A first approach to web services for the National Water Information System, *Environ. Modell. Software*, *23*, 404–411.

Horsburgh, J. S., D. G. Tarbotan, D. R. Maidment, and I. Zaslavsky (2011), Components of an environmental observatory information system, *Comput. Geosci.*, *37*(2), 207–218, doi:10.1016/j.cageo.2010.07.003.

INSPIRE (2007), Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE). *Off. J. Eur. Union*, *L108*, 1–14.

Jonsson, A. (2005), Public participation in water resources management: Stakeholder voices on degree, scale, potential, and methods in future water management, *Ambio 34*, 495–500.

Juston, J. M., A. Kauffeldt, B. Q. Montano, J. Seibert, K. Beven, and I. K. Westerberg (2013), Smiling in the rain: Seven reasons to be positive about uncertainty in hydrological modelling, *Hydrol. Processes*, *27*, 1117–1122.

Kim, S., C. Robson, T. Zimmerman, J. Pierce, and E. M. Haber (2011) Creek watch: Pairing usefulness and usability for successful citizen science in *CHI Conference on Human Factors in Computing Systems*, edited by D. Tan et al., pp. 2125–2134, ACM, N. Y., doi:10.1145/1978942.1979251.

Krueger, T., T. Page, K. Hubacek, L. Smith, and K. Hiscock (2012), The role of expert opinion in environmental modelling, *Environ. Modell. Software 36*, 4–18.

Lall, U., (2014) Debates–The future of hydrological sciences: A (common) path forward? One water. One world. Many climes. Many souls, *Water Resour. Res.*, *50*, 5335–5341, doi:10.1002/2013WR015141.

Lane, S.N., N. Odoni, C. Landström, S. J. Whatmore, N. Ward, and S. Bradley (2011) Doing flood risk science differently: An experiment in radical scientific method, *Trans. Inst. Br. Geogr.*, *36*, 15–36.

Laniak, G. F., et al. (2013), Integrated environmental modelling: A vision and roadmap for the future, *Environ. Modell. Software*, *39*, 3–23.

Macleod, C. J. A. (2015), Collaborative knowledge in catchment research networks: Integrative research requirements for Catchment Systems Science in Collaborative Knowledge in *Scientific Research Networks*, pp. 214–236, IGI Global, Pa.

Macleod, C. J. A., D. Scholefield, and P. M. Haygarth (2007), Integration for sustainable catchment management, *Sci. Total. Environ.*, *373*, 591–602.

Macleod, C. J. A., S. G. Sripada, A. A. R. Ioris, K. Arts, and R. van der Wal (2012), Communicating river level data and information to stakeholders with different interests: The participative development of an interactive online service, in *International Environmental Modelling and Software Society (iEMSs) 2012 International Congress on Environmental Modelling and Software Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany*, edited by R. Seppelt et al., International Environmental Modelling & Software Society, Manno, Switzerland. [Available at http://www.iemss.org/society/index.php/iemss-2012-proceedings.]

Montanari, A., et al. (2013), ''Panta Rhei—Everything Flows'': Change in hydrology and society—The IAHS Scientific Decade 2013–2022, *Hydrol. Sci. J.*, *58*(6), 1256–1275.

Muste, M. (2014) Information-centric systems for underpinning sustainable watershed resource management in *Comprehensive Water Quality and Purification*, vol. 4, edited by S. Ahuja, pp. 270–298, Elsevier, Mass.

Muste, M. V., D. A. Bennett, S. Secchi, J. L. Schnoor, A. Kusiak, N. J. Arnold, S. K. Mishra, D. Ding, and U. Rapolu (2013), End-to-end cyberinfrastructure for decision-making support in watershed management, *J. Water Res. Plann. Manage.*, *139*(5), 565–573.

Newman, G., A. Wiggins, A. Crall, E. Graham, S. Newman, and K. Crowston (2012), The future of citizen science: Emerging technologies and shifting paradigms, *Front. Ecol. Environ.*, *10*, 298–304.

Olsson, J. A., and L. Andersson (2007), Possibilities and problems with the use of models as a communication tool in water resource management, *Water Resour. Manage.*, *21*, 97–110.

Olsson, J. A., and K. Berg (2005), Local stakeholders' acceptance of model-generated data used as a communication tool in water management: The Rönneå study, *Ambio*, *34*, 507–512.

Quinn, P., C. Hewett, M. Muste, and I. Popescu (2010), Towards new types of water-centric collaboration, *Proc. ICE*, *163*(1), 39–51.

Savenije, H. G. G., and P. Van der Zaag (2008) Integrated water resources management: Concepts and issues, *Phys. Chem. Earth*, *33*, 290–297.

Silvertown, J. (2009), A new dawn for citizen science, *Trends Ecol. Evol.*, *24*, 467–471.

Tompkins, E. L., R. Few, and K. Brown (2008), Scenario-based stakeholder engagement: Incorporating stakeholders preferences into coastal planning for climate change, *J. Environ. Manage.*, *88*, 1580–1592.

Tweddle, J. C., L. D. Robinson, M. J. O. Pocock, and H. E. Roy (2012) Guide to citizen science: Developing, implementing and evaluating citizen science to study biodiversity and the environment in the UK, Nat. Hist. Mus. and NERC Cent. for Ecol. & Hydrol. for UK EOF, Swindon, U. K.

Vitolo, C., Y. Elkhatib, D. Reusser, C. J. A. Macleod, and W. Buytaert (2015), Web technologies for environmental Big Data, *Environ. Modell. Software*, *63*, 185–198.

Wagener, T., M. Sivapalan, P. A. Troch, B. L. McGlynn, C. J. Harman, H. V. Gupta, P. Kumar, P. S. C. Rao, N. B. Basu, and J. S. Wilson (2010), The future of hydrology: An evolving science for a changing world, *Water Resour. Res.*, *46*, W05301, doi:10.1029/2009WR0089606.

Wilkinson, M. E., P. F. Quinn, and P. Welton (2010), Runoff management during the September 2008 floods in the Belford catchment, Northumberland, *J. Flood Risk Manage.*, *3*, 285–295.

Wilkinson, M. E., P. F. Quinn, N. J. Barber, and J. Jonczyk (2014), A framework for managing runoff and pollution in the rural landscape using a Catchment Systems Engineering approach, *Sci. Total Environ.*, *468*, 1245–1254.

Wood, E. F., et al. (2011) Hyperresolution global land surface modelling: Meeting a grand challenge for monitoring Earth's terrestrial water, *Water Resour. Res.*, *47*, W05301, doi:10.1029/2010WR010090.

Yang, C., R. Raskin, M. Goodchild, and M. Gahegan (2010) Geospatial Cyberinfrastructure: Past, present and future, *Comput. Environ. Urban*, *34*, 264–277.

Zaslavsky, I., D. Valentine, R. Hooper, M. Piasecki, A. Couch, and A. Bedig (2012), Community practices for naming and managing hydrologic variables, in P*roceedings of the AWRA Spring Specialty Conference on GIS and Water Resources*, *New Orleans, LA*, 26–28 March, edited by S. Fox, Am. Water Resour. Association, Middleburg, Va. [Available at http://his.cuahsi.org/documents/IlyaZaslavsky_51e7c422_7956.pdf.]