BHS Working Group on the Future of Hydrology

Working Paper on Improved Observational Methods for Transformational Change in Hydrology.

Water is our planet's most critical resource. It is a paramount importance that we are able to understand and manage its presence in the environment for the benefit of human society and activities, and to protect and enhance natural systems. Dramatic changes to the planet's climate – many already evident - will often be felt most severely through water related phenomena. Impacts will vary, but in many locations a greater frequency and severity of extremes are likely. Long term changes in trends, combined with growing demand for water could bring severe environmental and geopolitical impacts. This is the challenge our community must address, by ensuring that our science, our tools, our practices and our understanding are all fit for a future where demands, and need for precision in our science, will be greater than ever (e.g. Wagener et al., 2010).

The UK has a strong tradition for excellence in hydrology; in hydrological theory, in observational tools, in modelling and in analysis. It is both a pressing imperative, and an exciting opportunity for us to ensure that the UK hydrology community continues to deliver leadership in all spheres of hydrological science.

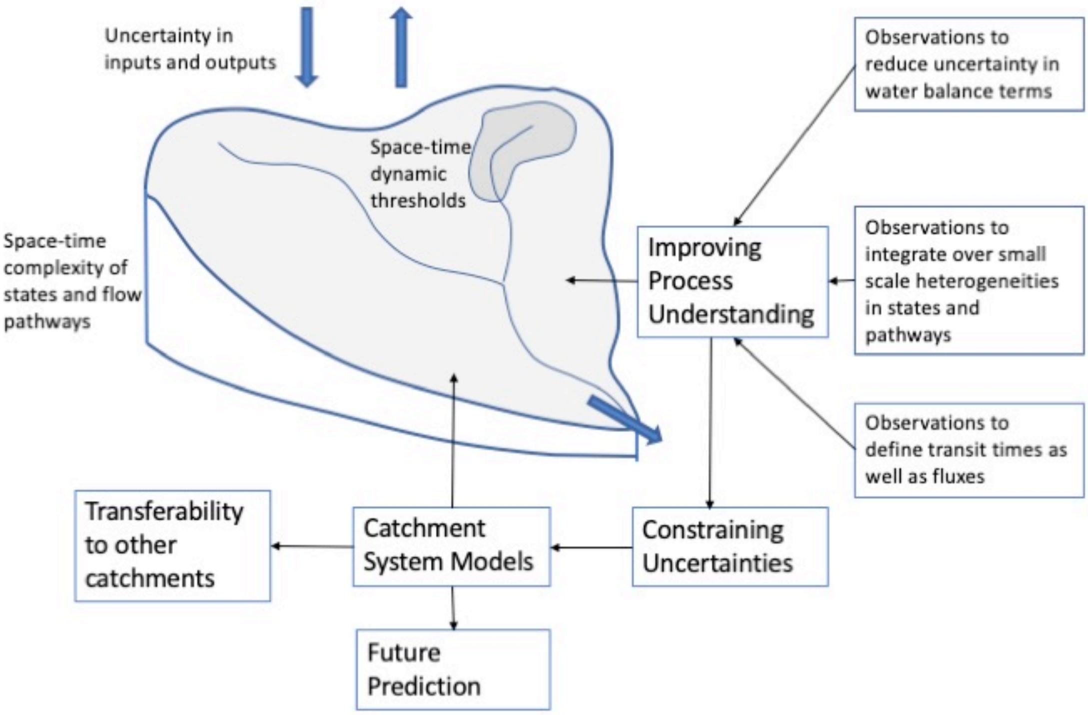
1. The need for better observations in hydrology

Hydrological Science is, and always has been, limited by the available observational methods at the catchment scale. This is a result of the spatial and temporal heterogeneities in inputs; in the catchment landscape (soil, vegetation/land management and geological characteristics); and in patterns of surface and subsurface streamflow generation and evapotranspiration. In fact, much of the detail of hydrological processes is unknowable using current measurement technologies, particularly in the subsurface. We also do not have well developed methods for tracking change in the catchment landscape due to both natural and anthropogenic forcings over time. The situation is much better for laboratory scale experiments, but these are limited in scale (with the largest currently being the artificial hillsides in Biosphere II, Hopp et al., 2009; Volkmann et al., 2018) and there is then a problem of upscaling or transferring such results to the catchment scales or catchment properties of interest.

Thus, hydrology can be considered one of the inexact sciences (e.g. Beven, 2019) such that any predictions are necessarily associated with significant uncertainties and within which hypothesis testing is difficult. It is evident that there are aspects of the details of hydrological systems that are going to remain unknowable for the foreseeable future. This therefore raises the question as what types of observations might be the most effective in gaining a better understanding of hydrological processes and their impacts, and how they might change over time. We wish to state explicitly here that this Working Paper is not simply making an argument for more extensive catchment monitoring. It is rather taking a longer view of what observational techniques might make a transformational difference to hydrological science. This will involve developing methods that have greater accuracy than those currently available and that are fit-for-purpose in quantifying the variables of the water balance, but also developing new types of observations that can throw more light on the complex hydrological processes that control catchment responses under flood and drought conditions.

Given these limits of current observational technologies and approaches, the question remains of "what is needed to effect a transformational change in hydrological science?" (Figure 1). It can be argued that this is not only a question of the open availability of existing data but rather of change in observational methods as it seems likely that any theoretical developments will follow rather than precede new observations in hydrology if only because of the difficulties in testing new hypotheses given current data limitations. We have started to produce a table of current observational capabilities using different methods but this is not yet complete.

Figure 1. The role of observations in effecting change in hydrological understanding



It also poses the question as to WHY such improvements are needed. The impact of current and future change on hydrology and water management is one of the most important aspects of change in many parts of the world (e.g. Wagener et al., 2010), including the UK, both in the form of direct anthropogenic impacts such as urbanisation, land use change and population growth, and through the indirect impacts of a rapidly changing climate. This is reflected in the current IAHS Panta Rhei decadal research initiative (2003-2022) with its focus on the anthropological impacts on hydrological systems (e.g. Montanari et al., 2013; Montanari, 2015; McMillan et al., 2016). Predicting and managing the impacts of future change requires having robust models available where the nature of that change can be reflected in the representation of hydrological processes. Such models need to be based upon reliable data that accurately captures the full range of conditions including, crucially, the extremes. In that we do expect the future to be different from the past, and that this might involve different types of hydrological response to those observed in the past, there is an important need to understand the nature of such changes to allow better predictions, as well as continuing to monitor catchments systems to identify change as it happens.

At present, it cannot be demonstrated that we have models that are fit for purpose in that respect since the available observations, even in research catchments, do not allow sufficiently rigorous hypothesis testing of process representations (and this is even more the case for water quality variables where it has been shown that some popular models are not fit for purpose, e.g. Hollaway et al., 2018). Indeed, it has been recently suggested that hydrological process information has little to add to machine learning methods when it comes to hydrological prediction (Nearing et al., 2020), though such methods can only be used when there are relevant past data available to be analysed and predictions of changed future conditions using such methods is more problematic (e.g. Singh et al., 2011; Hartmann et al., 2017; Reichstein et al., 2019). This has not stopped predictions of future change being made with current methods (there is a pressing need for such predictions in planning for the future) but significant improvements in observational capabilities will lead to better process understanding and process representations (perhaps through machine learning analyses, see Beven, 2020), more rigorous testing of those representations and better predictions of future hydrological responses and the quality variables that depend on water flows and transport.

In this context we can distinguish three types of observational needs that have significant implications for the hydrological understanding and management of water for societal needs, including economic impacts of extremes: the variables of the catchment water balance; observations of space-time variability of hydrological variables; and observations of other variabl;es linked to water flow and transport.

A. The variables of the catchment water balance

The need to improve accuracy and reduce uncertainty on observing the terms of the water balance equation at different catchment scales, in particular discharges, precipitation inputs (rain and snow); evapotranspiration and changes in storage. This is fundamental to hydrological understanding and modelling and yet we currently do not have adequate measurements of any of these quantities at large than “point” scales, and for subsurface storages (required to close the water balance) we do not have any adequate operational techniques at all (we are limited to the very near surface, e.g. COSMOS, or local profiles, both of which are inadequate to close the water balance). In some cases, these variables are very poorly estimated and may be disinformative (e.g. Kauffeldt et al., 2013; Beven and Smith, 2015; Beven, 2019a). An order of magnitude improvement in accuracy, which might require new technologies, would lead to much more rigorous hypothesis testing of hydrological models at the catchment scale (e.g. Beven, 2018; Beven and Lane, 2019). It has been shown that larger scale surface soil moisture measurements might have some value in this respect (e.g. Dimitrova-Petrova et al., 2020) but significant improvements are needed to reduce the uncertainty in all elements of the water balance equation. Thus, for the major terms of the water balance:

- River flows, particularly under high and low flow conditions where uncertainties remain high

- Precipitation, particularly local cells of high intensity and snow accumulation in windy conditions (radar can help in identifying rainfall structure, but uncertainties remain high in assessing intensities)
- Evapotranspiration, particularly under windy wet canopy conditions when high rates can be induced for small changes in humidity, and where it is difficult to integrate over heterogeneous surfaces (though improved laser scintillometers or Raman-lidar profilers might help in this respect)
- Storage, where direct measurements would provide an important constraint on water balance closure (there have been some experiments with surface based gravity anomaly measurements but these remain expensive to install and maintain; while the GRACE satellite observations are too coarse a resolution).

This mass balance approach could also be extended to the catchment energy balance which would be valuable in constraining hydrological responses, particularly in areas where evapotranspiration is the largest output component of the water balance. A theoretical framework exists for combining mass, energy and momentum balances at catchment scales (e.g. Reggiani et al., 1998; Reggiani and Rientjes, 2005) but has not been widely or completely used, primarily because the observations are not available to support adequate functional scale dependent relationships between fluxes and state variables (e.g. Beven, 2007, 2019b) or to define values for the increased number of parameters required in such an approach. Assessing the terms of the energy balance at larger scales remains difficult; most assessments have been limited to plots treated as 1-D profiles. The 3D form and water fluxes of catchments are clearly important in the energy balance however. To assess a larger scale energy balance we would need to assess:

- Total energy inputs from radiation, advection, precipitation and ground sources
- Total energy outputs as sensible and latent heat in evapotranspiration and river flows
- Changes in storage and use of energy within the soil, water storage and vegetation canopy.

While radiation and temperature are variables that are relatively easy and cheap to measure the complexity of the energy system and the difficulty of defining the boundary fluxes has meant that the energy balance is often closed by calculation, thereby lumping all the observational errors and uncertainties into the variable being calculated. This is the case, for example, in the satellite-based space-time estimates of evapotranspiration that are based on images of surface temperature (which are also uncertain, e.g. Marx et al., 2008; Hall et al., 2008; Long et al., 2014). In larger catchments assessments are complicated further by the recycling of energy and vapour through advection and rainfalls within the catchment area.

As a further transformational step within this category, we stress the importance of using high frequency tracer information to provide catchment scale information on transit times and residence times of water within the catchment system. This also has important implications for the understanding of water quality variables. Environmental isotope analysers are now available at reasonable cost (e.g. Picarro) but in the UK have not been widely deployed. World-wide only a handful of high frequency data sets at the catchment scale have been reported (Bermann et al., 2009; Herbstritt et al., 2012; Birkel et al., 2012; Pangle et al., 2013), perhaps because the analysers are not yet sufficiently robust for operational field use.

B. Observations of space-time variability of hydrological responses

We expect many hydrological variables to exhibit strong space-time variability, including variability in the connectivity of flow pathways. The result is that estimates of variables based on local point measurements will often have limited value (especially for rainfalls, snow, evapotranspiration and storage). However, we also consider in this category the need to have better information about key modes of behaviour in the spatial/temporal variability of hydrological responses. This would allow a transformational change in the representation of hydrological processes at the sub-catchment and hillslope scales, without the need for upscaling from the small scale. Important information to improve understanding at such scales would be:

- incremental discharges and solute concentrations along the stream network
- Patterns of initiation and fluxes of overland flows in response to intense rainfall
- Patterns of storage change in different parts of the system (along hillslopes and in different layers)
- Patterns of connectivity of fluxes along different flow pathways
- Preferential flows in soils and groundwater and their interaction with the river network
- Temporal response of wet canopy loss and transpiration over varied and heterogeneous land surfaces to atmospheric conditions
- …

Some of these might allow direct measurement; others might need to be inferred from surrogate measurements (e.g. from tracer information, from temperature signals in satellite retrievals, from site-based observations of evaporation and soil moisture combined with surface temperature observations). Some would require greater levels of accuracy than currently available, particularly where it is necessary to estimate quantities by differencing (e.g. for assessing incremental discharges).

There have been some studies in each of these areas, but not in any comprehensive way that would allow any general inference beyond improving understanding at specific sites. Such inference would be necessary in the transferability of information and understanding to other sites and in considering changed conditions in the future. Such information also provides additional tests for the predictions of models, especially those distributed hydrological models that purport to simulate the space-time hydrological responses of hillslopes.

C. Observations of variables linked to water flow and transport

Some of the most important aspects of future hydrological changes will be in water quality and ecohydrology, including erosion and sediment transport (e.g. Guswa et al., 2020). It is important that such observations are made in conjunction with water quantity variables. Such changes are even more difficult to predict than the water fluxes themselves, in part because of only limited understanding of surface and subsurface flow pathways, the relationships between land management, weathering and nutrient inputs, the importance of biological processes, and the spatial complexities of nutrient and sediment sources. This is an area that would greatly benefit from improved and integrated flux, tracer and biogeochemical monitoring. Cheaper robust and high frequency sensors are required (e.g. Johnes, 2007; Bieroza and Heathwaite, 2015, Mao et al., 2019) to maximise the number of sites that can be monitored continuously with minimal maintenance requirements (compared for example to the on-bank wet chemistry analysis monitoring). High temporal frequency of observations are required to understand the changing relationships with flow during events, and to identify “hot moments” and “hotspots” of high concentrations (e.g. Kraus et al., 2017). Environmental isotopes, suspended sediments and nutrients are perhaps the highest priority for monitoring, while noting that bedload can also have important consequences for flood damages and habitats. High frequency spatial sampling downstream in a river network could also be valuable in certain circumstances in determining concentration “hot spots”. Cheaper spatial coverage is becoming possible using unmanned autonomous vehicles and drones with different types of sensors (e.g. Glaser et al., 2018; Dugdale et al., 2019). Some continuous ecological monitoring, e.g. using spectral fluorescence in detecting phytoplankton, could also help constrain the hypotheses for ecohydrological process representations.

2. Observations for generating fundamental knowledge or understanding.

There will be a class of observations that it might be difficult to justify in terms of improved model predictions in the near-term but which are aimed at improving fundamental knowledge or understanding about hydrological and ecohydrological processes, with some overlap with the observations required to understand space-time variability of hydrological responses discussed earlier. Such studies would be expected to feed back into model process representations and reduced predictive uncertainty in the longer term., with consequent socio-economic benefits in terms of better understanding and resilience to future change.

The important issue here is that there is a lack of fundamental knowledge because the necessary observational techniques do not exist, or are difficult to deploy, at the scales required. A primary example is the role of preferential flows in infiltration and downslope flows. These have been observed in detail in the laboratory, for example using X-ray tomography, and their significance has been inferred from tracer experiments and the movement of pesticides and other pollutants at larger scales, but a non-destructive method for assessing their significance at hillslope and catchment scales is not yet available.

Other processes where better understanding is required include:

- Surface (rather than profile) controls on infiltration under different land management strategies
- Sources of transpiration in the soil profile (and the apparent fractionation of isotope concentrations of water used in transpiration)
- The interaction between velocities and celerities in controlling hydrograph responses and transit times of water.

- Movement of fine particles (and attached pollutants) through the soil
- The interaction of water and microbes in nutrient transport through the soil
- Triggering of algal blooms in rivers and lakes
- Sources and transport of microplastics through catchment systems
- Hot spots and hot moments in river-groundwater interactio
- Preferential recharge and nonlinear response to extreme rainfall events
- Understanding the breakdown of connectivity in soil and geological flow pathways under dry and drought conditions

There will be others, and one of the difficulties here is in identifying priorities where it will be realistic and cost-effective to make advances, either in the short term, or with the development of future observational techniques.

3. The Role of Geophysics

One of the traditional problems encountered in understanding hydrological processes has been that most of what is controlling hydrological responses to inputs is in the subsurface and methods of observing what goes on in the subsurface have been limited to either "point" (piezometers and observation wells, in-situ soil moisture measurements, tomography on laboratory samples) or rather coarse scales using geophysical methods (e.g, electromagnetic induction, ground penetrating radar, surface magnetic resonance, and gravity anomaly measurements). The latter also involve an inversion process that is generally rather poorly posed in respect of the changes in water storage of interest to the hydrologist.

There have, however, been some advances in geophysical methods that may prove valuable in the future. 3D electromagnetic induction observations can now be applied at a variety of scales without cables to both assess subsurface structure and, using repeat measurements, patterns of change of storage (e.g. Truffert et al., 2019). Similarly, repeated transects using ground penetrating radar (GPR) can be used to assess storage changes in the profile along the transects. Experiments have also been made with drone mounted GPR to assess the bathymetry of larger river sections and the near-subsurface structures below the river bed (see https://www.usgs.gov/media/images/usgs-tests-drone-based-ground-penetrating-radar)

Another interesting technique is the use of gravity anomaly methods. This has been used on the GRACE satellite to provide very coarse resolution estimates of changes in subsurface storage (with a basic resolution of 60km, with deconvolution to 25km scales) (see, for example, Schmidt et al., 2006; Syed et al., 2008; Frappart et al., 2011; Zhao et al., 2017). However, there have also been experiments with surface-based gravimeters capable of detecting total subsurface storage changes below the observation point (e.g. Fores et al., 2016; Güntner et al., 2017). There are issues about what storage changes the signal is actually detecting, in part because of difficulties of ground truthing. but this could be a very useful measurement in assessing this term in the water balance equation. To date, such gravimeters with the resolution necessary have been expensive to install and maintain, but there is a new generation of quantum effect gravitometers currently under development that might allow a more widespread implementation of such techniques (e.g. https://www.quantumsensors.org/news/quantum-gravimeters-leaving-laboratory/). The question is whether this technique, once proven, can be made cheap enough to allow deployment for hydrological applications.

Another geophysical method that has real potential for subsurface storage detection is surface nuclear magnetic resonance. This has the advantages that it is non-invasive; it can image directly groundwater from the surface and quantify volumetric water content; it can differentiate between moveable water in large pores from immoveable water that bound in small pores; can provide estimates of local hydraulic conductivitiies; and can provide profiles to depths of 150m (see https://www.vista-clara.com/non-invasive-surface-detection-solutions/). Comparisons with other methods and boreholes suggest that this method can provide useful information in obtaining hydrological information about the subsurface at resolutions of below 1 metre (e.g. Knight et al., 2012; Vouillamoz et al., 2012; Walsh et al., 2014; Singh et al., 2019).

4. The Role of Citizen Science

Another potential source of useful hydrological information is that collected by citizen scientists (Buytaert et al., 2016). This is not a new idea in hydrology; networks of observers for rainfalls have been providing data since the 19th Century. The network of volunteer observers built up by George J. Symons grew to some 3400 by the start of the 20th Century. This was relative to the staff of 50 "professional" observers reporting to James Glaisher at the Greenwich Observatory (Anderson, 2005; Illingworth et al., 2014; Shuttleworth, 2016). The contribution of volunteer observers continues with both the MetOffice and SEPA running sites where data can be entered (https://www.wow.metoffice.gov.uk, https://envscot-csportal.org.uk/rainfallobs/). Other possible variables to be measured are streamflow levels (Davids et al., 2017; Etter et al., 2020), and water quality variables including sampling for algae (Jollymore et al., 2017; Waterton et al., 2015).

The potential is there to expand the range of variables that might be observed by citizen scientists, to both expand the spatial coverage of different variables and involve more members of the public in activities relevant to climate science (Koch and Stisen, 2017; Starkey et al. 2017). Motivation is an issue, depending on circumstances, but incentivisation should certainly be possible linked, for example, for flood resilience projects. It can be easier to get involvement as a result of extreme events, including mapping of water levels after floods (Le Coz et al., 2016; Assumpção et al., 2018; Paul et al., 2018). The process might be made easier, and participation widened, by using citizen science apps on mobile phones, or by concentrating on involving stakeholders with direct involvement in an issue (e,.g, Jackson et al., 2016).

Zulkafli et al. (2017) discuss the effective implementation of a citizen science programme, for data collection including defining user motivations and goals; design of the system based on user interviews and testing; detailed design; and launch and feedback sessions with the local community. Paul et al. (2018) suggest going further, to include citizen stakeholders in data analysis and decision making, something that Haklay (2012) has called "extreme citizen science" (see also Buytaert et al., 2014). That implies some degree of training of the citizens and stakeholders involved (e.g. Etter et al., 2020).

One of the issues that arises in citizen science in the question of quality control of the data collected because of the methods employed, the care with which they are used, the possibility of bias due to vested interests, and commensurability issues with the information that might be required (Kosmala et al., 2016; Specht and Lewandowski, 2016; Aceves-Bueno et al., 2017). Table 1 (taken from Paul et al., 2018) lists some of the challenges in observing different hydrological variables using citizen science methods. In the UK the River Trust network is building up experience of using citizen science in river management.

Table 1. Some Commonly Measured Variables in Hydrological Risk Reduction, and Challenges and Opportunities Emerging from Citizen Science Applications (After Paul et al., 2018)

Variable	Opportunity	Challenges
Precipitation	Cheaper equipment (e.g., electronic tipping bucket rain gauges). Bulk analysis of environmental influences on rain capitation. Merging with remotely sensed observations.	Long-term data collection. Proper installation, maintenance, and documentation of local environmental conditions.
Soil moisture	Automatic measurements (e.g., Time domain reflectometry) becoming increasingly affordable.	Relationship to other soil properties; high spatial variability; dependence on local agricultural practices.
River level/stage	Low-cost, robust, and accurate measurements using latest range-finding technology (e.g., radar and lidar).	Proper maintenance and data download. Conversion to real-time transfer and display. Potential human interference with exposed sensors.
Streamflow (volume per unit time)	Collection of calibration data; cheap measurement technology; emerging image analysis techniques for stage and flow measurements	Proper installation and maintenance; technical support
Water use	Availability of electronic sensors; convenient data communication via the Internet in urban areas	Interpretation and extrapolation of generated data; potential human interference
Vegetation dynamics	Cheap and readily available technology (e.g., GPS, photography; remote identification	Hard to process and combine with remotely sensed

5. Observations and the digital environment

An important consideration in the use of new and improved hydrological observations is how the data are made available to the community within the digital environment in ways that allow more complete and sophisticated analysis of the observations, but which also allow information flows both to and from modelling activities. There was some consideration of this in the short-lived NERC Environmental Virtual Observatory project some years back (e.g. Wilkinson et al., 2013; Karpouzoglou et al., 2016) but this did not get developed further. A more recent look at implementing such a system within a current digital environment is provided by Blair det al. (2019).

There may already the possibility for some advances to be made based on existing UK data, if this could be made more readily available in a more coherent and consistent manner. There have been some improvements in this respect (e.g. the UKCEH Water Resources Portal, https://eip.ceh.ac.uk/hydrology/water-resources/) but there are still considerable constraints in putting together all the hydrological, water quality, abstraction and water transfer data for a catchment together, including the quality assurance / uncertainty information associated with the data. Such archives of data are important to making to making progress in hydrology (e.g. Hannah et al., 2011), but can also be associated with significant uncertainties that will not always be evident to users (e.g. Kauffeldt et al., 2013).

6. Justifying and prioritising future observational needs

At present, our understanding and management of complex and interlinked hydrological variables is significantly constrained by the limitations of observational tools and systems. Improving these, as an input to hydrological understanding, is an urgent necessity in the face of potential future change. There will be significant socio-economic benefit for flood and drought resilience in having improved and consistent hydrological data and model predictions. In flood hydrology, for example, inland flooding is a high priority on the National Risk Register with significant economic impact over the last 20 years, but the significant uncertainties associated with flood discharges means that the design of flood defences is associated with significant uncertainty in terms of both magnitude/frequency relationships and the relevant roughness characteristics to be used in flood inundation models. Uncertainty is generally handled implicitly in flood design by the application of "freeboard" which adds to the cost of the design. Similarly improved low flow information and drought prediction would help greatly in water resource management for water supply and ecological sustainability as well as giving key information ahead of time to communities who will then be better able to mitigate the impact of extreme wet and dry conditions. Better water quality information would also improve understanding of the occurrence of algal blooms in rivers, lakes and reservoirs and their associated costs.

This implies a form of cost-benefit assessment for prioritising observations for different purposes. Such an assessment, however, requires that the effect of different types of observation and their costs (for different accuracy and temporal or spatial resolution for example) be predicted beforehand and propagated forward within the chain of decisions about policies, standards or economic investment strategies as a counterfactual case, for comparison with a baseline (reflecting the current situation). This would allow the sensitivity of benefits from new information to be assessed but is dependent on the the use of models to demonstrate what would be the impact of having different levels of accuracy available for different types of observation applied for different purposes and for specific sites. That implies having a model representation that can take such information into account (e.g. that can make use of an estimate of total subsurface storage at a certain scale should such a measure exist; or that can predict residence times or nutrient concentrations if such observations are to be made available).

Such an assessment can be done in an abstract way without consideration of technical feasibility of making the observations(at least initially). For example, the value of different types of storage observation, or different levels of accuracy of catchment rainfall inputs, or evapotranspiration fluxes could be considered before such observations are available (e.g. Bashford et al., 2002). Such methods are routinely used in demonstrating the potential value of proposed satellite sensors for example, as a form of Bayesian pre-posterior prior analysis. There would be some catchments for which suitable models might exist already (at least for some purposes). Such studies should ideally be carried out before deciding on capital investment priorities but will involve a significant effort to implement and would therefore require some support.

7. Summary

A strategy has been outlined for developing improved observational strategies for hydrological science. Two types of observation are distinguished, those for which the benefits can be demonstrated in terms of reducing uncertainties in hydrological analysis and improved decision making; and those that might be used to improve understanding of hydrological processes and processes driven by water flow and transport. Within the context of the first category priorities for different types of applications might be assessed using ensemble model runs using a form of Bayesian pre-posterior prior analysis. Such an analysis can help define for example the requirements in increased accuracy for the basic terms of the water balance. Such model-based analyses can be made before any capital expenditure and can also be used to evaluate observational methods that are not yet available, subject to the limitations of current models. Tables 2 and 3 summarises the type of observations that might be implemented more widely in the near term future, or developed in the longer term, that might included in this type of value analysis. Such a study could take advantage of some existing catchment models but would, however, need to be resourced as a collaborative project.

Some suggestions are also made of the type of problems that need addressing in the second category. In this case it might not be possible to justify investment on the basis of improved decision making in the near-term, but the understanding gained would be expected to result in improve process representations in the longer term. The availability of these types of data would be truly transformational but will require time. It is thus important that initiatives are started now, if only to assess value and priorities for investment. It goes without saying that it would have been useful to have started such a process 20 years ago to have better techniques available now. It is, however, critical that we should not be in the same position in 20 years, with all the change we expect to occur in that time.

Table 2. Some observational methods that might be implemented more widely in the near term (not in order of priority)

	Method
1	Automatic dilution gauging for better and cheaper rating curve definition, including for incremental discharges downstream.
2	Surface velocimetry and 3D structure to improve discharge estimates at high flows using either fixed cameras or drones (might also be applied to surface runoff patterns and velocities where this is not through surface vegetation).
3	High frequency environmental isotope observation in the field (both rainfall inputs and discharge outputs).
4	X-band radar precipitation estimates, with proper integration of raingauge observations in real-time (including for flood forecasting purposes)
5	High frequency solute and suspended sediment observations.
6	Use of SWOT satellite images (to be launched Sept 2021).
7	Improved constraints on energy balance to reduce uncertainty in spatial ET estimates
8	Seismometry for river discharge measurement (and large scale sediment transport…?)
9	Rainfall measurement from attenuation of cellphone signal between towers
10	River discharge from high resolution satellite imagery

Table 3. Some observational methods that would be valuable to have available in the longer term (not in order of priority)

	Method
1	Integrated continuous storage measurements (e.g. using geophysical or gravity anomaly measurements).
2	A non-tracer based method for estimation of discharge in an arbitrary channel, sufficiently accurate for calculation of incremental discharges downstream.
3	Detection of patterns of subsurface flow velocities and flows through surface vegetation.
4	Space-time detection of pressure wave celerities.
5	Rainfall measurement from attenuation of cellphone signal between towers and phones and phone to phone…?
6	Potential of fibre-optic cables for river discharge sensing, including over floodplains

References

Aceves-Bueno, E., Adeleye, A.S., Feraud, M., Huang, Y., Tao, M., Yang, Y. and Anderson, S.E., 2017. The accuracy of citizen science data: a quantitative review. *The Bulletin of the Ecological Society of America*, *98*(4), pp.278-290.

Anderson, K, 2005, Predicting the Weather: Victorians and the Science of Meteorology (Chicago, IL: University of Chicago Press)

Assumpção, T.H., Popescu, I., Jonoski, A. and Solomatine, D.P., 2018. Citizen observations contributing to flood modelling: Opportunities and challenges. *Hydrology and Earth System Sciences*, *22*(2), pp.1473-1489.

Bashford, K. E., Beven, K. J. and Young, P C, 2002, Observational data and scale dependent parameterisations: explorations using a virtual hydrological reality, *Hydrol. Process.,*16(2), 293-312.

Berman, E.S., Gupta, M., Gabrielli, C., Garland, T. and McDonnell, J.J., 2009. High-frequency field-deployable isotope analyzer for hydrological applications. *Water Resources Research*, *45*(10).

Beven, K J, 2006, The Holy Grail of Scientific Hydrology: $Q_t = H(\underleftarrow{S}\,\underleftarrow{R})A$ as closure, *Hydrology and Earth Systems Science,* 10, 609-618*.*

Beven, K J, 2018, On hypothesis testing in hydrology: why falsification of models is still a really good idea, WIRES Water, DOI: 10.1002/wat2.1278.

Beven, K. J., 2019a, Towards a methodology for testing models as hypotheses in the inexact sciences, Proceedings Royal Society A, 475 (2224), doi: 10.1098/rspa.2018.0862

Beven, K. J., 2019b, How to make advances in hydrological modelling, *Hydrology Research*, 50(6): 1481-1494 doi: 10.2166/nh.2019.134

Beven, K. J., 2020, Deep learning, hydrological processes and uniqueness of place, *Hydrological Processes,* submitted.

Beven, K. J., and Smith, P. J., 2015, Concepts of Information Content and Likelihood in Parameter Calibration for Hydrological Simulation Models, *ASCE J. Hydrol. Eng*., DOI: 10.1061/(ASCE)HE.1943-5584.0000991.

Beven, K. J. and Lane, S., 2019, Invalidation of models and fitness-for-purpose: a rejectionist approach, Chapter 6 in: Beisbart, C. & Saam, N. J. (eds.), *Computer Simulation Validation - Fundamental Concepts, Methodological Frameworks, and Philosophical Perspectives*, Cham: Springer. 145-171.

Bieroza, M.Z. and Heathwaite, A.L., 2015. Seasonal variation in phosphorus concentration–discharge hysteresis inferred from high-frequency in situ monitoring. *Journal of Hydrology*, *524*, pp.333-347.

Birkel, C., Soulsby, C., Tetzlaff, D., Dunn, S. and Spezia, L., 2012. High-frequency storm event isotope sampling reveals time-variant transit time distributions and influence of diurnal cycles. *Hydrological Processes*, *26*(2), pp.308-316.

Blair, G.S., Beven, K.J., Lamb, R., Bassett, R., Cauwenberghs, K., Hankin, B., Dean, G., Hunter, N., Edwards, E., Nundloll, V., Samreen, F., Simm, W., Towe, R., 2019, Models of Everywhere Revisited: A Technological Perspective, *Environmental Modelling and Software*, https://doi.org/10.1016/j.envsoft.2019.104521

Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T.C., Bastiaensen, J., De Bièvre, B., Bhusal, J., Clark, J., Dewulf, A. and Foggin, M., 2014. Citizen science in hydrology and water resources: opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers in Earth Science*, *2*, p.26.

Davids, J.C., van de Giesen, N. and Rutten, M., 2017. Continuity vs. the crowd—Tradeoffs between continuous and intermittent citizen hydrology streamflow observations. *Environmental Management*, *60*(1), pp.12-29.

Dimitrova-Petrova, K., Geris, J., Wilkinson, E.M., Rosolem, R., Verrot, L., Lilly, A. and Soulsby, C., 2020. Opportunities and challenges in using catchment-scale storage estimates from cosmic ray neutron sensors for rainfall-runoff modelling. *Journal of Hydrology*, p.124878.

Etter, S., Strobl, B., Seibert, J., & van Meerveld, H. J.: Value of crowd-based water level class observations for hydrological model calibration. Water Resources Research, 56, e2019WR026108. https://doi.org/10.1029/2019WR026108, 2020.

Fores, B., Champollion, C., Moigne, N.L., Bayer, R. and Chery, J., 2016. Assessing the precision of the iGrav superconducting gravimeter for hydrological models and karstic hydrological process identification. *Geophysical Journal International*, p.ggw396.

Frappart, F., Ramillien, G. and Famiglietti, J.S., 2011. Water balance of the Arctic drainage system using GRACE gravimetry products. *International Journal of Remote Sensing*, *32*(2), pp.431-453.

Glaser, B., Antonelli, M., Chini, M., Pfister, L. and Julian, K., 2018. Mapping surface-saturation dynamics with thermal infrared imagery. *Hydrology and Earth System Sciences*, *22*(11), pp.5987-6003.

Güntner, A., Reich, M., Mikolaj, M., Creutzfeldt, B., Schroeder, S. and Wziontek, H., 2017. Landscape-scale water balance monitoring with an iGrav superconducting gravimeter in a field enclosure. *Hydrology and Earth System Sciences*, *21*(6), p.3167.

Guswa A.J., Tetzlaff D., Selker J.S., Carlyle-Moses D.E., Boyer E.W., Bruen M., Cayuela C., Creed I.F., van de Giesen N., Grasso D., Hannah D.M., Hudson J.E., Hudson S.A., Iida S., Jackson R. B., Katul G.G., Kumagai T., Llorens P., Lopes Ribeiro F., Michalzik B., Nanko K., Oster C., Pataki D.E., Peters C.A., Rinaldo A., Sanchez Carretero D., Trifunovic B., Zalewski M. and Levia D.F. (2020), Advancing ecohydrology in the 21st century: a convergence of opportunities, *Ecohydrology,* 13:e2208. https://doi.org/10.1002/eco.2208

Haklay M. Citizen science and volunteered geographic information – overview and typology of participation. In: DZ Sui, S Elwood, MF Goodchild, eds. *Volunteered Geographic Information, Public Participation, and Crowdsourced Production of Geographic Knowledge*. Berlin, Germany: Springer; 2012.

Hall, D.K., Box, J.E., Casey, K.A., Hook, S.J., Shuman, C.A. and Steffen, K., 2008. Comparison of satellite-derived and in-situ observations of ice and snow surface temperatures over Greenland. *Remote Sensing of Environment*, *112*(10), pp.3739-3749.

Hartmann, Andreas, Gleeson, T., Wada, Y., & Wagener, T. (2017). Enhanced groundwater recharge rates and altered recharge sensitivity to climate variability through subsurface heterogeneity. *Proceedings of the National Academy of Sciences*, *114*(11), 2842–2847. https://doi.org/10.1073/pnas.1614941114

Herbstritt, B., Gralher, B. and Weiler, M., 2012. Continuous in situ measurements of stable isotopes in liquid water. *Water Resources Research*, *48*(3).

Hollaway, M.J., Beven, K.J., Benskin, C.McW.H., Collins, A.L., Evans, R., Falloon, P.D., Forber, K.J., Hiscock, K.M., Kahana, R., Macleod, C.J.A., Ockenden, M.C., Villamizar, M.L., Wearing, C., Withers, P.J.A., Zhou, J.G., Haygarth, P.M., 2018, Evaluating a processed based water quality model on a UK headwater catchment: what can we learn from a 'limits of acceptability' uncertainty framework?, *J. Hydrology.* 558: 607-624. Doi: 10.1016/j.jhydrol.2018.01.063

Hopp, L., Harman, C., Desilets, S. L. E., Graham, C. B., McDonnel, J. J., and Troch, P. A. (2009). Hillslope hydrology under glass: confronting fundamental questions of soil-water-biota co-evolution at biosphere 2. 13:2105–2118.

Illingworth, S.M., Muller, C.L., Graves, R. and Chapman, L., 2014. UK Citizen Rainfall Network: a pilot study. *Weather*, *69*.

Jackson F.L., Malcolm I.A. and Hannah D.M. (2016), A novel approach for the design of large scale river temperature monitoring networks, *Hydrology Research*, **47**, 569-590 DOI: 10.2166/nh.2015.106

Johnes, P.J., 2007. Uncertainties in annual riverine phosphorus load estimation: impact of load estimation methodology, sampling frequency, baseflow index and catchment population density. *Journal of Hydrology*, *332*(1-2), pp.241-258.

Jollymore, A., Haines, M.J., Satterfield, T. and Johnson, M.S., 2017. Citizen science for water quality monitoring: Data implications of citizen perspectives. *Journal of environmental management*, *200*, pp.456-467.

Karpouzoglou, T., Zulkafli, Z., Grainger, S., Dewulf, A., Buytaert, W. and Hannah, D.M., 2016. Environmental virtual observatories (EVOs): prospects for knowledge co-creation and resilience in the information age. *Current Opinion in Environmental Sustainability*, *18*, pp.40-48.

Kauffeldt, A., Halldin, S., Rodhe, A., Xu, C.Y. and Westerberg, I.K., 2013. Disinformative data in large-scale hydrological modelling. *Hydrology and Earth System Sciences*, *17*(7), pp.2845-2857.

Knight, R., Grunewald, E., Irons, T., Dlubac, K., Song, Y., Bachman, H.N., Grau, B, Walsh, D., Abrahams, J. D., and Cannia, J.(2012). "Field experiment provides ground truth for surface nuclear magnetic resonance measurement." *Geophys. Res. Lett.*, 39, 3. doi:10.1029/2011GL050167

Koch, J. and Stisen, S., 2017. Citizen science: A new perspective to advance spatial pattern evaluation in hydrology. *PloS one*, *12*(5).

Kosmala, M., Wiggins, A., Swanson, A. and Simmons, B., 2016. Assessing data quality in citizen science. *Frontiers in Ecology and the Environment*, *14*(10), pp.551-560.

Krause S., Lewandowski J., Grimm N., Hannah D.M., Pinay G., McDonald K., Marti E., Argerich A., Pfister L., Klaus J., Battin T., Larned S., Schelker J., Fleckenstein J., Schmidt C., Rivett M.O., Watts G., Sabater F., Sorolla A. and Turk V. (2017), Ecohydrological interfaces as hotspots of ecosystem functioning, *Water Resources Research*, **53**, 6359-6376, DOI: 10.1002/2016WR019516

Le Coz, J., Patalano, A., Collins, D., Guillén, N.F., García, C.M., Smart, G.M., Bind, J., Chiaverini, A., Le Boursicaud, R., Dramais, G. and Braud, I., 2016. Crowdsourced data for flood hydrology: Feedback from recent citizen science projects in Argentina, France and New Zealand. *Journal of Hydrology*, *541*, pp.766-777.

Long, D., Longuevergne, L. and Scanlon, B.R., 2014. Uncertainty in evapotranspiration from land surface modeling, remote sensing, and GRACE satellites. *Water Resources Research*, *50*(2), pp.1131-1151.

Lowry, C.S. and Fienen, M.N., 2013. CrowdHydrology: crowdsourcing hydrologic data and engaging citizen scientists. *GroundWater*, *51*(1), pp.151-156

Mao F., Khamis K., Krause S., Clark J.R.A. and Hannah D.M. (2019), Low-cost environmental sensor networks: recent advances and future directions, *Frontiers in Earth Science- Hydrosphere*, **7**, Art. No. UNSP 221, DOI: 10.3389/feart.2019.00221

Marx, A., Kunstmann, H., Schüttemeyer, D. and Moene, A.F., 2008. Uncertainty analysis for satellite derived sensible heat fluxes and scintillometer measurements over Savannah environment and comparison to mesoscale meteorological simulation results. *Agricultural and Forest Meteorology*, *148*(4), pp.656-667.

McMillan, H., Montanari, A., Cudennec, C., Savenije, H., Kreibich, H., Krueger, T., Liu, J., Mejia, A., Van Loon, A., Aksoy, H. and Di Baldassarre, G., 2016. Panta Rhei 2013–2015: global perspectives on hydrology, society and change. *Hydrological sciences journal*, *61*(7), pp.1174-1191.

Montanari, A., 2015. Debates—Perspectives on socio-hydrology: Introduction. *Water Resources Research*, *51*(6), pp.4768-4769.

Montanari, A., G. Young, H. Savenije, D. Hughes, T. Wagener, L. Ren, D. Koutsoyiannis, C. Cudennec, S. Grimaldi, G. Bloeschl, M. Sivapalan, K. Beven, H. Gupta, B. Arheimer, Y. Huang, A. Schumann, D. Post, M. Tani, E. Boegh, P. Hubert, C. Harman, S. Thompson, M. Rogger, M. Hipsey, E. Toth, A. Viglione, G. Di Baldassarre, B. Schaefli, H. McMillan, S. Schymanski, G. Characklis, B. Yu, Z. Pang, V. Belyaev. 2013. "Panta Rhei – Everything Flows": Change in hydrology and society – The IAHS Scientific Decade 2013-2022. *Hydrological Sciences Journal,* 58(6), 1256-1275.

Nearing, G. S., Frederik Kratzert2 Alden Keefe Sampson, Craig S. Pelissier, Daniel Klotz, Jonathan M. Frame, Hoshin V. Gupta, 2020, What Role Does Hydrological Science Play in the Age of Machine Learning?, *Water Resources Research,* submitted.

Pangle, L.A., Klaus, J., Berman, E.S., Gupta, M. and McDonnell, J.J., 2013. A new multisource and high-frequency approach to measuring δ2H and δ18O in hydrological field studies. *Water Resources Research*, *49*(11), pp.7797-7803.

Paul, J.D., Buytaert, W., Allen, S., Ballesteros-Cánovas, J.A., Bhusal, J., Cieslik, K., Clark, J., Dugar, S., Hannah, D.M., Stoffel, M. and Dewulf, A., 2018. Citizen science for hydrological risk reduction and resilience building. *Wiley Interdisciplinary Reviews: Water*, *5*(1), p.e1262.

Reggiani, P. and Rientjes, T.H.M., 2005. Flux parameterization in the representative elementary watershed approach: Application to a natural basin. *Water Resources Research*, *41*(4).

Reggiani, P., Sivapalan, M., and Hassanizadeh, S. M.: A unifying framework of watershed thermodynamics: balance equations for mass, momentum, energy and entropy and the second law of thermodynamics, Adv. Water Res., 22, 367–398, 1998.

Reichstein, M., Camps-Valls, G., Stevens, B., Jung, M., Denzler, J., Carvalhais, N., & Prabhat. (2019). Deep learning and process understanding for data-driven Earth system science. *Nature*, *566*(7743), 195–204.

Schmidt, R., Schwintzer, P., Flechtner, F., Reigber, C., Güntner, A., Döll, P., Ramillien, G., Cazenave, A., Petrovic, S., Jochmann, H. and Wünsch, J., 2006. GRACE observations of changes in continental water storage. *Global and Planetary Change*, *50*(1-2), pp.112-126.

Shuttleworth, S.A., 2016. Old weather: Citizen scientists in the 19th and 21st centuries. *Science Museum Group Journal*, *3*(3).

Singh, R., Wagener, T., Van Werkhoven, K., Mann, M.E. and Crane, R., 2011. A trading-space-for-time approach to probabilistic continuous streamflow predictions in a changing climate-accounting for changing watershed behavior. *Hydrology and Earth System Sciences*, *15*(11), p.3591.

Singh, U., Sharma, P.K. and Ojha, C.S.P., 2019. Groundwater investigation using ground magnetic resonance and resistivity meter. *ISH Journal of Hydraulic Engineering*, pp.1-10.

Specht, H. and Lewandowski, E., 2018. Biased assumptions and oversimplifications in evaluations of citizen science data quality. *Bulletin of the Ecological Society of America*, *99*(2), pp.251-256.

Starkey, E., Parkin, G., Birkinshaw, S., Large, A., Quinn, P. and Gibson, C., 2017. Demonstrating the value of community-based ('citizen science') observations for catchment modelling and characterisation. *Journal of Hydrology*, *548*, pp.801-817.

Syed, T.H., Famiglietti, J.S., Rodell, M., Chen, J. and Wilson, C.R., 2008. Analysis of terrestrial water storage changes from GRACE and GLDAS. *Water Resources Research*, *44*(2).

Truffert, C., J. Gance, O. Leite, and B. Texier*,* 2019, New instrumentation for large 3D electrical resistivity tomography and induced polarization surveys, GEM 2019 Xi'an: International Workshop on Gravity, Electrical & Magnetic Methods and Their Applications Xi'an, China, May 19–22, 2019, 124-127

Volkmann, T.H., Sengupta, A., Pangle, L.A., Dontsova, K., Barron-Gafford, G.A., Harman, C.J., Niu, G.Y., Meredith, L.K., Abramson, N., Neto, A.A.M. and Wang, Y., 2018. Controlled experiments of hillslope coevolution at the Biosphere 2 Landscape Evolution Observatory: Toward prediction of coupled hydrological, biogeochemical, and ecological change. *Hydrology of Artificial and Controlled Experiments*, p.25.

Vouillamoz, J.M., Sokheng, S., Bruyere, O., Caron, D., and Arnout, L. (2012). "Towards a better estimate of storage properties of aquifer with magnetic resonance sounding." *J. Hydrol.*, 458, 51–58. doi:10.1016/j.jhydrol.2012.06.044

Wagener, T., Sivapalan, M., Troch, P. A., McGlynn, B. L., Harman, C. J., Gupta, H. V., et al. (2010). The future of hydrology: An evolving science for a changing world. *Water Resources Research*, *46*(5).

Walsh, D.O., Grunewald, E.D., Turner, P., Hinnell, A., and Ferre, T.P. (2014). "Surface NMR instrumentation and methods for detecting and characterizing water in the vadose zone." *Near Surf. Geophys.*, 12(2), 271–284. doi:10.3997/1873-0604.2013066

Waterton, C., Maberly, S.C., Norton, L., Tsouvalis, J., Watson, N. and Winfield, I.J., 2015. Opening up catchment science: an experiment in Loweswater, Cumbria, England. *Catchment and River Basin Management: Integrating Science and Governance*, pp.183-206.

Wilkinson, M., Beven, K., Brewer, P., El-khatib, Y., Gemmell, A., Haygarth, P., Mackay, E., Macklin, M., Marshall, K., Quinn, P. and Stutter, M., 2013. The Environmental Virtual Observatory (EVO) local exemplar: A cloud based local landscape learning visualisation tool for communicating flood risk to catchment stakeholders. *EGU GA*, abstract EGU2013-11592.

Zhao, M., Velicogna, I. and Kimball, J.S., 2017. Satellite observations of regional drought severity in the continental United States using GRACE-based terrestrial water storage changes. *Journal of Climate*, *30*(16), pp.6297-6308.

Zulkafli Z, Perez K, Vitolo C, Buytaert W, Karpouzoglou T, Dewulf A, De Bièvre B, Clark J, Hannah DM, Shaheed S., 2017, User-driven design of decision support systems for polycentric environmental resources management. Environmental Modelling and Software, 88:58–73.