# 16 The Need for a Virtual Hydrologic Laboratory for PUB

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## INTRODUCTION

There has been a long standing interest in hydrology in developing techniques that can be used in poorly gauged or ungauged basins; for example the work of Benson (1968) who tried to determine flood frequency characteristics on the basis of basin characteristics. During the first International Hydrological Decade (IHD), 1965–1974, significant efforts were made to understand hydrological predictions and water resources with limited data (e.g. see IAHS, 1974). During the last 30 years, the hydrological community expended limited effort to address predictions in ungauged and poorly gauged basins. Instead, research focused on understanding hydrological processes, understanding water and energy coupling between land and atmosphere and its representation in weather and climate models, and there was a general decline in "surface water" hydrological research.

During this period, the recognition that water is becoming a critical resource, especially in the often (semi-)arid climates of developing countries, added urgency to improving the predictive ability of hydrological models and especially to predicting hydrological variability, since hydrological designs are more sensitive to variability than to mean conditions. Additionally, over this period concern was raised that natural or anthropogenic climate change would render past observations as being non-representative of current and future hydrological conditions, making many gauged basins essentially ungauged. Such climate change could occur through greenhouse gas emissions and its potential impacts on precipitation, evapotranspiration and streamflow, and through the impacts of land cover change on local water budget terms. Recognizing the need to re-visit and seriously tackle the unsolved problems associated with ungauged and poorly gauged basins, the International Association of Hydrological Sciences (IAHS) launched the new initiative: Predictions in Ungauged Basins (PUB), with a central scientific theme being "the estimation and subsequent reduction of predictive uncertainty" for ungauged and poorly gauged basins (Sivapalan *et al*., 2003).

This chapter provides a personal perspective on the IAHS PUB challenge to the hydrology community, which we basically interpret to be: Can the community make significant progress in understanding catchment-scale hydrological processes to the extent that ungauged basins can be described statistically and modelled with acceptable accuracy? To us, it is unclear what sort of measures should be used to determine "described statistically" and "acceptable accuracy".

PUB has a very comprehensive science plan to help guide the community forward (Sivapalan *et al*., 2003). The plan identifies five scientific objectives in each of which hydrological measurements and observations play a key role. We review four of these objectives and some questions they raise in the authors' minds, since these questions lead us to the proposed *virtual hydrologic reality*, discussed later in this perspective, that we feel will help PUB move forward.

PUB scientific objective 1 "Develop an observational field programme for conducting research in highly instrumented basins … in different hydro-climatic regions", which raises the question: *What should be measured, for how long and what will be learned?*

PUB scientific objective 2 "Increase awareness of the value of data, especially the gauging of hydrological variables ...", which raises the questions: *How much information is in the data?* and, *Are some data more "valuable" than others and if so, which?*

PUB scientific objective 3 "Advance the technical capability to make predictions in ungauged basins, … and to constrain the uncertainty in hydrological predictions", which leads us to wonder: *How can we evaluate predictive skill for ungauged basins?*

PUB scientific objective 4 "Advance the understanding of climatic and landscape controls on the natural variability of hydrological processes … ", which raises the question: *How can we estimate the sources of hydrological variability, especially the role of climatic forcings versus landscape controls?*

The scientific objectives suggest that extensive measurements and observations are sufficient for progress. But we feel that little progress will be made through observational studies alone. There is the underlying assumption in the PUB science plan that, given the opportunity to make observations and measurements, hydrologists will know what measurements to take, how to make them and for how long, and with this new data and resulting new insights, hydrological processes and models, will make improved predictions for ungauged basins. It is the contention of this perspective that such an assumption is untested, probably wrong and would benefit from a supporting modelling activity as described herein.

Given the broad field of activity in studying hydrological processes, new theories about catchment responses across a range of scales, recent land surface modelling activities like the GEWEX Global Land/Atmosphere System Study (GLASS), new remote sensing capabilities by NASA, NASDA and ESA, and greatly increased computational resources through the availability of TByte RAID storage systems and Beowulf PC clusters, can a new approach to ungauged catchments be developed? It is our perspective that PUB requires a *virtual hydrologic laboratory* in which the measurement strategy underlying the various PUB science questions can be explored.

There is a long history of virtual hydrologic laboratories being used to investigate hydrological processes, usually under the guise of Monte Carlo simulations. For example, Freeze (1972a,b) used such a framework to investigate the role of subsurface processes in generating runoff and Freeze (1980) investigated runoff generation on a hillslope through a stochastic-conceptual modelling framework. More recently studies by Bashford *et al.* (2002) looked at issues of model and scale within the Little Washita

(USA) basin, and Weiler & McDonnell (2004) used a virtual reality based on the HillVi model (Seibert & McDonnell, 2002) to explore hydrological processes and their conceptualization at the hillslope scale. In fact the Japanese Earth Simulator (see http://www.es.jamstec.go.jp/esc/eng/index.html) is essentially a virtual earth systems laboratory.

This chapter provides a perspective on what such a PUB "virtual hydrologic reality" may look like: the design requirements, generating the science questions appropriate for such a modelling system with three specific examples, the relationship of the virtual reality to the PUB experimental catchment activities, and finally, an outline of how the computational platform could be developed.

## *DESIGN OF THE VIRTUAL HYDROLOGIC LABORATORY*

What sort of design criteria should be specified to make the virtual reality most useful to the PUB research community. We have thought about five elements that need to be addressed. These are:

1. A virtual hydrologic laboratory should be based on an actual catchment, and needs to be truthful to its climatic, vegetative and geomorphic setting.
2. The finest spatial scale should be ~$10^6$ smaller than the largest scale (a 1-km$^2$ hillslope/catchment would have a spatial modelling scale of 1 m$^2$ or 1 m resolution; a 100 km$^2$ hillslope/catchment , a 100 m$^2$ or 10 m resolution).
3. The landscape properties need to be observed or downscaled in a consistent manner (e.g. topography can be observed, soil texture needs to be downscaled, soil depth inferred from context).
4. Climate forcing (radiation, precipitation, etc.) needs to be downscaled to the finest model scales from coarse scale or sparse observations.
5. Downscaling needs to accommodate a variety of approaches or scaling theories.

## *GENERATING THE VIRTUAL HYDROLOGIC LABORATORY*

Once the design criteria are specified, the next step is to create or "generate" the virtual hydrologic laboratory. The core of the virtual laboratory, i.e. the modelling system, is a base-line model (or potentially a set of models) that mimic our best understanding of the underlying hydrological processes.

A wide variety of potential models are available and their suitability will depend on the hypotheses being tested. For example: Freeze (1980) used a finite element hillslope model; Bashford *et al.* (2002) used TOPLATS (Famiglietti & Wood, (1994); Weiler & McDonnell (2004) used HillVi. The model needs to include appropriate hydrological processes and spatial heterogeneity that allows for testing the science questions/PUB hypotheses. In addition, there needs to be a modelling environment that allows for ease of modelling and analyses across scales. This issue is addressed later in this perspective.

## *GENERATING THE SCIENCE*

Once "constructed", it is our belief that only the imagination of PUB can limit its usefulness. Within the PUB Science Plan (Sivalaplan *et al.*, 2003), there are a variety of science questions and themes. A few examples, related to the questions (Q) and themes (Th), for which we feel the virtual reality has great potential, follow.

Some PUB Science Questions that could be addressed:

1. Issues related to design of field experiments (Q3).
2. Testing of hypotheses related to hydrological processes (Q5).
3. Investigating tradeoffs between information and predictive uncertainty (Q2, Q6).
4. Evaluating new observational methods to reduce predictive uncertainty (Q4).

Some PUB Themes that can be addressed:

1. Further understanding about the effect of heterogeneity, scaling, nonlinear dynamics, and their measurement (Th2, Th5).
2. Investigate how existing techniques (modelling, data collection, calibration, data assimilation) and model transferability relate to predictive uncertainty (Th3).
3. Investigate the concept of rejecting process hypotheses (Th6).

It is also possible to go beyond the structure within the PUB plans and think about using the virtual reality to develop Calibration for Ungauged Basins Experiment (CUBEX), where the virtual reality can be used to develop explicit testing of calibration and hypotheses testing for ungauged basins. Such a framework would help understand the observational data needs for test hypotheses by "sampling" from the virtual reality. While this does not guarantee that a particular sampling strategy will resolve similar hypotheses in an ungauged basin, it will indicate whether a planned strategy has any hope in the real world that tends to be more complicated than the most complicated virtual reality. In many ways, using a virtual hydrologic laboratory in this manner (e.g. Freeze, 1980; Bashford *et al.*, 2002; Weiler & McDonnell, 2004) is similar to "identical twin" data assimilation experiments (Reichle & Koster, 2003).

## *EXAMPLES OF USING A VIRTUAL HYDROLOGIC LABORATORY FOR PUB*

### *Example 1: Understanding the mobilization of water from rain events.*

Kirchner (2003) attempted to understand the runoff and geochemistry (chloride) from the Tanllwyth stream at Plynlimon (UK). He found from three years of observations that the stream discharge responded quickly to rainfall but the passive chloride tracer was highly damped. This led him to pose a "double paradox": Paradox 1, related to the mobilization of old water, is "*How do these catchments store water for weeks or months, but then release it in minutes or hours in response to rainfall inputs?*"; and Paradox 2 is related to the variability in the water chemistry and was stated as "*How do catchments store "old" water for long periods, but then release it rapidly during storm events, and vary its chemistry according to the flow regime?*". He is rather baffled by a catchment having sufficient stored soil water to provide quick, large fluxes during high flows yet this water is "old" from the perspective of its passive tracer composition.

Kirchner (2003), in his commentary, muses about the potential of a unified theory, raising questions about hydrological processes and responses. He states:

> "*It is easy to envision models that can explain the prompt hydrologic response shown in Figure 1a* [in Kirchner, 2003]*, or the highly damped tracer response shown in Figure 1b, or the concentration–discharge relationships shown in Figure 2. What is much more difficult is to envision a single mechanistically plausible theory that can explain all three phenomena simultaneously!*"(Kirchner, 2003).

And he wonders whether there are catchment models today that can capture these observations (Kirchner, personal communication, 2004).

In response, Bishop *et al.* (2004) claim to have a resolution of the double paradox of Kirchner's for at least one case based on work at the Nyänget catchment in northern Sweden. As Bishop *et al.* (2004) stated: "*the resolution of the first paradox about how to mobilize so much old water so rapidly, is based on the transmissivity feedback mechanism.*" In this mechanism, they surmise that a rising water table results in a more laterally conductive zone that allows old, immobilized water in the unsaturated zone to move down slope rapidly. For the second paradox, the variable chemistry of old water, they claim "*is explained by a juxtaposition of the lateral flow rates on the vertical profile of riparian soil solution chemistry*", as shown in Fig. 16.1, below.

They go on to say that since glacial retreat, the soils have developed a particular catena, and vertical distribution of organic material and soil water solution chemistry. Depending on the flow path, the resulting discharge will have varying chemistry as indicated in Fig. 16.1. As long as water chemistry data more directly related to water age (like $^{18}O$) is unavailable, it is our prediction that the discussion regarding the double paradox is not yet resolved.

What potentially outstanding questions arise from reading Kirchner (2003) and Bishop *et al.*, 2004)? The first is whether the geochemical settings are equivalent? In Kirchner's catchment, the precipitation contains a natural inert tracer (chloride), and due to the unique nature of its concentration in the rainfall, a clear understanding between rainfall and runoff chemistry can be established. In Bishop *et al.* (2004) the measured discharge chemistry appears to be controlled by the soil and geology of the catchment—conductive, upper-layer organic soils and high $Ca^{2+}$ soil water at depth where there is low conductivity (see Fig. 16.1.)

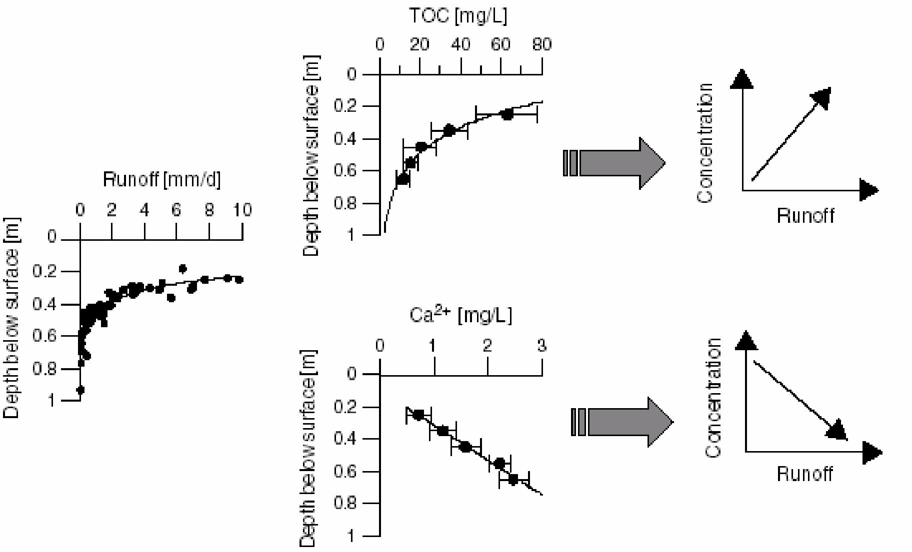

***Fig. 16.1*** *Bishop et al.'s conceptual framework for defining runoff chemistry as the integrated mixture of soil solutions "sampled" by lateral flow across the riparian zone. The amount sampled from each level of the riparian zone is defined by the lateral flow paths of the transmissivity feedback mechanism, which is consistent with an exponential increase in Ksat towards the soil surface (Reproduced from Bishop et al., 2004, with permission. ©2004 John Wiley and Sons Ltd).*

What role can a virtual reality play in resolving the questions? Can observations be used to reject competing hypotheses, or to infer inadequate hydrological process representation? Can a virtual reality help design field observations to test competing hypotheses?; basically, "sampling" from the reality. Bishop *et al.* (2004) clearly discuss the challenges of interpreting hydrological processes based on both water and chemical fluxes. It seems to us that a necessary condition is whether a model can be developed, with reasonable hydrological process hypotheses that can duplicate the responses of the catchments in both discharge and chemistry. If this cannot be done, what does it say about our lack of basic understanding? If we can do it for Bishop *et al.*'s Nyänget catchment, will the same model work for Kirchner's Tanllwyth stream at Plynlimon?

### *Example 2: Can hydrological theories be tested through a virtual hydrologic reality?*

Hypothesis 1 *The three dimensional structure of a catchment influences the observed hydrological response, and this influence can be measured and its structure can be inferred through measurements?*

The hydrology of catchments is driven by atmospheric factors such as precipitation and potential evapotranspiration, but controlled by the properties of the catchment. For example, throughflow velocity and capacity are controlled by soil hydraulic conductivity and thickness. In hydrological models, the driving factors are typically represented as input variables, and the controlling factors as model parameters. One of the key issues of hydrological models is: What are adequate values for these model parameters? In gauged basins, effective model parameter values are typically obtained though some kind of model calibration procedure. In ungauged basins, this is more difficult because runoff measurements are missing.

However, the common procedure of obtaining model parameters through calibration assumes that there is no or little *a priori* knowledge of adequate parameter values. The hypothesis put forward here is that this assumption is false, and that enough of this *a priori* knowledge can be collected to provide adequate model parameter values.

The key point is that the catchment and hillslope variables that are represented by the model parameters are to some extent predictable, because they are the result of (knowable) geological, climatological, geomorphic, pedological and biological processes and boundary conditions. An understanding of these "Earth system" components should ideally lead to an understanding of the corresponding model parameter values.

Science Question 1 *Can we parameterize target hydrological models (e.g. Topmodel, hsB) based on knowledge of geological, geomorphic and pedological processes occurring at the landscape scale; and what is the accuracy of the resulting hydrological predictions, given known forcing?*

Three different approaches can be followed to incorporate more Earth system knowledge into PUB problems.

First, some catchment properties can be known, even for ungauged basins. For example, since the Shuttle Radar Topography Misson (SRTM), 30 to 90 m resolution digital elevation models are available for catchments located between ±60° latitude. Land use, lithology, etc., can be derived from remote sensing, for example from NASA's MODIS instrument on Terra and Aqua.

Second, information can be transferred from "similar" but gauged catchments towards the ungauged basin. For example, neighbouring catchments sharing the same lithology, vegetation, etc., can be expected to have the same soil hydraulic properties. A more non-trivial example is the combination of information transfer and direct observations. For example, McGlynn & McDonnell (2003) use partitioning of a catchment into differently behaving hillslope and riparian areas. A successful transfer of information from gauged towards ungauged basins consists of both the measurement of (say hydraulic) properties within these units in the gauged basin, and the detection of the spatial distribution of these units within the ungauged basin, based on morphometric analysis. However, a critical issue here is what exactly defines "similarity" in terms of the hydrological behaviour of basins.

A third approach is to use landscape evolution modelling techniques (e.g. Dietrich *et al*., 1995; Tucker & Bras, 1998; Minasny & McBratney, 2001) to predict catchment and hillslope geometry and spatial patterns of soil properties. Current landscape models are predominantly *geomorphic* landscape evolution models, and soil processes are limited to soil production by weathering, and soil transport due to creep and erosion. The inclusion of (soil) biological and pedogenetic models into landscape evolution models might enable the *a priori* prediction of soil hydraulic properties. Pedogenetic modelling is, however, still in its infancy (Hoosbeek *et al*., 1999). Insights gained from landscape evolution modelling can be used to help transfer information between basins (perhaps by means of inverse modelling of gauged basins), or to make *a priori* parameter value estimations.

Figure 16.2 shows how simulated patterns of hillslope form and internal structure can be used to extract the spatial distribution of some parameters required for the semi-distributed hillslope storage Boussinesq (hsB) hydrological model (Troch *et al*. (2003).

Also, most catchment properties are not scalar variables, but two- or three-dimensional fields. They are thus characterized by both a certain "magnitude" and a certain "pattern" or spatial structure. For example, in basins underlain by bedrock the soil water storage capacity within the top soil layer is defined by both the depth-averaged porosity and the soil thickness. Here we consider only the latter variable. Soil thickness within a catchment will be the result of the interplay of a number of processes like weathering, erosion, creep and deposition. The overall balance between weathering and catchment scale erosion will determine the average soil thickness. For example, in tropical catchments within low-relief cratons (e.g. the African shield), average soil thickness can be expected to be large, while in high-relief, cold-climate catchments (e.g. Arctic orogens) soil thickness is expected to be small. On the other hand, spatial variability in the strength of the various processes involved causes variability within the catchment or hillslope. For example, in many uplifted areas that undergo active river incision, soils are thick on the plateau remnants that erosion has not yet reached, thin on the hillslopes bordering the incising river valleys, and thick on many valley floors because of colluvial infilling here and/or a declining sediment removal capacity since the Last Glacial.

### *Example 3: The use of new data collection approaches for process understanding, calibration and prediction*

The development and application of new measurement techniques, both *in situ* and remotely, holds great promise for improved understanding of hydrological processes.

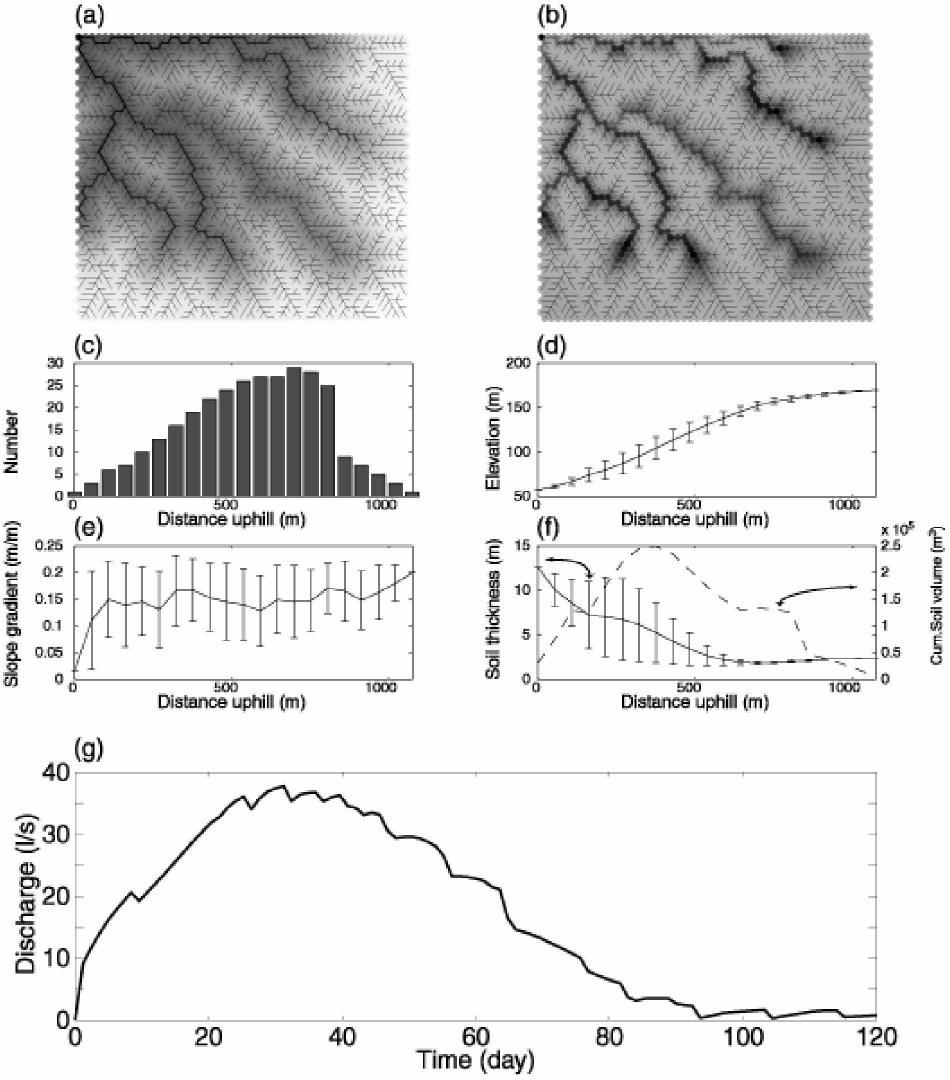

*Fig. 16.2 Extraction of hydrological relevant parameters from a simulated landscape. (a) Simulated topography; lighter grey denotes higher terrain. (b) Simulated soil thickness; darker shades are thicker soils. (c) Derived hillslope width function. (d) Derived hillslope profile function; errors bars indicate standard deviation. (e) Derived hillslope slope function. (f) Derived soil thickness and water storage capacity functions. (g) Computed hydrograph for drainage from 20% saturation using the model of Troch et al. (2003).*

For example, the development of inexpensive micro-gravity meters would help in understanding the recharge into groundwater systems, including the spatial pattern of recharge as well as its inter-annual variability due to wet and dry years.

Remote sensing, especially from new satellite sensors, has the potential to help our understanding of ungauged catchments. This leads to the following PUB hypothesis and science questions:

Hypothesis 1 *Hydrological predictions can be improved through the assimilation of remotely sensed observations?*

Science Question 1 *Can the remotely sensed data be useful for calibration of a hydrological model?*

Science Question 2 *What is the accuracy of hydrological predictions based on remotely sensed data, and can the prediction be improved by assimilating these data?*

The above can be explored through structured simulation studies, often referred to as twin experiments in data assimilation research (Reichle & Koster, 2003), or through observational satellite simulation experiments (OSSE). For example Crow *et al.* (2001) developed a satellite sensor virtual reality that consisted of a high-resolution hydrological model (run at a spatial resolution of 1 km), a land surface microwave emission model (LSMEM) (see Gao *et al.*, 2004, for a description of this model), and an explicit simulation of the orbital and scanning characteristics for the advanced microwave sensing radiometer (AMSR-E). An observing system simulation experiment (OSSE) was carried out over the 575 000 km$^2$ Red-Arkansas River basin to assess the impact of land surface heterogeneity on large-scale retrieval and validation of AMSR-E soil moisture retrievals from the 6.925 GHz channel.

Their OSSE study investigated how land surface heterogeneity and rainfall variability impacts satellite-based soil moisture retrievals due to the fundamental inconsistency in spatial scale between gridded soil moisture imagery derived from *in situ* point-scale sampling, numerical modelling, and microwave remote sensing sources. They found that for surfaces with vegetation water contents below 0.75 kg m$^{-2}$, these two scale effects induce root mean squared errors (RMSEs) of 1.7% volumetric soil moisture into daily 60-km AMSR-E soil moisture products and RMS differences of 3.0% volumetric soil moisture into 60-km comparisons of AMSR-E soil moisture products and *in situ* field-scale measurements of soil moisture sampled on a fixed 25-km grid.

These types of experiments are fundamental in interpreting cross-scale comparisons of satellite-based retrievals to high resolution *in situ* or hydrological model-based estimates, and require a virtual reality as the core of the OSSE system.

The science questions: "*What is the accuracy of hydrological predictions based on remotely sensed data?* and *Does including heterogeneity improve the accuracy of hydrological predictions?*" are addressed in Fig. 16.3 using the OSSE results of Crow *et al.* (2001). Soil moisture affects latent heat ($\lambda E$) through water availability, and the effect is nonlinear. Because of this nonlinearity and the heterogeneity in soil moisture, using averaged soil moisture at large scales to estimate latent heat will result in an error. This suggests that low-resolution satellite-retrieved soil moisture from passive microwave sensors like AMSR-E, when used in land surface evaporation models, will result in errors unless the heterogeneity is resolved. Figure 16.3 shows such results, based on the OSSE described by Crow *et al.* (2001), when the resolution of the retrieved soil moisture varies from 1 to 64 km. At 1 km, the hydrological model had a validation RMS error (when compared to turbulent heat flux measurements from *in situ* towers) of ~35 W m$^{-2}$. Ignoring heterogeneity and decreasing the soil moisture resolution to 64 km results in doubling this error (top curve, Fig. 16.3). Having a simple closure model based on a sub-grid variance, constant over the region, results in accuracy gains that are the difference between the top two lines (closed black squares

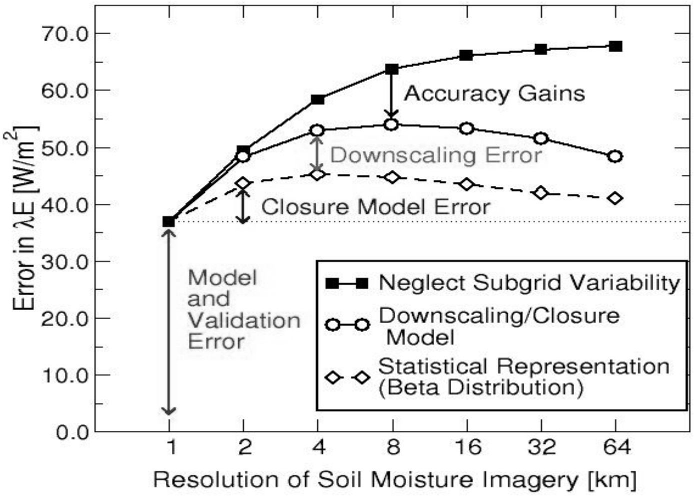

***Fig. 16.3** Accuracy in latent heat predictions based on soil moisture resolution and the representation of its sub-grid variability.*

and open circles). Extending the sub-grid soil moisture variability representation by assuming it follows a Beta probability distribution results in additional accuracy gains, labelled as “downscaling error”. Finally there is the unresolved closure model error that perhaps could be reduced though different or additional sub-grid representations. To understand these tradeoffs, even the range errors due to the handling of sub-grid heterogeneity requires a virtual reality, and therefore is central to the PUB science of using remote sensing for model calibration or validation.

## *IS A VIRTUAL HYDROLOGIC LABORATORY FOR PUB A FEASIBLE CONCEPT?*

What steps would be needed to make a virtual hydrologic laboratory for PUB feasible? It appears to us that three steps are necessary:

1. candidate locations from which we create virtual laboratories for a variety of climates and landscapes;
2. a computational, visualization, data integration system is needed that allows for recreating the virtual hydrologic laboratory across scales; and
3. we need the science questions and hypotheses (thoughtfully provided by the PUB Science Plan), a group of interested PUB scientists, and funding.

### *Paradise Creek Watershed: A potential virtual laboratory*

Paradise Creek watershed is located in the Palouse River (Idaho, USA) hydrological basin. The creek flows in a southwesterly direction for approximately 31 km through the City of Moscow (Idaho), across the Washington state line. The watershed is 50 684 ha in size with 30 554 ha located within Idaho. Elevations range from 770 m to 1330 m. The upper portion of the watershed is steeply sloped, with the majority of the drainage basin consisting of moderately steep rolling hills. These hills are very susceptible to erosion due to their topography, soil texture, climate and land use

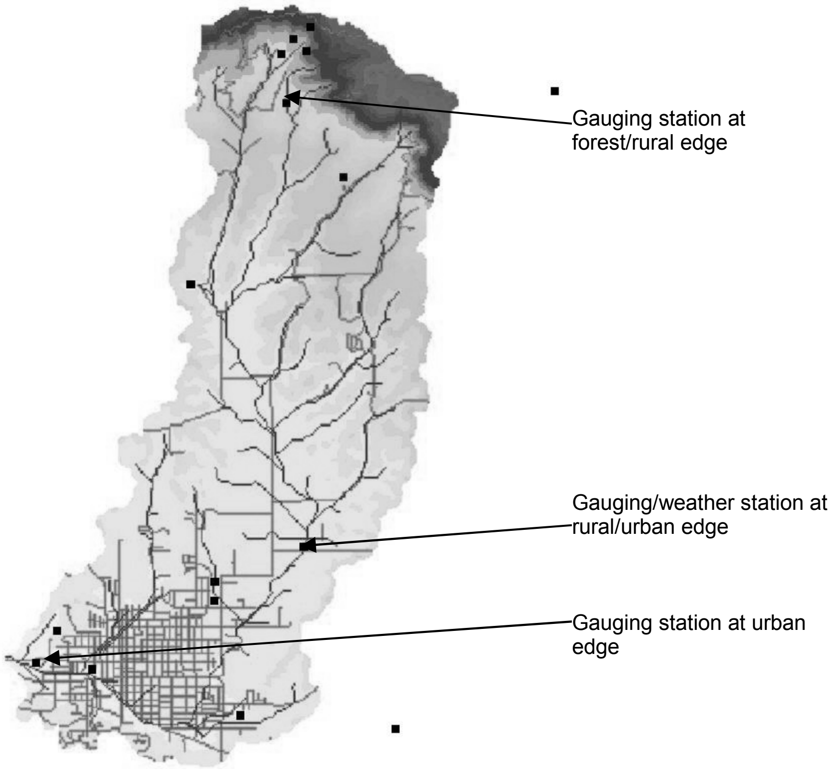

***Fig. 16.4*** *Paradise Creek watershed near Moscow, Idaho.*

practices. Land use consists of forest land (14.2% by area), agriculture (69.1%), and urban (16.6%). The predominant agricultural land use is non-irrigated cropland (e.g. wheat, barley, peas and lentils). The watershed is shown in Fig. 16.4.

Precipitation within Paradise Creek watershed is highest during December and January when it falls either as snow or a combination of rain and snow. Average annual precipitation in the watershed is approximately 580 mm, with an average snow depth of about 2100 mm. Rainfall on frozen soils and rainfall coinciding with snowmelt typically cause peak flows within the watershed. Hydrographs are characterized by low flows during the summer and autumn seasons, and peak flows during winter and spring seasons. Since rainfall intensities are low, most runoff events are caused by saturation excess overland flow. Most soils in the watershed are deep, moderately to well drained silt loam soils formed in loess with varying thickness of 0.5–20 m. In several soil types, a fragipan underlies the top 0.5–1 m of loose soil causing perched water tables in winter and spring. In 1994, Paradise Creek was identified as water quality limited from its headwaters to the Washington state line. The creek exceeds standards for the following pollutants: ammonia, nutrients, sediment, habitat modification, pathogens, flow alteration, and temperature. Cold water biota, secondary contact recreation, and agricultural water supply are the designated beneficial uses that require support. Primary nonpoint sources of pollution in the watershed are non-irrigated croplands, grazing lands, urban runoff, roads and forest land harvest activities. Soil erosion is a major concern. North and northeast facing slopes tend to be steeper than south facing slopes, which is attributed to higher erosion and slump potential on northerly slopes caused by snow drift accumulation. In the winter and spring, Paradise Creek is typically affected by suspended solids from eroding fields during high runoff. During the low flows of the late summer, phosphorus and nitrogen are present in high enough concentrations to stimulate algal and macrophyte populations. Nutrient and bacteria levels often exceed Idaho and Washington water quality standards.

Since 1999, scientists from the University of Idaho have instrumented this watershed to develop a database for testing of distributed hydrological models. Three gauging stations have been installed along the creek at the borders of the three land use types (Fig. 16.4). A fourth station is being installed in the urban area. Each station continuously measures stage height, turbidity, electrical conductivity and temperature. Rating curves have been established for discharge and total suspended sediment. Automated water sampling allows for determination of sediment, nutrient and other water quality analyses. A network of weather stations in and around the watershed has been maintained since 1999. A GIS database for the watershed includes DEM, soils data, land use data, streams and roads.

Paradise Creek watershed would be a potential watershed to serve as a natural laboratory after which the virtual laboratory can be modelled. Model simulations in this watershed can be performed in concert with real experimentation to validate model hypotheses. Possible hypotheses to be tested:

- element size (e.g. grid, polygon) affects (distributed and integrated) runoff prediction;
- plough pans determine initial conditions for rill development (plough pans cause a very shallow perched water system);
- hydraulic conductivity increases with scale only if heterogeneity (i.e. different porous media) increases with scale;
- streamwater temperature is reduced by increasing subsurface flow paths in agricultural and urban areas;
- sediment loads at the watershed outlet represent net erosion from the land surface filtered by routing dynamics of the stream (in other words, erosion modelling must include the linkage of distributed soil erosion modelling and sediment routing in the stream system to describe sediment delivery);
- watershed restoration (e.g. sediment reduction) takes decades (long-term simulations to understand cumulative effects);
- landscape organization rather than total catchment area is a first-order control on mean residence times in watersheds (e.g. the catchment is viewed as a network and that network structure determines catchment outflow).

### *NASA/Land Information System (LIS): A computational platform for a virtual laboratory?*

The Land Information System (LIS) is a high performance land surface modelling and data assimilation system, based on GSFC's Land Data Assimilation Systems. LIS is being developed under funding from NASA's Computational Technologies Round-3 Grand Challenge Investigation, with the effort being led by the Hydrological Sciences Branch at NASA Goddard Space Flight Center (see http://lis.gsfc.nasa.gov/).

As currently structured, the main software components of LIS are:

- LIS driver: A model control and input/output system that executes multiple offline land surface models over regional or global grids/tiles at spatial resolutions down to 1 km.
- Land surface models: The LIS source code currently includes three different land surface models, namely:
  - the NCAR Community Land Model (CLM);
  - the community Noah land surface model (Noah); and
  - the Variable Infiltration Capacity model (VIC).

The data used by LIS include:

- Parameter data: Properties of the land surface that change on time steps of a day or longer, e.g. soil, land cover, topography.
- "Forcing" data: Atmospheric inputs to the land surface models, including precipitation, radiation, and surface winds, temperature, pressure and humidity.

The usefulness of LIS as a computational platform for a PUB virtual hydrologic laboratory is its ability to handle multi-scale data, a driver that allows the incorporation of competing models with a minimum of effort using the ALMA data exchange convention (see http://www.lmd.jussieu.fr/~polcher/ALMA/) developed for land surface modelling experiments, and an analysis package based on the Grid Analysis and Display System (GrADS). Figure 16.5 shows the LIS architecture. As described at http://grads.iges.org/grads/grads.html: "*The Grid Analysis and Display System (GrADS) is an interactive desktop tool that is used for easy access, manipulation, and visualization of earth science data. The format of the data may be either binary, GRIB, NetCDF, or HDF-SDS (Scientific Data Sets). GrADS has been implemented worldwide on a variety of commonly used operating systems and is freely distributed over the Internet.*"

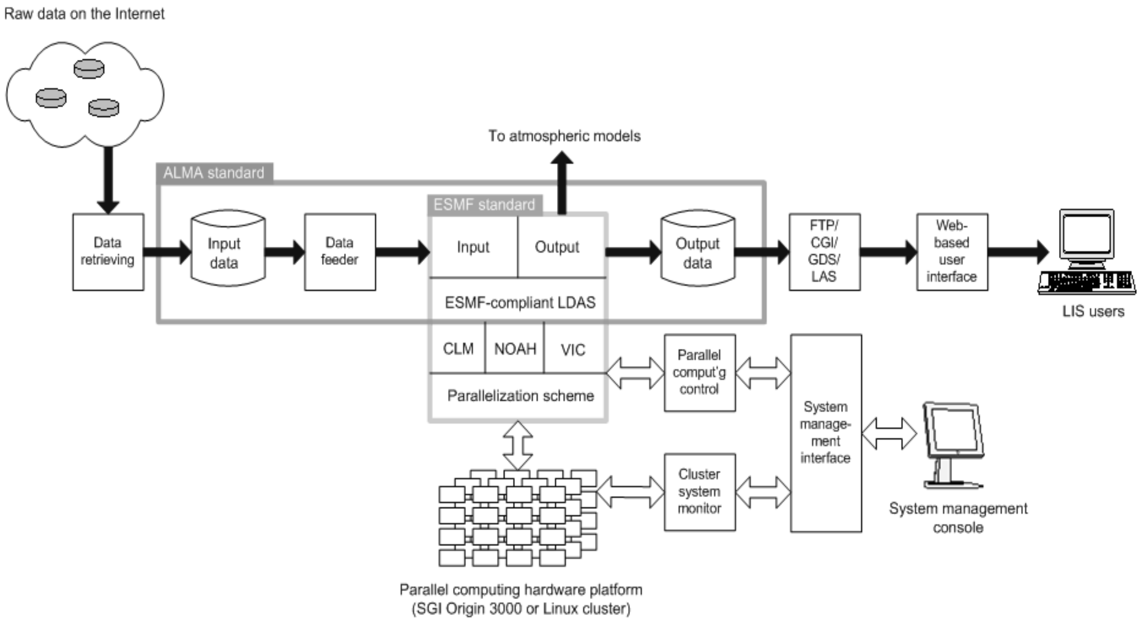

**Fig. 16.5** *Schematic of the LIS architecture.*

## CONCLUSIONS

The central hypothesis in this perspective is that PUB science questions can not be fully answered through field observations alone. Therefore, it is our belief that a virtual hydrologic laboratory is needed. With this laboratory one can explore a range of PUB science questions, as outlined in the examples provided. Using these laboratories, for example to explore catchment evolution and form in gauged catchments as described in Example 2 (see above), will result in increased understanding that will lead to improved hydrological predictions in ungauged basins. Similarly, such a laboratory will help guide observational programmes, and help distinguish between competing hydrological theories, such as in Example 1, or the usefulness of new observations as in Example 3. In summary, we feel that the creation of virtual laboratories for various catchments is not only feasible, but necessary.

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