5 Some Perspectives on Hydrological Prediction and the Role of PUB

DENNIS P. LETTENMAIER

INTRODUCTION

This chapter is an outgrowth of an invited "perspectives" talk at the PUB Japan-Australia Workshop held at the University of Western Australia in February 2004. For that presentation, I was asked to offer "personal perspectives" on PUB, and its planned activities. I selected three problems in hydrological prediction that I believe have implications for PUB, and the hydrological community more generally. These problems are: (a) prediction of the hydrological consequences of land use/land cover change; (b) understanding factors that control hydrological predictability in the context of seasonal streamflow forecasting; and (c) development of improved methods for predicting the hydrological consequences of climate change in a management setting.

For each area, I summarize the role of the specific problem for "ungauged basins", which I interpret somewhat broadly (i.e. specification of hydrological conditions at a point within a river basin that is ungauged qualifies, even if gauges do exist somewhere in the river basin). While my focus here is on water quantity, all three problems have implications for water quality as well.

I should note that, in this chapter, I write in a less structured format than I would for a formal journal publication. My intent is to be somewhat speculative as to how research in hydrology relevant to PUB is evolving in these three particular areas, and where opportunities lie. While I cite publications where they are relevant, I make no attempt to review exhaustively work that has been published to date. Instead, the citations I include are meant to be illustrative.

PREDICTION OF THE HYDROLOGICAL CONSEQUENCES OF LAND USE/LAND COVER CHANGE

Man's activities have now altered the land cover of most of the globe. The major changes have been conversion of forests, grasslands, and other land cover types to agriculture (Ramankutty & Foley, 1999), and changes in forest cover as a result of deforestation (especially in the underdeveloped world), but also, in the developed world, reforestation (World Resources Institute, 1996). Fires cause more ephemeral, but sometimes long-lasting, changes in land cover. Other types of land cover conversion, e.g. urbanization, can have substantial effects as well, albeit on more local scales.

Changes in land cover can substantially affect land surface hydrology. Clearly, changes in vegetation affect canopy interception capacity, which is related to leaf area index. Canopy interception represents a "fast" pathway for precipitation to recycle to the atmosphere. Where forests are replaced by pasture or cropland, the effect usually is to increase runoff, due both to reduction in interception capacity, and reduction in transpiration. Other indirect effects may exacerbate these changes; for instance, reduction in evapotranspiration leads to increased infiltration, and hence increased water table levels, which can increase saturation excess runoff. Removal of forests—either by logging or fires—can change the surface soil hydraulic characteristics, often such that infiltration rates are decreased, and "fast" runoff response is increased. Urbanization usually results in increased imperviousness, which likewise leads to increased runoff. In some cases, such changes are desirable—removal of vegetation, especially in riparian areas, has been used to increase catchment water yield, notwithstanding potentially negative ecological consequences. However, changes in land cover have also been implicated in flooding, with serious economic consequences (see e.g. Jones & Grant, 1996). Quantification of these changes is difficult, however, because of the large natural variability that may obscure them in historic records (Bowling *et al.*, 2000).

Therefore, predictive models are essential to estimate the hydrological effects of land cover change. Resources managers need to understand, for instance, the effects that land cover conversion and management will have on hydrological processes. Bowling *et al.* (2001) and La Marche *et al.* (2001) have shown how spatially distributed hydrological models can be used to predict the consequences of logging and forest road construction on flooding. Figure 5.1 shows a typical result from La Marche & Lettenmaier (1998) which indicates the magnitudes of predicted changes in 10-year return period floods in Hard and Ware Creeks, two small tributaries of the Deschutes River, Washington, USA, a semihumid mountainous forested watershed. A common question about results such as those in Fig. 5.1 is: *how confident are you in the results*? Because these are model-simulated results, they are dependent on the form, and parameters, of the model used, and may be in error. Often, however, critics focus on the ability of the model to reproduce past observed conditions. Whether this is the

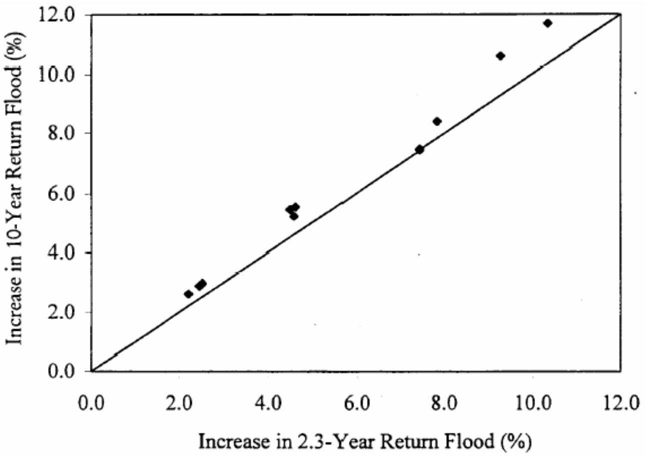


Fig. 5.1 *Predicted changes in 10-year return period flood vs changes in 2.3 year (mean annual) flood for selected subcatchments in the Deschutes River basin, Washington, USA, for a scenario with forest roads and mature forest as compared to no forest roads and mature forest. In general, road impacts are greater for higher return period floods. Source: LaMarche & Lettenmaier (1998).*

appropriate question is debatable. What we are interested in knowing is how well the model represents the system's sensitivity to change (in this case, of land cover), and not how well it is able to reproduce past conditions. Perhaps the two issues are connected, although at this point I don't believe that we know this definitively. Of course, almost everyone who has done simulation modelling has had the experience of trying to reproduce observations of phenomena a model is meant to represent. Typically, this is done by a process of calibration, and perhaps "validation" on an independent sequence of data. If the model conceptualization is appropriate to the system modelled (and in some cases, even if it is not), we may be able to get "acceptable" results for both the calibration and validation periods. Is this sufficient to allow us to argue that the sensitivities are correct?

Van Shaar *et al.* (2002) performed tests that may be relevant to this question. They applied both the Distributed Hydrology-Soil-Vegetation Model (DHSVM, also used in Bowling *et al.*, 2001, and LaMarche *et al.*, 2001) to four catchments with drainage areas ranging from 27 to 1023 km^2, all located in forested areas of the Columbia River basin (USA). They also applied the Variable Infiltration Capacity (VIC) macroscale model to the same river basins. Both DHSVM and VIC were calibrated to the four catchments, and observed conditions were reproduced reasonably well by both models in all four catchments. They then evaluated predictions of the effects of prescribed land cover change (vegetation removal) for the four catchments.

Figure 5.2 summarizes some of the results from Van Shaar *et al.* (2002). Clearly, the sensitivities (differences in hydrographs for base and altered vegetation scenarios) are quite different for the two models, which implies a wide range in the predicted consequences of forest cover changes. This illustrates a key issue—while we can conduct model experiments in which land cover is perturbed, *we lack methods for estimating the equivalent of confidence bounds about our predictions*. What this comes down to is estimating the errors in the sensitivities. Even if we can reproduce observed streamflows with our models, the Van Shaar *et al.* work shows that there is a great deal of uncertainty about the sensitivities. Traditional statistics do not help us much with this problem, since we do not have good data from which to derive the sensitivities—basically we only have one of the two end points. Prediction of hydrological consequences of alternate land cover, climate, and other conditions is a key need facing the hydrological community, and the question of uncertainty in such estimates (or equivalently, of evaluating the variability in model sensitivities, and placing them in a quasi-probabilistic setting) is an important issue to which PUB may be able to contribute.

HYDROLOGICAL PREDICTABILITY IN THE CONTEXT OF SEASONAL STREAMFLOW FORECASTING

Hydrological prediction is of practical importance for water management, and the ability to predict future hydrological conditions—either at a specified point in time, or under some alternative scenario of land use, climate, or other condition that affects hydrological processes—is at the heart of hydrological science. In this section, I consider a much more specific aspect of the hydrological prediction problem: prediction of seasonal streamflow for lead times out to about six months. This is a problem that lies at the interface between science and applications. The practical consequences are immediately apparent, as the ability to predict future streamflows is critical to effective water management. At the seasonal lead time, *a key issue is the relative*

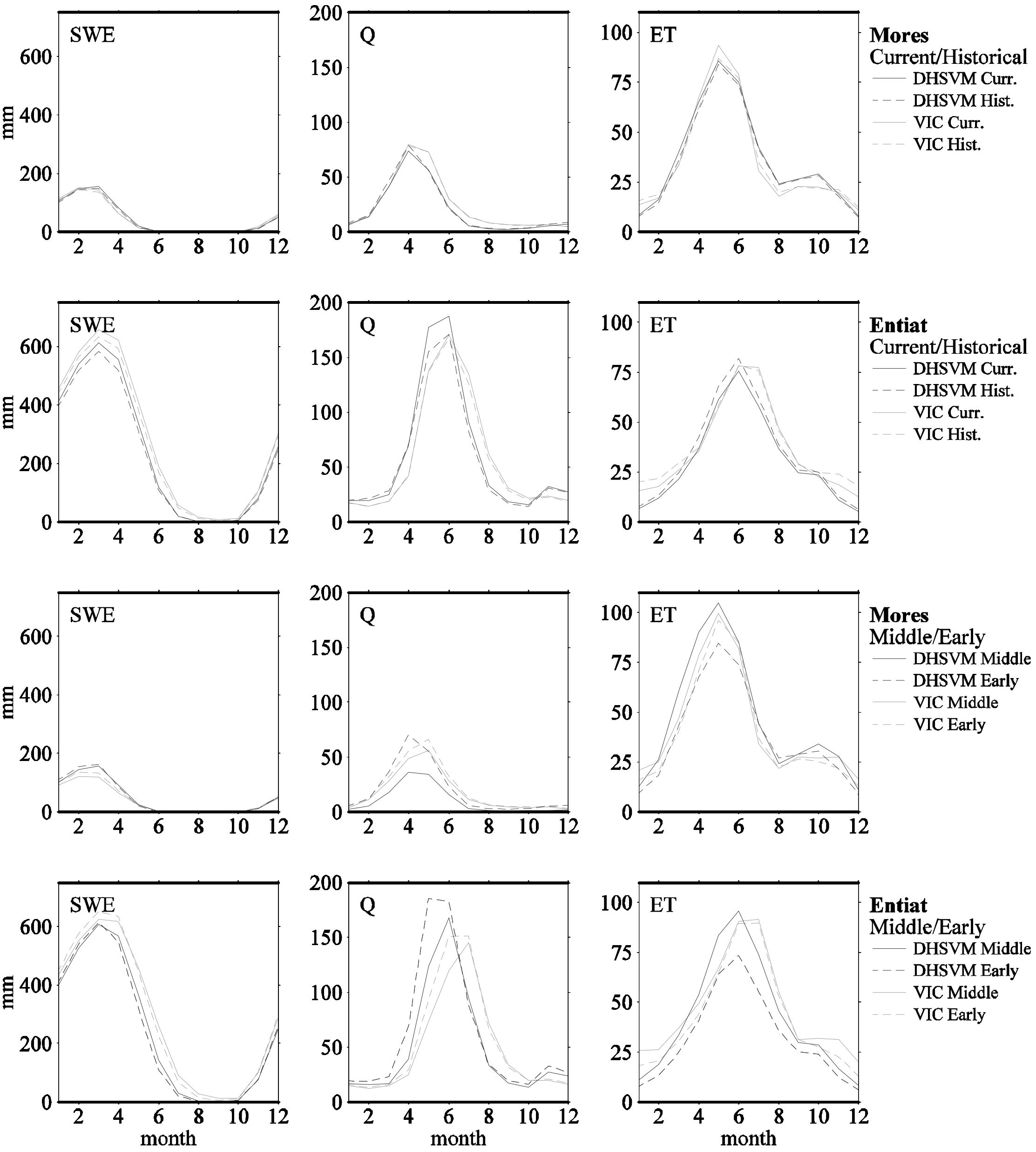


Fig. 5.2 *Predicted response of snow water equivalent (SWE), streamflow (Q), and evapotranspiration (ET) for two catchments within the Columbia River basin to vegetation change using the Variable Infiltration Capacity (VIC) and Distributed Soil-Hydrology-Vegetation Vegetation Model (DHSVM). "Current" vegetation is c.1990, while "Historical" is 1900; "Middle" and "Early" refer to experiments in which all vegetation was set to a medium and "early" (immature) status, hence sensitivities for the lower two rows are generally greater than for the upper two. Source: Van Shaar et al. (2002).*

importance of hydrological initial conditions in comparison with skill in forecasting the hydrological drivers, where the hydrological initial conditions are primarily moisture storage, either in the subsurface, or as snow water equivalent, and the hydrological drivers are primarily precipitation, but also evaporative demand, and the surface atmospheric variables that control them.

Considerable advances have been made in climate forecasting over the last decade. The so-called “limits of predictability” for weather forecasts (based on the essentially chaotic nature of the atmosphere) dictate a limit to prediction skill in weather forecasts beyond a week or so (Epstein, 1988). However, the thermal inertia of the ocean, and its influence on the climate system, facilitate predictive skill in climate forecasts for lead times of several months or longer (NRC, 1999; Goddard *et al*., 2001). Perhaps the best example is the El Niño phenomena, which is known to affect weather and climate strongly in the tropics, but also in many locations in the extra-tropics, among them the west coast of North America (Chen *et al*., 2004). Typically, so-called ENSO events, which basically are the pooling of anomalously warm water in the eastern tropical Pacific (El Niño, or the reverse for La Niña) are predictable in the spring or summer, and evolve over a period of a year or more. Hence, there is the potential to predict precipitation and temperature in, for instance, the northwestern USA as much as a year in advance (Hamlet & Lettenmaier, 2000).

Twedt *et al*. (1975) formulated the now widely used Extended Streamflow Prediction (ESP) method of seasonal streamflow prediction. They suggested that a temporally continuous, spatially lumped, hydrological model be run with observed precipitation and other atmospheric forcings up to the date of forecast, and that ensembles of future conditions be formed by resampling past observed time series of precipitation and other variables. While hydrological models have improved in the intervening years to better represent spatial variability in land surface conditions, to include more directly topographic effects on hydrological processes, and to represent better the underlying processes, the ESP approach remains at the heart of recent developments in hydrological forecasts, like the NWS Advanced Hydrologic Prediction Service (AHPS). One key difference is that recent developments are now exploring the use of climate forecast information, in lieu of ensembles based entirely on past observations (e.g. Wood *et al*., 2002).

Maurer & Lettenmaier (2003) and Wood *et al.* (2003) have both performed experiments that attempt to identify the relative skill in long-range (months up to a year) hydrological forecasts that is attributable to hydrological initial conditions *vs* forecast skill. Maurer *et al.* (2003) based their analysis on the Variable Infiltration Capacity (VIC) semi-distributed hydrological model, run over the Missouri River basin. They regressed simulated seasonal streamflow volumes given perfect forcings (precipitation and other surface variables) on model soil moisture and snow water equivalent at the beginning of the forecast period, and on the Southern Oscillation Index (SOI, an indicator of ENSO) and the Arctic Oscillation (AO). The first two variables (soil moisture and snow water equivalent) are hydrological initial conditions, while the latter two are climate indicators, and can be considered rough indicators of potential climate forecast skill. The specific values of SOI and AO used were the observed values during the forecast period, rather than predictions at the time of forecast, so in a sense the experiment is predicated on perfect skill in the predictions of the climate indicators.

Maurer & Lettenmaier (2003) found that: (a) soil moisture dominated runoff predictability for lead times of 1½ months, except along the western mountainous boundaries of the basin in summer, where knowledge of snowpack dominated; (b) over the western part of the basin, hydrological initial conditions had a stronger predictive capability than climate indicators for leads of two seasons, but in the eastern (more humid) part of the basin, the climate indicators provided greater predictive skill than hydrological initial conditions for lead times of one season or greater; (c) modest winter runoff predictability was present at a lead time of three seasons due to both climate and hydrological initial conditions, mostly in areas that produce little runoff; and (d) local summer runoff predictability is limited to the western mountainous areas that generate high runoff through a lead of two seasons.

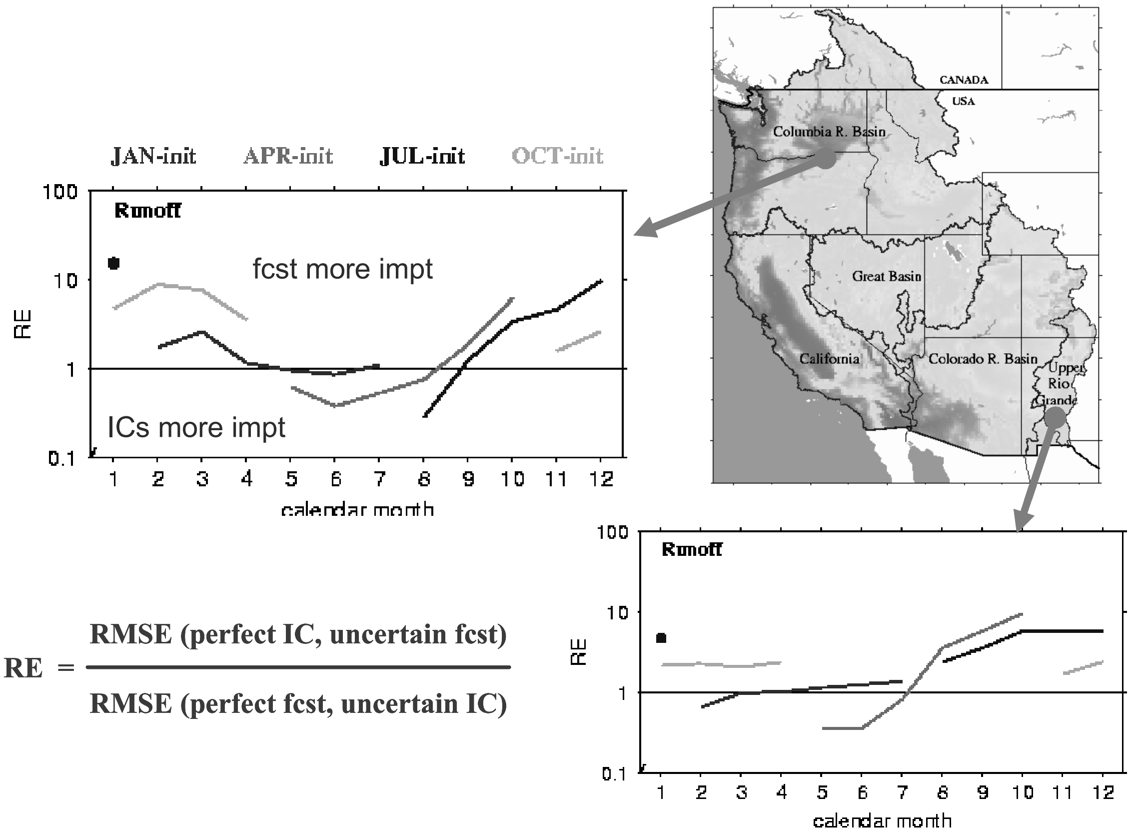
Wood *et al.* (2005) designed a somewhat different set of experiments. They also used the VIC macroscale model. However, rather than regressing forecast period streamflow on a set of indicators, they implemented the VIC model in ESP mode with ensembles derived both from resampling of observations as per Twedt *et al.* (1975), and from downscaling and bias correcting global ensemble climate forecasts (of six months duration). Details of the downscaling and bias correction approaches are given in Wood *et al.* (2002, 2004), but the general idea is to use probability mapping methods to relate model output to the observed climatology, and in so doing to correct for model biases. In contrast to Maurer *et al.* (2003), Wood *et al.* (2005) were able to evaluate conditions, and lead times, for which climate model forecasts yielded more accurate seasonal streamflow forecasts (over the western USA domain) than did ESP. The results showed that for most locations, forecast dates and lead times, climate model forecasts did not lead to improved streamflow forecast skill. The most important exception was for the Pacific Northwest, under ENSO conditions.

Wood & Lettenmaier (2003) performed a set of "reverse ensemble" experiments, in which the forecast period precipitation and other forcings to the VIC model were fixed, but the initial conditions were resampled from each of a set of *n* years in an historic data set (of length about 50 years). Figure 5.3 shows results for the Columbia and Rio Grande rivers, which are expressed as the ratio of the forecast root mean squared error (RMSE) with perfect initial conditions but no forecast skill (traditional ESP) to the RMSE with perfect forecast skill but the full range of uncertainty (resampled from historical runs) in the initial conditions. In general, for small lead times, the ratio is expected to be small, since initial conditions dominate, but it becomes larger with larger lead times. Both the Columbia and Rio Grande rivers are snowmelt dominated, so the ratios tend to be smallest for short lead times and forecasts made in spring, near the peak snow accumulation period.

The results of the Maurer & Lettenmaier and Wood & Lettenmaier studies are interesting, but are relevant to a fairly specific set of conditions (in particular, larger river basins in snowmelt dominated climate regimes). Furthermore, they are for one particular model, and may be dependent on both the hydrological, and climate forecast model (in the case of Wood *et al*., 2004). They do suggest a potentially useful pathway that merits investigation over a much larger set of hydrological conditions, models and forecast criteria.

PREDICTING THE HYDROLOGICAL CONSEQUENCES OF CLIMATE CHANGE

Climate change is one of the major scientific and social issues facing the hydrological community. Change in climate undoubtedly will affect land surface hydrology, but



$$RE = \frac{\text{RMSE (perfect IC, uncertain fcst)}}{\text{RMSE (perfect fcst, uncertain IC)}}$$

***Fig. 5.3** Ratio of forecast RMSE for perfect initial conditions and uncertain forecast to RMSE for perfect forecast and uncertain initial conditions, for a range of lead times and forecast dates for the Columbia and Rio Grande river basins. Initial conditions are most important for short lead times, and forecasts near the time of maximum snow accumulation (roughly months 4–5), and less important otherwise. Source: Wood et al. (2003)* (reproduced by permission from *J. Geophys. Res.* ©AGU).

defining those sensitivities is complicated by large uncertainties in the manifestation of changes in the surface radiative forcings associated with greenhouse gas emissions. For instance, temperature increases *per se* may not have much effect on the hydrological cycle through the dominant efflux from the land surface—evapotranspiration. There is even convincing evidence of decreases in pan evaporation over the last 50 years or so, especially in the USA and former Soviet Union, where networks are (or were at the time the observations were collected) the best (Roderick & Farquhar, 2002). These changes seem to be caused mostly by decreases in surface solar radiation (related to cloud cover increases), rather than (directly) to air temperature. This is one explanation for the paradox described by Brutsaert & Parlange (1998) that in a warming climate, pan evapotranspiration could be decreasing while actual evapotranspiration might be increasing.

The main effect of temperature on the land surface hydrological cycle is to change the vapour pressure deficit. While this clearly increases the evaporative demand, the effect is muted by the fact that evaporative demand is dominated in most locations by a second term in the so-called combination equation—net radiation. On the other hand, climate models mostly presume that increased temperatures in the lower troposphere will lead to increases in precipitable water (due to the increase in vapour pressure with temperature), and hence, at least globally, increases in precipitation (Morel, 2001). On the regional and finer spatial scales at which hydrological prediction focuses, the situation is even more complicated, as precipitation either increases or decreases depending on the specific model. In one area—snowmelt dominated watersheds—the situation is clearer, as temperature is the primary driver of hydrological changes (see e.g. Hamlet & Lettenmaier, 1999, among many other references).

Most assessments of the implications of climate change for hydrology and water resources use a chain of models similar to that shown in Fig. 5.4. At the global scale, climate change projections are taken from General Circulation Models of the coupled land–atmosphere–ocean system, and via a downscaling process, are translated into hydrological model forcings, usually at much higher spatial resolution than that of the climate model. This downscaling step has been the topic of numerous papers, which generally follow one of two pathways: statistical or dynamical. Statistical methods are essentially "trained" to observed data, typically using statistical methods like least squares or variations thereof (e.g. Wilby *et al.*, 2000). Dynamical methods use atmospheric models that typically are conceptually similar to GCMs, except that they run at higher spatial resolution, and with boundary conditions taken from a global GCM. Wood *et al.* (2004) show that even when dynamical downscaling is used, some form of statistical bias correction (which can be part of a downscaling process as well) is necessary to avoid having climate model biases dominate the hydrological and water resources projections resulting from a strategy like that shown in Fig. 5.4.

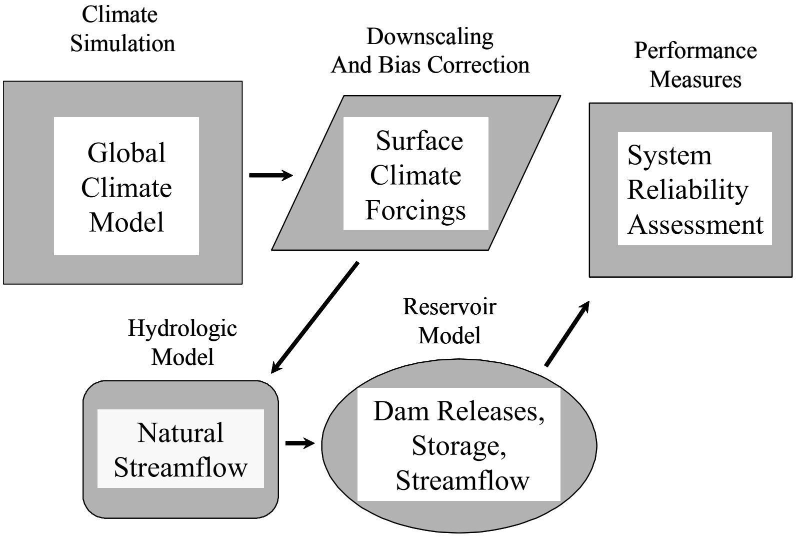


Fig. 5.4 *Typical chain of models used in hydrological and water resources assessments of climate change. Key sources of uncertainties are in climate model projections and hydrological predictions, which often are outside the range of conditions for which the hydrological model has been calibrated* (diagram courtesy of Alan Hamlet).

Regardless of how the downscaling and bias correction is performed, the hydrological model must be calibrated to reproduce observed hydrological conditions (typically streamflow being the primary consideration). One problem with this approach is that there is no assurance that the model calibrations will be valid under alternative climate conditions, particularly when they depart substantially from conditions observed in the past.

Nonetheless, resources managers are being called upon increasingly to incorporate climate change considerations into long-term planning. A classic example is water supply planning for urban areas. Most water supply systems incorporate a long-range planning process in which a range of projections of future demand is considered, and corresponding water supply sources are identified. At present, these exercises rely almost exclusively on observed historical sequences of streamflow, notwithstanding a long history of research in synthetic streamflow generation (for a brief review, see Lettenmaier, 2003). At present, there is no accepted practice for incorporating climate change information into these planning studies. In addition to the heavy reliance of such studies on specific periods of historic observations, most agencies are tied to "in house" water resource systems models, and hence results of studies, such as the several dozen referenced in IPCC (2001), are not considered credible. On the other hand, these in-house models are often "hard wired" to historic conditions and observations, and hence methods that derive streamflow sequences that are not tied to the historic observations may not be acceptable. It is clear that the next generation of practitioners will have to be trained in the development and/or use of methods that are relevant to these problems.

Snover *et al.* (2003) outline one possible approach to adjusting historic observations so as to reflect alternate climate conditions, while maintaining the sequencing inherent in the historic observations. In their approach, the historic sequence of streamflows is adjusted as if they had occurred under an alternative climate (Fig. 5.5). For instance, the 1976–77 California drought is represented as if it had occurred under future climate conditions. This approach, which perturbs historic conditions, is intended to allow more straightforward adaptation of planning methods that are already used in practice. Nonetheless, *the research community has yet to provide practitioners with an established, and reproducible, set of protocols for representing climate change in planning studies*.

CONCLUSIONS

I have outlined three problems facing the hydrological community to which PUB could contribute. These problems, and the particular challenges associated with them, are:

- Prediction of the hydrological consequences of land use/land cover change
  I conclude that *we lack methods for estimating the equivalent of confidence bounds about our predictions, which are dominated by the sensitivity of water balance processes to vegetation change, which varies considerably among models.*
- Hydrological predictability in the context of seasonal streamflow forecasting
  I conclude that *we need to better understand the relative contribution to forecast errors of uncertainty in hydrological initial conditions vs skill in forecasting climate (the hydrological drivers) over the forecast period. Initial work in this area needs to be broadened beyond western USA snowmelt-dominated hydrological regimes, and to consider a range of hydrological models.*

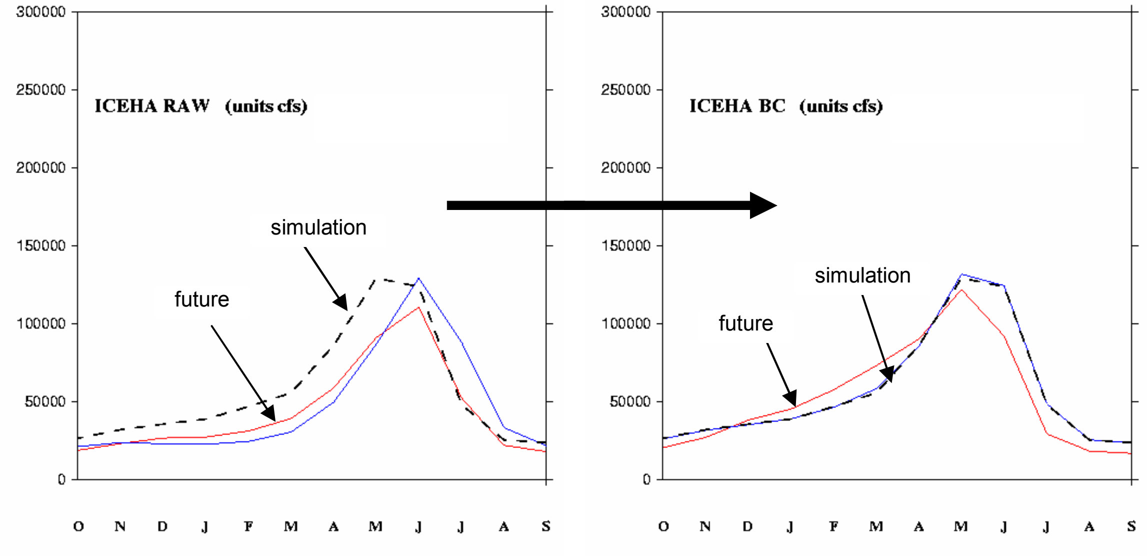


Fig. 5.5 Effects of bias adjustment on simulated streamflows (for the Snake River at Ice Harbor Dam, Washington) for current and future climate. In the left panel, the dashed line is the hydrological model simulation (monthly average discharge over a 40-year simulation period) while the line labelled future is the corresponding simulation for a future climate scenario. The unlabelled line in both left and right panels is from observations. In the right panel, both the historic and future climate results have been bias corrected, resulting in the simulations matching, on average, the observations nearly exactly, with a corresponding adjustment to future climate flows. Source: Snover et al. (2003) (reproduced by permission from Bull. Am. Met. Soc. © American Meteorological Association).

– Predicting the hydrological consequences of climate change
  I conclude that *the research community needs to provide practitioners with established and reproducible protocols for representing climate change in planning studies that will govern future management and/or development of water resource systems*.

PUB has the potential to mobilize the global hydrological research community to address problems of both scientific and practical relevance. I believe that these three problems meet both criteria, and are fundamental to the hydrological prediction underpinnings of PUB. Furthermore, all are, or could be, of great interest to the programme managers that support the research that the PUB community will undertake.

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