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Human impacts, complexity, variability and non-homogeneity: four dilemmas for the water resources modeller

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Abstract Water modellers are commonly faced with a range of dilemmas due to the complex, uncertain and conflicting nature of the problems currently studied. The limitations of present techniques to deal with the variability and non-homogeneity of future data sets in complex water systems are examined. The main limitations are in part due to changing human behaviour and linked anthropogenic land- and water-use impacts, as well as the uncertainty of climatic variability. Suggestions and questions for future practice are raised, as are technical based methods which are more likely to provide successful outcomes for integrated river basin management.

Key words water resources; variability; complexity; resilience; non-homogeneity; human impacts; modelling; ANN; Australia

INTRODUCTION

The construction and use of models to support understanding and decision making for water resources management and planning questions have been commonplace in a number of forms for many decades. Water engineering and management training is predominately based on learning a range of modelling techniques (mainly quantitative), which allows series of data to be analysed and used for a variety of purposes including optimization, forecasting and short- and long-term predictions. This paper aims to investigate whether such techniques are sufficient for dealing with the water management and planning problems faced by today's (and tomorrow's) practitioners, especially when the issues of complexity, variability, non-homogeneity and human impacts linked to water resources are taken into account.

COMPLEXITY

In the last 40 years, there have been major changes in the work requirements for a water engineer or manager. Doubling of populations in cities, environmental degradation and resource depletion all pose challenges to resolving water management problems, fuelled by the complexity, uncertainty, and conflict surrounding these problems. On the other hand, the rapid advances in computing power, new technologies and availability of information have assisted in the resolution of these problems, although one could now argue that they are just adding to the complexity of problem resolution. There is a current push for "sustainable" water management and development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). This means that physical system attributes, economic constraints and environmental impacts need to be considered when trying to manage water resources sustainably, as well as recognition of people's beliefs, values and practices. Due to such needs, use of "systems approaches" (Forrester, 1961; Checkland, 1981) has been heralded as the way forward to sustainable water management.

Defining system sustainability and measures of system performance

Loucks (1997) defined system sustainability in terms of reliability, resilience and vulnerability. Various criteria in terms of economic, environmental and social measures also need to be determined. In water resources problems, a specification of performance levels for a particular system needs to be established. The system is then considered to be in a satisfactory or unsatisfactory state relative to the threshold performance value for a particular criterion. A more in-depth discussion of system sustainability thresholds can be found in Foley *et al*. (2003) and Daniell *et al*. (2005).

Reliability can be defined by the probability that a system will achieve satisfactory performance for a certain period of time. For example, if there is a system that only fails to achieve the threshold performance for 36 days in a year, then: Reliability = number of satisfactory performance days/total number of days, i.e. 329/365 = 90%.

Resilience measures how quickly the system recovers from failure. In the example above, if the system recovered the next day to a satisfactory performance in 30 days out of the 36 days, then the resilience of the system would be the number of satisfactory days following unsatisfactory performance/total number of unsatisfactory performance days, i.e. 30/36 = 83%.

Vulnerability of a system aggregates both duration of failure and the severity of the failure. What are the implications of having a data set with more variability? If measures of reliability, resilience and vulnerability are used for measurement of system performance, then a simple appraisal of modelling will show that changes of state need to be measured.

What state was the system in at the start of modelling? If a particular change in a model forces other systems to adapt, then those systems also should be measured in terms of reliability, resilience and vulnerability. This should be paramount for man-made systems, but what about natural systems that man has altered by changing flows and then tries to manipulate by reversing some of the flows? Can ecosystems be modelled against the same criteria as the man-made systems?

Even if it is possible to determine a number of criteria (or indicators) which the system can be measured against, another factor, the system scale under analysis, must also be decided upon. Systems occur within a seemingly infinite nested hierarchy of other systems, the behaviours of which are likely to have some impact on “the system” under examination. Considering the complexity of the majority of water resources problems, many system elements on a large scale may have a small effect on the problem being studied. It is suggested that unless these effects are considered to be significant, the minimum necessary system size to deal with the problem “adequately” should be sought. It is noted that this “minimum” system size may not be an explicit spatial scale, but could also be a “problem scale” (Loucks, 1998).

Problem formulation, politics and human values

Another question related to the complexity of water resources problems, which is more commonly avoided by modellers or managers, is how these problems are formulated. What the problem may be (or even if there is a problem) is relative to the point of view of the beholder. Whether this is the modeller who is attempting to inform or solve his/her problem, a manager or politician, or another “stakeholder” who sees the problem from an entirely different point of view, it is necessary to be aware from which point, or points, of view the problem has been investigated. This issue is closely related to the “system scale” choice previously mentioned, as both factors will significantly impact upon the solutions proposed and whether the model produced is of use for decision makers if it is not “their model”, and what final mitigation strategies can perhaps be implemented or alternatively blocked by stakeholders.

Increasing conflict over problems such as the sharing of water resources has driven many management projects to a halt around the world. There are many examples of dam construction and grey-water recycling projects, amongst others, that have found themselves in this position. In the majority of these cases, the points of view and values of many important stakeholders were not sufficiently taken into account by the water management authorities at the earliest stages of these projects. Acceptance and use of models for aiding water resources management decisions are largely based on similar requirements for complex problems. If those stakeholders, who are to use or be affected by the decisions stemming from the use of a particular model, are not closely involved in the process of formulating the problem that the model is based upon, then there is a high chance of rejection of the model, its proposed solutions, and the final implementation. It is perhaps with this reasoning in mind that adding more “social stuff” (Nancarrow, 2005) to water models seems to be a current pre-occupation for those embracing the “sustainable and integrated” water management paradigms. However, exactly how these so-called “integrated” models are finally going to be used commonly appears less well thought through. It is suggested, therefore, that water modellers and managers decide prior to investing in these models: (a) Who will decide what the problem is to be studied in the model? (b) For whom and for what purpose is the model to be produced? (c) Will these peoples' needs be met by the model? (d) Should these people be involved, and in which capacities, throughout the modelling process, from problem formulation to model use?

VARIABILITY

Rainfall and streamflow variability is generally measured by the coefficient of variation which is the standard deviation divided by the mean value of a record. Australia and South African rivers have the world's greatest variability (McMahon, 1988; Finlayson & McMahon, 1988). Many form into a series of water holes for some part of the year and sometimes for many years. This variability is shown in Fig. 1 by the coefficient of variation of annual flows (Cv) for rivers with catchments greater than 1000 km^2 with a Cv of 0.9 for Australia and a Cv of 0.73 for South Africa rivers. Australian rivers also have larger peak and annual floods (relative to mean annual runoff and catchment size) than rivers elsewhere in the world (Finlayson & McMahon, 1988). This characteristic of variability, when harnessing water, results in larger storages being constructed relative to the streamflow mean. The size of the storage as a multiple of the mean annual flow to achieve 80% use of the mean annual flow, at 95% reliability, is also shown in Fig. 1. This characteristic means that if climate change increases variability in rivers, much more storage will be needed relative to the present state; or expressed another way, the reliability will drop significantly as variability increases.

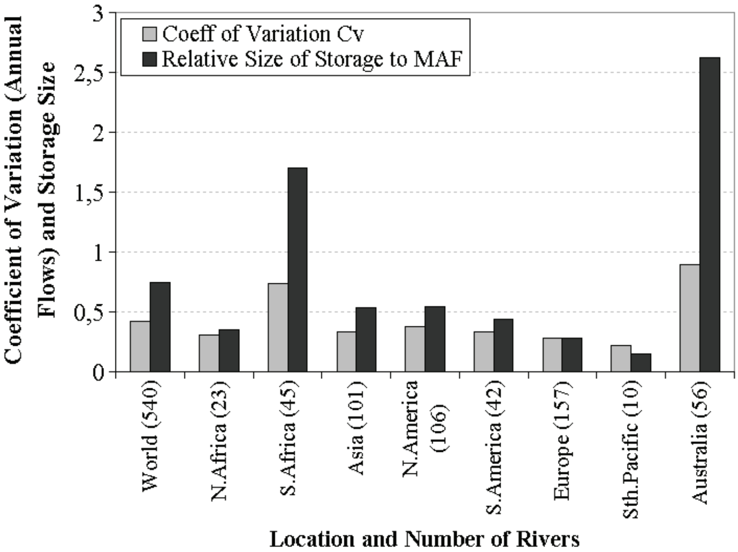

Fig. 1 Coefficient of Variation and Size of storage relative to Mean Annual Flow to achieve 80% draft of MAF at 95% reliability with catchments >1000 km^2 (adapted from data in Finlayson & McMahon, 1988).

Coping with changing variability

There are many contributing factors to increased variability. The way watersheds are cleared and managed, as well as climate change, already contribute to the variability of streamflow. Streamflow from pristine catchments can be dramatically changed by bushfires, not just in quantity terms but also in quality terms. The variability of quality and quantity of flows is not only very dependent on anthropogenic activities, but also on seasons and climate. The design and modelling of systems to cope with this increased variability has not generally been considered by water resources managers.

Recently, there has been a push to manage rivers so that environmental and ecological systems are not destroyed by the resulting change in variability of flows due to water supply and hydro-electric schemes. This is an attempt to improve degraded ecosystems and get them to adapt to a different variability. This allocation of water for the environment is in turn forcing water supply authorities to change demands on the system by various strategies to match the reduced supply. A changing boundary of variability around both these systems is that due to climate change, where increased overall variability of rainfall, and hence runoff, will impinge on how water systems are managed. Most water supply authorities now look at demand management with a focus on improving water use efficiency. Such methods of dealing with variability are therefore often linked to changing human behaviour, or at least encouraging the uptake of new technologies. It is human values and beliefs which largely govern whether such changes will be acceptable and whether conflicts over competing water uses and management strategies can be resolved. Exactly how to initiate change and incorporate competing human values into water related decision making practices should be a question that modellers reflect upon if their models are to be of practical use under variable and uncertain conditions.

HOMOGENEITY AND STATIONARITY

Where does homogeneity exist in a catchment? Certainly not in soil moisture, nor in soil types, nor in rainfall distribution for any event, nor in river flow, nor in evaporation, nor in land use as there is always a different distribution of vegetation dependent on non-homogenous factors such as moisture, radiation, fauna, temperature and soil types. Perhaps the only valid assumption of homogeneity is in time (but maybe not for a quantum physicist!). So our catchment is non-homogeneous; but what of the flow records emanating from it? Statistical tests on streamflow information to test homogeneity are commonly performed, but how valid are these? Vogel *et al.* (1998), in a major study of 1500 rivers for persistence, concluded that it only confirmed their "inability to discern the complex long-term persistence structure of natural flow records due to the fact that only short records are available. Assessment of the long-term persistence structure of actual flow records is further confounded by non-stationarity and non-homogeneity of those flow records".

Data are considered to be non-stationary if trends are present over time. It could be said that the assumption of *stationarity* has persisted because generally historical records of data are too short to accurately detect *non-stationarity*. For flood frequency analysis, data are examined for the statistical criteria of independence, stationarity and homogeneity. Anyone who has been involved in frequency analysis knows that removing outliers is necessary to develop a seemingly correct distribution. However, in reality, the "correct" probability distribution of extreme events has changed over time as frequency analysis models have developed that can cope with the non-stationarity aspects of trends, jumps and different causal mechanisms. Many researchers are working on frequency analysis methods and regionalization, and Kuczera & Franks (2004) highlight the non-homogeneous nature of flood peaks related to Interdecadal Pacific Oscillation events. Short-length data sets can meet homogeneity and stationarity considerations but in longer timeframes the climate causal mechanisms can relate to two or more populations of floods. Are the outliers the most important data points in a small data set? When confronted by an "outlier" flood event due to a landslip or a bushfire on a catchment, can it be justified that it was an unusual event and does not fit the homogeneous assumption for analysis? How often will this type of an event occur in 1000 years? Alternatively, if in a data set of 1000 years there were floods due to snow melt and there have been no significant snow falls for 200 years, is it reasonable to use the full data set for developing a frequency distribution? The issues of homogeneity and stationarity are ever present.

MODEL DILEMMAS AND EXAMPLES

We believe that there is no panacea for dealing with complexity, human impacts, variability and non-homogeneity in water resources problems, related data and their modelling processes. However, increasing general awareness of the importance of such issues is vital to improve water management and planning practices.

Modelling requirements and techniques—questions for reflection

Is it possible that if complexity, uncertainty and variability are too great, traditionally employed quantitative techniques may not be useful, or even possible, to use? In this case, would it be better to use qualitative techniques (such as cognitive mapping, causal diagrams or qualitative physics) or deliberation to find and debate management strategies or problem solutions (followed by cycles of monitoring and evaluation, continuous improvement and adaptive management)? One problem decision makers encounter when using most models is not knowing the range of uncertainty and potential errors related to outputs (or even inputs, in the case of varying qualities of data sets), and the assumptions employed in the model design. This often means that decision makers discard models and base their decisions on other information. If this is the case, should the model have been made in the first place, should another technique have been used, or should the decision maker have been more involved in the modelling process (i.e. "participatory modelling")?

Considering that the defined problem requires a model for a defined purpose, the next question is to determine what data is available and its quality. Depending on the type and quality of this data, as well as the final purpose of the model (optimization, prediction, forecasting, increasing understanding through scenario analyses), a relevant modelling technique may be chosen. For example, conventional deterministic or probabilistic models could be used with good quality quantitative data, as could data mining techniques such as Artificial Neural Networks (ANNs). Results for an ANN rainfall–runoff model developed for the Scott Creek catchment, an APFRIEND River (RSC, 2000), are shown in Fig 2. The results show how reasonably well behaved these models can be with suitable validation data. These models are not good at predicting outside the data regime that they were trained and tested on, but research is being carried out with Bayesian approaches to enhance their forecasting ability. The dilemma of the modeller here is to decide whether predictions can be made from current data, and which data are relevant to include.

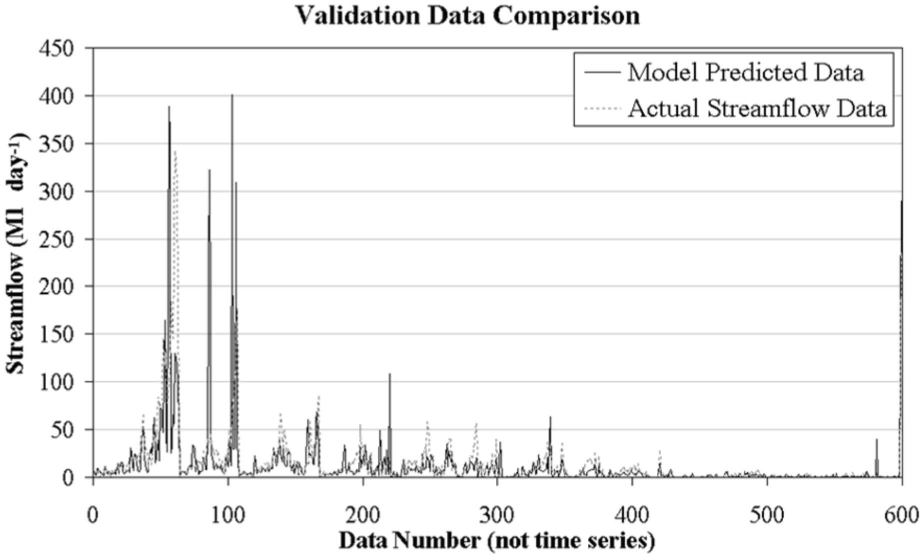

Fig. 2 ANN modelling results for Scott Creek in South Australia.

With lower quality quantitative data (or simply less data), techniques more capable of incorporating uncertainty or error bounds, such at Bayesian Networks or Markov Chains, may be more applicable. If qualitative and quantitative data need to be incorporated into a model, such as human behaviour, opinions, beliefs, goals and expert information, then modelling methods such as multi-agent systems could be used. A good example of such multi-agent systems modelling applied to water management in the Pacific island of Tarawa is given in Dray *et al.* (2006).

FINAL REMARKS

Although we can offer no definitive answers to water modellers who are (or will be) attempting to cope with the issues of variability, complexity, non-homogeneity and human impacts, we believe that it could be beneficial to reflect more deeply on a range of issues including:

(a) How, for whom, and for what purpose the models are being produced;

(b) How measures of resiliency, reliability and vulnerability can be used to monitor and more effectively manage water systems;

(c) What possible changes in current or future conditions (i.e. sudden climatic shifts or behavioural changes) could render data-driven models irrelevant;
(d) What methods (modelling or otherwise) are needed to cope with today and tomorrow's complex, uncertain and variable conditions; and
(e) Whether more data collection (i.e. streamflow, spatial climatic data) is needed so that changes can be identified.

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