Modelling and decision making in water resource management

HECTOR M. MALANO
Department of Civil & Environmental Engineering, University of Melbourne, Australia
h.malano@unimelb.edu.au.

Abstract Water resource systems modelling is a powerful tool to support evidence-based decision making in water management. Traditionally, water management decision making has been based on a single discipline rather than a multi-disciplinary and integrative approach involving physical, environmental, economic and socio-cultural dimensions. Water management has many of the characteristics of "wicked problems" – decisions are always made in an environment of great uncertainty, complexity and imperfect knowledge. To take into account this context, water management decision making must adopt a "whole-of-system and adaptive" approach that draws from a number of disciplines and can adapt to the continuously changing environmental, economic and social imperatives. Scenario planning provides a flexible and adaptive framework to couple modelling and science with decision making through an on-going collaborative partnership between decision makers and modellers. This is the opposite approach to the traditional one-off periodic planning activity which attempts to eliminate uncertainty from any strategic decision making. Integration of water resource modelling and decision making entails two dimensions – integration of the water cycle, economics and environmental modelling processes and integration of modelling with stake-holder support – a wide array of the models available to support one or more of these processes are usually not integrated. The modelling framework needed to support decision making must be selected to meet the needs of the specific system and nature of decisions supported. As such, a generic modelling framework must be constructed to integrate the multiplicity of physical, economic and environmental processes specific to each system. Two case studies are presented to illustrate the application of this scenario planning approach to supporting water management decisions: the Musi sub-basin, Andhra Pradesh, India, and the South Creek catchment, Sydney, Australia. In each case the nature of the decion-making environment, the scenario analysis and modelling framework are presented with a summary analysis of results and lessons learned. There are several prerequisites for this decion-making framework to succeed, including receptive institutions and a requirement for independent scrutiny, transparency and a sound modelling and scientific methodology.

Key words water resource systems; modelling; scenario planning; decision making; planning; multi-discipline modelling framework

BACKGROUND

Growing water diversions for economic uses are increasingly stressing many river basins, compromising the integrity of aquatic ecosystems by depriving them of the minimum sustainable flow and increasing the risk of water shortages and water security for economic activities. At present, irrigated agriculture consumes a large percentage of water diversions to supply some 280 million hectares of irrigated land. Sixty percent of these diversions are used consumptively while the rest become return flow downstream. Other economic uses, including potable, municipal, industrial, hydropower generation and recreation, account globally for about 30% of the total diversions although the consumptive portion is rather small as most of these diversions return to rivers and aquifers with a variable degree of quality degradation.

With the advent of greater and more accessible computer power, researchers have made great strides in modelling different components of water resource systems. These advances are all well documented in the scientific literature, and yet a large chasm still exists between these rapid advances and their adoption by water resource planners and managers. Explaining this dichotomy is rather difficult given the complex nature of water resource problems which involve aspects of many disciplines and the fact that our individual appreciation of these problems is always biased by our scientific background. There are often different objectives pursued by water resource modellers and water managers. Whilst modellers are inclined to focus on the specific physical and sometimes economic processes of water resources, policy makers are often preoccupied by delivering complex overarching policies that may include but are not limited to water management objectives.

A large volume of material has been published on the difficulties associated with the formulation of water management strategies that are supported by scientific evidence. Coupling water management with sound science is often hampered by many factors including the need to make decisions quickly within a time frame that does not overlap with the research timeframe, and the lack of an appropriate framework to support decision making on an on-going rather than an ad-hoc basis. As a consequence, the most common result is that policies and strategies become experimentation in an environment of great uncertainty; and while there will always be a certain amount of uncertainty associated with any water management strategy and it is not possible that anyone can provide a "unique" and "optimal" response, the challenge remains: How we can we ensure that the system is able to provide adaptive responses that are informed by scientific evidence as the implementation progresses?

The objective of this paper is to propose and discuss a framework for the use of water resource modelling to support the formulation of water management strategies in the context of an adaptive management framework. This paper begins with a characterisation of the nature of water resource management problems that stresses the concept of complexity and uncertainty present in these types of problems, followed by a discussion of scenario planning as an approach to integrate modelling (science) and stakeholders in partnership to inform water management policy and strategy development. Two case studies where this framework was applied are also presented and analysed to conclude with an attempt to identify the critical factors that influence the degree of success in applying this framework.

THE NATURE OF WATER RESOURCE MANAGEMENT PROBLEMS

Water resource systems (river basins) are complex systems with multiple interacting objects and activities occurring at different time and spatial scales. The ability to integrate all these objects requires a systems approach that allows the integration and explicit links that are needed to achieve a comprehensive understanding and analysis of their behaviour under different water resource policies (Elshorbagy & Ormsbee, 2005).

Traditionally, the prevailing discourse of classical organisations in water resource management thinking has been one based on a single discipline and focus to deal with water management problems alone. Very often, the focus to deal with these problems has been either on the hydrological or the economic aspects of the problem with little connectivity between these two or with other environmental, social, cultural and policy disciplines. Water resource modellers often start from the assumption that all decisions will emanate from the water resource perspective instead of the water resource modelling evolving with the rest of the elements such as economics, environmental and social-cultural aspects to provide a response that integrates all the dimensions of the decision that we aim to support.

Water management problems exhibit all the characteristics of wicked problems (William, 2002). These are often persistent problems despite considerable effort trying to solve them by conventional approaches. They exhibit a level of complexity, uncertainty, change and imperfection of knowledge that demand an entirely different approach to their solution. Water resource problems have three types of inherent uncertainties:

- *Cognitive uncertainty* due to lack of perfect scientific knowledge of the water cycle, environmental impacts and behavioural variables;
- *Strategic uncertainty* due to the many actors involved with different perceptions of the problem and its solutions; and
- *Institutional uncertainty* involving decisions made in different places by fragmented institutions with often different and conflicting agendas.

The complexity of water resources problems arise from the multiple, interacting and often conflicting factors of the physical, economic and social systems. Our knowledge of the physical and non-physical responses of the system to external interventions is always incomplete. For instance, we assume that more water allocated to meet environmental demand is better for the river ecosystem, but we often do not know how much water is needed and the appropriate timing to improve ecosystem performance as a large flow may have detrimental effects if it occurs when a low flow is needed. We know that climate change is coming at us and will impact water resources availability and demand. However, we do not know the magnitude of the impact and how it will impact other areas of economic and social life in order to design an appropriate adaptation strategy.

As such, these problems do not lend themselves to solution by the traditional approaches, are not amenable to optimal solutions based on a single discipline and require large-scale collaboration. Bammer (2005) posits that integration and implementation of solutions to these problems must draw from systems thinking, complexity science, participatory methods and knowledge management, exchange and implementation. He implies that the approach to dealing with this kind of problem involves multiple disciplines that can deal with the various subsystems that lie in the domains of water cycle hydrology, economics, environmental and social and cultural studies.

Problems are often artificially "tamed" and the solution is designed to address a sub-problem which is more tractable rather than the complex problem. Solutions to problems that are artificially tamed inevitably lead to more unintended consequences than if all the multiple factors and interconnections had been fully explored. For instance, allocation of water resource poses water managers with the typical challenge of sectoral competition for water between urban, agriculture and environment demands which are extremely difficult to predict with any degree of certainty. Whilst we have the necessary understanding to describe the surface and groundwater hydrological aspects of a river basin, our capacity to predict future water demand from economic uses and environmental uses is far less accurate given the changes that occur over time due to behavioural and public preferences. If the problem is tackled from a single hydrological perspective, a range of scenarios can be modelled that generate outputs in terms of water quantities allocated to each demand according to the level of priority assumed for each sector. Whilst perhaps it is feasible to physically implement each scenario, sound water management policy would need to consider the economic impacts and environmental dividends of each policy together with any institutional, legal or cultural barriers that may preclude its implementation (Khan *et al*., 2009). This type of complexity requires addressing two key elements: (a) to assess whether the policy meets the economic, environmental and social objectives requires a disciplinary assessment in all these dimensions, and (b) to do so within a framework that allows an on-going review and adaptation of policy that accounts for the continuous changes occurring in the policy environment.

The success of water management policy development often lies in the ability of water managers to understand and learn the dynamic nature of the systems they manage. Solutions are not direct, but the result of an interactive process. The nature of these problems is such that there is no "right" or "optimal" solution that will remain "static" over time; rather the solution must be adaptive and evolve over time. Adaptive approaches are necessary to enable managers to learn about systems behaviour as they evolve. This requires an on-going closed-loop integration of research–implementation–monitoring–review to ensure that the learning is incorporated into the continuous improvement process. Water management policy problems are nonlinear which makes it nearly impossible to predict outcomes from policy implementation. In water management, there is usually a set of different perspectives from stakeholders, and therefore the solution depends on how the problem is framed given that the prevailing water management priorities and constraints change overtime and the problem can never be solved definitively (Williams, 2002).

SCENARIO PLANNING FRAMEWORK

The traditional way of planning water resource management has been primarily from a position of certainty and this philosophy is best summed up by a statement such as "We have done the planning; we can now get on with making it happen". This is the traditional "rationalist" approach which involves the tacit assumption that there is a single best solution or strategy to address a water management problem. In this approach, planning is perceived to be a "one off" periodic activity. This approach attempts to eliminate uncertainty from any strategic decision assuming that the future is certain or otherwise uncertainties are well understood. However, as discussed in the previous section, water resource problems are characterised by large uncertainties about the future, especially in areas such as future climate change and water demand associated with economic activity and human behaviour. The deterministic approach is likely to work well only in situations that are very clearly defined and are predictable; and more importantly, where people always act rationally with full understanding. It has been demonstrated that our ability to predict future social and economic trends on the basis past trends usually performs very poorly after a short time (Van der Heijden, 1996). In a situation of uncertainty and complexity in which our ability to predict future physical and behavioural variables is limited, planning must become an on-going adaptive activity that enable planners to adjust their strategies to the new reality. Planning in this environment requires a degree of complexity, equivalent to the complexity of the environment in which it exists (Ashby, 1983). Robust planning is characterised by plans that can succeed under any future scenarios. And future scenarios always have a certain degree of uncertainty associated with them. In this context, scenario planning is a tool that allows planners to evaluate multiple future scenarios through a filter that is capable of assessing their physical, environmental and socio-economic performance and the risks associated with them.

In water resources, scenarios can be used in a pre-policy context to examine pathways to alternative futures. Formulation of these scenarios involves important "strategic conversations" with stakeholders and creativity about the possible futures which must be addressed by water management policies. Water resource planners commonly pursue multiple objectives in their water resource planning. Typically, government sponsored plans used to be evaluated from a single discipline lens, such as engineering or economics. More recently, government plans must satisfy the triple bottom line (TBL) criteria – economic, environmental and social. Even more critical from the point of the view of using modelling for scenario assessment is the ability to evaluate the "trade-offs" between the TBL objectives. As such, scenarios also provide a vehicle to cross disciplinary boundaries needed to address the complexity of water resource systems described in the previous section. These strategic conversations lead to "scientific conversations" that are crucial to allow researchers to make the necessary science connections across disciplines. These connections are especially important when the science and modelling framework used to evaluate strategic scenarios involves linking models across disciplines.

In this context, the selection of scenarios that can describe alternative futures is a critical process that involves key stakeholders associated with policy formation. Van Notten (2006) defines "scenarios" as "*consistent and coherent descriptions of alternative hypothetical futures that reflect different perspectives on past, present, and future developments, which can serve as a basis for action*". Scenario development entails constructing an explicit story about how the future may unfold. Water management scenarios are defined through an interactive process usually involving modellers and stakeholders. Scenario planning requires strong and committed stakeholders to decide which alternatives appear more plausible. Scenarios are not forecasts, but rather plausible different futures. They all must be given equal weight when plans or policy decisions are being considered. They can be used as a filter through which we analyse and test future policies and decisions (Fig. 1), and determine the modelling capability that must be assembled in order to assess their physical, economic and environmental performance.

MODELLING AND DECISION MAKING

There is ample evidence of the dichotomy that exists between researchers (modellers) and practitioners regarding the application or translation of research results to the day-to-day management of water resources. Whilst a great deal of new knowledge is generated by researchers and published in learned journals, very little of this knowledge is actually translated into actual management applications or assists in formulating evidence-based water management policy.

Integrated modelling to support decision making has two main dimensions: integration of water cycle, economics and environmental modelling processes, and integration of modelling with

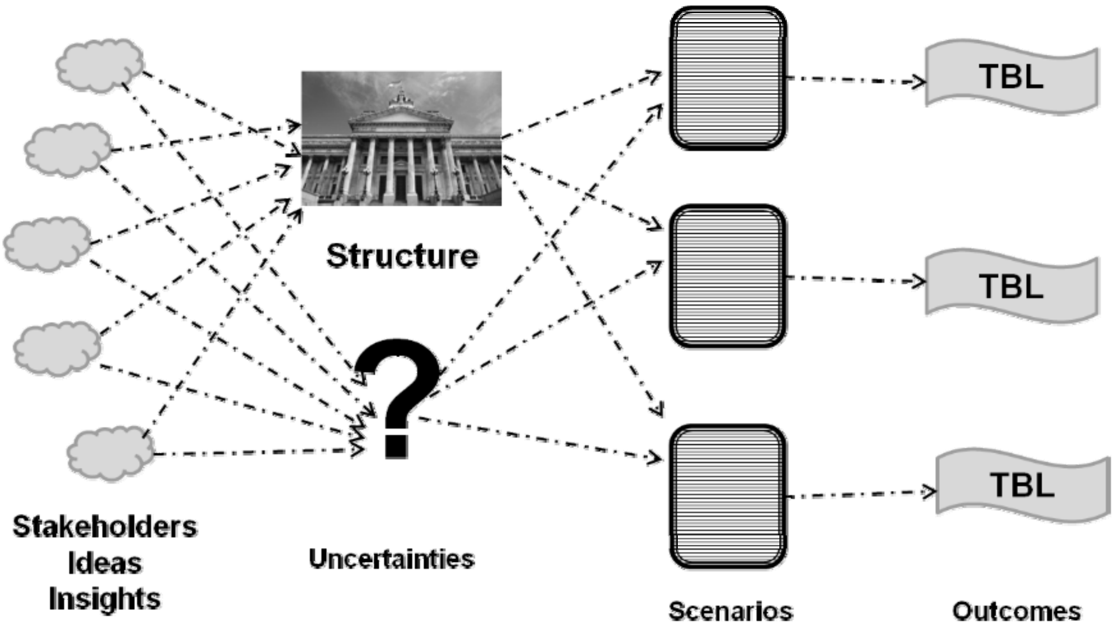

Fig. 1 Conceptual framework for use of planning scenarios (TBL is triple bottom line).

decision-making stakeholders. The proposed framework for integration of modelling and stakeholder decision support is based on the premise that water management decision making rests on key dimensions that can support TBL assessment of each decision including water cycle, economics, environmental and social, institutional and cultural analysis. Figure 2 is a depiction of the two-dimensional integration process that represents the generalised framework for integrating the elements of the water management modelling framework with water management decision support to stakeholders. This framework, first proposed by Khan *et al*. (2008) and Malano & Davidson (2009), is aimed at supporting the process of harmonising water extraction for economic uses and the environment whilst addressing TBL objectives. This framework also implies that there is a structured partnership between the modellers and scientists and planners and managers in

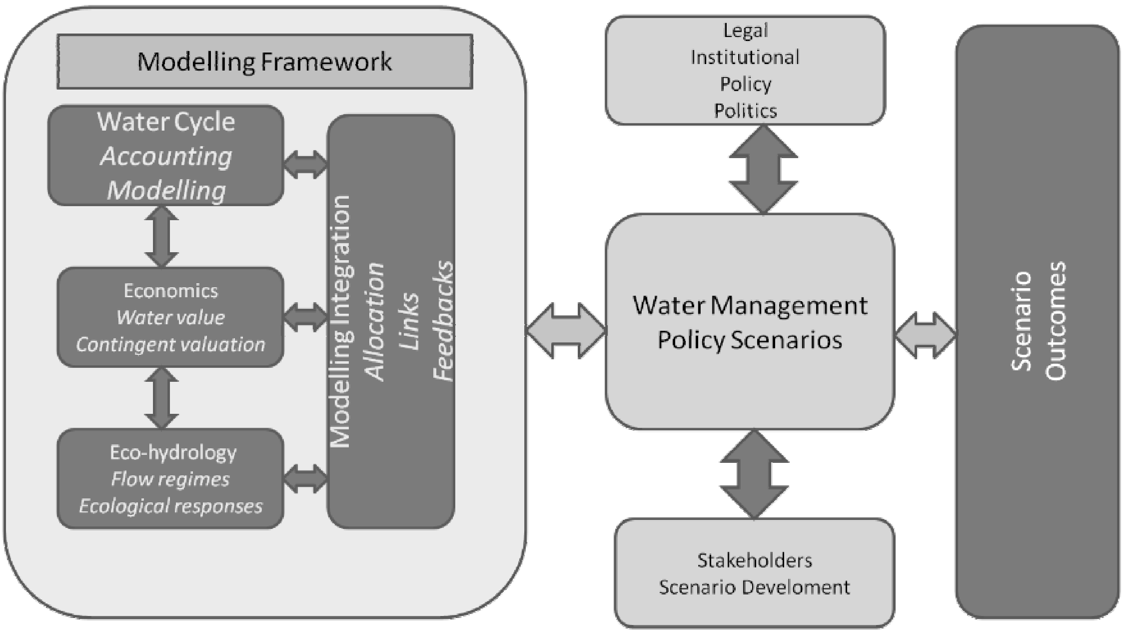

Fig. 2 Integrated modelling–stakeholder framework.

charge of water management strategies. This partnership between researchers and stakeholders also lays down the basis to guide the formulation and evaluation of strategic scenarios. The research elements of the framework are designed to inform the multiple stakeholders involved in this process of the water cycle responses (in water quantity and quality) and economic implications of alternative strategies (scenarios) for sharing the available resources.

WATER CYCLE MODELLING

The primary objective of the integration of water cycle modelling is to determine the impact that alternative water management planning interventions have on the behaviour the water and solute fluxes in the water cycle system. Typically, this is a three-stage process designed to describe the hydrogeology of the system, a snapshot of the current state of the water cycle in the form of water and salt balance analysis, and the development of a catchment/region specific modelling system designed to analyse the behaviour of the water cycle system under the selected water management scenarios.

Catchment systems are characterised by interacting, independent objects linked by strong and usually nonlinear links and exchanges of water and solutes. They represent complex systems which often present strong feedback loops that make it difficult to distinguish between cause and effects (Constanza *et al*., 1993).

Water resource system analysis and modelling is a technique used to understand the way these systems function. They require a clear and comprehensive conceptualisation of the multiple inter-relationships between its objects, and play a fundamental role in aiding understanding of the workings of the system. Lund & Palmer (1997) identify several ways in which systems modelling can assist in water resource management: better technical understanding of the problem, defining solution objectives, developing promising alternative solutions, evaluating the performance of alternative solutions, providing technical confidence in the solution agreed upon, and providing a forum for negotiations. Most water resource management problems facing the world today involve heavy competition for water both in terms of quantity and quality; and one can argue that the solution to these problems involves several or all of these elements.

The representation of the water cycle as a comprehensive water resource system is a powerful way of visualising and quantifying the links between the various sources and uses of water stocks and flows that occur between them. System representation and thinking enable the relationship between the various elements of the system to be better understood and identification of the impact of changes in the various components on the overall system performance. The reductionist approach often used to study the processes involved in the water cycle does not allow the representation and quantification of the multiple connections that occur between system elements.

For the purpose of describing the key processes involved in the water cycle, it is often convenient to subdivide the system in to different domains with appropriate links between them. It is, however, important to stress that this division is only for descriptive purpose rather than placing these processes in individual unconnected silos. For instance, it is possible to disaggregate the modelling of water allocation in individual catchments of a river basin and subsequently link them together for the whole of the river basin.

There are a number of models that have been developed to simulate various water cycle processes including: surface hydrology (including climate), the vadose (root) zone, groundwater modelling, resource allocation, river operation and quantity–quality dimensions. The level of process integration varies significantly between these models from generic applications which integrate most landscape hydrological and water demand processes (Andreu *et al.*, 1996; Flugel *et al.*, 2009) to single processes such as rainfall–runoff in the SWAT Model (Neitsch *et al.*, 2005), or groundwater hydrology in MODFLOW (Harbough *et al.*, 2000). Water management models often incorporate economic evaluation of alternative policies in addition to modelling the physical infrastructure of water supply systems. Harou *et al.* (2009) provide the most comprehensive summary of hydro-economic models reported in the scientific literature.

The processes that require modelling usually vary according to the configuration and prevailing hydrological processes in the catchment and the problem and range of policy interventions that are to be evaluated. Depending on the nature and objectives of the modelling task, very rarely can a single model or suite of models be used without either combining with other models or altering a pre-existing modelling framework. This in itself often poses a significant problem, in particular, when models chosen to simulate specific processes are not dynamically integrated and must rely on exogenous exchange of data inputs and outputs. Moreover, models or modelling framework components often operate on different time and spatial scales which require aggregation or disaggregation prior to their integration with other models. An additional integration challenge arises when models from different disciplines must be integrated such as linking hydrological and water system models and economic models.

Whilst the initial characterisation of the catchment water cycle can rely on a generic framework aimed to characterise stocks and flows of water in the system, the analysis of the system behaviour under specific water management policies and interventions requires modelling of specific processes. The specific nature of the modelling processes involved and models used in each catchment situation presents the biggest challenge to model integration.

Whilst the water cycle analysis concept can be applied to varied spatial-temporal scales, selection of the appropriate scales must yield an assessment framework capable of connecting processes through an objective, explicit and measurable set of criteria which include the ability to:

- capture and produce simplified descriptions of the bio-physical system;
- establish the minimum data requirement to characterise productive and environmental performance;
- assess the integration between multiple sources of water (wastewater, drainage, surface water and groundwater) and multiple demands for water (agriculture, urban, industrial and environmental);
- assess how irrigation systems interact with the surrounding environment (regional groundwater, receiving water bodies) within its assimilative capacity; and
- highlight the limits, constraints and opportunities for harmonising extractions and environmental allocation.

Thus, is model software integration a lofty pursuit? The experience from attempting to integrate models under a common shell has been patchy at best for various reasons. First, it is difficult to bring together all the model capabilities that may be required under a variety of catchment modelling scenarios. In addition, new models are developed over time which do not necessarily comply with the protocols set for integration. Perhaps an easier approach is to integrate input data sets in a common database platform which may be used by different models that will continue to run in standalone mode. This approach can also allow the coupling of models that rely on outputs from other models through the same integrated database.

FRAMEWORK APPLICATION: CASE STUDIES

The proposed modelling decision support framework is described in two case studies: South Creek, Sydney, Australia, and Musi sub-basin, Andhra Pradesh, India. The two case studies represent significantly different climatic, hydrological, institutional and socio-cultural settings. The case studies are also used to draw a number of observations about the generic nature of the framework and highlight the key modelling-policy support issues relevant to each case.

MUSI SUB-BASIN, ANDHRA PRADESH, INDIA

The Musi River is a principle tributary of the Krishna River in India, which supports a population of more than 10 million people in an area of approximately 11 000 km^2. The region has a semi-arid rain-fed agriculture typical of the Deccan Plateau. The mean annual rainfall of the catchment is 760 mm with an uneven distribution in space and time. The Musi sub-basin is a water stress region which is no longer able to meet the water demand from agriculture, urban and industry. The upper catchment of the Musi River is regulated by two reservoirs – Osman Sagar (OS) and Himayath Sagar (HS) – which supply water to Hyderabad City. The Musi medium scheme also supplies irrigation to 20 000 ha of agricultural land and provides drinking water to Suryapet town. A water reservoir transfer scheme supplies water from Nagarjuna Sagar Dam to irrigate 43 000 ha (George *et al.*, 2007). There are also some 45 000 groundwater boreholes in the sub-basin which account for about 60% of the water used for irrigation. Untreated wastewater effluent is used to irrigate several types of crops downstream of Hyderabad City. Water is currently imported from sources outside the basin (Sylvain *et al*., 2007). Intensive watershed development programmes supported by the Indian government appear to be impacting river flows downstream significantly, further modifying the hydrological balance of the sub-basin.

Scenario development

Policy makers in the Musi sub-basin face serious challenges in meeting the growing demand for water that arises from the rapid economic growth, industrialisation and population growth in its major city, Hyderabad. In addition, an increase in the expansion of agricultural practices has led to an increase in water demand which is filled by extracting groundwater resources in an unsustainable manner.

The complexity of the physical processes of water supply and demand, combined with some uncertainty in the future climate outcomes, makes informed decision making on water allocation difficult in this case. The dominant issue in this sub-basin is the severe shortage of water to meet agricultural, urban, industrial and environmental demand.

An extensive consultation process was undertaken with key water management stakeholders including the Andhra Pradesh Government, Hyderabad Municipal Water and Sewerage Service Board, national agencies and civic society to elicit views and discuss a number of future water supply scenarios for the sub-basin. This process was conducted over a period of 18 months and yielded the six most likely scenarios as listed in Table 1.

Table 1 Allocation scenarios analysed for the Musi Sub-basin, India.

Scenario	Description	Rationale
1	Satisfying all future urban demand (Hyderabad) from Nagarjuna Sagar Reservoir	There are a number of options to source additional water to meet future demand in Hyderabad City including further diversions from Nagarjuna Sagar Reservoir and the neighbouring Godavari basin.
2	Streamflow decline from climate change and watershed development	Streamflow in the sub-basin is likely to be impacted by future climate change. This scenario is aimed to carry out a preliminary assessment of the potential impact of climate change on water supply reliability.
3	Water savings in Hyderabad City	There are a number of options to improve water efficiency in Hyderabad City which would reduce future water demand from external sources. A detailed set of options is outlined in George *et al*. (2007).
4	Reservoir releases based on irrigation demand	Increasing electricity demand is driving reservoir releases in the Nagarjuna Sagar system which do not align with irrigation demand. This scenario is designed to evaluate the impact of shifting reservoir releases to match irrigation demand.
5	Maintain minimum river flow to meet environmental demands	Currently there are no allocation provisions to meet environmental demand in the Krishna basin. This scenario looks at the impact of imposing a monthly environmental release on the reliability to meet other water demands in the sub-basin.
6	Crop diversification strategies pursued by farmers	Rice is by far the crop that occupies most of the agricultural area and water demand in the sub-basin. This scenario is designed to evaluate the impact of reducing the rice planted area in favour of dry crops of lower water demand such as vegetables, jowar, groundnut and chillies.

Modelling framework

The modelling framework designed to evaluate the proposed scenarios consisted of three main components:

- a resource assessment and the modelling of supply (surface and groundwater resources) and estimation of water demand;
- an allocation model to distribute water to different demand centres based on agreed supply priorities; and
- an economic assessment model that includes the calculation of both the values of water used for different purposes and the net benefits from allocating water to each identified sector over time.

In this paper a summarised description of each modelling component is presented. The detailed description of the modelling concept and approaches used for each process is presented in George *et al*. (2010).

Resource assessment was based on a historical hydrological analysis and streamflow simulation to identify the most important components of the water balance at the sub-basin scale and to determine the main hydrological trends that have occurred over time. A monthly lumped conceptual rainfall–runoff model, SIMHYD, was used to model the rainfall–runoff process at key supply nodes in the catchment (Chiew *et al*., 2002). This model operates on a daily time interval and includes seven parameters that represent infiltration, storage capacity, maximum infiltration loss, infiltration loss exponent, soil moisture storage capacity, constant of proportionality in interflow, constant of proportionality in groundwater recharge and a linear baseflow recession parameter.

Allocation modelling was based on the integration of resource availability and water demand through a network allocation model. The Resource Allocation Model (REALM) was used in this study to represent the system network (James *et al*., 1996; Perera *et al*., 2005). The model was used to integrate water demand from urban, industrial, agricultural systems and in-stream requirements with the surface, groundwater and wastewater resources available and simulate the range of stakeholder defined scenarios. These scenarios also incorporate the sectoral and institutional priorities currently in place and those for which stakeholders requested evaluation.

The economic assessment of alternative allocation results was evaluated to determine the value of water and social cost–benefit associated with each demand centre and water use. The Output–Demand–Input–Network (ODIN) (Helleger & Davidson, 2010) was used to simulate this process. In this way, changes in economic outcomes from each allocation scenario can be referenced against the business-as-usual (BAU) scenario to determine the marginal impact from the changes in allocation policy.

The modelling framework included an environmental demand component based on the approach proposed by Smakhtin & Eriagama (2008), which is based on ensuring a flow regime capable of sustaining a target set of aquatic ecosystem processes. The approach, however, does not link flow regime and ecosystem responses in an explicit way. Such an approach requires extensive experimentation and long-term monitoring for its development, which are not available in this catchment.

The models selected to implement this modelling framework are outlined in Table 2. The integration of these models in all cases was implemented exogenously through the use of a simplified file sharing architecture based on Microsoft Excel™.

Scenario outcomes

The scenarios analysed in this study are the result of multiple consultations and strategic conversations maintained with stakeholders from government, academia and civic society throughout the planning cycle. A perception of independence by the modellers involved in this process was critical to the success of the partnership. Whilst the process was supported by all the stakeholders involved, often stakeholders representing different constituencies tend to focus their

Table 2 Summary of water allocation scenarios selected for the Musi sub-basin.

Model	Processes	Purpose	Reference
SYMHYD	Rainfall–runoff modelling	Surface water assessment. Simulation time series of river runoff	Chiew & McMahon (1993)
MODFLOW	Groundwater modelling	Groundwater behaviour and sustainable yield	Hill *et al.* (2000)
Resource Allocation Model (REALM)	Allocation of water by quantity and quality priorities	Evaluate alternative water allocation and substitution options	Perera *et al.* (2005)
Output–Demand–Input–Network (ODIN)	Value of water and cost–benefit analysis	Economic evaluation of water allocation options	Helleger & Davidson (2010)

attention on their own particular interests. In this environment, it was crucial that the evidence-based approach delivered strong credibility of the science provided to stakeholders.

A large volume of results was made available to stakeholders throughout the entire planning cycle. The results were typically expressed in the form of reliability of water supply and expected frequency of shortfalls, coupled with the economic outcomes expected from each scenario relative to the baseline (BAU) scenario. Table 3 shows a summary of key allocation volumes and economic costs and benefits associated with the scenarios outlined in Table 1. Integration of physical with economic results provides stakeholders with a holistic insight into the implications of alternative policies which can only be obtained from the application of a systems approach to water management modelling. For instance, against the prevailing view amongst government water managers that releasing water from reservoirs to meet irrigation demand instead of power generation demand would translate into large economic losses, the policy in fact translates into economic gains despite reducing the amount of water used in power generation.

SOUTH CREEK CATCHMENT, SYDNEY, NSW, AUSTRALIA

The South Creek catchment is located to the west of Sydney and covers around 625 km^2. The South Creek is one of the main tributaries of the Hawkesbury River. The region has moderate climatic conditions: warm to hot summer, cool to cold winter and an average annual rainfall of less than 800 mm with a fairly uniform distribution over the year.

The traditionally agriculture dominated area has been transformed to a peri-urban agriculture area where the urban area exceeds the area under agriculture. Not only has the agricultural area been reduced, but traditional agricultural activities of grazing and farming have been replaced by peri-urban agricultural activities such as market gardens, cut flowers, nurseries, greenhouses, hydroponics, etc. The area is home to five local councils: Hakesburry, Blacktown, Penrith, Liverpool and Camden. Agricultural land use in the region is likely to shrink due to competing demands for land and water resources by the growing urban population in western Sydney. The South Creek catchment currently supports a population of around 390 000 with the majority being resident in urban areas established in the central belt. The population is expected to grow to one million over the next two decades. The urban area in the catchment is likely to increase to around 60% of the total catchment area in the next 25–30 years to accommodate the projected population growth. These land-use changes are expected to have a significant impact on the hydrological responses of the catchment.

Scenario development

Preliminary analysis of the water availability and demand in the South Creek catchment indicates that there will be insufficient potable water to supply various water demands in future, including sports fields, parks and home gardens, and still maintain a healthy river ecosystem (Singh *et al.*, 2009). Water supply for other non-domestic uses will also be limited.

Table 3 Allocation and economic changes compared to the reference baseline scenario in the Musi sub-basin, India, for the period 2007–2031.

Scenario	Change in volume supplied ($\times 10^6$ m^3)				Change in net present benefits ($\times 10^6$ US$)					Change in net present costs ($\times 10^6$ US$)	Net present values ($\times 10^6$ US$)
	Agriculture	Domestic	Industrial	Power generation	Agriculture	Domestic	Industrial	Power generation	Total		
(1) Satisfying future urban demand (Hyderabad) from Nagarjuna Sagar as a priority	441	2385	42	–1977	5.00	618.00	1.00	–0.04	624.0	5038.0	–4414.0
(2) Streamflow declines by 20%	–5946	–238	–41	–17809	–124.00	–92.00	–2.00	–0.06	–218.1	–36.0	–182.1
(3) Water savings in Hyderabad	2507	2575	95	472	55.00	688.00	4.00	–0.02	747.0	1265.0	–518.0
(4) Reservoir releases based on irrigation demand	1815	70	65	–90911	51.00	78.00	3.00	–0.40	131.6	–8.0	139.6
(5) Environmental flows	–622	–6	–21	–19953	–23.00	–2.00	–2.00	–0.07	–27.1	0.0	–27.1
(6) Changing cropping patterns	–1694	69	42	6829	106.00	34.00	1.00	0.02	141.0	–60.0	201.0

Table 4 Summary of water substitution scenarios selected for the South Creek catchment, NSW, Australia.

CLIMATE CHANGE					
	Stormwater harvesting Water substitution options			Effluent re-use	Smart farms
LAND USE	Open space irrigation	Residential outdoor	Industrial		
Baseline (BAU) Natural growth predicted to remain constant in future Combined natural growth & growth centres Two growth centres are considered for future development	Use of stormwater to replace potable water for irrigation of parks and reserves	Use of stormwater to replace potable water for outdoor residential use	Use of stormwater to replace potable water in various industries	High quality effluent from three wastewater treatment plants will be allocated for outdoor use, agriculture and environmental flows.	Increasing water use efficiency of irrigated agriculture across the catchment including turf farms, field grown vegetable growers, nurseries (by retrofitting and irrigation scheduling) and greenhouse operations (re-use), water harvesting and re-use, and education and training

Scenario development to address future changes in demand and available supply in the catchment were completed through an extensive stakeholder consultation involving local government, State Government and local interest groups. There was overall consensus amongst the stakeholders that at a basic level there was a need for significant diversification of the water source portfolio for the region to meet future growth in demand. In addition, large hydrological impacts are expected from changes in land use towards a more urbanised catchment. The consultative process culminated in three basic water management scenarios: stormwater harvesting, smart farms and effluent re-use. These scenarios combined with three land use variations plus an over-arching climate change future scenarios formed the suite of scenarios analysed for this catchment (Table 4). The approach taken in this assessment was to use the BAU baseline scenario as a reference scenario for comparative purposes to evaluate the impacts of each future scenario.

Modelling framework

The modelling framework applied in this analysis was designed to represent the key bio-physical and economic processes involved in the agreed scenarios including:

– Assessment of the water supply and impacts of land use changes on runoff generation; and estimation of water demand. Land use in the South Creek catchment is expected to be severely modified as a result of increased urbanisation in future. This change is expected to lead to increased runoff as a result of an increase of impervious areas.
– Allocation and distribution of water according to sectoral demand segregated by quantity and quality based on agreed supply priorities.
– An economic assessment model that includes the calculation of both the values of water used for different purposes and the net benefits from allocating water to each identified sector over time.

The structure of the modelling framework is outlined in Fig. 3. Resource assessment and impacts of changes in land use in the catchment were modelled and evaluated with the BTOPMC model, which is a semi-distributed hydrological model that uses a block-wise combined with a Muskingam-Cunge runoff routing method (Nawarathna *et al*., 2004). The model was chosen for its capability to incorporate alternative land uses in the catchment and GIS interface capability.

The allocation-substitution alternatives for water supply replacement were evaluated using the REALM model (Perera *et al*., 2005) and the corresponding economic assessment was carried out in the same manner as in the Musi sub-basin study described above. The South Creek catchment presents an additional level of complexity due to the water quality restrictions that constrain the use of different water sources to specified uses. For instance, recycled stormwater and recycled effluent can only be used for strictly specified purposes that do not include indoor use. The economic assessment of water allocation-substitution scenarios was based on a similar approach to that applied to the Musi sub-basin case study described above (Helleger & Davidson, 2010).

Scenario outcomes

In this study, land-use and water demand options were combined to yield a suite of scenarios that were analysed through the modelling framework described in the preceding section. The modelling outputs were presented to stakeholders in a format that allows them to evaluate the volume and reliability of supply together with the economic outcomes expected from each scenario (Helleger & Davidson, 2010). As part of the consultative process, stakeholders are informed of the range of uncertainties surrounding modelling outputs.

The research-stakeholder partnership operates in this catchment under the System Harmonisation™ research program of the CRC for Irrigation Futures (http://www.irrigationfutures.org.au/). This partnership has spawned a new initiative on stormwater harvesting informed by the scenario planning process and modelling results, which involves the local councils in the catchment area. An infrastructure project to implement this initiative is currently under development.

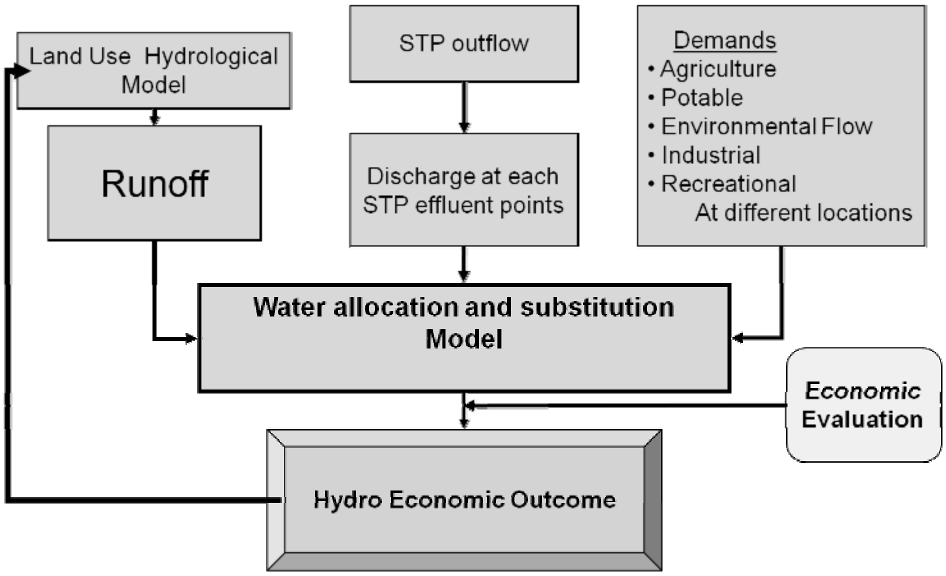

Fig. 3 Modelling framework applied in the South Creek catchment, Sydney, Australia.

LESSONS LEARNED

The above case studies revealed several lessons that contribute to making the application of scenario planning more successful. These lessons can be grouped in two different categories: research integration and research partnership.

Tackling water management problems using a scenario planning approach involves different disciplines which must be integrated towards addressing physical, economic, environmental and social aspects associated with each scenario. Real integration can only be achieved if there is a common understanding of the problem and solutions proposed through the various scenarios, and if there is real connectedness between the disciplines whereby results from disciplines can contribute to one another's analysis and results.

Strong and durable research–stakeholder partnerships are the key element to the formulation of evidence-based water management strategies. Modellers and researchers must be committed to both the generation of new knowledge that supports the formulation of selected strategies. On the other hand, stakeholders must have a clear understanding of their commitment to the partnership and be prepared to work collaboratively with researchers. The two case studies presented above, have demonstrated that this commitment must lead to science and evidence being embedded in the organisation's way of formulating water strategies. The difficulty in achieving this objective magnifies as the number of stakeholders and organisations increases, and in particular when different organisations have overlapping mandates and jurisdictions that frequently do not overlap with hydrological boundaries.

THE WAY FORWARD: OUTLOOK AND CHALLENGES

The use of "Scenario Planning" as a tool to deal with the uncertainty and complexity involved in water resource management forms the basis for an evidence-based approach to decision making that requires a policy-making process that is receptive to scientific evidence. Such a process must begin with a set of question rather than answers, and above all institutions that support scientific inquiry. The following observations are based on the author's experience and that of a number of scientists with whom he formed part of an interdisciplinary team. They reveal several lessons and premises that are important for a successful partnership between science and decision making and challenges that evidenced-based decision making must overcome in future.

Receptive institutions

Partnership between water management decision making and scientists must be an integral part of the institutions strategic planning process. Practical research engagement involves researchers, planners and stakeholders as they draw on each other's special skills to understand and solve complex problems. This approach can produce results that would not be possible otherwise, such as identification of emerging issues, access to sensitive information, and credibility with constituencies needed for greater impact. Robust strategic planning whereby evidence-based policy making forms part of the agency's strategic intent is a critical element to encourage robust partnerships between decision making and science. In water management policy, this principle entails that the selection of strategies is based on a sound understanding of the water cycle responses, environmental and economic responses and socio-cultural implications of alternative strategies. Only then we can put in place an effective monitoring and evaluation system that will provide the findings to assess progress in implementation and guide any future adjustments and improvements.

Independence, scrutiny and transparency

Trust and confidence in the scientific process is critical to the long-term success of researcher–stakeholder partnerships. All evidence and in particular, modelling, must be open to examination and must be explicit about the assumptions and methodologies for proper scrutiny and replication. Above all, modelling and modellers must be able to deliver robust results free of any influence that may compromise the robustness of results.

Sound methodology

It is critically important that the analytical approach or modelling chosen to analyse the problem allows for a proper consideration of the range of issues or scenarios that reflect the alternative options for present and future policy actions. As such, policy makers are interested in all the physical, environmental, economic and social dimensions of each policy option.

Whilst significant progress has been made in integrating water cycle processes and economics, the same cannot be said about environmental demand and responses. Integration of environmental demand into water cycle modelling frameworks to date is largely based on heuristic environmental rules that do not describe habitat responses to alternative flow regimes (Horne *et al.*, 2008). The ability to integrate environmental responses in an explicit way is critical to carry out a trade-off analysis of competing uses of water as discussed by Malano & Davidson (2009).

A vexed problem in the communication between modellers, water managers and stakeholders is modelling uncertainty. There is uncertainty associated with all water resources modelling. Uncertainty can stem from data inputs, model processes and model complexity which will set limits to the predictability of water management responses. Uncertain information is more useful than wrong certainty (Bloschl & Montanari, 2010); however, explaining the sources and implications of uncertainty can be difficult but absolutely necessary to ensure that water managers extract the correct information from modelling results.

Applying this modelling framework poses significant challenges. Models selected to simulate specific processes are not dynamically integrated and must rely on exogenous exchanges of data inputs and outputs. Moreover, models or modelling framework components operate on different time and spatial scales which require aggregation or disaggregation prior to their integration with other models. Synchronising time and spatial scales often requires manual upward or downward aggregation of inputs and outputs. For instance, the distributed rainfall–runoff model generates hourly runoff flows which will then be input into the water allocation-substitution model which expects monthly inflows.

CONCLUSIONS

Increasing diversions for economic and human use are reducing the ability of river basins to maintain their ecological integrity and at the same time support continuous economic growth.

Tackling these types of problems has proven difficult due to the complexity of factors involved in the management of water resource systems and the past tendency to deal with these problems by means of a mono-discipline reductionist approach.

Water management problems exhibit all the characteristics of "wicked problems" marked by complexity, continuous change and imperfect knowledge. To deal with such problems, the focus must be to consider:

– expanding the traditional "rationalist" mono-disciplinary breadth focused primarily on the physical aspects of water resource systems to embrace a systems thinking and multidisciplinary based approach; and
– adopting an adaptive "scenario planning" approach as the main tool to allow stakeholders to determine the plausible policy futures and enable managers to learn about systems behaviour as they evolve and adapt their planning accordingly.

Integrated modelling of the water resource system is an important tool in providing an "evidence-based approach" to the performance assessment of future scenarios that can be integrated into the decion-making process used by planners and managers.

Two case studies which incorporated various aspects of the proposed framework are presented: the Musi sub-basin, Andhra Pradesh, India, and the South Creek catchment, Sydney, Australia. In each case, the selection of scenarios, modelling framework and analysis of the lessons learned in this process are discussed.

Finally, key challenges to the successful integration of modelling with decision making that need to be overcome to ensure successful outcomes are discussed. These include receptive institutions which rely on sound technical and scientific evidence to support decision making, the ability to ensure trust and confidence through on-going partnership and sound methodologies to inspire credibility in the modelling outputs.

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REFERENCES

Allan, C. (2008) Can adaptive management help us embrace the Murray-Darling Basins' wicked problems? In: *Adaptive and Integrated Water Management: Coping with Complexity and Uncertainty* (ed. by C. Pahl-Wostl, P. Kabat & J. Moltgen), 61–73. Springer, Berlin, Germany.

Andreu, J., Capilla, J. & Sanchis, E. (1996) AQUATOOL, a generalised decision-support system for water resources planning and operational management. *J. Hydrol*. **117**(3-4), 269–291.

Ashby, W. R. (1983) Self-regulation and requisite variety. In: *Systems Thinking* (ed. by F. E. Emery). Penguin, New York. USA.

Bloschl, G. & Montanari, A. (2010) Climate change impacts – throwing the dice? *Hydrol. Processes* **24**, 372–381.

Brown, D., Bammer, G., Batliwala, S. & Kunreuther, F. (2003) Framing practice-research engagement for democratizing knowledge. *Action Research* **1**(1), 81–102.

Chiew, F. H. S. & McMahon, T. A. (1993) Australian data for rainfall–runoff modelling and the calibration of models against streamflow data recorded over different time periods. *Civil Engng Trans., Inst Engrs Australia* **CE35**(3), 261–274.

Costanza, R., Wainger, L., Folke, C. & Mäler, K.-G. (1993) Modeling complex ecological economic systems. *BioScience* **43**(8), 545.

CRC for Irrigation Futures (2010) System Harmonisation Research Program. http://www.irrigationfutures.org.au/ Accessed on 16 March 2010.

Elshorbagy, A. & Ormsbee, L. (2005) Object-oriented modelling approach to surface water quality management. *Environ. Modelling & Softw*. **21**(5), 689–698.

Flugel, W. A., Michl, C., Krause, P., Kralish, S., Fink, M., Hemlschrot, J., Busch, C., Bohm, B. & Bende-Michl, U. (2009) The DEWNET Network: JESAT a toolset for environment system assessment, analysis and management. In: *Proc. 18th World IMACS / MODSIM Congress* (Cairns, Australia) 3817–3823.

George, B. A., Malano, H. M. & Davidson, B. (2007) Integrated water allocation-economic modelling at a catchment scale. MODSIM-2007. In: *Proc. Int. Congress on Modelling and Simulation* (Christchurch, December 2007), 322–329.

Harbaugh, A., Banta, E. R., Hill, M. C. & McDonald, M. G. (2000) MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model–User guide to modularisation concepts and the ground-water flow process. USGS.

Harou, J. J., Pulido-Velazquez, M., Rosenberg, D., Mdellin-Azuara, J. & Howitt, R. (2009) Hydro-economic models: concepts, design, applications and future prospects. *J. Hydrol.* **375**, 627–643.

Hellegers, P. & Davidson, B. (2010) Determining the disaggregated economic value of irrigation water in the Musi sub-basin in India. *Agric. Water Manage.* doi:10.1016/j.agwat.2010.01.026.

Hill, M. C., Banta, E. R., Harbaugh, A. W. & Anderman, E. R. (2000) MODFLOW-2000, the US Geological Survey Modular Ground-Water Model – User guide to the observation, sensitivity, and parameter-estimation processes and three post-processing programs: *US Geological Survey Open-File Report 00-184*.

Horne, A., Freebairn, J., McMahon, T. & Stewardson, M. (2008) Environmental response curves – a first step in developing an environmental demand curve. *Proc. Water Down Under*, combined 31st Hydrology and Water Resources Symposium and the 4th International Conference on Water Resources and Environment Research, Adelaide, Australia.

Jakeman, T., Letcher, R. & Chen, S. (2006) Integrated assessment of impacts of policy and water allocation changes across social, economic and environmental dimensions. In: *Managing Water for Australia: The Social and Institutional Challenges* (ed. by K. Hussey & S. Dovers), Chapter 8, 97–112. CSIRO Publishing, Australia.

Khan S., Malano, H. & Davidson, B. (2008) System harmonisation a framework for applied regional irrigation business planning. *J. Irrig. Drain.* **57**(5), 493–506.

Lund, J. & Palmer, R. (1997) Water resource system modelling for conflict resolution. *Water Resources Update*, 70–82. http://www.ucowr.siu.edu/updates/pdf/V108_A6.pdf (accessed on 9 March 2009).

Malano, H.& Davidson, B. (2009) A framework for assessing the trade offs between economic and environmental uses of water in a river basin. *J. Irrig. Drain.* **58**, S133–S147.

Nawarathna, B,, Kazama, S. Sawamoto, M. & Takara, K. (2004) Method to delineate blocks in BTOPMC model for large scale watersheds. *Ann. J. Hydraulic Engng, JSCE* **48**, 61–66.

Neitsch S. L., Arnold, J. G., Kiniry, J. R. & Williams, J. R. (2005) Soil-water assessment tool theoretical documentation. Grassland, Soil and Water Research Laboratory, Agricultural Research Service. Texas, USA.

Perera, B. J. C., James, B. & Kularathna, M. D. U. (2005) Computer software tool REALM for sustainable water allocation and management. *J. Environ Manage.* **77**, 291–300.

Pineros Garcet, J. D., Ordonez, A., Roosen, J. & Vanclooster, M. (2006) Metamodelling: theory, concepts and application to nitrate leaching modelling. *Ecol. Model.* **193**, 629–644.

Sibley, D., Anderson, C., Heidemann, M., Merrill, J., Parker, J. & Szymanski, D. (2007) Box diagrams to assess students' systems thinking about the rock, water and carbon cycles. *J. Geoscience Education* **55**(2), 138–146.

Singh, R., Maheshwari, B. & Malano, H. (2009) Developing a conceptual model for water accounting in peri urban catchments. In: *Proc. 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation* (Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation, July 2009), 3654–3860.

Smakhtin, V. & Anputhas, A. (2006) An Assessment of Environmental Flow Requirements of Indian River Basins. IWMI Research Report 106, Colombo, Sri Lanka.

Van der Heijden, K. (1996) *Scenarios: The Art of Strategic Conversation*. John Wiley & Sons, Chichester, UK.

Van Notten, P. (2006) Scenario development: a typology of approaches, Chapter 4. In: *Think Scenarios, Rethink Education*.

Williams, P. (2002) The competent boundary spanner. *Public Administration* **80**(1), 103–124.