Tools for analysing hydrocomplexity and solving wicked water problems: a synthesis

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ARE WATER PROBLEMS COMPLEX AND WICKED?

The word hydrocomplexity is used to characterize the intricate arrangement of the water systems puzzle which has many parts that are interconnected with the social, environmental and economic systems. The tools represent approaches to characterizing the hydrocomplexity to present an array of solutions to solve wicked water problems. The term wicked problems is often used to highlight social and technical issues in water management which are difficult or impossible to solve because of incomplete, contradictory, and changing socio-economic and environmental requirements that are often difficult to recognize.

Rittel & Webber's (1973) formulation of wicked problems specifies characteristics in the context of social policy planning. These characteristics can be customised for water systems as below:

– There is no definitive formulation of a wicked water problem due to time, space variables and changing biophysical, socio-economic and policy conditions.
– Solutions to wicked water problems are not true or false, but better or worse in a socio-economic context.
– Every solution to a wicked water problem is a "one-shot operation" at a given time; however, there is a need for adaptive management at all levels.
– Wicked water problems have non-unique solutions; there is no well-described set of permissible rules that may be incorporated into the water plans.
– Every wicked water problem is unique and needs local tools to describe, visualise and manage it.
– Every wicked water problem can be considered to be a symptom of a broader socio-economic problem.
– The water scientists, planners and managers have no right to be wrong (scientists, planners and managers are liable to society for the consequences of the actions they generate).

In the context of the global water crisis, due to poor data, science and governance, many urban and rural water issues are becoming *super wicked problems* for the following reasons:

– Time is running out in many catchments due to irreversible global change damages to surface and groundwater quality and associated ecosystems.
– Poorly defined water rights for the environment leading to the "tragedy of the commons" in managing a common property.
– Difference between commitments and implementation of management plans for trans-boundary water resources due to a lack of a transparent and accountable central authority.
– Those seeking to solve water issues are also causing them, resulting in new super wicked problems.

SYNTHESIS OF THE CONTRIBUTIONS

This section presents a synthesis of the papers and extended abstracts/posters presented at the Kovacs Colloquium, and published here. Under each area of interest a summary of the invited keynote paper is followed by key learning from the extended abstracts in alphabetical order.

Monitoring and Evaluating the Water Cycle

Shuttleworth shows that hydrocomplexity occurs in the theoretical description of a hydrological process, which requires accurate representation of controlling features. This paper makes a critical reappraisal of currently recommended methods for estimating the water requirements of irrigated crops and reveals there is a fundamental theoretical inconsistency between present-day understanding of the interaction between plant canopies and the atmosphere as represented by the Penman-Monteith (P-M) equation and the procedures for estimating plant water requirements currently recommended by FAO. Broader adoption of irrigation practice using the Matt-Shuttleworth approach is recommended on the grounds that it is consistent with present-day understanding of the evaporation process, it is feasible and simple to apply, and will facilitate future adoption of realistic representations of the effect on transpiration of plant stress and of crops with partial ground cover. He recommends that pan-based estimates of reference crop evaporation rate should be made with recognition of the now-available theoretical formula for pan coefficient, and preferably using nearby measurements of wind speed and temperature, if available, or estimates of their values otherwise.

Adeloye and Rustum illustrate the role of data in managing uncertainties during the planning and management of water resources systems. They present the Kohonen Self Organising Map (KSOM) as a viable tool for multivariate prediction in the presence of data gaps. The goal of the KSOM is to transform an incoming signal pattern of arbitrary dimension into a two-dimensional discrete map. The KSOM has been demonstrated as a very useful tool for solving the problem of lack or inadequacy of data for effective water resources planning and management. KSOM is a multivariate approach and is unaffected by missing values; indeed one of its important outcomes is the prediction of such missing values.

Boland considers the Murray-Darling Basin, Australia, where there is a need to solve the multi-criteria optimisation problem of supplying critical human needs while maintaining – or indeed enhancing – the environmental health of the system. He presents one project that concerns a modelling of the weighted sum of rainfall at correlated sites for an estimate of the total volume of water as runoff from a catchment due to rain, and a stochastic dynamic programming model to improve water management in a large river system.

Mesquita and Koide report the importance of optimum design of networks for monitoring water quality as there is no universally accepted methodology for this purpose. In this context, they introduce the concept of using land use and drainage area to define the network’s ability to gather information, based on the entropy concept to maximize the value of gathered information. The methodology was applied to the Descoberto River basin in the central region of Brazil.

Larsen and Evenson demonstrate how the USGS will conduct a national assessment of water availability and use through the National Water Census. They also present recent examples from the USGS pilot study of water availability and use in the Great Lakes watershed, which concluded in 2009.

Prasad describes the use of modern technologies to estimate unaccounted water uses in the Murray-Darling Basin. Water measurement and accounting such as on-farm storages from multiple sources (streams, LSD, groundwater), and storage and distribution (pumps, pipelines and channels) infrastructure are used for both taking and using water. The ultimate challenge is how to convert an experimental model to a cost-effective operational tool that could be routinely used by water managers without being overwhelmed by the complexities involved.

Turczi et al. discuss the possibility of representing cross-border environmental themes on one database for territories with different characteristics, whilst satisfying the different demands of users. The availability of data is the main problem, along with the absence of coordination with other basins. The INSPIRE Directive (INfrastructure for SPatial InfoRmation in Europe) opens a new chapter in European GIS, and with the creation of the spatial data infrastructure, it contributes to a more effective coordination between the member states.

Linking Climate Change with Water Cycle Management

Taylor et al. present diagnostic tools to bridge the knowledge gaps in groundwater system responses to changes in climate and abstraction. The global aquifer map (WHYMAP) and satellite monitoring of changes in total water storage under the Gravity Recovery and Climate Experiment (GRACE) have recently been developed; their deployment is greatly constrained by a dearth of reliable and sustained observations of groundwater systems. They provide new insights into relationships between global hydrological change and groundwater systems including the impacts of intensive abstraction for irrigation on groundwater storage and changing rainfall intensity on groundwater recharge from basin-scale studies.

Stakhiv points out that water resources management is going through a transition phase, trying to accommodate the large uncertainties associated with climate change, while struggling with implementing a difficult set of principles and institutional changes associated with integrated water resources management and adaptive management. He reports that the US Army Corps of Engineers has adopted a pragmatic "proactive adaptive management" approach, comparable to the "no regrets" philosophy espoused by many advocates of climate change adaptation. The approach consists of risk-based planning and design of infrastructure to account for climate uncertainties and development of a new generation of risk-based design standards for infrastructure responding to extreme events (floods and droughts).

Brils presents risk-based management as the new approach required to achieve actual improvement of the ecological quality of our river basins, and thus sustain the goods and services they provide for the well-being of society. It involves the integrated application of three key principles: be well informed, manage adaptively and take a participatory approach. The conviction is that well-designed, coordinated and monitored "learning catchments" are needed to transform the general framework and develop best practice.

Hill illustrates climate change as a complex problem which crosses sectoral, disciplinary, temporal and national boundaries. In mountainous areas, impacts on glacial retreat and precipitation patterns, together with associated changes in runoff regimes, are already being observed. Effective water governance is seen as essential to building adaptive capacity to manage future climatic uncertainty and associated stress. A better understanding of adaptive capacity within the water governance framework is an important component of any proactive response strategy to the wicked problem of climate change impacts on water resources. The Valais (Switzerland) case area underlines that fact that numerous studies have shown that a substantial gap exists between the promise of process and practice in IWRM.

Normatov et al. argue that the creation of adaptation mechanisms can be a key to more cost-effective and environment-friendly water management. The efficiency of construction of reservoirs in foothill districts may influence formation of a microclimate.

Ogunbadewa presents a study which aims to test the suitability of data sets obtained from satellite sensors and hydro-meteorological stations for development of a climate change predictive model for water resources management. Using additional data sets from satellite sensors as a new tool will increase the possibility of obtaining improved information on climate change in relation to water resources management at both spatial and temporal scales.

Santoso and Harjono argue that an integrated model is necessary to explore and understand the multiple effects of changes in climate and land use on the hydrology of a river basin in relation to land-use and water-use planning and management for sustainable development. An integrated model such as INDOCLIM can help to explore the possible future states of a river basin under these pressures, which is useful for water-use planning and management in relation to sustainable development. The model is user oriented, and is basically designed for sensitivity analysis to answer "what could happen if" questions.

Parsimonious *vs* Complicated Approaches

Pande et al. show how parsimonious models for dryland areas can capture the dominant hydrological processes in a data-limited environment. They identified evaporation and subsurface flows as dominant processes and modelled them at monthly time steps for a study area in western India. They represent the model area by interconnected linear (in a storage–discharge relationship) reservoirs, where each reservoir is parameterized to represent the two fluxes. The parameters are estimated based on GRACE (terrestrial storage change) and MERRA2D (evaporation flux) data simultaneously. Finally, parsimony in parameters of the overall model (of interconnected linear reservoirs) is achieved by regionalizing recession parameters in terms of soil characteristics. This study elicits an approach that is urgently needed in data- and water-scarce regions.

Fenicia et al. argue the non-uniqueness of hydrological problems and, therefore, the need for a flexible model structure. They show application of the model to a headwater catchment in Luxembourg. They introduce a flexible threshold which is automatically determined, with the objective of balancing predictive capability and parameter uncertainty.

Garg presents a model aimed at achieving accurate forecasts of a hydrological time series using a combination of traditional time series and soft computing approaches as a solution for this wicked water problem. Knowledge of water level in advance can significantly improve the utilization of water resources and has considerable importance in decision making units for wicked water problems. Accurate water level can be forecast by the Water Index using the presented predictive model.

Jiménez-Espinosa and Jiménez-Millán report a project about the Alto Guadalquivir River, which is a shallow aquifer located in the central part of the province of Jaén in Spain, and that has groundwater resources which are mainly for irrigation of crops in an important agriculture-dominated area. A multivariate statistical treatment was carried out; allowing a reduction in the variability of the system and giving three factor variables that synthesize the original information. The result brought a probabilistic representation through the mapping of these variables, assessing the spatial variation of the main physical–chemical processes involved in the quality of the groundwater in this aquifer.

Khanchoul et al. report a methodology for surface runoff modelling in gauged and ungauged drainage basins of northeast Algeria. A gauged drainage basin was modelled using calibration against measured flow data, whereas streamflow in the ungauged basin was simulated by the SCS-CN procedure utilizing WMS. The synthetic determination of CN generated from GIS and WMS was a meaningful tool for modelling outflows in the ungauged basin. These results show efficient water availability for reservoir reliability and give some encouragement that, once more data become available, regional estimation procedures might be developed for flow estimation at ungauged sites for use in improved water resources assessments of Algeria.

Igouzal and Maslouhi describe a hydraulic model coupled with a water quality model implemented to study the River Sebou at the Gharb, Morocco. In this context, the developed model is proposed as a means of interdisciplinary management, based on scientific and rational concepts. Regarding the quality of the water, discharges of organic wastes as well as the closure downstream of the dam, certainly contribute to degradation of water quality. Several scenarios were tested, thus providing scientific evidence for water resource managers to define policies for interdisciplinary water management of the Sebou River in the Gharb.

Whole-of-System and Adaptive Approaches

Malano shows that water management has many of the characteristics of wicked problems since decisions are always made in an environment of great uncertainty, complexity and imperfect knowledge. He argues that 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. The scenario planning process needs to couple modelling and science with decision making through an on-going collaborative partnership between decision makers and modellers. He presents two case studies 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. He points out that there are several prerequisites for this decision-making framework to succeed, including receptive institutions and a requirement for independent scrutiny, transparency and a sound modelling and scientific methodology.

Need for Transdisciplinary Approaches to Deal with Water Related Ecosystems

Gong et al. present the hydrocomplexity of the ecohydrological system in northern China (including Inner Mongolia and around the Beijing area) which are facing several environmental issues such as shrinking of wetlands, water table decline, water quality deterioration, grassland degradation, dune expansion and the urban heat island effect. These merging issues make it necessary to consider the social context of interactive processes linking hydrology and ecology, and hence the need for the Ecohydrology Approach. They present an integration tool for various types of information, knowledge and techniques referred to as hydroinformatics for ecologically-sustainable development. They show that the large-scale remote sensing data processing system, CASMImageInfo, can be used to fast process hydro-ecological elements monitored by remote sensing for the system. They propose to study long-term regional hydrological change in the metropolitan and surrounding areas, and to determine the functionality and water cycle changes under controlled environment conditions in response to vegetation growth. Their framework provides an opportunity for linking hydrology and ecology, as well as integration with modern information technology, leading to ecologically sustainable development of the region.

Kiesel et al. point out the complex interaction and feedback mechanisms between aquatic ecology and hydrology, where integrated ecohydrological modelling can provide valuable insights into the dominating processes. There is a need to successfully implement these modelling strategies within the framework of integrated river basin management in order to possibly show impacts of land use, water management and climate change on aquatic habitats in scenario runs and thus integrate ecological aspects in decision making.

Mosello presents a case in an area of the Po River basin, Italy, where water resources management is made complex by the intricate nature of ecosystem dynamics, the impact of thresholds and feedback loops, and different human dimensions. The current governance landscape suffers from a high fragmentation, which translates into disequilibria between centralized and decentralized approaches, the exclusion of relevant users and constituents from decision-making processes, and a lack of coordination between regulations and policies, as well as institutions and stakeholders. The water governance system must provide public participation as a crucial way to respond to forecast climate-related challenges as well as mechanisms for information sharing, monitoring and regulation, in order to guarantee the correct and fair performance of water management arrangements. Adequate infrastructure and networks between stakeholders and institutions cannot be neglected to achieve sustainable and efficient water resources management in the long term.

Integrated Approaches

Nakajo introduces a “Spiral model” and “Keys for success” to help develop and implement UNESCO’s *IWRM Guidelines at the River Basin Level*. He argues that adaptive implementation of the IWRM process is illustrated by the Spiral model and the Keys for Success approach can be used to overcome difficult situations. Each step in the practical process begins with “recognizing/identifying” pressing issues or needs, then “conceptualizing” the problem itself and formulating possible solutions, “coordination and planning” among stakeholders in order to reach an agreement, and then “implementing/monitoring/evaluating” the plan and its outcomes.

Asabina reviews the ever-escalating scarcity of fresh water and proposes management of the annual runoff renewal as the tool for inexhaustible water use. The disappearance of small rivers, lakes and bogs is a reflection of the crisis of runoff renewal in the basin.

Bley and Klein argue that water loss is a wicked problem based on human failings, lack of maintenance, and the technical and managerial skills necessary. In order to analyse priority issues and gaps, an analysis was carried out based on questionnaires provided to 19 cities world wide. Their results show that in all successful cities stable socio-economic conditions facilitate appropriate measures to ensure the provision of reliable public services. A long-term strategy combining innovative integrated water resources management, applying appropriate technical standards and tools for maintenance, metering and capacity development can deliver reduced water losses of around, or even well below, 10% as a “side effect” at reasonable costs. To overcome competition between sectors, new integrated (urban) water management concepts are needed focusing on concepts between the urban and the peri-urban and the surrounding communities (including circular systems).

Chícharo et al. present the International Centre for Coastal Ecohydrology (ICCE), under the auspices of the UNESCO, in Portugal, which aims to contribute to the dissemination and implementation of the UNESCO-IHP Ecohydrology approach to coastal ecosystems world wide. Examples of the application of Ecohydrology to the sustainability of the Guadiana Estuary in southeast Portugal that are feasibly transferable to other estuaries suffering similar anthropogenic impacts, are also shown.

Gabriel and Khan describe the wicked water problem being faced by Lahore city and explore sustainable groundwater development policy options for adaptation to climate change as part of integrated urban water management in a stressed aquifer like Lahore. A parsimonious working surface water–groundwater interaction groundwater flow model, using the MODFLOW package, was developed for understanding the hydrogeological dynamics under different aquifer management interventions as part of climate responsive policy. The developed model was calibrated using the PEST (acronym for Parameter ESTimation) package.

Eimers and Markstrom illustrate application of GSFLOW, a Coupled Groundwater and Surface Water Flow Model. GSFLOW consists of the integration of three components: one component partitions precipitation into surface evapotranspiration, overland flow, interflow, and infiltration (PRMS); a second component routes surface flow in channels (SFR2); and a third component computes vertical unsaturated flow, exfiltration, and groundwater flow (MODFLOW).

Nair points out that in India, the claims of upper riparians and the declining availability of reliable water due to changes in climate and anthropogenic activities such as encroachment into water bodies, pollution and overuse, lead to disputes over allocation. Water is to be considered a national asset and the constitution needs to be amended to bring it under the direct control of the central administration. Resolving the conflict can result in better management of resources, economic and social development and better cooperation among different groups of people.

Ajayi et al. introduce the proposal to establish the “UNESCO Regional Centre for Integrated River Basin Management in Sub-Saharan Africa: NWRI Kaduna, Nigeria”. There is unanimous agreement among participating countries that the Centre will assist in resolving regional water problems in West Africa, using the IRBM approach.

Rana and Khan introduce an example of optimisation of agricultural drainage to manage irrigation salinity in Australia. In order to achieve the salinity targets a number of actions such as adoption of engineering options to manage irrigation salinity and best management practices, on-farm and regional management activities, and education and extension endeavours were implemented. The Wakool Tullakool Subsurface Drainage Scheme (WTSSDS) is an example of engineering options to manage irrigation salinity in the Murray Irrigation Area of New South Wales. Their study has also shown that a MODFLOW based surface–groundwater interaction model, using hydrogeology, soils, groundwater levels, groundwater pumping, channel network and net recharge information can be a useful tool to develop understanding of the groundwater dynamics. The simulation–optimization analyses can effectively be used to plan an optimal operation of the subsurface drainage scheme to control water logging and salinization in a hydro-economically viable way.

Soto presents the integrated water resources management approach for the Panama Canal Watershed (PCW) and reports on the *Hydrology for the Environment, Life and Policy* (HELP) initiative, the tools used and advances made so far in the implementation of this framework based on chronological information from the Panama Canal Authority, the Inter-institutional Commission for the Canal Watershed and the author’s own experience. Key results include the establishment of a community participation structure; the design of subwatershed participatory assessments; development of a pilot subwatershed management programme in a priority area selected by properly agreed criteria; and the design of a long-term sustainable development and integrated water management plan for the PCW.

Wibowo presents the problem of water shortage, which begins to appear each year when the rain season ends, leading to social conflicts between farmers or between farmers and Perum Perhutani (National Forest) on resource management water (Hendriks, 2010). Oldeman and Schmidt-Ferguson’s classification was used for 13 years (1993–2005) to analyse the problem of soil suitability for 21 crops on soil type Aquic Dystrudepts, Dystrudepts Humic, Typic Hapludolls and UDIC Haplustepts during the dry season.

Ahmad and Khan presents an analysis of the water-energy nexus in a large irrigation area in southeast New South Wales, Australia. Three types of infrastructure are mainly in place in the study area to deliver irrigation water to the farms namely: (1) gravity-based open channel network; (2) gravity-based open channel network with on-farm storages; and (3) an emerging technology, the integrated high pressure (IHP) system. The study presents a demand-based dynamic nodal network model which was developed to simulate water use and energy consumption by 11 citrus farms connected to the IHP system. While IHP system warrants more water savings, the open channel system is most cost effective due to a reduced use of energy. Looking at the irrigation scheme scale, a combination of these supply methods is recommended to achieve optimal savings in water, energy and cost.

Role of Knowledge Platforms for Community Engagement

Andersson et al. show that models need to be used as scenario tools for local planning of mitigation and adaptation to address environmental challenges. The participatory scenario modelling described in this keynote paper, implies modelling with people to formulate a locally proposed remedy plan to reduce nitrogen and phosphorus loads in local lakes and the coastal zone. They also demonstrate a model-assisted process to formulate local adaptation strategies to climate change impacts on water allocation, farming and the environment.

Islam et al. argue that water issues cross multiple boundaries and involve various stakeholders with competing needs and therefore they represent wicked problems. They present the case for a transformative knowledge base to synthesize explicit (scientific) and tacit (contextual) water knowledge, building on scientific objectivity while being cognizant of contextual differences inherent to water issues. They present Water 2100 and a tool which can lead to an interactive, searchable, web-based repository of water case studies from across the world, called *AquaPedia*. It will facilitate the sharing of water knowledge and promote discussion among stakeholders to resolve wicked water problems through negotiated solutions.

Chaves et al. present the RANA–ICE methodology that integrates hydrological, biological, and socio-economic information, related to river sections where the impact of hydropower developments is envisaged. The application of this methodology in the environmental impact assessment for the Reventazón Hydropower Project in Costa Rica, meant the inclusion of a mini powerhouse at the base of the dam to ensure environmental flows in the critical river section. It also meant modifications in the powerhouse design and operation, so that environmental flows could be guaranteed in the river section affected by regulation.

Ibrahim reports approaches for effective management of a watershed to ensure the sustainability of the water resource through prioritization of the watershed based on its critical level. The watershed's critical level is determined by analysing the status of water quality and the potential risk of soil erosion in the Selangor River watershed in Peninsular Malaysia. Remote sensing, a geographic information system (GIS), the Universal Soil Loss Equation (USLE) model and Numeric Index Approach were used in order to determine the priorities.

Santos et al. show that integration of hydrological models within hydrological modelling in the Brazilian Water Resources Information System (SNIRH) allowed the development team to create an open source and free software that can be run on any operational system that has a Java Virtual Machine. The use of an OpenGIS avoids the issue that new GIS functions need to be implemented. The distributed hydrological models allow separate simulation in each discretized element, and the system developed takes advantage of this to provide a graphical visualization of the results in order to facilitate the understanding of the spatial response of the basin to a rainfall event.

Silberbauer provides visualisation as an effective method for evaluating long-term data and the Google™ Docs Motion Chart provides a free platform for comparing water quality variables, particularly ratios of troublesome ions such as sulphate. The case study was associated with low natural discharge and high effluent loads where South African water managers need to make best use of all data at their disposal.

From Artificial to Embodied Intelligence

Samarasinghe argues that accurate estimation of river flows is crucial for effective water resource management. However, estimating flows in ungauged rivers, particularly those in difficult to access terrains, is a wicked problem for water scientists and managers. She suggests hydrological regionalisation (HR) to estimate river flows based on proxy-basin, interpolation and regression methods including neural networks. Artificial neural networks (ANN) models were developed for estimating monthly flows in ungauged rivers in New Zealand using hydrological and geomorphological attributes. Therefore, the study presents the hydrological community with improved neural networks tools based on HR to estimate flows in ungauged rivers for more effective water management.

Starzyk proposes an integrated modelling framework to assist with time-consuming and difficult tasks of decision making by water management practitioners, and to harmonize economic uses of water resources. Motivated machine learning, which is described very clearly in this keynote paper, supports intelligent decision making in a dynamically changing environment and could be used to consider alternative water management policies. Motivated learning systems learn to properly control the environment with competing goals. They provide a natural support for multi-objective decision making in the active search for balance between conflicting situations and adverse environmental conditions.

Water Allocation Dilemma

Abbas and Walker introduce the Murray-Darling Basin Authority (MDBA) as the new authority responsible for the development of the Basin Plan to manage the scarce water resources. The Plan will ensure that future water use is placed on a sustainable footing so that there is enough water for a healthy environment as well as other uses. A mandatory requirement of the Basin Plan is the setting of Sustainable Diversion Limits for surface water and groundwater. Water extractions from the Murray River are subject to the Cap on diversions that applies to most rivers in the Murray-Darling Basin.

Bapela et al. show that in order to optimise the generation of hydropower from the Gariep and Vanderkloof dams, and to supply the other water users at the required risk levels, a system utilisation agreement was formed between the Department of Water Affairs (DWA) of the Republic of South Africa (RSA) and Eskom (the national energy supplier within the RSA). As part of the agreement, DWA commissioned the Orange River System Annual Operating Analysis study to ensure that all the users are supplied at the required assurance and to determine the volume of water available for the generation of hydropower on an annual basis.

Schreider and Plummer report on how water pricing and water allocation models can be integrated to provide a better understanding of the true value of water used in the Goulburn-Murray irrigation district, Australia. Significant infrastructural changes are being implemented there with the objective of increasing the efficiency of water use in the region and increasing the amount of water allocated for the environment. In response to this challenge, a market where water allocations can be traded has been developed to allow water to flow to its highest value use.

Water Quality – a Critical Issue

El Amine presents an experimental study of channel bed deformation during the process of sedimentation and erosion. The measurement results show that under flow conditions a formation of ripples occur and the drag force is proportional to the velocity.

Akanda et al. report that recent findings underscore the role of the regional hydroclimatic extremes, such as droughts and floods, on cholera outbreaks in South Asia. The relationship(s) among seasonality of river flow, plankton blooms, sea-surface temperature and cholera outbreaks will make early cholera detection, a key for preventing an epidemic, possible.

Belyaev et al. attempted to evaluate post-fallout redistribution of the Chernobyl-derived radioactive ^{137}Cs in the Plava River basin (Central European Russia) by quantifying the main components of the basin-scale fluvial sediment budget. This isotope has been used as a tracer of soil and sediment redistribution for a few decades. The currently available results show that soil erosion on arable hillslopes is the main source of sediment and associated radioactive pollution input into rivers of the studied basin.

Jutla et al. include a satellite remote sensing approach as the most cost-effective and efficient way to monitor coastal plankton signatures over a range of time and spatial scales. They demonstrate how prediction of spring cholera (defined as average cholera incidence in March–April–May) is possible by using understanding gained from large-scale hydro-coastal processes combined with the latest advances in remote sensing.

Kristiana et al. describe large-scale algal blooms in Lake Burragorang (Australia) and decrease in bloom occurrences in the Swan River estuary as a complex issues. They use the Index of Sustainable Functionality (ISF) for the two studies, as a framework to assess the functionality and health of a domain for sustainability and to allow for the examination of possible (external) factors and their impacts. The ISF can direct and focus management activities on dominant factors within the domain for more effective management towards sustainable water resources. The study also emphasizes that the changing climate has a direct impact on system processes.

Lakkundi shows that groundwaters from the granitic and irrigated area of the River Sindhanur in India are characterized by excessive fluoride and >55% of the area is affected by fluoride hazard, including many areas with metavolcanics, which *may* be attributed to inter-basin groundwater migration and/or to anthropogenic sources. Although many defluoridation processes are known, it has been suggested to people consuming fluoride-contaminated groundwater to make use of a local, cost-effective and easy method of defluoridation which involves consumption of tamarind juice.

Majumdar and Das illustrate integrated geological, geo-electric and geochemical investigations to assess the prevailing surface water and groundwater conditions, viz. aquifer depth, chemical quality of groundwater and hydrological characteristics, in some parts of Sagar Island and the adjoining mainland, for groundwater resources. The chemical quality of groundwater is safe for drinking, domestic purposes, and suitable for irrigation purposes.

Sabat et al. present a study of suspended sediments in world rivers of very high importance for water quality management and challenging subjects in hydraulic and environmental fields. More than one concentration profile can be found in the literature and it is well known that they are highly sensitive to the parameters used to calculate them.

Saghravani et al. provide simulations of the phosphorus migration processes in groundwater and interaction between surface water and groundwater over 50 years using Visual MODFLOW. The simulation results are essential to determine the hydrocomplexity of the study area in Universiti Putra, Malaysia. Also, the use of fertilizers should be reduced to control the concentration of phosphorus in groundwater. Swamp areas, a main source of contamination, have more and more adverse effects on groundwater.

Urbaniak and Zalewski present an analysis of reservoirs which act as a sink for dioxins and are therefore important in pollution studies and monitoring of ecosystem stress. The hydraulic transport and deposition (sedimentation) of dioxins along the reservoirs, as well as biogeochemical characteristics determine the rate of congener transformations. Concentration and transfer of micropollutants along the river continuum may be diminished by anthropogenic retention through construction of reservoirs.

Wang et al. explore the potential implications of climate change on water security problems including flood prevention, water supply, aquatic environment, and water engineering security, in China. The frequency of flood risk is likely to increase, but annual runoff of the main rivers is likely to decrease. Water Demand Management (WDM) has been implemented by the Chinese government as a new method of water management with lower costs and for environmental protection.

Managing Hydrohazards

Alayande and Bamgboye discuss flood hazards in Nigerian cities. They collected and analysed rainfall and streamflow data for extreme events in the Kaduna River basin. Their analysis included determination of geomorphic characteristics of the river channel and flood plain, and development of a hydraulic model to predict the extent of inundation of the flood plain from floods of various frequencies and the socio-economic implications of each scenario. The study indicated that the

Kaduna flood plain was indiscriminately developed with no flood warning systems in place. Infrastructure developments along the Kaduna flood plain should be regulated and include construction of dykes along the banks to shield already-developed areas from flood water as a long-term measure.

Chebanov and Konoplya discuss the groundwater flooding problem as Ukraine's challenge for managing its environment. Groundwater flooding results in aquifer pollution, suffusion, soil subsidence, and landslide activities. Introducing sustainable development principles into the groundwater management has to be supported by some strong activities focusing on several strategic topics such as: political, legislative, environmental economy, technical, and socio-economic.

Lytton and Bolger argue about the need for new tools in the context of groundwater exploration, development and management, drawing on experiences in Chad, Sri Lanka and Sierra Leone. The lesson learnt from the authors' experience in emergency contexts is that a modest amount of appropriate planning, design, measurement and analysis will provide answers even for the most wicked water problems.

Matcharashvili et al. discuss a real-time monitoring system at Enguri High Arc Dam in West Georgia (the Enguri Dam International Test Area – EDITA). They present time series of hourly measured tiltmeter data sequences and daily water-level measurements in the reservoir behind the dam since the beginning of its filling by water, as a tool to detect and recognize small incipient changes in the model-predicted dynamics of the dam body system–large water reservoir.

CONCLUDING REMARKS

The papers presented in this book clearly show that complex interdependencies within and outside the water systems are creating new issues while solving one aspect of a wicked problem, and therefore a public-participation approach, building bridges (Fig. 1) is necessary for social acceptance, scientific feasibility and economic affordability of a range of solutions.

Fig. 1 Building communication bridges for resolving wicked water problems.

REFERENCES

Rittel, H. & Webber, M. (1973) Dilemmas in a General Theory of Planning. *Policy Sciences* **4**, 155–169.