Water resources and environmental management: issues, challenges, opportunities and options

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Abstract Managing water in an integrated and sustainable manner is currently challenging water resource managers throughout the world. It requires professionals from many disciplines working together with impacted stakeholders in crafting a strategy that is economically efficient, ecologically sound, and acceptable to all who are impacted by how this resource is managed over space and time. Such strategies cannot be formed from the top down. However those at the top levels of government must be involved in facilitating a bottom–up, public participatory process of helping all those who are impacted by how water is allocated and managed achieve a shared vision of how their water resource system functions. This shared vision should include the economical, ecological and social impacts of alternative management policies, and the tradeoffs among conflicting multiple purposes for which water serves and among all economic, environmental and social objectives for which water can achieve. Appropriate technology is continually being developed that helps us manage water better, but it appears the real constraints to more effective management are often institutional or social. This paper attempts to outline some of the current water resources and environmental management issues and concerns, and suggests some ways of addressing them.

Keywords Education; environment; governance; management; research; water resources

Introduction
The amount of water available and suitable for human use in the world is limited. Too many humans must live with less water than what they would like, and even need, to maintain their health let alone their overall welfare. We who plan and manage water resource systems are being challenged to provide everyone access to reliable potable water at reasonable costs. Regrettably, this goal is unlikely to be achievable, at least in the foreseeable future. Populations are increasing, as are per capita demands for water. The UN tells us about one person in six across the world lacks access to safe drinking water, and about one in three lacks safe sanitation. I repeat: one in six without adequate drinking water, and one in three without adequate sanitation, today! We use about 70% of the water we have for agriculture. The World Water Council believes that by 2020 we shall need 17% more water than is available if we are to feed everyone. Today, and every day, more than 30,000 children on average die before they reach the age of 5. These deaths are caused either by hunger or by water-borne and easily preventable diseases. Do all these grim statistics suggest a water crisis? Will there be a water crisis in the future? Much depends on how we manage our water and our watersheds (Rogers et al., 2006).

With perhaps few exceptions, those of us who live in North America are not without water or sanitation. If water is needed, we build reservoirs, canals and pipelines to collect and transfer it from where and when nature provides it to where and when people want it. Engineers are good at changing the spatial and temporal distribution of our water resources to meet human needs. We are fortunate. We seem to have enough water,
although recent droughts accompanied by extended heat waves and consequential increases in energy demands has shown us we can indeed run out of water at least for hydroelectric energy and power. Regional power outages are evidence of that. We probably do not have a real water crisis, but to keep our rivers flowing and clean, and our aquatic ecosystems functioning as they should, we often have a water management crisis. Professionals can manage our resources better, but deciding what is better involves more than just professionals. Politicians, and increasingly the public, are participants in this decision making. They define what ‘better’ is. And there are always more pressing matters that get their attention, and their money, until of course there really is a water crisis.

This has prompted the well known concept called the hydro-illogical cycle illustrating the lack of interest in planning for floods during periods of drought, or in planning for droughts when experiencing a flood or a recovery from one.

Water and environmental resource management
Many of the issues facing water and environmental resource managers today generally stem from:
- changing priorities of water and environmental management objectives over time – for example from economic efficiency to ecological health and diversity that require changes in past policies and even infrastructure,
- the way our institutions work,
- the need for multiple disciplinary inputs and public participation, and
- the uncertainties regarding future demands, supplies, and pollutant types and loads.
- a lack of adequate understanding of many natural and social processes affecting, and affected by, the management of water and environmental resources.

Managers and planners are challenged to develop plans and policies for serving often conflicting multiple purposes and satisfying multiple objectives expressed by multiple stakeholders representing multiple interests and backgrounds, all lacking perfect knowledge of what economic, physical, chemical, biological, ecological and social impacts will result from what ever decisions they make. We all could benefit from better science, better management tools, better training of professionals in all the applicable disciplines, and political institutions that can provide the expertise and leadership that will result in more integrated and sustainable water resources and environmental management plans and policies.

The following paragraphs outline some current institutional, research and education issues related to water and environmental resources management.

Institutional and governance issues
At the national level, we in the US currently lack the institutions we once had that provided leadership in integrated water and environmental resources planning and management at the basin or regional scale (Rogers, 1993; Loucks, 2003). Some of our federal agencies could, but Congress, the institution that allocates federal dollars to all federal agencies, seems to have no interest in what might be called integrated basin-wide management. Votes don’t come from integrated planning of basins or regions; they come from specific localities where specific projects can be implemented – such as reservoirs, levees, canals, wastewater treatment plants, and the like. The result is a collection of public agencies each with limited authority working with non-governmental organizations (NGOs) and local river basin authorities or commissions where they exist, usually in less than fully effective or efficient ways. The issue is how can institutions be changed to provide more beneficial products? At the federal as well as local levels, this is a political issue.
Interbasin issues usually imply a federal or national role. Dams and reservoirs affecting interstate waters imply a federal responsibility. Operating this infrastructure for multiple needs, including ecosystem restoration will require a federal as well as a local government role.

Collecting and archiving of data, and performing regional and basin-wide studies, are activities typically undertaken by the public rather than the private sector. Monitoring activities continue to be reduced by almost all agencies that have monitoring responsibilities as their funding is redirected to more pressing and immediate needs. To assist in the level of monitoring needed for both short-run as well as long-run planning and adaptive management, we should take advantage of multiple types of inexpensive sensors for collecting comprehensive and integrated environmental data over large spatial and long temporal scales. We need to develop a robust and adaptable cyberinfrastructure that can link these sensors to data bases. We need to collect and use social science data along with physical, chemical and biological data to address environmental problems caused by human activities (NRC, 2007).

We need to learn more about the effectiveness of different types of institution, markets, governments, international treaties, and formal and informal sets of rules that are established to govern resource management and use. We need to learn more about how culture influences human uses of natural resources, waste disposal, and other environmentally important activities. Such research should involve individuals trained in a broad array of social science disciplines.

**Education issues**

Recent decades have witnessed a shift in emphasis by US agencies providing funds for research and training of graduate interested in environmental and water resources management. The emphasis has been on addressing scientific uncertainties and less toward planning and management issues. One result of this shift away from research or fellowship funding focused on managerial issues has been the decline of academic programs in water management and planning. Ironically, weather- and climate-related research programs and large scale observation initiatives promoted by many in the hydrologic, environmental engineering and ecological research communities, among others, increasingly cite the benefits their programs will have on the management of water resource, environmental and ecological systems.

There are many scientific, technical, political, practical, and regulatory challenges to integrating advances in hydrologic science into policies for managing environmental and water resources. There may be an unrealized potential, for instance, for using improvements in hydrologic forecasting based on new data sources and methods (such as embedded environmental sensors and data assimilation techniques). As scientific research teaches us more about the processes taking place at the interface of hydrology and climate, and as the hydrologic, water-quality, and associated ecological implications of land cover change become better understood, ways are needed to incorporate this knowledge into management plans and policies. It doesn’t just happen by itself. Research is needed to figure out how best to integrate new knowledge into management plans and policies, and trained professional planners, policy analysts, and managers are needed to make it happen.

At various universities debates are taking place over a variety of issues, some of which are listed.

**Issue 1: Educational policy – should universities turn out more well trained professionals and scientists, or generalists?** Many will argue that there is an overarching need for people who know there is a world beyond where the live and work and can appreciate how
history and culture affects current events. There is a need for individuals who can evaluate, think, and speak and write effectively at technical and non-technical levels. Such skills should be obtained at the undergraduate level. In my opinion the best way to get this background is to obtain a liberal arts education (including foreign study). Expertise in specific technical disciplines can be obtained at the master’s level. After all, medicine, law and business are graduate subjects. Why not engineering as well? Obviously some pre-engineering courses would be expected at the undergraduate level, just as pre-med courses are expected for admission to most medical schools. This is not to say we cannot train students to become competent technical engineers at the undergraduate level but doing that eliminates the time needed for students to obtain the other skills that all should have who expect to become tomorrow’s leaders in what ever they do. Yet in much of the world attending universities costs money, especially at private universities. Furthermore, unless the profession of engineering can upgrade itself, engineering graduates are not likely to enjoy the status and income levels of medical doctors and lawyers, and hence are not likely to want to borrow the money medical and law students seem to be willing to do to get their graduate education. Currently we need fellowships and training grants to attract the best and brightest students to our water resources engineering profession.

Issue 2: Engineering curricula – does it need changing? Many universities need to take a serious look at their curricula more often than they do. It seems much easier to change course contents than the overall plan. Specific needs not often addressed in existing curricula and often desired by employers (Logan, 2006) include:
(a) the management of urban, suburban, and exurban water resources systems.
(b) water reuse, aquifer storage and recovery, and desalination,
(c) social sciences such as natural resource planning, economics, sociology, law, and policy,
(d) development and application of technologies to monitor the state of the hydrosphere (e.g., new remote sensing and data assimilation technologies),
(e) environmental restoration,
(f) scientific hydrology, including atmospheric, surface, and groundwater processes,
(g) decision support for complex systems involving stakeholders, economics, law and ecology,
(h) valuing non-monetary costs and benefits, and
(i) energy-water linkages from hydroelectricity to bio- and synfuels to building nuclear plants for desalination.

Professional engineering master’s level programs need to meet the needs for individuals who can develop and use predictive models as well as who can produce data and information on streamflow, sediment transport, precipitation and snowpack, evapotranspiration, infiltration and water losses, paleoclimate, paleofloods, drought probabilities, and extreme events. There is a need for those who understand and can quantify the exchange of water and its constituents among different media such as between groundwater and surface water.

Most educators support exposing students to interdisciplinary projects at both graduate and undergraduate levels. Students need to learn how to participate productively in such projects and recognize the approaches and issues of fields other than their own. Engineers and ecologists especially need to appreciate each other’s approaches to problem solving. Being exposed to case studies, including failed projects and those that get students out in the field is also beneficial. This gives them an appreciation of multidisciplinary team-building and dealing with multiple conflicting goals such as drought mitigation, flood management, flash flood prediction, water supply, transportation, emergency
management, agriculture, and ecosystem stewardship – and conflicting opinions about how to achieve them.

Issue 3: Continuing education: How can it best be provided to all professionals? Some have suggested that whatever the technical information students learn, it will be obsolete by the time they get their first job. The rate of increase in knowledge and the changes in technology seems to be increasing over time. In other words the second derivative of growth rate of available knowledge and technology is positive and increasing. The half-life of the technical information we teach our students is decreasing. On-the-job training and continuing education throughout one’s professional career is an absolute necessity. How can universities best meet this need? Some governmental agencies concerned with environmental and water resources management have programs for continuing education. However, a high turnover rate often makes this uneconomic. Professors themselves need continuing education as well. Their research provides some of this, but they also often benefit from what they do on their sabbatical leaves. All professionals should be provided such opportunities.

Issue 4: Funding. Can the needed changes in education be accomplished in the absence of changes in funding ‘carrots and sticks’? Difficulties in supporting students studying water and environmental resources management have led to the relative lack of students studying these subjects. University deans look for where the money is when they analyze continuing and new directions for a university. Fellowships, traineeships and research grants are influential. Industry can also provide support, and in many engineering disciplines they do, but in the water and environmental resources arena the private sector has limited resources. Managing water and environmental resources is primarily a public responsibility. Nevertheless industry has contributed to the American Water Works Association Research Foundation which provides some support for education.

Coop programs to bring students into the real world (internships, traineeships) may be a partial solution. USDA–CSREES’ coop funding program is an example for agricultural water management.

Employer needs

Employers working in the water management area often report difficulties in finding employees with the appropriate backgrounds. Because of the decrease in funding of research and training grants in the water planning and management area, few young graduate students are finding their way into the field. This leads to fewer students being trained in the areas of most interest to these employers. The report ‘Freshwater Ecosystems: Revitalizing Educational Programs in Limnology’ (NRC, 1996) included a chapter on linking education and water resource management.

Water is viewed as a public good, and thus those who manage it are often associated with government agencies. At a recent meeting of the National Research Council (Logan, 2006), several government agencies stated their need for young people prepared for

• working in an interdisciplinary and multidisciplinary teams, which is the nature of modern water management
• viewing problems in a broad systems context – water management decisions made upstream ‘reverberate’ downstream influencing ecosystems, fisheries, and the coastal zone in general.
• linking societal goals and objectives with performance measures and conceptual ecological models.
• adaptability in general and adaptive management in particular
quantifying and dealing with risk and uncertainty
conflict management/resolution in a stakeholder driven participatory political process.

Research issues
There are many research needs related to planning and management. While not new, we still need a better understanding of how to design, manage and operate infrastructure in the face of hydrologic (supply and demand) nonstationarity and uncertainty, how to identify and provide environmental flows in already over-allocated systems, especially in times of drought, and more about the environmental effects of reservoir operation and dam removal. Statistical stationarity assumptions now underlie essentially all methods used in practice. We know now this is not so but we don’t know just what to do about it.

Another research challenge is reevaluating our water resources planning and management capabilities, given changing climate and land use. How can we best develop our next-generation hydrologic prediction models that can be integrated into modern water planning and management processes? The dominant water resources planning issue of the 1960s–1970s was reservoir design and operation. It still is in countries such as Iran where reservoir construction is a major activity. However many planners and managers are confronted with reservoir reregulation in the face of changing uses and priorities, environmental and ecological uncertainties and needs, and possibly the removal of past engineering infrastructure such as dams and canals.

Let’s look at some of these research issues in more detail

Issue 1: Water quality and quantity. A planning and management challenge is to predict and then effectively respond to changes in freshwater supplies and demands and the environmental and economic impacts caused by floods, droughts, sedimentation, and contamination. Needed for this is an understanding of hydrologic responses to precipitation, surface water generation and transport, environmental stresses on aquatic ecosystems, the relationships between landscape changes and sediment fluxes, and subsurface transport, as well as mapping groundwater recharge and discharge vulnerability.

We need to better understand land-atmosphere interactions and water cycle aspects of climate, but also we need better ways of managing floods and droughts and pollution.

Climate models used to predict long-term changes in temperature and precipitation need representations of the components of the hydrologic cycle. The interactions among these components need to be validated. Advances in this area are fundamental to long-term sustainability planning. Advanced (improved) climate change impact assessments are also dependent on progress in this area.

Improving water quantity and quality forecasting, perhaps aided by networks of sensors, robotic water quality monitoring sites, real-time data collection, communication links, intelligent environmental control systems, will enhance the management of urban as well as more natural ecosystems. Such forecasting could provide an early warning for flooding, droughts, habitat degradation, and health hazards. Management responses could then be timelier.

We need to explore the impacts of environmental change on disease etiology, vectors, and toxic organisms.

Issue 2: Inefficiency in water use. Much of the water we consume is from inefficient infrastructure. The majority of our older urban water distribution systems leak, as does our household plumbing. Much of our agriculture irrigation systems allow excessive
wastage, with the water trickling away or simply evaporating before it can serve any beneficial purpose. And pollution reduces the amount of water available for beneficial uses without expensive purification.

Increasingly, water consumers are seeking to solve their water shortage problems by augmenting their surface water supplies with subterranean supplies of groundwater. Often this results in groundwater withdrawals that exceed its recharge. Such aquifers will eventually stop yielding water, at least at a price one is willing to pay to pump it. And using up irreplaceable groundwater does not simply mean the depletion of a resource. Rivers, wetlands and lakes that depend on it will experience reduced base flows and can dry out during low flow seasons. Saline seawater can replace the fresh water that has been pumped out of coastal aquifers. Emptied underground aquifers can be compressed, causing surface subsidence – a problem familiar in Bangkok, Mexico City and Venice and in many locations within the US as well.

**Issue 3: Scaling of dynamic behavior.** Almost all planning and management activities must address questions whose answers require knowledge of the quantitative relationships among various physical, chemical, biological and social process occurring at disparate spatial or temporal scales. Most frequently perhaps, these are problems of complex aggregation that are confounding our attempts to quantify predictions of large-scale hydrologic processes and their impacts in three-dimensional heterogeneous natural systems. Large scale observatories may be needed to obtain the data required to accomplish this research (e.g. as being planned for hydrologists, environmental engineers and scientists, and ecologists (NRC, 2006)).

Regional and continental scale forecasts and many issues of global change depend for their resolution on a detailed understanding of the state and variability of the global water balance. Many argue for large-scale observatories to obtain the data needed to estimate water resources and the fluxes of water and energy at regional and global scales. Such data are still largely unavailable as homogenous, coordinated global data sets.

How can we scale up to larger area forecasts from knowledge of smaller habitat patch scale ones? How can we estimate regional aquatic ecosystem processes over entire river basins often based on small plot experiments and observations?

**Issue 4: Land surface – atmospheric and hydrologic interactions.** Understanding the reciprocal influences between land surface processes and weather and climate is more than an interesting basic research issue. It has become especially urgent because of accelerating human-induced changes in land surface characteristics in the US and globally. The issues are important from the mesoscale upward to continental scales. We need better knowledge of the time and space distributions of precipitation, soil moisture, groundwater recharge, and evapotranspiration than we can get from point measurements. How do they vary, and how sensitive are they to local and regional climates and land surface properties in particular watersheds? Land use planners, and water managers, need to understand these interactions to most effectively manage them over time.

What is the extent and variability of carbon sequestration in wetlands, lakes, reservoirs, and fluvial systems? How do human activities influence carbon cycling in river basins?

**Issue 5: Contaminants in the environment.** How can we best to manage contaminated sediments and predict and reduce the harmful effects on aquatic and human health of residuals from pharmaceuticals and other household chemicals and products?
How do changes in land cover, climate, and land use affect water quantity and quality regimes and their impact on ecosystem health and other uses of water such as for drinking, irrigation, industry and recreation? Comparative studies, modeling, and field experiments perhaps on the proposed observatory systems (NRC, 2006) can help determine pathways of movement of water and solutes through human-dominated landscapes and forecast responses to changes.

Can further research in plant physiology, xylem hydraulics, and nutrient cycling improve our models of the soil-vegetation continuum to significantly improve the characterization of the impacts of alternative land covers and uses on water quantity and quality, and on ecosystems?

Issue 6: Managing land use and habitat alteration. Deforestation, suburbanization, road construction, agriculture, and other human land-sue activities cause changes in ecosystems. Those changes modify water, energy, and material balances and the ability of the biotic community to respond to and recover from stress and disturbance. Actions in one location, such as farming practices in the upper Midwest, can affect areas 1,000 km or so away because areas are joined by water and nutrient flow in rivers and by atmospheric transport of agrochemicals.

Issue 7: Managing chemical and biological components of the hydrological cycle. In combination with components of the hydrologic cycle, aqueous geochemistry is a key to understanding many of the pathways of water through soil and rock, for revealing historical states that are of value in climate research, and for reconstructing the erosional history of continents. Together with the physics of flow in geologic media, aquatic chemistry and microbiology will reveal solute transformations, biogeochemical functioning and the mechanisms for both contamination and purification of soils and water. Water is the basis for much ecosystem structure, and many ecosystems are active participants in the hydrologic cycle. Understanding these interactions between ecosystems and the hydrologic cycle is essential to interpreting, forecasting, and even ameliorating global climate change. Climate warming and variability strongly affect individual species, community structure and ecosystem functioning. Changes in vegetation affect climate through their role in partitioning radiation and precipitation at the land surface. Climate-driven biological impacts are often only discernable at a regional – continental scale. Regional changes in ecosystem processes affect global water and carbon cycles.

Issue 8: Managing biogeochemical cycles. The challenge is to further our understanding of the Earth’s major biogeochemical cycles, evaluate how they are being perturbed by human activities, and how they might better be stabilized. Important research areas include quantifying the sources and sinks of the nutrient elements and gaining a better understanding of the biological, chemical and physical factors regulating transformations among them; improving understanding of the interactions among the various biogeochemical cycles; assessing anthropogenic perturbations of biogeochemical cycles and their impacts on ecosystem functioning, atmospheric chemistry, and human activities, and developing a scientific basis for societal decisions about managing these cycles; and exploring technical and institutional approaches to managing anthropogenic perturbations.

Issue 9: Controlling invasive species. Invasive species affect virtually every ecosystem in the US, and can cause substantial economic and biological damage. The identification
of potentially harmful invasive species, the early detection of new species as invasion begins, and the knowledge base needed to prevent their spread require a comprehensive monitoring and experimental network and a mechanistic understanding of the interplay of invader, ecosystem traits and other factors including climate and land use that determine invasiveness.

Stakeholder participation and sustainability
Today’s planning and management environment involves public participation, not just at the final stages of planning, but throughout the process, including decision making. Tools are being developed to help all stakeholders gain a ‘shared vision’ of how their system works, and the physical, economic, environmental, ecological and sometimes the social impacts of various plans and management policies. Such public participation does not make the planning and management processes any easier, or more efficient, or cheaper. In fact just the opposite happens. But the end result has a far better chance of being robust to multiple interests and thus more sustainable in the long run (ASCE, 1998).

Uncertainty and adaptive management
Planning and management decisions must be made before we are able to address each research issue that would give us a better understanding of just how these decisions will turn out. In spite of our predictive modeling capabilities, we do not have sufficient understanding of all the processes that will be impacted by our decisions. Hence we cannot predict with precision the physical, economic, natural and social responses over time to those decisions. So, we may need to modify our decisions in the future, i.e., we may need to adapt. We may need to alter our decisions in response to undesired impacts and new knowledge. Adaptive management often challenges our institutions and their regulations and laws that may reduce the freedom to adapt, or at least make such adaptation more difficult.

Monitoring as well as modeling are essential components of an effective adaptive management strategy, yet monitoring budgets and programs are more often being reduced instead of increased. With the advent of improved and cheaper remote as well as on-site sensors, linked to communication and computational networks (cyberinfrastructure) may help reverse this trend. It is hard to adapt to what is not known. Establishing hydrological and ecological monitoring networks will improve our understanding of the biogeochemical processes taking place in our environment, how we humans impact those processes, and how we can better manage those processes (NRC, 2007).

Conclusion
Given these and other issues we face today, what should we do? How should we better manage our environmental and water resources? As a start, I suggest the following

- Develop and implement plans and strategies for managing our natural resources that are robust and perform well under a range of possible, but uncertain, future conditions.
- Design transparent and open social learning processes as key features of sustainable water management regimes.
- Build trust among all stakeholders for problem solving and collaborative governance.
- Implement and maintain a capacity to continue to learn about and adapt to changing conditions of our natural resource systems.
- Trust in a collaborative process as a more robust management strategy under conditions of change and uncertainty.
• Provide for creative and out-of-the-box thinking. Entrenched perceptions and beliefs block innovation and change.

• Increase the technical and managerial skills of public servants in local, state and federal governmental agencies who are responsible for managing our nation’s water and land resources. There is a significant need to train a new generation of water management practitioners skilled in participatory system design and implementation and who are competent enough to direct and judge the quality of work carried out by private contractors.

Managing our natural resources, including our ecosystems in our natural and built environments involves both technical and administrative expertise. It involves both the ‘hard’ as well as the ‘soft’ sciences. As one of my colleagues has observed, the hard sciences are relatively easy. The laws of physics, biology, chemistry, and mathematics are well established. The same cannot be said of the social and political sciences. Thus the ‘hard’ sciences are easy. The ‘soft’ sciences are hard. Clearly, however, we need more people more competent in both to address many of the issues natural resource managers are facing today.

References