FUTURE DIRECTIONS IN WATER RESOURCES SCIENCE AND ENGINEERING: A VIEW FROM THE U.S. GEOLOGICAL SURVEY

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Recent discussions within the Water Resources Division of the U. S. Geological Survey aimed at developing our strategic directions for the next 10 years have led to the following vision of the future issues that our organization must be poised to address. We think it is useful to share these views with the academic water-resources community. We do this for three reasons. First, to gain feedback on the validity of our thinking about the most important future issues in water resources. The second is to provide insight to our academic colleagues on the future focus of USGS efforts so that they can use this information to design the best possible educational programs that will develop the hydrologic researchers and practitioners of the future. Finally, we believe that advance notice of future directions for our water resources program will allow us to make better plans with the academic community for collaborative research and for academic research that uses USGS data.

BACKGROUND

In looking outward, the single most important global trend underlying many issues is population growth accompanied by economic growth. United Nations projections suggest that the world could reach a population of 8 billion people by 2025 (compared to today's 5.5 billion people). A growing world population and world economy will increase the global demand for food. U.S. agriculture could become more intensive, with an increased use of chemical and biological products that could change the environment and create a greater demand for water. The use of engineered species and other aspects of biotechnology may reduce fertilizer and pesticide use but create problems with which we have little experience.

The influences of global scale issues will be especially important in situations where human pressure on ecosystems and health systems is greatest. For example, significant impacts from global climate change could be exacerbated where the world or a continent are most crowded, where aspects of the civilization are least flexible, and (or) where effects are added to other stresses. Although population growth will not be as rapid in the U.S. as in less developed nations, growth will likely lead to more rapid suburbanization around major cities and of once sparsely populated areas. Recent trends in U.S. demographics indicate people have and will continue to relocate in areas at risk from hydrologic hazards such as coastal areas, floodplains, the base of hillslopes, and alluvial fans. Increasing development in the United States will result in increased pressure to use terrestrial and aquatic resources of all types.

There is likely to be increasing concern about human and environmental health. This could be driven by an environmental catastrophe such as a significant waterborne disease outbreak somewhere in the U.S. or conclusive proof that chemicals in the environment are causing reproductive stress or other significant but sublethal effects in animals or humans. Environmental concerns could also be driven by an accretion of smaller challenges. Even in the absence of significant new environmental issues, the costs of monitoring and treating drinking water, cleaning-up existing contamination, preventing future contamination through effective isolation of municipal and industrial waste, and taking precautions to prevent accidental releases of contaminants will exert pressure on the U.S. economy.

Advances in technology (such as instrumentation, models, and biotechnology) will enhance our ability to detect, analyze, mitigate, remediate, and disseminate solutions to water resources problems. Advances in analytical chemistry are allowing improved detection of contaminants while increased knowledge of biology and ecology brings greater understanding of the impacts of environmental perturbations. Improvements in measurement of streamflow in real time and improvements in models for decision-makers will facilitate new abilities to manage water more effectively but will also demand the highest degree of reliability and availability of that data. The recent tremendous increase in use of the Internet and other advances in communication make it possible to disseminate hydrologic and other scientific information to both the scientific community and the general public instantly and inexpensively.

Within the context of the broad trends described above, five requirements for successful water resource management are likely:

1. Active management for multiple uses--Water resources will need to be simultaneously managed to provide water for human consumption, agriculture, industry, power generation, recreation, and habitat for fish and wildlife. These competing demands are already generating disputes in many parts of the country. In the future, needs for information will be greatest in arid regions, near the coasts, and where water moves across State borders or between ground water and surface water.

2. Effectiveness and efficiency--The public will demand greater efficiency and effectiveness in environmental regulation and resource management. Issues that will be increasing in importance include: (1) prevention of pollution, thereby avoiding the high costs of environmental clean-up; (2) site-specific evaluation of risks to water resources which will justify more flexibility in enforcing regulations; and (3) use of watershed-based management which will build on local interests and minimize the inefficiencies that come from managing only a part of the resource.

3. Shift away from engineered solutions--There will be less dependence on engineering solutions to water resource problems and increasing reliance on conservation and natural systems. Few new large water projects such as dams or interbasin transfer systems are underway or planned. Instead, water managers are using water conservation to reduce demand for water for irrigation, public supply, and industrial uses. Conservation has the added benefit of reducing the amount of water that must be treated after use. Water resource managers are beginning to take advantage of natural systems to remove contaminants from water. For example, attempts to use natural or artificial wetlands to remove heavy metals from mine drainage are underway and natural bacterial processes are being used to remediate contaminated ground water.

4. Demand for timely information--The public expects advance warnings of flood events and other hydrologic hazards. Farmers, public water systems, recreational boaters, and environmentalists all want near real-time information on the quantity and quality of the water they use. Water data must be provided in a timely fashion. They must also be accurate. Yet, increasing accuracy often requires more time. Water resource managers and those who supply water data will need to be aware of and address this dynamic tension between accuracy and timeliness.

5. Increasing interest from the public--People are concerned about the availability and quality of water. Few major water resources decisions in the future will be made without coverage by the media and the attention of interested citizens. It is expected that citizen action and monitoring efforts across the country, which include watershed management associations, farmers and growers associations, and environmental interest groups will play an increasing role in managing and monitoring water resources.

PRIORITY WATER RESOURCE ISSUES

In our USGS planning effort, we have identified nine water resource issues that we believe will be areas of increased emphasis during the next 10 years. Other issues and technical areas still have much value and the USGS will continue to collect data and conduct projects related to them. However, as projects end and new projects begin, more human and financial resources will be directed to the nine high-priority issues.

USGS has an existing scientific infrastructure and much of the expertise needed to address these issues. We will build upon and enhance these strengths by directing our hiring and staff training in these directions and by forming partnerships with, Water Resource Research Institutes, the academic community, and scientists from State, local, and other Federal agencies. We also will work closely with land and water managers in the public and private sectors to better identify their information needs. Through these partnerships, we will form interdisciplinary teams to address the priority water resource issues.

Issue 1: Effects of urbanization and suburbanization on water resources

Urbanization and suburbanization change the natural flow and recharge of water, introduce sediment, nutrients, and contaminants to surface and ground water, and increase demand for fresh water. To meet these challenges, we must develop tools necessary to effectively manage watersheds as the complex systems that they truly are. In addition to creating the geographic information systems and models, we will carry out field studies to determine the effects that various land and water management practices have upon existing water-quality and quantity conditions. We will provide information to policy makers and resource managers as a basis for decision making on issues such as: the use of buffer zones along streams and around lakes; pesticide and fertilizer applications around homes, businesses, transportation corridors and recreational facilities; and alternative approaches to stormwater management.

Issue 2: Effects of land use and population increases on water resources in the coastal zone

It is estimated that by the year 2010, 75 percent of the U.S. population will live within about 50 miles of the Atlantic and Pacific coast or one of the Great Lakes. Pressures on the coastal zone include an aging urban infrastructure as well as demands for additional supplies of drinking water and a safe means to dispose of human and industrial waste that result from new growth. Population growth in the coastal zone also will add to stress on coastal ecosystems that provide recreation and critical habitat for waterfowl, shellfish, and finfish.

To properly manage and protect coastal ecosystems it will be necessary to have meaningful annual estimates of the fluxes of major chemical species (especially nutrients) at key inflow points to the Nation's estuaries, coastal zone and the Great Lakes. Coupled with these estimates is the need to sort out the sources of these chemicals - including geologic sources, atmospheric deposition, urban use, industrial discharge, chemical fertilizer use, and animal waste.

Proper management of coastal resources requires studies of salt-water intrusion into aquifers, movement of salt water upstream in tidal rivers, and the effects of water withdrawals on coastal wetlands. The USGS has given this issue considerable emphasis in developing plans for an expanded Ground Water Resources Program.

Issue 3: Drinking water availability and quality

Drinking water in the United States is currently safe and abundant in most places. Maintaining a safe supply of drinking water in the future will require considerable expenditure of money for protection of drinking water sources, treatment of drinking water, and monitoring drinking water quality. Drinking water is a necessity and major population centers will certainly continue to be supplied but there will be intense competition between cities and agriculture for water. Disputes will also arise in cases where withdrawal of ground water or surface water for public supply may impact aquatic habitat.

The USGS recognizes the need to provide an ongoing assessment of the availability and sustainability of the Nation's ground-water resources and major factors affecting these resources. Water resource managers need better models to evaluate the consequences of various management alternatives on the quality of water available in aquifers. Among the tools of great potential use to State and local land managers are empirically based ground-water and surface-water quality vulnerability assessments. These models can provide, with a known level of accuracy, risk estimates that can be used to optimize monitoring expenditures for drinking-water sources and for controls on land-use practices to protect source waters.

There is a pressing need to develop and test effective detection and monitoring methodologies for infectious, water-borne pathogens, such as Giardia and Cryptosporidium. Once such methods are developed and tested it will be very important to relate the occurrence of these pathogens to land use and other factors. The presence of natural organic compounds as precursors to disinfection byproducts will be an important area where information is needed to provide safe drinking water supplies. Finally, the occurrence of arsenic and various metals and radionuclides from natural geologic sources will be an area where the USGS will be called upon to provide the source water characterizations needed to evaluate the risks of a variety of alternative drinking water sources for individual homes and communities.

Issue 4: Suitability of aquatic habitat for biota

Aquatic habitat in this country has been severely altered by human activities, including construction, agriculture, and deforestation that increase sediment loads in rivers; construction of dams that impede migration of fish and other aquatic species; drainage of wetlands areas; and increases in concentrations of nutrients and other chemicals. Because of public concerns and environmental regulations, there is a concerted effort to minimize further alteration of habitat and, in some cases, to restore previous habitat and ecosystem functions. Issues in need of study, through theoretical and experimental means are: effects on habitat of variations in reservoir operating policies; effects of changes in sediment transport on the characteristics of gravel and sand bars and backwater areas; functioning of natural and man-made wetlands; effects of ground-water use on streams and wetlands; and impacts of the removal of man-made barriers such as dams and levees.

A topic in need of special attention is the effects on various aquatic species of low-level (non-toxic and non-carcinogenic) chronic exposure to one or more chemicals.

These effects include impacts on reproduction and development from endocrine-mimicking chemicals.

Issue 5: Waste isolation and remediation of contaminated environments

There are several hundred thousand sites in the United States where the environment has been contaminated by past industrial, mining, military, agricultural, and commercial activity. The estimated cost of cleaning up these sites ranges up to almost a trillion dollars. Costs of preventing future contamination are also significant for Federal, State, and local governments and the private sector as they attempt to manage industrial and domestic waste and find a suitable repository for radioactive waste.

The USGS can make important contributions to risk evaluation, waste isolation, and remediation through its combination of knowledge of hydrology, chemistry, and biology and its ability to conduct complex interdisciplinary studies of environmental contaminants. Our role will be to continue to conduct studies of the basic processes controlling transport and fate of contaminants. These studies will place increased emphasis on understanding the factors that make a system more or less vulnerable to contamination, thereby, providing valuable information for those who must design waste disposal sites. If remediation systems are going to be improved in the future it will be vital that long-term scientific investigations are carried out to determine the actual effectiveness of these systems. The monitoring and modeling of these systems, in partnership with public sector and private sector organizations who are responsible for the clean ups, will be an important role for the USGS to play in the future.

Issue 6: Hydrologic hazards

Every year hydrologic hazards, floods, droughts, subsidence, landslides, and tsunamis, result in the death of hundreds of people, hundreds of millions of dollars in damages, and the disruption of thousands of lives. Better understanding of hydrologic hazards, better warning systems, and better risk information can minimize the consequence of these hazards.

The role of the USGS in helping to mitigate the impact of these hazards is threefold. The first aspect is to provide accurate and useful estimates of risk before the event takes place, so that landowners and public officials can make the best possible decisions regarding the siting and design of facilities that could be vulnerable to the hazard. The second aspect is to provide rapid reports of hydrologic conditions as events unfold to help individuals and public officials make time-critical response decisions. These decisions include: removal of vehicles, personal property, or other moveable assets from flood plains; setting reservoir releases rates; using alternative water sources; and deployment of relief and recovery efforts. The third aspect is to conduct investigations in the aftermath of the event, thus making the greatest possible gains in information to feed back into the risk assessment process in advance of future events. These assessments could include new frequency analyses, new models, and new descriptions of physical processes such as deposition and erosion. The re-analysis of risk needs to be an ongoing process that considers changes in land use, climate variation or trend, and engineering modifications of the hydrologic system.

Issue 7: Climate and water resources management

The uncertainty associated with model projections of future regional climatic conditions, and their consequent effects on streamflow, is high compared to much more certain changes that will be driven by factors such as demographic, technological, economic, or regulatory change, Thus, it is difficult to justify changing design features or operating rules on the basis of simulated climatic change at the present time. However, recent extreme climatic variations have demonstrated that water resource managers must develop their management systems in a context that assumes a wide range of possible climatic conditions.

Plans that assume that future climate will be a repeat of the recent past climate are destined to perform poorly as compared to plans that recognize the potential for significant and long-lasting departures from historically normal conditions. The ingredients for a robust water management strategy include: studies of long climate and proxy-climate records covering several centuries to bring a wider range of variation into the managers' views; continued attempts to model future climate; river-basin simulation models that are able to predict flow conditions from the first principles of climate, topography, land use, and engineering; and robust observational systems to provide current data on temperature, precipitation, streamflow, and ground-water conditions to managers on a real time basis. These scientific inputs to water managers define a USGS agenda for the issue of climate and water resources.

Issue 8: Surface-water and ground-water interactions as related to water resources management

Management of water resources has focused traditionally on either surface water or ground water as if they were separate entities. Yet, nearly all surface-water features, including rivers, lakes, wetlands, and estuaries interact with ground water. As development of land and water resources intensifies, it is increasingly apparent that development of either water source affects the quantity and quality of the other. For example, contaminated aquifers that discharge to streams can result in long-term contamination of surface water, and, conversely, streams can be a source of contamination to aquifers. Furthermore, ground water is typically the primary source of baseflow during low-flow periods, providing the necessary discharge to support aquatic environments.

The nature of the interaction of ground water with surface water varies across the United States in response to differences in geology, physiography, climate, and other factors. There is a need to address a number of issues in different environments, including effects of ground-water withdrawals on streamflow, surface-water levels, and aquatic ecosystems; ground-water recharge from surface-water bodies; effects of climatic variations on the discharge from shallow ground-water systems; and effects of ground-water/surface-water interactions on efforts to restore wetlands or construct new wetlands. Improved tools for simulating interactions between ground water and surface water in different environments are particularly needed to quantitatively account for the interactions and the effects of humans.

Issue 9: Hydrologic system management, including optimization of ground-water and surface-water use.

Recent experience with resolution of difficult water management and allocation problems has shown that a capability to simulate the behavior of the hydrologic system, at watershed scale, is critical. What is needed are water management models, accepted by the various competing interests in water conflict, which are capable of showing the consequences of various decisions over a wide range of hydrologic and climatic conditions.

In recent years, simulation models have been combined with techniques of optimization to address various water-resources problems. Combined simulation and optimization models account for the complex behavior of the hydrologic system and identify the best management strategy for a particular objective(s) and set of constraints. The approach offers a rigorous way to provide information of management relevance. As applied in USGS studies, management agencies and others provide information on the objectives and management constraints, while USGS scientists provide expertise in simulation and optimization techniques and help to formulate the management problem in a simulation-optimization context. The USGS will continue to be a neutral party in water management disputes and provide scientific information to help resolve the dispute by improving models to simulate the behavior of hydrologic systems.

PREPARATION OF FUTURE WATER SCIENTISTS AND ENGINEERS

What are the ingredients that lead to success in the kind of scientific work we have described above? A few points stand out in our minds.

1. The scientists involved must be able to do two things very well: they must know how to make and use high-quality field measurements of hydrologic variables and they must understand the processes taking place in the environment they are studying. Field measurement capability means knowing the standard methods, knowing how to carry out appropriate quality assurance, and how to adapt and develop new measurement methods when existing ones will not suffice. Process understanding demands that they have a conceptual model of the system under investigation. In addition, they must be accustomed to reaching out to experts in other sub-disciplines to obtain the insights they need to fully understand the process interactions relevant to their system.

2. Hydrology is changing from being a largely observational science to an experimental one. Tracer tests, pump tests, experimental flow releases, are now important tools of the trade. If we are to understand how hydrologic systems behave, we need to define experiments that test their behavior under different conditions. Modeling is rarely successful if there is not a strong input signal that results in a strong output signal. Further, the outputs measured usually need to be multiple variables, for example: (a) measurement of multiple solutes (some reactive some non-reactive) at many points in the hydrologic system, or (b) measurement of surface-water stage and discharge along with concentrations of conservative tracers and sediment. We have found that even if the goal was originally just to understand flow, chemical measurements (isotopes, various ions, and atmospherically derived tracers) can be of great value in understanding the physical processes affecting the flow system.

3. The scientists involved must be able to think about multiple disciplines. The difficult problems that need to be solved today can almost never be solved within one discipline. Scientists need to be rooted deeply in some specific discipline, but to be successful they must become familiar with and be conversant with many fields. The fields of

importance include: surface-water and ground-water hydrology, geology, ecology, microbiology, organic and inorganic chemistry, atmospheric sciences, civil and sanitary engineering, and economics. One of the approaches that universities can use to assure that Masters and Doctoral students gain the needed cross fertilization of many of these disciplines is to strive to find opportunities for students at research sites where many scientists are working on a wide range of problems.

The USGS sites that provide opportunities for interdisciplinary science include: our Water, Energy and Biogeochemical Budget (WEBB) watersheds, locations where the National Water Quality Assessment (NAWQA) Program conducts flow-path studies, and Toxic Substances Hydrology field research sites. The USGS welcomes university collaboration at these sites, coordinated through site managers. In addition, the National Science Foundation provides ideal research sites through the Long Term Ecological Research (LTER) Program and the Agricultural Research Service and Forest Service operate several excellent research watersheds.

There can be great cost efficiencies in conducting thesis research at these existing sites due to the large investments that have already been made in infrastructure, site characterizations, and historical data bases. There are also great benefits to be had through the scientist-to-scientist interactions that can take place while conducting a research project at such a site.

CONCLUSION

It is our hope that these thoughts are useful to our colleagues in the university water-resources community. They are intended to provide you with insights on our thinking about the future direction of our agency and the water science and engineering community in general. Your reactions are welcome and can be directed towards either of us (rhirsch@usgs.gov or gmallard@usgs.gov). We hope these ideas are thought provoking and useful.

BIOGRAPHICAL SKETCH

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