

WATER RESOURCES MANAGEMENT: CHALLENGES AND OPPORTUNITIES

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Water-related challenges are numerous, diverse, and inevitable. Several compelling worldwide statistics are compiled below (*from recent publications of the World Bank and the United Nations* [FAO 1995a, 1995b; Engelman and Leroy 1993]):

- Human water use has increased more than 35-fold over the past three centuries;
- Worldwide, 69% of water used is agricultural, 23% industrial, and 8% domestic;
- One third of the world's food crops are produced by irrigated agriculture;
- In the past 30 years, 50% of food supply growth was attributed to agricultural expansion, a rate which is no longer sustainable;
- Per capita water consumption in North and Central America is twice that of Europe, three times that of Asia, and seven times that of Africa;
- About 1 billion people in developing countries do not have access to potable water and approximately 1.7 billion have inadequate sanitation facilities;
- Unsafe water is implicated in the deaths of more than 3 million people annually and causes about 2.4 billion episodes of illness each year;
- The World's population, now 5 billion, is expected to increase to at least 8 billion by 2025 and 10 billion by 2050, which would dramatically raise the demand for water and food;
- According to United Nations' projections, by 2050 almost half of the world's population will live in 58 countries experiencing either water scarcity (less than 1,000 cubic meters of renewable water per capita per year) or water stress (between 1,000 and roughly 1,700 cubic meters);
- The financial requirements to meet future demands for irrigation, hydropower, water supply, and sanitation

investments in developing countries are estimated to be \$600-800 billion over the next decade.

These daunting facts are evidence of a global water resources crisis with escalating conflicts. Examples can be cited for all countries. In the Nile Basin, Egypt, which owes its existence to the Nile, is concerned about upstream developments in Ethiopia and the Equatorial region. Ethiopian plans for hydropower and agricultural expansion along the Blue Nile could change the flow regime and threaten the Egyptian economy. At the same time, water augmentation projects on the White Nile may provide a temporary relief to the increasing demand for irrigated lands but would impact the vast region of the Sudd swamps with unpredictable effects on the global climate. In China, every summer, millions of people along the middle and lower reaches of the Yangtze River live under the constant threat of flooding. In one such incident, the river claimed 145,000 lives and inundated 3.4 million hectares of farmland. The Three Gorges Dam would greatly reduce the risk of flooding and would generate enough electricity to meet the power needs of central and eastern China for decades. However, the dam would inundate vast areas, force the relocation of more than one million people, and cause irrevocable environmental damage. Similar controversies surround the Mekong, Amazon, Rhine, Euphrates, Jordan, and almost every other major river system.

In the western United States, conflicts and litigations over water allocation have raged for many years. Recently, similar disputes have also emerged in the water-abundant southeast where the Savannah, Apalachicola-Chattahoochee-Flint, and the Alabama-Coosa-Tallapoosa Rivers are at the center of a major multi-state conflict. These rivers drain approximately 33,000 square miles in five southeastern states (Alabama, Georgia, Florida, Tennessee, and South Carolina), and they support multiple water uses including hydroelectric energy generation, flood control, water supply, navigation, and ecosystem management. The controversy started when Georgia requested the reallocation of some storage in Lake Lanier for Atlanta's growing water needs. To many, more water for Atlanta translates to less "clean" water for the downstream users in Alabama and Florida, igniting a hot political debate in the 1990 elections for state gubernatorial and Congressional representatives. To avoid protracted legal battles, the three states are presently

experimenting with a new conflict resolution paradigm, pursuing a comprehensive investigation and trust building exercise to develop equitable water allocation agreements.

In view of the inevitable population growth, industrialization, and urbanization, it is apparent that current water resources management practices are no longer sustainable. There is an urgent need for *new* water resources policies that accomplish both good economic performance *and* improvements of environmental and ecological quality, that see the environment as an objective, not as a constraint in the exploitation of natural resources. Water resources planners and managers (ministers, senior administrators, specialists, professionals, and others active in the water sector) must heed the lessons of the last decades and develop a shared vision of new water resources management principles. In this process of renewal, universities like Georgia Tech along with international organizations, funding and lending institutions, and professional societies have an important role to play: They must jointly promote education, research, and technology transfer and prepare policy makers for the challenges that lie ahead.

DECISION SUPPORT FOR WATER RESOURCES MANAGEMENT

Planning/policy issues

Man-made hydraulic works can alter natural river flow regimes, turning costly hazards and risks into regional assets, and providing the means for sustainable economic development. Those involved in hydro systems planning and management, however, face a challenging task, for they must carefully consider and weigh a large array of complicating and uncertain elements. Among them are the dynamics and uncertainties of the rainfall-runoff process, the hydraulic response of the reservoir and river reaches, the characteristics of dams and other regulatory structures, the risk of floods and droughts, the climatic variability and change, the requirements for agricultural, industrial, and municipal water supply, the conjunctive use of surface and ground water, the economics of hydropower, the management of water quality, the demand for recreational activities, the impacts to ecosystems, the potential for local and regional conflicts, and the long term sustainability of water policies.

Sustainable water resources management is a complex undertaking that involves policy (strategic) as well as operational (tactical) decisions. At the policy level, most pressing questions arise from the competing nature of system objectives and their complex interactions. Do economic gains from hydropower outweigh increased flood risks? What are the relative rights of upstream versus downstream water users? Does water supply for agricultural and industrial expansion take precedence over ecosystem restoration? Are water policies in harmony with the rights of future generations? These matters quickly become the subject of intense political debate and cause regional conflicts, especially when water users bearing the costs and those receiving the gains fall in different sectors of the economy, different states, or as it happens with international rivers, different nations. Those

missing from the debate—the future generations—will have no other choice but to live our legacy of water resources management. In turn, among the choices that we now *still* have is to leave a legacy supporting human and ecological values in a lasting and sustainable manner.

In the past, water policies were predominantly formulated in response to crises situations, and then almost always favored supply-side solutions. Thus, whenever the demand for a certain water use increased, the popular solution was to develop new supplies. This era, however, is ending, and policy makers are now facing the challenge to establish demand-management mechanisms, re-allocate existing supplies, encourage more efficient water use, and promote more equitable access. In this effort, they need to fully appreciate the inter-dependent nature of water uses and the feedback connections between the “water sector” and other parts of the economy, not only in the short run, but even more importantly over the longer term. Thus, there is a need to *measure* the sustainability of various water resources management policies. Such measures, however, are still in the realm of academic research.

Operational issues

At the operational level, decision support systems (Figure 1) focus on day-to-day management tasks like flood protection and hydropower scheduling, and they commonly include two primary components: forecasting and control. These two components may be complemented by various other elements and address a wide range of water resources issues.

Forecasting

The purpose of this component is to use hydro meteorologic data together with models of the water transport physics and dynamics to make reliable predictions at key locations within the river basin. Hydro meteorologic data may be obtained from automated on-site sensors like rain gages, stream gages, and surface meteorologic stations (measuring evaporation, humidity, temperature, wind velocity and direction, and snow water equivalent), as well as remote sensors like weather radar and satellites. Specifically, streamflow prediction involves the following steps: (1) estimation of rainfall from satellite, radar, and rain gage observations; (2) simulation of the watershed rainfall-runoff and snow accumulation and melting processes; and (3) river and reservoir routing within the stream network. Given enough hydro meteorologic data, the hydrologic and hydraulic models can be spatially distributed, using Geographic Information Systems, digital terrain elevations, and remotely sensed land-use data bases.

Areas of active research related to operational river forecasting include the understanding of the soil moisture behavior in space and time and its controlling influence on runoff and evapotranspiration; the development of computationally efficient models for spatially-distributed hydrologic forecasts; the quantitative precipitation forecasting over watershed scales; the reliable estimation of rainfall (combining satellite, radar, and rain gage measurements); and the development of reliable methods for characterizing the uncertainty through the various steps of the

streamflow forecasting process.

Control

Even after strategic decisions are made, challenging questions remain. The issues at this stage relate to shorter time scales; How can strategic decisions be implemented to meet day-to-day and hour-to-hour water use requirements in timely and reliable ways? Which operational plan would be able to effectively balance water availability, flow and power capacity constraints, water travel delays, and ecosystem response against increasing water and power demands, environmental preservation and restoration, and ecosystem well-being?

Although, significant progress has been made in years past in answering these questions, opportunities for improvement still exist. Among them are the development of integrated water

quantity, quality, land use, and ecosystem models within a general decision support framework, and the reorganization of our institutional structures in ways which would allow for conflict resolution between social, economic, and environmental objectives. Both of these improvement opportunities stem from the realization that water management issues must be considered *systemically*. Today's fragmented and sectoral approach—different agencies managing the same resource for different uses—ignores important inter-sectoral interactions (like pollution), and allows them to reinforce each other and eventually impair *all* water uses.

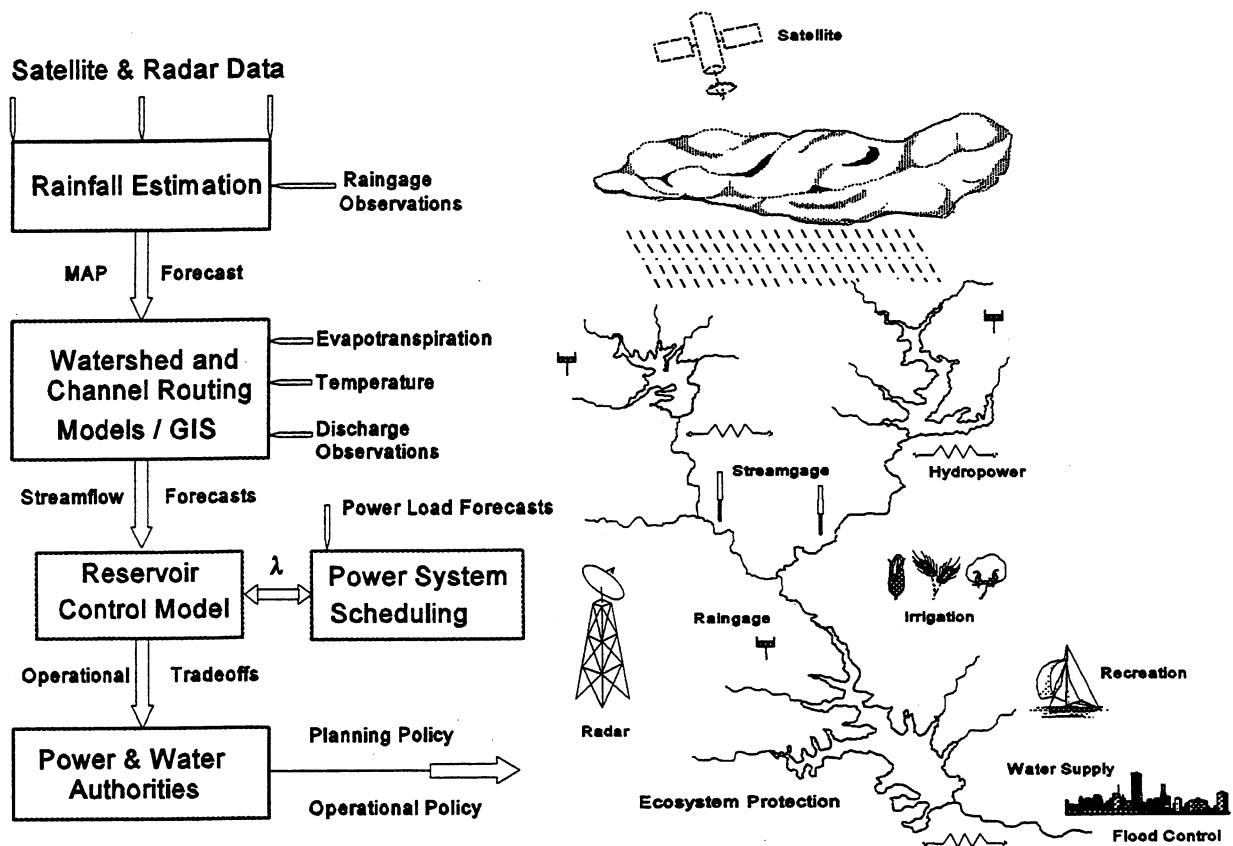


Figure 1. Decision support systems for water resources management.

GEORGIA TECH'S WATER RESOURCES PROGRAM

The goals of the water resources program at Georgia Tech are to (1) research integrated decision support systems for sustainable water resources management, (2) educate students, professional engineers, and policy makers on concepts and tools of decision support systems, and (3) transfer new technology for water resources planning and operation to industry and government.

Research

Georgia Tech is actively involved in the research, development, and implementation of decision support systems for several river basins around the world. Some of these efforts are collaborative with other research organizations including the Office of Hydrology of the National Oceanic and Atmospheric Administration (NOAA), the Hydrologic Research Center in California, Delft Hydraulics Institute in the Netherlands, and other universities.

An integrated decision support system like the one previously referenced is presently being developed for the Nile River in east-central Africa. One of the most historical and spectacular rivers in the world, the Nile begins its 4,000 mile journey from the Equatorial Lakes and flows north towards the Mediterranean Sea sustaining more than 250 million people and a vast ecological diversity of animals and plants. For some Nilotic nations (i.e., Egypt and northern Sudan), the Nile is literally everything, while for others (i.e., Ethiopia, Tanzania, Uganda, Kenya, Zaire, Burundi, and Rwanda), it is the engine waiting to power their future economic development. These regional differences, accentuated by the fast pace of demographic growth, agricultural expansion, and industrialization, create serious conflicts and threaten the region's peace and stability.

For example, Ethiopia, which commands the sources of one of the two major Nile tributaries (the Blue Nile), has been considering the possibility of major hydroelectric developments that would also enable the expansion of its agricultural lands. Construction of these projects, however, would alter the river's flow regime and would potentially impact the downstream countries of Sudan and Egypt. Although the impact may in fact be positive (leading to hydropower gains for Egypt and Sudan), the uncertainty surrounding this issue causes international tension. Similar concerns beset the water conservation projects proposed for the other major Nile tributary, the White Nile. At issue there is the regulation of the Equatorial Lakes and the construction of a canal to bypass an extensive swamp area that absorbs almost 50% of the Nile water, creating a unique wild-life refuge. Although these projects would augment water supply for the downstream nations, they would also impact the riparians (mostly Tanzania, Kenya, Uganda, and southern Sudan) ecologically and, possibly, in other respects. To date, efforts to promote water agreements among all Nile Basin nations have had very limited success because (1) well defined water resources development plans for each nation are lacking, (2) decision support tools for reliable evaluation of different water development scenarios and impacts are missing, and (3) good technical expertise and understanding of water management issues in the Nile Basin nations is at best

sporadic.

The decision support system being developed is designed to assist the Nilotic nations in three ways. First, to provide the means for establishing water development strategies and negotiating water allocation agreements basin-wide; Second to optimize day-to-day hydro system operations; and third to develop technological expertise. At the strategic level, the system is designed to provide policy makers with the information necessary to understand the joint tradeoffs and gains that would result from proposed hydropower and water conservation projects and from the coordinated operation of all Nile Basin storage facilities. This information is the basis for developing realistic water master plans and negotiating equitable water allocation agreements. Only when all riparian states have a clear understanding of these issues, can such agreements actually be achieved and regional conflicts avoided.

At the operational level, the decision system explores mid-range operational tradeoffs, solicits the input from the decision making authorities, and finally determines the day-to-day and hour-to-hour operation of the hydro system units in a way which implements the strategic decisions and optimizes the water utilization efficiency. Thus, the design philosophy of the decision system is *not* to suggest a particular decision. Rather, the objective is to quantify the impacts of several decisions that could potentially interest the management authorities. Once a selection is made at the strategic level, the model determines the operational policy that implements it. Furthermore, as conditions change, decisions can be re-evaluated and revised as often as desired. Presently, the system includes four principal components: (1) Primary Data User System (PDUS), (2) Meteorological Data Distribution (MDD), (3) Nile Forecast System (NFS), (4) Nile Basin Management (NBM) System.

The PDUS continuously processes image data from the meteorological geosynchronous METEOSAT satellite. These data include visible, infra-red, and water vapor images which are incorporated with other hydroclimatic data to provide areal rainfall estimates over the Blue and White Nile catchments. The MDD system provides observed real-time meteorological data which are available through the Global Telecommunication System of the World Meteorological Organization (WMO). The NFS contains hydrologic models and GIS software necessary to produce rainfall estimates, soil moisture distribution and changes, river flow forecasts, and river stage hydrographs along the Nile River system. Lastly, NBM uses these forecasts to quantify various tradeoffs and develop planning and operational policies for parts or the entire Nile River system. NBM includes models for river and reservoir routing, reservoir control, power and water demand forecasting, energy pricing, system simulation, and tradeoff analysis. The models operate on workstations as well as personal computers and are accessed through a user-friendly, graphical interface. In the near future, the system will be further expanded to include components for water quality and ecosystem simulations, conjunctive use of surface and ground waters, agroeconomics, and climate change impact assessments.

The Nile decision support system has already been installed and made operational at the Nile Forecast and Control Center

(NFC) in the Planning Sector of the Ministry of Public Works and Water Resources (MPWWR) in Cairo. Several senior Egyptian officials and engineers have been extensively trained in its theory and use and are presently responsible for its operation. Similar centers and technology transfer activities have already started at other Nilotic nations with the purpose of creating a network of water management centers sharing information and becoming a vehicle for communication and conflict resolution.

In addition to the Nile River, Georgia Tech is involved in the development of similar systems in several other countries (rivers) including China (**Yangtze**), Greece (**Acheloos**), Mexico (**country wide**), Argentina (**Tunuyan**), Chile (**Bio-Bio**), and Brazil (**Iguacu**). In the United States, decision support systems have been developed for the **Savannah River**, the Southeastern U.S. reservoir system [encompassing the **Savannah**, the **Appalachicola-Chattahoochee-Flint** (ACF), and the **Alabama-Coosa-Tallapoussa** (ACT) Rivers], and the **Upper Des Moines** River in the Midwest.

This research has given rise to unique, state-of-the-science decision support products. These products include integrated forecast-control systems able to (a) incorporate observations from remote and on-site sensors and account for their uncertainty, (b) handle large, spatially distributed water resources systems in an efficient optimization framework, and (c) generate multi-objective tradeoffs for policy and operational decisions. In part or as a whole, these products can be used for flood forecasting/warning applications, for decision support in water resources planning and operation, and for the design of optimum hydro-meteorologic observation networks. Agencies who can gain from the use of these products include flood forecasting bureaus, water resources management authorities, electrical utilities, and environmental protection agencies.

Education and Technology Transfer

Georgia Tech's educational program in water resources includes regular courses at the B.S., M.S., and Ph.D. levels, short courses and seminars for the continuing education of engineering professionals, training, and technology transfer activities. Regular courses cover a wide range of disciplines such as surface and groundwater hydrology, hydraulics, fluid mechanics, meteorology, water quality, remote sensing, geographic information systems, economics, systems analysis, uncertainty characterization, water resources management, conflict resolution, and sustainability. Distance learning opportunities are also available and continue to grow.

Continuing education courses have traditionally been offered on a variety of water resources subjects. These courses are presently being expanded and restructured in a more comprehensive and coherent program that will be introduced in collaboration with experienced industry and agency professionals. This joint university-industry-government effort is viewed as a key partnership for successful and lasting contributions in continuing education. Similar partnerships have also been established with *international* research and educational organizations with the purpose of offering continuing education opportunities worldwide. One such initiative is planned to take place in Cairo targeting

engineering professionals in Africa and the Middle East.

Training and technology transfer activities are essential to the development of *sustainable* decision support systems. Activities include workshops, short and regular courses, seminars, and "hands on" training. To be useful, decision support systems must be understood by their potential users, gain their acceptance and endorsement, and become integrated within the decision process. This is a difficult proposition, especially because it often requires a change in working attitude throughout all levels of the administrative structure, and, possibly, an administrative restructuring as well. Thus, training and technology transfer is required for senior executives as much as for engineering staff. The former should develop a clear understanding of the system capabilities, determine how it can benefit the existing decision process, and structure an institutional framework conducive to this purpose. Engineers and support staff should become intimately familiar with the decision system, obtain "hands-on" experience with it, learn how to maintain and improve it, and eventually transfer this knowledge to others who will succeed them in this role. Experience shows that the most effective means for this to happen is to include in the development team a selected core of engineers who will contribute to the system development substantively, eventually becoming agents of knowledge and technology transfer.

In spite of their obvious value, decision support systems are uncommon, both in the U.S. and abroad. The general practice continues to be one of using ad hoc methods, heuristic procedures, and outdated technology. Two of the main reasons are that (1) the development of effective decision support systems requires advanced knowledge and experience, time, and effort on the part of the developer, as well as the resources and willingness to change entrenched practices on the part of the user, and (2) standardized systems are not commercially available.

Building on its past research experience, Georgia Tech's water resources program is working on developing standardized decision support modules for general applications. Making high quality decision support products more widely and easily available will certainly have a positive impact on water resources management, eventually promoting equitable and generally-shared water allocation principles and values.

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