

## **SANDIA REPORT**

SAND2001-0756

Unlimited Release

Printed March 2001

# **Integrating Monitoring and Decision Modeling Within a Cooperative Framework: Promoting Transboundary Water Management and Avoiding Regional Conflict**

Vincent C. Tidwell, Reynolds M. Salerno, Howard D. Passell, Kelli L. Larson, Elena Kalinina, Aaron T. Wolf, J. Arlin Cooper, Jan Curtis, Stephen H. Conrad, Dick P. Thomas, and Orman H. Paananen

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## **Abstract**

Surface and groundwater resources do not recognize political boundaries. Where nature and boundary cross, tension over shared water resources can erupt. Such tension is exacerbated in regions where demand approaches or exceeds sustainable supplies of water. Establishing equitable management strategies can help prevent and resolve conflict over shared water resources. This paper describes a methodology for addressing transboundary water issues predicated on the integration of monitoring and modeling within a framework of cooperation. Cooperative monitoring begins with agreement by international scientists and/or policy makers on transboundary monitoring goals and strategies; it leads to the process of obtaining and sharing agreed-upon information among parties with the purpose of providing verifiable and secure data. Cooperative modeling is the process by which the parties jointly interpret the data, forecast future events and trends, and quantify cause and effect relationships. Together, cooperative monitoring and modeling allow for the development and assessment of alternative management and remediation strategies that could form the basis of regional watershed agreements or treaties. An example of how this multifaceted approach might be used to manage a shared water resource is presented for the Kura River basin in the Caucasus.

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## Acronyms

GUI	graphical user interface
MCL	maximum contamination level
PI	principal investigator
UNHCR	United Nations High Commissioner for Refugees
WCW	World Commission on Water
WHO	World Health Organization

# 1. Introduction

Economic, social, and often political vitality depends on a safe, secure, and sustainable supply of water. In 1994, an estimated 1.3 million people worldwide did not have access to clean drinking water (WHO 1996). The world's population, which has doubled over the last 50 years, continues to grow, straining finite freshwater resources. Depending on future rates of population growth, approximately 2.4 to 3.4 billion people may be living in water-scarce or water-stressed conditions by 2025 (Engelman et al. 2000).

A recent study by the World Commission on Water for the 21<sup>st</sup> Century indicated that more than half of the world's major rivers are being seriously depleted and polluted, degrading and poisoning the surrounding ecosystems and thus threatening the health and livelihood of the people who depend upon them for irrigation as well as drinking and industrial water (WCW 2000). In 1993, the number of environmental refugees was estimated at 25 million, and projected to increase to 150 million by the year 2050 (Myers 1993). The number of war-related refugees in 1993 was estimated at 23 million, and the number of environmental refugees has exceeded the number of war-related refugees ever since (UNHCR 1994).

Management of scarce water resources is complicated by the fact that 80% of the world's largest rivers, which account for 87% of the annual flow, are shared by at least two countries. These shared rivers constitute 261 international basins, which cover 45.3% of the earth's land surface (Wolf et al. 1999). Since 1950, approximately 1200 disputes over shared water resources have occurred; however, only 7 of these have led to violence or military conflict (Wolf 1998).

While water has only recently become a critical aspect of many international and regional disputes, the management of freshwater resources has long been the subject of international and regional negotiations. Over 3,600 water treaties have been signed into international law (Wolf 1998). Despite the abundance of water-related treaties, tension over shared water resources continues as social, economic, environmental, and political changes within basins alter the delicate balance on which the treaties are predicated.

Development of equitable management strategies for transboundary freshwater resources is an arduous process with many complicating factors. First, assessing the sustainable water supply is subject to numerous complex, interacting physical processes that are spatially and temporally variable. Second, historical data are generally sparse and the data that are available are seldom shared across international boundaries. Third, water is valued in many different ways (e.g., economic, political, social/cultural, and environmental), which are often conflicting, interrelated, and difficult to quantify.

This paper argues that the tension created by transboundary water issues can also function as a catalyst for building trust and collaboration between and among parties. Cooperating on data gathering in international basins around the world has built "epistemic communities"—cross-border communities of professionals who speak a similar scientific language—that have often been instrumental in promoting political dialogue. In these scientific collaborations, ideas pertaining to ongoing disputes can be proposed and discussed without the occasionally contentious atmosphere of official political negotiations.

For these epistemic communities to function, a basis of collaboration is required. Because data collection and resource evaluations are a critical component of managing water resources, information sharing and joint resource assessments are common elements of international water management and, more specifically, treaties. Thus, river basin communities benefit from a common set of tools with which to evaluate the health and sustainability of their shared water resource, and to explore alternative management strategies. Members of these communities include the donor countries, nongovernmental organizations representing community and international interests, scientists, and resource management and government officials. Reaching consensus among these various interests in the basin may be facilitated by cooperation on two related fronts: monitoring and modeling. Cooperative monitoring provides a means of developing a consistent database that is shared and approved by all parties, while cooperative modeling provides the computational framework with which the parties interpret the available data and test alternative water management strategies.

Few treaties and/or transboundary water arrangements have benefited from current monitoring and modeling technologies. This is in part due to the rapid growth in the technology sector over the past 10 to 20 years. Problems in the past illustrate where such technologies can aid international water management and negotiations. One of the most striking and recent examples where remote sensing might have made a major contribution to the process of water conflict resolution is along the Ganges River, where India and Bangladesh spent more than 30 years in various stages of dispute or negotiation. A perceived lack of data has been a critical issue in both the process and the substance of negotiations: over the years, India has claimed that the lack of river data or the inaccuracy of existing data prevented proper negotiations, while Bangladesh was suspicious of Indian data. Furthermore, the state of the river in any given period is often determined by factors outside the territory of both countries (e.g., the snow pack in Bhutan), where data simply was not available through traditional collection methods. As a consequence, a treaty was not signed until December 1996. Access to remotely sensed hydrologic and land-use data not only would have placed negotiations within a more equitable context, but also could have precluded the dispute that occurred immediately after the treaty was finally signed. The conflict erupted when water passing the border dropped below the minimum provided in the treaty, prompting a Bangladeshi request for a review of the state of the watershed.

Here, our purpose is to develop a generic framework for addressing transboundary water issues. The methodology integrates monitoring and modeling within a framework of cooperation. It demonstrates the application of this approach using the Kura River watershed as an example. The Kura is the most important river in the Caucasus region, whose transboundary basin includes Azerbaijan, Armenia, Georgia, Iran, Turkey, and Russia.



## **2. Methods**

This section describes a methodology that could help prevent conflict over and promote international and regional cooperation on transboundary water issues. Central to this approach is the integration of monitoring and decision modeling within a cooperative framework (Figure 1), with all elements equally important. Monitoring provides verifiable and secure data, while decision modeling allows for the interpretation of the data, forecasts future events and trends, and quantifies cause-and-effect relationships. Unless the development and implementation of these tools are pursued in parallel and in an environment of collaboration, successful water management—sustained indefinitely by the riparians themselves—may be elusive. Cooperative monitoring and modeling together allow for the development and assessment of alternative management and remediation strategies that could form the basis of regional watershed agreements or treaties.

### **2.1 Cooperative Monitoring**

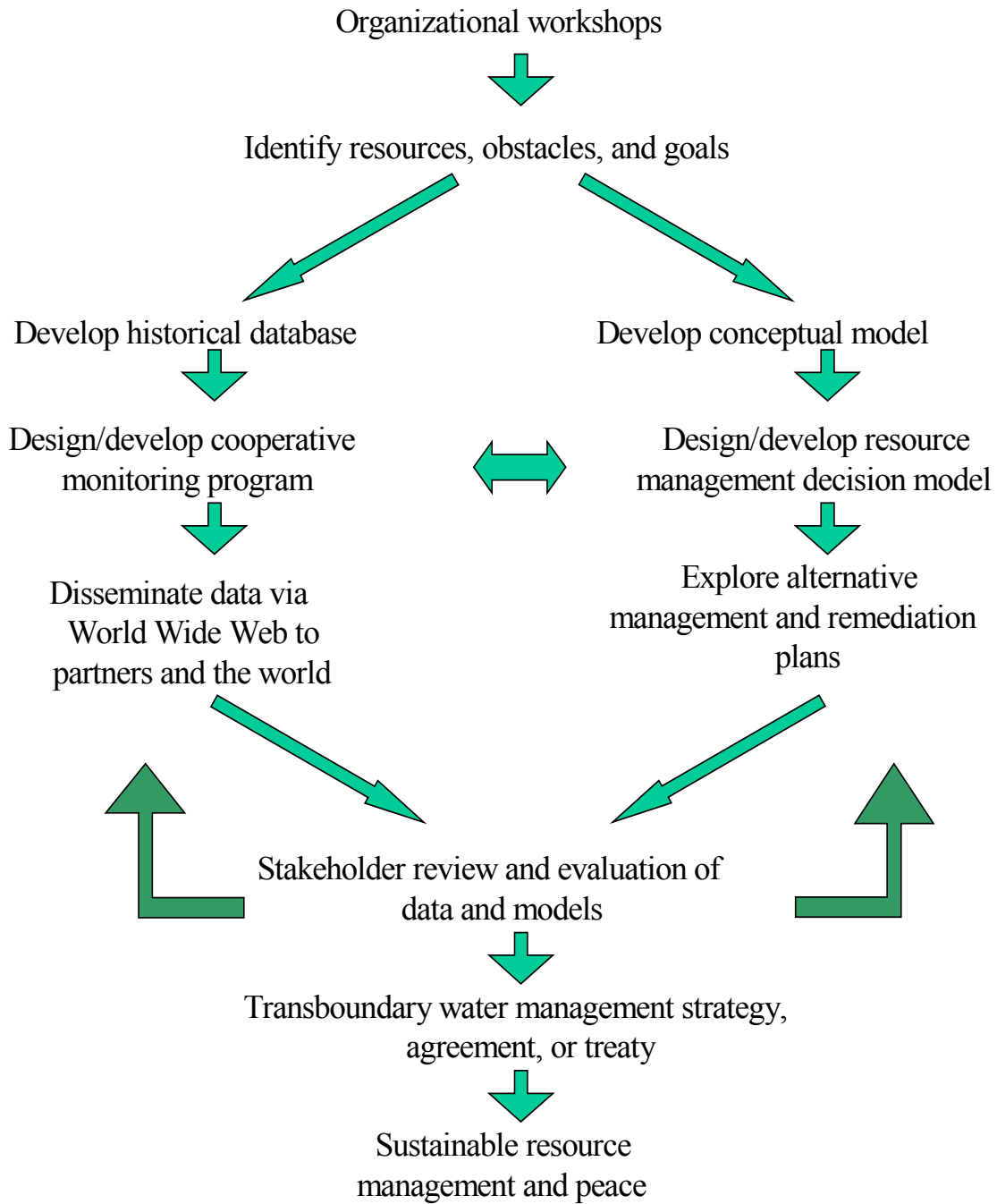
Cooperative monitoring is the process of obtaining and sharing agreed-upon information among parties. The objective of cooperative monitoring is the design of a mutually acceptable monitoring regime that employs sharable technologies, assures equal access to results, and establishes procedures to handle anomalies.

Cooperative monitoring offers many benefits. The most obvious of these are the acquired data, which are necessary to ground decisions in reality. Potential roles for data include baseline information for long-term resource management, enhancing understanding of key environmental processes, environmental emergency warning, and verification of progress toward shared goals. Cooperative monitoring also provides a physical and social infrastructure for international scientific and political collaboration. Through these means, the riparians can strengthen their communication and trust.

Cooperative monitoring is required by the deficiency or absence of adequate data. Many developing nations lack the infrastructure to establish and operate comprehensive monitoring networks. In other cases, data are collected but not shared across national boundaries. The rapid developments in technology now also allow for the monitoring of additional parameters at increased resolution with improved precision and accuracy, improving the breadth and significance of previously available data.

#### **2.1.1 Implementation**

Cooperative monitoring is aimed at building both transboundary databases and transboundary cooperation and collaboration. Together, all these achievements can foster sustainable transboundary natural resource management, which in turn can enhance regional security and peace. Cooperative monitoring, therefore, begins with communication, which would be fostered by a



**Figure 1. Process of cooperative monitoring and modeling to avoid conflict over shared transboundary water resources.**

series of workshops attended by the riparian stakeholders, the financial sponsors of the project, and the facilitators. Initial workshops would allow participants to express problems, concerns, and goals, while project initiators could introduce technology options and help the parties articulate their data needs. The objectives of the initial workshops would be to develop a joint monitoring strategy and to organize the resources for program implementation. In the initial phases of the monitoring program, the participants would develop baseline data for modeling and decision support. Later workshops would allow participants to modify and improve methods. Over time, the baseline data would be augmented with historical data sets. All available data would then be interpreted with the aid of decision management modeling. Modeling and statistical analyses of historical data could identify gaps in the monitoring system, allowing for appropriate revisions to the monitoring system. The cooperative nature of all these steps and the repeated meetings of participants could contribute to the development of a strong foundation of trust, which could foster other transboundary cooperation as well.

### **2.1.2 Data Collection**

Essential to any monitoring program is the development of a coherent sampling strategy. The strategy must define the scope of the monitoring program as well as where and when to sample. The sophistication of the program would be dictated by the nature of the problem and available resources. Design of the monitoring strategy should be approached cooperatively. The resulting design would incorporate the expert knowledge unique to each party and address their specific concerns.

The scope of potential data needs for resolving transboundary water issues could be quite large. In a broad sense, data requirements might include information on water supply, water quality, water use, agricultural irrigation demand, economic conditions, population growth, and public perceptions regarding problems and alternative management strategies. To narrow the scope, the stakeholders must cooperatively identify and prioritize the key transboundary water issues. Data collection would then focus on those features that most directly impact management decisions. Sensitivity of management decisions to data could be determined through expert elicitation and modeling exercises.

Once data needs are identified and prioritized, appropriate means for acquiring the data must be determined. In selecting the technology to accomplish the necessary measurements, the investigators must consider the precision and accuracy of the instruments and the analytical techniques, and the scale of the measurement, specifically in relation to stakeholders' needs. The instruments' practicality must also be considered, including power supply, portability, durability, potential for theft, and ease of operation. Protocols for sampling must also be established for various sampling methodologies, such as, at what point in a stream should a water quality sample be collected, what volume of water should be sampled, and how the sample should be filtered. Capabilities of analytical laboratories must be assessed and, if analysis is to occur in different labs across borders, then differences in equipment and techniques must be considered and standardized, if possible.

The monitoring strategy must also define where and when to sample. Available resources generally limit the number of samples that can be collected. Within this constraint, the number of monitoring stations versus the frequency of sampling must be carefully balanced. Selection of monitoring stations involves both biased and structured sampling. Prioritized sampling procedures place stations near strategic locations such as international boundaries, known sources of environmental contamination, or key indicators of resource supply. Other samples should be spaced on a semi-regular pattern to characterize spatial variability. The frequency of sampling must be based on the time scales critical to the transboundary issue, such as diurnal or seasonal fluctuations, long-term climatic variations, or patterns associated with mining or manufacturing processes. Critical space and time scales can be determined from expert elicitation, statistical analysis of historical data, and modeling sensitivity studies.

### **2.1.3 Securing the Data**

Cooperation on securing data is an important factor in transboundary water monitoring. Each partner generating data has the responsibility to implement procedures that assure the precision, accuracy, representativeness, comparability, and completeness of the data.

A principal investigator (PI) should be selected from each partner country to manage the project within that country, and to serve as the custodian of the data. An internet site located on one central server and accessible by all the partners would be a critical component of the cooperative monitoring system. Data, either collected from field instruments or from laboratory analysis, should be routed from each country into a peer review holding file in the project's central server. Data in the holding file should be subjected to a peer review process that includes all the PIs. After any issues with potential data errors are raised and resolved, the data should be added to the database, which could then be made available through the internet to the global scientific community and the public, or which could be held as proprietary for use only by the collaborating partners.

Data collection and transmission can be approached in a number of ways. Where sufficient resources exist, some data could be collected in real time from remote stations across the region and transmitted via satellite to the central server, where the data are posted into the peer review holding file on a regular, perhaps hourly, basis. Alternatively, remote stations could be designed to collect water samples automatically at preset intervals, and then periodically a technician could visit the stations, collect the samples, and deliver them to a laboratory for analysis. In other scenarios, technicians could travel among monitoring stations, collecting water samples by hand, performing some field analysis and transporting samples to labs for further analysis.

### **2.1.4 Data Sharing, Applications, and Transparency**

Data sharing, data applications, and transparency are all achieved through the project's internet site, which would be designed to provide links to existing data sources, present partner information, share data generated by the individual partners, and archive relevant documents such as field forms, maps, sampling locations, flow charts, data entry and transmission protocols.

The internet site could also provide a medium in which data analysis and other research projects in progress could be reviewed and commented upon by co-authors. Some of these sites could be accessible to the public, and some could be password protected for viewing by project partners only.

As the project matures, the internet site could also provide a direct link to decision modeling applications. In this way, acquired data could be used to update program models, thus providing a means for real-time, transboundary management of shared water resources, and for tracking progress toward the development of a sustainable transboundary water resource.

## **2.2 Cooperative Modeling**

Cooperative modeling is the means by which opposing water parties engage in the decision process by allowing each party to explore the shared data in the context of the problem they seek to solve. Historically, water agencies have benefited from using models to interpret and visualize the results of resource analyses in graphic or map form. As one water engineer stated, “seeing the problem gives a more accurate assessment of the actual behavior of the system.” (Lang 1992: 49) Decision modeling can aid human understanding of resource problems and alternative management strategies that involve interrelationships among complex variables. This is particularly important given human limitations in processing large amounts of information. However, decision-support tools have only begun to be applied to the context of group decision-making and negotiations. Collaborative planning/support systems have much promise in this area, as they can lead to the generation of remediation strategies and consensus building by empowering stakeholders to explore policy solutions through a common platform (Simonovic and Bender 1996). The key to a successful modeling system is through participatory development of the decision tool; more specifically, model developers must be sensitive to the stakeholders’ needs and concerns throughout the development process.

### **2.2.1 Approach**

Difficulty in managing transboundary resources arises both from the natural system, with its inherent complexity, and from human culture, with its broad and often conflicting values over the allocation of available resources. Any decision should balance the needs of individuals and nature while maintaining a perspective on the whole system. In this way, a single integrated model for the basin would be needed to assess the complex interrelations among climate, the hydrologic system, agricultural/municipal/industrial water demands, economic forces, environmental impacts, and social/cultural/political values. This would demand involvement from a broad array of regional stakeholders, many of whom may have diverse interests. This study advocates a top-down (i.e., simple to complex), systems-level approach to modeling, where the focus is on capturing the broad framework of the water system. Although systems-level models can be very sophisticated, they are based on “easy to understand” physical concepts and make use of computationally efficient algorithms, allowing application on PC-based simulation platforms. Thus, systems-level modeling could be made easily accessible to water managers, policy makers, regulators, and others with limited modeling experience. Additionally, the

systems-level models would be uniquely suited to serve as an interface to more sophisticated process-level models (e.g., groundwater flow models, snow-pack estimation models) should refinement of a particular system be deemed necessary.

### **2.2.2 Model Description**

A dynamic water budget lies at the heart of the systems-level model described here. Conceptually, a water budget is founded on the principle of continuity of mass that is invoked by tracking the inflows, outflows, and changes in storage of the system. In efforts to achieve a sustainable solution, the dynamic water budget model tracks changes in time but not in space; however, a single basin may be subdivided into multiple units. In simple terms, the water budget treats the basin as a series of reservoirs, each representing a unique mode of water storage in the system (e.g., groundwater, surface water). Water transfers (between reservoirs), injections, and withdrawals are modeled in one of three ways: by direct accounting that uses a single number or lookup table to determine the water exchange; by a transfer function formulated to mimic the physical process governing the water exchange; or by external process-level modeling linked directly to the systems-level model.

This same dynamic modeling architecture is employed to track other critical commodities. Solutes, environmental contaminants, revenue (economics), energy, agricultural products, and population are just a few of the many important commodities that have direct bearing on the management of shared water resources. Within this framework, the connection between the commodity and water is modeled as well as the interrelationships among the different commodities (e.g., agricultural production and revenue).

Other influences on the water management decision process cannot be easily or accurately modeled using the dynamic “commodities” budget approach. These factors include social and cultural values. One approach to this problem is to use soft mathematical aggregation (Cooper 1999), which establishes a decision framework by identifying key values and their interrelationships. Subjective weights are assigned to each of the factors, which are then linearly or nonlinearly aggregated to determine their total contribution to the decision.

### **2.2.3 Input/Output**

The relevance of the model is determined largely by the adequacy of the data. Fortunately, there is flexibility in the types of data streams that can be used in the systems-level modeling. Data can be treated in a deterministic mode. Historical data and constrained parameters (e.g., legally defined limits) are examples of deterministic data. Where there is uncertainty concerning the absolute value of a parameter, either due to limited data or projected behavior (e.g., future rainfall), data may be treated as a stochastic variable. In this mode, the data are prescribed in terms of a probability distribution function rather than as a known value.

To facilitate operation of the model, a user-friendly interface should be employed to control input of key decision parameters. Input for select parameters can be controlled interactively by operating slider bars and/or radio buttons. In this way, parameters that play a key role in

managing the shared resource (e.g., groundwater pumping rates, rainfall rates) can be quickly adjusted and the effect assessed. It is important to note here that resource managers have failed to employ many decision tools because of the technically complex user interfaces. This circumstance has arisen despite significant advances in the development of graphical user interfaces (GUIs) designed to ease and encourage operation (Dunn et al. 1996). Thus, it is critical to evaluate frequently the effectiveness of the interface and value of the overall model.

The display of results is also accessed interactively within the model. Once the model has been run, results are presented in a clear, easy-to-read graphical format. The graphs are fully annotated to facilitate interpretation. Again, the degree to which users comprehend these displays must be considered to ensure continued use of decision models. A model that is well designed becomes not only a valuable decision support tool, but also a tool that can be used to demonstrate system dynamics to a wide variety of audiences, including scientists, managers, policy makers, and the public.

Simulations generally involve both the historical performance of the system as well as the performance of the system projected into the future. Graphical comparison of historical data and the simulated historical performance of the system provide some indication of the validity of the model. Results are expressed in a deterministic or stochastic framework, depending on the nature of the input data. The graphical display is designed around the desires of the users, focused on the metrics most useful in managing the shared water resource.

#### **2.2.4 Implementation**

The development and utilization of a joint resource management model is an excellent vehicle for building cooperation and collaboration among nations that share a transboundary watershed. Alternatively, if modeling exercises are pursued without full participation of the riparians in all stages of the effort, chances are slim that the models will ever achieve their intended purpose. Cooperation must begin with the conceptualization of the model; that is, representing the physical system in the form of a mathematical model. Each party must also participate in building the model database. Facilitated workshops can be used to build the necessary consensus in the model and database; however, several iterations will likely be necessary before this is achieved. Cooperation must also extend to the calibration and testing of the model, which is key to building scientific and political credibility.

Beyond cooperation, two other important products are derived from decision modeling. First, consensus is built around a common understanding of how the natural system operates. Second, a consistent model and database is developed to aid in managing shared water resources. The model can be exercised both jointly through a series of workshops or small working groups and independently through shared software or the Internet. Applications for the decision/management model include:

- Design of monitoring systems that aid in determining how, where, when, and frequency of sampling.

- Data interpretation, which identifies critical system sensitivity, improves understanding of key processes, and prioritizes future data gathering and research.
- Forecasting trends and their impact on the water system, including economic, political, climatic, and other changes.
- Resource management in which each party can explore alternative strategies for mitigating joint transboundary issues, understand and quantify the consequences of their decisions, communicate throughout the remediation strategy development process, and prioritize management projects.
- Public education.

Because a watershed is a constantly changing system, the monitoring and modeling must also be dynamic. As new data and understanding of the system become available, the parties must revise the model accordingly. Likewise, the model must reflect the positive and negative changes that occur within the basin.



## **3. Kura River Case Study**

To help convey the proposed methodology, this paper introduces a simple example applied to the Kura River in the Caucasus region of Central Asia. After presenting pertinent background information on the Caucasus region and the Kura River, this study proposes a baseline transboundary monitoring program. This is followed by the results of decision modeling used to assess the potential health, economic, and social impacts of untreated municipal sewage on downstream water users. This paper also describes the cooperative framework that would be used to develop and implement such a program.

### **3.1 Background on Caucasus**

#### **3.1.1 Political/Economic Situation**

The geographic province known as the Caucasus is a mountainous region that extends from the Black Sea in the west to the Caspian Sea in the east, and includes parts of Russia and three former Soviet republics – Georgia, Armenia, and Azerbaijan. For many centuries, the Caucasus region has been a place of tension and instability as a result of its strategically and economically important location, its rich natural resources, and its ethnically diverse population (Brawer 1994).

With the breakup of the Soviet Union in 1991, historical ethnic and territorial disputes emerged that had previously been held in check by rigid Soviet rule and control. Current examples of these trends include conflicts in Chechnya, Nagorno-Karabakh (Azerbaijan-Armenia), Ossetia, and Abkhazia (Georgia). These disputes account for the region's tremendous political instability. A significant number of refugees, at least 1.5 million, now exists in the region. Georgians, who were forced out of their homes in Abkhazia in the early and mid-1990s, want to return and reclaim their properties. Many Armenians and Azeris have long lived isolated in areas dominated by their rival group. The economic and psychological difficulties faced by refugees foster ethnic and religious hostilities and thwart regional security. This situation is exacerbated by an inadequate and often corrupt legal system, a thriving black market, routine smuggling throughout the region, and widespread cross-border crime.

The region also faces a severely depressed economic situation. The states of the Caucasus were dependent upon the Soviet Union both for raw materials and as a market for manufactured and processed goods. Since the breakup of the Soviet Union, industrial and agricultural productivity has declined as much as 80 and 50% respectively. Production of commercial and agricultural goods stands at an estimated 20 to 25% of calculated physical capacity (Ismailov and Akhoun-Zade 1997).

Current economic and political conditions along with the past policies of the Soviet Union have significantly affected the state of the region's environment. For example, the overwhelming majority of industrial and municipal sewage in the region is discharged directly to rivers and lakes without any treatment. As a result, limited water resources and freshwater contamination and pollution have become serious regional problems. Sixty-five percent of the region's major rivers are heavily polluted with hydrocarbons, solvents, metals, fertilizers, and pesticides. In

many cases, these pollutants are at concentrations in excess of 10 to 100 times international standards. Sixty percent of the land is subject to erosion due to poor land management practices, leading to sediment loads of 45 million tons per year. It is anticipated that all three countries will face a severe shortage of water resources within ten years.

The region's natural resources and geostrategic significance provide opportunities for economic growth and increased national wealth. It is estimated that up to 20% of the world's oil and natural gas reserves are located in the greater Caspian region, and these resources are just beginning to come on line. For this reason, the U.S. has backed a \$2.5 billion pipeline plan that will transport Caspian crude oil from Baku through Georgia to the Turkish Mediterranean port of Ceyhan by 2004. Notably, this pipeline will not pass through Armenia and thus will likely not provide any direct economic benefit to Armenians. The development of a proposed surface transport corridor between Europe and Asia through the Caucasus could also have positive economic consequences for the region. However, increased international capital investment and economic activity in the region could actually contribute to a further deterioration of the region's environment if remediation strategies are not implemented in a timely fashion (Bird and Salerno 2000).

### **3.1.2 Kura River**

The Kura River and its tributaries form the principal drainage feature in the Caucasus (Figure 2). Likewise, the Kura River is a critical source of water for irrigation, industrial processing and cooling, and municipal consumption. Contamination of this important watercourse is a recognized problem throughout the region.

The Kura River and its main tributary, the Araks River, drain much of Azerbaijan, Armenia, and Georgia, and parts of Russia, Turkey, and Iran. The Kura basin, encompassing an area of approximately 188,000 km<sup>2</sup>, originates in the mountains of eastern Turkey and flows approximately 1400 km to the Caspian Sea (UNEP 1996). The Araks River, which drains another approximately 102,000 km<sup>2</sup>, originates in Turkey and flows 1072 km before reaching the Kura (Kurkjian 1998). The average annual flow of the Kura River before it discharges into the Caspian Sea is approximately 29 km<sup>3</sup>/yr, while the Araks River contributes on average approximately 9 km<sup>3</sup>/yr (Ismailov and Akhoun-Zade 1997). Along their course, numerous dams regulate the flows and generate limited electric power.

The Kura River and its tributaries are the primary water source for eastern Georgia, southwestern Armenia, and all of Azerbaijan. Two of Georgia's largest cities, Tbilisi and Rustavi, along with all of Azerbaijan's metropolitan areas, rely on the Kura River for their water. In 1992, Azerbaijan alone abstracted 0.4 km<sup>3</sup> of water for municipal use, 3.3 km<sup>3</sup> for industrial use, and 9.7 km<sup>3</sup> for agricultural irrigation (Ismailov and Akhoun-Zade 1997).



**Figure 2. Map of the Caucasus region.**

Azerbaijan, as the easternmost country in the Kura-Araks basin, is the last to receive surface water from the river system. Only 30% of Azerbaijan’s surface water resources originate within its own boundaries. Consequently, Azerbaijan’s upstream neighbors influence the quantity and quality of the surface water in Azerbaijan.

The Kura River and its tributaries receive considerable contamination from human activities in and around its basin. Principal sources include direct discharge of raw industrial and municipal wastewater and agricultural return flows. Armenia, Azerbaijan, and Georgia are each responsible for the current problem. From 1992 through 1994, Georgia discharged over 3 km<sup>2</sup> of wastewater annually into the Kura basin, while chemical plants, tire manufacturing, thermo-electric facilities, and metallurgical facilities in Armenia contributed contamination to the Araks River. Similarly, Azerbaijan discharged 0.2 km<sup>3</sup> of untreated municipal sewage and 0.6 km<sup>3</sup> of industrial sewage to local surface water bodies annually from 1992 through 1993 (Ismailov and Akhoun-Zade 1997).

These practices have resulted in elevated levels of contamination in the Kura River and its tributaries. Average annual concentrations of key contaminants are routinely measured above international maximum contamination levels (MCLs). Problem contaminants include phenols at 13 to 20 times the MCL, oil products at 1.5 to 10 times MCL, ammonia-nitrogen at 4 to 7 times MCL, copper in excess of 220 times MCL, and zinc concentrations 65 times above the MCL (Ismailov and Akhoun-Zade 1997).

## **3.2 Example of Cooperative Monitoring and Modeling for the Kura River**

Currently, no treaties govern the quantity or quality of transboundary discharges of the Kura River. From the background information presented above, it is apparent that both the quality and quantity of international waters are potential points of tension for the nations of the Caucasus. Quantity is a concern for Azerbaijan since most of the country is arid and depends on inflow from transnational rivers for approximately 70% of its surface water resources. As economic conditions improve, water demands will increase. An even more daunting problem than water quantity is water quality. Economic policies and practices of the former Soviet Union have degraded the water well below international quality standards. Because contamination is a predominant regional concern, the monitoring and modeling example described here focuses on water quality issues.

### **3.2.1 Cooperative Workshops**

Since more research has focused on technical advances for decision tools and less on the implementation of these tools by resource managers, many water-related systems have not been adopted or used by managers (Langendorf 1985; Lovejoy et al. 1997; Zigurs et al. 1999). Therefore, a fundamental element for developing a successful decision-support tool is consideration of the stakeholders' requirements and perspectives. Specifically, donors, project facilitators, and riparian interests must understand both short- and long-term management needs and processes, as well as integrate the manner in which the information would be collected, distributed, interpreted, stored, and utilized. A particularly important goal must be the creation of a user-friendly interface and understandable output displays to ensure the usability of the decision tool. To sustain the monitoring and modeling effort over time, allowing for consistent remediation strategy implementation, all of the decision-makers and stakeholders must cooperatively develop and evaluate the project's methods and decision tools.

Cooperative workshops involving an interdisciplinary group of project scientists and relevant stakeholders would be a critical first step in establishing the cooperative monitoring and modeling framework. Stakeholders in the Kura basin would include concerned nongovernmental organizations representing cultural, environmental, economic, or international interests; scientists; and resource management and government officials. Representatives of the country or organization sponsoring and facilitating the cooperation would also be included. In the context of the workshop, these groups would work together to identify critical concerns and problems in the basin, understand currently available data and other resources, and select data monitoring and modeling technologies appropriate for the resource conditions and human concerns in the basin. In addition, workshops would be held to familiarize stakeholders with data collection and modeling technologies, assess the model's usefulness for stakeholder needs, and evaluate overall progress in the use of these systems. These workshops would be critical for ensuring the relevance of the monitoring and modeling system for the people living in the basin and making decisions regarding the basin's resources.

In other basins around the world, these small, focused, facilitated meetings have helped to identify strategies for ameliorating water-related tensions and have helped to prioritize resource allocation. In some basins, tensions are such that workshops could be held in neighboring countries, but in a parallel and coordinated manner, rather than as a single international gathering. This arrangement could be effective, occasionally leading to greater integration as trust builds, provided a neutral third party could coordinate activities and work toward common goals. These parallel meetings could lead to true international meetings.

Various tasks would be accomplished during the initial workshop(s). First, a PI would be identified for each principal party. Second, a work plan would be developed. The work plan would define project objectives, the work needed to accomplish those objectives, and a schedule for completion of the work. The work plan would also identify key governmental agencies with responsibility for environmental quality and define their role within the monitoring program. Third, a Sampling and Analysis Plan would be developed to provide information and guidance necessary to perform the monitoring program. This plan would function as an instruction manual on where and how to perform sample collection activities, sample equipment operations and procedures, sample handling, laboratory analysis, detection limits, sample preparation, and instrument procedures. Not only could the Sampling and Analysis Plan build a level of confidence in the project's scientific objectives such as consistency, quality control, methodology, accuracy, and precision, but it could also guide the participants and identify resources necessary for a cooperative project.

### **3.2.2 Cooperative Monitoring**

The most immediate problem for the Kura River and its drainage basin is contamination by human activities. The Kura River receives contamination from a multitude of sources; thus, an assessment of the river's health would require a broad spectrum of analysis. Here, we propose a theoretical monitoring program, based on the limited data presented above, in order to help establish the water quality of the Kura River basin.

Five broad water-quality metrics form the basis of testing: common ions, nutrients, metals, organics, and bacterial pathogens. Common ions include sodium, magnesium, calcium, potassium, chloride, sulfate, carbonate, bicarbonate, and fluoride. Common ions have their origin primarily in the natural weathering of rocks and soils, but their composition in rivers can be affected by many anthropogenic influences. Ultimately, common ion chemistry is important in understanding mineral phases, chemical complexes, and the fate and transport of many other water constituents, some of which might be deleterious to human systems.

Nutrients, such as nitrogen compounds, phosphorous compounds, and carbon, are also naturally occurring. However, river inflows containing agricultural fertilizers or municipal sewage can impact the delicate natural balance among these constituents. Metals such as lead, copper, zinc, selenium, mercury, and arsenic are added to river and stream waters most commonly by mining and industrial activities, and can be toxic to aquatic organisms and humans. Organics, which include pesticides, herbicides, and chlorinated compounds, are introduced through agricultural and industrial activities. Bacterial pathogens are some of the most immediately dangerous of all

the pollutants added to rivers and streams. Various bacteria along with giardia protozoans enter streams as part of untreated human and livestock sewage.

River water quality monitoring designed to address this full suite of parameters can be very laborious and costly. In the U.S., the analysis of one water sample for all the constituents listed above costs approximately \$1000, and it requires sophisticated laboratories and analytical instruments.

In addition to these specific analyses, basic water-quality data such as conductivity, total dissolved solids, dissolved oxygen, salinity, pH, redox, alkalinity, turbidity, and temperature must be acquired. Recent technological advances allow these parameters to be measured inexpensively, and in real time, with hand-held multisensors available from several manufacturers. These instruments can be deployed in open waters for either long- or short-term periods of monitoring. Short-term deployment implies a manual, drop-and-collect operation, while long-term deployment could include securing the instrument to a bridge or pier. These instruments can relay data by modem, cellular phone, or satellite, or they can log data for later downloading.

Another parameter—water quantity or discharge—must also be included since it influences water-quality data. Water-quality data often fluctuate with discharge, with constituents sometimes being diluted by higher flows or concentrated by lower flows. Ideally, water quantity measurements should be made at established gauging stations where the contour of the river bottom has been mapped and different river levels have been correlated empirically to different discharge volumes. The Soviet Union installed permanent stations like these throughout the Caucasus but those stations have fallen into disrepair. In the absence of established stations, hand-held river discharge instruments are available. Discharge data could be collected from boats, bridges, or by technicians wading across a river, using either traditional mechanical current meters, or new electronic instruments that employ Doppler technology.

A scheme for establishing consistent methodologies for the collection and analysis of water-quality data and optimizing the data value would be developed. First, laboratory analysis for either a subset of the categories named above, or for representative members of all the categories, would be accomplished on a periodic basis. Second, a prioritized set of samples would be collected at some shorter time interval. Sampling would focus on contaminants of immediate concern to stakeholders and compounds targeted as posing immediate health and environmental risks as determined from the initial stage of sampling. Third, basic water-quality data (conductivity, total dissolved solids, etc.) would be acquired so that correlations could be made between those data and the laboratory-based analyses. In this way, basic water-quality data can be used to indicate significant changes in contaminant loading and the overall health of the river.

For the initial sampling stage, a biased scheme could focus on specific sources of pollution and locations of particular international interest (i.e., borders). Collecting five to ten samples near the headwaters of the Kura and its major tributaries would give baseline understanding of the ambient conditions of the river. Other samples could be collected at international border crossings of the Kura and its tributaries. Specific locations could include the Kura border crossing between Georgia and Azerbaijan; the Iori River as it passes into Azerbaijan from Georgia; the Araks River as it passes from Armenia to Azerbaijan, Azerbaijan to Armenia, and then back to

Azerbaijan; the Oxucay from Armenia to Azerbaijan; and finally the Kura River as it discharges to the Caspian Sea. Sampling could also be conducted downstream of major metropolitan, industrial, and agricultural areas. These locations include downstream of Tbilisi, downstream from Yerevan on the Hrazdan River, downstream of the Mingachavir Reservoir, and just above the intake canal for Baku's public water system (near Sabirabad). The project stakeholders would participate in and approve the final selection of the sampling sites, satisfying all of their various concerns and political sensitivities. Additional sampling locations could be added after the first stages of sampling once the initial monitoring and modeling results provide insight into previously unknown details about the physical system.

The collection of water-quality and discharge data on a monthly basis is a standard environmental monitoring practice. However, new modeling approaches designed to predict changes in water quality as a result of atmospheric or anthropogenic effects require data at much more frequent intervals—either daily, or several times daily. This type of data collection could be achieved with instruments installed on bridge pilings or other permanent structures. Data could then be transmitted in near real time to central storage and processing locations, or they could be periodically uploaded by technicians who visit the field sites. These remote systems would allow collection of basic water-quality data, while traditional labor-intensive sample collection and laboratory analyses would be collected on much less frequent intervals.

### **3.2.3 Cooperative Modeling**

Developing a comprehensive model of the Kura River basin is beyond the scope of this paper and cannot be achieved without full participation of the Caucasus stakeholders. This section presents a simplified decision model that is based on limited contact with the riparians and a sparse data set. Engaging the local experts in every phase of the modeling process and acquiring a more comprehensive set of historical data would allow for the development of a much more accurate and coherent model than the conceptual one presented here.

The purpose in this case is not to present results of sophisticated quantitative modeling, but to demonstrate decision-support modeling in the context of a real problem. This exercise highlights key components of the process and important feedback loops among monitoring, modeling, and the cooperative process. Nevertheless, “back of the envelope” calculations, as performed here, are also an important resource in the initial stages of any monitoring and modeling program. These simple calculations are a valuable tool for quickly screening whether various issues and processes are relevant to the problem. This step helps to focus and guide efforts rather than allowing the process to become overwhelmed by details.

The decision model presented here investigates the consequences of raw sewage discharges to the Kura River. In particular, it explores the potential health effects borne by Azerbaijan citizens resulting from waste disposal practices in Tbilisi, a metropolitan area in Georgia that is approximately 55 km upstream of Azerbaijan. This issue was selected because significant quantities of untreated sewage are being discharged to the Kura River, posing a significant and direct health risk to the public. Also, the effects of fecal coliform bacteria (a key constituent of

raw sewage) on human health are relatively well understood. In addition to its risks to public health, the raw sewage imposes ecological and aesthetic impacts on the river.

As this test case is relatively simple, computations are accomplished solely with the aid of a spreadsheet. The systems-level model is comprised of three modules: a river hydrology module, a bacterial degradation module, and an exposure/cost module. The model only considers the section of the Kura River between Tbilisi and the Mingachavir Reservoir.

The hydrology module of the decision support model was used to estimate the rate of bacterial transport (i.e., flow velocity of the river) and dilution of the bacteria concentration by inflows to the river (i.e., change in the volumetric discharge with distance downstream from the source). A mean flow velocity was determined by using information on the mean annual flow rate (7.2 km<sup>3</sup>/yr at Tbilisi), low channel gradient (0.00225 m/m), and broad channel width (approximately 500 m). It was also assumed that the discharge could vary seasonally from 0.5 to 2.5 times the annual mean. Accordingly, it was estimated that the high flow velocity of the Kura River is approximately 25 km/day while the low flow rate is approximately 5 km/day. Inflows to the Kura were modeled along the reach of the river, including groundwater recharge (0.01 km<sup>3</sup>/yr /km of river) and discharge from the Chrami (1.8 km<sup>3</sup>/yr), Agstafachay (0.041 km<sup>3</sup>/yr), and Achindjanchay (0.16 km<sup>3</sup>/yr) Rivers.

Next, the bacterial degradation module was used to estimate bacteria decay downstream of the source. Bacteria are destroyed by self-purification processes, including starvation, consumption by predators, and other means of inactivation. The self-purification process can be described by following the simple mathematical relationship (Canter 1977)

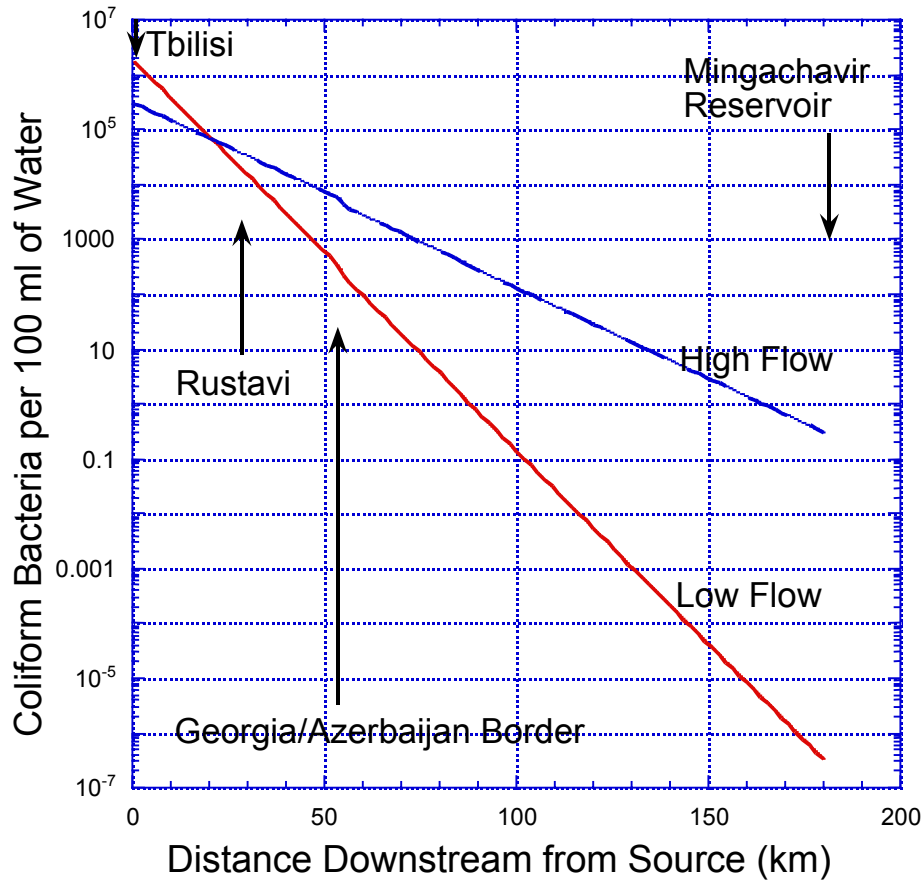
$$B_t = B_0 * 10^{-Kt}$$

where  $B_t$  is the bacterial residual after  $t$  days,  $B_0$  is the initial number of bacteria, and  $K$  is the bacterial death rate (day<sup>-1</sup>). The bacteria load  $B_0$  is a function of the number of people and how many coliform bacteria they produce.

On average,  $200 \times 10^9$  coliform bacteria are produced per capita per day (Velz 1970) and it is conservatively assumed that 50% of the Tbilisi population (approximately 600,000 people) is connected to a sewerage water system discharging untreated waste to the Kura River (nationally, only 13% of all domestic wastewater is treated). The bacterial decay rate,  $K$ , is reported to range from 0.35 to 0.65 for large rivers (Velz 1970) with the death rate increasing with rising ambient temperature. For purposes of these calculations,  $K=0.35$  is set for the winter low-flow months and  $K=0.65$  for the high-flow spring/early summer months.

The hydrology and bacterial degradation modules are used together to determine the bacteria concentration distribution downstream of the source. Specifically, the bacterial residue  $B_t$  calculated for a specific time  $t$  is related to downstream location by multiplying the stream flow velocity by  $t$ . Bacteria concentration is then determined from  $B_t$  and the change in the volumetric discharge (i.e., due to dilution).





**Figure 3. Bacterial concentration downstream of Tbilisi.**

Even this relatively simple model (subject to limited data) produced useful results. Specifically, bacterial contamination from Tbilisi poses relatively little threat to the health of Azeri citizens. The modeling results suggest a rapid decay in bacterial concentration downstream of Tbilisi (Figure 3). The decay in bacteria concentration is a function of both self-purification processes and dilution (discharge from tributaries that are assumed to be unpolluted).

By the time the sewage reaches the Azerbaijan border, bacterial concentrations have decayed to 4000 coliform bacteria/100 ml of water for high flow conditions and 200 coliform bacteria/100 ml of water for low flow conditions. As a point of reference, international standards place limits of 200 coliform bacteria/100 ml of water for discharges of treated municipal sewage to surface waters, while drinking water standards call for 0 coliform bacteria/100 ml of water (Gleick 1998, p. 216).

Finally, the exposure/cost module was used to assess the threat posed by bacteria contamination. First, an assessment of the threat in terms of potential health effects was considered. This required a calculation of the risk of infection due to exposure to bacteria-contaminated water. Risk of infection was determined by multiplying the morbidity rate (i.e., illness caused by ingestion of contaminated water), which rises with increasing coliform bacteria concentration, by the receptor population. The morbidity rate was extrapolated from Gleick (1998, p. 199), while

the receptor population was taken to include all residents living within 15 km of the river [taken from population density values in Brawer (1994)].

Next, the economic costs resulting from infection were calculated. The only cost considered was that caused by lost wages associated with illness. Costs were calculated by assuming each infected person lost two weeks of work a year because of a bacterial infection (i.e.,  $cost = infected\ persons \times per\ capita\ income \times 2/52$ ). Although other costs are involved (e.g., multiple infections in a year, health care costs), consideration of these costs in the calculations would not change the basic conclusions of the model.

Modeling results indicate that the cost of adverse health effects is borne primarily by Georgians living downstream of Tbilisi, particularly in the vicinity of Rustavi (Figure 4). The potential costs of Tbilisi's municipal sewage discharge exceed \$100,000 at Rustavi and fall below \$300 at the Azerbaijan border. The rapid decay in bacterial concentration coupled with the sparse population downstream of Rustavi causes this result. Thus, this simple calculation suggests a potentially important finding: Georgians will benefit most from any efforts they might undertake to improve the treatment of municipal sewage effluents.

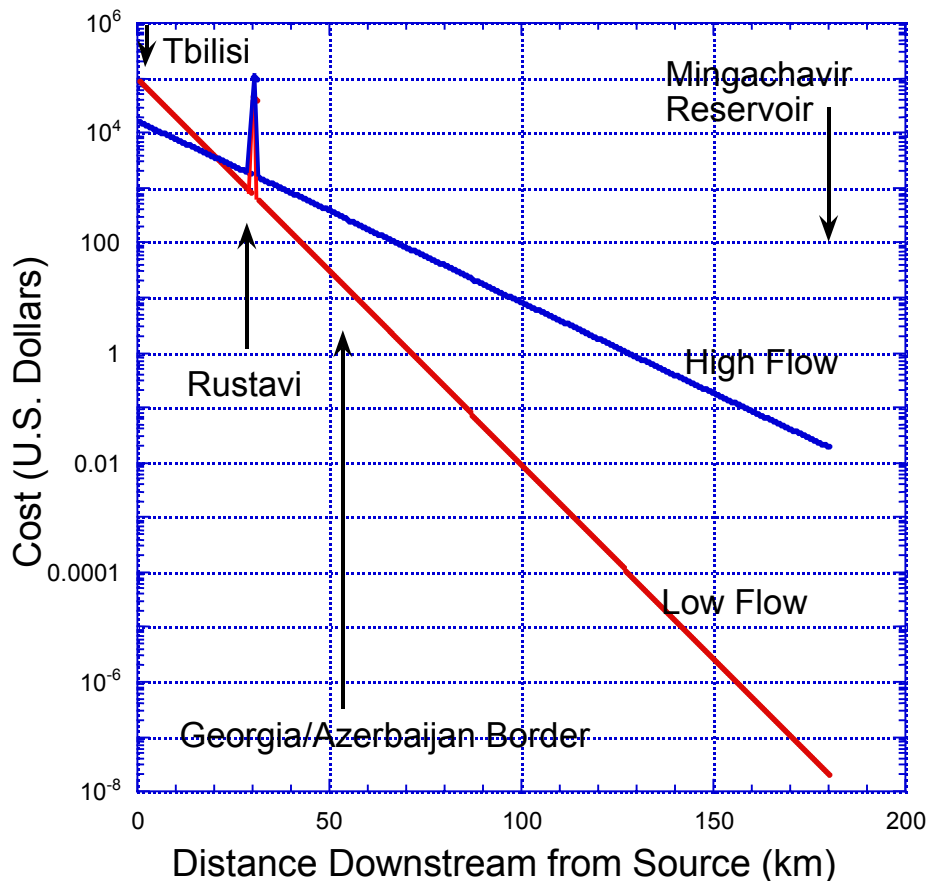
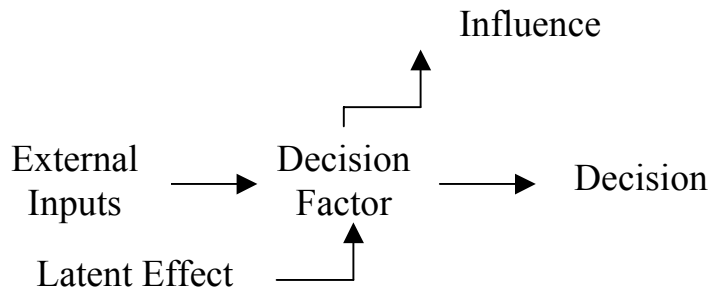


Figure 4. Costs posed by raw sewage discharges to the Kura River.

Further review of the results helps identify key system sensitivities. The parameters/processes to which the model is most sensitive represent areas where additional research and/or monitoring would be most beneficial. In this model, bacterial transport is sensitive to the contaminant load discharged to the river, the rate at which the bacteria are carried downstream, and the bacterial decay rate. These data needs can easily be met by making some basic changes to the monitoring program. For instance, the program could include a network of monitoring stations beginning at the contaminant source and extending downstream. Along with water quality and discharge measurements, flow velocity profiles could be measured. Analysis of the combined data package would help in determining the rate at which various contaminants decay, identifying possible mechanisms responsible for the decay, and estimating the role of dilution on contaminant concentration. Similar measurements would also be useful for modeling other contaminants that may pose a greater threat than coliform bacteria to downstream receptors.

Discharge of raw sewage to the Kura River also imposes social impacts. Associated costs are difficult to model using the traditional approaches demonstrated above. Accordingly, we employ soft mathematical aggregation to determine whether the sentiments of Azerbaijan and the international community toward Georgia’s sewage disposal practices could prompt Georgia to take remedial action.

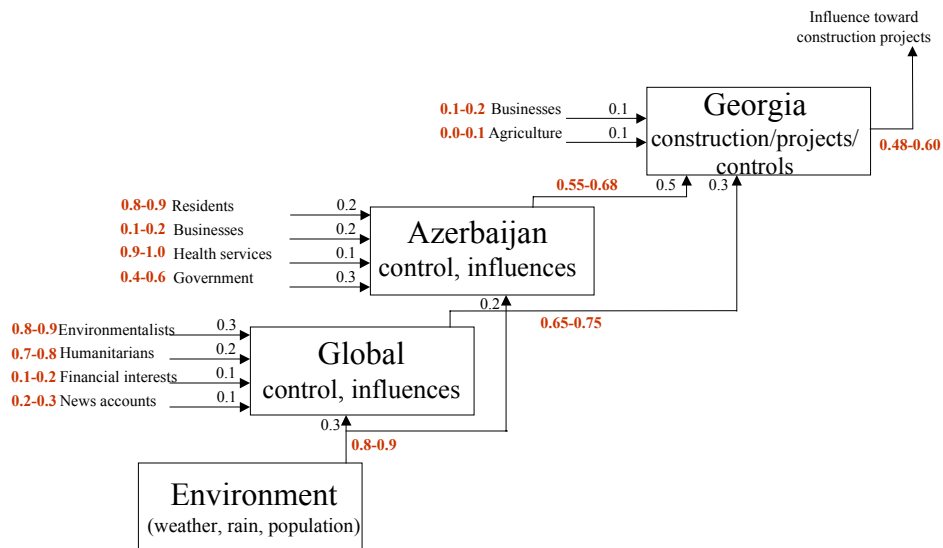
This analysis is initiated by developing a decision tree, which is comprised of a series of modules. Each module (Figure 5) represents a particular factor that influences the decision process (e.g., actions taken by Azerbaijan). In turn, each factor is influenced by a variety of external inputs (e.g., citizen protest) and latent effects (i.e., influence imposed by other factors or modules, such as environmental conditions). Each external input and latent effect is subjectively assigned an attribute value and weighting factor. The attribute values and weights are qualitative choices, mapped onto a scale of 0 (very weak influence) to 1 (very strong influence). The weighting factors reflect the ability of an attribute to influence the decision, while attribute values reflect the amount of pressure arising from each particular source. In the example, each attribute is assigned a range of values to reflect uncertainty. The output of each module is simply the computed weighted sums of the inputs.



**Figure 5. Basic subsystem module.**

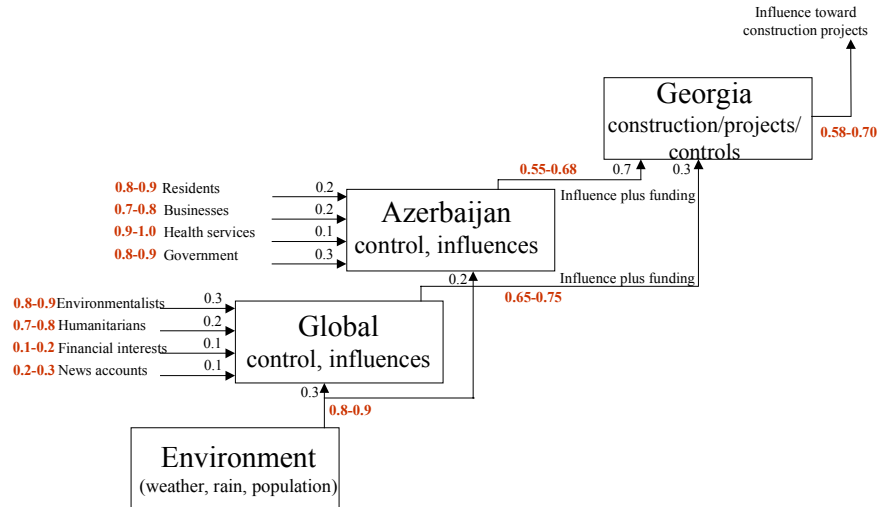
The decision tree comprises a number of subsystem modules interconnected in a selected architecture. The basic strategy is to begin with the module of the most long-range effects, which in this case would be the environment. The decision tree then moves systematically to global actions, local action taken by Azerbaijan, and actions taken by Georgia—the most short-term influence. The final outcome in this case is the implementation of construction projects by Georgia that are aimed at improving water quality.

In this example (Figure 6), the results indicate moderate but not overwhelming pressure on Georgia to improve its water quality. That is, the output values of 0.48 to 0.60 suggest that Georgia would be only slightly more likely to undertake wastewater treatment projects than not. Of course, accurate results depend on realistic subjective judgment, so it is important to utilize as much expertise as possible in determining attribute values and weights, as well as architecture. Nevertheless, the model provides a basis for discussing the factors that influence the decision and for exploring the views of various parties about what the weights and architecture should be.



**Figure 6. Influences on Georgia toward water-quality improvement.**

Such modeling could also be useful for evaluating alternative strategies for influencing Georgia to build treatment plants. As an example, the model considers the effects of increased Azerbaijan government and business activism, and the potential to use financial resources to supplement persuasion. This would intensify Azerbaijan’s influence on Georgia, as reflected in the model by increasing the latent effects weighting factor from 0.5 to 0.7 (Figure 7). The result indicates an improvement in the amount of influence that could be exerted (0.58–0.70), but not enough so that action by Georgia could be assured. This illustrates how difficult it is to make major changes in a system by changing only a few of a multitude of factors. However, one of the values of the model is that it provides guidance in determining the most potentially productive changes.



**Figure 7. Modified strategy for influencing Georgia toward water-quality improvement.**

This simple, “back of the envelope” model assesses the human health effects and social impacts related to the discharge of raw municipal sewage to the Kura River. Similar calculations could be performed for other contaminants of concern. Calculations could also assess other potentially important physical/chemical/biological processes, such as contaminant mixing/degradation in the Mingachavir Reservoir. These basic models help identify system sensitivities that require monitoring, support the design of the monitoring network, and help to focus decision-support modeling on the key issues. These models also lay the foundation for developing a common basis of understanding and remediation among the stakeholders.

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## 4. Summary

Worldwide there are thousands of rivers and groundwater aquifers that cross international borders. As the demand for fresh water increases, tension over shared resources will escalate. This study develops a framework for managing tension over transboundary water resources. It suggests a methodology that links resource monitoring with decision-support modeling, all applied within a framework of cooperation. Specifically, cooperative monitoring is the process of obtaining and sharing agreed-upon information among parties with the purpose of providing verifiable and secure data. Cooperative modeling is the process by which the parties jointly interpret the data, forecast future events and trends, and quantify cause-and-effect relationships. Together, cooperative monitoring and modeling enable the stakeholders to develop and implement sustainable remediation strategies.

The second part of this paper demonstrates how this methodology could be applied to the Kura River basin in the Caucasus region. Such a program would be initiated with workshops jointly attended by all parties. The workshops would be carefully structured to encourage the parties to work together to identify key issues, locate historical data, develop sampling plans, and formulate conceptual models of the basin. Each party would then be responsible for acquiring specific sets of data, which would then be shared among all the participants. Specific details concerning a plausible sampling program are given in the text. Concurrently, a resource management model would be developed for the basin. A simple example is provided that evaluates the human health effects and aesthetic impacts caused by the discharge of raw municipal sewage into the Kura River. Using the acquired data and resource management models, the parties could jointly evaluate and prioritize remedial actions that would benefit the region before conflicts escalate.

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