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GIS APPLICATION TO WATER QUALITY MANAGEMENT IN THE UPPER VOLGA RIVER BASIN: JOINT TVA/RUSSIA PROJECT

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ABSTRACT

The Water Problem Institute of the Russian Academy of Science and the Tennessee Valley Authority are participating in a joint project to demonstrate the use of geographic information systems (GIS) in managing water resources under the changing economic system in Russia. The purpose is to improve decisions by better organizing, analyzing, and presenting water resource data and management options. Results to date include development of a conceptual approach and review of existing data. The project area includes the Upper Volga River Basin which encompasses the Moscow metropolitan area. Data are being managed at three levels depending on the scale and detail (i.e., regional, watershed, and local). Initial conclusions indicate a great potential for this technology, but many obstacles due to the current economic situation.

KEYWORDS

Water; watershed management pollution control; nonpoint sources; geographic information system.

INTRODUCTION

Dramatic changes are occurring in Russian laws, property ownership, and economic incentives as the country moves from a centrally planned economy to a free market system. These changes have significant implications for water resource management. Likewise, water resources can either impede or facilitate the transition, depending on how they are managed. This critical period in Russian history increases the need to properly address existing problems and to implement effective technical, legal, and financial solutions.

To this end, the Water Problem Institute of the Russian Academy of Science and the Tennessee Valley Authority are participating in a joint project to demonstrate effective methods of integrated water management under the changing economic system. The project focuses on the Upper Volga River Basin with an ultimate goal of promoting economic development while maintaining or improving environmental protection of the river system. Specific purposes of the project are as follows:

Develop and demonstrate a decision support system for regional water resource planning and management, using GIS and mathematical models.

Establish a model water quality monitoring network and watershed database for the demonstration area.

Develop guidelines for legal requirements and socio-economic incentives to support integrated water resources planning and management.

Establish training and specialist exchange programs to transfer scientific results and promote improved methodologies.

This paper describes the scope of the first activity. It illustrates the type of data needed and how it will be organized to address typical management issues. The Upper Volga River Basin (figure 1) was selected because of its importance to the city of Moscow as a water supply source, because pollution loads and water quality problems are substantial in the region, and because a variety of data are available.

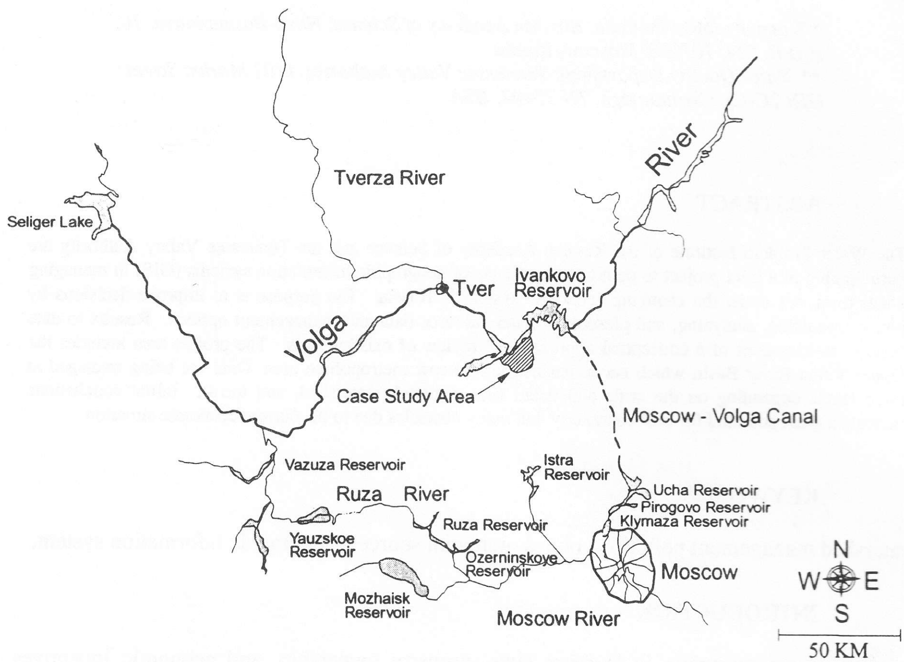

Fig. 1 Upper Volga River Basin.

APPROACH

The purpose of the proposed GIS is to improve decisions by better organizing, analyzing, and presenting water resource data and management options. The task is especially difficult in Russia because of economic and institutional changes and because existing data are dispersed, inconsistent, and usually stored in paper rather than computer files. Planning and proper design will be critical to success (Coffelt, 1991).

For the demonstration, data will be managed at three levels of resolution, depending on the aerial extent, detail, and type of decisions to be supported. Level I will contain basic information for a large region (e.g., the Upper Volga River Basin). Level II involves more specific information for a particular resource management issue within the region (e.g., water quality management for Ivankovo Reservoir). Level III focuses on detailed information about individual problems, causes, and solutions for a small area (e.g., nonpoint source controls for tributary watersheds of Ivankovo Reservoir). There will be an interface between levels such that coarser information will be available to, and can be refined by, the more detailed levels (e.g., Level I information will be common to and eventually replaced by information in Levels II and III). These different levels offer flexibility to deal with multiple objectives, analytical methods, and types of data, while avoiding the danger and expense of covering the entire region with information sufficient for the most exhaustive applications.

Level I would typically cover several hundred thousand km^2, with GIS map scales of 1:1,000,000 or more. A graphic data file would include basic regional information such as rivers, reservoirs, cities, water intakes, and wastewater discharges. A tabular database would include physical characteristics such as stream flows, reservoir capacities, water demands, and major pollution loads. Information at this level would support decisions concerning regional priorities for water allocation, pollution control, and new projects. Analytical procedures might focus on reservoir operations, network river flow routing models, or optimization of wastewater treatment expenditures.

Level II may cover an area of several thousand km^2, with map scales of 1:100,000 to 1:1,000,000. Graphic data include major land uses, soils, and topographic and cultural features. Tabular data include water quality conditions, point and nonpoint source pollution loads, and physical characteristics by subwatersheds. The information may be used to identify priority areas, assess cumulative impacts, evaluate alternative solutions strategies, and formulate management programs. Spatial analyses and simulation models may be used in making these determinations.

Level III provides the most detailed information and might cover areas of less than one thousand km^2. The graphic file would include detailed land use and physical characteristics such as the location of livestock operations, wetlands, groundwater wells, or eroding fields. Attributes of these components, such as area, pollution load, well yield, or erosion rate, would be contained in the tabular database. Parameters would typically be studied on an annual or seasonal basis. Statistical analyses might be used to analyze water quality impacts. Simulation models might examine the transport and fate of pollutants or the optimization of control measures. The data and results would be used to determine the cause of specific problems, evaluate alternative solutions, and target individual sites for corrective action.

The following sections illustrate the type of information and analyses that would be used at each level to support management decisions in the case study area.

LEVEL I - REGIONAL DATA AND ANALYSES

The Level I demonstration area includes the Moscow River basin and that portion of the Volga River upstream of the Moscow-Volga canal (figure 1). The region has an area of approximately 75,000 km^2 and a population of almost 15 million. Elevations range from 120 to 310 m. Average monthly temperatures vary from -10 degrees Centigrade in January to 19 degrees in July. Precipitation is greatest in the summer with an annual average of 614 mm and a typical range of 595 to 721 mm. Average annual evapotranspiration is 474 mm, and average annual runoff is 140 mm.

The system of reservoirs shown in figure 1 is vitally important to the region, providing hydropower, navigation, flood protection, recreation, and water supply benefits. Demands on the reservoirs are taxing their capacity. For example, about 74 m^3/s of the water supply demand for Moscow is provided by waters withdrawn from the Moscow River and the Moscow-Volga canal. Minimum flows in these waterways are 51 and 82 m^3/s, respectively, at a 95 percent probability. Wastewater discharges from the Moscow metropolitan area to the Moscow River are 58 m^3/s and are included in the minimum river flow (table 1).

Table 1 Water Supply Capacities and Wastewater Discharges in the Moscow Region (cubic meters per second)

Water Sources	Capacity, 95% probability	Water Withdrawal		
		Moscow	Upper Cities	Total
Volga Canal	82	37	3	40
Moscow Basin	51	37		37
Groundwater	95	14	53	67
Totals	228	88	56	144

Receiving Water	Mean Flow	Wastewater Discharges
Volga River upstream of Tver	295	7
Volga Canal	82*	28
Moscow River/Other Tributaries	51	105
Total	346	140

*Diverted from and included in mean flow for Volga River.

A complex system of reservoir operating procedures is required to meet the Moscow demand for water supply and minimum flow for waste assimilation. The water supply system depends on withdrawals from the Volga River and its tributary reservoirs by means of flow regulation. The Upper Volga branch of the system consists of Ivankovo Reservoir and the 80 km Moscow-Volga navigation canal. The latter has five pumping stations (lifting water up to 38 m) and several small reservoirs for sedimentation and water storage.

The Moscow Basin includes the Moscow, Istra, and Ruza Rivers. Five reservoirs provide storage capacity for water supply and other uses (figure 1). The Vazuza Reservoir and canal were constructed to divert water from the Upper Volga River to the Ruza River. About 19 m^3/s are diverted to Moscow through this system to avoid pollution associated with industrial areas near Tver.

Pollution control is a major need in the region. Surface water resources are subject to intense pollution. The total discharge of sewage from all sources is equal to approximately 140 m^3/s. The municipal discharge of sewage is about 60 m^3/s with approximately 80 percent receiving biological treatment and the rest on primary treatment systems.

Groundwater aquifers also require protection. In the Moscow area, for example, groundwater pollution has been observed at depths of 200-250 meters. Sewage discharge areas, such as the Luberezkoe irrigation field, have produced concentrations of NO_3-N up to 100-110 mg/l over a 15 km^2 area.

Water quality management in the region has focused primarily on abatement of point sources of pollution. Nonpoint sources are a growing concern, especially in the upper reaches of the river system where the water supply reservoirs are located. As agricultural production shifts from state farming to the private sector, drastic land use changes could increase water quality degradation. The proposed project will demonstrate tools for evaluating these problems.

Mathematical models will be used to simulate reservoir system operation, alternative pollution control strategies, and various water supply options. Simulations will be designed to provide information to decision makers, regulators, and private operators on the consequences of alternative actions. The GIS will integrate information such as natural resources, physical characteristics, demographics, and environmental conditions. Using the GIS, planners will compile data from maps, monitoring, remote sensing, and field notes into a consistent, interpretable base of information. The regional data and GIS will allow spatial analyses and visual communications to the public and key decision makers.

LEVEL II - WATERSHED DATA AND ANALYSES

The Level II demonstration area is the 41,000 km^2 watershed of Ivankovo Reservoir (figure 1). This reservoir which was created in 1937 is heavily used for recreation and supplies over half of the municipal water needs of Moscow. Average inflow to the reservoir is 9.3 km^3/yr with approximately 2.5 km^3/yr released down the Moscow-Volga canal. The reservoir is a typical shallow lake with a surface area of 327 km^2. The maximum lower level during the April flood period is 124.0 m and the average seasonal fluctuation is about 3.0 m. Before construction of the dam, seasonal water levels could fluctuate as much as 12 m.

Reservoir water quality is an important management concern because of color, taste, and odor impacts to the Moscow water supply. Land management practices and nonpoint sources of pollution are the primary cause. During the last decade, the reservoir experienced an 8-10 fold increase in algal concentrations. This is believed to be due to increased and inefficient use of fertilizer. Average grain yields are low (1.2 t/ha in 1987) and do not correspond to the high fertilizer rates. Only 30 kg of nitrogen are consumed by grain crops per ton of grain yield. The rest is available to be leached from the soil. Livestock manure application rates are often 800 kg/ha of nitrogen, which exceed the recommended rates of not more than 300 kg/ha.

Land use and land management data will be used in the Level II analyses to deal with the water quality problems of Ivankovo Reservoir. The GIS will initially contain information on the attributes of the area (e.g., topography and soils) and the network of streams (e.g., lengths, drainage areas, segments not meeting standards). As additional data are collected, from satellite imagery for example, land use classifications will be added to the demonstration GIS.

Table 2 Pollutant Inflows to Ivankovo Reservoir from Point and Nonpoint Sources (Gordin *et al.*, 1990)

	Nitrogen*				Phosphorus*			
Indices	1	2	3	4	1	2	3	4
Point sources, metric tons/yr	437	437	437	437	82	82	82	82
Nonpoint sources metric tons/yr	1294	5148	4310	2802	86	686	555	321
Ratio of nonpoint to point loads	3.0	11.8	9.9	6.4	1.1	8.4	6.8	3.9
Observed conc. mg/L	1.81	1.71	1.00	1.11	0.18	0.17	0.16	0.13
Estimated conc. mg/L	1.81	1.64	2.52	2.24	0.18	0.22	0.33	0.27
Ratio of observed to estimated	1	1.04	0.40	0.50	1	0.85	0.48	0.48

*1-winter, 2-spring, 3-summer, 4-fall

At this level of detail it is not possible to identify individual nonpoint sources of pollution or to consider physical processes of pollution generation and transport. It is possible, however, to examine basic elements of the problem such as seasonal dynamics and the relative contribution of point and nonpoint sources. Table

2 shows the typical seasonal variations in inflow loads to Ivankovo Reservoir from point and nonpoint sources.

The ratio of observed to estimated concentration reflects the assimilative capacity of the reservoir and transport losses within the watershed. In the summer and fall, for example, a major portion of the pollution load is assimilated by algae and macrophytes (i.e., 6,000 tons of nitrogen and 700 tons of phosphorus).

LEVEL III - SUBWATERSHED DATA AND ANALYSES

The Level III demonstration site covers a 337 km^2 drainage area on the south bank of Ivankovo Reservoir (figure 2). At this level, detailed information on individual problems (e.g., individual wastewater dischargers) can be collected and analyzed. Sources of information include topographic maps, aerial inventories of land use, detailed soils and geologic maps, and field surveys. Analytical results not only help solve local problems, but also provide an understanding of cause and effect relationships that can be applied in other areas.

The demonstration area includes two small tributaries to the reservoir (the Suchock and the Doybiza). The landscape is typical of the Russian plain with mixed deciduous conifer forests, temperate climate, diverse soils and vegetation, and intense human impacts to the natural resources.

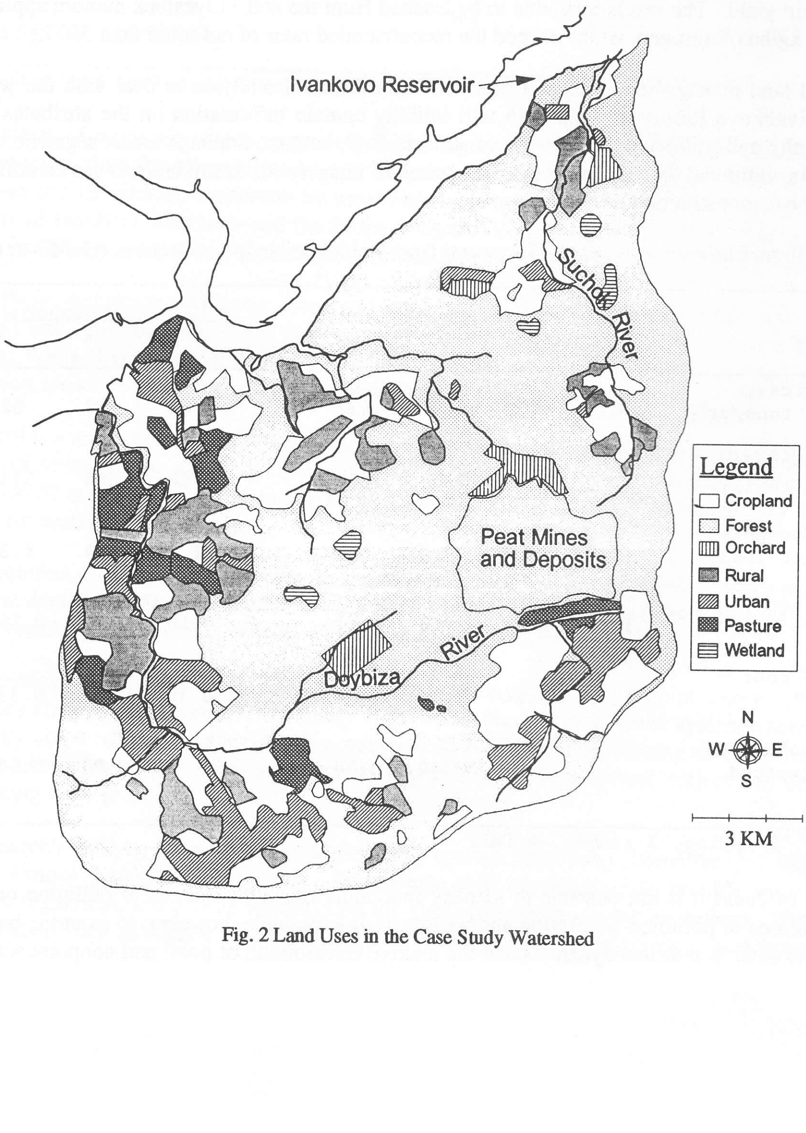

Fig. 2 Land Uses in the Case Study Watershed

Economic activities in the watershed include livestock operations, crop production, open peat mines, drained lands, industrial enterprises, urban and rural development, seasonal gardening, and tourism. Heavy pollution loads from these activities cause eutrophication and water quality degradation in the reservoir. As indicated above, fertilizer application rates are high (150-300 kg/ha). Field data show nutrient concentrations as much as 17 times higher for cropland than for natural soils.

During the spring snow melt period, surface runoff samples show maximum concentrations of nitrates of 6 mg/l from fertilized cropland and 1 mg/l from unfertilized pasture and hay lands. During the remainder of the year, the values are 1 and 0.2 mg/l, respectively. Surface and subsurface runoff result in reservoir nitrate concentrations of up to 2.2 mg/l. The $N\text{-}NO_3$ concentrations stabilize at 0.8-1.0 mg/l during the winter, and 0.4-0.5 mg/l during the summer.

Groundwater inflow is also a problem in the Ivankovo Reservoir watershed. Groundwater in the lowlands adjacent to the reservoir is close to the surface. Seasonal fluctuations of 0.5 to 3 m cause nutrient flushing from the soil root zone. On the higher plains the average depth is more than 3 m. Seasonal fluctuations are 0.8 to 1.0 m and soil leaching is much slower. Groundwater inflow to Ivankovo Reservoir is estimated to be 142,000 m^3/d or 1.64 m^3/s. Monitoring data are very scarce for nonpoint source pollution in the area and chemical export to the reservoir by surface and subsurface inflow. Some samples of groundwater in heavily fertilized lowlands show nitrogen concentrations from 35 to 100 mg/l. This is much higher than the average groundwater concentration of 0.5 mg/l. Average $N\text{-}NO_3$ concentrations in groundwater inflows to Ivankovo Reservoir are 2 to 8 mg/l.

This type of specific watershed problem illustrates the need for improved data collection, storage, and analytical capabilities. Long-term data for the case study watershed were either not collected or, if collected, are not readily available for other applications. Current studies are just beginning to process and store information for multiple users and GIS applications. The potential for GIS ranges from quantifying basic descriptive statistics for individual variables to understanding complex relationships among landscape, hydrological features, and human activities that influence watershed pollution (Belyaeva, 1989). By examining the water quality problems of Ivankovo Reservoir, this project will demonstrate GIS applications for managing data in attribute files. Examples of the type of information are as follows:

1. General physical characteristics.
2. Soil properties.
3. Natural vegetative cover.
4. Geological data on groundwater aquifers.
5. Land uses and major point sources of pollution.
6. Basic surface and subsurface flow parameters.
7. Pollutant loads by source and area.
8. Stream uses and impacts.

The information will assist in identifying problems, relating cause and effect, and targeting corrective actions. A variety of analyses and output products can be produced to show the results of alternative management strategies and control practices. Depending on the availability of data, simulation of nonpoint source processes may be undertaken for the case study watershed.

Sound resource management requires a methodology that integrates both technical and economic considerations. The state-of-the-art in aquatic and terrestrial ecosystem modeling makes it possible to consider a variety of biological and chemical processes in detail (Vachaud *et al.*, 1990). However, mechanistic models do not generally provide the complete results necessary for decision making. There is a growing demand, especially in Russia at this time, to meet both environmental and economic objectives. This project will demonstrate a decision support system that facilitates the move to greater economic productivity while maintaining and improving environmental quality. This will be accomplished through GIS applications and improved data analyses.

For example, one analysis might consider the impact of water quality and aquatic habitat on ecosystem stability, community dynamics, and habitat interactions. In this area a combination of GIS and simulation modeling could be useful (Walker, 1989). There are a variety of models for assessment of chemical exports from heterogenous agricultural watersheds (Beasley *et al.*, 1980; Knisel, 1980; Novotny, 1986; Haith, 1987; DeCoursey, 1990). These models are sensitive to climatic, hydrological, and soil and vegetation changes. An aggregation of input data would be reasonable with regard to both accuracy and availability.

An assessment of pollution sources, total nutrient export, and aquatic impact could be undertaken after a model analysis of several interrelated problems:

> An assessment of surface and subsurface inflows from uniform watershed areas depending on climatic conditions and land use patterns.
>
> An assessment of unit loads of nutrients for uniform cropland areas with regard to natural and economic conditions of land resource use.
>
> An assessment of total nutrient exports for large heterogeneous areas taking into account alternative land uses, climatic scenarios, management strategies, and economic and environmental constraints.

Empirical analyses and simplifications could be introduced to account for data shortages, complexities in soil/crop/water interactions, and the effects associated with uncertainty and sensitivity to input variables. A set of equations can be used to describe major functional links. Input parameters are available from standard data sources (climatic, hydrological, topographic, soil property, and other data used for water resource planning, design, and operation). Special procedures can be developed for simulating stages or constituents for which input data are not available from the GIS database.

SUMMARY AND CONCLUSIONS

Dramatic changes are occurring in Russia. These changes create both a necessity and an opportunity for improved resource management. Geographic information capabilities and conventional methods of data analysis can assist in protecting environmental quality while improving economic conditions. A joint project between the Tennessee Valley Authority and the Water Problem Institute of the Russian Academy of Science is planned to demonstrate these technologies. A decision support system will be tested for three levels of water problem analysis: regional, basin, and watershed. Specific problems, data sources, and methods of analysis will be examined at each level. The results are expected to improve resource management capabilities and technology transfer between the two countries. The demonstration will contribute to better solutions to environmental management issues during the transition period and will help to integrate the efforts of related agencies.

The Moscow region provides the following opportunities for meeting project objectives:

1. The political and social significance of the area lends itself to successful dissemination of the project results.

2. High population density, agricultural and industrial development create numerous environmental problems requiring extraordinary measures of control and external sources of funds under the current economic crisis.

3. Water resources in the area have a high value. Improvements have significant water supply and other benefits for the Moscow metropolitan area.

4. Water quality problems are closely related to land use since 90 percent of the Moscow water supply is withdrawn from surface reservoirs that are experiencing increased loads of point and nonpoint source pollution.

5. Compared with other parts of the country, this area is experiencing rapid development of new democratic institutions and businesses, including environmental consulting. Numerous new usinesses are being created from former governmental agencies and research facilities. These rely on qualified personnel, but lack equipment, software, and capital. The situation is favorable for demonstration of improved, more economical approaches.

6. Drastic land use changes are occurring with the recent adoption of new legislation governing land ownership and summer vacation gardens. The private ownership increases the value of GIS technologies in data management, land taxation, and associate environmental controls.

7. The availability of data and qualified personnel provide the opportunity to achieve both the research and educational goals of the project.

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