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PREFACE

IIASA's history of research accomplishments is recorded in a wide variety of research publications, correspondence files, annual reports, books and working papers. Especially in the area of water resources research, which has spanned the entire 15-year history of IIASA, this amounts to a sizable number of papers stored or stacked in a wide variety of places inside and outside of IIASA's home, Schloss Laxenburg. For some time I have thought it would be useful to have a summary report available to those who come to IIASA not knowing this history of experiences and accomplishments. Hence some months ago I asked Janusz Kindler, whose tenure of leadership of the water resources area was the longest of anyone to date, to undertake the writing of such a summary history. He subsequently asked Pete Loucks, who has observed what has been happening at IIASA since 1974, to help, and together they have prepared what is contained in the pages that follow.

Any recording of history is merely a perception. It could well be that the perception of what took place over these past 15 years, as summarized in this document, may contain errors or omissions. We hope everyone associated with IIASA's water resources research programs will send to the authors any comments they think would add to the completeness and accuracy of this record.

R.E. Munn
Head
Environment Program

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Water Resources Research at IIASA: 1973–1988

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Introduction

The International Institute for Applied Systems Analysis, IIASA, is a non-governmental interdisciplinary research institute. It is located in a reconstructed castle, Schloss Laxenburg, just 15 km south of Vienna, Austria. Scientists at the Institute typically come for one- to three- year durations to work on economic, environmental, social and technical problems common to many countries in the East and West, regardless of their economic or political systems. IIASA has no permanent scientific or senior management staff.

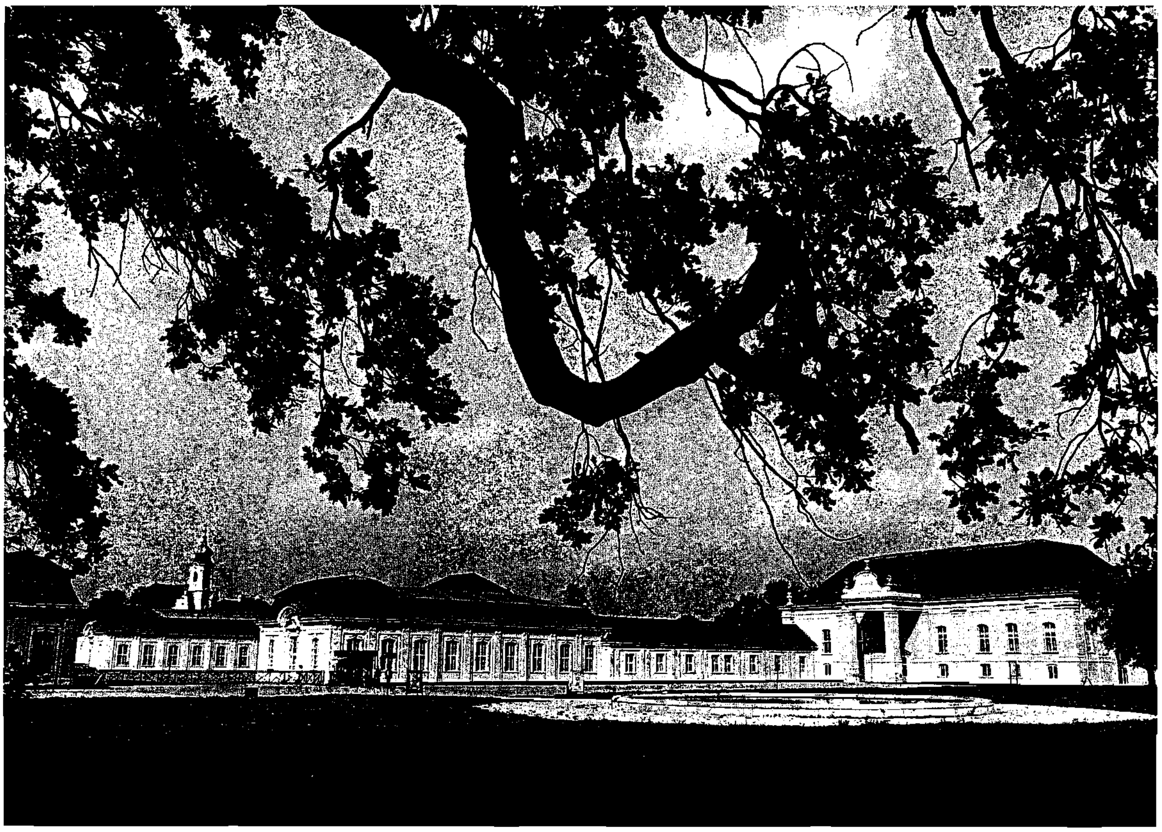
From its founding in October, 1972, IIASA has had an active research program in numerous subject areas. Water resources has been one of these subject areas. Unlike many areas, that after a number of years are replaced by different areas, there has been an active research program in water resources throughout the entire life of the Institute. Within this program, numerous projects have been initiated and completed. This paper attempts to describe many of these projects and, where possible, speculate on the impact that this research has had in the practice of water resources planning, management and policy making.

Due to the transient nature of the research scientists at IIASA, and the continuing collaborating relationship often developed between IIASA and other research institutions throughout the world, there is now a network of over 80 scientists in the East and West who know each other and who have, to a greater or lesser extent, worked together and participated in one or more water resources research activities at IIASA. The total number of scientists collaborating with IIASA, and who have participated in one or more of IIASA's water resources workshops or conferences, exceeds 250. Over 220 documents (books, journal articles, working papers, etc.) have been published reporting on the results of IIASA's research in water resources over these past 15 years. Some of these are listed at the end of this paper.

Front of Schloss Laxenburg, the home of IIASA

IIASA officially initiated its water resources research program some eight months after its birth. The founders of IIASA recognized that improvements in water resources management are essential to successful sustained regional development and the quality of human life. They also believed that a systems approach could aid those involved in water resources development, planning and management.

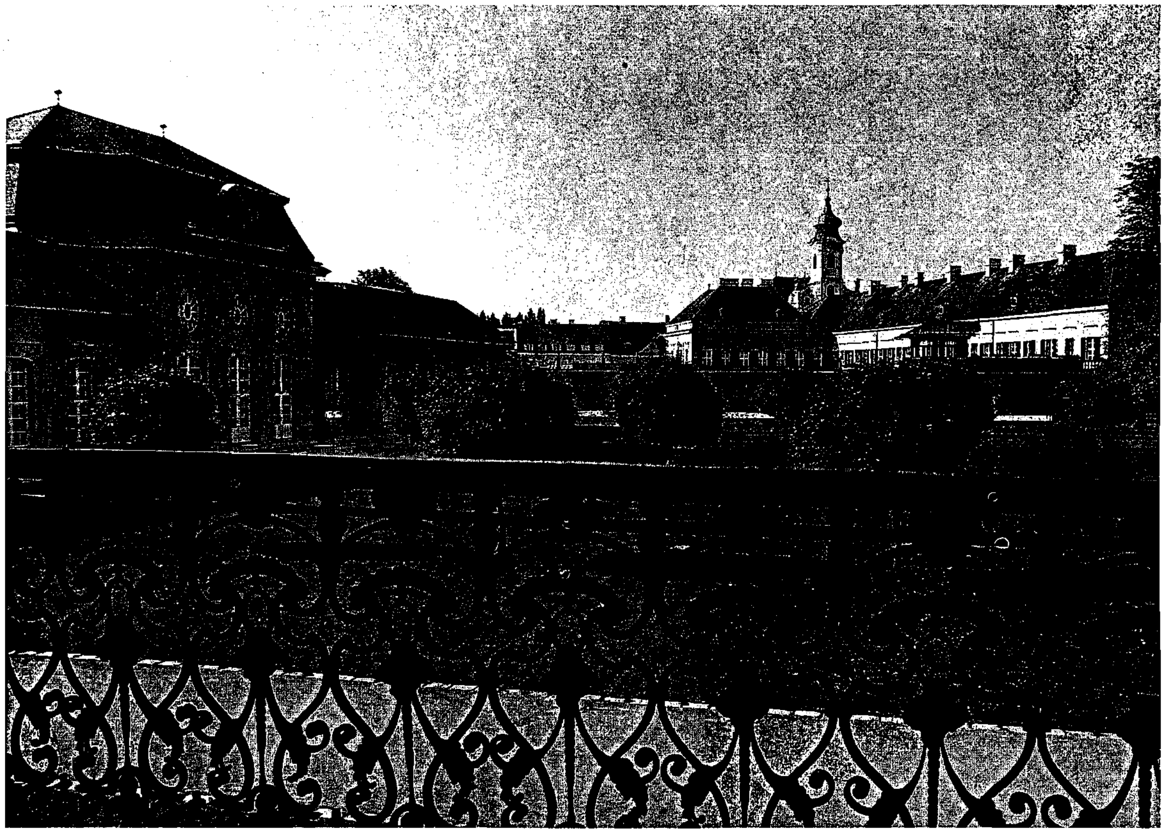
The first water resources project, and almost all of the projects that have followed, had a regional character. The prospects of severe regional water shortages, localized flooding, or water supply contamination in the face of abundant global supplies of sufficient quality, underline the regional nature of water resources management. There is no world water economy. Except in very severe droughts, as in parts of Africa recently, it is rarely even meaningful to speak of a national water emergency. Regional development adapts to the water that is available or that can be made available. It also adapts to some extent to the reliability of that supply. Within regional hydrologic, economic or political jurisdictions, a balance is created between supply and demand and between



View of Schloss of Laxenburg from adjacent park

wastewater generation and discharge and water quality protection. But due to the uncertainty and variability of both supply and demand, for both quantity and quality, this balance is often changing. The resulting problems vary in scope and scale. The size of the region appropriate for the study of various management problems may vary from small watersheds within a single political jurisdiction to large watersheds encompassing several countries. Throughout IIASA's research in water resources, various sized regions have been selected as research "laboratories" to test and evaluate the research results. Most of the water resources studies have been done in close collaboration with regional, national and international institutions concerned with the particular issues being investigated.

The water resources research projects undertaken at IIASA can be grouped into a number of broad areas. These areas will be identified and discussed in the following sections. It is also interesting to review the chronological succession of projects that have been undertaken over the 15-year period. Occasionally, a new project appears to be very similar to an older one, but of course the scientists involved are different and some of their approaches or tools are different. The discussion that follows will attempt to review

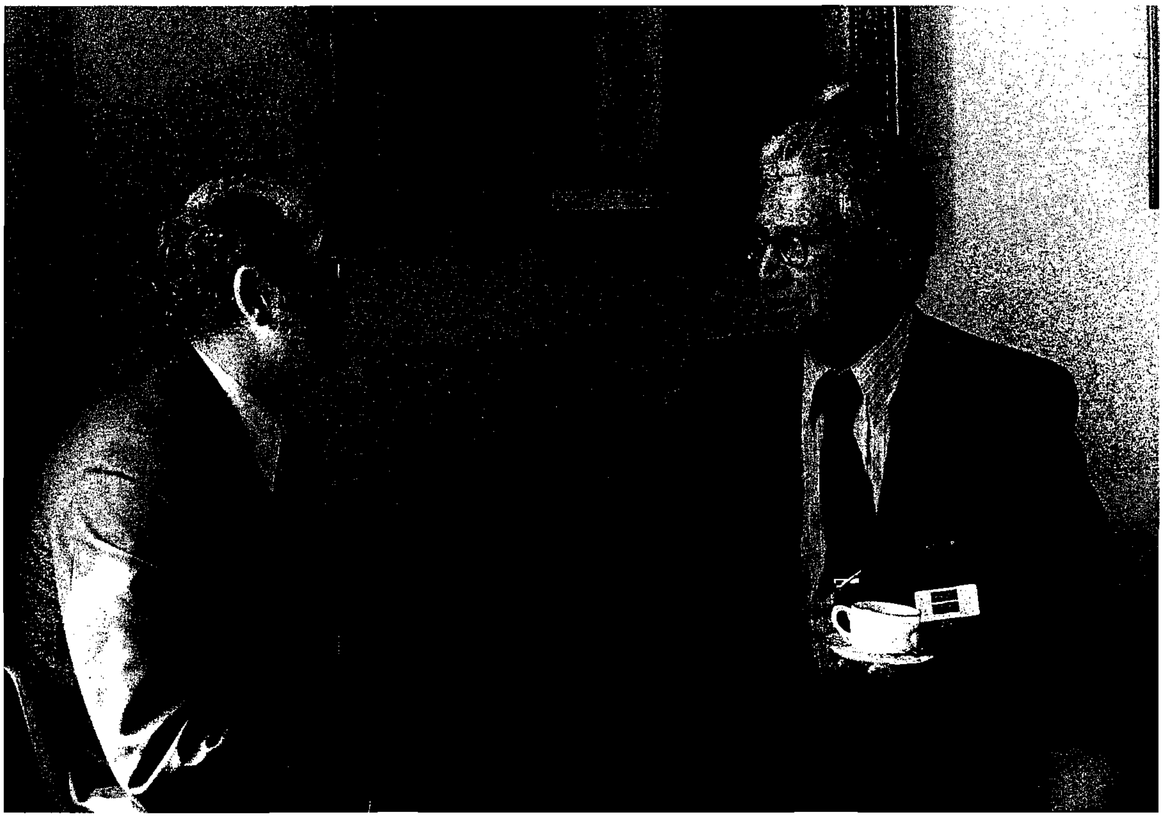


One of the interior courtyards of Schloss Laxenburg

projects within these broad areas as well as provide a chronology of what has happened over these past 15 years.

The Beginning: Some Case Studies in Planning

Professor A. Letov (USSR) was appointed the first Deputy Director of IIASA and the first leader of the "Water Resources Project". He and his colleagues identified two main research themes reflecting the common concerns of many in the water resources research systems community at the time. One theme focused on the planning of large-scale water resource development and the complex interaction between the physical, economic, legal and political systems which affect such development. Little did anyone realize then how complex these interactions really are, and what difficulties this "new" systems methodology would encounter when applied to these very complex technical and social problems. The other research theme focused on the methodology itself (Rozanov, 1973a,b; Lotov and Rozanov, 1974). Research on methodology was, and remains, the easier of the two themes identified in 1973, but what is not so easy, and what has always been stressed, is the implementation and evaluation of that methodology.



Professor Howard Raiffa, the first Director of IIASA, and Professor A. Letov (right), the first Deputy Director and Leader of the first Water Resources Project

On 29 September 1974, IIASA's first leader of the water resources program died. The Institute was less than a year old.

In November, 1974, Professor Z. Kaczmarek from Poland became IIASA's second leader of the water resources group. Under his leadership the area grew in both the number of scientists working at IIASA and the number of outside scientists collaborating with IIASA scientists. Close in-house collaboration was established with the Methodology Group led by Professor G. Dantzig and later by Professor T. Koopmans.

Research began on hydrologic and water quality models and on optimization techniques as applied in analysis of water resources systems. At the same time several cooperative studies were initiated on "real world" problems, notably with the Soviet, Polish and Hungarian water resources authorities.

It was recognized that over the previous ten years the construction of empirical stochastic models for the analysis and generation of rainfall and streamflow events has been immense. Some models had been formulated on a purely statistical basis using only the

Dr. J. Kindler, Professors Z. Kaczmarek and O. Vasiliev leaders of the water resources activities during much of the 1970's

observed rainfall or discharge records, while others tried to incorporate a physical understanding of the hydrologic processes as well as a statistical basis. Because of the complexity of the hydrologic processes and the relative scarcity of the data, it was not clear which models did and which did not perform well. Thus, an intercomparative study on stochastic models was carried out, culminating in the International Workshop on *Stochastic Models in Water Resources* held at Laxenburg in February, 1976.

Related studies were concerned with flood frequency model uncertainty (e.g. Wood, 1974a), application of reliability analysis to flood levee design (Wood, 1975), uncertainty in rainfall-runoff models (Wood, 1974b), hydrodynamic aspects of determining levee height (Koryavov, 1975) and optimal prediction scheme for multiple input-multiple output hydrologic models (Szöllösi-Nagy, 1975).

IIASA's research accomplishments included the development of new prediction algorithms for real-time forecasts of hydrologic time series and a survey of techniques applicable to the adaptive real-time control of water resource systems. This work culminated in a workshop organized in 1976, jointly sponsored with the World Meteorological Organization (WMO), and a book entitled *Real Time Forecasting/Control of Water Resource Systems* (Wood and Szöllösi-Nagy 1980).

In recognition of the basic importance of the storage problems, work began on further development of stochastic storage theory (Rozanov, 1974; Kaczmarek, 1975; Anis and Lloyd 1975a,b). This work continued until 1977 (Lloyd 1977; Anis and Lloyd 1977). Related work focused on operation of water resources systems under water shortage (Rozanov 1974), statistical equilibrium of processes in dam storage (Rozanov 1975a) and optimal control of storage reservoirs (Gouevsky 1974, 1975; Rozanov 1975b; Gouevsky and Popchev 1975).

The cooperative studies focused especially on the Vistula River in Poland and Tisza River in Hungary (a tributary of the Danube which is now being used as a case study for the current research at IIASA). These studies culminated in an international workshop held in 1975 (Szöllösi-Nagy, 1976). They have provided an excellent framework for review of recent methodological developments in river basin planning and management.

Within the framework of cooperative studies work also began on multiple objective analysis with special attention given to the multiattribute utility theory (Gros and Ostrom, 1975; Ostrom and Gros, 1975; Keeney *et al.*, 1976).

These studies increased the awareness of IIASA concerning the difficulties and needed research in a) the management and planning of water resources, b) the forecasting and real-time control of water systems, c) the identification of objectives and placing weights on multiple objectives, and d) the integration of the non-technical or more social aspects of water resources planning and development into the planning and management processes. It set the stage for the studies to take place at IIASA after the departure of Professor Kaczmarek to Poland in August, 1976.

The Middle-Period: 1977–1983

Dr. J. Kindler from Poland, a former student of Professor Z. Kaczmarek, took over the leadership of the Water Resources Program in September, 1976. The projects that J. Kindler and his colleagues undertook included the management of water demands, demand-supply integration, interregional water transfers, and water quality control, management and operation.

Management of Water Demands

In 1976, much of the previous work throughout the world in applying systems analysis methods to water resources management focused on the management of supplies to meet given demands. Not much attention had been given to the management of demands. As demands for water increase relative to its supply, the intensity and efficiency of water resources management must be further enhanced; hence the interest at IIASA developed into a broader notion of "management" in which both the uses of water as well as its supply receive increased attention (Fisher, 1977). The primary objectives of IIASA's studies on water demands, initiated in 1976, were to compare and refine water demand models and to demonstrate their usefulness through case studies (Kindler, 1978).

The Vistula study on water demand for generating electricity began in 1977 as a collaborative arrangement between IIASA, the Institute of Meteorology and Water Management (IMGW) in Warsaw, Poland, and the Industry Studies Program of the University of Houston, Texas, USA. The purpose of the study was to develop and apply a mathematical programming model of a large (3 000 MW) coal-fired electric power plant located in the middle reach of the Vistula River. The modeling effort focused on the impacts of resource prices and environmental standards on the patterns of resource use in the plant, especially on water and fuel use and their interaction. The model was set up and used at IIASA, and in 1977 it was transferred to the computer installations at IMGW. It has been applied within the framework of policy studies that led to the establishment of heat discharge standards and wastewater discharge fees for the thermal power plants in Poland (Stone *et al.*, 1982).

Already in 1976 IIASA began a study of the Silistra region. This large agro-industrial complex in the northeastern part of Bulgaria covers a territory of about 2 700 km^2 with a population of some 200 000. A water demand study was of particular importance in the Silistra region, because a vast irrigation development project was to take place over the coming decade. Water resources were limited to those available from the border Danube River. Groundwater was available only in small quantities at depths exceeding 400 m, which made it an insignificant resource. A water demand model, developed at IIASA in collaboration with scholars from the Sofia Institute for Water Projects, was used to determine the least-cost alternative for the region's irrigation system. In 1978 the model was transferred to the computer installations of the Bulgarian Ministry of Agriculture and Food Industry. It was used extensively by the Bulgarian institutions to plan not only Silistra, but other irrigation systems in the Danube valley as well. It has helped achieve significant cost reductions (Gouevsky *et al.*, 1980).

In 1979, a study on water allocation and pricing in California, USA, was undertaken at IIASA. The study showed the need to examine institutional issues, such as water rights and water transfer mechanisms, when considering the possible reallocation of water among different user sectors. Various institutional structures were studied by successively adding constraints to a water allocation pricing model. The model has been used to test the sensitivity of the value of additional supply to different institutional structures and to explore the implications of data uncertainty, particularly for price elasticities of demand.

Also in 1979, IIASA scholars in collaboration with the University of Lund began to study municipal water demand in the Skane region in southern Sweden. The study examined possible reasons for the differences among the municipalities in total gross and total per capita municipal water use. Analyses were based on data from original bills for household and industrial water use and wastewater disposal in representative districts of Malmo, Sweden. The study provided important insights into the problem, directly relevant to the water policies of the Skane regional authority (Hashimoto and de Mare, 1980).

Parallel to the study of municipal water demand in Skane, an effort was made to understand better the demand for supplemental irrigation in this region and to evaluate expected benefits of such irrigation schemes in terms of how they would reduce uncertainty due to occasional precipitation shortages. By simulating present irrigation procedures, using precipitation data for the past 75 years, the probability distribution of the amount of water needed for irrigation was estimated. The investigations also showed, among other things, the extent to which the expected annual income of sugar-beet farmers could have been increased if variability in natural water supply (precipitation) had been reduced to zero. This is roughly how much these farmers might have been willing to pay to develop a supplemental irrigation system that would guarantee the amount of water needed during the growing season. This particular study has produced results useful to other regions in several IIASA member countries where agricultural production, like that of the Skane, is highly vulnerable to variations in the amount of precipitation (Anderson, 1981).

The IIASA studies on water demand were continuously supported by about 50 scientists and practitioners from practically all IIASA NMO countries. These scientists worked on a short-term basis on selected problems of water demand. In 1984, experience derived from the individual research and case studies was summarized in the book *Modeling Water Demands* (Kindler and Russell, 1984). The editors of the book have received several letters confirming that the book has been of assistance to those carrying out water demand studies elsewhere (e.g. municipal water demand study of San Francisco).

From Water Demand to Demand/Supply Integration

The year 1978 was one of transition: a research group was formed at IIASA to study the problems of integrating water demand with water supply (Guariso *et al.*, 1978). This study was built upon earlier studies in water resources planning applied to the Vistula (Poland) and Tisza (Hungary) rivers. The Tisza case was especially important, since this tributary of the Danube is an international river whose basin extends over six countries. It therefore creates a potential for transboundary conflicts. Research focused on four real-world complexities common to all water resources systems: criteria selection for assessing alternative courses of action; conflict resolution over resources allocation and use; treatment of risk and uncertainty in water resources planning and operation; and incorporation of institutional constraints in water management studies.

IIASA's work on integrating water demand and water supply drew heavily on the situation encountered in the Skañe region in southern Sweden. The effort involved both external collaboration with the University of Lund, and internal collaboration with other research groups (System and Decision Sciences, and Regional Development) at IIASA.

The regional water supply system of Skañe was based at the time on two local lakes which together with some groundwater resources were used as sources of industrial drinking water for a population of about 750 000. Unlike many other lakes, water in the Skañe lakes is still of acceptable quality. However, occasionally there was just not enough water. The region is one of the very few in Sweden where water resources are relatively scarce.

In 1965, a forecast of water use in Skane was made by extrapolating past trends. A comparison of forecasted water use levels with the locally available resources indicated that there would be a serious future water shortage in the area. A decision was made, therefore, to develop a new source of water from Lake Bolmen situated about 150 km north from Skane. In the late 1960s, 12 municipalities of Skane formed the Sydwatten AB company, that in the early 1970s began building the Bolmen–Skane water transfer facilities, including a large tunnel approximately 60m km long.

By the mid-1970s, the earlier forecasts had proven to be incorrect. The effects of environmental legislation enforced in the late 1960s had not been anticipated. These laws led industrial water users to install new water recycling equipment with the aim of cutting the costs of complying with the new water quality standards, the incidental effect being to reduce water withdrawals substantially. This reduction in water withdrawals took place in spite of a substantial increase in industrial production over the same period.

This classical case illustrates that demand uncertainty involves not only random variations around some estimated mean future demand, but also abrupt structural shifts in the evolution of demand (Pawlowski, 1978). A mathematical model to analyze the implications of such surprising shifts was developed and applied as part of a study launched to decide on the future of the Bolmen-Skane water transfer.

The Skañe region consists of 20 municipalities, each of which enjoys considerable autonomy. However, all the municipalities come together, negotiate, and eventually agree on decisions concerning the entire region. One such decision had to do with the regional water supply system and its extensions. The principal issue to be solved was the allocation of the joint costs among participating municipalities. The IIASA team developed new methods, based on game theory, for solving cost allocation problems of the type encountered in Sweden (Young *et al.*, 1980).

Taking advantage of the presence of Japanese scholars at IIASA, the Weak Least Core method was applied later to the cost allocation problems of a multipurpose reservoir project in Japan. This application led to a decision in the early 1980s by the Japanese Ministry of Construction to modify substantially its regulations concerning allocation of cost of multipurpose water projects.

In another methodological study of the Skane region, an interactive procedure for multiobjective analysis of water resources allocation was developed and used to analyze the allocation of water to several conflicting uses, such as irrigation, municipal supply, recreation, maintenance of instream quality standards, and maintenance of minimum acceptable flows (Kindler *et al.*, 1980; Bushenkov *et al.*, 1982).

Finally, IIASA scholars in collaboration with their Swedish colleagues explored the advantages and disadvantages of integrating subregional solutions into a regional water resources system. Criteria used for this assessment included economic efficiency, increased reliability of system operation, and system vulnerability and robustness (Hashimoto *et al.*, 1982). A simulation model was used to carry out this study. The model, a modification of one originally developed at the Massachusetts Institute of Technology in the USA, incorporated highly complex operation rules for storage reservoirs, time-variable demands for municipal and supplemental irrigation water, and flexibility with respect to future management options (Strzepek, 1981).

In 1981, the final results of the Skane studies were presented to the regional authorities and the Swedish National Environment Protection Board. The report included policy recommendations and 25 research reports and journal articles inspired by the Skane investigations. The water management studies in Skane have shown, *inter alia*, that the intensity of use of locally available water can be increased considerably by matching water supplies of different qualities to the minimum quality requirements of various water-using sectors.

The Skañe investigations also underscored the need for conjunctive management of surface and groundwater quantity and quality. Although major research effort on these problems was initiated two years later (see the following section on *Regional Water Policies*), in 1981 an exploratory study addressed the issues of the analysis and control of non-point nitrate pollution of municipal water supply sources. Together with collaborating researchers in the FRG, the GDR, Hungary, the Netherlands, Poland, the United Kingdom, the United States and the OECD, IIASA developed an approach for analyzing the impacts of the use of nitrogen in the agricultural sector. A major source of nitrogen compounds originates from fertilizers and affects water quality and human health (Zwirnmann, 1982).

In collaboration with Utah State University (USA), a one-year project was begun in 1981 on the possible use of saline water as an alternative to its disposal. Indeed, saline water represents a large part of the total regional water resources in a number of countries, including France, Poland, the Soviet Union and the United States. The study, which was coordinated with the US Bureau of Reclamation, sought to identify approaches for salinity management in the Colorado River and to assess their technical and economic feasibility. A set of generalized simulation/optimization models was developed for evaluating salinity management alternatives. They were applied to specific problems in the Colorado River Basin. This resulted in recommendations for policy changes and institutional innovations for improving salinity management within the Basin (Hughes *et al.*, 1983).

The study results suggested a number of possible institutional innovations for solving these problems, such as "banking" mechanisms that permit the transfer of capital and water rights among water users. The potential for other salinity management alternatives, such as the use of low quality water for industrial cooling and the final disposal of brines in nonconvective solar ponds, was also explored and reported.

The study findings indicated that at some Colorado basin sites, the additional costs of both brine concentration in the waste stream of the power plants and the construction of nonconvective ponds could be balanced by revenues from solar-generated electricity and the savings resulting from the prevention of downstream salinity damage. Moreover, there could be social benefits from preserving the traditional patterns of agricultural production.

Survey on Interregional Water Transfers

In 1979, under the leadership of Professor G.N. Golubev from the USSR, a study was carried out on the transfer of large amounts of water over long distances. In-house research was concentrated on both conceptualizing the problem and assessing possible environmental impacts of large-scale projects such as the water transfer from the Ob River mouth to the Volga River basin and then to Central Asia. Large water transfer schemes proposed in India, Mexico and the USA were also studied. As a result of these studies, all of which identified the difficulties of predicting the environmental impacts and the related risks of such large-scale projects, IIASA adopted for a few years the role of a clearinghouse for information on interregional water transfers. Meetings were organized and books were published (Golubev and Biswas, 1979).

These studies on interregional water transfers contributed to the decision made much later by the Soviet Government to abandon the huge and quite controversial plan for implementing a large water transfer from the north to the south. In fact, IIASA's study on interregional water transfers was proposed by the Soviets, who wanted to learn through IIASA more about the environmental implications of similar undertakings elsewhere.

Water Quality Control and Management

In 1977 under the new leadership of Professor O.F. Vasiliev from the USSR, Deputy Director of IIASA, IIASA also expanded its research on water quality control and management dealing with lake eutrophication, modeling of poorly defined environmental systems, and operational problems of water quality management. Eutrophication is a natural process in the aging of lakes that becomes a problem when it is artificially accelerated by discharges of nutrients from sewage effluents and from agricultural runoff. In several parts of the world, especially those regions where the lakes are shallow and located in densely populated flatland areas, there is strong interest in lake quality management. For this reason, when the Hungarian Academy of Sciences suggested in 1977 that the problem of Lake Balaton be adopted as a case study, the suggestion was readily accepted by IIASA.

The application of systems analysis to the problems of lake eutrophication is appropriate for a variety of reasons, viz., the complex biological, chemical and hydrodynamical processes involved, the strong interrelation between the various processes and phenomena, the stochastic variability due to changing meteorological influences, and the many side effects of possible alternative management strategies that need careful examination.

Lake Balaton seemed an ideal "laboratory" for a lake eutrophication study. This is the largest lake in Central Europe and one of the largest shallow lakes in the world. A reasonable amount of data was available at the beginning of the study and intense, mainly experimental, research was underway at various Hungarian institutions. Besides the scientific interest, there was also a strong economic interest in the solution of this real-life problem. Roughly 40 percent of the hard currency income from tourism in Hungary stems from the superb scenery and agreeable summer climate of the Balaton region. From the standpoint of IIASA, the study offered the prospect of developing systems techniques that could be applied to other shallow lakes with similar problems. The study was directed first by Dr. G. van Straten from the Netherlands, and later by Dr. L. Somlyody from Hungary.

The case study presented formidable problems of communication. Because of the interdisciplinary nature of the study, a common language had to be developed – not without some difficulties – among chemists, biologists, mathematicians, hydrologists, engineers, economists, computer specialists and managers. Perhaps one of the major achievements of the study was that the Balaton team was able to work out a common language. The participants totaled about thirty scientists from Hungary and some twenty scientists from eight other IIASA nations. Experimental scientists came to appreciate the work of modelers, managers, biologists, and so on. Many fruitful discussions took place between those involved in data collection and those in modeling, and between those in research and those in management. It was indeed an educational experience for all involved.

Methodological advances resulting from this research included advances in model development, parameter estimation, model structure identification, sensitivity and uncertainty analysis, and coupling of hydrophysical, biochemical and management models.

The Balaton study, completed in 1982 (Somlyody *et al.*, 1983, 1986), served as a unified basis for introducing regulatory measures to protect the quality of the lake water. The methods developed at IIASA to explain the artificial aging of this shallow lake were later used on a comparative basis to study similar problems of Lake Erie, the shallowest of the Great Lakes that form part of the border between Canada and the United States. Many of the principal scientists involved in this project are applying their knowledge, as UN consultants, to other parts of the world as well.

In the years 1981–82, the Institute also sought practical solutions to the problems of eutrophication of the Neusiedler Lake and the group of Alpine lakes in Austria. Through the use of interactive programming and computer graphics, IIASA was able to explore with planners and members of the Austrian provincial governments the effects of different eutrophication strategies on the development of the tourist industry and reed harvesting in the region surrounding the lakes (Fedra, 1984).

During all twelve years of IIASA's work on water quality and management problems, there was particular emphasis on the methodology of model development (Beck, 1980; 1981) and calibration in the presence of uncertainty, with special reference to uncertainty in field data and imprecise prior knowledge of the dominant relationships between the system variables (Fedra *et al.*, 1981).

Until the late 1970s most water quality experts believed that "reality" could be more accurately described by including more and more differential equations in a model. As a result, there has been a rapidly growing concern with uncertainty analysis, i.e. the analysis of the propagation of prediction errors. In 1980 IIASA initiated research on the methodological aspects of accounting for uncertainty and the modeling of the behavior of poorly defined environmental systems. The limitations of current analytic methods for model development with *in situ* field data (system identification) have been fully exposed and the scientific inquiry included several new areas such as the ambiguity of forecasts, the conditions determining radically different future behavior and possible structural changes in the system.

A number of case studies supported the methodological developments needed to tackle these problems. For example, field data from the River Ouse in Bedfordshire in the UK were used to examine the problem of model structure identification. A sensitivity analysis was made for a water quality model for a similar lowland river – the Berkel River in the Netherlands. A recursive algorithm for computing the propagation of errors in long-term forecasts of water quality changes was developed on the basis of IIASA's study of Lake Ontario in North America (in cooperation with the Canada Centre for Inland Waters and Manhattan College in New York, USA). The results of this study have been published in a book entitled *Uncertainty and Forecasting of Water Quality* (Beck and Van Straten, 1983).

Following a joint IIASA-IAHS (International Association of Hydrological Sciences) International Symposium on Water Quality Modeling held in Baden in 1978, a survey of the state-of-the-art in water quality modeling began. The survey, involving scientists at IIASA together with collaborating scientists, was limited to models of streams, lakes and reservoirs. This survey lasted almost five years, and culminated in a book edited by Professor G.T. Orlob *Mathematical Modeling of Water Quality* (Orlob, 1983). The charge to those involved in this survey was to capture the essence of water quality modeling, and the basic principles upon which it is based, the practical problems in conceptualizing real-world phenomena in mathematical form, and the use of models in decision making. This project was under the general direction of Professor Kaczmarek who (during his period of leadership in the mid-1970s) initiated the project, and Professor Oleg Vasiliev during most of the time the survey took place. In a parallel effort, review of the development and application of water quality management models was completed (Beck, 1985).

Operational Management: Beyond Planning and Design

Since the beginning of its water studies, IIASA gave special attention to the fact that operational day-to-day management of water resource systems is no less important than their planning and design. In fact, in many IIASA NMO countries, almost all dams, reservoirs, navigation canals and hydropower plants that could be built within the boundaries of physical and economic efficiency constraints already exist. In such situations, the central issue is how to increase the operational efficiency of the existing systems. The stochastic character, space-dependence and the usual nonlinearity of those systems make the problem especially difficult.

Among the problems given special attention were those associated with the operation of storage reservoirs. In 1979 an international workshop on this topic was organized jointly with the Polish Academy of Sciences. Participants reviewed the state-of-the-art and suggested future directions for research on the operation of multiple reservoir systems (Kaczmarek and Kindler, 1982). In 1980, following recommendations made at this workshop, IIASA scholars, in collaboration with the Institute of Automatic Control of the Warsaw Technical University in Poland, developed and applied to the Upper Vistula System in Poland a new method of control. This method was based on the technique of hierarchical control and price coordination (Salewicz and Terlikowski, 1981). Another approach, developed in collaboration with the University of Birmingham in the UK was based on the rolling control effect of a forecast-decision-control scheme, with the iterative dynamic programming algorithm used to identify control decisions (Harwood, 1981). This approach has been applied to simulate the operation of a conjunctive pumped-storage-aquifer system in the UK and the Upper Vistula System in Poland.

In the summer of 1981, IIASA and the Polytechnical University of Milan, Italy, initiated another study of the problems of real-time forecasting and operation of water resource systems. Scientists from Austria, Italy, Finland, Poland and the Soviet Union worked together on developing analytic approaches to problems of multiobjective dynamic control under uncertainty, and on linking those with models for forecasting snowmelt and rainfall runoff. To demonstrate applicability of these methods, the Lake Como system in northern Italy was chosen (Guariso *et al*, 1982).

Lake Como stretches for almost fifty kilometers beneath the spectacular peaks of the Central Alps near Italy's border with Switzerland. By June of each year, the lake is filled with the snowmelt from a catchment area in the Alps of over 4 500 km^2. Over the hot dry summer, the lake is drained by the River Adda which flows 140 km across the Padana plain southeast of Milan before merging with the River Po. In autumn the lake is refilled by rain.

Since Roman times, this typically Alpine cycle has benefited farmers downstream from the lake, where the yields of wheat, corn and forage from the area of about 144 000 ha can be greatly improved by irrigation. The water users were subject to the caprices of nature, however, until the early 1940s when a dam was constructed at the lake outlet. The dam was built to regulate the lake's outflow for agricultural purposes over the summer and to increase the power production of the seven downstream hydroelectric plants.

The major conflict at Lake Como was between those advocating more flood control and those in favor of increased water supply for agricultural purposes. The study team worked with the manager of the Lake Como dam to develop heuristic operational control strategies. As a consequence, the local manager is now using the methods and software developed by the IIASA and Politecnico di Milano teams to determine how much water should be released daily from the lake functioning as a storage reservoir. In 1982 the Italian Ministry of Public Works revised previous formal rules concerning operation of the dam, enabling the dam manager to adopt a more active control strategy. To provide more flood protection, the municipality of Como decided to repave and elevate part of the town that had sunk as a result of previous floods.

The study made a significant contribution to the theory of storage control problems with uncertain supply and multiple objectives (Rinaldi, 1982; Orlovsky *et al.*, 1982). It also began to make IIASA scientists more aware of the need to develop tools in cooperation with the potential users of those tools. This notion fits the growing interest in developing interactive decision support systems for water resource managers. This theme, conceived in the early 1980s both within the water resources program and in the IIASA program called Systems and Decision Sciences, characterizes much of the water resources research carried out at IIASA since that time until present (Loucks *et al.*, 1985; Fedra *et al.*, 1985; Fedra, 1985).

The Latest Period: 1984–Present

Regional Water Policy Analyses

Upon the return of J. Kindler to Poland in December 1983, S. Orlovsky from the USSR assumed the leadership of the water resources research program. At this point the program was considerably reduced in size due to both financial constraints and management decisions, but nevertheless still actively continuing two projects begun in the early 1980s. At that time IIASA and collaborating institutions initiated research on some problems related to the conjunctive management of groundwater and surface water systems. The goal of the project was to develop and evaluate a decision support system (DSS) that regional authorities and analysts could use to identify and evaluate alternative regional water resource management policies for regional development. Mathematical models and less formal methods of game theory and multiobjective analysis were used to analyze how the socio-economic and environmental subsystems compete for, or are impacted by, the quantity and quality of the region's water resources, and how institutional arrangements and human behavioral influence decision making in the region.

The IIASA team studied, in particular, certain problems of agricultural land and water use in the Netherlands and problems of groundwater quantity and quality management in areas of surface pit mining in the German Democratic Republic. These studies, completed in 1986, provided insights into how conflicts arise among the various interest groups, the different institutional arrangements for their management and eventual reconciliation, and the overall effectiveness of the analytical models coupled with interactive computer graphics as decision support systems for addressing these problems.

The Southern Peel region of the Netherlands (Orlovsky and van Walsum, 1984) served as a prototype for the study of water and related resource problems in regions where agriculture is the dominant activity – both in terms of economic value and through its impact on regional ecology via the surface and groundwater systems. Collaboration with the Institute of Land and Water Management Research (ICW) in Wageningen, the Netherlands, resulted in the development of a DSS that ICW currently uses to explore strategies for reconciling the objectives of farmers, municipal water supply agencies, environmental protection groups, and regional development planners.

Open-pit mining for lignite is a water-intensive activity that can seriously constrain supplies of high quality surface- and groundwater. The study of this economically vital activity in the Lusatia region of the German Democratic Republic (Kaden *et al.*, 1985) has provided insight into how to manage conflicts among those advocating the further development of the country's coal resources, municipal authorities responsible for satisfying the water demands of the region, and environmental groups favoring the protection of

Dr. S. Orlovsky, leader of the Regional Water Policies Project in the early 1980's

natural resources. The Institute for Water Management in Berlin, the Technical University of Dresden, and the Institute of Lignite Mining in Dresden worked with IIASA in designing flexible tools for aiding the decision process. In 1985, the system was installed on the computer facilities in Berlin for use in addressing environmental development imbalances of Lusatia and other regions of the country faced with similar difficulties.

Both of the DSS's developed by IIASA's Regional Water Policies group and its collaborators have been designed to be user-friendly, reliable, robust, and credible. They are based on a hierarchy of mathematical models that account for the interdependencies of economic development processes and water resources, as well as the region's complex decision-making structure; they incorporate interactive techniques for treating multiple and conflicting objectives under uncertainty, and widely different potential policy actions (Orlovsky *et al.*, 1986).

Decision Support Systems for Large International Rivers

Before returning to the USSR in May 1986, S. Orlovsky initiated work on a proposal for what has become the current activity in water resources research at IIASA. It is a natural extension of the regional water policy research he and his colleagues were undertaking while he was at IIASA. The current project focuses on the management of transboundary conflicts in large international rivers. The project was under the leadership of Professor G. Kovács (Hungary) from August 1985 to October 1987, and Dr. K. Salewicz (Poland) since November 1987.

The project stems from the recognition that problems of resource management and environmental protection, especially involving transboundary conflicts, are as much in need of improved institutions and processes of conflict reduction as improved scientific understanding. The strategic objective of the project is to assess the extent to which these institutional processes can be supported by the development and use of modern decision support systems. Since development of interactive decision support systems (DSS) for resource management and environmental protection is still in its early stages, the project creates an excellent opportunity not only to develop and apply interactive DSS for the planning and management of environmental resources within specific river systems, but also to gain insight and guidance on the use and acceptance of DSS's in various complex institutional, social and political settings. The project approaches the problems of transboundary river basin management and conflict resolution from the viewpoint of those who are trained in applied systems analysis and who have direct experience using systems analysis methods to assist water resource management agencies. However, the intention of the project is to provide results useful to a wider audience than only specialists in water management. Thus, the results of the investigations should be of value to a wide range of individuals involved in planning, managing and negotiation.

The late Dr. György Kovács, and his secretary, Y. Taher, both of whom initiated the current water resources project

The core of the DSS is an interactive computer program prepared for personal computers of the type that are widely available both in the East as well as in the West, and in the developed as well as less developed regions of the world. The applicability of the DSS is being investigated using two case studies: the Danube basin and the Zambezi basin. The Danube basin is an example of a temperate zone, industrialized region where the main problems of water management are caused by increasing pollution. Further important decisions are also needed in connection with canalization and flood control. The Zambezi basin, located in an arid subtropical zone, is shared by several developing countries. The main problems of land and water management here are the control of flow by large reservoirs, the utilization of water for irrigation, and the increase in cultivated areas and associated deforestation.

Although the completion of a complete decision support system including the most important modules will require more than the two years, it is expected that some independently applicable components will be available for practical utilization by late 1988.

International organisations, especially river basin commissions, are the most likely users of this system, but national institutions responsible for the formulation of land and water management policies could also use it for comparing the consequences of different policy options in large national river basins.

Since the beginning of the project, implementation efforts have been made to build up a network of collaborating institutions. During the preparatory period of the project implementation (autumn 1986) IIASA participated in several symposia dealing with the management of large international rivers. At these meetings IIASA staff members and collaborators of the project presented papers explaining the purpose, structure and approach of the project. Project personnel at IIASA are cooperating with a number of international agencies (WHO, UNEP, UNESCO) and institutions from Austria, Hungary, Czechoslovakia, Poland, Portugal and USA. Efforts are being made to establish contacts and cooperation with some institutions from the Zambezi River Basin countries.

It is perhaps interesting to note that what distinguishes this project from most previous IIASA water research projects, in part, is that rather than needing to identify a single client or potential user of a methodology to provide a means of applying and evaluating that methodology, this project must find at least two clients who are in conflict with each other and have them agree to work together in this project. This is not easy and takes time. It will be interesting to see how successful this project will be in achieving agreements of conflicting parties just to work with IIASA in an effort to resolve such conflicts (or at least to identify what the significant conflicts are) even at the scientific level.

Conclusions

Over the past fifteen years IIASA has had an active research program in water resources research. Its focus has continually been towards improving the methods one can use to manage, plan, design and operate various types of water resource systems. To test research results, regional case studies have been undertaken. These case studies often involve institutions responsible for recommending decisions if not making them. These case studies have been both intranational and international in scope, depending on the issues being studied. All case studies have been selected so as to be representative of problems and issues found in many other regions of the world.

The number of scientific staff resident at IIASA at any one time and involved in these water resources research activities has varied from three to about fifteen. These scientists usually have been aided by scientists outside IIASA working at their home institutions in collaboration with those at IIASA. This research coordination role is an important part of the management of research at IIASA.

As previously stated, more than 80 scientists from many countries have contributed to the water resources research programs at IIASA over these fifteen years. Their work has made an impact in the profession of water resources planning and management.

Perhaps the most valuable result is not only what has been accomplished and reported in the literature or implemented in the field, but also what each scientist has learned from his or her association with scientists from different countries having similar interests but very different backgrounds, experiences and training. They all have worked together to improve and apply the systems approach to large, complex, interdisciplinary and sometimes politically sensitive problems related to the planning and management of water resources. And the job is not over.

REFERENCES

Anderson, R.J. (1981) An Economic Analysis of Supplementary Irrigation in Skane. RR-81-033, December, 45 pp.

Anis, A.A. and E.H. Lloyd. (1975a) Analytical Studies of the Hurst Effect: A Survey of the Present Position. RR-75-029, August, 26 pp.

Anis, A.A. and E.H. Lloyd. (1975b) Stochastic Reservoir Theory: An Outline of the State of the Art as Understood by Applied Probabilistics. RR-75-030, September, 22 pp.

Anis, A.A,. and E.H. Lloyd. (1977) On the Distribution of the Hurst Range of Independent Normal Summands. RR-77-016, July, 29 pp.

Beck, M.B. (1980) Model Structure Identification from Experimental Data. RR-80-004, February, 37 pp. (Reprinted from *Theoretical Systems Ecology: Advances and Case Studies*, E. Halfon, ed.)

Beck, M.B. (1981) Hard or Soft Environmental Systems? RR-81-004, March, 22 pp. (Reprinted from *Ecological Modelling*, Vol. 11, 1981)

Beck, M.B. (1985) *Water Quality Mangement: A Review of the Development and Application of Mathematical Models.* Springer-Verlag, Berlin, Heidelberg, New York, Tokyo.

Beck, M.B. and G. van Straten (Eds.) (1983) *Uncertainty and Forecasting of Water Quality*, Springer-Verlag, Berlin, Heidelberg, New York, Tokyo.

Bushenkov, V., F. Ereshko, J. Kindler, A.V. Lotov and L. de Mare. (1982) Application of the Generalized Reachable Sets Method to Water Resources Problems in Southwestern Skañe, Sweden, WP-82-120, IIASA, Laxenburg, Austria.

Fedra, K., G. van Straten and M.B. Beck. (1981) Uncertainty and Arbitrariness in Ecosystems Modelling: A Lake Modelling Example. RR-81-026, October, 26 pp. (Reprinted from *Ecological Modelling*, Vol. 13, 1981)

Fedra, K. (1984) Interactive Water Quality Simulation in a Regional Framework: A Management Oriented Approach to Lake and Watershed Modelling. RR-84-012, May, 27 pp. (Reprinted from *Ecological Modelling*, Vol. 21, 1983/1984)

Fedra, K. (1985) A Modular Interactive Simulation System for Eutrophication and Regional Development. *Water Resources Research*, Vol. 21, No. 2, February.

Fedra, K. and D.P. Loucks. (1985) Interactive Computer Technology for Planning and Policy Modeling. *Water Resources Research*, Vol. 21, No. 2, February.

Fisher, A.C. (1977) On Measures of Natural Resource Scarcity. RR-77-019, August, 30 pp.

Golubev, G.N. and A.K. Biswas (Eds.) (1977) Interregional Water Transfers: Projects and Problems. RR-79-001, June, 160 pp.

Gouevsky, I.V. (1974) On Optimum Control of Multireservoir Systems. RR-74-025, December, 24 pp.

Gouevsky, I.V. (1975) Optimal compensation programmes in water control distribution. RM-75-007, IIASA, Laxenburg, Austria.

Gouevsky, I.V. and I.P. Popchev. (1975) Man-Machine Procedure for Multiobjective Control in Water Resource Systems. RR-75-018, June, 40 pp.

Gouevsky, I.V., D.R. Maidment and W. Sikorski. (1980) Agricultural Water Demands in the Silistra Region. RR-80-038, IIASA, Laxenburg, Austria, 120 pp.

Gros, J.G. and A.R. Ostrom (1975) A decision analytic approach to river basin pollution control. RM-75-009, IIASA, Laxenburg, Austria.

Guariso, G., D.R. Maidment, S. Rinaldi, and R. Soncini-Sessa. (1978) Supply-Demand Price Coordination in Water Resources Management. RR-78-011, July, IIASA, Laxenburg, Austria.

Guariso, G., S. Rinaldi and R. Soncini-Sessa (1982) The management of Lake Como. WP-82-130, IIASA, Laxenburg, Austria.

Harwood, D.A. (1981) A Different Approach to Complex Water Resource System Control by the Use of Inout Forecasts. WP-81-045, IIASA, Laxenburg, Austria.

Hashimoto, T. and L. de Mare (1980) Municipal water demand study of western Skañe, Sweden – Background analysis with some preliminary results. WP-80-076, IIASA, Laxenburg, Austria.

Hashimoto, T., D.P. Loucks and J.R. Stedinger. (1982) Reliability, Resiliency, Robustness and Vulnerability Criteria for Water Resource Systems. RR-82-040, November, 18 pp. (Reprinted from *Water Resources Research*, Vol. 18, No. 1, 1982)

Hughes, T., S. Orlovski and R. Narayanan. (1983) Salinity Management by Use of Low Quality Water. WP-83-018, IIASA, Laxenburg, Austria.

Kaczmarek, Z. (1975) Storage Systems Dependent on Multivariate Stochastic Processes. RR-75-020, July, 21 pp.

Kaczmarek, Z. and J. Kindler (Eds.) (1982) The Operation of Multiple Reservoir Systems. CP-82-S03, May, 402 pp.

Kaden, S., J. Hummel, L. Luckner, D. Peukert, and K. Tiemer. (1985) Water Policies: Regions with Open-Pit Lignite Mining. WP-85-004, IIASA, Laxenburg, Austria.

Keeney, R.L., E.F. Wood, L. David and K. Csontos. (1976) Evaluating Tisza River Basin Development Plans Using Multiattribute Utility Theory. CP-76-003, March, 29 pp.

Kindler, J. (Ed.) (1978) Proceedings of a Workshop on Modelling of Water Demands. CP-78-006, June, 156 pp.

Kindler, J. P. Zielinski and L. de Mare (1980) An interactive procedure for multiobjective analysis of water resources allocation. WP-80-085, IIASA, Laxenburg, Austria.

Kindler, J. and C.S. Russell (Eds.) (1984) *Modelling Water Demands.* Academic Press, Inc. (BK-84-801; ISBN 0-12-407380-8).

Koryavov, P. (1975) Hydrodynamical aspects in the problem of determining the height of a dike along river reaches subject to flood. RM-75-028, IIASA, Laxenburg, Austria..

Letov, A.M. and Yu.A. Rozanov (1974). On optimal compromise for multidimensional resource distribution. RR-74-008, IIASA.

Lloyd, E.H. (1977) Reservoirs with Seasonally Varying Markovian Inflows and their First Passage Times. RR-77-004, March, 46 pp.

Loucks, D.P., Kindler, J. and Fedra, K. (1985) Interactive Water Resources Modeling and Model Use: An Overview. *Water Resources Research*, Vol. 21, No. 2, February.

Orlob, G.T. (Ed.) (1983) *Mathematical Modeling of Water Quality.* IIASA International Series, Vol. 12, John Wiley & Sons (BK-83-112; ISBN 0-471-10031-5).

Orlovski, S., S. Rinaldi and R. Soncini-Sessa. (1982) Uncertainty and Multiple Objectives in Storage Control Problems (A Min-Max Approach). CP-82-017, April, 26 pp.

Orlovski, S. and P.E.V. van Walsum (1984) Water policies: regions with intense agriculture (Introduction to the IIASA study). WP-84-040, IIASA, Laxenburg, Austria.

Orlovski, S., S. Kaden and P. van Walsum. (1986) Decision Support Systems for the Analysis of Regional Water Policies. WP-86-33, July.

Ostrom, A.R. and J.G. Gros. (1975) Application of decision analysis to pollution control: the Rhine river study. RM-75-045, IIASA, Laxenburg, Austria.

Pawlowski, Z. (1978) The Use of Alternative Predictions in Long-Term Inference into the Future (with special References to Water Demand), RR-78-015, IIASA, Laxenburg, Austria.

Rinaldi, S. (1982) Some Remarks on Periodic Stochastic Linear Reservoirs. WP-82-113, IIASA, Laxenburg, Austria.

Rozanov, Yu.A. (1973a) Some approaches to the water project. RM-73-008, IIASA, Laxenburg, Austria.

Rozanov, Yu.A. (1973b) Some problems on the stochastic flood control. RM-74-013, IIASA, Laxenburg, Austria.

Rozanov, Y.A. (1974) Some System Approaches to Water Resources Problems I. Operation Under Water Shortage. RR-74-017, IIASA, Laxenburg, Austria.

Rozanov, Y.A. (1975a) Some System Approaches to Water Resources Problems II. Statistical Equilibrium of Processes in Dam Storage. RR-75-004, IIASA, Laxenburg, Austria, 32 pp.

Rozanov, Y.A. (1975b) Some System Approaches to Water Resources Problems III. Optimal Control of Dam Storage. RR-75-017, June 1975, 18 pp.

Salewicz, K.A. and T. Terlikowski (1981) A case study in hierarchical control – the upper Vistula multireservoir system. WP-81-044, IIASA, Laxenburg, Austria.

Somlyody, L., S. Herodek, and J. Fischer (Eds.) (1983) Eutrophication of shallow lakes: modeling and management. The lake Balaton case study. CP-83-S03, IIASA, Laxenburg, Austria.

Somlyody, L. and G. van Straten (Eds.) (1986) *Modelling and Managing Shallow Lake Eutrophication – With Application to Lake Balaton.* Springer-Verlag, Berlin, Heidelberg, New York, Tokyo.

Stone, J.C., F.D. Singleton, M. Gadkowski, A. Salewicz and W. Kikorski. (1982) Water Demand for Generating Electricity – A Mathematical Programming Approach with Application in Poland. RR-82-016, April, 64 pp.

Strzepek, K.M. (1981) MITSIM-2 A Simulation Model for Planning and Operational Analysis of River Basin Systems. WP-81-124, IIASA, Laxenburg, Austria.

Strzepek, K.M. and J. Kindler (1982) Integrated water demand/supply management in southwestern Skañe: a preliminary analysis. WP-82-022, IIASA, Laxenburg, Austria.

Szöllösi-Nagy, A. (1975) An adaptive identification and prediction algorithm for the real-time forecasting of hydrologic time series. RM--75-022, IIASA, Laxenburg, Austria.

Szöllösi-Nagy, A. (Ed.) (1976) Workshop on the Vistula and Tisza River Basins. February 11–13, 1975. CP-76-005, April, 146 pp.

Wood, E.F. (1974a) A bayesian approach to analysing uncertainty among stochastic models. RR-74-016, IIASA, Laxenburg, Austria.

Wood, E.F. (1974b) Analysis of Uncertainty in Deterministic Rainfall Runoff Models. RR-74-018, IIASA, Laxenburg, Austria.

Wood, E.F. (1975) The analysis of flood levee reliability. RM-75-015, IIASA, Laxenburg, Austria.

Wood, E.F. and A. Szollosi-Nagy (Eds.) (1980) *Real-Time Forecasting/Control of Water Resource Systems. Selected Papers from an IIASA Workshop, October 18–21, 1976.* IIASA Proceedings Series, Vol. 8, Pergamon Press (BK-80-509; ISBN 0-08-024486-6).

Young, H.P., N. Okada and T. Hashimoto. (1980) Cost Allocation in Water Resources Development – A Case Study of Sweden. RR-80-032, September, 42 pp.

Zwirnmann, K.-H. (Ed.) (1982) Nonpoint nitrate pollution of municipal water supply sources: issues of analysis and control. CP-82-S04, IIASA, Laxenburg, Austria.

Appendix: IIASA Water Resources Publications

Serial Index

BOOKS

BK-80-509. *Real-Time Forecasting/Control of Water Resource Systems. Selected Papers from an IIASA Workshop, October 18-21,1976.* E.F. Wood, A. Szollosi-Nagy, editors. IIASA Proceedings Series, Vol. 8. Published by Pergamon Press. ISBN 0 08 024486 6, 1980.

BK-83-112. *Mathematical Modeling of Water Quality.* G.T. Orlob, editor. (IIASA INTERNATIONAL SERIES, Vol.12. Available from John Wiley and Sons Ltd.) ISBN 0 471 10031 5, 1983.

BK-83-402. *Uncertainty and Forecasting of Water Quality.* M.B. Beck, G. van Straten, editors. Published by Springer-Verlag, Berlin, Heidelberg, New York, Tokyo. ISBN 3-540-12419-5, 1983.

BK-84-801. *Modeling Water Demands.* J. Kindler, C.S. Russell, editors. Published by Academic Press Inc. ISBN 0-12-407380-8, 1984.

BK-85-401. *Water Quality Management: A Review of the Development and Application of Mathematical Models.* M.B. Beck. Published by Springer-Verlag, Berlin, Heidelberg, New York, Tokyo. ISBN 3-540-13986-9, 1985.

BK-86-401. *Modeling and Managing Shallow Lake Eutrophication--With Application to Lake Balaton.* L. Somlyody, G. van Straten, editors. Published by Springer-Verlag, Berlin, Heidelberg, New York, Tokyo. ISBN 3-540-16227-5, 1986.

RESEARCH REPORTS

RR-74-008. *On Optimal Compromise for Multidimensional Resource Distribution.* A.M. Lotov, Yu.A. Rozanov. June 1974. 36 pp.

RR-74-016. *A Bayesian Approach to Analysing Uncertainty Among Stochastic Models.* E.F. Wood. September 1974. 19 pp.

RR-74-017. *Some System Approaches to Water Resources Problems - I. Operation under Water Shortage.* Yu.A. Rozanov. October 1974. 29 pp. (Microfiche only.)

RR-74-018. *Analysis of Uncertainty in Deterministic Rainfall Runoff Models.* E.F. Wood. October 1974. 40 pp.

RR-74-025. *On Optimum Control of Multireservoir Systems.* I.V. Gouevsky. December 1974. 24 pp.

RR-75-004. *Some System Approaches to Water Resources Problems II. Statistical Equilibrium of Processes in Dam Storage.* Yu.A. Rozanov. February 1975. 32 pp.

RR-75-017. *Some System Approaches to Water Resources Problems III. Optimal Control of Dam Storage.* Yu.A. Rozanov. June 1975. 18 pp.

RESEARCH REPORTS . . .

RR-75-018. *Man-Machine Procedure for Multiobjective Control in Water Resource Systems.* I.V. Gouevsky, I.P. Popchev. June 1975. 40 pp.

RR-75-020. *Storage Systems Dependent on Multivariate Stochastic Processes.* Z. Kaczmarek. July 1975. 21 pp.

RR-75-029. *Analytical Studies of the Hurst Effect: A Survey of the Present Position.* A.A. Anis, E.H. Lloyd. August 1975. 26 pp.

RR-75-030. *Stochastic Reservoir Theory: An Outline of the State of the Art as Understood by Applied Probabilists.* A.A. Anis, E.H. Lloyd. September 1975. 22 pp.

RR-77-004. *Reservoirs with Seasonally Varying Markovian Inflows and Their First Passage Times.* E.H. Lloyd. March 1977. 46 pp.

RR-77-016. *On the Distribution of the Hurst Range of Independent Normal Summands.* A.A. Anis, E.H. Lloyd. July 1977. 29 pp.

RR-77-019. *On Measures of Natural Resource Scarcity.* A.C. Fisher. August 1977. 30 pp.

RR-78-011. *Supply-Demand Price Coordination in Water Resources Management.* G. Guariso, D.R. Maidment, S. Rinaldi, R. Soncini-Sessa. July 1978. 22 pp.

RR-78-015. *The Use of Alternative Predictions in Long-Term Inference into the Future (with special Reference to Water Demand).* Z. Pawlowski. November 1978. 30 pp.

RR-79-001. *Interregional Water Transfers: Projects and Problems.* G.N. Golubev, A.K. Biswas, editors. June 1979. 160 pp. Reprinted from Water Supply and Management, Vol.2, No.2, 1978. No longer available from IIASA.

RR-80-004. *Model Structure Identification from Experimental Data.* M.B. Beck. February 1980. 37 pp. Reprinted from Theoretical Systems Ecology: Advances and Case Studies (E.Halfon, editor). Available for a handling charge of $3.00.

RR-80-032. *Cost Allocation in Water Resources Development--A Case Study of Sweden.* H.P. Young, N. Okada, T. Hashimoto. September 1980. 42 pp.

RR-80-038. *Agricultural Water Demands in the Silistra Region.* I.V. Gouevsky, D.R. Maidment, W. Sikorski. November 1980. 120 pp.

RR-81-004. *Hard or Soft Environmental Systems?* M.B. Beck. March 1981. 22 pp. Reprinted from Ecological Modelling, Vol. 11(1981). Available for a handling charge of $3.00.

RR-81-026. *Uncertainty and Arbitrariness in Ecosystems Modelling: A Lake Modelling Example.* K. Fedra, G. van Straten, M.B. Beck. October 1981. 26 pp. Reprinted from Ecological Modelling, 13 (1981). Available for handling charge of $3.00.

RR-81-033. *An Economic Analysis of Supplementary Irrigation in Skane.* R.J. Anderson. December 1981. 45 pp.

RESEARCH REPORTS . . .

RR-82-016. *Water Demand for Generating Electricity--A Mathematical Programming Approach with Application in Poland.* J.C. Stone, F.D. Singleton, M. Gadkowski, A. Salewicz, W. Sikorski. April 1982. 64 pp.

RR-82-040. *Reliability, Resiliency, Robustness, and Vulnerability Criteria for Water Resource Systems.* T. Hashimoto, D.P. Loucks, J.R. Stedinger. November 1982. 18 pp. Reprinted from Water Resources Research, volume 18 number 1 (1982). Available for a handling charge of $3.00.

RR-84-012. *Interactive Water Quality Simulation in a Regional Framework: A Management Oriented Approach to Lake and Watershed Modeling.* K. Fedra. May 1984. 27 pp. Reprinted from Ecological Modelling, volume 21(1983/1984). Available for a handling charge of US $3.00.

IIASA REPORTS

IR-80-201. *IIASA Reports, Vol.2, No.1, pp. i-vi and 1-240. Water Resources and Climate.* IIASA. September 1980.

IR-81-301. *IIASA Reports, Vol.3, No.1, pp. i-vii and 1-236. IIASA Conference '80. Applied Systems Analysis: From Problem through Research to Use.* IIASA. March 1981.

IR-81-402. *IIASA Reports, Vol.4, No.2, pp. 199-388. (Completing Vol.4.).* IIASA. December 1981.

IR-82-602. *IIASA Reports, Vol.6, No. 2, pp.217-407. (Completing Vol.6).* IIASA. December 1982.

RESEARCH MEMORANDA

RM-73-008. *Some Approaches to the Water Project.* Yu.A. Rozanov. December 1973. 13 pp.

RM-74-013. *Some Problems on the Stochastic Flood Control.* Yu.A. Rozanov. June 1974. 6 pp.

RM-75-007. *Optimal Compensation Programmes in Water Control Distribution.* I.V. Gouevsky. March 1975. 20 pp.

RM-75-009. *A Decision Analytic Approach to River Basin Pollution Control.* J.G. Gros, A.R. Ostrom. March 1975. 24 pp.

RM-75-015. *The Analysis of Flood Levee Reliability.* E.F. Wood. April 1975. 33 pp.

RM-75-022. *An Adaptive Identification and Prediction Algorithm for the Real-Time Forecasting of Hydrologic Time Series.* A. Szollosi-Nagy. May 1975. 25 pp.

RM-75-028. *Hydrodynamical Aspects in the Problem of Determining the Height of a Dike Along River Reaches Subject to Flood.* P. Koryavov. June 1975. 8 pp.

RESEARCH MEMORANDA . . .

RM-75-045. *Application of Decision Analysis to Pollution Control: The Rhine River Study.* A.R. Ostrom, J.G. Gros. August 1975. 45 pp.

RM-77-044. *Agricultural Water Demands: Preliminary Results of Silistra Case Study.* I.V. Gouevsky, D.R. Maidment. September 1977. 91 pp.

WORKING PAPERS

WP-80-076. *Municipal Water Demand Study of Western Skane, Sweden--Background Analysis with Some Preliminary Results.* T. Hashimoto, L. de Mare. May 1980. 48 pp.

WP-80-085. *An Interactive Procedure for Multiobjective Analysis of Water Resources Allocation.* J. Kindler, P. Zielinski, L. de Mare. May 1980. 23 pp.

WP-81-044. *A Case Study in Hierarchical Control – The Upper Vistula Multireservoir System.* K.A. Salewicz, T. Terlikowski. April 1981. 71 pp.

WP-81-045. *A Different Approach to Complex Water Resource System Control by the Use of Input Forecasts.* D.A. Harwood, April 1981. 56 pp.

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WP-86-033. *Decision Support Systems for the Analysis of Regional Water Policies. Final Report of the Collaborative IIASA "Regional Water Policies" Project (1984-1985).* S. Orlovsky, S. Kaden, P.E.van Walsum, editors. July 1986. 345 pp.

COLLABORATIVE PAPERS

CP-76-003. *Evaluating Tisza River Basin Development Plans Using Multiattribute Utility Theory.* R.L. Keeney, E.F. Wood, L. David, K. Csontos. March 1976. 29 pp.

CP-76-005. *Workshop on the Vistula and Tisza River Basins, 11-13 February 1975.* A. Szollosi-Nagy, editor. April 1976. 146 pp. (Microfiche only.)

CP-78-006. *Proceedings of a Workshop on Modelling of Water Demands.* J. Kindler, editor. June 1978. 156 pp.

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