WATER DEMAND FOR GENERATING ELECTRICITY: A Mathematical Programming Approach with Application in Poland

J.C. Stone, F.D. Singleton, Jr.
University of Houston, Industry Studies Program, Houston, Texas, USA

M. Gadkowski, A. Salewicz
Institute of Meteorology and Water Management, Warsaw, Poland

W. Sikorski
International Institute for Applied Systems Analysis, Laxenburg, Austria

RR-82-16
April 1982

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
Laxenburg, Austria

International Standard Book Number 3-7045-0036-4

Research Reports, which record research conducted at IIASA, are independently reviewed before publication. However, the views and opinions they express are not necessarily those of the Institute or the National Member Organizations that support it.

FOREWORD

Since IIASA was founded, its research on problems of resources and the environment has included work on issues arising in water resource systems. Increasing demands for water generate needs for water resources to be managed with improved sensitivity and efficiency. To generate inputs to planning, design, and operating decisions, these needs must be met by increasingly sophisticated analyses, including economic, social, and environmental evaluations of development alternatives.

Early in the Institute's work on water resources it became apparent that the fundamental aspects of water resource management that must support such evaluations were not adequately understood. Therefore, in 1977 IIASA began to focus attention on modeling and forecasting water demands.

This paper, the tenth in the Institute's water demand series, reports the findings of an analysis of water demands for a 3000-megawatt coal-fired power plant on the Vistula River in Poland. This study considered the impacts of alternative resource prices and environmental standards on water demand with the aid of a mathematical programming model developed jointly by IIASA, the Industry Studies Program at the University of Houston (Houston, Texas, USA), and the Institute of Meteorology and Water Management (Warsaw, Poland). The model encompasses the power plant and its environment, as well as several related activities: coal transportation, coal beneficiation, and the evacuation of saline water emerging from the mining operations. While the application is quite specific, the approach is inherently general and can be followed in other geographical and economic contexts.

Thanks are due to Stiftung Volkswagenwerk, Hannover, Federal Republic of Germany for funds supporting part of this study.

JANUSZ KINDLER
Chairman
Resources and Environment Area

CONTENTS

WATER DEMAND FOR GENERATING ELECTRICITY: A Mathematical Programming Approach with Application in Poland

J.C. Stone, F.D. Singleton, Jr.
University of Houston, Industry Studies Program, Houston, Texas, USA

M. Gadkowski, A. Salewicz
Institute of Meteorology and Water Management, Warsaw, Poland

W. Sikorski
International Institute for Applied Systems Analysis, Laxenburg, Austria

SUMMARY

This report documents a water demand study developed as a collaborative effort between the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria; the Institute of Meteorology and Water Management (IMGW), Warsaw, Poland; and the Industry Studies Program of the University of Houston, Houston, Texas, USA. Participants in the study developed and applied a mathematical programming model of resource use in an electric power plant. The model specifically represents a hypothetical, coal-fired plant located on the Wisła (Vistula) River in Poland. The modeling techniques, however, have very general applicability.

Section 1 of the report provides some background information and introduction. Section 2 is a nonmathematical description of the model. The principal decision variables with respect to plant design and operation are identified, and the objective according to which the decisions are made is specified to be minimization of the costs of annual operation. Applicable constraints limiting the design and operating options are identified next. These constraints relate primarily to standards of air and water quality. Logical conditions pertaining to the technical options also require the use of a limited number of integer (0,1) variables in the model. The model explicitly represents plant operations in each of a number of user-defined seasons and simultaneously optimizes plant design and plant operation in all of the defined seasons.

Section 3 describes in detail the principal options of plant design and operation, making extensive use of flow diagrams. Modeled options relate to fuel provision and the cooling system. Two grades of coal are available for use, and two alternative modes of coal transport, railroad and slurry pipeline, are modeled. The optimal choice depends on cost

and on air and water pollution standards. The options for the cooling system are extensive and include:

1. *How much the temperature of cooling water rises in condensing the exhaust steam from the turbine*
2. *Whether or not a cooling tower is used and, if so, whether water from the tower is discharged or recycled*
3. *Whether the flow of cooling water across each of six condensers is independent or the flow passes across two paired condensers*
4. *How much the temperature of cooling water falls when circulated through a cooling tower*
5. *How much the concentration of dissolved solids is allowed to build up in a cooling tower with recycle flow*
6. *Whether to discharge or treat the so-called blowdown extracted from the flow through a cooling tower with recycle*
7. *Whether or not to dilute heated cooling water (with additional river water) before discharge to the river*
8. *Whether or not to recirculate some amount of heated cooling water to maintain a minimum required temperature at the inlet to the condenser*

The optimum choice over these options depends on a complex interplay of cost, water pollution constraints, and also air pollution constraints through the effects on plant thermal efficiency of alternative cooling system configurations.

Following the discussion of design and operating options for the plant, the structure of the model is described in detail. Specifically, modeling correspondences are established between plant processes and model columns and between flows of materials or energy and model rows. Some general issues in establishing these correspondences are briefly discussed. The specification of model structure is completed by detailing the mathematical formulation of identified constraints, e.g., those relating to air and water pollution, and of an accounting structure for water use.

How the model's structure is filled in with specific numerical coefficients is described next. In practice, the coefficients are specified by using so-called matrix generators, which automate the calculations. The general logic behind the specification of coefficients is described in the report. The section concludes with a brief discussion of the availability of data for the model, generally good, and a few comments on the definition of seasons.

Section 4 focuses on the use of the model, and includes a brief discussion of procedures for operating the model, its size, and computability. A wealth of information is available from the model. In particular, it can be used to estimate the capital and operating costs, resource demands and pollution loads that result from operating the plant under a wide variety of conditions. The report presents the results of some illustrative analyses of water demand performed with the model. These include calculation of derived demand curves for water withdrawals and heat discharges, of the trade-off between water losses and water withdrawals, and of the effects on the marginal and average costs of electricity caused by reducing water withdrawals. The results are not definitive but highlight the power of the method and the importance of an integrated approach to studying water demand and other aspects of industrial resource use.

1 INTRODUCTION

Mathematical programming has for some time been an important tool for modeling industrial operations. Such models have seen widespread application to the solution of scheduling, resource allocation, and transportation problems. Models have also been developed for analyzing and forecasting industrial activities under new economic and/or regulatory conditions, and since the early 1970s, serious attempts have been made to expand them to include considerations of residuals generation and management. Many of these attempts have their conceptual origins in the work of Russell (1973). Plant-level models of petroleum refining (Russell 1973) and of iron and steel production (Russell and Vaughn 1976) have been developed at Resources for the Future in the USA. Plant- and industry-level models have been developed at the University of Houston, USA, for electricity generation, petroleum refining, and manufacture of several important chemical products, such as chlorine and caustic soda, ammonia and other nitrogenous fertilizers, ethylene and other organic chemicals, synthetic rubber, and certain plastics and polyesters (Thompson et al. 1976, Thompson et al. 1977, Thompson et al. 1978). Plant-level models of paper mills have been developed by Sawyer et al. (1976).

The water demand study in this report developed as a collaborative arrangement between the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria; the Institute of Meteorology and Water Management (IMGW), Warsaw, Poland; and the Industry Studies Program of the University of Houston, Houston, Texas, USA. The operational objective of this collaborative effort was the development and application of a mathematical programming model of a hypothetical, coal-fired power plant located on the Wisła (Vistula) River, Poland. This choice of focus reflected the recognition that electricity generation is an enormously important component of industrial water demands. The problem, while hypothetical, deals with sufficiently realistic issues to render the results of the analysis useful to Polish decision-makers. The objective of the modeling effort was thus analytical rather than predictive – specifically, the development of a tool for quantifying the impact on water demand of alternative resource prices and standards for both pollutant discharges and environmental quality.

Figure 1 provides a geographical perspective on the modeled decision problem. The plant is assumed to be located on the middle reach of the Vistula River and has a rated capacity of 3000 megawatts (net). The potentially substantial water demands of the power plant are supplied exclusively from the river, with the minor exception of slurry water recycle. The significant quantities of coal required to fire the plant must be transported from the Silesia mining region, approximately 300 kilometers distant. Two alternative grades of coal are available – run-of-mine or "regular" coal and washed or "beneficiated" coal – and two modes of transport possible: railroad and slurry pipeline. A third option of barge transport was dismissed as currently uneconomical. The principal economic decisions for the plant are: the mix of coal types to burn, the mode of coal transport, and the design and operation of the plant cooling system.

The configuration of the cooling system is the principal determinant of water demand for the plant. Flow levels in the middle reach of the Vistula are not so low as to demand direct restrictions on the intake of water. However, problems with heat discharge render it impossible to operate an entirely "once-through" cooling system the whole year round. The problem, therefore, is to determine the optimal design and schedule of operating

FIGURE 1 The geographical setting of the modeled problem.

modes for a cooling system which can operate in an appropriate combination of open- and closed-cycle modes, depending upon the situation (see Section 3.1.3 for definitions of these terms). The optimal design and pattern of operation are a complicated function of capital and operating costs, meteorological and hydrological conditions, environmental quality standards, and any prices or charges imposed on water withdrawals, water consumption, and effluent discharges.

The provision of boiler fuel is also modeled in some detail, both because of the importance of fuel provision in power plant economics and because of a desire to make the model robust enough to enable the study of issues other than water demand. Each of the problems of coal supply, coal transport, and air emissions control is important enough in its own right, but various water-related aspects of the fuel provision issue also merit consideration in the present study (see Section 3.1.1).

The problems of water management in a power plant cannot be completely divorced from other aspects of plant design and operation. Water is only one of the basic factors of production, and accurate modeling of the derived demand relationships for water requires due consideration of the full range of relevant factor substitutions in production activities. For electricity generation it is probably sufficient to consider three factors: capital, water, and fuel. To this end, the present study has developed a model of resource use in electric energy generation which is believed to represent the variables and constraints of greatest importance in determining water demand, and also provide a modeling base for analysis of other relevant issues.

The discussion of the case study is divided into three major parts. First, a general description of the structure and components of the mathematical model is provided, in essentially nonmathematical terms. Second, the process of model construction and specification is briefly outlined. In particular, basic process options are identified and depicted in the form of flow diagrams. Components of these flow diagrams are then related to corresponding rows and columns in the programming model; the formulation of model constraints is described; and the procedures for specifying important model coefficients are discussed. The section concludes with some brief comments on the available data for specifying model coefficients and a note on seasonality. Third, we give a brief discussion of model operation, size and computability; a description of the kinds of analyses which can be performed with the model; and a summary and analysis of representative model results.

2 A NONMATHEMATICAL DESCRIPTION OF THE MODEL

In this present section we describe the structure and substance of the model in conceptual terms, without resorting to complicated algebraic notation. We address each of the principal components of the programming model in turn: decision variables, objective function, and constraints. We also include some discussion of integer requirements and of the structural representation of seasonality in the model.

Our model of resource use in electricity generation belongs to the general class of mixed-integer programming problems. It can be conceptually specified as follows:

Minimize

- Annual net costs of production

Subject to

- Seasonal production requirements
- Seasonal constraints on discharges to the water
- Seasonal constraints on discharges to the air
- Nonnegativity of decision variables (simple constraints to prevent logical and physical absurdities)
- Integer (0,1) requirements on certain variables

2.1 Decision Variables

The set of process variables (columns) in a programming model is typically composed of two classes of model activities: a set of decision variables which represent the array of controllable real-world options; and a set of "artificial" variables which perform certain logical, accounting, and integrating functions within the model. The latter set is fairly extensive and quite important in the operation of our model but merits no particular discussion. The emphasis is more on the process combination decisions which together provide the optimal solution for the plant.

Needless to say, electricity generation is a complex process involving a myriad of decision points in both plant design and day-to-day plant operation. The model developed for this study identifies a limited number of design and operating decisons which are believed to be the most significant determinants of water and fuel use patterns in the modeled plant. These key decisions are listed here; a more detailed description is provided in Section 3.1. The principal design decisions modeled are:

- Design temperature rise of cooling water across plant condensers
- Capacity of the cooling tower and water treatment facilities
- Capacity of slurry coal transport facilities (if any)
- Height of the stack for diffusing gaseous discharges

The principal (seasonal) operating decisions are:

- Basic flow pattern of plant cooling water, which itself comprises a set of decisions
- Disposition of cooling tower blowdown
- Disposition of slurry water (if any) and other briny streams
- Mix of alternative coal types burned

Two other important decisions are predetermined. First, the size of plant is given as 3000 MW net, divided into six basically identical blocks (or units) of 500 MW net each. Second, since by its nature the modeled facility is a baseload plant, the level of output is essentially determined by the number of blocks in operation at a given time and the expected rate of utilization for operational units. In a new baseload plant, this rate of utilization will tend to be high, and it is furthermore desirable to maintain it fairly constant. For present modeling purposes, therefore, it can be reasonably assumed that the average utilization rate is constant, at least over a short enough period of time. In terms of defining the problem for our study, this means that the size of plant and level of output (in net terms) cease to be economic decision variables. Gross capacity and output will vary because of the impact of various decision variables on plant efficiency (see Section 3.1.3).

Logically, the domain of relevant operating decisions is dependent upon the design decisions, and the impact on operating decisions must be considered in the design decisions. The patterns of water withdrawal, consumption, and discharge are derived results of these operating and design decisions.

2.2 Objective Function

The cost-minimizing objective function specified for the model may be resolved into the following components:

1. Annualized charge for capital investments
2. Operating costs (or penalties) for the following activities in each season:
   - electric energy generation
   - water withdrawals and water consumption
   - water handling and treatment
   - waterborne residuals discharges

  - coal supply
  - coal transportation and handling
  - coal combustion (including sulfur penalty)
3. Cost reduction applied for extra supplies of coal transported by pipeline (if any)

The annualized capital charge of 12 percent is based on a 4 percent depreciation charge and an 8 percent discount rate. The other cost coefficients, as well as the capital investment requirements to which the capital charge is applied, are based on either engineering estimates or policy specifications. While it is not appropriate here to detail the engineering cost estimates, we identify the following policy-dependent prices and penalties, which may be varied by the user for purposes of demand analysis and impact evaluation:

- Price of water withdrawals
- Price of water consumption (losses)
- Penalty for heat discharges
- Penalty for dissolved solids discharges in excess of a defined standard (except the discharges from open-cycle cooling systems)
- Penalty per percent of sulfur per ton of coal combusted
- Price of coal

We specify a cost-minimization objective for a number of reasons. First, a proper derived demand analysis requires that all factor inputs be evaluated according to a common unit of measure, and monetary cost is a commonly used criterion for analysis of industrial production activities. Second, this specification seems consistent with the planning structure of the industry and economy. Third, because of the essentially predetermined output profile of a baseload plant, a profit-maximizing objective would reduce to cost minimization anyway. Finally, using monetary cost permits a comparison between the indirect values and prices derived by our model with those of other models and applications using the same measure.

Our choice of objective function does not imply that the optimum "social" decision for design and operation of the power plant is necessarily based on production cost minimization alone; this decision may require a much broader purview and consideration of nonmonetary objectives. To some extent we have been able to incorporate some of these broader social perspectives and objectives in the form of constraints, prices, and penalties in the programming model. These specifications can in turn be used in performing economically sound analyses of cost and derived demand for use in the social decision process. In other cases, the relevant social considerations may not be so readily parameterized, and analysis proceeds by solving the model under various assumptions (or scenarios) so as to obtain some quantitative measure of the social trade-offs.

2.3 Constraints

As is the case with most complex programming models, a significant portion of the constraint set for our model is composed of equations representing logical conditions, performing accounting functions, and assuring proper materials and energy balances. These equations are essential and are discussed in Sections 3.2 and 3.3. In addition the model includes three subsets of constraints which, in the more conventional sense of the term, represent actual requirements or limitations imposed on plant activities. We briefly describe each of these.

Seasonal production requirements. The time pattern of plant output levels is translated into the model as a set of seasonal production requirements specifying the total number of megawatt-hours which must be generated (for transmission) in each season. These requirements take the form of a (greater than) row constraint for each season, and the dual values (shadow prices) associated with these rows may be interpreted as marginal costs of producing electricity in each of the seasons.

Seasonal constraints on discharges to the water. Four types of constraints are imposed on discharges of waterborne residuals. The first two are based on defined ambient standards, while the latter two are defined standards for the effluent stream itself. These standards may be summarized as follows:

1. Maximum allowable increase in river temperature
   - 4°C in June, July, August
   - 5°C in September
   - 6°C in all other months
2. Maximum allowable river temperature
   - 30°C
3. Maximum allowable temperature of plant discharge
   - 35°C
4. Maximum concentration of dissolved solids in discharge (except that from open-cycle cooling systems)
   - 500 mg/1

In constraint (4) higher concentrations are not strictly prohibited, but a penalty is applied for each kilogram of excessive solids discharge. In the model only the stricter of constraints (1) and (2) is specified for a given month. It is not readily determined whether this constraint is more or less strict than constraint (3) in a given month; hence, both constraint (3) and the stricter of constraints (1) and (2) are specified in the model.

The algebraic formulation of these constraints is somewhat complicated because of a need to express quantity-weighted averages in terms of quantities not known until the model solution is calculated. By careful formulation of intermediate accounting structures, however, each standard is ultimately expressed as a single (less than) constraint for each season. Interpretation of the dual values for these constraints requires algebraic manipulation to express them in meaningful terms.

Seasonal constraints on discharges to the air. An ambient standard for the maximum allowable ground-level concentration of sulfur dioxide is established by policy. For any given season, the difference between this standard and an expected background concentration may be interpreted as the maximum allowable concentration which may be produced by emissions from the power plant in that season. In order to incorporate the ambient standard in the model, it is necessary to translate this concentration allowance into an emission constraint for the modeled coal combustion activities. This translation has been accomplished with the aid of an atmospheric dispersion model developed by IMGW. Solutions to this model have determined – for each season and for a range of alternative stack heights over 150 meters – the maximum ratio of regular to beneficiated coal that can be combusted at full load consistent with the allowed increment in ground-level sulfur dioxide concentration. This ratio can in turn be converted into upper limits on the amounts of regular coal and of total coal – regular plus beneficiated – that can be combusted in a given season at a particular stack height.

In the model these upper limits take the form of two row constraints for each season. These constraints directly limit the quantities of coal combusted to amounts specified internally by the design choice of stack height; that is, for each additional meter of stack height constructed, an increment is added to the allowable amounts of regular and total coal combustion. The dual values for these constraints, only one of which can be binding in any season, represent the potential savings to the plant of burning one more ton of coal given a fixed stack height as determined in the solution.

2.4 Integer Requirements

A limited number of integer (0,1) variables are included in the model to impose certain logical constraints on plant design and to insure proper consideration of the economies of scale in slurry pipeline construction. Because the capacity of the power plant is predetermined, scale economies can be properly accounted for by calculating costs appropriate to an installation containing six 500 megawatt blocks. It is important, however, to insure that only one "type" of power plant is constructed with respect to the design temperature rise across the condenser; this requires integer variables. A similar integer control structure is required to insure complete and exclusive construction of only one size of slurry pipeline instead of linear bits and pieces of pipelines of various sizes.

2.5 Seasonal Structure

We incorporate the time dimension in the model by dividing the year into a number of seasons and modeling plant operations in each season in accordance with seasonally specified values for exogenous variables. These seasonal operations are tied together by certain annual resource constraints and by a fixed design of installed capital equipment. Thus, the optimal design decision is a function of the operating conditions in all seasons, and the optimal pattern of operations in a given season is dependent upon the operations in all other seasons through the common demands on annual resources and the design configuration. Again, the optimal overall decision requires a simultaneous determination of the design decision and all seasonal operating decisions, consistent with the seasonal time pattern of specified exogenous variables.

The essence of this interdependence and simultaneity must be incorporated in the mathematical structure of the model. Fortunately, this is not especially difficult. Seasonality is handled in a straightforward manner by defining separate column variables and constraints to represent plant operations in each of the defined seasons. The structure of each seasonal submatrix is virtually identical, but for each season a separate set of parameters represents charges for water use and residuals discharges, available supplies of water and other resources, and allowable discharges to the air and water. The coefficients of the electricity generation processes also vary, thus reflecting the impact of output level and of meteorological and hydrological factors on the operating conditions of the power plant and cooling system. A careful distinction is made between activities representing the provision of capital capacity for a given process (a one-time occurrence) and the operation of that process in each of the defined seasons. In each seasonal activity, capital capacity (if relevant) is treated much as any other required input, and a separate (one-time) activity is modeled to jointly provide capital capacity for all defined seasons.

3 MODEL CONSTRUCTION AND SPECIFICATION

In this section we describe the construction and specification of the model, following a typical logical sequence in the development of a progamming model. First, the basic process options are identified and depicted, where helpful, in the form of flow diagrams. Second, modeling correspondences are established between the components of the flow diagrams and the rows and columns of the model matrix. Third, model constraints are logically and algebraically formulated, and, fourth, the coefficients of model column activities are specified. We conclude the section with some comments on data availability (an issue which must always be kept in mind when developing the structure of a model) and a note on seasonality.

3.1 Basic Process Options

With the aid of several flow diagrams, the basic process options represented in the programming model are outlined. Figure 2 shows an overview of processes and materials flows with emphasis on activities outside the basic electricity generation processes. Figure 3 displays in greater detail the processes contained in the box for the electric power plant in Figure 2; it identifies the major flows of water, steam, and fuel-related materials in the power plant. Subsequent flow diagrams show the alternative configurations for the plant cooling system and are essentially a detailed expansion of the processes and flows in the dashed rectangle of Figure 3.

3.1.1 Fuel Provision Activities

Figure 2 gives an overview of the entire operation, with emphasis on the activities related to fuel provision. The coal supply for the modeled plant is assumed to be obtained from four Silesia mines with a combined annual capacity of 20 million (10^6) metric tonnes. This total is perhaps twice the expected coal requirement for the power plant. Mined coal may be transported directly to the plant site by railroad or may be beneficiated (crushed, washed, and gravimetrically separated) to produce a coal of higher heat content and lower ash and sulfur content. The quality characteristics of these two available coal types are given in Table 1.

The beneficiated coal may be transported to the plant site via railroad or slurry pipeline. Three alternative capacity options are considered for the slurry pipeline: 4.5, 9, and 16 million (10^6) metric tonnes per year. The largest capacity option represents transport

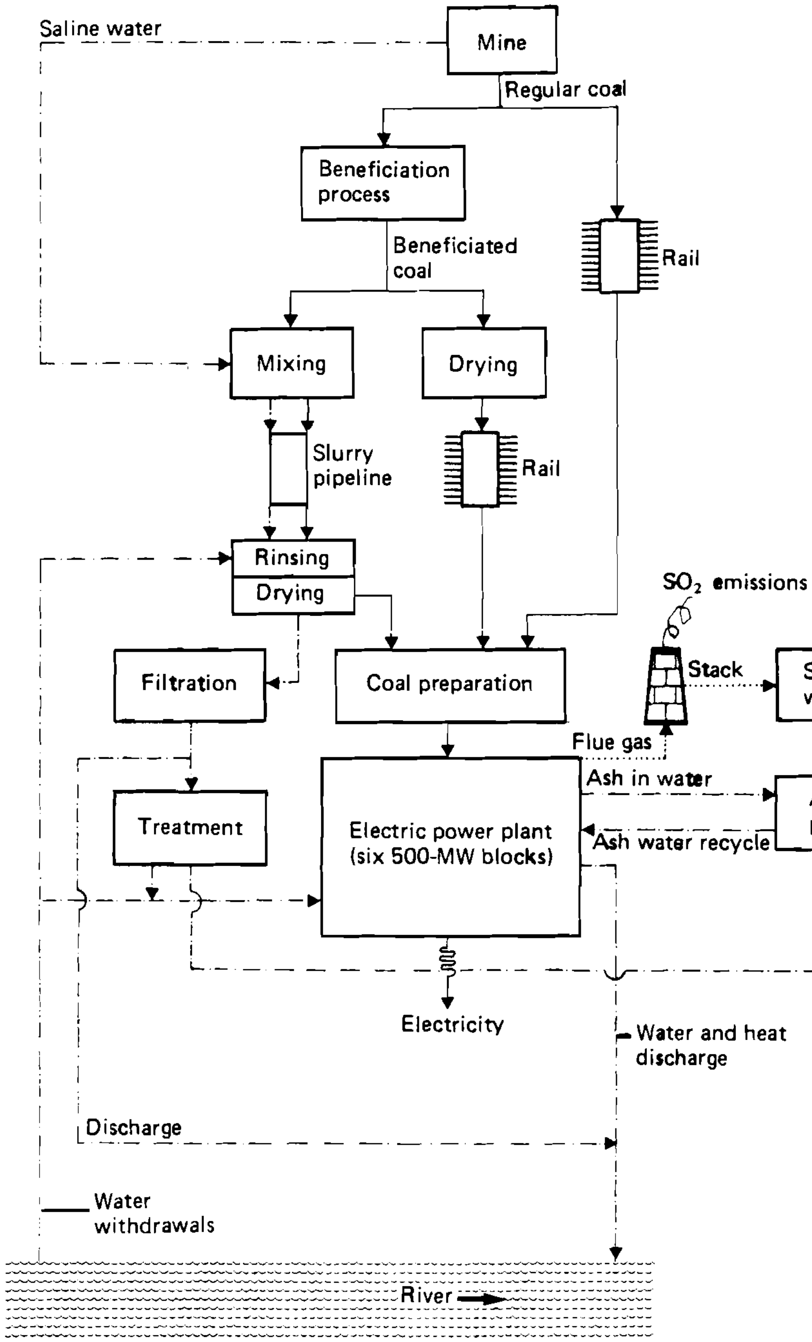

FIGURE 2 Flows of processes and materials in the generation of electricity with emphasis on coal handling and combustion, where – – – shows river water, – · – shows polluted water, ——— shows coal, and · · · · · shows flue gas or solid waste.

TABLE 1 Characteristics of run-of-mine and beneficiated coal.

	Heat content (kcal/kg)	Ash content (%)	Sulfur content (%)
Run-of-mine (regular)	4,400	26.4	2.5
Beneficiated	5,300	12.7	1.4

of the maximum yearly production of the four available mines, minus losses of 25 percent in the beneficiation process. The excess coal transported by this largest pipeline may be supplied to other users, with an appropriate benefit recorded in the objective function for the power plant.

We did not model two other coal transport options because preliminary cost calculations demonstrated them to be currently uneconomical in all circumstances. The first is slurry transport of regular grade (run-of-mine) coal, the cost effectiveness of which is always inferior to slurry transport of beneficiated coal on a delivered kilocalorie basis. This is because of the inferior heat and ash content characteristics of the regular grade coal and because the crushing and watering required for slurry transport are essentially the first two steps of the beneficiation process anyway.

The second uneconomical option is barge transport of either grade of coal which, in the case of the largely undeveloped Vistula River, is, at least for the present, inferior to railroad transport. This demonstrable inferiority arises from higher estimated unit costs and from the necessity for extra storage facilities at the power plant to insure adequate coal supplies during winter months, when navigation is inhibited by ice on the river.

None of these mining, beneficiation, or transportation processes is modeled in any great detail. Emphasis is on accurate representation of the costs of these operations and of the water balances for the slurry pipeline. We assume a one-to-one ratio for the water/coal mixture in the slurry; and IMGW estimates water losses – primarily through absorption – at 12 percent.

Another consideration concerning cost and water use involves water management in the mining region. Planners believe that the water used for slurry preparation and transport could be supplied from the large volumes of saline wastewater generated in mining operations. The major technical question to be resolved with respect to this option is the corrosive potential of the wastewater on the pipeline itself. If saline water usage proves feasible, a significant disposal problem will be alleviated as some of the wastewater is transported away from the mining area, where river flow is naturally low. From a social point of view, the economics of the slurry pipeline should incorporate these benefits, and the model includes an appropriate reduction in the operating costs of the pipeline to account for them.

The cost to be balanced against this benefit arises from the logical consequence that, at the plant site, slurry-transported coal must be dewatered, and the separated water must be discharged or treated for use in plant operations. We make the operational assumption that the slurry water is discharged through the same channel as the plant cooling water. This routing has the effect of somewhat diluting the solids concentration of the slurry water and the elevated temperature of the cooling water. While the flow of slurry water is not great – of the order of 0.5 cubic meters per second for the maximum size pipeline – the dissolved solids concentration of the stream may be as high as 10,000 mg/l. This concentration renders its disposal a nontrivial water management consideration, and the optimal decision depends upon the price of water withdrawals and on any environmental standards or effluent charges on dissolved solids discharges. The management of slurry water is thus one of the areas of interaction between the issues of water demand and of the provision of boiler fuel.

The other important consideration affecting the provision of boiler fuel is the extent of constraints and/or charges on gaseous discharges from the plant. We assume that the plant employs the most efficient available electrostatic control measures for particulate emissions and that these emissions do not require explicit analysis. We do, however, consider emissions of sulfur oxides in more detail. These emissions are subject to penalties based on the sulfur content of combusted coal and are further constrained to be in accordance with established standards for ambient concentrations of SO_2. The available alternatives for "control" of these emissions are the mix of run-of-mine and beneficiated coal combusted – the plant cannot operate entirely on regular coal because of the SO_2 standards – and the height of the stack, which affects dispersion of gaseous discharges rather than emission levels. Thus, there is an obvious interdependence between these considerations of gaseous discharges and the choice of coal supply and transport. As already indicated, the transport considerations represent an area of interaction between water use and boiler fuel.

There is, however, another area of interaction related to the impact of the cost of boiler fuel on the economic substitutability of cooling systems. The reduction in plant thermal efficiency attributable to the utilization of a cooling tower results in a higher fuel requirement per net kilowatt-hour of generation. This energy penalty must be considered, along with the additional capital requirements, in the comparative economics of open- and closed-cycle cooling systems. Proper evaluation of this energy penalty in turn requires consideration, at least to the extent of costing, of the full range of fuel provision activities from coal supply, to transport, to combustion in accordance with applicable standards for gaseous residuals discharges.

Finally we consider the disposal of solid waste from coal handling and combustion operations only to the extent of assignment of costs. We incorporate estimates of the average water requirements for removal of ash from the boiler, but the small magnitude of ash water flow does not justify detailed consideration – both data collection and modeling – of the weather-dependent management problem of managing the water in the ash pond. We use the ash pond frequently in our modeling as a convenient sink for small but dirty wastewater streams. This seems an acceptable approximation in light of the far greater significance of cooling water flows, which are at least 10 times as great even in the case of a closed-cycle system. The routing also makes operational sense because of the dilution and settling of materials in the ash pond.

3.1.2 Electricity Generation Processes

Figure 3 illustrates the major interrelationships among the most basic processes for power generation. Flows to and from the boundaries of this figure directly correspond to the flows entering and leaving the power plant shown in Figure 2. Figure 3 shows the basic water use patterns for process cooling, boiler make-up, and ash removal. Certain other minor water uses, such as cleaning water for the boiler, are omitted from the figure but

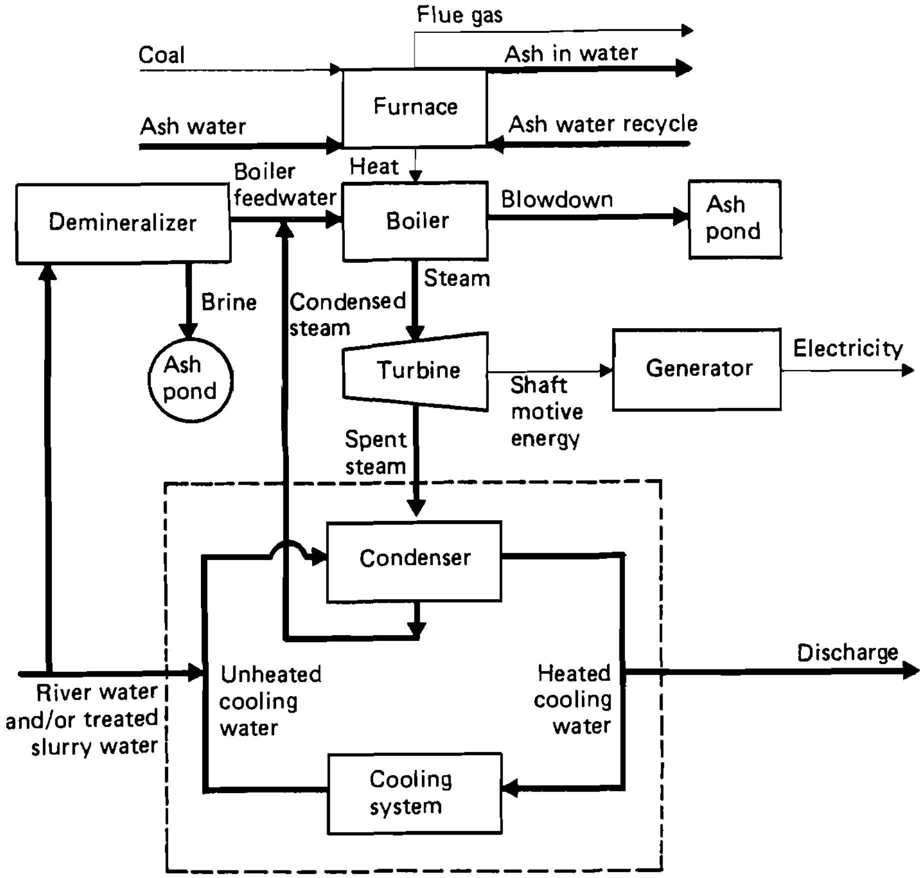

FIGURE 3 Basic unit processes for the electric power plant.

are included in the modeling analysis. Also illustrated are two typical uses of the ash-pond sink for "disposal" of small waste streams.

Of the three types of water use depicted, the boiler make-up and ash water flows are fairly small. The more substantial flows used in process cooling and the alternative configurations of the cooling system merit further consideration.

3.1.3 Cooling System Options

Figure 4 is a basic reference diagram of the eight major cooling system options (A–H) considered in our study; Figures 5–9 highlight one or more of the flow patterns shown in Figure 4. The basic options are characterized as follows:

(A) Temperature rise across condensers
(B) Type of cooling system
(C) Single or series condensers
(D) Wet bulb approach factor for cooling tower

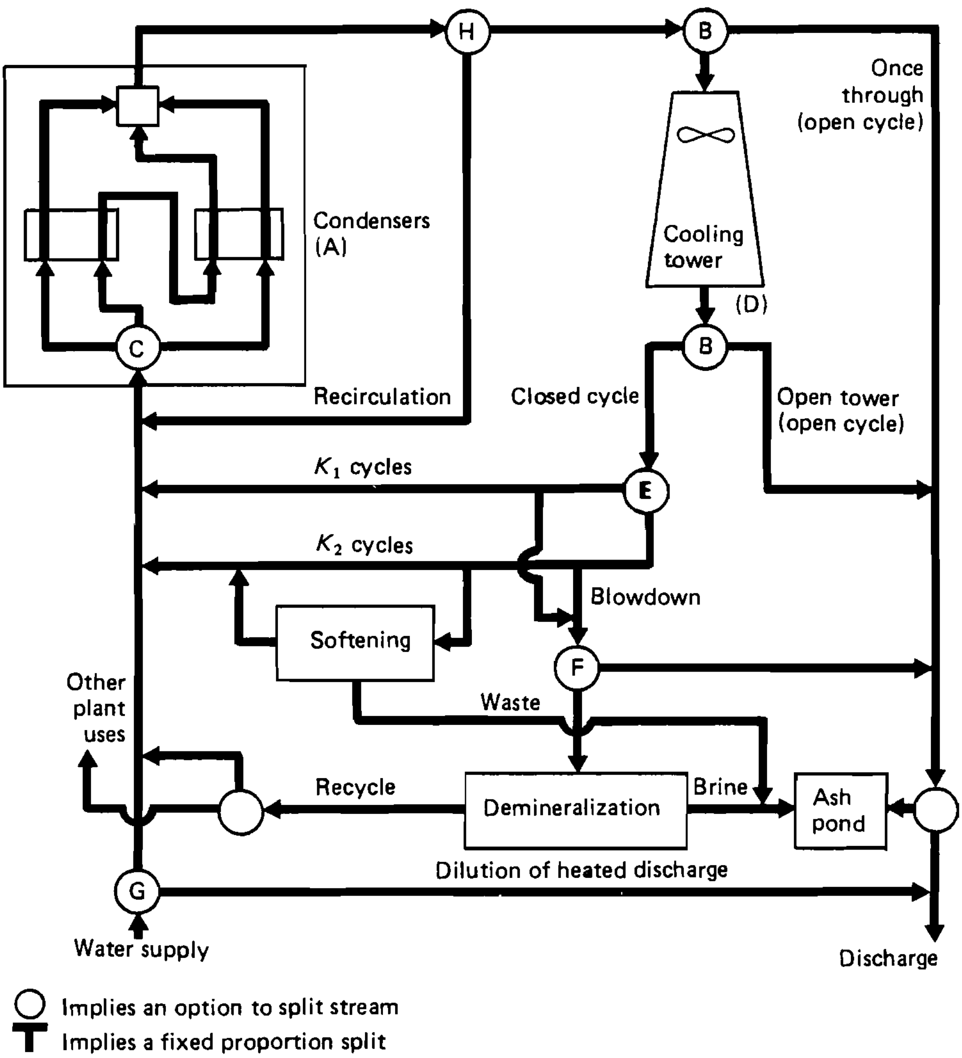

FIGURE 4 Cooling system options.

(E) Cycles of concentration in cooling tower
(F) Treatment of cooling tower blowdown
(G) Dilution of heated discharge
(H) Recirculation for temperature maintenance

Temperature rise across condensers (A). The process of heat exchange in a condenser condenses the turbine exhaust steam at the expense of an increase in the temperature of cross-current cooling water. The magnitude of this increase in cooling water temperature ΔT is a design decision variable which, for a given rate of waste heat removal H, determines the necessary rate of flow of cooling water across the condenser Q. In brief

$$H/c = Q\Delta T \tag{1}$$

where c is the appropriately scaled heat capacity of water. As can be seen, water flow Q is a decreasing function of ΔT, and the choice of ΔT is an important determinant of water demand in the plant.

As an additional important consideration, the value of ΔT determines – for given inlet water temperature and equipment design – the condensing temperature of the turbine exhaust steam. Because the pressure on the exhaust end of the turbine is an increasing function of this temperature, it follows that an increase in ΔT decreases the pressure drop across the turbine, with a resultant loss of generating power. This decrease in thermal efficiency results in an increase in both water and fuel requirements for a given level of net output.

Because both of these effects influence operating conditions throughout the plant, and because a condenser and its accessories must be designed for operation over a fairly narrow range of flow rates and ΔT, the choice of ΔT is a fundamental decision variable in plant design. In this study we consider three discrete options for ΔT; only one of these options may be chosen by the model.

Type of cooling system (B). The two decision nodes labeled B in Figure 4 represent the second fundamental choice in the cooling system configuration. Depending upon the flow routings at each of these points, the resulting configuration may be classified as one of the following basic types, or a combination of the three:

1. Open-cycle sytem
   a. "once-through"
   b. "open-tower"
2. Closed-cycle system

In Figure 5 the basic flow pattern for a once-through system is indicated by the broken lines; in Figure 6 that for an open-tower system is similarly indicated. In both cases, water from the river is pumped directly across the condensers and then discharged back into the river. This basic flow pattern characterizes these systems as open-cycle. In the once-through system, the discharge to the river is direct, and the temperature of the discharge stream is essentially the same as that at the outlets from the condensers. In the open-tower system, the condenser outlet water is pumped through a cooling tower before being discharged; this lowers the temperature of the discharge stream to that in the cooling tower basin (see option D for the determinants of basin temperature). The open-tower system has two important effects on water demand. First, water consumption is increased, relative to a once-through system, because of evaporative and drift losses in the tower. Second, overall water withdrawals must increase, again relative to a once-through system, because the energy requirements of the pumps and fans for the tower (assumed to be mechanical draft) increase the gross energy generation necessary to produce the same level of net output.

In our analysis we have crudely estimated the evaporative losses from a once-through cooling system that are caused by the spreading of heated cooling water over the river surface. As this is a very complicated problem involving a number of variables not otherwise considered in this analysis, we have used for the present an approximation based on more

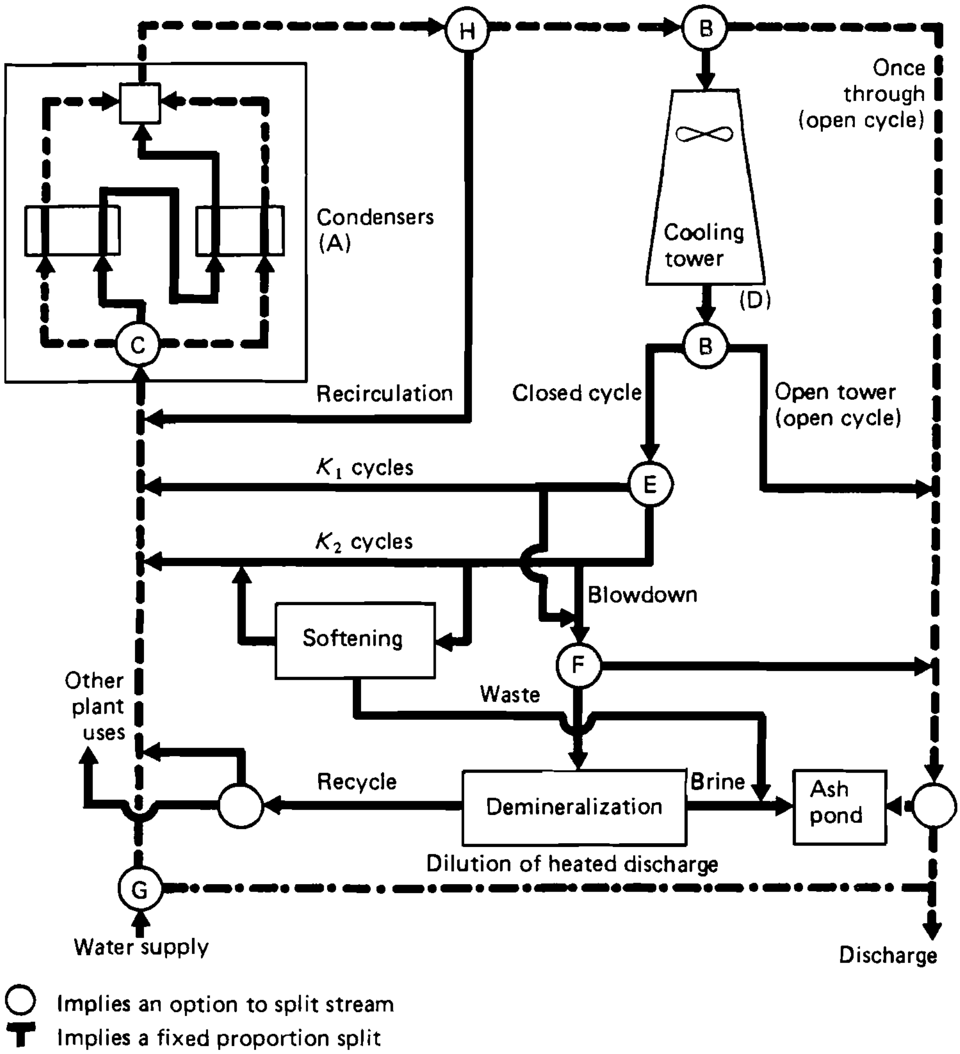

FIGURE 5 Flow pattern for a once-through cooling system (indicated by broken line), where A–H are cooling system options.

straightforward formulas for losses in the cooling tower. In general, the losses from a once-through system are less, perhaps 25 to 50 percent less, than those from a cooling tower system.

In either open-cycle system, it is possible – as shown at the bottom right of Figures 5 and 6 – to divert a small proportion of the cooling water discharge to the ash-removal system. In general, there is no reason not to employ this routing since it decreases slightly both heated water discharges and river water withdrawals for ash removal.

Figure 7 illustrates the basic flow pattern of a closed-cycle system. Now the emphasis is on the recycle routing at node B under the cooling tower. This flow pattern reduces the potential discharges from the system to the amount of blowdown collected at node F.

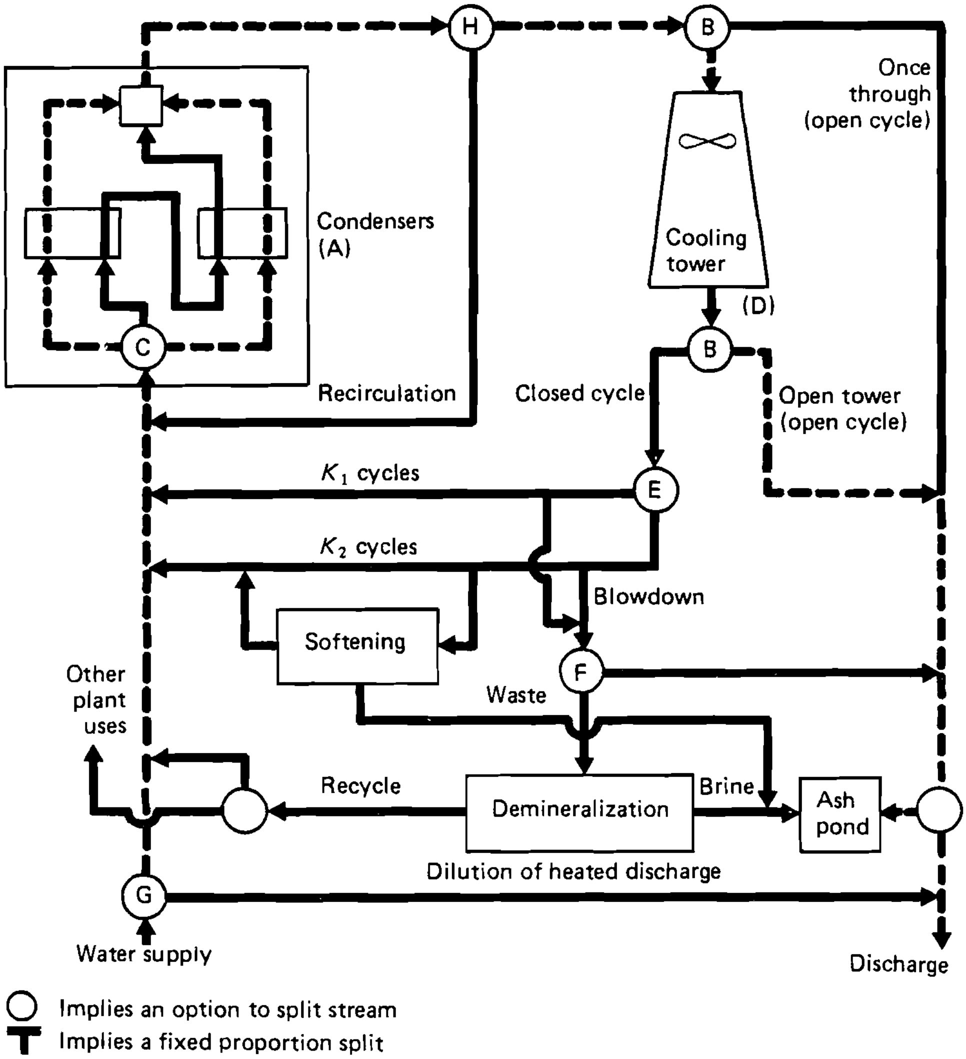

FIGURE 6 Flow pattern for an open-tower cooling system (indicated by broken line), where A–H are cooling system options.

This blowdown stream is extracted from the recirculating cooling water in order to maintain an acceptable concentration of dissolved solids in the system; this concentration would otherwise be continuously increasing because of the evaporative water losses in the cooling tower. The magnitude of blowdown is quite small, generally about 1 percent of the total flow of recirculating cooling water. The only withdrawal requirements of the closed-cycle system are a make-up stream to account for evaporative and drift losses, and blowdown extraction.

While drastically reducing water withdrawals for cooling purposes, the closed-cycle system increases water consumption (relative to that of a once-through system) because

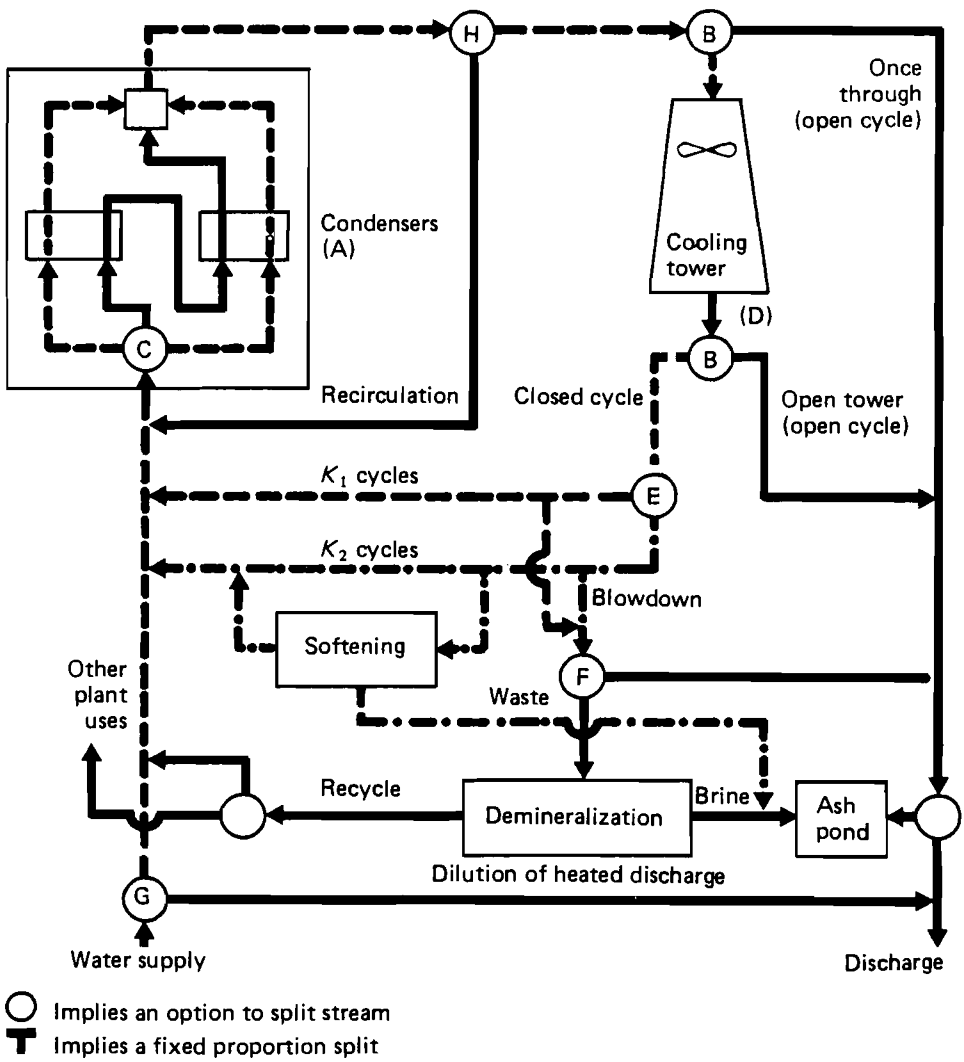

FIGURE 7 Flow pattern for a closed-cycle cooling system (indicated by broken line), where A–H are cooling system options.

of water losses in the tower. Similarly, heat discharges are rendered virtually insignificant by closing the system, but discharges of dissolved solids may become a problem because of the higher solids concentration of the blowdown (see option F). There are also two effects on plant thermal efficiency. The first involves the additional energy requirements for the pumps and fans as described for the open-tower system. The second relates to the temperature of the recycle water from the cooling tower. To the extent that this temperature is higher than that of the river water, the plant suffers a loss in thermal efficiency relative to that of an open-cycle system. This is because (for a given ΔT) the higher temperature cooling water increases the condensing temperature of turbine exhaust steam.

While this higher temperature is typical, under certain conditions the recycle water may actually be cooler than the river water (see option D). In this case the steam cycle thermal efficiency is improved, but this effect is outweighed by the additional energy requirements for the pumps and fans.

The essence of the water management problem at the power plant is determining an optimal combination of the three "pure" types of cooling systems (once-through, open-tower, and closed-cycle). This decision is an operating decision as well as a design decision, because the flow patterns through existing equipment can be altered to fit a given situation. (There is also an important interdependence between these decisions and the design choice of ΔT.) As a very simplified generalization, we can say that it is presumably necessary to construct a large enough cooling tower to assure compliance with heat discharge standards during low river flow and high temperature conditions. Beyond that, the tower capacity may be expanded and/or the time pattern of flows in the cooling system may be altered in optimal response to the time pattern of other environmental quality constraints, of meteorological and hydrological conditions, and of prices and charges for water withdrawals, water consumption, and effluent discharges.

Single or series condensers (C). In the normal mode of operation for the cooling system, the flows through the condensers of the various blocks (or units) are independent, although they may share the same channels for water intake and discharge. This "single condensers" mode of operation is illustrated by the broken lines in the box representing condensers in Figure 7. Under certain conditions, however, it may prove advantageous to route the heated cooling water from the outlet of one condenser to the inlet of a paired condenser. This alternative "series condensers" mode of operation is illustrated by the solid flow lines in the box in Figure 7. The series configuration has two economic and water use advantages. First, the cooling water requirements for the paired condensers are only a little over half those for singly operated condensers. Second, in the case of open-tower and closed-cycle systems, the increased outlet temperature from the second paired condenser means a higher temperature at the top of the cooling tower. For a given basin water temperature, this results in a greater temperature drop across the tower and accordingly more effective heat rejection. This improvement may allow for construction of a smaller cooling tower. The optimal configuration decision must weigh these advantages against the decline in thermal efficiency implied by the higher cooling water temperature in the second paired condenser.

Wet bulb approach factor for cooling tower (D). The water temperature in the cooling tower basin T_B is related to the wet bulb temperature T_W and a so-called wet bulb approach factor P, which depends upon cooling tower design, fan speed, and other considerations. We make the fairly typical assumption that

$$T_B = T_W + P \tag{2}$$

where all magnitudes are in degrees Centigrade.

This wet bulb approach factor affects the efficiency of heat rejection in the cooling tower – and therefore its necessary size – as well as the temperatures of the discharge stream in an open-tower system and of the recycle stream in a closed-cycle system. These temperatures in turn have definite implications for environmental quality and thermal efficiency. For low enough values of T_W and P, T_B may actually be lower than the river water temperature. This situation reduces somewhat the energy penalty for a closed-cycle cooling tower and enhances the capacity of an open-tower discharge to dilute the excess heat in a once-through discharge. In this study we use the value of the wet bulb approach factor as a kind of proxy design and operating option for the cooling tower. Four discrete values of P are incorporated as options, and linear combinations are allowed to increase the flexibility of the model in representing the design and operation of the cooling tower.

Cycles of concentration in cooling tower (E). The make-up water requirements for a closed-cycle system are a function of the evaporative losses in the cooling tower, the naturally occurring solids content of the make-up water (i.e., the river), and a so-called cycle factor K. This cycle factor further determines the amount and dissolved solids concentration of cooling tower blowdown. The following relationships hold:

1. Make-up requirements decrease with K
2. Blowdown decreases with K
3. Blowdown solids concentration increases with K

A maximum value of K is essentially determined by the concentration and composition of dissolved solids in the make-up water and the allowable build-up of solids of that composition in the cooling system. This base maximum value of K can be increased by removal of solids from the system or by softening a fraction of the cooling water to render a given solids concentration less harmful to the mechanical equipment. This latter option is considered here and is represented by decision node E in Figure 7. If no treatment is employed, the relevant flow pattern is that indicated by the upper broken flow line. In this case, the base cycle factor K_1 is 3. If a fraction of the recycle stream is treated, the flow pattern is that of the lower, dashed-dotted line, and the cycle factor increases. Our study models treatment of an amount of water equivalent to the make-up requirement, and this process increases the cycle factor K_2 to 6. We assume that the small waste stream from the treatment process is routed to the ash pond.

Treatment of cooling tower blowdown (F). The cooling tower blowdown collected at node F must be disposed of in an optimal manner consistent with liquid effluent discharge standards and effluent charges. Direct discharge of this blowdown is illustrated in Figure 8 by the upper, dashed-dotted flow line at node F. Some fraction of this discharge may be routed to the ash pond as indicated. Alternatively, all or some of the blowdown can be demineralized, producing a clean recycle stream for plant use. This option is illustrated in Figure 8 by the lower broken flow path from node F. The briny waste stream from this process is assumed to be routed to the ash pond. Demineralization of all cooling tower blowdown essentially eliminates discharges from a closed-cycle cooling system.

Dilution of heated discharge (G). Under certain conditions the temperature of the cooling water discharge may exceed the standard imposed on discharge temperature. In this case it may be advantageous to use a certain amount of river or other available water to "dilute" the heated discharge to an acceptable temperature. This incidental option is illustrated by the dashed-dotted flow line across the bottom of Figure 5. This procedure does not, of course, change the value of the total heat load added to the river; it just reduces the temperature differential at the discharge outlet.

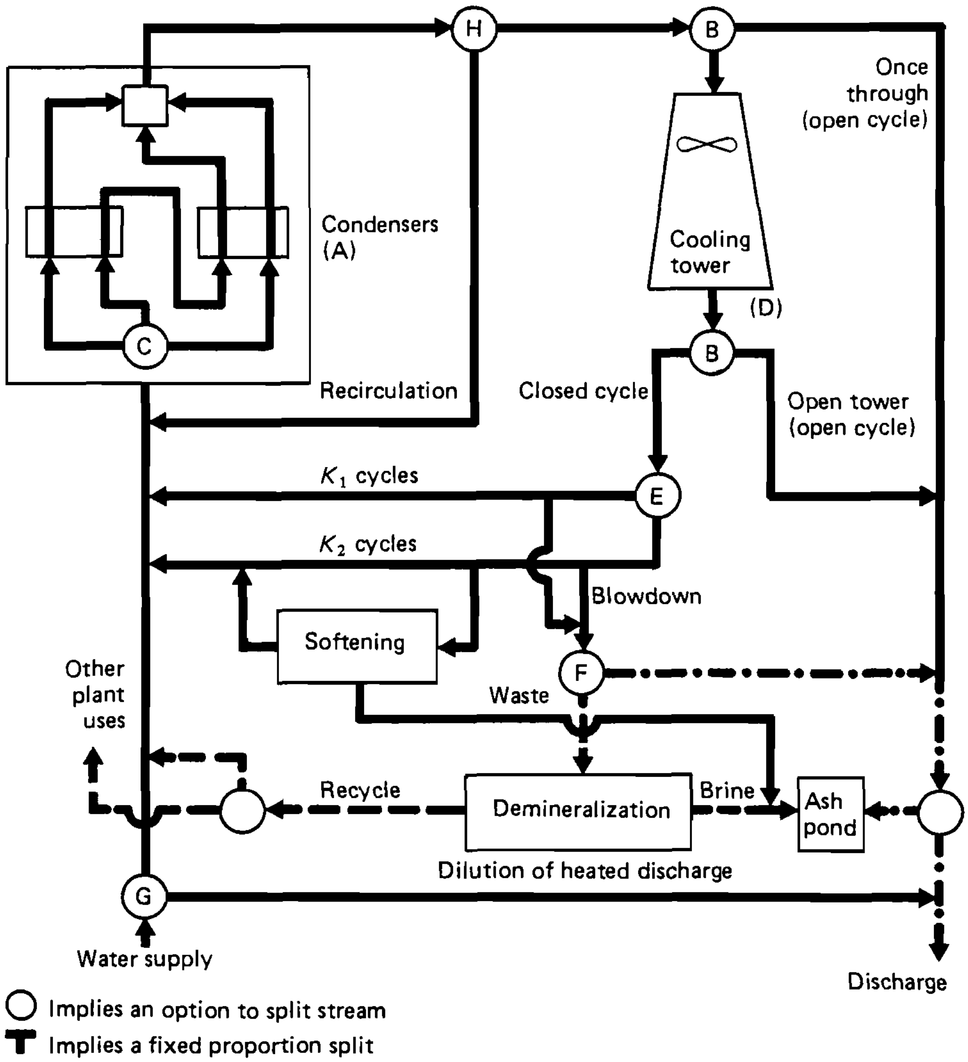

FIGURE 8 Disposition of cooling tower blowdown (indicated by dashed and dashed–dotted lines), where A–H are cooling system options.

Recirculation of condenser outlet water for temperature maintenance (H). The design of the condensers is such that a minimum inlet temperature of 10°C must be maintained. During some parts of the year, however, the temperature of the river – and even that of the recycle stream from a closed-cycle system – may fall below 10°C. In such a situation, the minimum inlet temperature can be maintained by recirculating just enough of the heated outlet water from the condensers to bring the inlet water temperature up to 10°C. This flow pattern is depicted by the dashed-dotted line at node H in Figure 9. Logically, the remaining flow of water proceeding to discharge or cooling tower circulation is reduced by the amount of this recirculation. Water withdrawals are similarly reduced, although the effect is somewhat complicated in the case of a closed-cycle system. If the river water

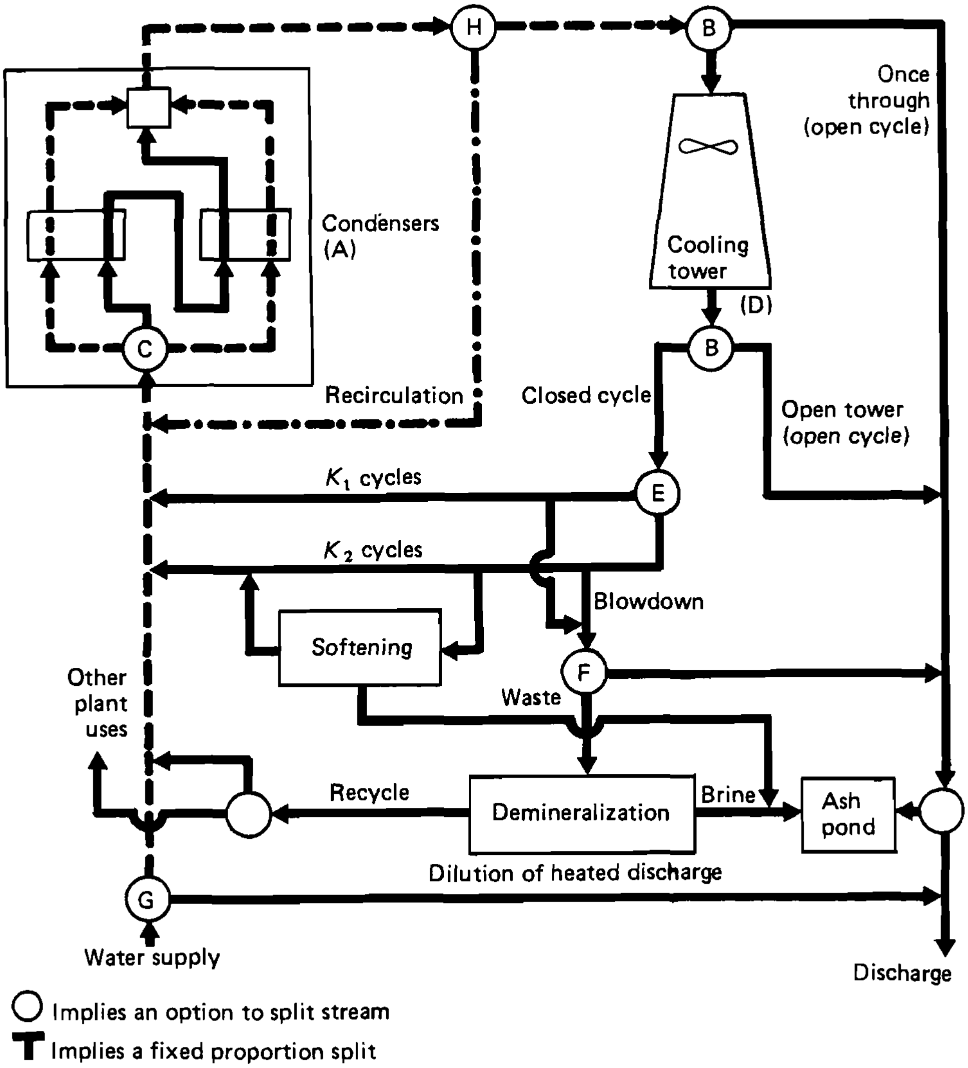

FIGURE 9 Recirculation of condenser outlet water (indicated by dashed–dotted line), where A–H are cooling system options.

temperature is less than 10°C but the temperature of cooling tower recycle is greater than 10°C, minimum condenser inlet temperature can be maintained by a proper combination of open- and closed-cycle flows.

3.2 Correspondence of Flows and Processes to Model Rows and Columns

Once the relevant material flows and unit processes have been identified (see Figures 2–9), the next modeling task is to develop a correspondence between these flows and processes and the rows and columns of the mathematical programming model. There are any number of ways in which this can be done. At one extreme, a one-to-one correspondence may be developed between each material flow and a model row and between each unit process and a model column. At the other extreme, an entire complex operation can be represented by a single column, with rows defined only for those materials with a net flow across the boundary of the operation. In practice, the correspondence employed is usually a compromise between the two extremes, and the modeler's choice depends upon a number of modeling and budgetary considerations. Four of these – model size, extent of true options, identification of important flows and process options, and linear and integer relationships – are identified here because of their general applicability and because of their particular importance in the formulation of our model.

The first consideration is *model size.* Budgetary or data processing limitations almost inevitably constrain the size of model which can be manageably manipulated and successfully solved. Generally a trade-off must be made between manageability/computability and the degree of material flow and process detail explicitly represented in the model. This directly conditions the kinds of correspondences which can be made between material flows and rows and between unit processes and columns. This is particularly so in models which attempt to capture the time dimension by representing flows and processes in each of a number of specified time periods. This trade-off regarding model size is an important factor in the resolution of the next two considerations.

The second consideration is the *extent of true options* in the flow and process configurations modeled. Given the model size consideration, it makes little sense to explicitly represent unit processes (and related flows) whose activity levels relative to other processes are logically fixed rather than being actual decision variables. In some cases the distinction is dictated by the basic technical relationships of the modeled technology; in other cases it is a consequence of a modeling decision not to model certain design or operation options. This leads to the third, related, consideration which is an identification of the *important flows and process options.* Here, too, it makes little sense to expand the size of the model with detail on flows and processes which do not significantly interact with the principal decisions, constraints, and flow patterns that are the target of the modeling analysis. In many cases, the flow diagrams themselves are an early stage in this simplification; the figures presented thus far already reflect considerable simplification of the water, energy, and residuals flows in the power plant.

The fourth consideration arises from the representation of power plant activities in terms of *linear and integer relationships.* Such a representation is motivated by the powerful algorithms and software available for solving linear programs and so-called mixed-integer programs with a manageable number of integer variables. This is not to say that the underlying relationships of electricity generation are linear (indeed, they are not), but rather that for a given application these relationships may be adequately approximated by well-formulated linear relationships, possibly supplemented by integer variables. The implication for model formulation is that the correspondence between unit processes and model columns should be defined so that the cost and input–output coefficients of linear model columns are independent of the activity levels of all model columns. As illustrated later, these correspondences may subsume in one column highly nonlinear relationships, or a group of linear columns may be used to piecewise-approximate a nonlinear relationship. Supplemental integer variables may be used to incorporate such considerations as mutual exclusiveness or "all-or-none" decisions, and they may further be used to ensure that the linear segments of a piecewise-approximated relationship are selected in the proper order.

To show how these four correspondence considerations relate to the construction of our model, we can illustrate the derivation of rows and columns from the various flow diagrams through a partial matrix tableau. A matrix tableau displays the rows and columns of the programming model and identifies the nonzero matrix coefficients which define model relationships. A partial tableau focuses on a particular subset of model rows and columns and as such may not display all nonzero entries in a given row or column. For present purposes, numerical values for many coefficients are not tabulated both because the values are subject to user discretion and because such generality allows for shorthand representation of several rows or columns as a generic class. The existence of positive coefficients is indicated in the tableaus by "+", and negative coefficients are indicated by "–". Rows and columns identified as seasonal in the tableaus are structurally replicated in the model as many times as there are seasons defined.

We use several partial matrix tableaus in the discussion of modeling correspondences and constraint formulations. As an aid in relating these tableaus to each other and to the overall model structure, Table 2 shows the different classes of rows and columns in the complete model. Classes of activities relating to coal (supply, transport, and combustion), air emissions, power plant construction and operation, and water use are given vertically; classes of rows pertaining to cost, coal, air emissions, heat, electricity, and water use are given horizontally. As can be seen, many parts of the matrix have little or no interaction with other parts, and the partial tableaus reflect these logical separations.

We can best identify one specific point of the model's structure in the context of Table 2. A logical accounting row is used in the model to accumulate the total capital investment in the power plant. A specified fraction of the investment (12 percent here) is prorated as an annual capital charge and "transferred" to the objective function by a special column. The objective function coefficient of this column is thus a convenient focus for altering or parameterizing the capital discount rate. As a further note, certain activities are seen to have entries in both the objective function and capital investment rows. The objective function coefficients for these activities represent the unit maintenance costs of the activities and are in addition to the annual capital charge.

3.2.1 Modeling Correspondences: Coal Transport and Combustion

Table 3 presents the partial matrix tableau corresponding to the coal transportation activities depicted in Figure 2. The correspondence applied is straightforward and almost one-to-one. This approach does not yield the minimum number of rows and columns but expands the size of the model somewhat for the sake of ease and flexibility in altering or parameterizing certain cost or technical coefficients. The number of rows and columns is kept small by modeling coal supply, beneficiation, and transport activities on an annual basis. This simplification is based on the assumption that monthly variations in these activities do not significantly affect costs or the pattern of water use in the power plant.

Separate column variables are defined for each of the activities of mining (supplying) coal, beneficiating coal, and transporting each type of coal from the mine to the power plant. Slurry transportation is modeled by three integer column variables, each representing the construction and (by assumption) uniform annual operation of a given capacity pipeline. As a simple example of the true option correspondence criterion, the logically

TABLE 2 Overview of model structure.

		Annual capital charge	Coal supply and transport	Coal combustion	Air emissions accounting	Air emissions accounting
		Logical	Annual	Seasonal	Seasonal	Annual
Cost (objective function)	Annual minimum	.12	+	+		+
Capital investment	Logical = 0	–1				
Coal	Annual ⩾ 0		+	—		
Air emissions constraints	Seasonal ⩽ 0			+		
Air emissions accounting	Seasonal = 0			+	—	
Air emissions accounting	Annual = 0				+	—
Heat to boiler	Seasonal ⩾ 0			+		
Intake water	Seasonal = 0			—		
Water handling capacity	Seasonal ⩾ 0					
Electricity generation	Seasonal ⩾ 0					
Wastewater	Seasonal = 0		+			
Water discharge constraints	Seasonal ⩽ b					
Water use accounting	Seasonal ⩽ 0					
Water use accounting	Annual = 0					
Integer control rows	Logical ⩽ or = 1		+ 1 Slurry			

necessary processes for drying beneficiated coal prior to rail transport and for mixing and drying coal on either end of the slurry pipeline are subsumed in the column variables for the transportation activities. Similarly, the coal preparation activities at the power plant are subsumed in column variables for plant construction and operation. Each slurry column variable provides a given quantity of slurry water at the power plant in each modeled season; two column variables are defined for each season to represent the options of discharging slurry water or treating it for plant use. A single column variable records the benefit of any excess coal transported to the Middle Vistula region by the slurry pipeline.

Plant construction	Electricity generation and cooling	Water discharge	Water treatment	Water use accounting	Water use accounting
Build	Seasonal	Seasonal	Seasonal	Seasonal	Annual
+	+		+		+
+					
Stack					
—					
	—				
	—		+	+	
+	—				
ΔT options					
—	+				
	+	—	—		
		+/—		+/—	
		+/—		+/—	
				+	—
ΔT options					
+ 1					

In terms of the rows defined for this sector of the model, only material flows directly affecting fuel and water use at the plant are represented; water flows at the mine are not explicitly modeled. Hence, there are annually specified rows for regular and beneficiated coal at both the mine and the power plant and seasonally specified rows for slurry water, intake water, and ash water at the power plant. The cost row (objective function) may be considered a material flow or a purely logical or accounting row. A logical row must also be defined to insure that only one slurry column variable is chosen, and another is defined to insure that excess coal benefits are applied only to slurry-transported coal.

TABLE 3 Partial matrix tableau: coal transportation.

		Coal supply	Coal beneficiation	Rail transport – regular coal	Rail transport – beneficiated coal
		Annual	Annual	Annual	Annual
Cost (objective function)	Annual minimum	+	+	+	+
Regular coal at mine	Annual ⩾ 0	1	–1.25	–1	
Beneficiated coal at mine	Annual ⩾ 0		1		–1
Regular coal at plant	Annual ⩾ 0			1	
Beneficiated coal at plant	Annual ⩾ 0				1
Slurry wastewater	Seasonal = 0				
Plant intake water	Seasonal = 0				
Ash water (pond)	Seasonal = 0				
Constraints on discharge to water	Seasonal ⩽ b				
Integer control row – slurry	Logical ⩽ 1				
Control row – excess coal benefits	Logical ⩾ 0				

Table 4 presents the partial matrix tableau corresponding to the coal combustion activities depicted at the lower right of Figure 2 and at the top of Figure 3. (To a certain extent, the separation of furnace and boiler in Figure 3 is a modeling abstraction.) Coal combustion is represented by two column variables in each season, one for regular and one for beneficiated coal. These variables convert a ton of coal into a calculated amount of kilocalories of usable heat in the boiler (a seasonally defined row). Water required for ash removal is recorded explicitly in the (seasonal) ash water row. Solid waste is represented only by its disposal cost incorporated in the cost coefficients for the combustion column variables. A sulfur accounting is made through logical rows defined for each season and annually. Seasonally specified column variables transfer the seasonal sulfur accounting to the annual row, and the coefficient in this row (identified in the tableau as "ratio") can be used to apply proportionately different penalties in the various seasons. An annually specified column variable records the total sulfur penalty in the cost row.

Slurry pipeline option 1	Slurry pipeline option 2	Slurry pipeline option 3	Excess coal benefits	Slurry water discharge	Slurry water recycle	Other matrix entries
Annual Integer	Annual Integer	Annual Integer	Annual	Seasonal	Seasonal	
+	+	+	–		+	+
–4.5	–9	–16				
						–
4.5	9	16	–1			–
+	+	+		–1	–1	
					.95	+/–
					.05	+/–
				+/–		+/–
1	1	1				
4.5	9	16	–1			

The key relationship in Table 4 is that between the combustion column variables and the column variables defining the height of the dispersion stack. As indicated in Section 2, this relationship indirectly models the constraint imposed on plant operation by the ambient air quality standard for sulfur dioxide. (There is no explicit row representation for flue gas or sulfur dioxide.) External to the programming model, an atmospheric dispersion model is used to calculate the maximum amount of regular and of total coal which can be combusted in a given season consistent with the air quality standard. These amounts are dependent on the height of the dispersion stack, and this dependence is incorporated in the model by means of seven explicit column variables, which together construct a stack of optimal height. The first such variable is constrained to provide a stack of minimum height (150 meters); the remaining six provide increments of up to 25 meters each. These columns piecewise-approximate a nonlinear relationship of increasing incremental capital costs per increment to the allowable quantities of coal combustion. Opposite signs of the

TABLE 4 Partial matrix tableau: coal combustion.

		Build minimum stack	Build higher stack	Burn regular coal	Burn beneficiated coal	Sulfur accounting	Sulfur penalty	Annual capital charge	Other matrix entries
		Fixed = 1	6 options (each ⩽ 1)	Seasonal	Seasonal	Seasonal	Annual	Logical	
Cost (objective function)	Annual minimum			+	+		+	.12	+/–
Capital investment	Logical = 0	+	+					–1	+
Regular coal at plant	Annual ⩾ 0			–1					+
Beneficiated coal at plant	Annual ⩾ 0				–1				+
Constraint on total coal combustion	Seasonal ⩽ 0	–	–	1	1				
Constraint on regular coal combustion	Seasonal ⩽ 0	–	–	1					
Heat to boiler	Seasonal ⩾ 0			+	+				–
Ash water	Seasonal = 0			–	–				+/–
Sulfur accounting	Seasonal = 0			+	+	–1			
Sulfur accounting	Annual = 0					Ratio[a]	–1		

[a]Used to apply proportionally different charges in each season.

coefficients for the stack-building and combustion column variables in the two rows constraining coal combustion imply that adequate stack height must be provided for coal combustion in all seasons. The model optimally balances stack costs against differential coal combustion costs.

3.2.2 Modeling Correspondences: Electricity Generation and Cooling System

The water withdrawal and discharge activities shown in both Figures 2 and 3 are represented by separate columns defined for each season. The interaction between these columns and a system of accounting rows and columns for water use charges and discharge constraints is rather complex, and is discussed in Section 3.3. We consider now the rest of the unit processes and flows shown in Figures 3 and 4. In short, the correspondence applied here is much at the opposite extreme of that applied to the coal transportation and combustion activities. Almost all of the processes depicted are subsumed into a single column variable representing electricity generation and a particular configuration of the cooling system. (The exceptions to this scheme are nodes F and G in Figure 4 and the unlabeled node in the lower right of the same figure. The column variables representing these decision points are shown in Tables 7 and 8.)

The combination of generation and cooling processes in a single column variable is motivated by all of the previous correspondence criteria, although reduction in model size may not be readily apparent. The true option criterion is applied to the combination of the boiler, turbine, generator, and condenser as no additional uses for the steam or turbine shaft energy are modeled. Similarly, demineralization of boiler feedwater is essential, and since no other uses are modeled for the demineralized water or the demineralization unit, it makes sense to combine the unit with the other four. (We assume that optional demineralization of cooling tower blowdown would involve a separate and cheaper unit since the treated water need not be of boiler purity.)

This combination of processes not only eliminates the need to define separate column variables for each process, it also eliminates the need to explicitly define rows to represent steam, shaft energy, or boiler feedwater. The important flow criterion is used to avoid row definitions for demineralizer brine or boiler blowdown; these small flows are assumed to be routed to the ash pond. This criterion is also used to aggregate all minor water flows for such purposes as boiler cleaning and resin regeneration in the demineralizer. These water inputs are furthermore indistinguishable (in source) from cooling water intake and demineralizer input for boiler feedwater; hence, all water inputs are aggregated into a single row for water intake.

This combination of unit processes and flows yields a fairly simple input–output structure for the electricity generation activity: water and boiler heat in and electricity and ash water out. The key modeling correspondence, however, involves the relationship between the generation activity and the cooling system. While conceptually (and to a large extent physically) separable, the generation and cooling processes are subsumed in a single column variable to maintain linearity in model relationships (the fourth correspondence criterion). As discussed earlier, the net heat rate for electricity generation depends upon the configuration of the cooling system, and the water input for cooling purposes in turn depends upon the net heat rate. Because of this interdependence, it is not possible to accurately define linearly separable column variables for generation and cooling processes; the heat and water input coefficients of the generation activity would be dependent upon the activity levels of the column variables representing cooling system options. Thus, the modeling correspondence applied defines (for each season) a number of column variables representing prespecified combinations of the generation activity (at a given condenser ΔT), a single or series flow pattern across the condenser, and a particular choice of options for the cooling system configuration. The resulting column enumeration scheme is summarized in Table 5; the options identified can be readily related to the options and decision nodes discussed in the context of Figures 4 through 9.

TABLE 5 Enumeration of plant design and operating mode combinations.

Design/mode	Combinations (in each season)		
Cooling system type	Once-through	Open-tower	Closed-cycle
Condenser ΔT	3	3	3
Single vs. series condensers	(Series not used)	2	2
Wet bulb approach factor	Not applicable	4	4
Cycles of concentration for closed-cycle cooling tower	Not applicable	Not applicable	2
Recirculation for maintenance of condenser inlet temperature[a]	1 or 2[b]	1 or 2[b]	1 or 2[c]
Total column variables defined	3 or 6	24 or 28	48–96

[a]When necessary. Two options are available:
1. Recirculation of sufficient amount of condenser outlet water
2. Combination of open-cycle and closed-cycle flow, if temperature of closed-cycle recycle exceeds 10°C

[b]Two options are defined if (and only if) river temperature is below 10°C and temperature of closed-cycle recycle exceeds 10°C for at least one of the defined wet bulb approach factors.

[c]If river temperature is below 10°C, two options are defined only for those combinations with a wet bulb approach factor which produces a recycle temperature greater than 10°C.

The column variables enumerated for each season represent "pure" system configurations; each represents a particular combination of fully implemented process options. While only one choice of condenser ΔT is allowed, mixed system configurations with respect to the other options are modeled via linear combinations (in the programming model solution) of the column variables for pure system types. This mixing by linear combination applies not only to combinations of once-through, open-tower, and closed-cycle cooling systems but also to combinations of single and series condenser flow patterns and to combinations of wet bulb approach factors or cooling tower cycle factors. Thus, the model indirectly has many more configurations available than the particular "pure" options enumerated at the identified decision points. Of course, these linear combinations are linear approximations to complicated nonlinear relationships, but it is believed that this approximation is significantly better than that accomplished by defining separate column variables to represent each of the modeled processes or decision points. From a computational viewpoint, this improved approximation is paid for by a marked increase in the number of column variables, but at the same time a significant number of rows is saved. In our model, this saving in the number of rows keeps the incremental computational burden of added columns within acceptable limits.

TABLE 6 Partial matrix tableau: interaction between generation/cooling and capacity provision activities.

		Plant construction ΔT option 1 Integer	Plant construction ΔT option 2 Integer	Provide water intake capacity Build	Provide cooling tower capacity Build	Provide softening unit capacity Build	Generation and cooling ΔT option 1 Seasonal	Generation and cooling ΔT option 2 Seasonal	Annual capital charge Logical	Other matrix entries
Cost (objective function)	Annual minimum	+	+	+	+	+	+	+	.12	+/–
Capital investment	Logical = 0	+	+	+	+	+			–1	+
Integer control row – ΔT options	Logical = 1	1	1							1
Electricity generation – ΔT option 1	Seasonal ⩾ 0	–					1			
Electricity generation – ΔT option 2	Seasonal ⩾ 0		–					1		
Water intake capacity	Seasonal ⩾ 0			1			–	–		–
Cooling tower capacity	Seasonal ⩾ 0				1		(–)[a]	(–)[a]		–
Softening unit capacity	Seasonal ⩾ 0					1	(–)[a]	(–)[a]		–

[a]If relevant.

A partial matrix tableau of the considerable number of column variables defined for a given season would be more cumbersome than useful. Instead Tables 6 and 7 are used to illustrate two important kinds of interaction between the generation/cooling column variables and other sectors of the model matrix.

Table 6 shows the relationship between seasonally defined generation/cooling activities and column variables defined to represent construction of various power plant units. Only two options for condenser ΔT are illustrated. As in all tableaus, rows and columns identified as seasonal are structurally replicated in the model as many times as there are seasons defined. The tableau illustrates two important aspects of model structure. First, the capital construction ("build") activities provide capacity in all defined seasons. The level of capacity provision depends upon the maximum seasonal requirement, as determined by the activity levels of the generation/cooling column variables; there may be excess capacity in seasons with less than the maximum capacity requirement. Second, the quantity of electricity to be generated in each season is specified by means of the (negative) coefficients of the integer plant construction activities in the seasonal electricity generation

TABLE 7 Partial matrix tableau: disposition of cooling water effluent.

		Generation with once-through cooling	Generation with open-tower cooling	Generation with closed-cycle cooling	Discharge once-through effluent
		Seasonal (given ΔT)	Seasonal (given ΔT)	Seasonal (given ΔT)	Seasonal (matched)
Cost (objective function)	Annual minimum	+	+	+	
Heat to boiler	Seasonal $\geqslant 0$	–	–	–	
Intake water	Seasonal $= 0$	–	–	–	
Electricity generation (given ΔT)	Seasonal $\geqslant 0$	1	1	1	
Ash water	Seasonal $= 0$	+	+	+	
Once-through effluent[a]	Seasonal $= 0$	+			–1
Open-tower effluent[a]	Seasonal $= 0$		+		
Closed-cycle blowdown[a]	Seasonal $= 0$			+	
Discharge accounting	Seasonal $\leqslant 0$				+/–
Control row[b]	Seasonal $= 0$	(–)	(–)	(+)	

[a]At known temperature and dissolved solids content.
[b]Used only when condenser inlet temperature maintenance is necessary and can be achieved by combination

rows. Since only one of the (0,1) integer variables can be chosen, these rows define not only how much electricity must be generated but also which class of generation/cooling activities (with respect to condenser ΔT) must be used to provide it.

Table 7 shows the interaction between generation/cooling activities and column variables for the disposition of cooling water effluent. These latter variables in turn interact with the structure for discharge constraints and water use accounting described in Section 3.3. The important observation here is that separate sets of rows are defined in each season for once-through, open-tower, and closed-cycle effluent. The once-through effluent rows are differentiated by temperature of the effluent stream, which is essentially determined by river temperature and condenser ΔT; thus, there are as many once-through effluent rows in a given season as there are options for condenser ΔT (three in this study). The open tower effluent rows are also differentiated by temperature, which in this case is determined by wet bulb temperature and the approach factor for the cooling tower. Thus, there are as many open tower effluent rows in a given season as there are options for the cooling tower wet bulb approach factor (four in this study). The dissolved solids concentration of

Ash pond once-through effluent	Discharge open-tower effluent	Ash pond open-tower effluent	Discharge closed-cycle blowdown	Ash pond closed-cycle blowdown	Recycle closed-cycle blowdown	
Seasonal (matched)	Seasonal (matched)	Seasonal (matched)	Seasonal (matched)	Seasonal (matched)	Seasonal (matched)	Other matrix entries
					+	+/−
						+/−
					.95	+/−
						−
1		1		1	.05	+/−
−1						
	−1	−1				
			−1	−1	−1	
	+/−		+/−			+/−

of open- and closed-cycle flow.

open-cycle effluent is not represented in the model, as no constraints or charges are imposed on the solids content of such discharges. The situation is quite the reverse, however, for closed-cycle effluent. There, the rows for cooling tower blowdown are differentiated by dissolved solids concentration, which is determined by the concentration in the intake water and the number of cycles for the tower. Since the flow of blowdown is quite small relative to river flow and open-cycle discharges, the differences in temperature of blowdown at different wet bulb approach factors are ignored, and only two blowdown rows are defined for each season (one for each cycle option). The temperature of the stream is approximated by using the average of the four wet bulb approach factors.

As indicated in the tableau, all open-cycle effluent streams may be discharged to the river (subject to constraints and charges) or routed to the ash pond. The same two options apply to closed-cycle cooling tower blowdown, and a third option is defined for demineralization and recycle of this stream. Briny waste from the demineralizer is routed to the ash pond. Since the ash water row is defined as an equality, no more cooling water effluent may be disposed of in this manner than is required for ash removal. It is important to recognize that specific column variables for discharge, ash pond routing, and demineralization/recycle are matched to each cooling water effluent row. In this manner, the proper concentration-dependent costs can be assigned to the demineralization options, and stream temperatures and dissolved solids concentrations are well-defined for the discharge activities. This characteristic of the formulation is essential for proper interaction with the model structure for discharge constraints and water use accounting.

TABLE 8 Partial matrix tableau: seasonal water use accounting and discharge constraints.

		Total water withdrawals QW	Dilution of heated discharge QF	Once-through discharge QO	Open-tower discharge
		Seasonal	Seasonal	Seasonal	Seasonal
Intake water	Seasonal $= 0$	1	-1		
Water discharge	Seasonal $= 0$			1	1
Water losses	Seasonal ≤ 0	1	-1	$+e$	
Constraint on temperature rise in river	Seasonal $\leq QR(DT)$	DT	$-DT$	$TO - TR$	$TC - TR$
Constraint on maximum discharge temperature	Seasonal ≤ 0		$TR - TM$	TO	TC
Heat discharge	Seasonal ≤ 0			$(TO - TR)/C$	$(TC - TR)/C$
Excess dissolved solids discharge	Seasonal ≤ 0				

3.3 Formulation of Model Constraints and Water Use Accounting

In Section 2 we identified three important classes of constraints in the model: seasonal production requirements, seasonal constraints on discharges to the water, and seasonal constraints on discharges to the air. Here we describe the formulation of the constraints on discharges to the water along with the general model structure for water use accounting. The formulation of the other two classes of constraints has already been discussed in the context of Table 4 (air emission constraints) and Table 6 (electricity generation requirements).

The structure devised for discharge constraints and water use accounting is depicted in two partial matrix tableaus. Table 8 displays the constraint and accounting structure for a given season, while Table 10 shows the interaction between four seasonal column variables and a set of annually defined rows and column variables which apply specified charges or penalties for water withdrawals, water losses, heat discharges, and dissolved solids discharges (in excess of the prescribed standard). Table 9 defines the abbreviations used for parameters of the important coefficients in Table 8.

Table 8 reflects the complexity of the model structure, which arises from the nature of the constraints themselves. Some of the constraints require calculation of weighted averages for which the weights are activity levels of column variables that are unknown before the model is solved. For simplicity of notation, the once-through, open-tower, and closed-cycle discharge variables are treated as though a single variable represented each class; in the model, however, there are a number of column variables in each class. Each such variable is treated in the same manner.

Closed-cycle discharge	Slurry water discharge	Total water discharge *QD*	Total water losses *QL*	Total heat discharge	Excess dissolved solids discharge	Other matrix entries
Seasonal	Seasonal	Seasonal	Seasonal	Seasonal	Seasonal	
						+/–
1	1	–1				
		–1	–1			
TB – *TR*	*TS* – *TR*	–*DT*				
TB	*TS*	–*TM*				
(*TB* – *TR*)/*C*	(*TS* – *TR*)/*C*			–1		
DB/1,000	*DS*/1,000	–*SD*/1,000			–1	

TABLE 9 Definition of parameters used in Table 8.

QR	Total river flow in the season
DT	Maximum allowable temperature increase in river; calculated as the minimum of (1) the specified temperature increase allowance for the season, either 4°, 5°, or 6° C, and (2) the difference between maximum allowable river temperature, 30°C, and upstream river temperature
TR	Upstream river temperature
TO	Temperature of once-through discharge (condenser outlet temperature)
TC	Temperature of open-tower discharge (cooling tower basin temperature)
TB	Temperature of closed-cycle discharge (cooling tower basin temperature modified somewhat by presence of wastewater from a pretreatment unit)
TS	Temperature of slurry water discharge
TM	Maximum allowable discharge temperature (35°C)
C	Heat capacity of water
DB	Dissolved solids concentration of closed-cycle discharge
DS	Dissolved solids concentration of slurry water discharge
SD	Concentration standard for dissolved solids in discharge (500 mg/l multiplied by a seasonal proportionality constant, if desired)
e	Coefficient expressing evaporative losses in the river per unit of once-through discharge

We have adopted the convention that total withdrawals from the river QW include withdrawals for dilution purposes only QF; this gives rise to the negative unity coefficient for the dilution variables in the intake water row. This structure implies that any charges for water intake are also paid for dilution withdrawals. Should this not be the desired charging scheme, it is necessary only to remove the dilution variable coefficients in the rows for intake water and for the temperature rise constraint. Water withdrawn for use in the plant QI is simply $QW - QF$.

The row for water discharge simply accumulates the total discharge of cooling water and slurry water. This total, as reflected in the activity level of the total water discharge variable QD, is essential to the formulation of the discharge constraints.

The water loss accounting row accumulates losses QL as the difference between plant intake and discharge plus an estimate of the in-river losses caused by once-through discharge QO. Algebraically, the row states

$$QW - QF + e(QO) - QD - QL \leqslant 0$$

This can be rearranged as

$$QL \geqslant QW - QF + e(QO) - QD = (QI - QD) + e(QO)$$

which is the desired accounting when equality holds. (The inequality is merely a modeling convenience which improves computability and allows for the possibility of negative losses without defining another column. Negative losses might occur because of slurry water discharge.)

By appropriately defining DT as indicated in Table 9, the modeled constraint on temperature rise in the river reflects the stronger of the two policy conditions on maximum temperature rise and maximum downstream temperature (see the definition of water discharge constraints in Section 2). In notation, this constraint requires that

$$TR' \leqslant TR + DT$$

where TR' is the temperature of the river downstream of the plant (after complete mixing).

The key to formulating the constraint is expressing TR' in terms of variables contained in the model. Logically, this temperature is the flow-weighted average of the upstream river temperature and the plant discharge temperature TD; the weights are river flow remaining after plant intake and plant discharge. Hence

$$\frac{(QR - QI)TR + QD(TD)}{(QR - QI) + QD} \leqslant TR + DT$$

$$(QR - QI)TR + QD(TD) \leqslant (QR - QI)(TR + DT) + QD(TR + DT)$$

$$QD(TD - TR - DT) \leqslant (QR - QI)DT$$

$$QI(DT) + QD(TD - TR) + QD(-DT) \leqslant QR(DT)$$

$$(QW - QF)DT + QD(TD - TR) + QD(-DT) \leqslant QR(DT)$$

$$QW(DT) + QF(-DT) + QD(TD - TR) + QD(-DT) \leqslant QR(DT)$$

The constraint form used in the model is obtained directly from this last inequality by appropriately resolving $QD(TD - TR)$ into the various components of total discharge (i.e., once-through, open-tower, closed-cycle, and slurry water).

The constraint on maximum discharge temperature is obtained by a reformulation similar to that applied above. The flow-weighted average temperature of the mixed discharge and dilution streams must not exceed the specified maximum. In notation,

$$\frac{QF(TR) + QD(TD)}{QF + QD} \leqslant TM$$

$$QF(TR) + QD(TD) \leqslant (QF + QD)TM$$

$$QF(TR - TM) + QD(TD) + QD(-TM) \leqslant 0$$

The constraint form used in the model is obtained by resolving $QD(TD)$ into the four discharge components.

The row for accounting total heat discharges straightforwardly accumulates the incremental heat content of each discharge stream. By definition, this heat loading (per period of time) is the discharge volume multiplied by the temperature differential (between discharge and river) and then divided by the heat capacity of water. The column variable for heat discharge records the total amount of this heat load added to the river (over the course of a season).

The accounting for excess dissolved solids discharges is applied, by specification, to closed-cycle and slurry water discharges only. Since taxation of the excess is applied on the basis of a quantity of solids, the coefficients in the accounting row must be scaled in order to convert concentration multiplied by discharge volume (per season) into the appropriately measured quantity of solids. The row thus accumulates solids discharged in blowdown and slurry water and subtracts a nonpenalized allowance determined by the product of the specified concentration standard and the discharge volume. The difference, if positive, is recorded by the activity level of the column variable for excess dissolved solids discharges. We include the volume of open-cycle discharges in determining the nonpenalized allowance, but do not count the solids content of open-cycle discharge. This convention can be easily changed, either to exclude open-cycle volume or to include open-cycle solids.

Shifting focus to the annual application of charges and penalties for water use, Table 10 details the four points of intersection between the seasonal and annual accounting structures. The structure is quite straightforward, although not the most efficient in terms of the number of rows and columns defined. The motivation for this structure is the same as that alluded to earlier for sulfur accounting. The formulation allows for the specification of proportionately different charges and penalties in different seasons while at the same time defining a limited number of base values for these charges and penalties, which can be easily accessed for alteration or parameterization. These base values are recorded as positive objective function coefficients in the four annual accounting columns. Seasonal values are specified through the "ratio" entries in the seasonal accounting columns. Each ratio coefficient is the ratio between the seasonal value and the base value in the annual column. This feature is employed in our study to "zero-out" withdrawal and loss charges in March, April, and May (high river flow months) and to zero-out heat discharge taxes in December through February (when inhibition of freezing may be a benefit). Parametric analysis on the base charges and taxes is reported in Section 4.

3.4 Specification of Model Coefficients

Once the row and column structure for the programming model has been established, matrix coefficients must be specified. This task may vary greatly in complexity from one sector of the model to another. In many cases coefficient specification amounts to little more than arranging basic data in a manner that is consistent with respect to units and the period of time over which flows are averaged and measured. Such is the case, for example, with most of the coefficients for coal transportation and combustion (Tables 3 and 4) and with the coefficients for water use accounting and discharge constraints (Tables 8 and 10, noting some overlap with Table 7). In other cases, however, coefficient specification is computationally complex because the coefficient represents the net effect of many technical relationships. Such is the case with the coefficients for allowable coal combustion in the stack-building column variables and with most of the coefficients for activities related to electricity generation and cooling. The procedures developed for specifying these coefficients are central to the modeling analysis.

3.4.1 Use of Matrix Generators

Operationally, the coefficient matrix for our programming model is specified through the use of so-called matrix generators. Essentially, a matrix generator is a specialized computer program designed to accept raw data and instructions from the user and to calculate (according to specified mathematical and logical relationships) the input–output

TABLE 10 Partial matrix tableau: water use charges and penalties.

		Water withdrawal charge	Water loss charge	Heat discharge penalty	Excess solids discharge penalty	Total water withdrawals	Total water losses	Total heat discharge	Excess dissolved solids discharge	Other matrix entries
		Annual	Annual	Annual	Annual	Seasonal	Seasonal	Seasonal	Seasonal	
Cost (objective function)	Annual minimum	+	+	+	+					+/–
Accounting row – water withdrawal charge	Annual = 0	–1				Ratio[a]				
Accounting row – water loss charge	Annual = 0		–1				Ratio[a]			
Accounting row – heat discharge penalty	Annual = 0			–1				Ratio[a]		
Accounting row – excess solids discharge penalty	Annual = 0				–1				Ratio[a]	
Intake water	Seasonal = 0					1				+/–
Water losses	Seasonal $\leqslant 0$					1	–1			+/–
Heat discharge	Seasonal $\leqslant 0$							–1		+/–
Excess dissolved solids discharge	Seasonal $\leqslant 0$								–1	+/–

[a]Used to apply proportionally different charges in each season.

coefficients for each of a specified set of column variables in the programming model. Utilization of such a program is particularly useful (often necessary) when calculations are numerous and/or complex and especially when such calculations must be performed repeatedly according to different specifications of the arguments. In our model, the seasonal and other multiple-option structures give rise to a high degree of repetition for calculations ranging from trivial to extremely complex (even iterative). In short, the model developed for this study could not be specified without the aid of matrix generators.

Five independent (FORTRAN-coded) matrix generators have been developed to produce the entire programming model matrix. One of these programs specifies the column variables related to coal transportation and combustion. Three key programs specify the large number of column variables representing electricity generation and cooling, as well as the columns representing disposal of cooling water effluent. A final program generates everything else, primarily additional water-handling activities, certain construction activities, and accounting procedures for the constraints and charges on waterborne discharges.

3.4.2 Coefficient Specification

For the coal transportation and combustion sector (Tables 3 and 4), much of the process of coefficient specification involves accumulating the various cost components for the operation of a modeled activity. These accumulated costs must then be expressed in terms of a unit level of operation of the defined column variable, which in the case of the integer variables for the slurry pipeline amounts to an entire year of operation. Slurry wastewater in a given season is simply a loss-adjusted fraction of annual flow, which is in turn the product of coal-carrying capacity and the assumed water-to-coal ratio (one in this case). Heat delivered to boiler per ton of coal combustion is defined as the heat content of the coal divided by an assumed parameter for boiler efficiency. Ash water input is proportional to the ash content of the coal, and the coefficient in the seasonal sulfur accounting row is nothing more than the fractional sulfur content of the particular grade of coal.

As indicated previously, the coefficients for the two (seasonal) coal combustion constraints involve more complicated calculations. Most of this analysis was performed "off-line," and the matrix generator serves only to convert the results of this analysis to a form and units consistent with the structure of the programming model. The basic logic and intent of the analysis were briefly outlined in the nonmathematical description of the model in Section 2.

Coefficient specification is relatively simple for the tableaus relating to water use accounting and discharge constraints (Tables 8 and 10). Here most of the work has already been done in the formulation of the structure itself. The logical function of the coefficient within this structure straightforwardly dictates its numerical assignment. As can be seen in the two tableaus and the definitions provided in Table 9, the coefficients are either basic data inputs or simple mathematical operations on those inputs.

The most complex specification task is the derivation of the column vector representations for the electricity generation/cooling system combinations. This is a multistep procedure involving three separate matrix generators (one for each type of cooling system). Ignoring the operational separation of these programs, the basic procedure may be summarized as follows.

First, an enumeration is made of the different combinations of plant design and operating modes to be considered; Table 5 is an example of such an enumeration. Second, the number of seasons to be considered is defined and a tabulation is made of the plant design and operating combinations considered sensible operating schemes in each season. (Essentially, this is a determination of the seasons during which the recirculation and series condenser options are to be considered.) For each defined season a tabulation is also made of various plant and environmental factors influencing the operation of the steam cycle or heat removal components of the power plant. The steam cycle operation is influenced by the plant utilization rate and the temperature of the water in the cooling system. Cooling system performance and resulting water temperature are influenced by river water temperature, dry and wet bulb atmospheric temperatures, and humidity.

Third, a set of design operating conditions is calculated for each plant type configuration on the basis of data on nominal operating conditions for a typical 500-MW generating unit in Poland. Estimates of power requirements for pumps, fans, electrofilters, and other incidentals are employed to convert from a gross to a net basis of operation. The key operating conditions calculated (all unitized on one net megawatt-hour of production) are net steam cycle heat rate, net overall heat rate, and net cooling rate.

Fourth, for each combination of plant design and operating mode, a progression is made through each defined season of operation in order to calculate variations from the design operating conditions brought about by seasonal variations in the plant and environmental factors. Two functional relationships are central to this determination. The first calculates the steam cycle heat rate as a function of steam condensing temperature and the plant throttle factor.* This factor has a fundamental effect on steam cycle efficiency and is a function of the plant utilization rate, plant up-time, and the net-to-gross operating ratio. The steam condensing temperature can be related to the outlet temperature of condenser cooling water, which is in turn a function of cooling water flow rate, condenser cooling water inlet temperature, and the required rate of waste heat removal. Since this last factor is in turn a function of the steam cycle heat rate, a certain circularity results in the functional relationship. This problem is resolved by means of an iterative convergence calculation on the throttle factor, the condenser flow rate, and the condenser inlet and outlet temperatures. We derived the functional form for the relationship (and particularly the dependence on throttle factor) from data published by the United States Environmental Protection Agency. Constants of the equation appropriate to Polish plant conditions were obtained by fitting the equation to data on nominal turbine performance for a 500-MW generating unit. (It was necessary to assume that the Polish data correspond to a throttle factor of one.) Figure 10 shows sample curves and the fitted data points.

The second important functional relationship involved in calculating seasonal operating conditions is a determination of cooling tower performance (when relevant) based upon the cooling water flow rate and the environmental factors listed previously. The important outputs of this determination are the temperature of the cooling tower basin water and the required dimensions of the cooling tower itself. In the case of a closed-cycle system, the temperature of the recycle water feeds back into the steam cycle equation because of its influence on condenser inlet temperature. Tower size also feeds back into the steam cycle equation because the pump and fan energy requirements for a given size tower affect the net-to-gross ratio and hence the throttle factor. These determinations must accordingly be part of the convergence loop for the steam cycle equation.

*The throttle factor may be defined as the ratio of the actual rate of heat delivery to steam (under a given operating condition) to the nominal rate of heat delivery to steam for a given plant design.

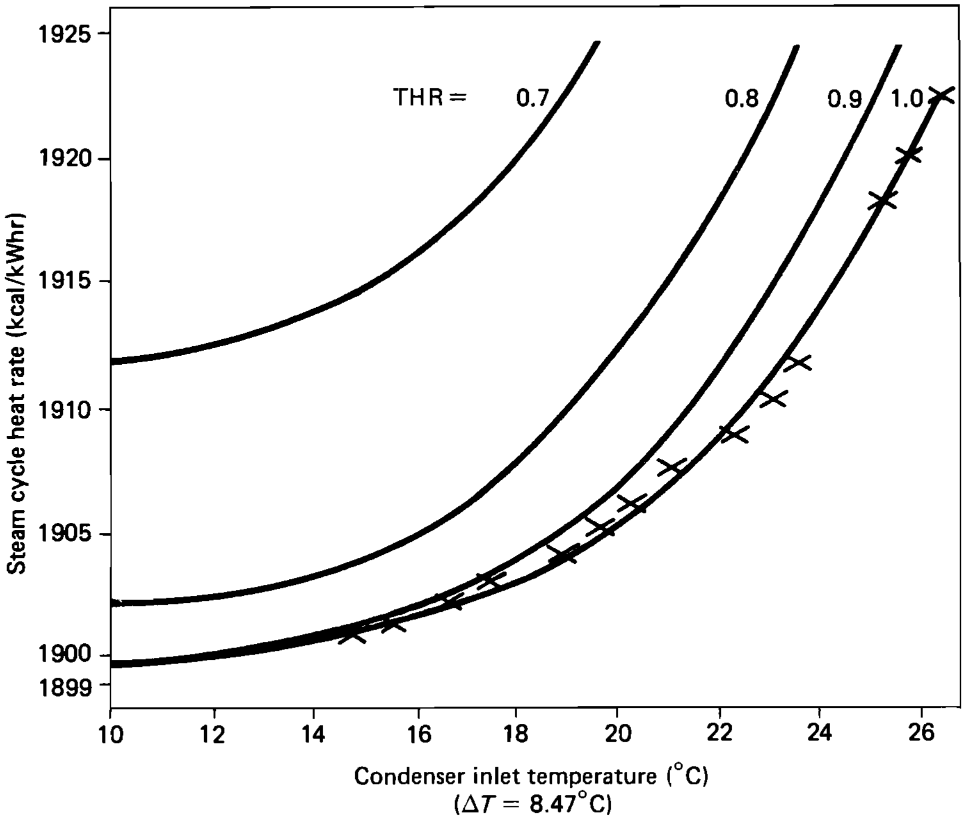

FIGURE 10 Steam cycle relationship. THR indicates throttle factor.

The final step in this procedure (for a given plant type, operating mode, and season) is specification of the actual input–output coefficients for a column variable, based on the important operating conditions determined in the convergence loop. As depicted in Tables 6 and 7, the specified inputs are boiler heat, water, and installed capacity (generation, water intake, cooling tower, softening unit). The specified outputs are electricity (one megawatt-hour net), ash water, and cooling water effluent of a known temperature and dissolved solids concentration. Since the characteristics of the effluent are known at this stage in the procedure, the coefficients of the column variables for disposition of the effluent are also specified.

All of these calculations and coefficient specifications are performed automatically by the matrix generators for each plant design, season, and operating mode selected by the user.

3.5 Data Availability

Aside from its educational value, a mathematical programming model is only as good as the economic and technical data available for defining its coefficients. We were able to construct a fairly complex programming model for this study because the data were deemed good enough to justify it. For the most part, the data base was collected by the IMGW research team and is specific to Polish conditions. Where gaps appeared during the course of model development, technical information based on similar technologies in the USA was employed, but use of cost data from the USA was successfully avoided.

Some of the more important components of the collected data base include the following:

1. A set of highly detailed specifications for the design characteristics of the power plant
2. Engineering cost estimates for the construction and design of power generation and water treatment processes
3. A tabulation of average monthly values for a wide range of meteorological and hydrological variables needed in the analysis, including a monthly specification of low flows in the river (flows exceeded 90 and 95 percent of the time)
4. A set of relationships and parameters for calculating the size of cooling tower required to dissipate a given amount of waste heat under specified meteorological conditions (plus the costs of tower construction)
5. A specification of the physical, chemical, and combustion properties of the two available grades of coal
6. Engineering cost estimates for the various coal handling and combustion processes
7. An assessment of the water management benefits accrued from the use of saline wastewater in the slurry pipeline
8. A full specification of relevant environmental standards and constraints
9. A set of relevant prices and penalties for various aspects of water and coal use, along with ranges of variation in these values for use in water demand and other analyses

On the whole, the data base is more than sufficiently reliable to produce sound modeling results. Those aspects of the data base in greatest need of further refinement are: (1) the cost structures for coal beneficiation, slurry transport, and certain incidental water treatment processes; and (2) the benefit assessment for use of saline wastewater in the slurry pipeline.

3.6 Seasonality

Throughout our discussion, the concept of seasons has been frequently employed, but generally with an intentional vagueness as to number and duration. The key determinations which must be made in defining model seasons are: (1) how short a time period is necessary to accurately capture the important time-dependent variations in operating conditions; and (2) how short a time period can be manageably considered in the modeling analysis (which involves not only model size but also data collection and interpretation of results). In general, there must be some trade-off between accuracy of representation and manageability. In this study we define 12 "seasons" corresponding to the months of the year.

Treating the time-dependent conditions in order of increasing complexity, we note that policy specifications tend to show the least time-dependent variation. In our model, a month-by-month specification of charges and standards is perfectly adequate and manageable. Output levels for a baseload plant may also be reasonably assumed to be constant over a short period of time; the most significant variation is caused by the schedule of planned plant maintenance which calls for shutdown of each block at least once a year. In our study, the knowledge that these shutdowns are concentrated in the summer months and require an average of six weeks for completion allows us to make a straightforward specification of the fraction of plant capacity in operation in a given month. Applying a constant baseload utilization rate to this operating fraction provides a monthly time pattern of plant output levels.

As is to be expected, the time pattern of meteorological and hydrological conditions demonstrates the shortest period of variation. Ultimately the availability of data and the manageability of the problem formulation dictates the choice of time period. For this study, monthly data are available for the most important meteorological/hydrological conditions, and careful design renders the problem manageable at this level of detail.

The model specifications for the defined time periods need not be based on average values, nor is it necessary to define approximately uniform time periods. These choices depend on the analyst's conception of the proper context for optimizing plant design. For example, it may be considered appropriate to optimize plant design according to expected values for the time pattern of operating conditions. On the other hand, it may be desirable to design the plant to meet a time pattern of "worst possible" conditions or conditions exceeded in adversity only 5 or 10 percent of the time. Perhaps the most sophisticated treatment would involve an optimization of design and operation in accordance with a time pattern of both average and critical conditions, with time periods for each defined in relation to expected frequencies of occurrence of the various sets of operating conditions. In the present case, manageability and data considerations dictated a composite approach employing monthly time periods, average meteorological factors, and low flow in the river defined as that with a 90 percent probability of being exceeded monthly. The model structure is sufficiently flexible, however, to allow for easy redefinition of time periods and operating conditions.

4 USE OF THE MODEL

The previous sections have dealt primarily with a description of the model and its development; this section deals with three aspects of model use. First, a few comments are made on the operation of the model, its size and computability. Second, a brief discussion is provided of the kind of information available from the model and its potential uses. Third, some representative results are presented based on preliminary analyses performed with the model in the latter stages of its development at IIASA.*

4.1 Model Operation, Size, and Computability

A serious attempt has been made in the development of the model to render it accessible to users without a great deal of mathematical programming experience. To use

*Ultimately the model was transferred to IMGW computer installations in Warsaw.

the model it is necessary to execute five FORTRAN matrix generators, collect the various sectors of the matrix produced by these programs, and then solve the model using an available solution algorithm. Accordingly, a user must have some knowledge of the host computer system, FORTRAN, and the available mathematical programming software.

From the standpoint of model specification, a user with only a general understanding of model intent and structure can produce a matrix by defining three modest data tables. These tables contain key cost specifications, meteorological and hydrological data for each season, and policy-dependent discharge constraints, prices, and penalties for each season. Through these tables the user also selects the number and length of seasons, and the number and nature of important options such as temperature rise across the condenser and cooling tower wet bulb approach factor. The matrix generators automatically expand on the other kinds of options described in this report. By this procedure, the model expands or contracts in a structurally consistent manner to accommodate the level of detail desired by the user. This frees the user to concentrate on parameter refinement and definition of desired analyses, rather than on the details of model structure. The more experienced user, naturally, may desire to alter the inner workings of the matrix generators in order to modify the structure of the model or the nature of available options.

In its present form the model encompasses 12 month-long seasons, 3 options for condenser ΔT, 4 options for the cooling tower approach factor, 2 coal types, and 3 slurry pipeline options. In addition to these specifications, the model includes the full range of fuel provision and water management options selected for this study. At this level of detail, the model contains approximately 350 rows and 1,400 columns.

These dimensions do not constitute an especially large problem, and continuous linear programming solutions posed no particular difficulties on an IBM 370/168 computer employing the SESAME linear programming system. An integer algorithm, however, was not readily available within the time constraints for the study. Fortunately, because of the limited number of integer variables, it was possible to heuristically determine optimal solutions – often by inspection and occasionally, in case of doubt, by limited enumeration. On the whole, our computing experience with the model has been highly favorable.

4.2 Information Available and Potential Uses

One of the major advantages of programming models is the wealth of information which can be derived from well-conceived patterns of model solutions. Our model can be straightforwardly applied to estimate the capital and operating costs as well as the resource demands and pollution loads that result from operation of the power plant under a wide variety of conditions. Standard parametric and ranging techniques can be employed to test the sensitivity of these estimates to model assumptions and specifications. Using such techniques to identify the important constraints and cost values conditioning the model's solution not only contributes to an understanding of the real-world system but also indicates which aspects of model development should be most closely double-checked for accuracy and reasonableness.

The potential also exists for expanding the boundaries of the problem to include a direct interface between the programming model and models of water and air quality. Our present method employs such environmental models in the background as a means of calculating rigid discharge constraints, but makes no attempt to determine the environmental impacts of relaxing or tightening those constraints and to compare such an impact to the economic effect on power plant operations. Such an approach can be a useful means of evaluating public policy and the costs of environmental protection. It is, perhaps, most profitably implemented by means of a direct interface between the emission level component of the programming model and the residual load component of the corresponding environmental model. Residual loads are then traced through the environmental model to determine the impact of plant operations on environmental quality. This technique has been successfully employed in a number of documented cases (e.g., Spofford 1976). Such an interface can, but need not, involve a simultaneous solution of disparate models according to some unitary objective criterion. It can also be used more informally to assess the trade-offs between air and water pollution or between economic and environmental objectives of social policy.

The primary purposes of this case study and model were to investigate the patterns of water use in a power plant on the Vistula River and to estimate the demands for water, both as a process input and as a medium for disposal of process wastes. IMGW therefore developed a slate of variants for the seasonal charges for water withdrawals, water losses, heat discharges, and dissolved solids discharges. Some fraction of the many possible combinations of these variants can be investigated to determine the induced changes in optimal plant design and operation. These changes map out derived demand functions for water in its various capacities; such functions may be determined jointly or independently. Shifts in these functions brought about by changes in model constraints or parameters can also be studied, both for their own sake and as a means to identify important interdependencies among various water uses or among water use, fuel use, and air pollution considerations. This is only a cursory listing of the kinds of analyses that can be performed with the Vistula model; it would not be unrealistic to assert that the primary limits to the information that can be obtained are the imagination and stamina of the analyst, and perhaps the computing budget.

4.3 Representative Model Results

Model analyses performed at IIASA were directed almost exclusively to the impact of variations in the charges (prices) for water withdrawals and losses, although some less extensive variations in the penalty for heat discharges and the price of coal were also investigated. We did not analyze the impact of changing the constraints on discharges to the water and air or the penalty on excess dissolved solids discharge. While we summarize key results of these limited analyses in this section, it is important to remember that model solutions contain a great deal more information than that presented here.

The (base) price for water withdrawals was varied in fixed steps over a range from 0.0 to 5.0 złoty (Zł) per cubic meter (1.0 Zł = 100 groszy ≅ 0.03 US dollars, at the time of the study, 1977–78). The charge for water losses was fixed at 25 times the price for water withdrawals. Initial penalties for heat and excess dissolved solids discharges were set at 0.5 Zł/10^6 kcal and 0.5 Zł/kg, respectively. Alternate heat discharge penalties of 1.0 and 2.0 Zł/10^6 kcal were investigated at three different water prices. The minemouth price of regular grade coal was specified as 320 Zł/ton for most of the modeling analyses, but this price was increased to 1000 Zł/ton (at three different water prices) to investigate the interaction between thermal efficiency and water use. All model constraints were held constant throughout the analyses.

We can make three generalizations about the model results. First, the maximum-size slurry pipeline proves to be the preferred mode of coal transportation in all cases. This consistently preferred option underscores a need to carefully verify the cost and feasibility assessments reflected in model specifications. Ideally, an investigation should be made of the range of costs over which the slurry (at any size) remains the preferred option.

Second, the maximum of the three specified options for condenser ΔT proves to be the preferred option for plant type in almost all model solutions. This preference arises both from reduced water flows and from lower capital costs relative to the other two options. The sharp rise in coal prices, however, shifts the preference to the middle option, indicating a dominance of the improvement in thermal efficiency over both increased water flows and capital costs. More sophisticated sensitivity analysis would be required to determine the precise switchpoint and/or to determine the relative importance of water flow vs. capital cost in the choice of condenser ΔT. It also seems that future analysis would be improved by providing a yet higher option for ΔT and removing the lowest option.

Third, the model solutions show great variation in the patterns of water use and in the marginal costs of electricity from season to season (i.e., from month to month). This is, of course, the expected result given the considerable seasonal variation in operating conditions, constraints, and prices and penalties. As a weak generalization, the open-tower cooling configuration seems to be a preferred option for complying with discharge constraints. The costs specified for make-up water treatment (even at three cycles) render a closed-cycle system the option of last resort. This sensitivity points to a need to carefully verify the treatment costs applied in the model.

Rather than presenting more specific results by season in this report, we can communicate the "flavor" of the model results by using certain annual totals or weighted averages. Since withdrawal and loss charges and heat discharge penalties are not applied in certain seasons, the annualized results presented must inevitably dilute somewhat the impact in price-sensitive seasons; impacts are nonetheless quite visible.

Figure 11 illustrates the derived demand relationship for water withdrawals, given the standard specifications for coal price and heat discharge tax. The axes are defined according to the convention in economics, even though price is specified and quantity observed. Withdrawal quantity is the annual total expressed in m^3/sec; this expression allows for a comparison with river flow over the middle reach of the Vistula. Mean annual flow is 297 m^3/sec, and low flows with a 10 percent probability of being exceeded range from as low as 89 m^3/sec in fall and winter to 249 m^3/sec in the spring.

Line segments connecting observation points in the graph are provided as an aid to visualizing the general shape of the relationship. They do *not* represent the response surface of the programming model. This response surface is actually a step function following the basic pattern indicated in the graph. Each step in this function identifies a range of prices over which the optimal process configuration in the model does not change. Since we specified alternative prices *a priori* rather than determining them by a parametric algorithm (which finds switchpoints in the model solution) our analysis did not identify all of the steps in the response surface. As a result, a given observation may represent either an endpoint or an interior point of the relevant step.

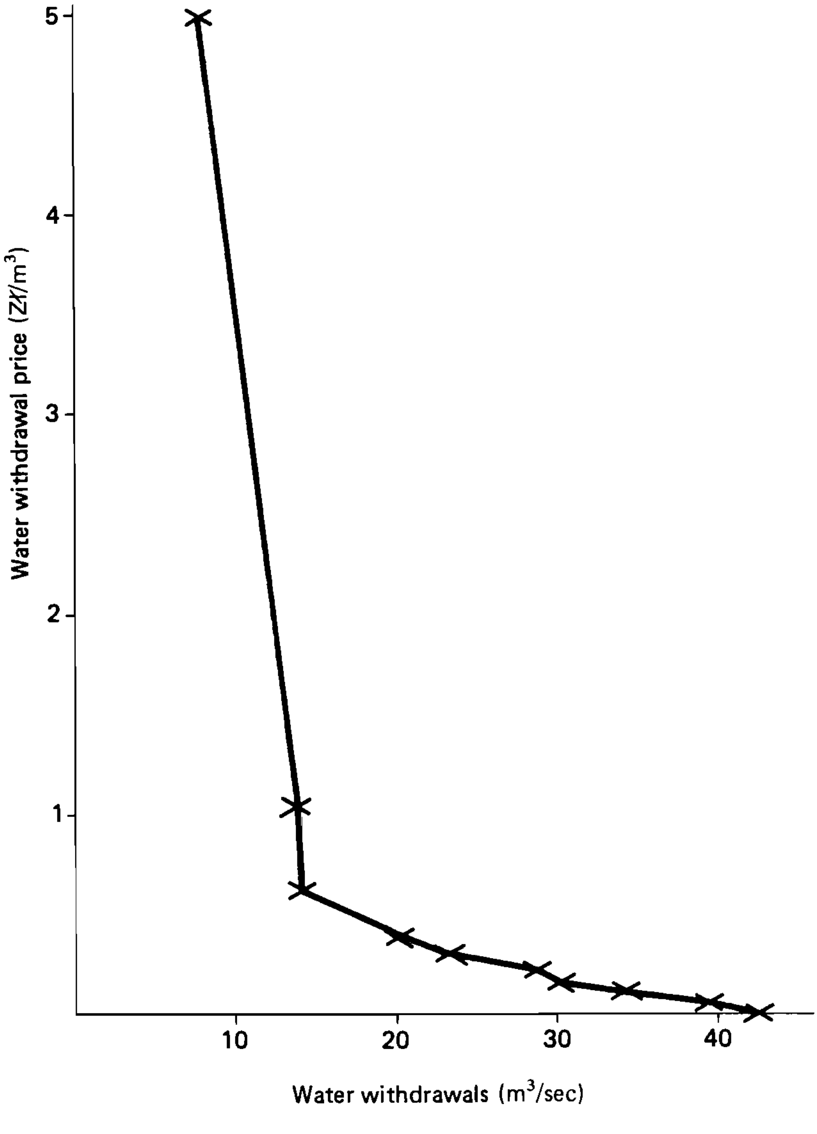

FIGURE 11 Derived demand for water withdrawal.

This limitation notwithstanding, the basic price sensitivity of withdrawal demand is readily apparent in Figure 11. Withdrawals decrease significantly as price is raised from 0.0 to 0.6 Zł/m^3, but higher prices produce only modest reductions on an absolute scale. On a proportional scale, the pattern is roughly similar, but the change at 0.6 Zł/m^3 is not as abrupt. This can be seen in Figure 12 which plots the same results on a logarithmic scale.

The significance of a logarithmic plot is that the slope of a demand curve (or, more precisely, the reciprocal of the slope) can be interpreted as a price elasticity of demand. The price elasticity of demand is a standard economic measure of sensitivity defined as

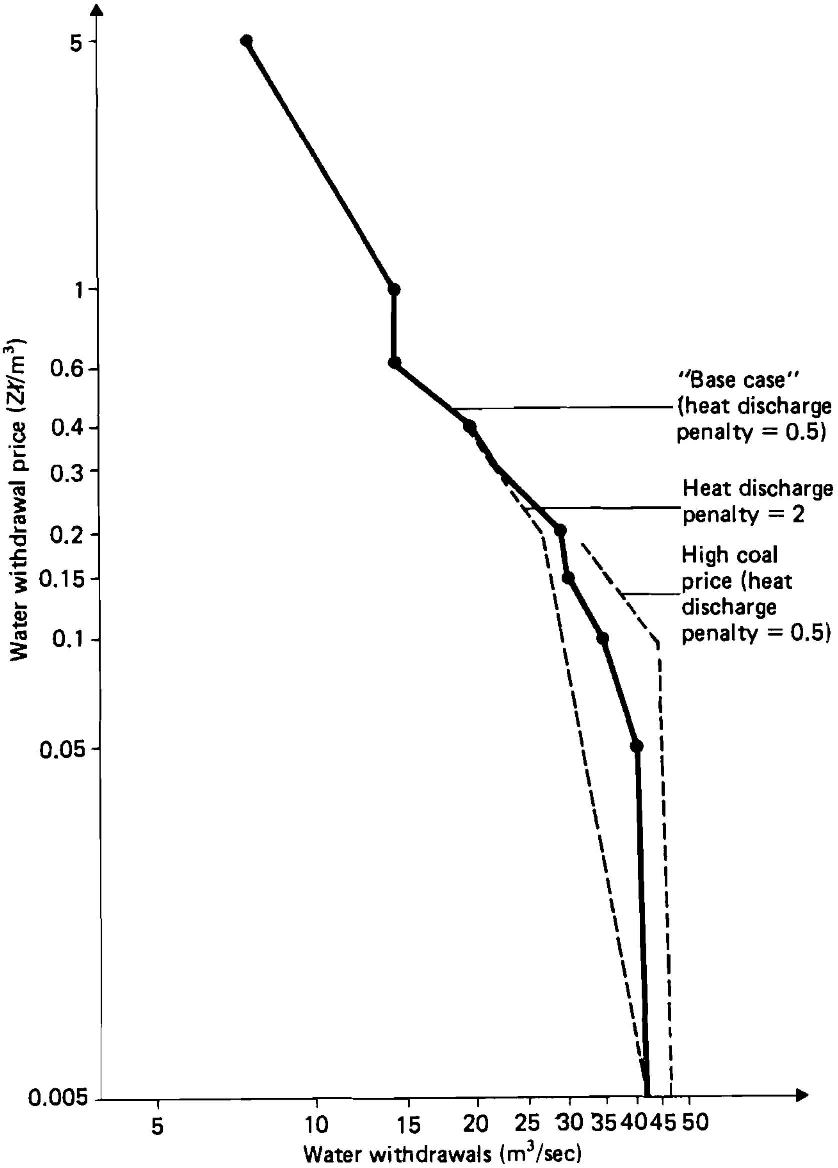

FIGURE 12 Derived demand for water withdrawal (logarithmic plot).

the percentage change in quantity divided by the percentage change in price. For very small changes in price, a point elasticity is defined as

$$(dQ/dP)(P/Q) = d\ln Q/d\ln P$$

From this arises the significance of a logarithmic plot. For larger variations in price, the so-called arc elasticity of demand defines an average elasticity between two price-quantity points as

$$(Q_2 - Q_1)(P_1 + P_2)/(P_2 - P_1)(Q_1 + Q_2)$$

This is the most appropriate quantitative measure for our results, while the logarithmic plot aids in their visual interpretation. (Note that because the underlying model response surface is a discontinuous step function, the elasticity interpretations must be rather loose.)

Over the price range from 0.0 to 0.05 Zł/m^3, the arc elasticity is merely −0.02, confirming the visual impression of an inelastic range. Demand becomes more elastic over the price range from 0.05 to 0.6 Zł/m^3, for which the arc elasticity is −0.56. The apparent changes in elasticity over this range are typical of linear programming model response surfaces, but no rigorous interpretations can be made here because the observation points do not necessarily represent switchpoints in the model solution. Demand again becomes quite inelastic over the price range from 0.6 to 1.0 Zł/m^3 (and possibly beyond), but a less inelastic range is indicated somewhere between 1.0 and 5.0 Zł/m^3.

Figure 12 also shows shifts in the derived demand relationship for water withdrawals brought about by separate increases in the heat discharge penalty and the coal price. A higher coal price brings about increased water withdrawals at each price investigated. This substitution of water for energy reflects the lower value of condenser ΔT chosen at the high coal price. Although higher water prices were not investigated at the high coal price, the near convergence of the graphs at a water price of 0.2 Zł/m^3 supports the logical prior hypothesis that the graphs will approach each other as higher water prices dictate greater and greater use of closed-cycle cooling. Higher water prices may also raise the value of condenser ΔT chosen under a high coal price.

The impact on water withdrawals of a fourfold increase in the heat discharge penalty is almost unnoticeable at the 0.0 and 0.4 Zł/m^3 withdrawal prices. Some divergence is apparent at the 0.2 Zł/m^3 withdrawal price, but the large apparent divergence at 0.05 Zł/m^3 is probably caused only by the absence of an observation in that range for the higher heat discharge penalty. These results indicate a dominance of withdrawal price over heat discharge penalty, given the constraints defined for discharges. Further evidence of this dominance is provided in Figure 13 which shows derived demand relationships for water as a medium for heat dissipation. Three curves illustrate the "penalty-responsiveness" of heat discharges at three different prices for water withdrawal. As is readily apparent from the spread of the three curves, heat discharges are much more sensitive to the price of water withdrawal than to the penalty for heat discharge. Again, present information allows this conclusion only for the set of discharge constraints defined on temperature and heat.

These results reflect the logical complementarity between water withdrawals and heat discharges. With a few minor exceptions, the process substitutions to decrease (increase) withdrawals simultaneously decrease (increase) heat discharges – and vice versa. The opposite relationship is for the most part demonstrated between water withdrawals and water losses (principally because of the losses in cooling towers). Figure 14 shows the general increase in water losses as the process configuration responds to higher and higher prices for water withdrawal. (The initial decrease in water losses results from a shift to a higher wet bulb approach factor in open-tower cooling flows. This shift lowers the temperature differential across the tower and decreases evaporative loss.) The largest part of the increase in water losses occurs over the range in which once-through and then open-tower

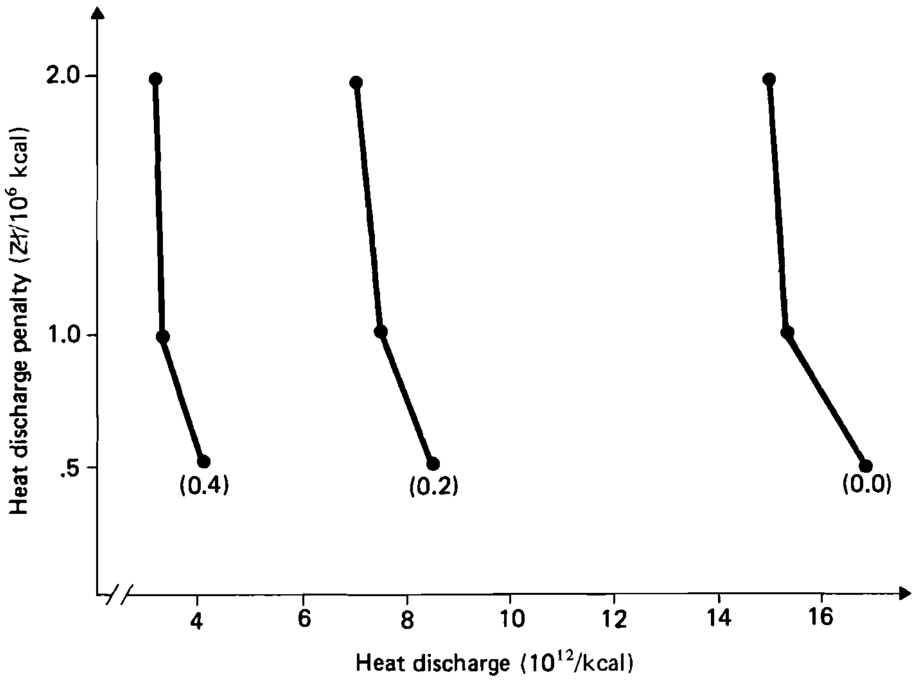

FIGURE 13 Derived demand for heat discharge. Water withdrawal prices are shown in parentheses.

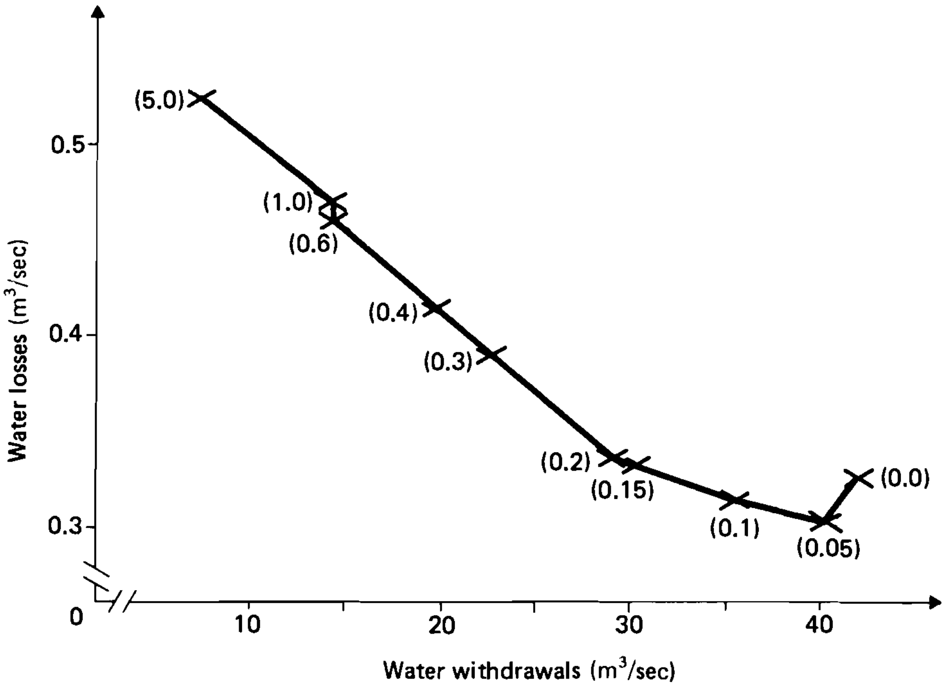

FIGURE 14 Water losses vs. water withdrawals. Water withdrawal prices are shown in parentheses.

flows are progressively replaced by closed-cycle configurations. Interestingly, the relationship is linear over much of the response range investigated, with incremental increases in water losses amounting to around 1 percent of incremental savings in water withdrawals.

We have focused exclusively on water use relationships without any indication of the cost consequences of the changes in process configuration. Since it is a cost minimization, after all, which determines the patterns of water use (subject to the defined constraints), these cost consequences are also of interest. In the end they must be borne by someone, whether or not model prices permit an interpretation of the costs as proper social costs. As an indication of these cost consequences, Figure 15 shows the average and marginal costs of plant operation as water withdrawals are varied in response to the programmed variation in withdrawal prices. Both cost figures include the outlays for withdrawal and

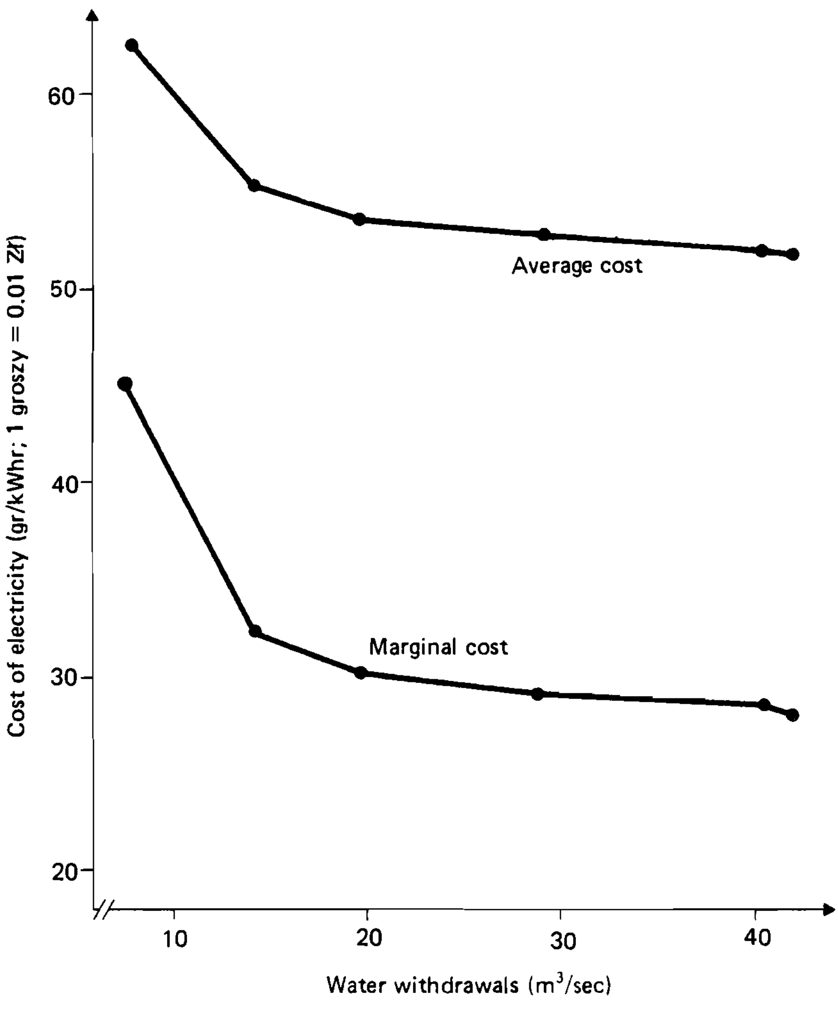

FIGURE 15 Cost of electricity vs. water withdrawals.

loss charges and for penalties on heat and excess dissolved solids discharges. Average costs are significantly higher than marginal costs because the model structure and solution essentially treat the costs of plant installation and slurry operation as fixed cost components. As the construction of the cooling tower, water intake station, blowdown demineralizer, and combustion stack are modeled linearly, the capital costs of each of these units are reflected in the marginal cost for at least one season; this cost in turn shows up in the (weighted average) marginal cost of Figure 15 as well as in the average cost.

Figure 15 shows that an initial 66 percent decrease can be attained in water withdrawals at a fairly minor increase in electricity cost; average costs increase only 7 percent while marginal costs increase 15 percent. In absolute terms, electricity costs per kWhr increase by less than 0.16 groszy for each m^3/sec of reductions in water withdrawals. The final steep increment is considerably more costly in both absolute and relative terms. The incremental cost per m^3/sec of withdrawal savings is over 1.1 gr/kWhr in this range, and the proportional cost increases are approximately threefold higher than those observed over the flatter range. This result is properly reflective of the economic law of diminishing returns, and identification of this high cost region is essential to any cost-based determination of the socially optimal rate of water withdrawal.

While a myriad of other economic and resource use relationships are contained in even the limited set of analyses performed at IIASA, it is hoped that the results selected for presentation here sufficiently illustrate the analytical potential of the programming model. In particular, these results should demonstrate the usefulness of programming models for extracting information about water demand relationships which might not be available in the statistical record.

5 CONCLUSION

In this report we have addressed the objectives, structure, and development of a mathematical programming model of resource use in electricity generation. We applied the methodology elaborated to the modeling of a hypothetical coal-fired power plant on the middle reach of the Vistula River in Poland. While this application is quite specific, the basic methodology is inherently general and may be applied in other geographical and economic contexts. The modeling results presented in Section 4 are illustrative and should not be interpreted as definitive quantitative assessments of the identified water demand issues. The results do highlight, however, the significant interrelationships between the various dimensions of water demand and the importance of taking an integrated approach to the study of industrial water demand relationships.

ACKNOWLEDGMENTS

The authors wish to acknowledge and thank a host of colleagues and friends for their assistance and cooperation in the conception and development of the Vistula Case Study and its model of electricity generation:

IIASA

Janusz Kindler, Leader of the Water Demand Research Task for project conception, initiation, and management

William Orchard-Hays for assistance in solving the model
Denise Promper for clerical assistance and logistics
Vicky Hsiung for typing assistance

Institute of Meteorology and Water Management (IMGW) and other Polish Organizations
Zdzislaw Kaczmarek, Director of IMGW, for project conception, initiation, and management
Jerzy Pruchnicki, Deputy Director of IMGW, for air pollution modeling and management
Karol Budzinski (IMGW) for air pollution modeling
Hanna Spoz-Dragan (IMGW) for meteorological and hydrological data
Ewa Czarnecka (IMGW) for clerical assistance, interpretation, and logistics
Aleksander Laski (Hydroproject) for model review and advice, water policy specifications
Czestaw Mejro (Warsaw Technical University) for model review and advice

University of Houston, Industry Studies Program
Russell G. Thompson, Director, for project conception, initiation, and supervision

Reviewers
George B. Dantzig, Stanford University
Trevor C. Hughes, Utah State University

This study was supported in part with funds provided by Stiftung Volkswagenwerk, Hannover, Federal Republic of Germany.

REFERENCES

Russell, C.S. (1973) Residuals Management in Industry: A Case Study of Petroleum Refining. Baltimore and London: Johns Hopkins University Press.

Russell, C.S., and J. Vaughn (1976) Steel Production, Processes, Products, and Residuals. Baltimore and London: Johns Hopkins University Press.

Sawyer, J.H., Jr., B.I. Bower, and G.O.G. Löf (1976) Modeling process-substitutions by LP and MIP. In R.M. Thrall et al., eds., Economic Modeling for Water Policy Evaluation. Amsterdam: North Holland Publishing Company.

Spofford, W.O., Jr., C.S. Russell, and R.A. Kelley (1976) Environmental Quality Mangement – An Application to the Lower Delaware Valley. Research Paper R-1. Washington, D.C.: Resources for the Future, Inc.

Thompson, R.G., J.A. Calloway, and L.A. Nawalanic, eds. (1976) The Cost of Clean Water in Ammonia, Chlor-Alkali and Ethylene Production. Houston, Texas: Gulf Publishing Company.

Thompson, R.G., J.A. Calloway, and L.A. Nawalanic, eds. (1977) The Cost of Electricity: Cheap Power Vs. a Clean Environment. Houston, Texas: Gulf Publishing Company.

Thompson, R.G., J.A. Calloway, and L.A. Nawalanic, eds. (1978) The Cost of Energy and a Clean Environment. Houston, Texas: Gulf Publishing Company.

RELATED IIASA PUBLICATIONS

BOOKS

Real-Time Forecasting/Control of Water Resource Systems. Selected Papers from an IIASA Workshop, October 18–21, 1976 E.F. Wood, A. Szöllösi-Nagy, editors (IIASA Proceedings Series, Vol. 8. Available from Pergamon Press) ISBN 0 08 024486 6	BK-80-509	
Logistics and Benefits of Using Mathematical Models of Hydrologic and Water Resource Systems. Selected Papers from an International Symposium, October 24–26, 1978 A.J. Askew, F. Greco, J. Kindler, editors (IIASA Proceedings Series, Vol. 13. Available from Pergamon Press) ISBN 0 08 025662 7	BK-81-515	

RESEARCH REPORTS

Some System Approaches to Water Resources Problems – 1. Operation under Water Shortage Yu. A. Rozanov (Microfiche only)	RR-74-17	$4.00
Analysis of Uncertainty in Deterministic Rainfall Runoff Models E.F. Wood	RR-74-18	$5.00
On Optimum Control of Multireservoir Systems I.V. Gouevsky	RR-74-25	$4.00
Transient Flow Routing in Channel Networks E.F. Wood, B.M. Harley, F.G. Perkins	RR-75-1	$5.00
Some System Approaches to Water Resources Problems II. Statistical Equilibrium of Processes in Dam Storage Yu. A. Rozanov	RR-75-4	$5.00
Some System Approaches to Water Resources Problems III. Optimal Control of Dam Storage Yu. A. Rozanov	RR-75-17	$4.00
Man-Machine Procedure for Multiobjective Control in Water Resource Systems I.V. Gouevsky, I.P. Popchev	RR-75-18	$5.00
Storage Systems Dependent on Multivariate Stochastic Processes Z. Kaczmarek	RR-75-20	$4.00
Computer Assisted Procedures in Water Project Evaluation I. Belyaev, I. Zimin	RR-75-27	$5.00
Analytical Studies of the Hurst Effect: A Survey of the Present Position A.A. Anis, E.H. Lloyd	RR-75-29	$4.00
Stochastic Reservoir Theory: An Outline of the State of the Art as Understood by Applied Probabilists A.A. Anis, E.H. Lloyd	RR-75-30	$4.00

(continued overleaf)

RESEARCH REPORTS (*continued*)

The IIASA Water Resources Project: A Status Report Water Project (Microfiche only)	RR-76-15	$4.00
Sensitivity Analysis of Streeter–Phelps Models S. Rinaldi, R. Soncini-Sessa (Microfiche only)	RR-77-1	$4.00
Reservoirs with Seasonally Varying Markovian Inflows and Their First Passage Times E.H. Lloyd	RR-77-4	$6.00
Optimal Allocation of Artificial In-Stream Aeration S. Rinaldi, R. Soncini-Sessa (Microfiche only)	RR-77-7	$4.00
On the Distribution of the Hurst Range of Independent Normal Summands A.A. Anis, E.H. Lloyd	RR-77-16	$4.00
On the Monetary Value of an Ecological River Quality Model H. Stehfest	RR-78-1	$4.00
Supply–Demand Price Coordination in Water Resources Management G. Guariso, D.R. Maidment, S. Rinaldi, R. Soncini-Sessa	RR-78-11	$4.00
The Use of Alternative Predictions in Long-Term Inference into the Future (With Special Reference to Water Demand) Z. Pawlowski	RR-78-15	$4.00
A Comparative Case Study of Dynamic Models for DO-BOD-ALGAE Interaction in a Freshwater River M.B. Beck	RR-78-19	$7.00
Interregional Water Transfers: Projects and Problems G.N. Golubev, A.K. Biswas, editors Reprinted from Water Supply and Management, Vol. 2, No. 2, 1978. No longer available from IIASA	RR-79-1	
Model Structure Identification from Experimental Data M.B. Beck Reprinted from Theoretical Systems Ecology: Advances and Case Studies (E. Halfon, editor)	RR-80-4	
Cost Allocation in Water Resources Development – A Case Study of Sweden H.P. Young, N. Okada, T. Hashimoto	RR-80-32	$6.00
Agricultural Water Demands in the Silistra Region I.V. Gouevsky, D.R. Maidment, W. Sikorski	RR-80-38	$10.00
Mathematical Modeling – A Management Tool for Aquatic Ecosystems? K. Fedra Reprinted from Helgoländer Meeresuntersuchungen, Vol. 34 (1980)	RR-81-2	
Hard or Soft Environmental Systems? M.B. Beck Reprinted from Ecological Modelling, Vol. 11(1981)	RR-81-4	

COLLABORATIVE PAPERS

Proceedings of a Workshop on Modelling of Water Demands J. Kindler, editor	CP-78-6	$11.00
Hydrophysical and Ecological Models of Shallow Lakes and Reservoirs: A Summary Report of an IIASA Workshop S.E. Jorgensen, editor	CP-78-14	$12.50

THE AUTHORS

John C. Stone received a bachelors degree in Economics (1974) and a masters degree in Environmental Health Science (1977/78) from Harvard University. Between degrees he joined the research staff of the Industry Studies Program at the University of Houston, and through that group obtained an invitation to do work at IIASA following his masters degree. Upon leaving IIASA he continued to work with the Industry Studies Program and then moved with the group to a Houston-based private-sector corporation, RGT, Inc. (now Operational Economics, Inc.), where he has been the Director of Mathematical Modeling and Economic Analysis. He is currently pursuing a doctoral degree in Operations Research at Stanford University, USA.

F. Dail Singleton, Jr. received a bachelors degree in Chemical Engineering (1965) from the University of Delaware, and a doctoral degree (1971) from the University of Rochester. After working in the chemical industry, he was among the first professionals to join the Industry Studies Program at the University of Houston. His experience in industrial modeling led to an invitation to work at IIASA in 1977. Upon leaving IIASA he resumed work with the Industry Studies Program and then moved with the group to a private-sector corporation, RGT, Inc. (now Operational Economics, Inc.), where he is the Director of Systems and Engineering Analysis.

Andrzej Salewicz is the leader of the Water System Control Group of the Institute of Meteorology and Water Management, Warsaw. He received an M.Sc. in Automatic Control from Warsaw Technical University. He is currently working on the operation of multiple reservoir systems, concentrating on the case study of the Upper Vistula System.

M. Gadkowski is currently with the Institute of Meteorology and Water Management, Warsaw.

Witold Sikorski was at IIASA from June 1977 to September 1978. Mr. Sikorski studied Electrical Engineering at Warsaw Technical University, where he received his M.Sc. in 1973. In 1974 he completed his postgraduate studies in didactics and methodology of teaching. He is currently at the Institute of Environmental Engineering of Warsaw Technical University.