MODELLING OF INDUSTRIAL WATER DEMANDS

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SYNOPSIS

This paper is based on the forthcoming IIASA book on "Modelling of Water Demands". Following introduction of industrial water use, requirements, and demands, the dimensions of industrial water demands and its determinants are briefly presented. Two broad approaches to modelling water demands are introduced, one of which is called statistical, the other, engineering. Examples of application of these approaches to modelling the water demands of individual industrial activities are supplemented by discussion of water demand modelling at the regional and national levels. At the end, the possible ways of making water demand models more useful in the future are discussed.

INTRODUCTION

Whenever investment in a water resources project is under consideration or new water policy is contemplated, several important questions relating to water demand usually arise. Typically they are concerned with how much water will be used, where, and for what purposes at various points of time. The amounts of water actually demanded depend on many time-related variables such as government policies, population levels and distribution, energy use, cost of energy, per capita disposal income, technological development, pricing of water withdrawals and wastewater disposal, consumer habits and lifestyles. It is only with the aid of analytical approaches that relationships among these variables can be developed, and alternative levels of water demand then estimated for different sets of possible conditions.

This paper is based on the forthcoming IIASA book: "Modelling of Water Demands" edited by J. Kindler and C.S. Russell, in collaboration with B.T. Bower, I. Gouevsky, D.R. Maidment, and W.R.D. Sewell. The book describes several approaches to modelling of water demands and includes illustrative examples of how they can be used for analyzing water demand relationships in industry, agriculture and municipalities. Focusing on modelling of industrial water demands, this paper presents an overview of the forthcoming book based on water demand studies carried out during the years 1976-1980 at IIASA. In addition, some general reflections on the role of industrial water demand modelling, its limitations, and further research needs are presented.

INDUSTRIAL WATER USE, REQUIREMENTS, AND DEMANDS

Most industrial processes use water as an input, though the purposes to which the water is put vary widely. In some cases water is an input in the classic sense and forms part of the product. The beverage industry is an obvious example, but water or steam is also used as feedstock or processing agent in numerous chemical and pharmaceutical processes. In other plants it is used to convey the product from one stage of production to another. For example, in paper making, pulp is carried in slurry from the pulping operation to bleaching and paper-making. In the canning industry fruits and vegetables are often transported through the production process in a water stream.

Where excess or unwanted heat is generated by a mechanical process or chemical or nuclear reaction, water is the obvious choice as the heat removal medium. This use is nearly universal, but is on an especially grand scale in the steam-electric power generating industry.

Water is used for washing and cleaning throughout industrial facilities. In the canning industry fruits and vegetables are washed with water at the beginning of the production process. Hydraulic debarking in the pulp and paper industry is a standard method for removing the bark and cleaning the dirt from incoming logs. Water is also used to wash final products. Water is, of course, used for personal and plant hygiene and for other overhead purposes such as lawn watering, vehicle washing and fire protection. Steam may be used for space heating. Moreover, an examination of the water utilization system of an industrial plant may show that water is actually a net output of some stages of the production process as when liquid residuals result from the production of some dry foods.

Nonproduct residuals other than energy are also commonly removed from industrial processes in water streams, and treatment and disposal of the resulting "wastewaters" is a major concern of public policy in most industrial nations.

The discussion so far has referred rather generally to the multiplicity of different uses of water by individual plants. However, the industrial water users should not be implicitly or explicitly assumed to have inflexible requirements for water (per unit of output, per employee, or whatever). While all these activities may have certain irreducible requirements for water, for the most part, analysis goes on and policies are made concerning quantities of use above these requirements. At these higher use levels, as price or cost rises it is possible for the activities to substitute more of some other input or inputs for water. It should be recognized that all else being equal, industrial enterprises will choose to use less water when the price or cost per unit is high than they will when that cost is low. Thus, the "requirement approach" should be abandoned and the economic concept of water demand substituted for it.

THE DIMENSIONS OF INDUSTRIAL WATER DEMAND AND ITS DETERMINANTS

As indicated earlier, the water use of an industrial activity is a multidimensional phenomenon and consequently, some separate dimensions of water demand can also be distinguished. These are:

(1) quantity of water withdrawn at the intake(s) of a given activity (withdrawals);

(2) total quantity of water used, including any recirculation (gross water applied);

(3) quantity of water evaporated, incorporated in a product, or otherwise lost before discharge (consumptive use);

(4) quantity of water discharged (discharge);

(5) quality of water discharged (wastewater disposal services demanded); and

(6) the time patterns of each of the above dimensions.

At a given point in time, industrial water demands with respect to all six dimensions set out above are determined by the following inter-related factors:

- production technology;
- product mix and quality specifications;
- qualities and prices of raw materials, including fuel and electrical energy;
- unit values of recoverable nonproduct materials and energy;
- price of purchased water of given quality at the intake to the plant;
- costs of different amounts of self-supplied intake water, e.g., costs of intake facilities, treatment, and recirculation;
- limitations, standards, or unit fees imposed on the discharge of liquid, gaseous, and solid residuals from the plant, either directly to the environment or to some collection and disposal system;
- costs of different degrees of in-plant residuals modification;
- capital availability;
- climate.

DEMAND MODELLING

The preceding section immediately suggests that planners at all levels should take into account the responsiveness of quantity demanded to price (as well as to other factors and policy instruments), whether setting out to analyze the effect of new policy initiatives on water resources or deciding about the desirability of new supply and transmission capacity increments in a region. A large part of the book upon which this paper is based is concerned with guidance on how to do that, the technique generally involving the production of water demand relations using either of two approaches: stastical or engineering. The first of these tries to infer from observations on many users at a point in time, or the same user over a period of time, or from a combination of both types of observations, the structure of water demand relation producing the observations. The second attempts to construct the relation from fairly detailed engineering knowledge of the production or consumption unit processes, and the associated substitution possibilities, carried out by the activity.

Some of the complications and extensions relevant to these two approaches should be mentioned. In particular, for the statistical approach, these are lack of appropriate data in sufficient quantity, and the difficulties posed by simultaneous determination of prices (or costs) and quantities. In connection with the engineering approach, the potential complexity of the resulting model, seen as all possible combinations of the relevant unit processes, and the great practical difficulty of finding solutions to particular problems (such as finding the lowest cost reaction by an industrial plant to an increase in the cost of water withdrawals) are to be mentioned. Into this breach is thrust mathematical (usually linear) programming. This technique was shown to be a way to organize the information developed in the engineering approach in such a way that a well-developed and quite efficient algorithm is available for finding optimal paths through the set of all possible unit process combinations, for different specifications of the policy instruments, such as price or waste discharge standards.

The basic concepts and techniques of water demand modelling have been illustrated by IIASA through case studies undertaken in cooperation with several institutions from the IIASA National Member Organization countries. Regarding industrial water demand, the book upon which this paper is based contains two examples of both major techniques: statistical and engineering/programming*. The first one describes a small scale attempt to develop a statistical water demand equation for Dutch paper mills using available data on water use and effective price, plant size, product, and type technology. Along the way it was necessary to come to grips with the identification problem, and arguments about regionally differentiated administered prices will be especially useful reading for modellers considering this method. The results of the exercise are disappointing, not because of poor technique, but because of the ubiquitous problem of data poverty. This disappointment should not make the example less useful to the reader, however, for it illustrates very clearly one of the major problems in modelling industrial water demands.

The second example deals with modelling the water demand relations for a fossil-fuel, thermal-electric power plant, the particular plant being a Polish project

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[*] The "Industrial Water Demands" chapter by John C. Stone (University of Houston, Industry Studies Program, Houston, Texas, USA), and Dale Whittington (Department of City and Regional Planning, University of North Carolina, Chapel Hill, USA). Both authors are associated with IIASA's water demand study.

located on the Vistula River. In this section, the engineering realities of this production process are discussed at some length and then it is shown how these realities can be combined with principles of programming model design to determine the structure of the constraint matrix for the plant model. The derivation of some coefficients in that matrix is also illustrated, but since the aim of the book is not specific to power generation, the detailed submodels required to choose consistent combinations of temperatures and water flows, and hence to specify other elements of the matrix are not described. Examples of the output available from the model include the derived demand function for cooling withdrawals and illustrate shifts in that function due to changes in other parameter values.

To supplement the material on modelling water demands of individual industrial, agricultural, and municipal activities, the book contains two chapters on aggregated analysis of these demands on the regional and national scales. The first of them deals with regional demand for shared water resources--either as source for withdrawals or as sink for discharges. The emphasis here is on the constraints that would be necessary to reflect the sharing problem in the context of a regional resource, with the overall objective being to maximize net benefits from the activities taken together. These constraints were taken to arise from a policy of maintaining streamflow in the shared rivers in the face of water withdrawals and consumptive uses. It was clear even in this simple context, however, that regional models of water demand could become large and complicated rather quickly.

The complications necessary both in the individual activity models and in the regional constraints, in order to reflect standards for regional water quality, are also briefly described. The second half of the chapter provides a case study--though not an IIASA sponsored one--of a regional water quality model. This is the Lower Delaware River Valley model constructed at Resources for the Future, largely for research rather than actual planning or policy implementation purposes. A recitation of the dimensions of this model gives the point made about potential model size a certain reality. (Though it must be noted that the Lower Delaware model dealt with air as well as water pollution). A major lesson obtained from the model seemed to be that introducing nonlinearities is asking for trouble--both in the area of computational difficulty and cost and in the matter of the reliability of the results.

The next level of aggregation beyond the region is the nation, and another chapter deals with national water demand modelling. It is not, however, symmetric with the regional aggregation chapter; not because one could not imagine building a national water demand model by bringing together the required set of regional models (as by including interbasin water transfer activities and a national economic model), but because it seems that this sort of national model does not exist. What does seem to exist in fairly great number are studies of projected national water use, often based on the aggregations across industrial and household sectors, and with almost no reflection, either of the role of price or cost in affecting water demand, or of the importance of natural recirculation via water courses. The chapter emphasizes, therefore, the problems with such use projections, especially in the contexts of policy analysis and demand-supply balancing, but also in baseline forecasting. While true national water demand models, constructed as aggregations of regional models, could be very large and complex, the decisions made at the national level may involve extremely large and costly undertakings, such as interregional water transfer projects or sea coast desalting installations. It is not clear, therefore, that national models are "too expensive", for they might point policy makers away from truly enormous mistakes.

THOUGHTS FOR THE FUTURE

If one takes seriously the proposition that models of water demand relations can be useful additions to the armories of water resource management agencies and other concerned institutions, it is tempting to ask as a final question: Are there ways to make these models more useful in the future? In particular, are there developments to be sought or areas of application to be opened or expanded?

Four suggestions seem appropriate as a partial answer to the question. First, the reader will have noticed that even brief discussions of approaches and applications presented herein have been dominated by data problems. Quite often it is necessary to favor an engineering approach because of its relative independence of historical data. But statistical modelling has considerable appeal, particularly because a well done statistical demand relation may mimic the important behavior of a very complex linear program while being itself compact and easy to use once estimated. (See, for example, HAZILLA, KOPP AND SMITH, 1980). Therefore, the potential social payoff to more and better data on activity-level water use and related variables is large. Whether that social payoff could be translated into individual rewards (for data collection can be thankless work) or whether it could be used to outweigh the negative aspects of confidentiality claims, agency inertia, and hostility to further forms and questionnaires, is doubtful. On the other hand, data gathering required by existing laws, especially those laws governing environmental policy, already produces an enormous quantity of data, and a systematic exploration of these would be valuable.

Another subject worthy of more attention than it has historically received is that of the costs and benefits of model simplification. In approaching a water demand (or any other) policy problem, the first impulse of the modeller(s) is often to try to capture every detail of the situation: that is, to include every conceivable variable instead of thinking about and even testing which ones make little difference; to introduce non-linearities when linear approximations are or can be made available; to use the newest and most abstruse computational packages though it is unclear whether any gain is obtained; or to imbed the water demand model in a general equilibrium context without analyzing the importance of doing so. Each such decision is likely to be approved by the disciplinary colleagues of the modellers. Indeed, the choice of a simple technique over a complex and sophisticated one is likely to be greeted in seminars and informal conversation with a "But don't you know about the problem of ...?", or "But haven't you seen the latest paper by _____, where he develops a technique that allows for _____?". Professional pride, in other words, is not the ally of simplicity. But each complicating step also tends to make the resulting model more inflexible, idiosyncratic in operation, and opaque to the planners and decision-makers who ultimately should be the ones to benefit from the exercise.

These planners and decision makers are not, however, blameless in the matter. Their preference for a detailed regulatory approach to achieving public policy goals in such a field as water resource management leads to a need for quite specific and detailed prescriptions. Thus, if one must tell refinery X exactly what to do about water withdrawals, consumption, or waste water discharge, a simple model is not likely to be considered particularly useful, since it will be easy for the refiner to claim that his real refinery is so much more complex, contains so many more processes and so many more interconnections, uses such a variety of crude oils, etc., that the simple model's results cannot be applied. Detailed regulation demands detailed knowledge. At the same time, it tends to reduce the need for optimizing models aimed at, for example, minimizing the cost of achieving some regional or plant-wide result. Thus, the allowable waste water discharges for an industrial enterprise might be calculated on the basis of the application of specified treatment devices to raw waste loads. There is really no response model required (though someone, somewhere, might be interested in asking whether the specified loads could be achieved more cheaply via another method). Thus, it might be said that certain regulatory practices create situations in which either models are hardly necessary, or only very specific and complex models will do.

On the other hand, it must be admitted that we do not know much about the costs of using simpler models, in terms of information and accuracy lost, nor about the benefits in terms of the costs of model construction and of subsequent computation avoided. This is perhaps because it is difficult to find the time or money to support the analysis of various levels of modelling complexity aimed at a particular problem; usually one round of analysis exhausts budget, time, and researchers. One water demand model that was eventually subjected to this kind of investigation was a linear programming model of steel production and associated water use and pollution (RUSSELL and VAUGHAN, 1976). Vaughan subsequently constructed two other, simpler and smaller models covering the same steel production processes and, with only a few exceptions, the same array of water use options and of water- (and air-) borne residuals. One of these models was derived from the full Russell-Vaughan LP by averaging over some input options to get "typical" inputs, removing some activity vectors almost never chosen under a wide variety of imposed conditions, and reducing the product mix complexity. This model was about 45 percent as large as the full model (size being measured by number of rows). The third model was developed by an entirely different route: by adding residuals generation, treatment and discharge, and some additional detail on heat balances to a previously published steel-production LP, (TSAO and DAY, 1971), which in turn was based on aggregate average data on input use per ton at the several stages of integrated steel making. This model was about 80 percent as large, in terms of row numbers, as the second, or about 35 percent as large as the full LP. (SMITH and VAUGHAN, 1980).

Smith and Vaughan have provided estimates of the cost of developing and operating the largest and smallest of the three models. These figures indicate diseconomies of scale, with both development and operating costs growing faster than row size. Development costs go up by a factor of more than five as row size goes up by a factor of slightly less than three. And cost per run, based on experiments and cost curve fitting, would vary as the square of row size--or by a factor of 9 as row size triples.

Unfortunately, however, the results of the Smith-Vaughan analysis do not allow us to say that the smaller model would serve "just as well as" the larger. First, because the authors have no measures of objective reality against which to compare the various models' responses to such stimulii as changes in discharge constraints and in factor input prices, it is impossible for them to say which of the models does best at mimicking real steel mills. Moreover, the models give different results, whether measured informally via graphs or the marginal and average costs of various discharge reducing requirements; or statistically via tests for the equality of Cobb-Douglas cost functions estimated from data points based on repeated runs of the models across different input price sets and residuals discharge constraints. As Smith and Vaughan say:

> "The level of process detail can lead to quite different patterns of firm (or plant) responses that are depicted by these models. These differences can have direct and indirect effects on outputs of the models that are of central interest to policy-makers."

Thus, what little we know about model simplification reinforces the old adage that model building is an art and that one of the most important talents needed by the artist is a feeling for where to make cuts. Simpler may always be cheaper, but is also different, though not necessarily worse, in terms of outputs generated. More work on this question would be very valuable.

Specific attention ought also to be given to improving the analytical basis for short run water management decisions, especially on how to cope with the threat of water shortages. While there exist quite sophisticated reservoir operating models, and while hydrological prediction capabilities seem to be improving, knowledge of short run demand phenomena is, it seems, vestigial. Yet it is such knowledge that will allow more intelligent choice among alternative rules for reacting to particular combinations of storage and use levels and extended weather forecasts. This is true even though the rules may not involve short term price changes but rather regulations such as prohibition of lawn sprinkling and car washing. For in order to evaluate the true costs of such regulations and to balance them against the possible costs of not taking action (that is, the expected value of losses over all possible future precipitation patterns) it is necessary to have the demand curves for the water uses to be regulated and for those that will be affected by actual shortage. A discussion of research and policy needs in this area may be found in RUSSELL, 1979; and examples of the methodology of loss estimation are given by RUSSELL, AREY, KATES, 1970, and YOUNG, TAYLOR, and HANKS, 1972. Again, there is considerable scope for useful work in this area--in the measurement of the relevant demands, the study of response to regulations, and the development of (nearly optimal) rules of thumb for water system managers.

Finally, modelling water demands provides an important part of the information required for water demand forecasting. It does not by itself, however, yield estimates of future demands. The latter are conditioned by a variety of considerations exogenous to the water management itself. Important in this connection are such factors as the future state of the economy, shifts in various political situations, the likelihood of technological breakthroughs, alterations in government policies which might affect either management of water resources or the demand for goods and services in which water is an input--changes in levels of support for housing programs, policies for regional economic expansion, and the alteration of water quality standards are germane in this connection. Because each of these can take various paths of development, none of which can be foreseen with complete accuracy, the fundamental step upon which all water demand forecasting is based involves examination and quantification of "alternative futures". Building consistent scenarios of "alternative futures" is one of the most complex undertakings and much remains to be done to supplement this concept with the sound guidelines of an operational value.

In speculating on future developments in water demand forecasting, it is important to note that the improvements brought about by modelling water demand relations can only be useful to the extent that the structure of these relations, based on the historical and existing conditions, endure into the future. If the structure changes in some unanticipated way, the most technically sophisticated and elaborate model will be little better than the crudest sort of extrapolation (ASCHER, 1978). There is plenty of empirical evidence that the likelihood of structural changes in the long run, (i.e., 10 years or more) is very high; therefore, the water demand models discussed in this paper seem to be more suited for application within the framework of short-run policy analyses in water resources management. Such applications, however, may yield several insights concerning sensitivity of water demand to different demand generating factors. Such information, if used with proper care, can certainly improve our long-term policy choices.

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