THE ROLE OF REAL-TIME FORECASTING AND CONTROL IN WATER QUALITY MANAGEMENT

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PREFACE

The traditional view of water quality management in a river basin concerns itself with determining an optimal allocation of capital investment in facilities for storage and treatment of water and wastewater. If these investments do not permit the desired water quality standards to be achieved, it is usual to question, for example, whether the treatment plant configuration was correctly designed in the first place with the appropriate contaminant removal technologies. It is not common practice at the "design" stage of water quality management to consider how the system will perform at the "operational" stage of management. Neither is it customary, when standards are not met, to ask whether the design/operational requirements are incompatible, and to enquire whether standards could not in fact be achieved, if the system were to be operated more effectively.

About five or six years ago the first few articles on river water quality control began to appear in the literature of control theory. It has been a relatively easy exercise to show that, in principle, many aspects of river water quality - better to say, river water quality models - are amenable to the techniques of real-time control system synthesis. But that does not resolve the major practical issues of day-to-day operation in water quality management. Thus, more recently, it has been evident that on-line instrumentation and especially the use of the information so derived for management decisions, is receiving more detailed attention. Again, in principle, algorithms are available for real-time estimation, forecasting, and associated on-line data analysis. It has also been duly recognised, in view of the lack of operating flexibility in pollutant removal unit processes, that for river water quality control the storage and manipulation of flows, be they sewage discharges, stream discharges, or flows routed through treatment plants, is vitally important. But these considerations do not resolve the issues of whether real-time forecasting and control are desirable, inevitable, or necessary.

This paper takes another step backwards from the original control theoretic approaches to river water quality control It is apparent, for instance, that laws, economics and institutions all partly determine the nature of technological innovation in the water and wastewater industries. That, then, is the more "macroscopic" environment in which the paper examines the relevance of real-time forecasting and control to river water quality management. It would be of great benefit to the author if the reader would be generous enough to offer his criticisms of the discussion. In this way the arguments will become clearer, more relevant and more coherent.

1. INTRODUCTION

The terms "management" and "river pollution control" can be interpreted in several ways. There are social, legal, economic, and engineering views on how to manage the quality of our water resources. Among these views, views which may indeed be conflicting, the majority would agree that the development of mathematical models for water quality management is best approached from the domain of engineering and the physical sciences. However, the results subsequently obtained from the models so developed will frequently be applied to the evaluation of costs and legal or public health standards. Further, one can expect that from the beginning institutional arrangements and economic objectives would influence the nature of the model developed for assisting the solution of the particular management problem. And ultimately the prevailing political and economic atmosphere will determine whether action is taken which is consequent upon the guidelines provided by the application of the model. As ZumBrunnen (1978) has observed, it is naive to imagine that the most efficient and economic piece of technology will be innovated if there is not sufficient incentive or inducement for that device to be installed, operated and maintained.

It is thus impossible to ignore economic considerations and institutional arrangements when applying mathematical models to water quality management. The problem is clearly not purely a technical problem. The predominant attitude towards models for water quality management has been that the model should, among other things, assist in screening the information required to make the correct <u>long-term capital investment</u> in new and expanded facilities for water and wastewater treatment, for low-flow augmentation, and for artificial in-stream aeration (Loucks, 1978). There is ample evidence of this attitude in the literature, for example Deininger (1975), Spofford et al (1976), Anglian Water Authority (1977), Warn (1978), Davies and Lozanskiy (1978). That this should be the case is quite consistent with much of present-day needs and practice: we should not talk about incentives to operate a device adequately if that device has not yet been installed nor even adequately developed. But the problem of water quality management is not merely a problem of economics.

In this paper it will be argued that to promote construction of facilities in the long-term but to ignore subsequent short-term operational policies for those facilities is not good practice. Moreover, in terms of economics alone it is simply not sufficient to say that the cost-benefit function has been minimised for the chosen investment programme if one of the major technical options, real-time forecasting and control, has not been included in the minimisation procedure. The subject of models for day-to-day management and control will be the concern of the paper. A speculation, therefore, is offered. Of couse, such speculation frees us from the burdensome constraints of pragmatism. But should massive investment be committed for 25 years hence if some of this expenditure could have been avoided 10 years hence by the innovation of on-line control? This is a matter of adaptive water quality management; of being able to keep many options open; of being able to respond with flexibility to new developments. There is no suggestion that real-time control has to be necessary; this remains to be seen. But perhaps now is an appropriate time to consider the possibilities.

2. WATER QUALITY MANAGEMENT AND TECHNOLOGICAL INNOVATION

We have already mentioned that legal, economic, and institutional arrangements for water quality management have a profound effect on the technical solutions to problems of water pollution. We must first consult these legal and institutional matters in order to establish how they might determine different locations at which pressure is applied for different types of technological innovation. There are two types of technological development and innovation which will be of particular, though not exclusive, interest: on-line data acquisition and communication facilities; and on-line data processing, including mathematical models.

Figure 1 identifies four "pressure groups":

(i) The application of effluent discharge standards (ES);
(ii) The competition for land use (LU);
(iii) Considerations of public health (PH);
(iv) The application of in-stream water quality standards (SS).

Four "technical sectors" are in addition defined as:

(i) Wastewater treatment (WWT);
(ii) Surface and groundwater storage, i.e. regulating reservoirs and conjunctive use of aquifers (SGS);
(iii) Water purification for potable supply, including bankside storage (WPS);
(iv) Artificial in-stream aeration facilities (AIA).

Lastly, we have four categories of "primary required technology" under the headings:

(i) Wastewater treatment plant instrumentation and control, including facilities for direct recycling of the treated water;

(ii) Reservoir and conjunctive sources operation;

(iii) Water purification plant instrumentation and control;

(iv) In-stream water quality sensors and monitoring networks.

From a preliminary, and therefore somewhat superficial analysis of this arrangement of the water quality management problem, Figure 1 indicates the <u>dominant</u> directions of the forces applied to each technical sector and the resulting reaction in terms of technological development. For example, the legal specification of uniform effluent standards, irrespective of any intended subsequent use/reuse of the receiving water body, might tend to encourage widespread innovation of automation and computer control in the wastewater industry. Conversely, the use of in-steam water quality standards coupled with a consideration of both the river's self-purification capacity and the quality required for recreation or downstream supply, might accelerate the introduction of on-line stream quality monitoring and forecasting networks. If one wishes to draw any conclusion from Figure 1, then the following can be stated. The basic thrust of discharge standards would seem to be uni-directional, whereas the pressures exerted by stream standards are multi-directional with incentives for innovation more evenly distributed across the various technical sectors.

A system which is forced to develop in one direction only may eventually turn out to be quite an <u>inflexible</u> arrangement, both at the planning and the operational stages of water quality management. In fact a rigid and rigorous system of effluent standards, since it focuses on this one technical sector, must inevitably place great emphasis on the <u>reliable operation</u> of wastewater treatment plants. A fallacy of depending exclusively upon the long-term planning strategy, in respect of applying effluent standards, is therefore that the desired objectives and standards may not be achieved or maintained because:

(i) day-to-day plant operation is not adequate; and

(ii) in solving the design problem the subsequent operating problems of the given design have been overlooked.

And there is evidence that this may indeed be so. A recent evaluation of operating performance at several US wastewater treatment plants noted that some of the highest ranking factors which limited good performance concern <u>process design</u>, including <u>process flexibility</u> and <u>process contollability</u> (Hegg et al, 1978).

All this, of course, grossly simplifies the situation. A background of many other complicating aspects of the problem has to be set against any temptation to draw further premature conclusions. It is not obvious in which directions the "forces" and "reactions" might act in Figure 1. For instance, were we to assume a different strategy, say one based upon individual, purpose-oriented* in-stream standards, the water quality management programme would resemble much more closely a strategy implied by the Water Resources Board (1973): "our approach to the planning of water resources development involves making growing use of rivers for moving water to places where it is needed". As we have said, this would force technological innovation in a number of different directions. But though more flexible, such a strategy also has disadvantages. Okun (1977) argues against the Water Resources Board strategy on the

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*Purpose here means recreation/amenity, municipal re-use, industrial re-use, wastewater conveyance, etc.

grounds that it does not pay sufficient attention to the problems of water quality management. In particular, public health aspects would demand that increased direct abstractions from polluted sources are not only bacteriologically safe but will also not induce risks from long-term ingestion of carcinogenic and mutagenic _synthetic organic chemicals_. In Okun's opinion, elimination of these substances at source is "hardly realistic"; monitoring their passage along the water course might be possible in the distant future; and therefore dual supply systems deserve evaluation, although they may not be the most feasible or the most economic solution. However, there is more to the case of the slowly degradable synthetic organic chemicals. If, as the survey by Cembrowicz et al (1978) says, the Streeter-Phelps (1925) form of water quality model continues to be widely applied in water quality planning studies, it would seem that we are intending to manage merely the easily degradable organic portion of future waste discharges. Perhaps here, then, the merits of adaptive management and planning should be recommended.

Real-time operational control may not offer many clues to the solution of the foregoing problem; but what of the matters of _accidental spillages_, plant failures, and storm overflows? Okun (1977) anticipates that a growing proportion of pollution events will occur from accidents. The application of mathematical models for on-line forecasting of pollutant dispersion emerges thus as a distinctly useful possibility. The key elements of "response to alarm conditions" are:

(i) speed in evaluation of management decisions; and

(ii) flexibility of operation.

We seek also, therefore, answers to questions about how management strategies and technological innovation affect the flexibility of operation in a system. While he refers to "flexibility" in a rather different sense, Marks (1975) criticises the US Federal Water Quality Act Amendments of 1972 for making management alternatives less flexible, which here would be argued to be undesirable. In contrast, de Lucia and Chi (1978) suggest that the National Environmental Policy Act and US Public Law 92-500 shift the burden of proving non-damage of the environment onto the responsibilities of the individual dischargers. Since this implies a strong incentive for data collection it may well transfer the forces of an effluent standards strategy beyond the wastewater treatment sector alone.

Some implications of standard-setting, public health, and flexibility of operation have been but briefly considered. Let us turn now to some details of <u>costs</u>. Again Okun (1977) has a pertinent remark to make. Speaking of wastewater treatment plant facilities and the US situation, he says "designs are promulgated that commit funds to higher capital costs and lower operating costs because only the latter must be met entirely from local funds". In other words it is possible that certain funding programmes of a water quality management strategy can favour construction of treatment plant facilities and <u>discriminate against improvement of their performance</u>. Hence, the desired force for innovative advances in plant operation and control is actually being dissipated in other directions. Okun's views are confirmed by the report of Hegg et al (1978) who observe that the more freely available construction grants have attracted commitments to undesirable plant design configurations. This is hardly likely, as Hegg et al also note, to encourage the design of wastewater treatment plants which:

(i) are sufficiently flexible to allow subsequent adaptation to different modes of operation;

(ii) embody the instrumentation desirable for operational control;

(iii) permit evaluation of the significant trade-offs that can exist between capital investment and operating costs--a properly controlled plant may reduce the required design size of the facility, or it may defer subsequent plant expansion, see for example, Andrews (1978).

To be a little indiscreet, a strong vested interest in large construction ventures may be counter-productive in terms of better wastewater treatment plant designs.

3. DATA AND MODELS FOR REAL-TIME MANAGEMENT

It is thus not at all easy to summarise the opposing currents of opinion about water quality management and technological innovation. But perhaps the arguments introduced at the beginning of the paper can now be restated. First, it is important to guard against the promotion of inflexible systems of water quality management. Many factors associated with design, with long-term planning, and with capital investment do not encourage flexibility for the future. An adaptive form of management is preferable; a form of management that can respond easily to the risks of short-term crisis, such as accidental toxic spillages; a form of management that can respond easily to longer-term changes in quality problems and to innovative changes in management practice. Thomann put this same idea rather succinctly in 1968 when he said:

> "This principle of dynamic water quality management is simply that one manages the environment on a more or less

> continuous basis and not on a static, once every decade basis" (Thomann et al, 1968).

And secondly, it is argued that one of the options which may preserve flexibility of management, namely real-time forecasting and control, is not usually found in the range of options to be evaluated in current cost-benefit analyses. This is not surprising, as we shall see from the following.

3.1. The past.

The search for previous interest in real-time operational control of water quality is a tantalising affair of finding oblique references to the subject in brief concluding statements on long-term management plans. This excludes, of course, the work of Thomann as quoted above. It also excludes "feasibility studies" such as those of Tarrasov et al (1969), Young and Beck (1974), Beck (1977a), Whitehead (1978), and Gourishankar et al (1978). From these latter we can say that much is possible *in principle*; however, it is of greater interest to find statements about what ought to be possible *in practice* from authors who are not control engineers. Some of the less obscure references to the topic we shall now discuss.

(a) *Estuarine water quality forecasting.* Thomann (1972) reports an interesting application of a *dynamic model for chloride distribution* in the Delaware estuary. During a severe drought in 1965 the salt water "front" in the estuary had moved considerably further upstream than normal and thus posed a threat to the abstraction at Torresdale which supplies the city of Philadelphia. The model was used once every three or four days to make forecasts for the coming thirty-day period; a number of monitors at various locations supplied conductivity measurements with a frequency of at least more than twice per day.

(b) In-stream water quality control. As early as the mid-1960s artificial in-stream aeration devices were installed in an impounded section of the Ruhr River in Germany (Imhoff and Albrecht, 1977). The aeration devices were, and still are operated by being switched on or off at prescribed values for dissolved oxygen concentration when these values are recorded on an associated continuous monitor. No mathematical model or forecasting algorithm was required; nevertheless, this is real-time control in practice. Similar schemes for aeration have also been tested on the Teltowkanal in Berlin (Leschber and Schumann, 1978). Here, however, there are plans for an on-line model which in the future would be employed not only to govern the operation of the aeration units but also to co-ordinate the operation of a cooling water circuit at an adjacent power plant. But while it is useful as a measure for control at critical times, Imhoff and Albrecht (1977) conclude from an analysis of performance during 1976 that artificial in-stream is no real substitute for effective secondary biological wastewater treatment.

(c) Water and wastewater treatment plant control. This brings us to the current interest in instrumentation and automation of wastewater treatment plants, which is impressive in its scope, see, for example, Progress in Water Technology (1978). Consequently, it is impossible to capture in a single paragraph the essence of this interest. Instead, taking the experience of Andrews (1978) as a guideline, we note that the use of individual control loops for the various unit processes is quite commonplace, but that an integrated plant management strategy which takes into account all unit process interactions is not yet feasible. Suffice it to say, therefore, that some of the more advanced control applications are reported by Olsson and his co-workers in Sweden, e.g. Olsson and Hansson (1976), Gillblad and Olsson (1978). Interest in the instrumentation and automation of water purification plants is rather less well publicised; this may already reflect a trend in the response to legislation for water quality management.

The confrontation between control engineering, "automation", "computerisation", on the one hand, and wastewater treatment plant behaviour, on the other, is especially intriguing. As a major area of unit process operations, the nature of wastewater treatment is something of a challenge to the methods of conventional process control engineering. In section 3.2 we shall return to this point, and to the matter of whether automation and computerisation necessarily imply more efficient day-to-day management.

(d) Water quality monitoring networks. In its brief report on the optimisation of water quality monitoring networks the World Health Organisation (W.H.O., 1977) makes some very pertinent remarks on short-term operational management. For instance, data from the network would be required for "...ensuring the optimum control of water treatment and wastewater treatment plants...". Further, "an optimal monitoring network would...be adaptable so as to take advantage of changes in technology" (emphasis added) and "mathematical modelling techniques should be exploited to the full in network design for operational and predictive purposes". Almost as if in anticipation of the WHO's recommendations, a growing body of literature on the application of statistical estimation techniques* to network design can be identified, e.g. Moore (1973), Lettenmaier and Burges (1977), Kitanidis et al (1978).

(e) Hydrological precursors. One can observe in general that for many aspects of water quality modelling, forecasting, and control a precedent has been created in the more quantitative areas of hydrology. There is much to be gained, therefore, from an examination of the potential, the successes, and the failures of on-line hydrological simulation. If we take the River Dee Regulation Scheme in the UK as an example, Lambert (1978) summarises three year's operating experience with "...the inescapable conclusion...that the practical operation of the system demands the use of on-line mathematical models". We may also note from this project that all important investment decisions are said to depend fundamentally upon the choice of model for real-time simulation and that ultimately relatively simple hydrological models were found to be the most appropriate for on-line forecasting. It can not, of course, be proved that the high capital costs of the forecasting system are justified in terms of more efficient operation (e.g. lower costs of flood damage). The same would be true for the "advantages" offered by real-time forecasting and control of water quality. However, if we suppose that flood damage prevention and drought alleviation are more obvious targets for capital investment in monitoring networks, the incremental costs of adding water quality instrumentation to such existing installations ought not to be prohibitively large.

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*Techniques which will be discussed in more detail below.

3.2. Towards the future.

Past experience shows that some isolated attempts at and examples of real-time forecasting and control of water quality do exist; there are even indications of plans to augment research and development activities in this direction. Much, however, remains to be accomplished. Our purpose in this section is to offer a speculation on the future of mathematical modelling and related techniques in day-to-day, short-term water quality management. So we shall neither discuss matters of hardware development, e.g. sensors and microprocessors, nor discuss pricing, taxation, or standard-setting mechanisms as instruments of a management policy. Nor do we consider those forms of institutional arrangements that would facilitate the implementation of such proposals, though an underlying integrated approach to river basin management is clearly implied. Of primary interest are answers to the question: what would be possible if it were desirable? One can think of the answers as dealing with the retrieval, processing, and restructuring of measured information.

(a) Further model development and model calibration. Let us take as a premise the fact that river water quality is never in a steady-state situation nor can its behaviour be completely determined. The system is therefore intrinsically dynamic and uncertain. Any models that are to be developed must at least be accommodated with this premise, although that would not preclude simplifying assumptions. If the current use of models for management, both short-term and long-term, is to be criticised in any way, then firstly it would be because many such models do not consider the problem of uncertainty. There is uncertainty in the present state of water quality in a river basin, uncertainty in the estimates of the model parameters (coefficients), and uncertainty in the future disturbances of the system.

Secondly, in the past there has been a distinct lack of overlap between models describing those water quality characteristics which are affected by waste disposal and models describing those water quality characteristics which in turn affect the suitability of river water for industrial and domestic consumption. A classic example is the case of dissolved oxygen concentration, so often quoted as the central index of water quality with respect to effluent disposal, yet a variable which is not in itself a vitally important characteristic for establishing whether river water is fit for consumption. This absence of "linkage" would impose severe constraints on the use of models in the day-to-day management of intensively used water resource systems.

Model calibration may be defined as the process of estimating the model parameters and of verifying the performance of the model--as an approximation of reality--by reference to a set of field data. For dynamic model calibration the demands for suitable field data are undoubtedly heavy, as illustrated in two recent examples, Beck and Young (1976), Whitehead (1978). Usually the field data are required in the form of time-series with a sampling frequency of at least once per day; and should diurnal variations be important for solving the given problem, then the sampling frequency would have to be increased to a minimum of six times per day. At present, evidence of exhaustive dynamic model calibration is scarce, partly because the data are required at such a relatively high frequency and partly because in the absence of specialised experiments it is not an easy matter to calibrate models under "normal operating conditions", see for example Beck (1976). However, a technique for model calibration that performs well under these "normal operating conditions" will be equally well matched with the kind of records likely to be generated by on-line water quality monitoring networks.

(b) Estimation and forecasting. We are now entering the domain of models as aids to operational decision-making. Estimation and forecasting refer thus to the use of models for estimating the present and (short-term) future state of river water quality at a number of fixed spatial locations. There are two aspects of the problem of particular interest:

(i) the prediction of future events, such as storm runoff entering a treatment plant; and

(ii) the reconstruction of information about variables which are not directly measured by on-line sensors.

It is in fact difficult to talk about estimation and forecasting yet avoid mention of the Kalman filtering technique (see, for example, Gelb, 1974): a recursive algorithm ideally suited to digital computation and an algorithm which has come to enjoy almost unbounded popularity (see, for example, Chiu, 1978). The potential of this algorithm merits brief consideration.

There are many ways in which to present the concepts of the filter. Figure 2 provides an outline of some of its basic features which are appropriate to this discussion. (Here we have called the filter an extended Kalman filter which merely denotes that nonlinear models may be treated with this method). Suppose, for the sake of illustration, that "reality" is a reach of river. The filter embodies a model of reality: given the measured information on the input (upstream) conditions, the model simulates, or predicts, the corresponding changes in the output (downstream) conditions. The predictions are compared with the measured output information and then corrected--in the block labelled "estimation algorithms"--to yield newly revised estimates of the state of water quality ($\hat{\underline{x}}_m$ and $\hat{\underline{x}}_u$) for the computations of the next time-period. Reality, not surprisingly, is subject to unknown, random disturbances, and all measured information is subject to errors of measurement. The filter may account for this by the respective levels of uncertainty (error) assigned to the model, as an approximation of reality, to the input disturbances, and to the errors of observation. These levels of uncertainty will influence the performance of the estimation algorithms and are in turn translated into estimates of the inevitable errors of prediction about the present and future behaviour of reality.

Now let us look at the filter from the point of view of an information processing mechanism. We note from Figure 2 that the information passed to the filter comprises the input/output measurements. The information derived from the filter consists of statistically based estimates of the state of the system and, if so desired, estimates of the parameters ($\hat{\underline{\alpha}}$) appearing in the filter's model of reality. The term "filter" lends an intuitive feeling to what is happening: the filter behaves so as to discriminate against the unwanted, but ever-present, effects of noise in the measured information. However, it must be acknowledged in all humility that the originator of the device would discourage such an interpretation (Kalman, 1978). Were we to require predictions of the future, the filter could be run in an "open-loop" fashion without the feedback of measured information on the state of the system. It would in this case, nevertheless, be necessary to provide the filter with assumptions (or predictions) about the short-term future input disturbances of the system. Alternatively, the filter may be employed to reconstruct on-line estimates of water quality variables ($\underline{x}_u$ in Figure 2) which are not readily measured by on-line sensors; this is known as state reconstruction. And in a more general sense, since it can revise the estimates of its model parameter values, the filter can be applied in an adaptive or learning mode. In other words, the algorithm combines the operations of model calibration and forecasting.

A number of closely related companion algorithms of recursive estimation are available, e.g. Young (1974), and in addition there exist simple techniques of adaptive prediction (Holst, 1977). The details of these methods and of the filter need concern us no further. But what might be the potential applications of such techniques? There are several to which we can already point.

(i) In his introduction to the use of mathematical models in the Bedford-Ouse Study (Anglian Water Authority, 1977) Newsome suggests that "Authorities would...welcome a reliable forecast of the likely variation of water quality at the [supply] intake on an hourly basis, notwithstanding the fact that there is probably bankside storage to buffer such variations" (Newsome, 1977). With respect to accidental upstream pollution a simple adaptive estimator of pollutant dispersion and time-of-travel would appear to be particularly attractive if it could be based upon easily available measurements such as regular observations of conductivity (Beck, 1978a).

(ii) An adaptive predictor has been proposed for real-time (hourly) forecasting of influent sewage discharges to a wastewater treatment plant (Beck, 1977b). For this case the adaptive nature of the predictor is directed towards the fact that storm conditions significantly alter the input/output dynamic behaviour of the sewer network.

(iii) Schrader and Moore (1977) report the application of a Kalman filter to a short-term in-stream temperature forecasting problem associated with power plant cooling water circuit operation when discharges are subject to temperature constraints.

(iv) The Kalman filter has also been employed as a state reconstructor for providing operational information on nitrifying bacteria concentrations during activated sludge treatment of wastewater (Beck et al, 1978). A similar use of the algorithm would be involved for estimating variations of non-point pollutant loadings along a stretch of river.

So to summarise, the future value of these techniques will lie in the balance between their considerable potential benefits and the difficulties that one can anticipate in their practical application.

(c) Management and control. The adaptive predictor mentioned above actually has its origins in an earlier self-tuning, or adaptive regulator (Åström and Wittenmark, 1973). The adaptive controller, as one would expect, attempts to combine the calibration and control functions. It can do this in several ways, including one whereby the input control action is formulated in a manner which simultaneously probes, i.e. experiments with, the behaviour of the process under control--a kind of trial and error operating experience. Thus the adaptive controller can be quite sophisticated, but not so sophisticated that it is not amenable to micro-processor realisations, see for example Clarke et al (1975). Among a number of areas of application Marsili-Libelli (1978) has examined the feasibility of a self-tuning controller for a clarification unit with chemical flocculant addition in a municipal water purification plant.

Further discussion of designs for automatic controllers, however, would miss the primary purpose of this section. Rather it is questions about the nature of the control and management activity itself which are of greater relevance. The self-tuning controller is but one among many methods of control system design, all of which strongly depend upon the following factors for their success in practice:

(i) A valid and accurate model of process dynamic behaviour;

(ii) The availability of a reliable, robust instrumentation for the rapid collection of information about actual process performance;

(iii) For the case of mass transfer processes, the (physical) capacity to store flows and substance masses;

(iv) The ability to specify clear, precise, unambiguous process performance objectives.

Because each of the above cannot be taken completely for granted, it has been argued elsewhere (Beck, 1978a, Beck, 1978b, Beck et al, 1978) that real-time control of water quality demands approaches which may differ from those of conventional control system design procedures. We shall not repeat those arguments here, except to pose the key question:

> Should automation, computerisation, and control always seek to eliminate the human element from the control loop?

One point about this question deserves special mention for it brings us to a subtle difference between "automation" and "control". Automation is understood as the automation of information retrieval and communication and the automation of implementing control actions. Control is interpreted as the use of information retrieved for the determination of the control actions to be implemented. And in this latter context of control our answer to the question would be that the human element should not be removed from the control loop.

For the future, therefore, we may visualise mathematical models and on-line forecasting procedures as a kind of support service for day-to-day operational management of water quality. That is to say, the models may be used for rapid evaluation of the short-term consequences of operational management decisions. Yet there is more to the "human element in the control loop" than that. As Hegg et al (1978) note in their assessment of factors limiting wastewater treatment plant performance:

> "The highest ranking factor contributing to poor plant performance was operator application of concepts and testing to process control."
>
> "....present plant personnel are an untapped source for achieving improved performance."

And this is precisely the motivation behind the studies reported in Beck et al (1978). What is really required is first a mechanism for formalising the continuously accumulating trial and error experience of the management function and second a calculus for carrying out manipulations with a set of such control rules. The suggestion is, therefore, that an approach rejoicing in the name of "fuzzy control" (see, for example, Tong, 1977) may well have a vital role to play in real-time water quality management. The human element is not necessarily to be supplanted in this control process: mathematical models and a formalised distillate of past experience are perhaps best employed as aids to decision-making on a day-to-day basis.

4. CONCLUSIONS

This paper has argued a case in favour of recognising the problems of operating river water quality management schemes. Management literally does not consist only of building for a better future; what has been built also has to be operated effectively. Solutions to the design, long-term planning, and capital investment aspects of management ought ideally to strive for integrated flexible strategies of river pollution control. Among the range of options that could preserve flexibility of management, it is further argued that real-time forecasting and control of water quality deserves special attention. It is not suggested that real-time operating policies are a panacea for water quality management, but neither should they be ignored for the reason that they are not practical at present.

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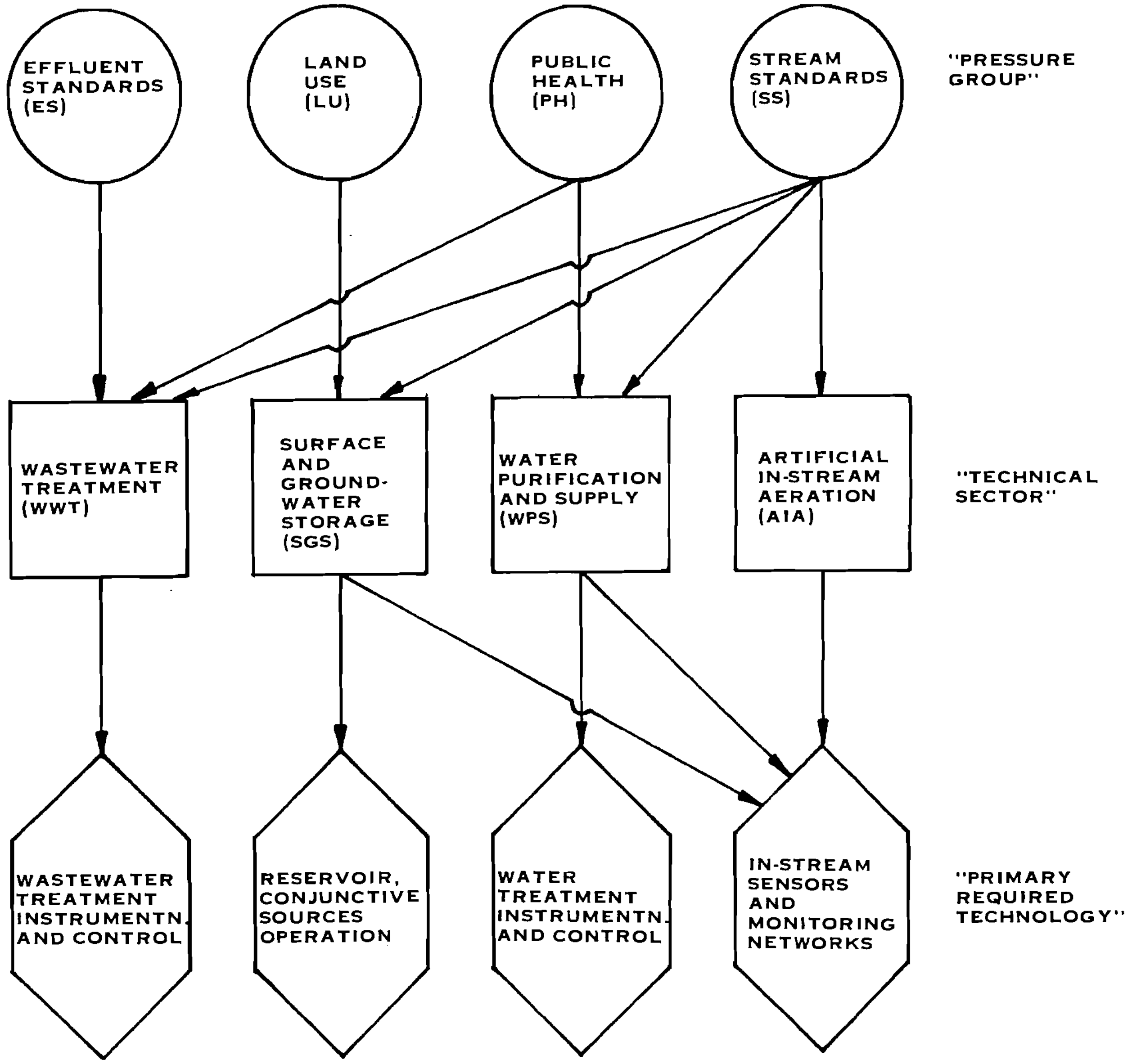

Figure 1. Water quality management: the forces acting upon different technical sectors and the requirements for different kinds of technological innovation.

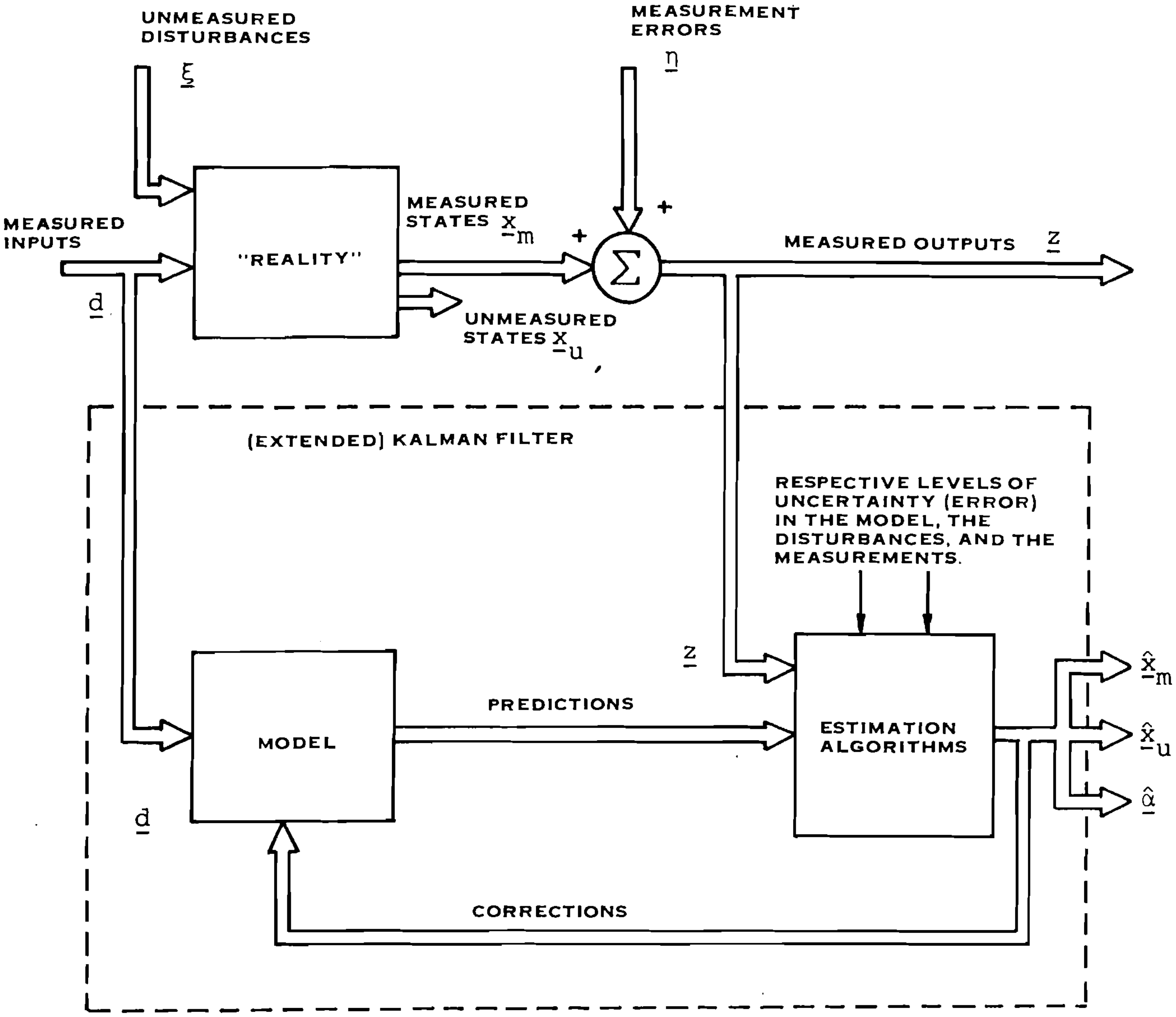

Figure 2. The (extended) Kalman Filter, an algorithm for estimation and forecasting; $\underline{\hat{x}}_m$, $\underline{\hat{x}}_u$, and $\underline{\hat{\alpha}}$ are respectively estimates of the measured state variables, the unmeasured state variables and the model parameters.