Working Paper

TIME-VARIABLE WATER QUALITY MANAGEMENT - A POLICY STUDY

M.B. Beck

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International Institute for Applied Systems Analysis
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PREFACE

This year (from June 1979 to June 1980) several projects are being supported at IIASA through the U.S. National Academy of Sciences under a program for International Cooperation in Systems Analysis Research. One of these projects is entitled "Real-time Water Quality Management". It is a collaborative project and forms part of the Research Task "Models for Environmental Quality Control and Management" of IIASA's Resources and Environment Area. The final objective of the project is to prepare a policy-oriented report that fairly sets out the practical prospects for real-time forecasting and control in water quality management.

In a previous paper (IIASA Working Paper WP-79-1) the background to the need for and problems of real-time water quality management has been described. The scope of the present paper is somewhat broader. Here, the problem of time-variable water quality management is considered since this permits an analysis of the interaction between long-term strategic planning and short-term (real-time) operational management. The level of the discussion is essentially that of a policy analysis. The primary aim is to develop a picture of the changing character of water quality problems and their management. In doing this, and by analyzing the subject from different perspectives, an important objective has been to define more clearly the relevant context and overall direction of the project "Real-time Water Quality Management".

This is indeed a working paper. The arguments presented are perhaps more coherent than the arguments presented previously, but they are not complete and it may be that they do not address pertinent issues. For that reason the paper needs the corrective application of feedback comments.

SUMMARY

Interactions between the long-term (planning) and short-term (operational) functions of stream water quality management are considered in this paper. It is argued that the problems and, therefore, the strategies of water quality management do not remain constant with time. In particular, the paper identifies what may be an important change of emphasis in water quality management from the essentially curative strategy of the past 20-30 years to a preventive strategy for the coming years. This change of emphasis suggests that more attention in research and development should be given to matters associated with the operational aspects of management. The analysis of the paper is undertaken from several different perspectives, for example, from the perspectives of economics, innovation, legislation, and institutional arrangements. The areas in which interaction between long-term and short-term management is likely to be most pronounced are: in changing the way in which water quality can be monitored, and thus in changing the way in which water quality objectives can be specified; and in increasing the range of options available to management.

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> " 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).

1. INTRODUCTION

This paper assesses some accepted principles and suggests some new principles of water quality management. The phrase "time-variable" in the title of the paper is particularly significant: it allows consideration of long-term planning, where variations with time are understood as variations from year to year; and it allows consideration of short-term (real-time) operations, where variations with time on an hour-by-hour basis are important. The framework for the analysis of the paper is that of process dynamics and process control. Both the long-term and the short-term management functions should account for the fact that the system to be managed, its input disturbances, its output responses, and the management procedure itself, all change with time.

Typically, because the time-scales of "long-term" and "short-term" are so different, the long-term and short-term management problems have been treated independently. This is not unreasonable. Variations of water quality in the short-term may be considered as rapid perturbations about a constant level, although in fact that constant level is part of a relatively slowly changing trend in the long-term. The long-term management function may be undertaken without consideration of short-term transient variations provided the system performance and its accompanying objectives <u>are</u>, or are <u>defined</u> to be, insensitive to these transient perturbations. Transient perturbations might also be ignored if the management of such variations (in real-time) is thought to be impractical. Certainly, in the past it has been the tradition that long-term water quality management was considered to be the principal, if not the only, problem to be solved in water quality management.

Real-time water quality management, however, is becoming a practical possibility and thus it has to be recognized as such within the procedure of long-term, strategic planning. This paper argues, then, that there are significant interactions between long-term and short-term (planning and operational) water quality management. The two problems should not be treated independently. And not only are the interactions between them important because of the increasingly practical potential of real-time control, but they are also important because it may not be sufficient to equate desirable system performance (desirable water quality objectives) with acceptable average, year-to-year standards. In short, the availability of operational control affects the long-term planning process and vice versa.

2. A FRAMEWORK FOR ANALYSIS

Figure 1 provides the framework for analysis of both the long-term and short-term components of water quality management. This framework is, as it were, a conceptual model for the arguments of subsequent sections. Once the reader is familiar with the terminology of process dynamics and control engineering, which we shall define in this section, it will merely be necessary to follow alternating changes between the long-term and the short-term views of water quality management as seen through Figure 1.

The block labelled "Process to be controlled" in Figure 1 means, in very general terms, all those activities which affect, and are affected by, the water quality in a river system. A convenient way of gathering together most of the major such activities is to take the basic unit of an urban/industrial community, as in Figure 2. Figure 2 shows that the various activities can be grouped together to form four subsystems (Beck, 1976): (i) the abstraction, purification, and supply of potable water; (ii) urban runoff and the sewer network; (iii) wastewater treatment facilities; (iv) in-stream water quality in a reach of river. One must imagine that many units of the form described by Figure 2 may be coupled to each other according to the pattern of any given river basin. Additional activities that are not indicated in Figure 2, but which nevertheless would be part of the "Process to be controlled", include cooling water usage, water for agriculture, agricultural runoff, upland surface water storage, groundwater pumping, and pumped lowland storage.

In spite of the guiding principle that all of the above activities have to be considered in an integrated approach to water quality management, there is a predominant tendency, both in this paper and elsewhere, to see water quality management as a problem essentially of wastewater treatment.

2.1 Long-term Management

Classification of the types of variables shown in Figure 1 is helpful.

The input disturbances account for changes (with time) in the industrial/agricultural activities and population of the river basin. It might also be appropriate for the analysis to consider changes in water pollution control legislation as input disturbances, if the legislative procedure is not perceived as coincident with the "Controller or control function". This is in fact the approach adopted later in section 6.1. There may, however, be good reasons for any current planning procedure to include anticipated future changes of legislation as input disturbances. The defining character of the input disturbances is that they are not manipulated as part of the control function; and although they can affect the system's output response in both a positive and negative manner, the problem of management will be more concerned with their deleterious effects on system performance.

The output responses of the process (system) are those features of river water quality that may be easily measured and that give a meaningful indication of the "state" of the river system. Such features would be sensitive to the way in which the river system responds to the input disturbances and to the control actions, where control actions could include the construction of a new treatment facility or a new reservoir. The output responses are required to be easily measurable simply because the desired performance of the system must be specified in similar terms. It would be inappropriate, for instance, to specify the desired system performance in terms of a minute concentration of a particular micropollutant, when that given concentration was at the limits of detectability with current laboratory methods. The proper execution of management cannot be carried out when the perceived mismatch between desired and actual performance is sensitive to errors of observation. Thus typically, the response of the system is quantified in terms of, say, yearly average biochemical oxygen demand (BOD) and dissolved oxygen (DO) conditions at various locations in the river basin.

The "Controller or control function" is an agency, authority, or institution responsible for the management of water quality in the river basin. This authority collects and processes the information (data) about input disturbances and output responses, from which it then determines a control action (a management policy) to be applied to the process.

The regulating variables are part of the long-term plan. They essentially comprise decisions regarding capital investment, designs for wastewater treatment and water purification plants, the location of industrial units, and so forth. The regulating variables are used by the controller to compensate for those effects of the input disturbances that either degrade the performance of the system or cause inconsistencies between actual and desired (legal) performance. Two simple illustrations of the ways in which the regulating variables may be applied are given in Figure 3. Suppose that for the foreseeable planning future water quality standards remain constant, but the input disturbances to the system, i.e. the "load" on the system, changes with time. For example, in Figure 3(a) let us assume that an increasing population leads to a steadily deteriorating sewage discharge quality until eventually a new piece of plant is commissioned. This is the regulator problem; it is concerned with taking control action (building the new treatment facility) to compensate for the effects of load changes on the system. The servomechanism problem, shown in Figure 3(b), requires control action to be taken in order to follow changes in the desired system performance, e.g. changes in water quality standards--improved water quality standards require improved wastewater treatment performance.

Lastly, although not indicated explicitly in Figure 1, the notion of the system's environment may be introduced. Here environment is understood as any physical, institutional, economic, or political process that affects, or is affected by, the inputs and outputs of either the process to be controlled or the controller.

2.2 Short-term Management

For short-term management problems the variations in river water quality can be considered as input disturbances when water is to be abstracted from the river for potable supply purposes. Day-to-day fluctuations in the stream phytoplankton or nitrate-N concentrations affect the efficiency of plant operation--for example, the clogging of sand filters, or the level of treatment required to meet supply standards for permissible nitrate-N levels. Clearly, if the system to be controlled is decomposed into subsystems, as it is in Figure 2, then the output response of one process may be the input disturbance of another process. The output response of a wastewater treatment plant can be measured in terms of the ammonium-N, BOD, and suspended solids concentrations in the effluent discharged to the receiving water body. These quantities can in turn be viewed as either regulating variables or input disturbances of the quality in the reach of river to which the effluent is discharged.

If, for instance, the BOD concentration of the effluent were manipulated on an hour-by-hour basis in order to achieve a DO standard at a point downstream in the river system, then the sewage effluent BOD concentration is being used as a regulating variable. Of course, in order to use the effluent BOD concentration in such a fashion, it would first be required that certain regulating variables in the wastewater treatment plant (e.g. sludge wastage rate and recycle ratio in an activated sludge unit) can be manipulated in order to achieve the desired BOD removal performance. Thus a cascade, or hierarchy, of control functions may exist (see Figure 4), both in the short-term management context and in long-term water quality management.

The controller can take several forms: a simple analog unit; a dedicated microprocessor unit; a digital algorithm programmed on the plant computer; the plant manager; or a combination of manager and computer. Once the control action is determined, however, the effectiveness of the controller is often fundamentally limited by the capacity to act, i.e. by the capacity to implement the control decision. Suppose, for example, that the controller determines that a rapid increase is required in the level of nitrification obtained in an activated sludge unit. Changing the sludge wastage rate, recycle ratio, or aeration rate will do little to achieve the desired response quickly, because it takes a number of days and weeks to increase the size of the nitrifying bacteria population. The controller is therefore constrained in its range of feasible and effective control actions.

3 FEEDFORWARD STRATEGIC PLANNING

The conceptual model of Figure 1 is now ready to be used as medium in which current procedures for long-term water quality management can be interpreted. First, however, and by way of introduction, it is instructive to quote at length some comments of Cantley on monitoring and control of the implementation of strategic plans (Cantley, 1978):

> "If planning is to be more than a paper-producing exercise, it has to be followed by action. The plans are necessarily made on assumptions and forecasts, which are <u>uncertain</u>. Plans are made only at intervals--in the case of strategic planning, perhaps longer than a year. The adequacy of the original plan as a guide for continuing action is therefore bound to decline with time. Monitoring is the process of <u>information-gathering</u> by which the organization checks both its performance relative to targets, and the behaviour of the environment, assumptions about which formed part of the basis for the plan and the targets. Control actions result from the monitoring, and are typically:
>
> (a) to change current actions to ensure closer alignment with the plan;
> (b) to re-interpret planned targets in the light of the latest environmental information, and then as (a) above ... .
>
> At a higher level [assuming that we have a hierarchical control problem of the type introduced in section 2.2 and Figure 4], other results of monitoring may be:
>
> (c) to discover whether an assumption made as a basis for planning (e.g. a postulated relationship) has in fact proved correct; if in fact it is wrong, or a more accurate assumption is now available, an adjustment to the plan may be made;
> (d) to discover that even the perfect achievement of a planned target is not found to be satisfactory, e.g., because it has not contributed towards the

> policy objective to which it was supposedly related. The target may then be abandoned, modified, or replaced, and action as in (a) initiated." (emphasis added)

Let us make the important assertion that the large majority of procedures for long-term water quality management are carried out in a feedforward control manner. Such a situation can be represented by Figure 5 (and compared with Figure 1). We assume that legislation provides the basis for the desired performance of the system, where this performance can be specified by in-stream water quality standards and/or effluent discharge standards. The controller, i.e. control institution, has several functions to perform. It may take historical trends of the measured input disturbances (industrial activities, population growth), derive a model of these trends, and make predictions over the given planning horizon of the future (measurable) input disturbances of the system. The predicted input disturbances are themselves used to obtain forecasts of the expected future response of the system, where probably a model might be employed in order to simulate the behaviour and responses of the processes to be controlled. The next function of the controller is to determine those future changes in the regulating variables (treatment plant construction, treatment capacity expansion) that will compensate for the predicted effects of the future input disturbances. Finally, the planned regulating action (the sanitation programme) is implemented. The essential aim of the long-term management strategy is to cancel out the deleterious effects of the anticipated input disturbances.

Figure 5 and the procedure we have just outlined are significantly different from some of the elementary components of control introduced in section 2 and Figure 1. It is clear that even the best model of the system to be controlled and its future input disturbances cannot afford perfect prediction of the future response of the system. The system and its disturbances are inherently uncertain; indeed, some of the unmeasured and unpredicted disturbances may be so substantial as to render the plan ineffective before it is fully realized. Inevitably there will be misalignment between the desired and actual performance of the system. And if there is no further evaluation of the output responses against their desired values, as is the case in the idealized picture of Figure 5, then in Cantley's terms there is no feedback of information with which to modify current actions in order to ensure closer alignment with the original plan.

4. MANAGEMENT WITH FEEDBACK

The feedforward strategy just described suffers from certain disadvantages. It exploits the principle that information about the input disturbances can be fed forward to a controller, which initiates control action according to the assumed effects of those disturbances on the system response. It overlooks the fact that not all disturbances and their effects can be predicted. The key feature of the feedback controller principle (see

Figure 6) is the comparison of desired and actual system performance, followed then by regulating action consequent upon any perceived mismatch between the two. The purpose of feedback control is to mitigate the undesirable effects of uncertainty in the system disturbances and uncertainty in the knowledge of those relationships which govern the system's behaviour. In the following discussion of management with feedback special emphasis is placed upon how and why short-term operational management should interact with long-term planning.

4.1 Specifying the Desired System Performance

In order to apply feedback control the goals for system performance have to be stated clearly. The definition of desired system performance requires reassessment for it is a crucial factor affecting the feasibility of short-term operational management. Again, for the purposes of the argument, we make an important assertion: that current standards for water quality management (in the short-term and in the long-term) are exclusively specified as constant, <u>average</u>, <u>yearly</u> maximum/minimum bounds for quantities such as BOD concentration, suspended solids, etc. If these, then, are <u>defined</u> to be the objectives, it is not surprising that real-time management is difficult to justify without first demonstrating that it would provide significant improvements in average yearly performance. But is this average performance the only desirable objective? Suppose, as is clearly now happening in many industrialized countries (OECD, 1979), that general macroscopic levels of river water quality are improved by the widespread installation of mechanical and biological wastewater treatment facilities. Let us also assume that water quality can be measured by an index Q^* and hence postulate a simplified picture (Figure 7) of past (P) and future (F) performance in water quality management. There is no doubt, in this particular picture, that the average level of water quality achieved in the future is better than the average level of water quality maintained in the past. There is, however, the problem of the "transient crises" indicated in Figure 7 by events P_A, P_B and F_A, F_B, which may be assumed to represent accidental spillages or equipment failures. In the past, with rivers receiving a higher pollutant load, the <u>relative</u> effects of P_A and P_B might have been regarded as only <u>minor</u> perturbations in system performance. For the future, the relative effects of similar crises F_A and F_B will be significantly greater. And as public awareness of an improved average water quality becomes well established, the responsibilities of management to avoid such crises increases. It may well be argued, therefore, that precisely because of the successes of past long-term management policies, the day-to-day, short-term management of water quality--inasmuch as it relates to transient crises --assumes much greater significance. Thus the definition of desirable system performance in average terms alone may not be appropriate for the future. The objectives of water quality management change with time, as do the problems to which that management has to address itself. In section 7 we shall return to a discussion of how present management strategies affect the risks of transient pollution crises in the future.

4.2 The Capacity to Observe

A second prerequisite for the application of feedback control is the ability to perceive any mismatch between desired and actual performance of the system (see also Figure 6). One may think of this, in Cantley's terms (section 3), as monitoring implementation of the long-term plan. A first, and perhaps trivial example of how it would not be possible to apply feedback in the management of strategic plans would be if the goals for system performance were specified in terms of output responses that cannot be measured. For instance, imagine that a stated objective is for the daily average DO concentration at location X to be not less than 4 gm^{-3} on any two consecutive days of the year when DO measurements are taken only once per week. It would simply not be possible to perceive whether the system were achieving its desired performance and it would be impossible to correct for any deviation from that performance.

If the system performance has, therefore, to be specified in a way that is consistent with current measurement and sampling practice, it is equally appropriate that this specification can be altered in the event that measurement practice changes significantly. In view of recent developments in specific-ion electrodes and the installation of telemetered water quality monitoring networks, therefore, the volume of information generated concerning actual system performance is likely to increase beyond previously imagined proportions. This single development could have several important consequences. First, it may facilitate the specification of more complex objectives for water quality management, although complexity is not necessarily a virtue. Of special significance, however, would be the ability to specify and monitor system performance at the level of short-term variations, such as the transient crises of Figure 7. Second, this development reveals the possibility for monitoring and evaluating real-time operational control of wastewater treatment plants according to its effects on the receiving water body. Third, it creates quite a new and different requirement for information processing by the control authority (refer back to Figure 1). Newsome (1979) calls this "stage 3" in the development of water data collection schemes, whereby "the data collection systems are progressively refined and closely resemble those used in process control applications".

Another significant feature of monitoring the strategic plan, a feature which is also evident in Figure 6, is that all measurements of the system's output response are subject to errors and uncertainty. In an ideal world management would prefer to act upon the misalignment between the desired and hypothetical, error-free response of the system. In reality, however, management has to base its control action upon an uncertain and estimated misalignment between desired and actual performance; an awareness of, or an insensitivity of the control action to that uncertainty is thus advisable.

4.3 The Capacity to Act

Once a suitable control action has been determined it must be possible to put that action into practice. Hence, as indicated in section 2.2, a third basic feature of control (not only feedback control) is the capacity to act. Present practice in the short-term operational management of wastewater treatment, stream water quality, and water purification suggests that the capacity to act in that context is quite limited. The same may be true of long-term water quality management. Whether or not that is so, let us make yet another assertion (see also Walters, 1975): that any current control action that restricts the range of options for future control actions is not desirable. This assertion applies, in particular, to the decision-making function in long-term planning. As an example, consider the case of building an activated sludge unit for treating wastewater. The design and construction of the unit (decisions taken now) may adversely prejudice subsequent decisions to have, first, a fully nitrified effluent and then, later, an effluent subject to restrictive constraints on permissible ammonium-N and nitrate-N concentrations. "Creative" or "innovative" planning would seek to encourage the development of wider ranges of control options for future strategic management. Indeed, one could argue the case that a long-term strategy which stimulates the development of real-time operational management is in fact a good illustration of such a creative plan. In the example of activated sludge design, a step-feed type of unit with real-time DO profile control has the potential for meeting the subsequent nitrification and nitrification-denitrification objectives merely through adaptation of the unit's operating policy. Thus even in a crude sense the practical possibility of real-time water quality control can be seen to increase the range of actions that are feasible at the planning and design phase of management. To the existing options (a) construct new treatment facility, (b) expand capacity of old treatment facility, (c) add different unit treatment process, we could in principle add the options (d) install "operational control" at existing facility, (e) expand capacity and install "operational control" at existing facility, and (f) operate existing unit processes differently.

4.4 Interaction Between Long-term and Short-term Management

Some useful conclusions can be drawn from the analysis of management with feedback. Our aim in doing so is to look, as stated earlier, at the influence of short-term operational management on strategic long-term management, and vice versa (see Figure 8).

The practice of real-time control must inevitably change the nature of the system, whose behaviour the planning function seeks to manage in the long-term. An expanding facility for real-time water quality monitoring--the increased capacity to observe--permits different goals for the desired system performance to be specified and evaluated. These different goals might address the problem of managing transient, severe pollution incidents; evaluation of system performance could include monitoring the net benefits of operational wastewater treatment control as quantified by its effects on in-stream water quality. It may indeed be necessary to specify different goals for the system's performance precisely because of the response achieved from implementing earlier water quality management strategies (see also section 7). The increased capacity to observe demands also an equally increased capacity for information processing, otherwise the control function may be overwhelmed by a surfeit of observations it cannot usefully interpret. In particular, one of the main aims of information processing is evaluation of those tentative assumptions about system behaviour (the models) that were made in the preparation of the management strategy. And lastly, we made the point in section 4.3 that real-time operational management positively influences the range of options available for long-term management.

Those, then, are some of the potential benefits that short-term management offers to long-term management. Two factors are of key significance at all stages in the implementation of a strategic plan, as Cantley (1976) and Storey and Walker (1978) have pointed out. They are: the generation of useful information about system behaviour; and an awareness of uncertainty. Consider by way of illustration, the following dilemma. A planning authority has a predetermined sum of capital to spend in undertaking a water quality management programme. This sum will buy either two new wastewater treatment plants or one new treatment plant and a comprehensive water quality monitoring network. Which option should the planning authority choose? In the ensuing debate the authority should at least recognize the positive contribution of a strategy that aims to reduce uncertainty and that may thereby enhance the system's and the controller's ability to adapt easily to the changing problems of the future. The strategic plan has a responsibility to invest in improved understanding and in scanning the future for new and, as yet, undetected problems. These are themes to which the discussion will return in section 7.

5 ECONOMICS AND INNOVATION

In water quality management there is not really any product quality specification to which strict adherance (or from which minimal deviation) is required at all times of the day, week, or year. This is an inescapable difficulty in formulating an analysis of economics and innovation in water quality management. There are, of course, public health specifications, and these do apply rigorously to the product of a water purification plant. But in economic terms it is not easy to justify the installation of operational forecasting/control purely on the grounds that it would improve the "reliability" of product quality. Given that current objectives for water quality management are defined as yearly, average, maximum/minimum bounds for the permissible concentrations of various substances, real-time control will have to justify itself in those terms. In other words, it is inappropriate to advocate or dismiss real-time operational control at the scale of (economic) performance on an hour-by-hour basis--at least this is inappropriate given present objectives. A recent study of automatic DO control in an activated sludge unit clearly supports this view (Flanagan et al., 1977); in fact, the dominant benefit of automatic control is found to be the yearly saving in energy consumption. An economic analysis of real-time control, as it effects the economics of long-term management, must therefore account for the variable costs of operational management in some aggregated year-by-year index. But this rather begs the question, for it requires the prior assumption that real-time water quality management will, or will not be feasible in practice; normally it has been assumed to be infeasible. Consequently, there has not been any proper analysis of water quality management in which the trade-offs between capital (fixed) and operating (variable) costs might be explored. Indeed, even the framework for such analysis does not yet appear to be well established, although Olivieri and Smeers (1979) have initiated studies in that direction. Extensions of their work promise the encouraging prospect of an analytical framework for examining questions of, for example: the benefits of high capital cost/low running cost equipment vis-a-vis low capital cost/high running cost equipment; the "costs" of equipment failure; the balance between unit processes operated on a seasonal basis and unit processes operated throughout the whole year; and integration of treatment plant operation with stream-flow regulation (Smeers, 1979).

One may observe, therefore, that under present circumstances it is not realistic to attempt to justify the economic benefits of short-term operational management within the time-scale of hours and days. It is logical to tackle the issue from the other end of the spectrum, within the time-scale of years, where variable costs can be assessed together with fixed costs. Having said that, and having noted the re-emergence of a framework for analysis of such problems, it is as well to remind the reader of statements made over a decade ago (Thomann, et al., 1968):

> ".... There is ample evidence to indicate that seasonal waste treatment can result in significant economic savings. This is especially true if a base level of intermediate to secondary treatment is assumed throughout the year to meet an overall water quality objective. At certain times...it may be necessary to step up treatment by using any number of waste treatment schemes.
>
> The other mode of operation is to require a high degree of waste removal on a year-round basis with no recognition of the changing assimilative capacity of the river or estuary. If this mode of operation is required, it is seen that...for most cases the quality of the water body is usually above minimum standards for a substantial portion of the year. If the variable waste control is permitted, individual waste disposers can recognize the tradeoffs between capital intensive waste treatment devices and those with high operation-maintenance costs."

It is thus perhaps discouraging to reflect upon the progress in the intervening years. However, as we shall see, objectives change with time and economic arguments are not the only factor to be considered in determining an innovative strategy of water quality management.

5.1 Innovative Forces

From the preceding discussion we might hypothesize that the real innovative force in wastewater treatment plant technology--a specific example in which real-time forecasting/control is technically feasible--is the desire to minimize operating costs. This would be particularly important in an economic environment where the costs of energy supply have a higher rate of inflation than the costs of labour and equipment. Indeed such a situation is significantly different from that which has prevailed in the past. It is interesting, therefore, to note how a major report on wastewater treatment in the U.K., published in 1974 but clearly based upon pre-1973 cost data, saw the problem of innovation (Institution of Chemical Engineers, 1974):

> "The need for innovation arises not for its own sake but to fulfill needs which cannot be met, in whole or in part by present technology. These needs are:
>
> (a) The continual increase in demands for higher standards of treatment.
> (b) The growing shortage of water which is likely to bring about increased demand for re-use.
> (c) The proposals for a considerable increase in public expenditure in the field in the near future.
> (d) The challenge inherent in the proposals for the reorganization of the industry".*

The need to reduce operating costs was not apparent. It was not apparent because the same report found that "...capital costs greatly outweigh running costs in sewage treatment..."since"... when expressed in terms of the capital cost, the annual operating cost was approximately 3% of the total capital cost." That this situation has changed radically is brought into sharp focus by Andrews et al (1979) who make reference to a survey of the Engineering News Record (1977). The survey showed that the average number of years elapsed from the time a plant was put into operation to the point at which operation and maintenance costs totalled more than the initial investment was 6.1 years.

Over a period of just five years (since 1974) the forces of innovation in the wastewater treatment industry have thus changed quite dramatically. Perhaps "changed" is even the wrong word, for it is not clear what incentives to innovate have existed in the more distant past. For example, the Institution of Chemical Engineer's report makes the following observation (Institution of Chemical Engineers, 1974):

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*The U.K. water industry was reorganized in 1974.

> "A second difficulty which lies in the way of innovation is the difficulty associated with the inertia which often arises from the circumstances surrounding what might be called a traditional industry. Such industries can acquire an inordinate sense of uniqueness which leads to isolation from the main stream of technology and, in addition, they tend to trivialize basic principles to fit their own specialized requirements. Furthermore, they tend to make existing methods and techniques into ends in themselves spending time and money on refinements of existing practice when what is needed, perhaps, are radically new approaches.
>
> Probably as good an example as any of a traditional industry is the town gas industry as it was a quarter of a century ago. Dependent upon coal as its raw material, it evolved a specialized, isolated technology with its own peculiar nomenclature. Since that time it has had to undergo two complete upheavals and the technology of producing gas from coal is now almost completely dormant in the United Kingdom today."

We can at least be reasonably confident that "operational cost savings" will be an important and clearly directed innovative force of the immediate future.

There has never been a particularly strong innovative force arising from the maintenance and improvement of the "product quality" of wastewater treatment, although one must be careful to distinguish between essentially economic and essentially legal factors in this respect. The difficulties of an economic justification of product reliability have already been mentioned. If, however, it can be assumed that the first of the needs for innovation quoted from the Institution of Chemical Engineers report--that of a "continual increase in [legal] demands for higher standards of treatment", then we might postulate the following. Effluent standards, or in-stream water quality standards, act on the process of innovation in a diffused and distributed fashion. Since they specify only the condition required to be met by the effluent, they do not have the ability to focus attention on any one particular aspect of treatment plant design or plant operation where innovation might be necessary to assist in achieving the new standards. To argue that legal aspects are weak innovative forces is, however, to criticize them for not achieving that which they were not intended to achieve. In very simple terms, water pollution control legislation has been designed to protect environmental quality and not to modernize wastewater treatment technology. Should it not, nevertheless, do both? Orr supports the expected affirmative answer to this (largely rhetorical) question when he remarks that "...a very strong case can be made for a shift in emphasis in policy formulation from allocative efficiency to long-term technical adaptation" (Orr, 1976).

Let us continue the discussion of legislative, innovative forces. A common rebuttal of the proposition that real-time forecasting and control are beneficial is the question: why should a manager operate his plant less effectively than is possible merely to comply with a control objective that unrealistically penalizes performance which is better than effluent (or stream) standards require? Recall, for the purpose of this question, that it is the nature of conventional control designs to penalize system performance that deviates in both a positive and a negative sense from the desired system performance. Recall also that operational decision-making might seem an unnecessary level of sophistication if a plant is already complying with standards without such decision-making. Consider then the following. Andrews, et al. (1979) describe a control system for nitrification in the oxygen activated sludge process. The basic aim is to remove ammonia from the waste stream. The Texas Department of Water Resources, however, requires the wastewater treatment plant effluent, in this specific case, to be chlorinated in order to maintain a minimum chlorine residual of 1.0 gm^{-3}. The chlorine residual may be a combined residual--such as chloramines formed from the reaction between chlorine and ammonia--or it may be a free residual. The concentration of ammonia in the activated sludge plant effluent affects, in a very complex manner, the ability to keep within the stated chlorine residual standard. In fact, from the point of view of operating costs, the plant manager might be encouraged to carry out less effective nitrification than is possible in order to satisfy chlorine standards.

The example studied by Andrews et al. has also a second interesting feature. Suppose the regulatory agency imposes, as it does, instantaneous, 7-day average, and 30-day average constraints on the allowed concentration of ammonia in the plant effluent. For a given situation, for instance, a spillage of toxic material into the sewer network, the plant manager could well be faced with an awkward dilemma. If he takes action to avoid process failure, his plant effluent may violate the instantaneous limit; if he does not take such action, the process may indeed fail and several weeks might be required for the growth of a new (nitrifying) culture. During those weeks the probability of violation of the 7-day average or 30-day average limit would be high.

The conclusion to be drawn from the above two accounts is that the question posed earlier (about less effective treatment than is possible) is an over-simplified view of the problem of operational management. The legal requirements of water quality management do not remain fixed, as has been emphasized in section 2. Standards change with time; in fact they appear to be becoming increasingly sophisticated (see also Taylor, 1977; Price and Pearson, 1979). And as the standards to be met become more sophisticated, so the introduction of at least an equal level of sophistication in day-to-day operational management is justified.

5.2 The Human Factor

Two assumptions have dominated the discussion of this section on economics and innovation. They are:

(i) that operational management depends solely upon the innovation of technical equipment such as computers, microprocessors, instrumentation, etc., and will therefore involve capital investment;

(ii) that innovative changes result solely from economic feasibility studies.

It is significant for the arguments of this paper that these assumptions are not entirely valid. In Figure 1 the attributes of the "Controller or control function" are clearly identified as the "Processing of measured information" and the "Determination of control action". But there is no suggestion that improved or innovative operational management has to depend upon costly investment in new equipment. It is also evident from the preceding discussion of nitrification control that the element of (human) decision-making is critically important. 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."

Clearly, innovative practice in water quality management does not necessarily require prior capital investment. It does, however, require an investment in <u>human</u> resources, and this is now widely recognized both at a policy level (see, for example, Wubbena, 1979; Hill et al, 1979) and at the detailed technical level of individual unit process operation (Beck, 1977, 1978).

Let us turn to the second assumption given above and make an alternative hypothesis: in many instances major technological innovation, such as the installation of a process computer, occurs because a key individual decides that it is attractive, irrespective of costs.

In a recent study of the general problem of technological innovation, Robinson (1979) offers the following observation:

> "Consumer values and perceptions are critical to product success. Design and marketing activities of a soft nature, including advertisement and considerations of reliability, user convenience, and aesthetics cannot be dismissed as cosmetics. They may be decisive factors in determining the success of a technical innovation of a hard engineering nature."

Suppose, therefore, that a decision is taken to install a computer and an instrumentation system for wastewater treatment plant control or for in-stream water quality monitoring. Automation and computerization of this form should then neither assume the purely passive role of logging plant performance, nor aim for elimination of the human element from the control function. Rather, these technological innovations should be designed to foster an active interaction of man and computer in improving operational management. The alternative is that such technical aids to operational decision-making will lie stagnant and the advocates of real-time forecasting/control will be left to justify the failure of their rare opportunities to demonstrate the benefits of their ideas.

6 INSTITUTIONAL AND LEGISLATIVE ARRANGEMENTS

The importance of institutional and legislative arrangements should already be apparent. Institutional and legislative arrangements are essential components of long-term and short-term management functions described in section 2. They may also be decisive factors in the process of technological innovation (see section 5). It is instructive to reconsider some of these previous arguments from the specific point of view of laws and institutions in water quality management.

Both the (U.K.) Institution of Chemical Engineers' report (Institution of Chemical Engineers, 1974) and the recent (U.S.) Water Pollution Control Federation White Paper (Hill et al, 1979) express concern at the way in which the management of water quality is organized and administered. For example (Institution of Chemical Engineers, 1974):

> "The responsibility for designing plant often rests with firms of consulting engineers only a few of whom employ staff qualified to appraise novel equipment. In addition the system of remuneration can be considered to act as a disincentive. A consulting engineer has to spend extra time and money to devise or to appraise new equipment which, if it results in a lower capital cost for the works, will result in a smaller fee for the consulting engineer."

And in a similar vein (Hill, et al, 1979):

> "Equipment suppliers under the spur of an overly simplistic, competitive procurement philosophy sometimes deliver minimally accepted and short-lived hardware.
>
> The initial spurt of large amounts of construction funds led to instances of poor design and construction of many facilities, thus creating operation and maintenance problems that make plant control difficult. In truth, many consultants, however capable mechanically, electrically, or structurally, seriously lack operation and maintenance expertise."

Okun (1977) also observes how "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". Andrews, et al (1979) continue this line of thought when they state that "it can be expected that funds for treatment plant operation and maintenance will become more difficult to obtain since they must be provided by increases in local taxes and user charges whereas 75% of the funds for plant design and construction are provided by the Federal Government". Such a situation is extremely short-sighted when one recalls the rapidly increasing running costs of treatment plants (section 5).

One can only presume that this kind of psychological separation of the concepts of design and operation is either wilfully maintained or deeply ingrained in the minds of those responsible for water quality management. Again, the White Paper of the Water Pollution Control Federation adopts a strong attitude (Hill et al, 1979):

> "The owners, including the public, must realize that to provide efficient, economical treatment, their interest in the wastewater treatment facilities cannot stop at the completion of construction... . They can no longer ignore the local responsibility of day-to-day operation and maintenance of the facilities.
>
> During the past few years, there has been a steady decline in the priority EPA has given to national programs in operation and maintenance and training. In view of the serious problems it is difficult to understand how EPA can justify such reductions."

Perhaps the Institution of Chemical Engineers' report captures the essence of the problem when it recommends "that those who design sewage works should be given opportunities to commission them and also to evaluate their performance". Certainly, the International Association for Water Pollution Research has for some time recognized this same problem and has convened two workshops under the title "Design-Operation Interactions at Large Wastewater Treatment Plants" (Jenkins, 1972, 1977).

There can be little doubt, therefore, that an unwillingness to consider design and operation as parts of the same control function--to consider jointly long-term and short-term management--is undesirable. One wonders whether this process of keeping different features of the problem in their own isolated compartments has its professional counterpart. To what extent, for example, do sanitary engineers, water engineers, and water resource systems analysts co-ordinate their activities towards integrated river basin management? And how quickly does an innovative idea or piece of technology propagate between operational management in water treatment, wastewater treatment, and reservoir systems? The fact that these complex questions are intricately related to legislative matters seems to be confirmed by the following statement in a report from the Committee on

Public Works and Transportation of the U.S. House of Representatives (Committee on Public Works and Transportation, 1975):

> "Even among consulting engineers and public servants with long experience in waste treatment there is a need for expanded environmental awareness. In the minds of too many professionals, PL-92-500 is a law to build waste treatment facilities in the same manner that they have always been built. It is vital that these key persons seek to apply the visionary concepts of PL92-500 without repudiating the practicality of the past.
>
> [Wastewater treatment facilities] should be operated in a manner that is consistent with total environmental protection. Conventional thinking must be altered."

Elsewhere, De Lucia and Chi (1978) suggest that the National Environmental Policy Act and U.S. Public Law 92-500 shift the burden of proving non-damage of the environment onto the responsibilities of the individual dischargers. Since this could imply a strong incentive for data collection it has important consequences for the technology of water quality monitoring. In other words, legislation can direct, or misdirect, the forces of innovation and it can distribute these forces between different technological sectors, where sectors might be defined as the traditional sectors of the water industry, i.e. wastewater treatment, water purification, stream management.

6.1 Public Law 92-500--A Retrospective Analysis

One of the key responsibilities of the institutional management function, as evident in the statements quoted from Cantley (1978) in section 3, is the responsibility to continue to learn more about the way a system behaves. At the basic level of a laboratory experiment one would learn by deliberately changing some of the input variables and by measuring how the output variables respond to these changes. The experimenter must then reconstruct from these observations the relationships between cause and effect. The drought of 1976 in the U.K. was an important natural experiment on the "system". So too, in retrospect, was the passage of PL-92-500 in the U.S.; it was a significant perturbation of the institutional system of water quality management. It is thus instructive to analyze, within the framework provided by section 2, what can be learned from that disturbance of the system.

Let us recall Figure 6. For the following analysis, which is based on the previously quoted 1975 report of the Committee on Public Works and Transportation, it is difficult to define the precise physical components of the "system" and the "controller". Clearly the system to be controlled includes the treatment plants, purification plants, and river basins. Simply for the sake of argument, let us also assume that:

(i) governmental legislation, which specifies the goals of water quality management as embodied in PL92-500, is part of the environment surrounding the system and controller;
(ii) the U.S. Environmental Protection Agency (EPA) is the essential component of the controller;
(iii) the system, besides its natural and man-made fabric, also includes the municipal agencies and professional groups responsible for providing the design and operating functions.

There are obvious weaknesses in drawing these distinctions. For example, the EPA might be more appropriately viewed as part of the same system as the standard-(objective-) setting procedure. It does, however, act basically as an agent administering and interpreting a received objective and it would, presumably, have to interact with other (political and legal) institutional systems--here defined as part of the environment--in order to bring about changes in that objective. The technical design-operating agencies might really be a part of the controller, although the situation of "confrontation" that has developed between the EPA and these agencies suggests more the picture of agencies responding to control actions imposed upon them by the EPA. The simplification afforded by the above assumptions is not in any way intended to trivialize the successes and difficulties of current U.S. policy on water quality management. It is, in fact, apparent that Figure 6, to which we have referred, represents only a part of a complex hierarchical control situation. However, without simplification the analysis that follows would almost certainly not yield useful insight into the problem of water quality management.

When PL92-500 was passed in 1972 it specified a timetable for a sequence of objectives: the issuance of permits to all municipal and industrial dischargers by December 31, 1974; the 1977 deadline of "best practicable control technology currently available" for industry; and the goal of fishable/swimmable waters by 1983. As a control problem the law's objective can thus be viewed as a classical <u>servomechanism</u> problem (see Figure 3(a) and section 2.1). It requires the performance of the system to be adjusted to a time-varying desired level of performance rather than the maintenance of a fixed level of performance in the face of a time-varying load on the system (the regulator problem). The law did not simply demand a feedforward control strategy in the sense defined in section 2; it was not designed to mitigate the effects of known disturbances of the system. However, like many feedforward controllers, which are well-suited to systems whose output responses to input changes are very slow, control action required by the law was based upon a "model" of the system's dynamic behaviour. In other words the controller based its actions, one assumes, on predictions of the system's future performance. But even though it may have acknowledged that the system's response would be slow, the law still assumed an over-estimated speed of response. The system was simply not able to meet the required objectives in the required amount of time. Indeed, the report of 1975 noted that "ironically, where [improved water quality] is being achieved, along Lake Erie beaches, in the Hudson River, the Willamette River, and other lakes and streams, it is the result of earlier state and federal legislation, and particularly the 1965 federal act". That significant observation suggests a time constant for the system response of the order of 10 years and not 2-3 years.

Seen from the system's point of view the law's objectives--its desired changes in the level of system performance--might well have been received as known, but unwanted input disturbances. However, in a spirit epitomizing the monitoring and control of strategic plans (see the comments quoted earlier from Cantley, 1978), Garber (1977) has subsequently proposed that: "a major effort [be made] to evaluate and confirm numbers so that design consistent with the goal of environmental improvement can be achieved". He concludes that "standards appear to be necessary as guidelines, but if these cannot be based on scientific reality, achievement of a net positive impact of the great effort of PL92-500 is in no way assured". In other words, we might interpret Garber's statements as tantamount to testing the assumed relationships (or model) upon which the intent of PL92-500 had been based. The implementation of regulatory actions can be designed to control the system response, to experiment with and thus to learn more about the system's behaviour and to modify that behaviour. Equally so, however, a controller can adapt itself in order to compensate for some of the fundamental and immutable characteristics of the system's behaviour.

The Committee report pays particular attention to the considerable level of detail in the requirements of PL92-500. A consistent level of detail (and accuracy) must therefore be assumed for monitoring the system's performance. Yet one obtains the impression from Garber (1977) and from the Committee Report, which states that "the decision-making framework is almost always fuzzy and imprecise", that the level of detail specified by the law was unrealistically high. The objectives for the performance of the system may well have been defined either in terms of response variables that were extremely difficult to measure, or in terms of variables subject to substantial amounts of uncertainty (error)--consider, in fact, the idealization of Figure 6. Not unnaturally it would be virtually impossible to match the desired and actual performance of the system under such circumstances. Indeed, as has happened, the comprehensive and detailed nature of the monitoring effort required by the law would lead to a great increase in the time devoted to information processing. There may also be confusion as to whether the determined control action would, with any reasonable confidence, bring about the desired system response. This might have been particularly relevant in view of the Committee Report's observation that "economic uncertainties make it extremely difficult to predict funding levels into the future". It is all too easy to say that the feedback part of the controller should have been designed in order to compensate for the effects of these unknown disturbances of the system performance. But as we have said, at the beginning of section 4, the principle of feedback control is one of cancelling the deleterious effects of unknown input disturbances of the system.

7 RISK AND PROBLEMS FOR THE FUTURE

From a number of sources it is possible to conclude that water quality in the rivers and lakes of industrialized countries is improving (Environment Agency, Japan, 1979; OECD, 1979; Casapieri and Owers, 1979; Woodward, 1979). This is, of course, a statement with macroscopic focus. The essential motivation behind this papers lies in its title: time-variable water quality management. Above all else the paper has stressed that objectives, problems, and performance in water quality management change with time. A recent OECD report on a meeting of the Ministers of Environment of the OECD countries conveniently summarizes two points that will guide the discussion of this section. In the report's own words (OECD, 1979):

(i) "Prevention [is] less costly than cure"--the title of the report;

(ii) "The quality of fresh water has improved in that pollution by suspended solids and oxidizable matter (BOD) has stabilized or decreased in countries where action has been taken..."; but "as to pollution by specific pollutants and micropollutants...the situation is a cause of increasing concern" where "among the specific pollutants phosphorus and nitrogen compounds play a particularly important role."

It may be assumed that an industrial society generates as much potentially polluting matter today (1979) as it generated, say, ten or fifteen years ago. The observed situation of an improving water quality in rivers and lakes, at least in terms of suspended solids and easily degradable organic matter, is a situation in which a bad environmental condition has been restored to a more or less acceptable condition. Management of water quality over the past decade has correctly been interpreted as a curative strategy. And as we already described in section 4 and Figure 7, there is a growing awareness that on a (long-term) average basis river water quality has improved. The difference between the beginning and end of the current decade is that governments have, over that period, invested in the widespread construction of wastewater treatment facilities. At present a greater amount of control effort is expended in preventing a larger portion of the potentially polluting matter from being discharged to receiving waters.

There is justifiably a feeling of success and of satisfaction at this achievement. Many of those involved in water quality management might indeed feel that their job has been well done and that the size of staff establishments in water authorities could thus be reduced. But the nature of water quality management is shifting from a curative to a preventive strategy. There is now a greater responsibility to prevent failures in the system of pollution control because, first, a greater number of facilities and complex processes need to be operated in order to maintain control and, second, any failure--such as the transient "crises" of Figure 7--will be relatively much more apparent and damaging. A steadily improving average water quality might also encourage the tendency for greater utilization of river water for potable supply (in the event that the demand for potable water continues to increase). Where such abstraction facilities exist the element of risk is already evident. For example, Wallwork (1979), in describing a monitoring system for the protection of a water supply intake, observes:

> "A different and severe risk to water quality arises from the fact that for 17 km above the intake works the river flows between two major roads... . During the past three years there has been a history of some dozen spillages into the river from road drainage outfalls and other sources, the commonest pollutants being hydrocarbon fuels."

All of this does not necessarily imply that real-time forecasting/control systems are indispensible to every water quality management scheme; but it will redress the imbalance of research and development activities, which currently favour the design rather than the operational function of management.

As the OECD report points out, the type of water quality management problems to be solved are changing with time. The management of nitrate and phosphate levels, or the management of micropollutants, requires different techniques, technologies, and strategic planning. In particular, the strategic planning function carries with it the responsibility to pursue actively a procedure for scanning the medium-term future (say 10-20 years hence) for emergent problems. One must at least ask the questions: how do the plans that are implemented today affect the ability of the system and its controller to adapt to the problems of the future; if the emergent problems of the future are in fact discernible, how does that effect the decisions taken today? Developments in the water industry have been remarkably rapid over the past few years. For example, who, four years ago, would have risked his reputation on predicting that telemetering networks for real-time stream monitoring would be implemented, as they now have been, in more than one U.K. water authority? Or again, given the dominant Swedish thinking that phosphorus compounds control the rate of eutrophication in lakes, why should there now be an increased interest in achieving nitrification in Swedish wastewater treatment plants? And, if, because the removal of ammonia, through its effects on pH and alkalinity, enhances phosphorus removal, how can existing plants be adapted with minimum modification--and particularly by different operating policies--to achieve the new objectives? Furthermore, given the resulting increased levels of nitrate in discharges, would Swedish lake eutrophication then shift from being a phosphorus-controlled to a nitrogen-controlled process? The same rate of change in the problems, practice, and objectives of water quality management, which has been observed in the recent past, can be expected to prevail in the near future. In particular, one might well now ask what is the potential for small-scale (microprocesser) computing applications in water quality management.

At a detailed technical level such computing facilities are especially important for real-time operational forecasting and control; at a managerial level it has been suggested (Fick, 1979) that these facilities will be particularly important as "on-line" aids to thinking and planning.

So the strategic and longer-term planning functions of water quality management must deal not only with economic investment but also with future-problem searching and with testing current assumptions about both the system's behaviour and the "best" management practice. A recently completed prototype study of the Willamette river basin in the U.S. illustrates some of those points. It concluded that (Rickert and Hines, 1978):

> "The most noteworthy finding was that across-the-board advanced water treatment was not the answer to the problem of meeting stringent water quality standards established for the Willamette River. This implies that rigid nationwide standards and regulations are likely to result in unneeded expenditures in some river basins and in unachieved standards in others. It was also found that existing water quality data collected under [routine] monitoring- and surveillance-type programs are inadequate for defining the critical cause-effect relationships that control river quality problems. Intensive, synoptic surveys keyed to local problems and conditions are required to provide an adequate information base for making key management decisions."

Moreover, to reiterate the introductory remarks of this paper, it is necessary to examine how strategic, long-term planning affects day-to-day operational management and vice versa. If water pollution control legislation specifies rigid effluent standards this could have adverse consequences for the ability of the system to adapt to new problems. Imagine, for instance, that the rigorous administration of effluent standards for micro-pollutants forces a significant acceleration of innovation of new technology for wastewater treatment. This might engender the situation in which very few advances are made in the technology of removing micropollutants during water purification for potable supply. Such legal arrangements would lead (albeit inadvertently) to an increasing vulnerability of directly abstracted water supplies to the risks of accidental upstream spillages and the failure of equipment at wastewater treatment plants. Consider also, in a different context, the novel suggestion of a U.K. industrialist that the conditions specified for his plant's discharge should be coupled to <u>time-varying</u> river flow conditions (Price and Pearson, 1979). This suggestion met with the understandable response that it might not be possible to find suitable legal wording for this kind of consent to discharge to a receiving water body.

To summarize, therefore, what is required for future water quality management are elements of <u>adaptability</u>, <u>flexibility</u>, <u>safe-failure</u>, <u>learning procedures</u>, and a sound appreciation of time-variability. That this paper adopts such a view is due significantly to the work of Holling and his associates in adaptive environmental management (see, for example, Holling, 1978; Walters and Hilborn, 1978; and Clark et al, 1979) and to an educational background in control engineering. In practice, those basic elements mean:

(i) adaptability - both the system to be controlled and its controller can adapt to significant changes in the technology, the problems to be solved, and the desired objectives for water quality management;
(ii) flexibility - the means for easy adaptation are continuously being sought;
(iii) safe-failure - given that a system cannot be designed that will not fail in some sense, then the ability to fail "safely" is desirable;
(iv) learning procedures - the system of water quality and its management are not completely known, and thus resources should be allocated in order to learn more;
(v) time-variability - very little, if anything, remains invariant with time.

8 CONCLUSIONS

There are a number of points of view in discussing the problem of water quality management. The discussion of this paper reflects some of those points of view, for example, the analytical framework of control systems, and the perspectives of economics and innovation, of institutional and legislative arrangements, and of risk. The principal argument of the paper is that water quality management is a time-variable problem; in particular, present trends in water quality management require long-term strategic planning to be considered together with short-term operational management. An objective of this argument has been to examine how matters of policy formulation affect the need for and feasibility of real-time water quality management. Our conclusion is that there are sound reasons for addressing increased research and development attention to real-time water quality management.

Because the paper looks at water quality management from different perspectives, it is not appropriate to try and conclude with a strictly linear argument in support of the paper's objective. The following is thus an assembly of inter-related, but not necessarily sequentially dependent, factors influencing the desired principle of time-variable water quality management.

- We have said that there are significant interactions between long-term and short-term water quality management. The importance of these interactions becomes particularly apparent when strategic long-term management is interpreted as a feedback and adaptive control problem.

- Those areas in which interaction between long-term and short-term management is likely to be most pronounced are: in changing the way in which water quality can be monitored, and thus in changing the way in which water quality objectives can be specified; and in increasing the range of options available to management.
- Real-time forecasting and control techniques in water quality management can be viewed as a problem of technological innovation or of innovative practice. Institutional and legislative arrangements can have a significant effect upon the promotion or suppression of innovation. For this and other reasons it can be instructive to perform retrospective analyses of the formulation and implementation of laws relating to water pollution control.
- When considering the process of innovation,human factors may be just as significant as economic factors in determining changes in conventional practice. Moreover, one must distinguish between "automation" and "operational control"; short-term water quality management is very much concerned with the latter and with the important role of management decision-making in operational control.
- Specific areas of new technology for the water industry include microprocessor applications and the use of models as aids to operational decision-making. It would be helpful to have critical studies of the prospective benefits of these new and rapidly developing techniques.
- In a few, but increasing number of cases, operational river basin management schemes have been implemented. These schemes include telemetered in-stream water quality monitoring networks, on-line sewer network and wastewater treatment plant control, and water supply distribution control. Initial operating experience from such schemes is an invaluable source of feedback for the formulation of future management policies.
- From recent reports of the quality of water resources in industrialized countries it may be concluded that a basic shift in water quality management, from a curative to a preventive strategy, is in progress. On the basis of this observation, it can be argued that emphasis in research and development activities should be transferred from the design to the operational function of management.
- The changing nature of water quality management may potentially lead to an increasing awareness of the risk of failures and accidents in the system of management. How, if at all, are real-time forecasting/control and institutional/legislative arrangements related to this problem?
- An area in which design/operation (long-term/short-term management) interactions are especially important is wastewater treatment. Current designs for wastewater treatment plants seriously affect the capability of management to adapt, possibly through different operating policies, to different water quality problems and objectives in the future.

- Lastly, part of the difficulty in justifying short-term water quality management is the lack of a suitable framework for economic analysis. Such a framework for analysis would have to be capable of assessing fixed (capital) and variable (operating) costs together, of accounting for equipment failure, and transient pollution incidents, and of integrating the costs of, for example, streamflow regulation and wastewater treatment.

In this paper the basic concern has been one of analyzing the changing nature of water quality problems and of analyzing how that changing nature requires an evolving management strategy. Further analysis is necessary before the synthesis of new guidelines for policy formulation in water quality management.

REFERENCES

Andrews, J.F., P.E. Sørensen and M.T. Garrett (1979), "Control of Nitrification in the Oxygen Activated Sludge Process", Preprint, IAWPR Workshop on Treatment of Domestic and Industrial Wastewaters in Large Plants, Vienna, September.

Beck, M.B. (1976), "Dynamic Modelling and Control Applications in Water Quality Maintenance", Water Research, 10, pp.575-595.

Beck, M.B. (1977), "Critical Assessment of Present-Day Attitudes Toards Control Systems in Water and Wastewater Management", Prog. Wat. Tech., 9, Nos. 5/6, pp. 13-15.

Beck, M.B. (1978), "Modelling and Operational Control of the Activated Sludge Process in Wastewater Treatment", Professional Paper, PP-78-10, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Cantley, M.F. (1978), "Strategic Control for a U.K. Regional Health Authority - A Conceptual Framework", Research Memorandum, RM-78-54, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Casapieri, P. and P.J. Owers (1979), "Modelling the Thames--A Management Use of a Mathematical Model", Preprint, U.K. Water Research Centre Conference on River Pollution Control, Oxford, April.

Clark, W.C., D.D. Jones and C.S. Holling (1979), "Lessons for Ecological Policy Design: A Case Study of Ecosystem Management", Ecological Modelling, Vol. 7, pp. 1-54.

Committee on Public Works and Transportation (1975), "...Addressing Messy Practical Issues", Interim Staff Report of the Subcommittee on Investigations and Review, Committee on Public Works and Transportation, U.S. House of Representatives, on the Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500), U.S. Government Printing Office, Washington, April.

De Lucia, R.J. and T. Chi (1978), "Water Quality Management Models: Specific Cases and Some Broader Observations", in Davies, T.T. and V.R. Lozanskiy (Eds.) "American-Soviet Symposium on Use of Mathematical Models to Optimize Water Quality Management", Report No. EPA-600/9-78-024, U.S. Environmental Protection Agency, pp. 92-126.

Engineering News Record (1977), "Rising Sewage Plant Operation Costs Beg Engineered Solution", Engineering News Record, October 6, p. 71.

Environment Agency, Japan (1979), "Quality of the Environment in Japan, 1978", Environment Agency, Japan.

Fick, G. (Ed.) (1979), "The Managerial and Organizational Consequences of Small Scale Computer Systems: A Cooperative Pre-Research Study", Collaborative Paper, CP-79-2, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Flanagan, M.J., B.D. Bracken and J.F. Roesler (1977), "Automatic Dissolved Oxygen Control", Proc. Am. Soc. Civil. Engnrs, J. Env. Eng. Div., 103, EE4, pp. 707-722.

Garber, W.F. (1977), "Effluent Standards - Effect Upon Design", Proc. Am. Soc. Civil Engrs., J. Env. Eng. Div., 103, EE6, pp. 1115-1127.

Hegg, R.A., K.L. Rakness and J.R. Schultz (1978), "Evaluation of Operation and Maintenance Factors Limiting Municipal Wastewater Treatment Plant Performance", J. Wat. Pollut. Contr. Fedn., 50, pp. 419-426.

Hill, W.R., T.M. Regan and C.S. Zickefoose (1979), "Operation and Maintenance of Water Pollution Control Facilities: A WPCF White Paper", J. Wat. Pollut. Contr. Fedn., 51, pp. 899-906.

Holling, C.S. (Ed.)(1978), "Adaptive Environmental Assessment and Management", Wiley, Chichester.

Institution of Chemical Engineers (1974), "Water Borne Waste", Supplement to The Chemical Engineer, October.

Jenkins, S.H. (Ed.)(1972), "Design-Operation Interactions at Large Plants", Progress in Water Technology, Vol. 5.

Jenkins, S.H. (Ed.) (1977), "Design-Operation Interactions at Large Waste Water Treatment Plants", Progress in Water Technology, Vol. 8, No.6.

Newsome, D.H. (1979), "Archiving Data - An Archivist's Viewpoint", Preprint, U.K. Water Research Centre Conference on River Pollution Control, Oxford, April.

Okun, D.A. (1977), "Principles of Water Quality Management", Proc. Am. Soc. Civil Engrs., J. Env. Eng. Div., 103, EE6, pp. 1039-1055.

Olivieri, S. and Y. Smeers (1979), "Water Quality Management with Nonlinear Dynamic Ecological Model", Discussion Paper No. 7916, Center for Operations Research and Econometrics, Université Catholique de Louvain, Belgium.

Organisation for Economic Co-operation and Development (OECD) (1979), "Prevention Less Costly than Cure", The OECD Observer, No. 98, May, pp. 9-13.

Orr, L. (1976), "Incentive for Innovation as the Basis for Elluent Charge Strategy", American Economic Review, 66, pp. 441-447.

Price, D.R.H. and M. Pearson (1979), "The Derivation of Quality Conditions for Effluents Discharged to Freshwaters", Water Pollution Control, 78, pp. 118-138.

Rickert, D.A. and W.G. Hines (1978), "River Quality Assessment: Implications of a Prototype Project", Science, 200, No. 4346 (9 June), pp. 1113-1118.

Robinson, J.M. (1979), "Technological Shift: A Cybernetic Exploration", Working Paper WP-79- , International Institute for Applied Systems Analysis, Laxenburg, Austria.

Smeers, Y. (1979), personal communication.

Storey, D.J. and M. Walker (1978), "Water Pollution Control Theory - An Economic Taxonomy", J. Env. Management, 7, pp. 205-217.

Wallwork, J.F. (1979), "Protecting a Water Supply Intake: 1 - River Water Data Collection and Pollution Monitoring", Preprint, U.K. Water Research Centre Conference on River Pollution Control, Oxford, April.

Walters, C.J. (1975), "Foreclosure of Options in Sequential Resource Development Decisions", Research Report, RR-75-12, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Walters, C.J. and R. Hilborn (1978), "Ecological Optimization and Adaptive Management", Annual Review of Ecology and Systematics, Vol. 9, pp. 157-188.

Woodward, G.M. (1979), "The Trent Re-visited", Preprint, U.K. Water Research Centre Conference on River Pollution Control, Oxford, April.

Wubbena, R.L. (1979), "Operator Training: Who is responsible?" J. Wat. Pollut. Contr. Fedn., 51, pp. 890-898.

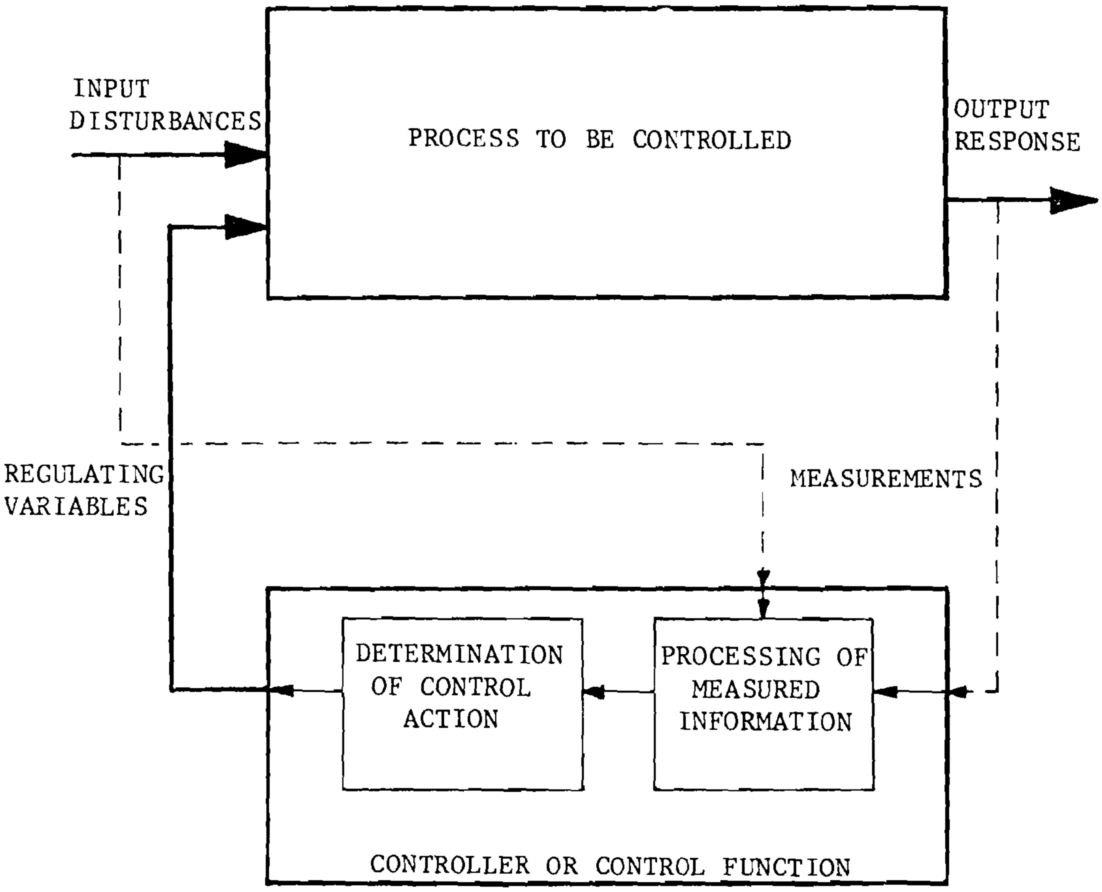
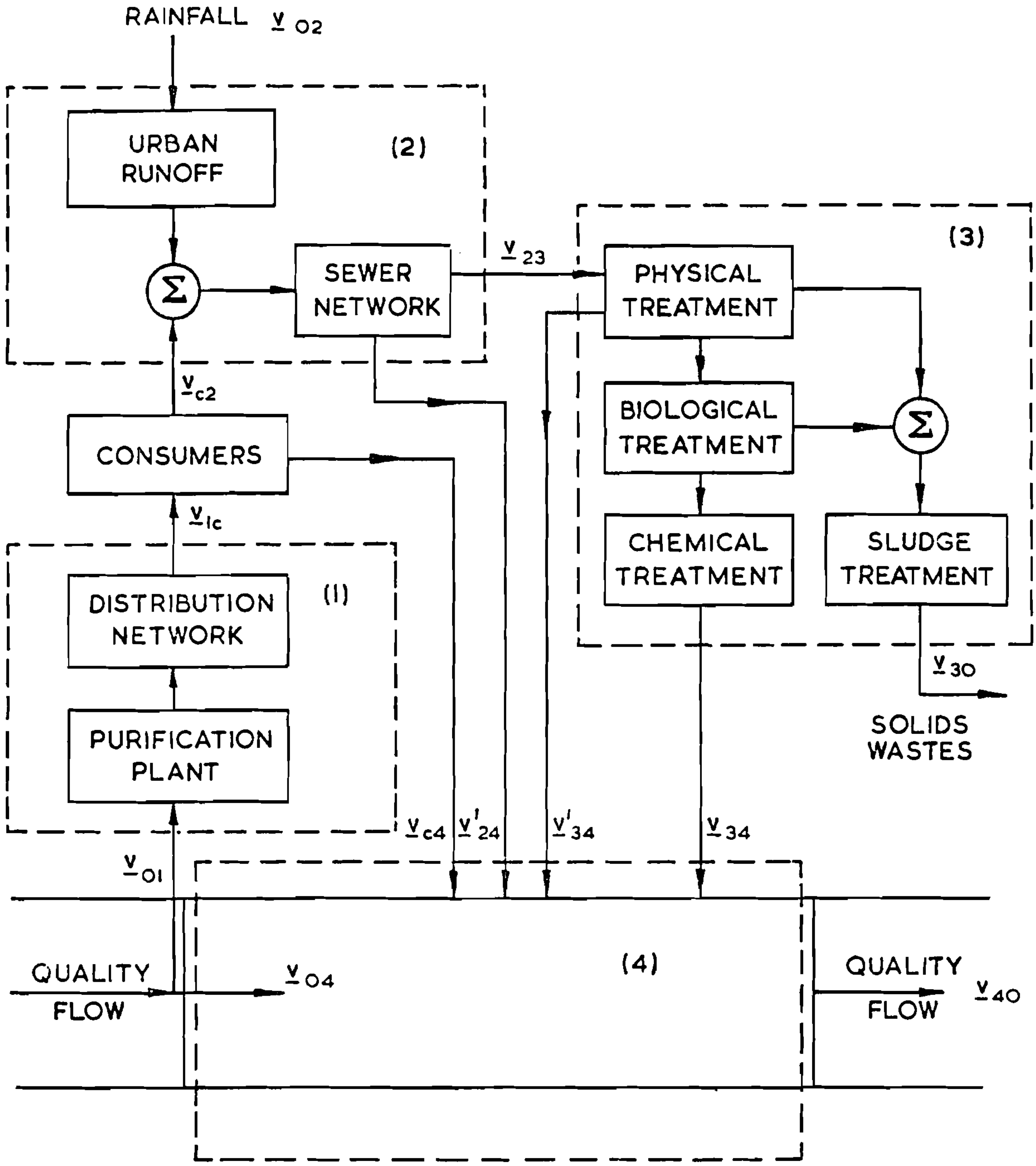


Figure 1. A framework for analysis: basic components of a process control system (dashed lines indicate measurements).



SUBSYSTEMS :-

(1) POTABLE WATER ABSTRACTION, PURIFICATION, AND SUPPLY NETWORK

(2) URBAN LAND RUNOFF AND THE SEWER NETWORK

(3) WASTEWATER TREATMENT PLANT

(4) A STRETCH OF RIVER

Figure 2. The basic unit of an urban/industrial community: activities that affect, and are affected by water quality.

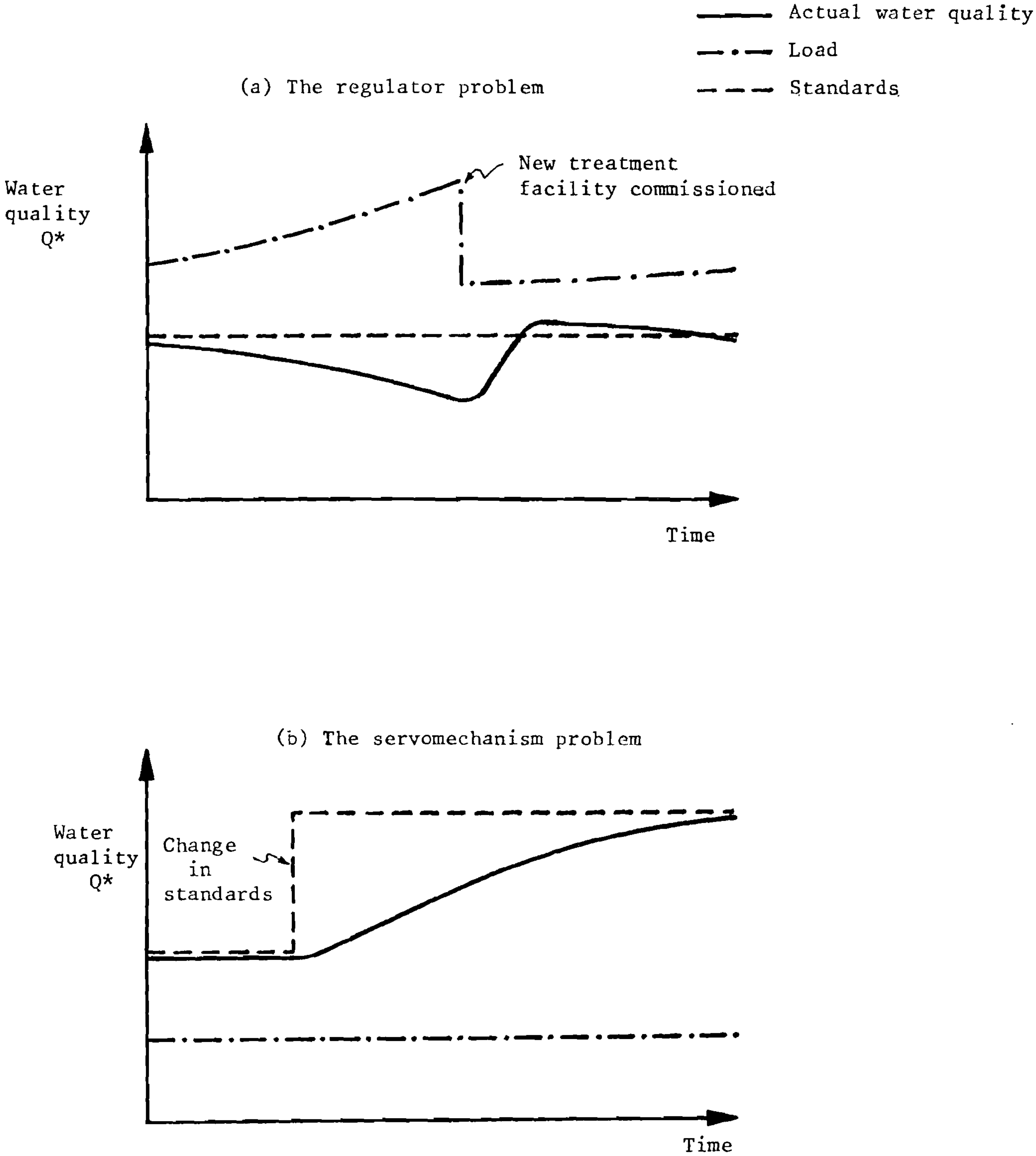


Figure 3. Two types of control problem: (a) the regulator problem; (b) the servomechanism problem.

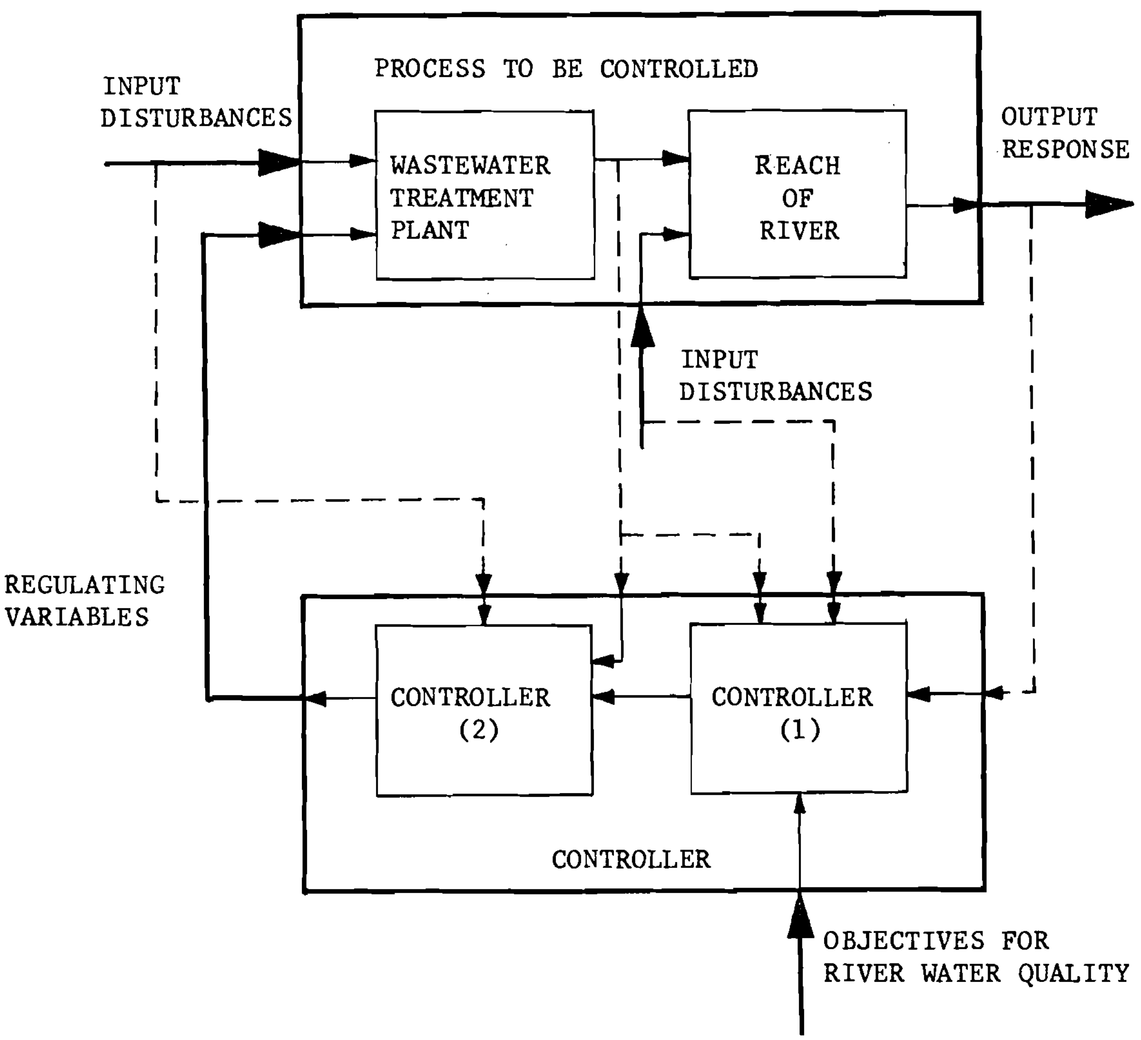


Figure 4. A hierarchical control scheme: controller (1) specifies the desired performance (objectives) for controller (2) (dashed lines indicate measurements).

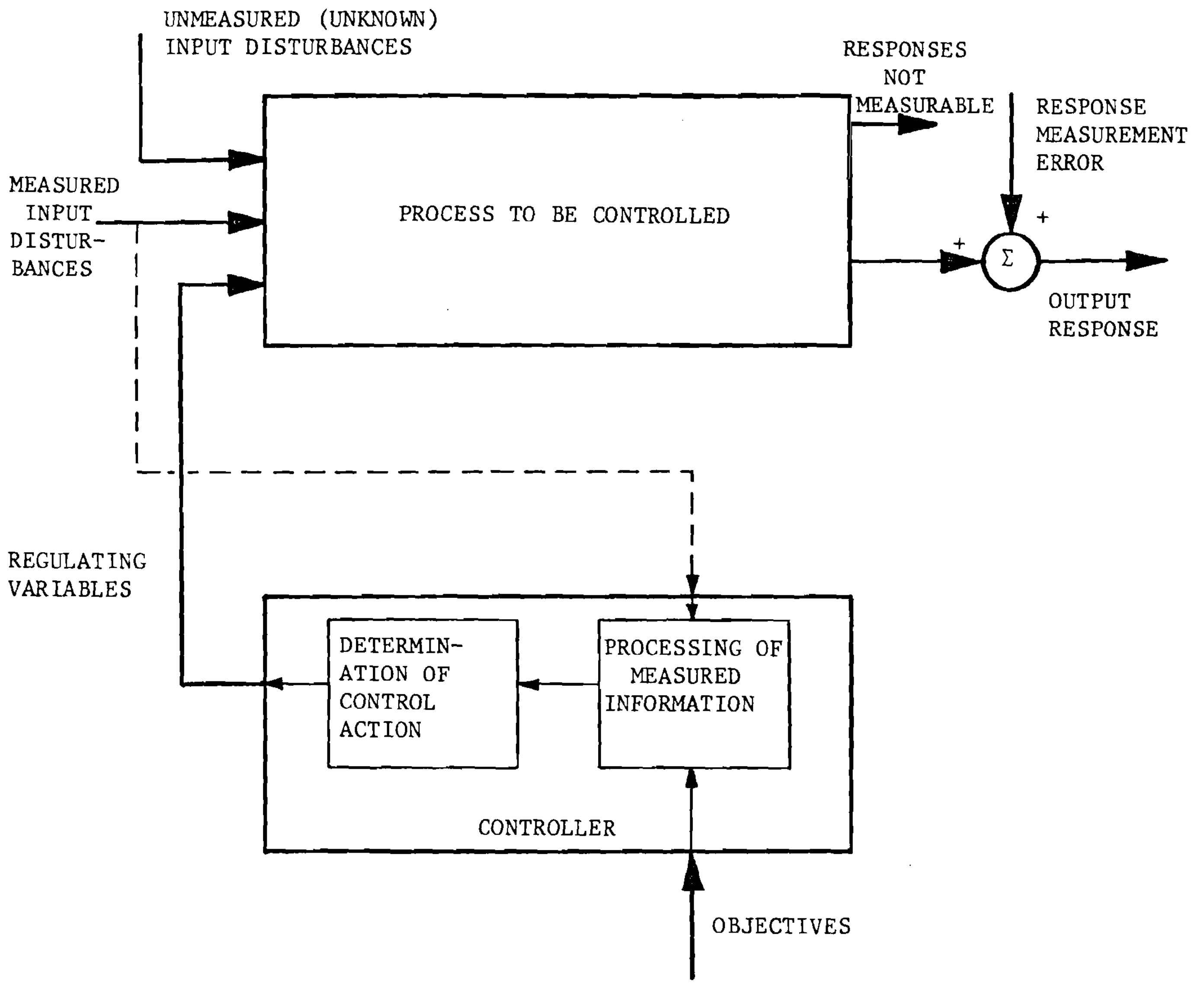


Figure 5. Feedforward strategic planning (dashed line indicates measurements).

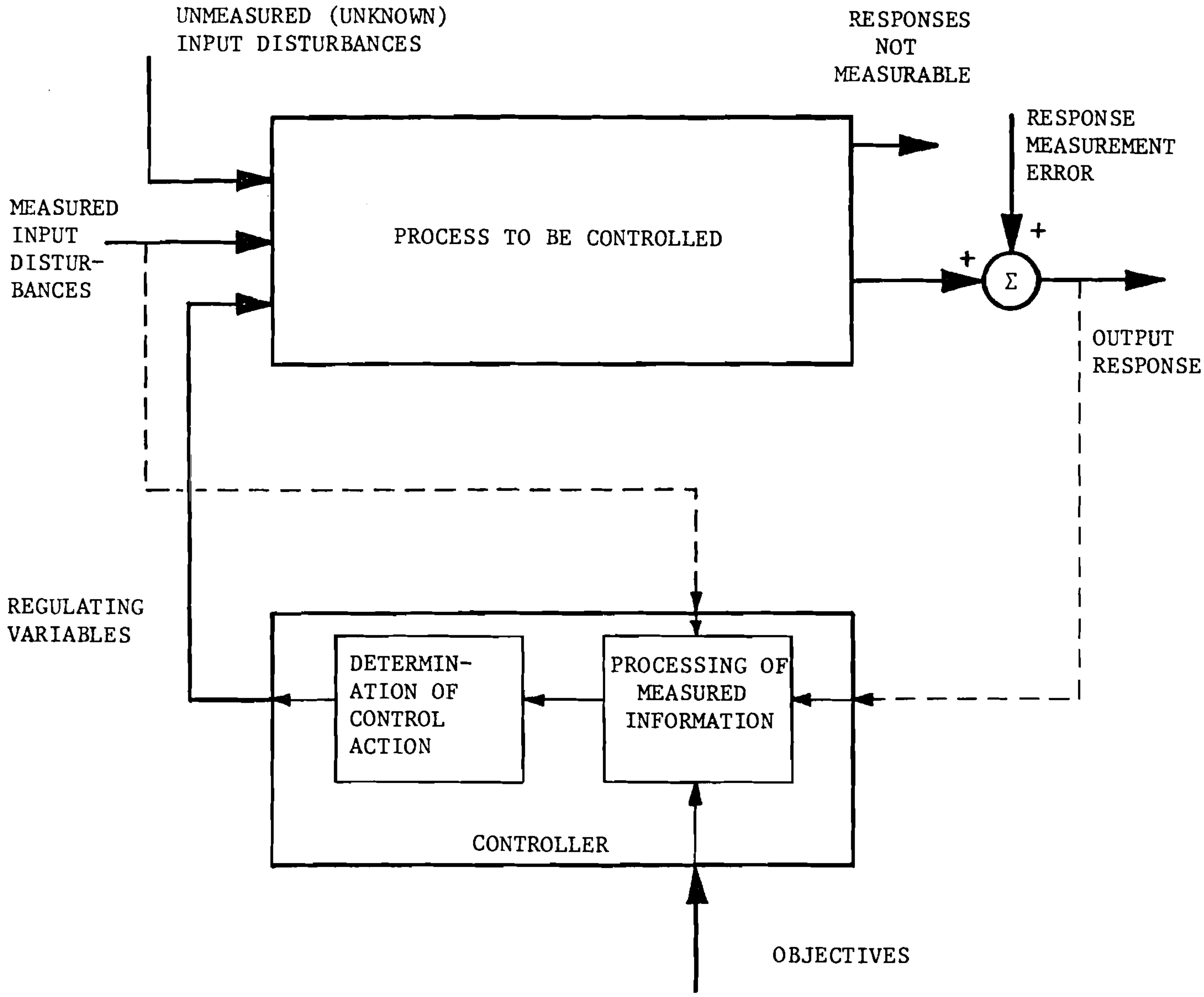


Figure 6. Management with feedback (dashed lines indicate measurements).

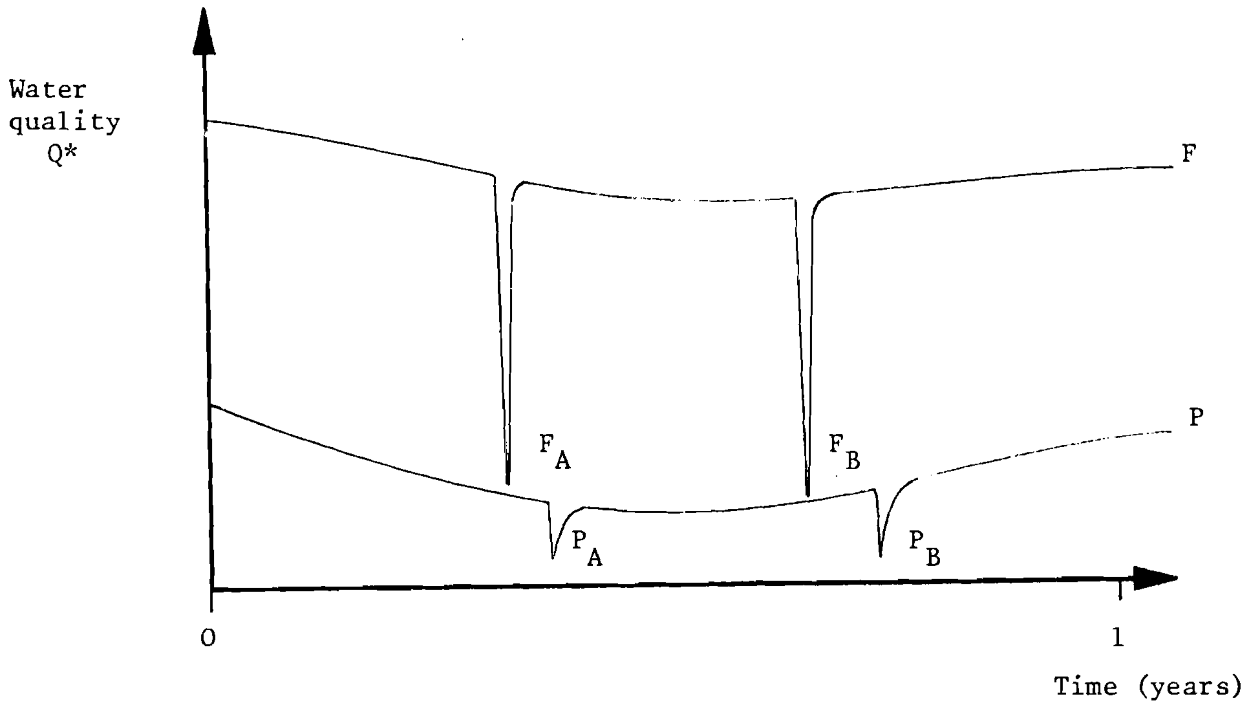


Figure 7. Past (P) and future (F) performance in water quality management. P_A, P_B, and F_A, F_B represent transient severe pollution incidents.

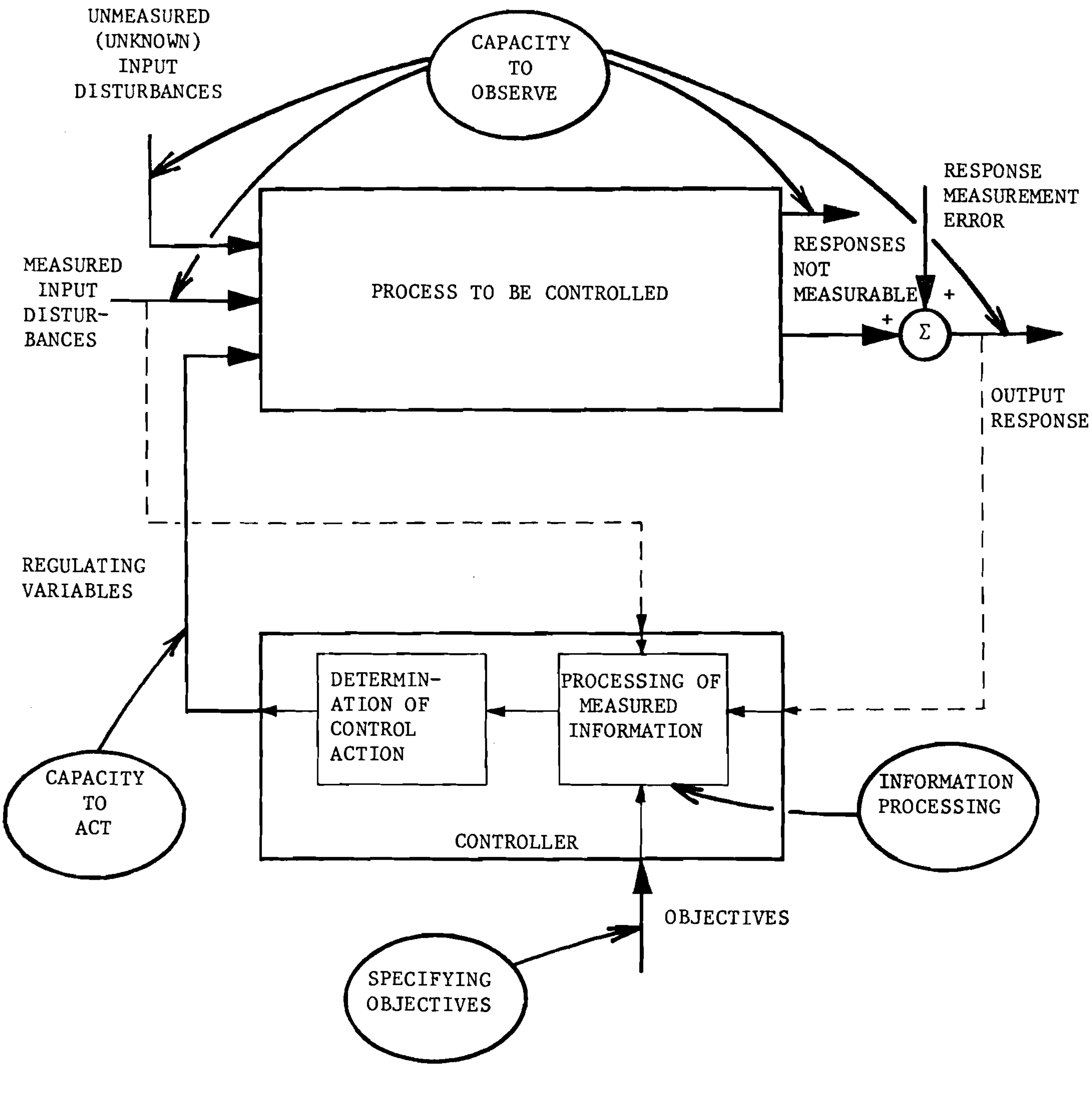


Figure 8. Influence of short-term operational management on strategic long-term planning.