REAL-TIME WATER QUALITY MANAGEMENT
Proceedings of a Task Force

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PREFACE

During this past year (from June 1979 to June 1980) several projects were 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 was entitled "Real-time Water Quality Management". It was a collaborative project and formed part of the Research Task "Environmental Quality Control and Management" of IIASA's Resources and Environment Area. The principal objective of the project was to prepare a policy-oriented report that fairly sets out the practical prospects for real-time forecasting and control in water quality management.

In these proceedings all the contributions made to the project and the papers presented at a Task Force Meeting at IIASA (March 12-14th, 1980) are collected together. The proceedings therefore represent some of the technical support material for the policy-oriented report, a draft of which is currently under review by the Task Force members.

Previous papers on this subject (IIASA Working Papers WP-79-1 and WP-79-125) are reproduced here with minor revisions. An extended summary of the proceedings is given in the "Introduction" prepared by the editor.

ACKNOWLEDGEMENT

As editor of these proceedings it is my pleasure to acknowledge gratefully the efforts of all those who contributed to the Task Force. In addition to those persons noted in the list of contributors and participants, I would like to thank Dr. H. Baumert of the Institut für Wasserwirtschaft, Berlin, G.D.R., and Mr. William F. Garber, Assistant Director, Bureau of Sanitation, City of Los Angeles, for stimulating criticisms of the paper on "Time-variable Water Quality Management--A Policy Study". I also assume full responsibility for any errors in the English text of these proceedings.

Finally, I wish to thank Jean Bolton and Judy Pakes for their work in preparing the manuscript.

Bruce Beck

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INTRODUCTION

M.B. Beck

1. A POLICY-ORIENTED PROJECT

In 1979 a (U.S.) National Academy of Sciences-National Academy of Engineering program was initiated to develop modest U.S. industry support for research and other activites at IIASA. There were 16 industrial concerns that contributed to this program, known formally as the program for "International Cooperation in Systems Analysis Research" (ICSAR); the funds were used to support eight projects for one year from May 1979 to May 1980. The purpose of this Collaborative Publication is to report some of the results of one of the projects, "Real-Time Water Quality Management."

The motivation for the project lies in a recognition of the following. During the 1960's and 1970's, management of water quality in river basins was almost exclusively interpreted as a function of longer-term strategic planning. There was a predominant emphasis on problems of capital investment, and on problems of design and construction of water and wastewater treatment facilities. If these investments did not permit the desired water quality standards to be achieved, it was usual to question, for example, whether the treatment plant configuration was correctly designed in the first place with the appropriate contaminant removal technologies. It was not common practice at the "design" stage of water quality management to consider how the system would perform at the "operational" stage of management. Neither was it customary, when standards were not met, to ask whether the design/ operational requirements were incompatible, and to enquire whether standards could not in fact have been achieved, if the system were to be operated more effectively. Thus a basic weakness of exclusive dependence on the long-term planning strategy is that water quality management objectives are (as yet) not being achieved nor maintained because: short-term operating policies are inadequate;

and solution of the planning and design problems does not imply solution of operational problems. In short, there has been a reluctance to look beyond the problem of planning and a lack of incentive to consider the management of problems that cannot otherwise be managed by planning and design alone, i.e. problems that require real-time (operational) water quality management.

The objective of this study has therefore been to assess the feasibility and potential benefits of real-time forecasting and control applications in water quality management. Both a convergence between theory and practice and the changing character of water pollution control problems make this an opportune moment for such a feasibility study. In practice, there have been rapid developments, for example, in the application of computers and automation to water and wastewater treatment facilities and in the installation of telemetered, on-line, river quality monitoring networks. In theory, there is now a deeper and more appropriately focused understanding of how control and systems analysis can have a useful part to play in the development of real-time water quality management.

But the question of the feasibility of operational management is really only the initial question that was formulated for the project. For as the project progressed through its early stages it became clear that this initial, well-defined question was in fact much less well-defined. There were many more questions to be answered: not only "is it feasible?"; but also "is it desirable, if so where, is it inevitable, how does it affect design and planning, what are the longer-term trends in pollution problems, and how is management responding to these strategic changes in the problems?" Perhaps like all "good" problems amenable to systems analysis then, the problem of the feasibility of operational water quality management was found to have many faces to it. And most previous studies of the topic, as Figure 1 shows, were really only one-sided views with limited perspectives. For example, intensive research on wastewater treatment plant control would tend to overlook the possibilities for stream discharge regulation as a means for managing water quality; detailed exercises in automatic control system design (technology) would not have given due consideration to the economics of operational management; and economic studies, while finding minimum cost solutions under certain criteria, would probably not have analyzed the costs of equipment failure and accidental, transient pollution events (risk/reliability).

The two purposes of the IIASA project were therefore to promote interaction among the previously somewhat independent technical studies of a group of interested researchers and to provide a synthesis of the more macroscopic policy implications emerging from these individual studies. The organization of the project and the collaborative studies undertaken are reflected in the papers collected together in these proceedings. The first and second papers in fact represent respectively the background material used for initiation of the project and a mid-term synthesis of policy-oriented results. The other papers in these

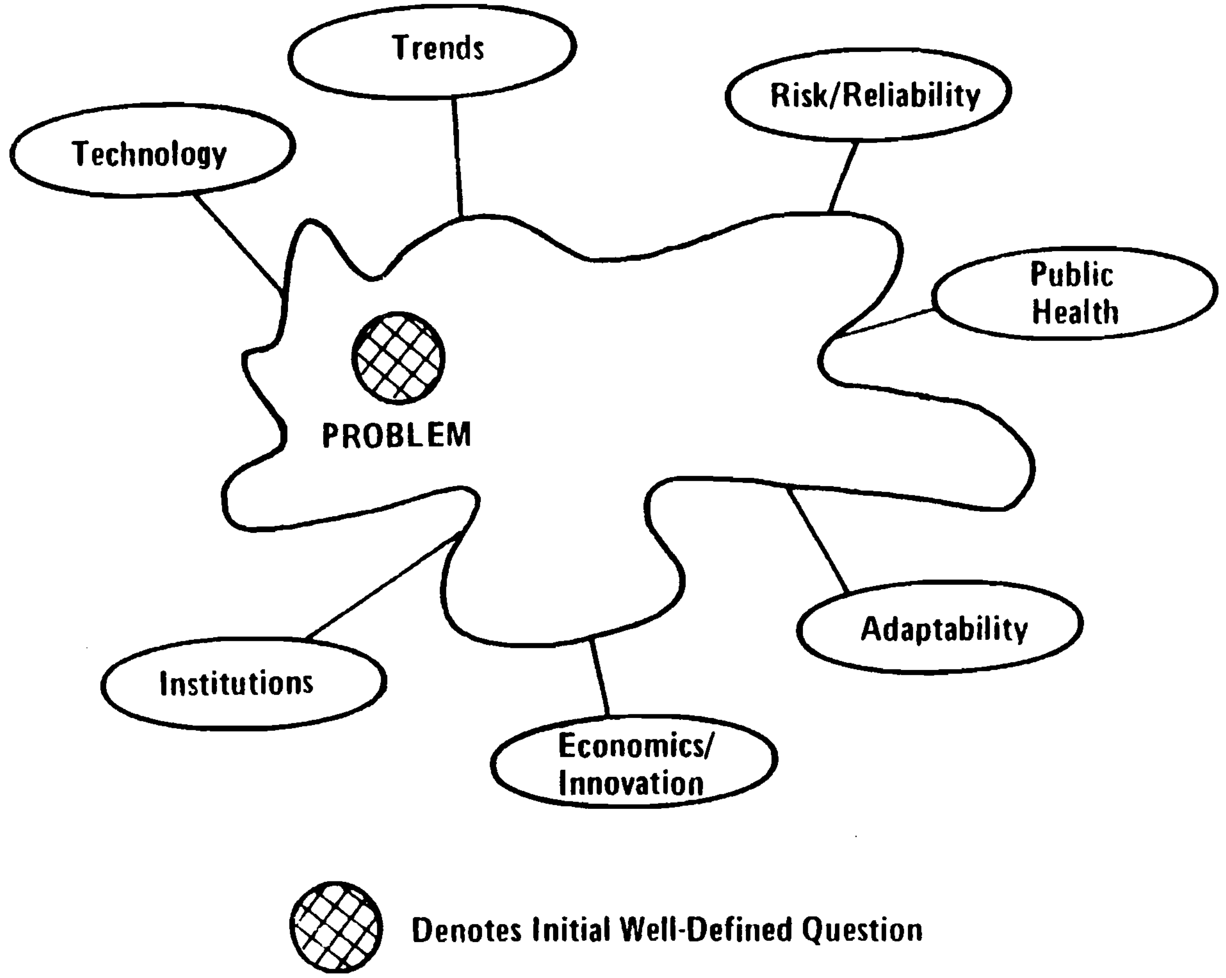

Figure 1. Different perspectives on the problem of Operational Water Quality Management.

proceedings were prepared for a meeting of the Task Force members held at Laxenburg during March 12-14, 1980. Since this meeting was to be the only occasion for direct contact among the group members, its major objective was to prepare an outline of a report dealing with the policy questions of the project and intended for circulation to an audience of decision-makers and policy analysts. (At present this report is at the draft stage and publication as an IIASA Executive Report is under consideration.) Since to the best of our knowledge this has been one of the first policy-oriented evaluations of the feasibility, desirability, or necessity of operational water quality management, it was agreed that initially such a broadly based, non-technical report of the Task Force's findings would be extremely important for justifying further progress at a detailed, economic and engineering level.

Optimism, qualified by pragmatism, will thus set the tone of the policy report that is to accompany these Task Force proceedings. Very briefly, some of the principal conclusions that we have drawn from this first year's study are as follows:

(i) Operational water quality management is, in general terms, technically feasible; a major problem, however, is its level of "acceptability" to the practicing profession.

(ii) Longer-term changes in the nature of water pollution problems (including the increasing probability of accidental pollutant spillages and equipment failure), more complex specifications for water quality standards and their surveillance, and a changing economic climate (rising operating costs) are all factors increasing the need for improved operational management practice.

(iii) In the growing number of river basins with existing systems of facilities for water quality management, adaptability of operational performance will be of key importance in meeting the changing problems of the future.

(iv) The sustained innovation of "electronic engineering equipment" has radically improved management's capacity to receive operating information, while the lack of such remarkable advances in "civil engineering" innovations continues to limit the capacity to implement control actions.

2. BRIEF SURVEY OF THE PAPERS IN THE PROCEEDINGS

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--although more truthfully, 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 recognized, 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 especially important. But these considerations do not resolve the issues of whether real-time forecasting and control are desirable, inevitable, or necessary.

The first paper ("The Role of Real-Time Forecasting and Control in Water Quality Management") takes yet another step away from the original control theoretic approaches to river water quality control; this is a step too, albeit tentatively, in the direction of a "policy analysis." The second paper ("Time-Variable Water Quality Management--A Policy Study") confirms the intention of the first paper to approach problems of a policy nature; it brings together a preliminary discussion of the different aspects (economics, innovation, legislation, and reliability, for example) that have been noted in Figure 1. Because of a relatively rapid development in ideas, both of these papers already appear "historical" and out-of-date in some senses. Nevertheless, they are useful as two snapshots in a sequence of movements and their juxtaposition allows here a retrospective clarification and distinction of the usage of the terms "real-time (operational)" and "time-variable" water quality management. The first of these two terms has in fact been defined implicitly in the opening paragraphs of this introduction: explicitly, operational management means the management of problems that cannot otherwise be managed (or resolved) by planning (and design) alone. Time-variable management expresses the notion that there are important interactions between management in the long-term (planning) and management in the short-term (operational); it embraces these two components within a single framework. Thus the justification for operational management has to be seen against the background of longer-term changes; indeed, the availability of operational management can be argued to be a factor enhancing the ability of management to adapt to such changes in the long-term. Perhaps the essence of time-variable management is that it reflects merely the time-honored attribute of applied system analysis to alternate the focus of considerations between "foreground" and "background," i.e., in this case, between planning and operations.

The third and fourth papers ("Some Practical Considerations for Water Quality Management" by D.H. Newsome; "Institutional and Practical Constraints on Time-Variable Water Quality Management" by H. Fleckseder) provide a counterbalance and a pragmatic response to the first two papers. Newsome's paper introduces, among other matters, a historical perspective on river basin development and management (clearly the longer-term "background" referred to earlier). His key conclusion deserves to be quoted here in full, since it points to the central difficulty of "acceptability":

> The concept of time variable water quality management seems to induce one of two reactions in those who are currently involved in water quality management. Either they think that, while it has no relevance in their situation, they can appreciate its conceptual niceties, or alternatively, they claim that perhaps with slight extensions, it is no more than the setting out formally of what they practise intuitively or have arrived at through long years of experience. Either reaction amounts to a display of resistance to the acceptance of the different perspectives suggested in the total systems approach. This can only be overcome by patience and persistence (but not annoyance) and a readiness to seize any opportunity to implement the concept when the occasion arises.

Fleckseder's paper gives breadth to these proceedings in that it offers two cautionary reminders: that operational management is not the only problem of water quality management; and that the central European experience (Austria, southern Germany, and Switzerland) is different from that of the U.S. and U.K.

Given the analysis of this first year of the IIASA project it is possible to identify some contemporary and prospective problems of water quality management, a set of potential solutions geared to operational management, and a number of policy implications associated with these solutions.* Some of the problems and policy implications have already been mentioned. The potential solutions are comprised of six principal components linked to: (i) economic analysis; (ii) sensitivity analysis; (iii) control system design; (iv) support services in decision-making; (v) estimation and forecasting; and (vi) computing and control. Across this spectrum of constituents, we have been particularly interested in the synthesis of potential solutions that stand between the previous extremes of investment-cost-dominated economic analyses and exclusively technical studies of on-line, automatic, control schemes. Again, in broad terms, there is a conceptual division between the first and second triplets of constituents. The first grouping, of items (i), (ii), and (iii) above, is concerned with procedures for the analysis of problems prior to the implementation of operational management in practice. That is to say, these "potential solutions" relate directly to the planning and design stages of management and attempt to alter those preconditions that have so far prevented or hampered applications of operational management. The second grouping deals with problems of day-to-day practice; an important element here is a recognition of, and response to, the challenge of synthesizing solutions that will work in spite of the ever-present practical constraints.

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*These, then, are the subject matter of the accompanying policy report of project.

An economic analysis of operational management schemes is of obvious importance. Over a decade ago Thomann and his colleagues suggested that seasonal waste treatment could result in substantial economic savings and that permission for variable waste control would allow tradeoffs between capital-intensive treatment facilities and facilities with high operation and maintenance costs. Neither suggestion appears to have been seriously considered, doubtless because at least before the oil-price rises of 1973 the time was not yet ripe. Since the earliest attempts at obtaining optimal solutions (investment cost minimization) to water quality management in the mid- to late-1960's, the development of applicable methods of optimization has been substantial. Thus the paper "On the Economics of Time-Varying River Quality Control Systems" by Y. Smeers is particularly significant: it opens up opportunities to work within a framework for economic analysis where the planning of strategies for water quality management can address jointly both investment and operating costs. Other factors which are then easily accommodated within Smeers' framework include: uncertainty in the knowledge of stream behavior; extreme or abnormal operational events, such as toxic substance spillages, or treatment plant bypassing and overflows; and coordination of pollutant removal facilities with low-flow augmentation facilities.

G. Olsson's paper on "Design and Operation Interactions in Wastewater Treatment" is clearly concerned with aspects of the problem of "civil engineering" innovations. This paper also reflects--in a strictly engineering context--the interplay between long-term and short-term variations in water quality management that has usually been ignored or underestimated in the past. Because wastewater treatment plants have been designed and constructed without the consideration of operational efficiency and flexibility, this tends to limit the effectiveness of post hoc control system applications. This, of course, tends in turn to reinforce the view that operational control is not feasible. The detailed, technical study of design-operation interactions that Olsson suggests is especially relevant to the matter of changing those preconditions that have so far prevented successful innovations in operational management.

As with almost every other area of industrial activity, water quality management is currently confronted with the need to evaluate the real and appropriate potential of small-scale computing facilities (microprocessors, in particular). For this reason, S. Marsili-Libelli was asked to prepare his contribution to these proceedings on "The Role of Microprocessors in Water Quality Management: Problems and Prospects." It is difficult indeed to assimilate the full importance of such developments and innovations of "electronic engineering equipment," as has already been observed with respect to the policy implications of operational water quality management. Given presently available technology, for example, 300 items of water quality data (30 monitoring stations, say, with 10 measuring instruments at each station) can be transferred from an on-line monitoring network to a central computer once every five minutes. These are data received, therefore, at a frequency orders of magnitude faster than previously imagined proportions. It is as though in a single step we have created an information system potentially capable of supporting operational management.

P.G. Whitehead's paper on "Modeling and Forecasting Water Quality in Non-Tidal Rivers: The Bedford-Ouse Study" is likewise associated with the new opportunities created by the advent of the "electronic age." If one had suggested to the control theoretician in the early 1970's that by the end of the decade he would have been able to assume an operational river water quality monitoring network as a given practical reality, a mutual disbelief would have existed between theoretician and practitioner. Indeed, the installation of such a network on the Bedford-Ouse river system is a particularly apt example of the convergence between theory and practice. Whitehead's paper is indicative, rather than definitive, in its discussion of the operational aspects of a water quality monitoring network. He provides a somewhat more complete view of planning, design, and operations in water quality management.

The last six papers of these proceedings introduce some perspectives on case histories in operational water quality management. Experiences in two countries are represented: Finland ("Real-Time Water Quality Management in Finland: Current Research and Some Computer-Based Applications" by A. Halme) and Japan ("Application of Computer Systems for Real-Time Water Quality Management in Japan" by M. Ohnari). Again, in these papers, the problem of "acceptability" of operational management is evident. Halme, for example, concludes that:

> Technical readiness to utilize more advanced monitoring and control systems in treatment plants is in general good (only the motivation is lacking).
>
> ...the realization of integrated real-time systems for regional water quality management seems to be a matter for the next century.

Perhaps that will be the case. But then this is not so discouraging; after all, the past ten years have seen some quite remarkable changes of attitude, and the next century is just twenty years hence!

3. FUTURE DIRECTIONS FOR THE PROJECT

At the end of the first year of the project the following observations can be made:

(i) that the policy analysis has been sufficient (given the limited objectives), but is incomplete;
(ii) that we have achieved a measure of interaction among individual technical studies of real-time water quality management;
(iii) that <u>real-time</u> water quality management is too narrow a definition of the subject being addressed;

(iv) and that there is a need to prepare a detailed technical document to support the policy analysis.

Thus a second year's extension of the project (for 1980-81) is now in progress under the broader title of "Time-Variable Water Quality Management."

It has been argued that there are important interactions between the long-term and short-term aspects of water quality management. The first year's study has focused on the latter (operational management), while keeping considerations of longer-term changes in water pollution problems in the background. The policy oriented analysis of the second year's study is intended to reverse this focus. In other words, the discussion pertinent to operational management will remain as important background material, but the principal concern will be with the study of how management structures can be adapted in the face of long-term changes in the problems (this is related to a primary conclusion from the first year's study). To some extent, therefore, Newsome's discussion of river basin development in these proceedings gives a first impression of the desired perspective of the analysis. Clearly, such analysis would require retrospective case histories of highly developed river basins. Of course, one cannot predict future changes in the problems, but that which is retrospective for the developed river system may well be prospective--and thus useful--for the expected changes of less-developed systems.

The initial interaction that has been achieved among the earlier technical studies can best be utilized to provide the support for the first year's policy analysis, but it requires coordination and a focus. In an earlier part of this introduction there was mention of a set of potential solutions to contemporary water pollution problems that are geared to the use of operational management. Six important components of the potential solutions were identified: (i) economic analysis; (ii) sensitivity analysis; (iii) control system design; (iv) support services in decision-making; (v) estimation and forecasting; and (vi) computing and control. If the studies that have already been initiated could be coordinated in such a manner that they illustrate how these six components are related to each other, this would be highly desirable. Moreover, if the studies could be focused by means of an (informal) case study, this would even be approaching the ideal: the Bedford-Ouse river system (discussed here by Whitehead) offers thus an attractive opportunity for such a focus. Bearing this in mind, five preliminary proposals for associated work have been prepared (some have already matured from proposals to studies in progress):

(i) The Economics of Time-Variable (Operational) Water Quality Management;
(ii) Risk Analysis in Water Quality Management;
(iii) Operational Wastewater Treatment and its Effects on River Quality--A Simulation Study;

(iv) On-Line Estimation of Operational "Failures" and Maintenance Requirements;

(v) Evaluation of Operations with an On-Line Water Quality Monitoring Network.

In general, therefore, the structure of the second year's project is designed to reflect the nature of problem shown in Figure 1.

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

M.B. Beck

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 climate 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 long-term capital investment 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 minimized for the chosen investment program if one of the major technical options, real-time forecasting and control, has not been included for consideration. The subject of models for day-to-day management and control will be the concern of the paper. A speculation, therefore, is offered. Of course, 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 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

It has already been 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 examine 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);

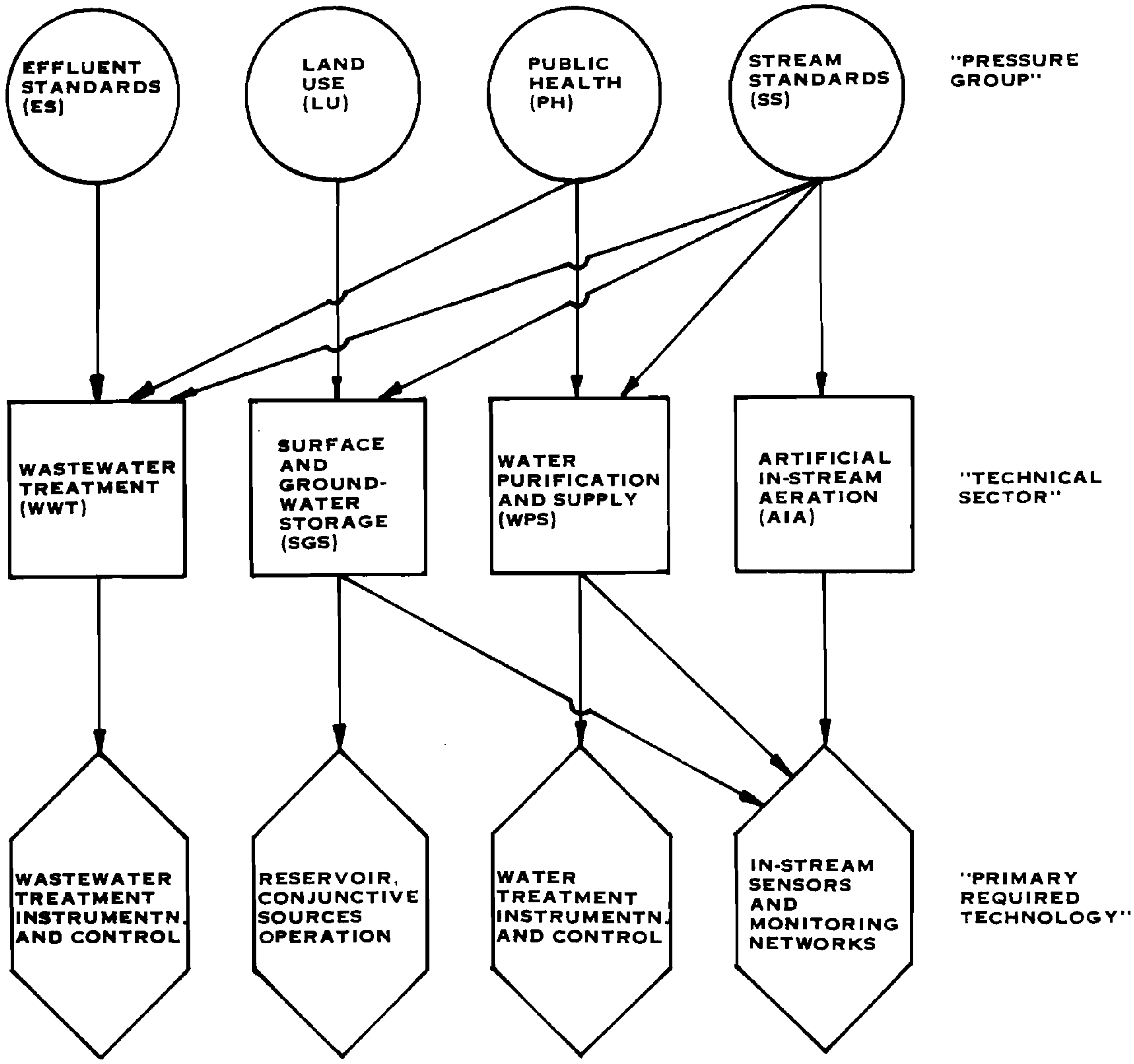

Figure 1. Water quality management: the forces acting upon different technical sectors and the requirements for different kinds of technological innovation.

(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 dominant 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 wide-spread innovation of automation and computer control in the waste-water industry. Conversely, the use of in-stream 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. Activities in all the four technical sectors would be affected in some way by the development and implementation of standards for in-stream water quality. Competitive interests in land use, especially in a highly developed river basin, tend to restrict the opportunities for capacity expansion of surface water storage facilities. In turn this tendency might stimulate more efficient reservoir operating policies, a greater concern for stream regulation, and a more widespread use of direct abstractions from lowland rivers for potable water supply. Considerations of public health are clearly factors affecting the innovation of new technology in wastewater treatment and water purification plant operation. These considerations, when linked with increased abstractions of river water for potable supply, would also influence the need for developments in in-stream water quality monitoring networks.

Tentatively one might draw the following conclusion from Figure 1. 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 of facilities which is forced to develop (technically) in one direction only may eventually turn out to be quite an inflexible 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 one technical sector, must inevitably place great emphasis on the reliable operation 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 process design, including process flexibility and process controllability (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 program would resemble much more closely a strategy implied by the (UK) 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 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.

Real-time operational control may not offer many clues to the solution of the foregoing problem; but what of the matters

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

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) criticizes the US Federal Water Quality Act Amendments of 1972 for making management alternatives less flexible, which in this paper 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 distribute the innovative 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 costs. 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 programs of a water quality management strategy can favour construction of treatment plant facilities and discriminate against improvement of their performance. 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 summarize 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 crises, 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 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-1960's 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 when prescribed values for dissolved oxygen concentration 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 publicized; this may already reflect a trend in the response to legislation for water quality management.

(d) Water quality monitoring networks. In its brief report on the optimization of water quality monitoring networks the World Health Organization (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 modeling 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).

* Techniques which will be discussed in more detail below.

(e) Hydrological precursors. One can observe in general that for many aspects of water quality modeling, 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) summarizes three years' 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 have been said to depend fundamentally upon the choice of model for real-time simulation and that ultimately relatively simple hydrological models have been 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.

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 modeling 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 starting point for discussion 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 recognize that such is the nature of "reality", although that would not preclude simplifying assumptions. If the current use of models for management, both short-term and long-term, is to be criticized 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 specialized 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. This topic is primarily concerned with the use of models as aids to operational decision-making. Estimation and forecasting refer thus to the application of models for estimating the present and (short-term) future state of river water quality at a number of fixed spatial locations. Of particular interest are the problems of:

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

(ii) the reconstruction of information about variables that 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 that 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 <u>inevitable errors of prediction</u> about the present and future behaviour of reality.

Now let us look at the filter from the point of view of an <u>information processing mechanism</u>. 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 <u>state</u> 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. 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) that are not readily measured by on-line sensors; this is known as <u>state reconstruction</u>. And in a more general sense, since it can revise the estimates of its model parameter values, the filter can be applied in an <u>adaptive</u> or <u>learning</u> mode. In other words, the algorithm combines the operations of model calibration and forecasting.

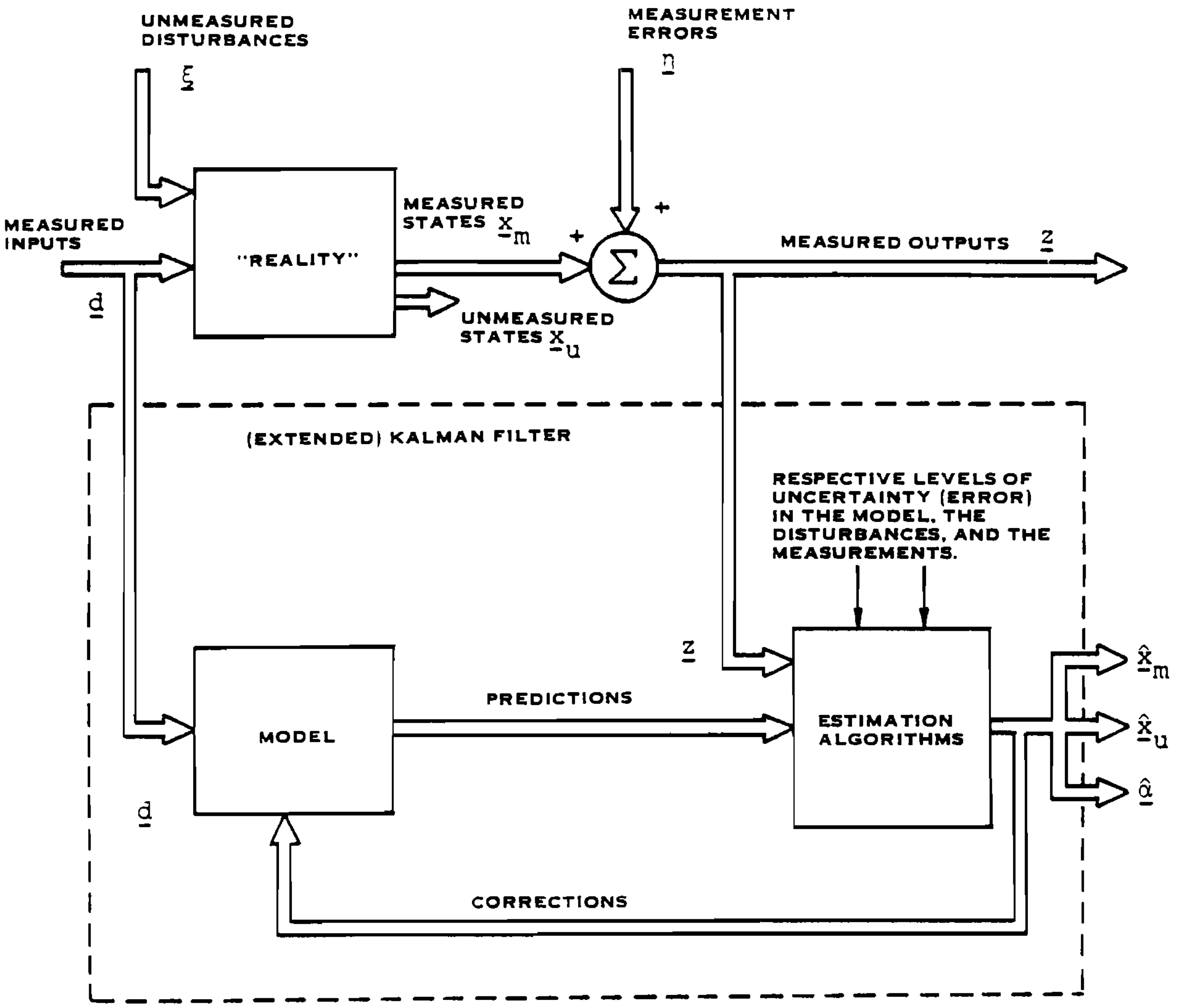

Figure 2. The (extended) Kalman Filter, an algorithm for estimation and forecasting; $\hat{\underline{x}}_m$, $\hat{\underline{x}}_u$, and $\hat{\underline{\alpha}}$ are respectively estimates of the measured state variables, the unmeasured state variables and the model parameters.

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.

(c) Management and control. The adaptive predictor mentioned above 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 microprocessor realizations, 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, computerization, 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". <u>Automation</u> is understood as the automation of information retrieval and communication and the automation of implementing control actions. <u>Control</u> 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 <u>not</u> be removed from the control loop.

For the future, therefore, we may visualize mathematical models and on-line forecasting procedures as a kind of <u>support service</u> 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). The human element is therefore not necessarily to be supplanted in the procedures for operational control: mathematical models and a formalized distillate of past empirical operating 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 recognizing 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 completely ignored because they are thought to be impractical at present.

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TIME-VARIABLE WATER QUALITY MANAGEMENT - A POLICY STUDY

M.B. Beck

" 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 decade to decade; and it allows consideration of short-term (real-time) operations, where variations with time on a day-to-day or 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 are, or are defined 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.

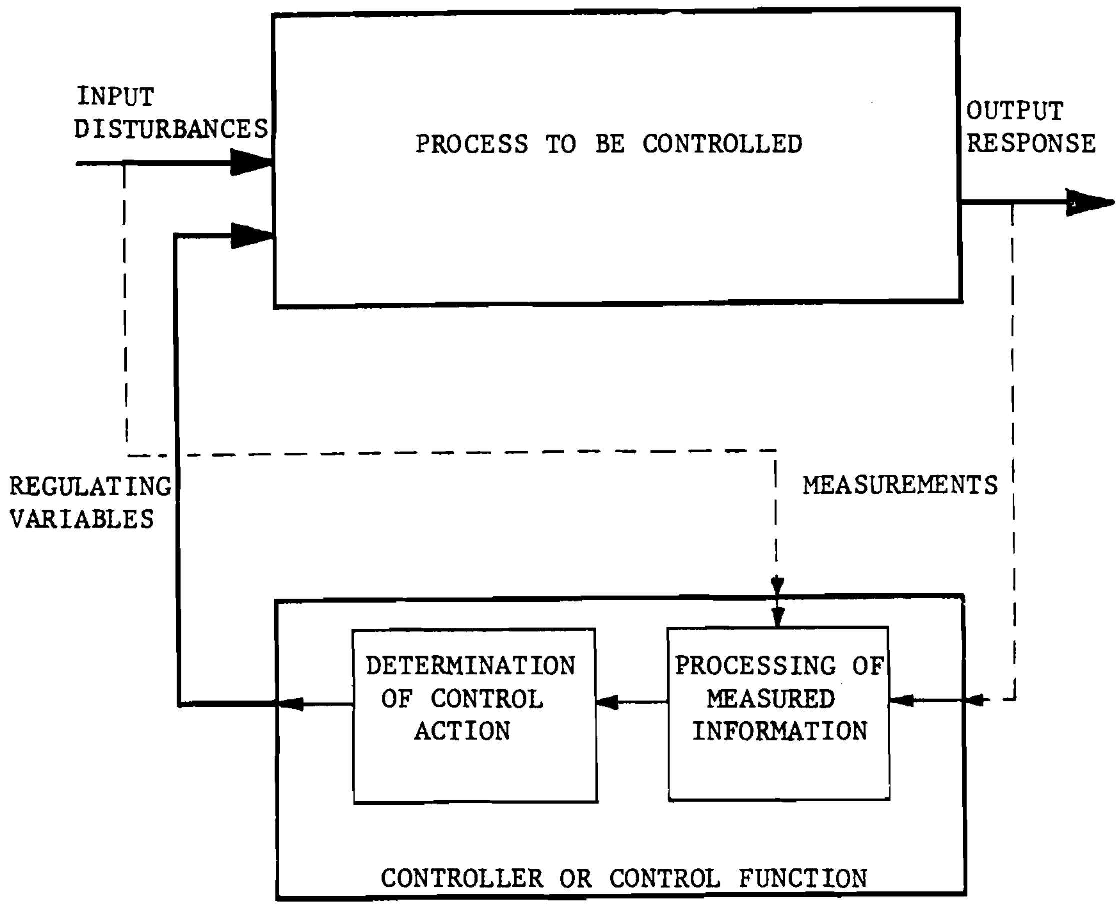
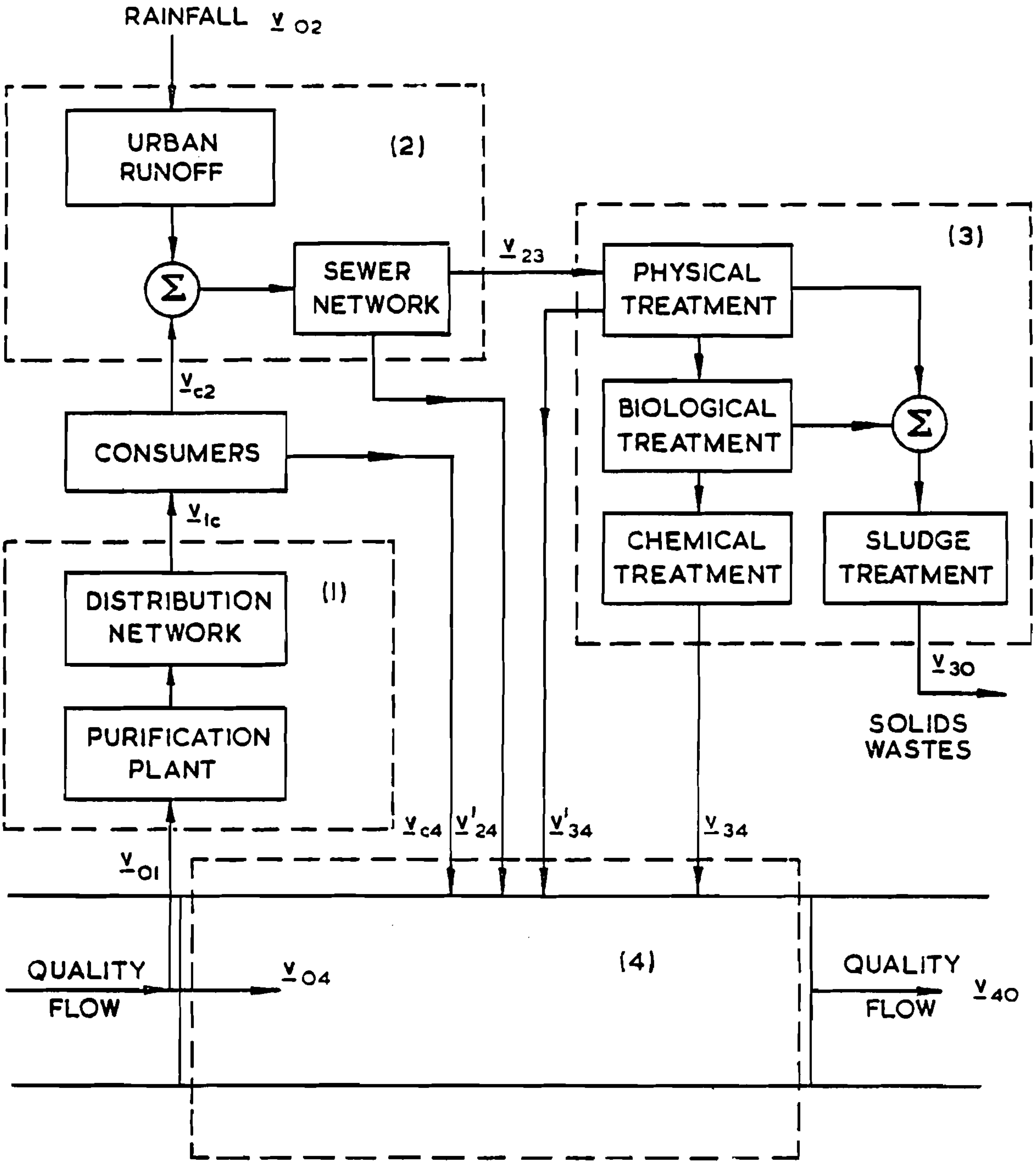


Figure 1. A framework for analysis: basic components of a process control system (dashed lines indicate measurements).



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.

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 specifiy 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 overly 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,

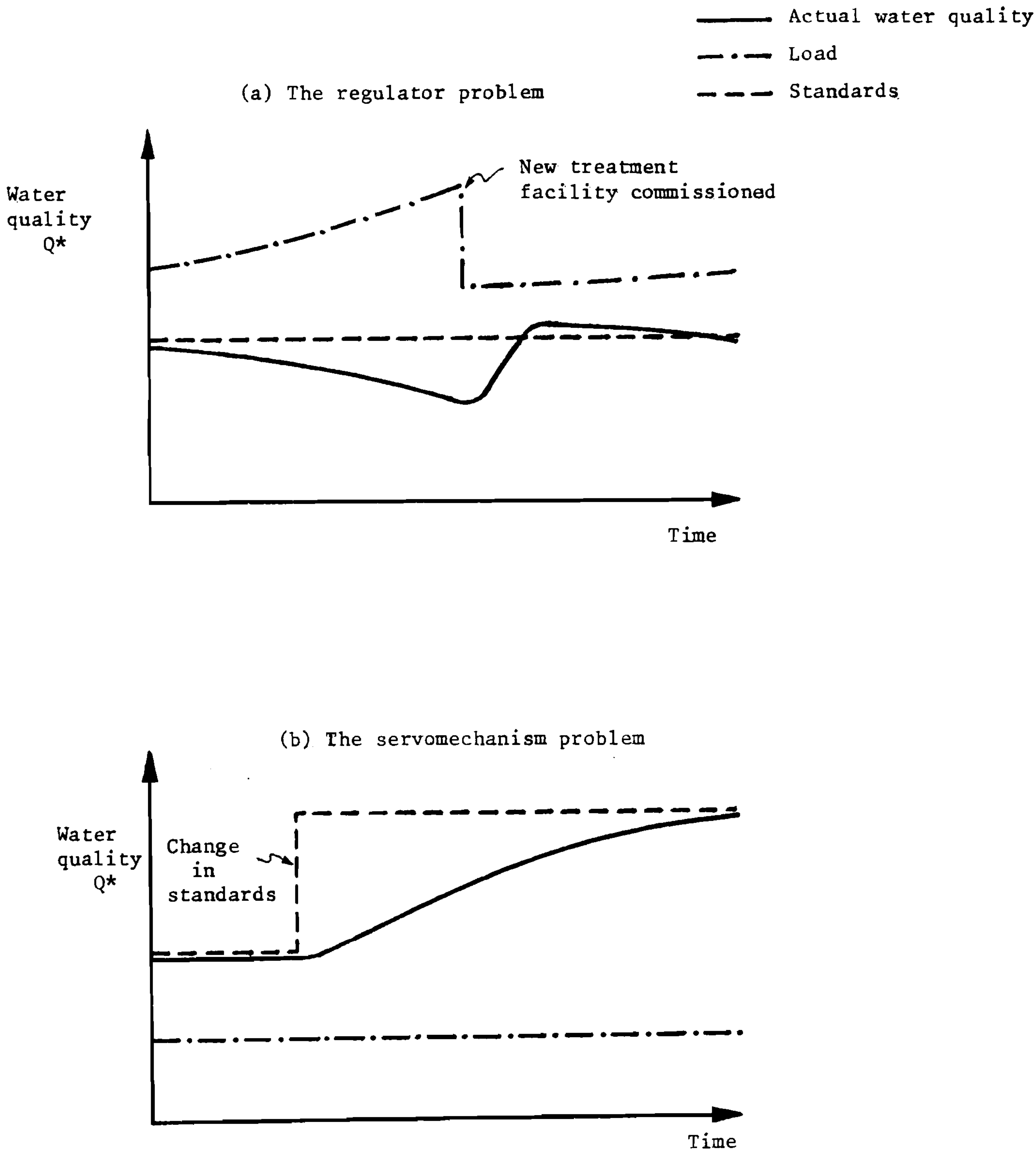


Figure 3. Two types of control problem: (a) the regulator problem; (b) the servomechanism problem.

changes with time. For example, in Figure 3(a) let us assume that an increasing population leads to a steadily increasing discharge of pollutants until eventually a plant expansion 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

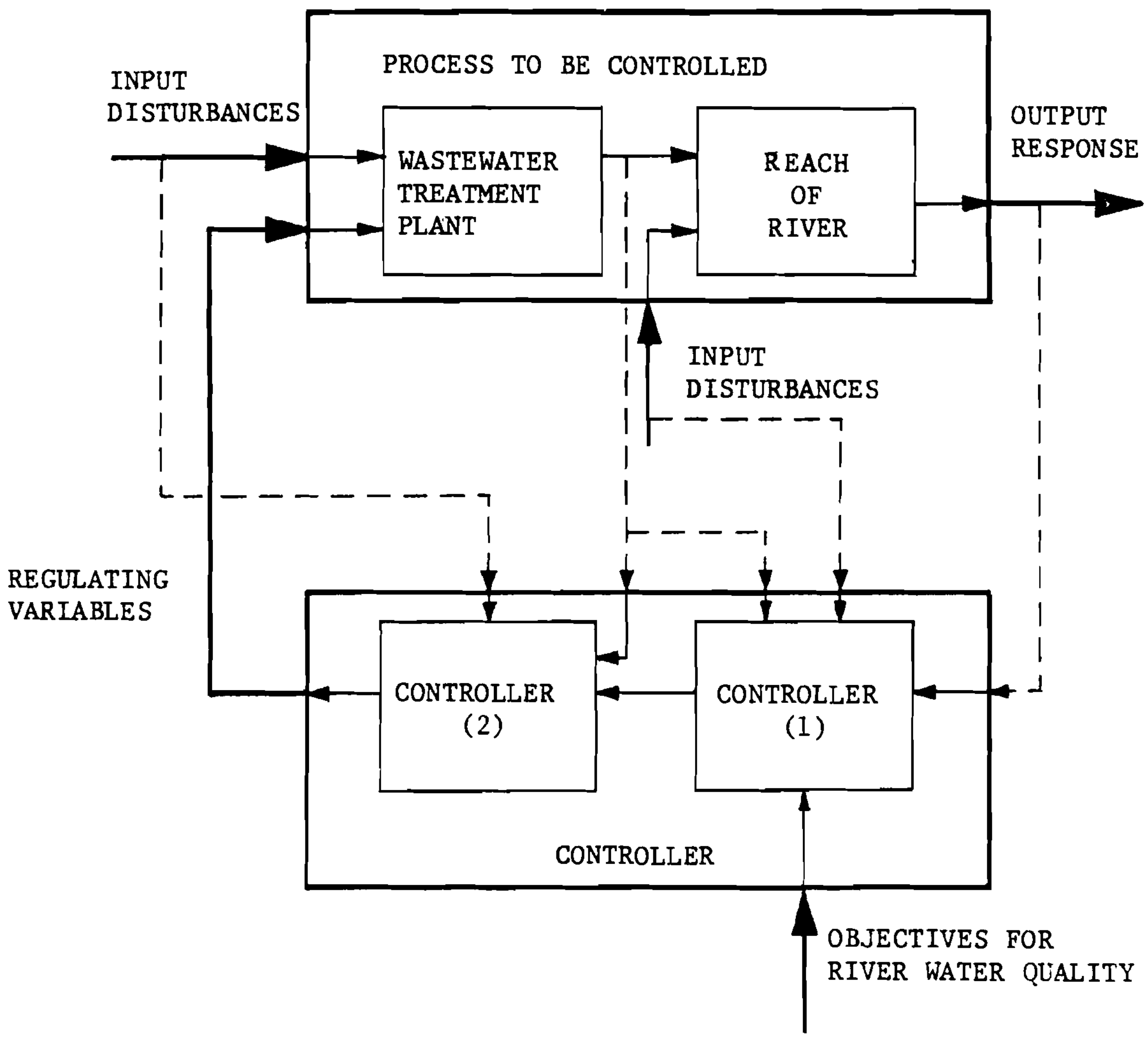


Figure 4. A hierarchical control scheme: controller (1) specifies the desired performance (objectives) for controller (2) (dashed lines indicate measurements).

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 uncertain. 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 information-gathering 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

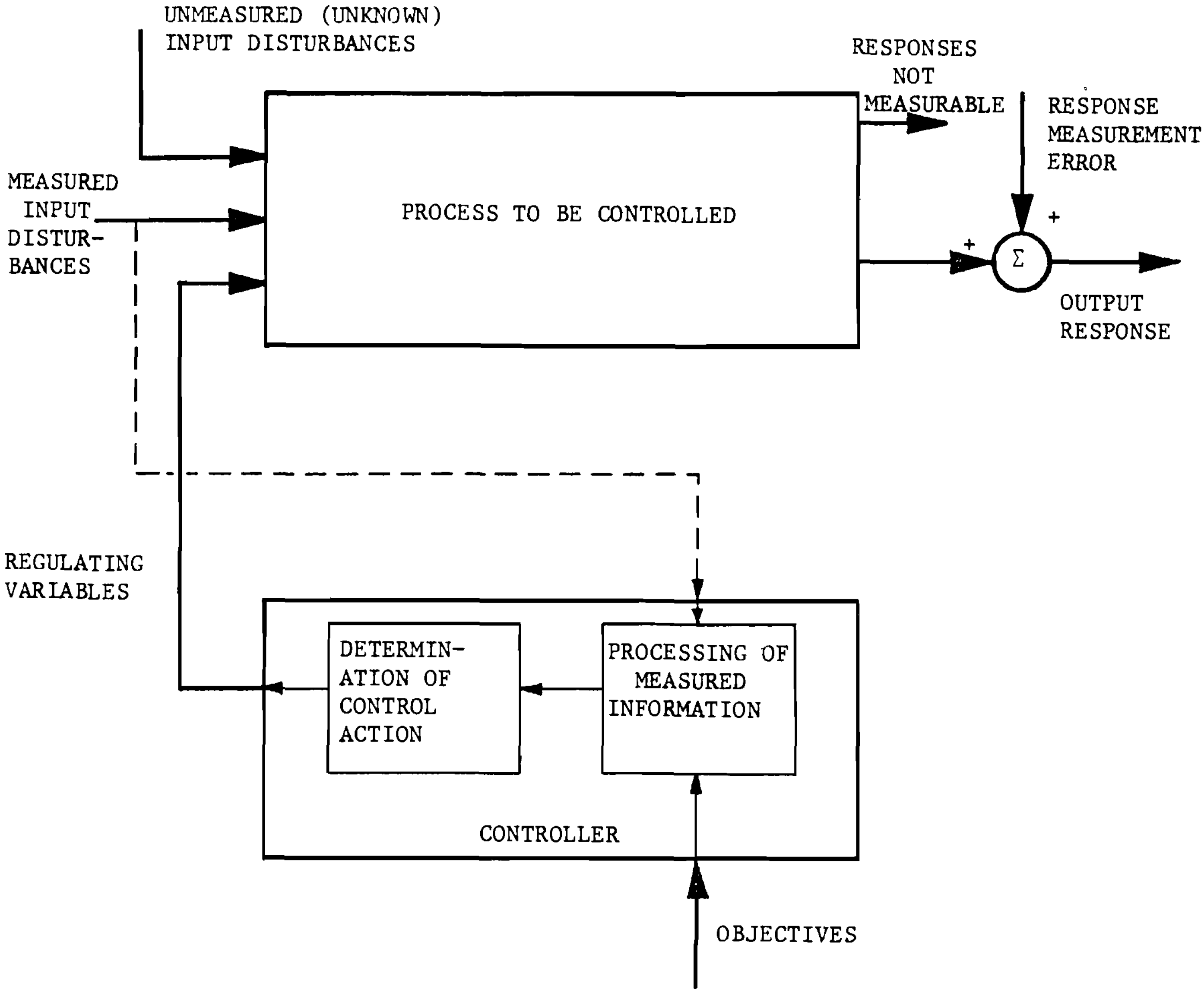


Figure 5. Feedforward strategic planning (dashed line indicates measurements).

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 minor 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.

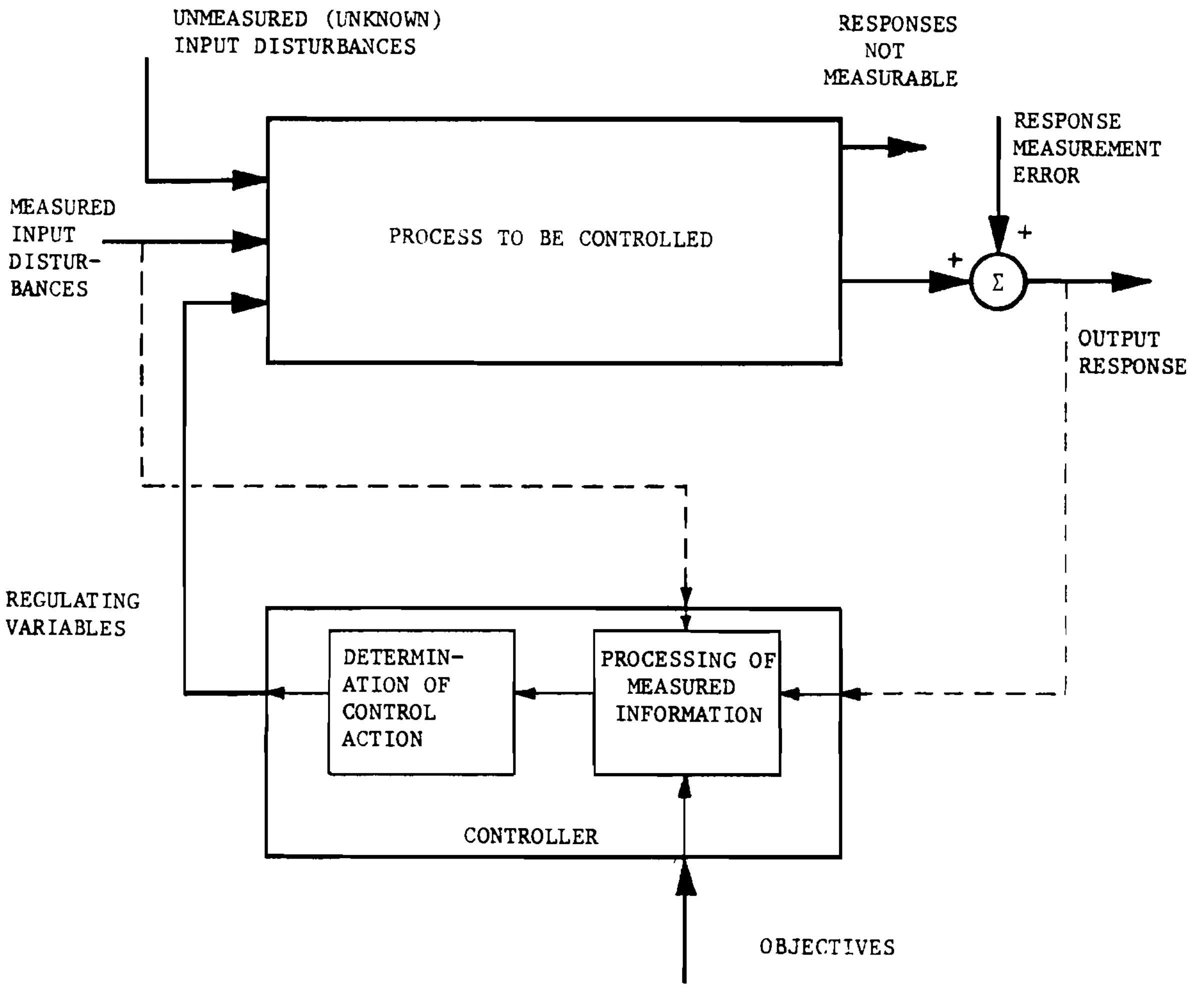


Figure 6. Management with feedback (dashed lines indicate measurements).

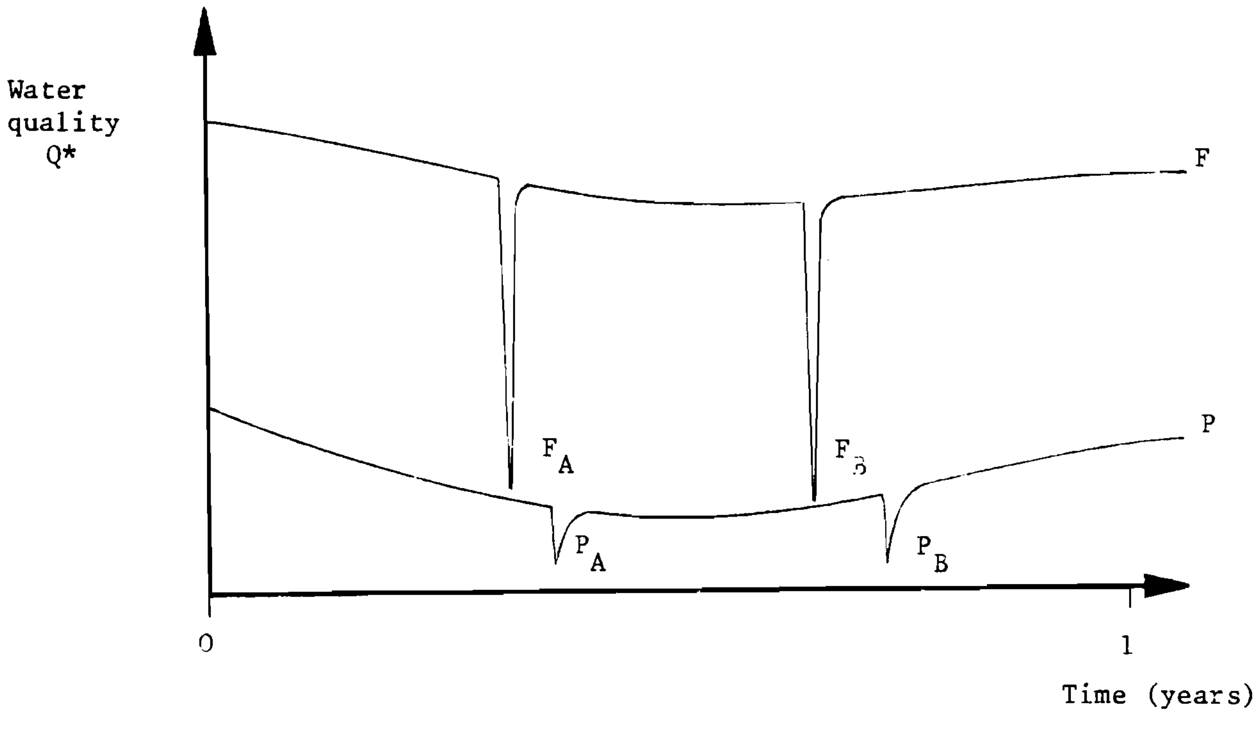


Figure 7. Past (P) and future (F) performance in water quality management. P_A, P_B, and F_A, F_B represent transient severe pollution incidents.

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 sensors 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

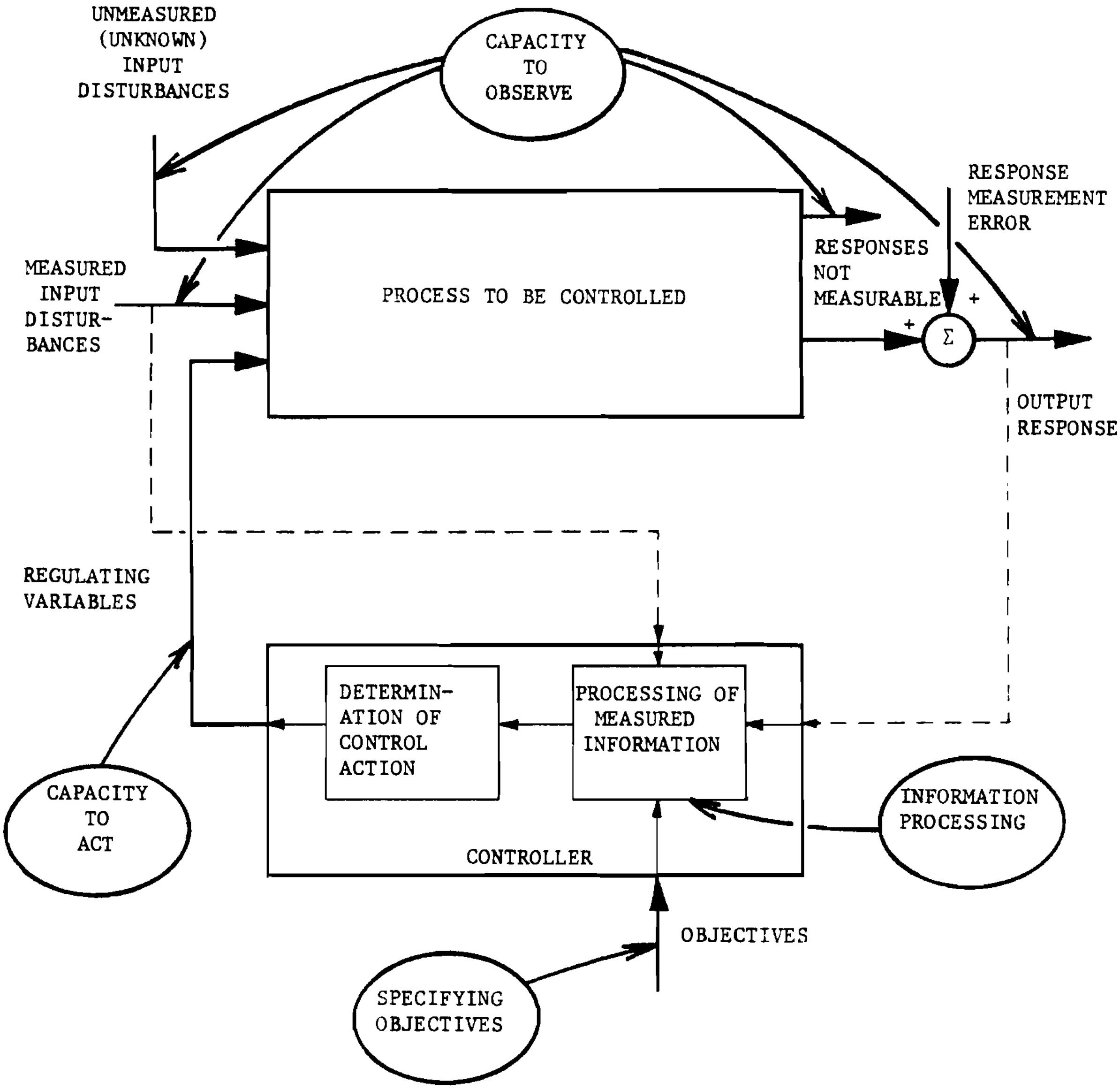


Figure 8. Influence of short-term operational management on strategic long-term planning.

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 frequently 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 may, 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 operating 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. A greater amount of control effort is now expended in preventing a larger proportion 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 in developed river basins 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 <u>minimum modification--and particularly by different operating policies--to achieve</u> the new objectives? The same rate of change in the problems, practice, and objectives of water quality management that 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 (microprocessor) computing applicatings 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 legislation relating to water pollution control.
- When considering the process of innovation,human factors may be just as significant as economic factors in influencing 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.

- o 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.

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SOME PRACTICAL CONSIDERATIONS FOR WATER QUALITY MANAGEMENT

D.H. Newsome

> "I find the great thing in this world is not so much where we stand, as in what direction we are moving. To reach the port of heaven, we must sometimes sail with the wind and sometimes against it - but we must sail and not drift, nor must we lie at anchor."
>
> O.W. Holmes

1. INTRODUCTION

In the past, management of water quality has concentrated exclusively on regulating long term trends rather than short term variations. "Time variable water quality management" (Beck, 1980) questions this and suggests alternative approaches. It is certain to be viewed with suspicion by water management, not least because the new ideas have been derived as a result of a total systems approach to the subject.

In all except a few special cases, it will not be possible to implement all the ideas in full, but the concept should not be dismissed on that account. Rather, it is an approach which should be borne in mind by all those concerned with the quality of water in our lakes, rivers and streams whose natural regimes are about to be, or already have been, disturbed by the activities of man.

The introduction of agriculture, or changes in its practice; an increase in the population living in the catchment area or the introduction, expansion or change of process by industry may each, in its own way, have profound effects on the hydrological characteristics of a river basin and on the quality of water draining from it. Such developments are invariably accompanied by demands for some or all of the following: water resources development, water supply, sewerage and sewage treatment and flood control.

Meeting these demands requires the ordered management of water resources and ultimately the river system itself. Such management involves both strategy and tactics. For each, management should concern itself with the variables--water quantity and water quality, the facilities (plant) and constraints (for example, legal, economic and political). This paper will demonstrate how water quality can be better managed by optimizing the use of the variables, the facilities and constraints available.

Not unexpectedly, time variable water quality management is concerned with the control of the short-term variations in water quality and thus has implications for operational (short-term) management. More surprisingly perhaps, it also involves the planning function (or long-term management) which is concerned with the control of longer-term trends in water quality. Because these two aspects, long and short term, are in reality a continuum, the planning function and operational management must interact. For example, decisions taken during the planning phase of a proposed effluent treatment plant will have direct consequences for those charged subsequently with its operational management and for the planned maintenance program for the plant.

Thus the concept of time variable water quality management should find application in all the stages of development of a river basin which is to be utilized extensively for multifunctional purposes. That is, a river basin which may be used for some or all of the following: water supply, the carriage of sewage and industrial effluent, irrigation, industrial use, navigation and (becoming increasingly important) recreational purposes such as sailing, water ski-ing and fishing.

2. THE DEVELOPMENT OF A RIVER BASIN

While the development of a river basin is essentially a continuous activity, three phases can conveniently be identified (Benjamin, 1976; Newsome, 1978).

Phase 1. Water resources development

At its simplest, this phase consists of the development of a reliable, unpolluted supply of water to users located within the catchment. The collection of sewage, its treatment and disposal is usually, but not always, the responsibility of a different authority. Co-ordinated management is therefore nil, or at an extremely low level.

Phase 2. River management

As development within the basin continues, water conservation measures, water supply and effluent disposal, become increasingly interactive and thus should be brought together under the control of a single authority. The effects of all these activities on the river have to be monitored. Formal river management is thereby introduced and legislative measures may have to be enacted to preserve an aesthetically acceptable quality of water in the river.

Phase 3. Integrated river basin development

In this phase, management of the river to meet several, often conflicting objectives is introduced. The river water is used intensively, often being re-used for supply purposes, and this requires positive (that is, active rather than passive) water quality management both from the planning and operational points of view. In this situation, the resources of the basin must be viewed as a whole and, for example, reclamation of treated effluent can become as important a conservation measure as the construction of an additional storage reservoir.

Though the concept of time variable water quality management is applicable to an increasing degree throughout all the phases of development in the river basin, it is in Phase 3 that it becomes possible to realize its greatest potential. This will only be achieved if management receives relevant information continuously which is timely, reliable and presented in a form in which the content is clear and not open to misinterpretation. (This in itself is a major problem.) It is therefore pertinent to discuss the significant attributes of a management information system which will meet this specification.

3. THE DEVELOPMENT OF A DATA COLLECTION SCHEME (Newsome, 1978)

Three main types of data can be identified:

Static	e.g.	the catchment area and its characteristics; water treatment plant details, etc. (Collection of such data requires an initial effort but can then be maintained by subsequent minor updating).
Dynamic	e.g.	measurements of physical, chemical and biological characteristics. (This is a continuous activity.)

Socio-economic and political	e.g.	population, its size and rate of change. (Acquisition of these data requires discrete, periodic surveys.)

Studies of many different information systems suggest that there is a common thread running through their development pattern which can be divided into three stages which correspond broadly to the phases in river basin development. These are:

Stage (a). This comprises the acquisition of basic knowlege, and the accumulation of records for planning, research and other non-operational purposes.

The static data are gathered (principally by surveys) to establish the catchment area and its characteristics, for example, its boundary, geomorphology, geology, vegetation cover and land use, and to put them into a basic reference framework, for example, a national grid referencing system.

The dynamic data comprise regular measurements of all surface and ground water parameters. Analysis of these data will seek to derive the limits of variation in the key parameters--flow and quality--and the variation within these limits. An understanding of the relationships between the parameters and their variation must be gained because this is essential for planning purposes.

The collection of socio-economic data is probably limited to an examination of proposed development plans for the basin.

Although Stage (a) may take many years to complete, it is finite. It will be complete when it is considered that a working knowledge has been obtained of the system under normal conditions. Knowledge about extreme conditions must continue to be gained at every opportunity.

Stage (b). There is no clear cut boundary between Stages (a) and (b) but Stage (b) can be said to have been started when an overall plan for the development of future operational schemes has been adopted by management. Such plans should include data collection and information systems which are an inherent part of, and of fundamental importance to Phase 2 operations.

Static data collection in Stage (b) will consist of refinement of the data acquired under Stage (a), updated as necessary when plans are implemented, for example when a new wastewater treatment plant is commissioned.

Procedures for dynamic data collection change significantly from those used in Stage (a). The wide ranging and leisurely data collection of that stage is largely replaced by schemes designed to serve the needs of operational management, initially in "sensitive" areas only--such as critical stretches of the river.

Because operational data are normally used immediately by operational management and are then discarded, special steps will become necessary to preserve certain data for the record. The one exception to this change is dynamic data about extreme events which will be collected as before.

Socio-economic data play an increasingly important role in Stage (b), since plans for phased water resources development should have regard to forecasts of population, agricultural and industrial growth and to the spread of urban areas.

Typically, Stage (b) will be entered when considerable volumes of water are abstracted for public water supply, industrial and agricultural use and where effluents are returned to the river. These conditions require that water resources must be partially or selectively managed in limited areas although no overall control may be exercised over the hydrological cycle and the distortion of it caused by man's activities. A Stage (b) data collection scheme providing data in "real-time" will be necessary to enable such management to be effective in the areas where active control is introduced.

Stage (c) will become essential where integrated river basin management has become necessary because of the need to use available water resources intensively and perhaps for multiple purposes. The data collection systems for static, dynamic and socio-economic data will be further refined to enable direct management of the water resources of the basin as a whole to be exercised. This control, of course, must cover both water quantity and water quality.

4. THE IMPLICATIONS FOR MANAGEMENT

Most of the world's river systems are still in development Phase 1. Because the data are being collected for retrospective analysis and to cover a broad spectrum, it is convenient and economic to deal with them centrally where most of the experience and expertise will be found. Also, there is no need for a "real-time" system. Due to difficulties of access, travel time and so forth, it may be convenient to collect data on a regular but infrequent basis, say once per month or per week via a transmission link which may be landline, radio or satellite. It should be noted that if such links are installed in Stage (a) of the data collection system, it makes the transition to a Stage (b) easier. Nonetheless, it must be borne in mind that regular visits to site are essential, albeit at less frequent intervals, to make subjective observations of site conditions. These constitute an essential background to observe variables such as structure and water condition which are not amenable to measurement by instrument.

In Stage (a), one of the important requirements is to identify areas where time variable water quality management is important, that is, potentially "critical" stretches of river. This should lead to the consideration of the type and capacity of effluent treatment plants that are to be installed. Both these aspects are, of course, of a research/planning nature and can be considered part of the long-term quality management function.

Because, generally, management is not formally co-ordinated, the operation of water treatment plants must be considered separately. Here the quantity of raw water entering the plant and of the treated water leaving it are recorded, and the rate of dosage of chemicals and the condition of the water are continuously monitored. Should the water quality vary outside pre-set limits, an alarm may be sounded and remedial action is taken. Frequently this is a manual action.

Up to now, sewage treatment plants have not been instrumented to the same degree as water treatment plants because of the difficulty of measuring meaningful parameters on a continuous basis. Much more emphasis has, therefore, been laid on the skill of the plant manager and his staff. Their performance has been monitored by analyses of regularly taken samples for BOD and suspended solids entering and leaving the plant, but these records can only be examined in retrospect. Similar, but less frequent, determinations are made of other variables, for example, nitrogen and the form that it is in, and heavy metal concentrations. Continuous monitoring of any variable, even flow, is still rare, but is becoming more commonplace, especially in the larger plants. A notable exception is the measurement of aeration or an alternative measurement for it.

As has been mentioned earlier, when Stage (b) is entered the emphasis of dynamic data collection changes quite dramatically. The wide ranging, leisurely data gathering activities of Stage (a) are replaced by smaller networks of data capture stations which report to the operational management in real-time. The requirement is for accurate and timely data upon which decisions can be made and action taken. Examples of this type of data can be drawn from every facet of a water authority's activities. Obvious ones include:

<u>in regulated river systems</u> the monitoring of

- -- rainfall
- -- levels or flows at key points in the river system
- -- rates of release of regulating water
- -- reservoir levels
- -- the status and availability of pumps feeding pumped storage reservoirs

<u>in water supply</u> the monitoring of

- -- the performance of water treatment plant
- -- levels in reservoirs and water towers
- -- pressures at key points in the distribution system

-- the status and availability of pumps used both for abstraction and for boosting pressures in the distribution system
-- the level of groundwater

<u>in effluent treatment</u> the monitoring of

-- the rate of flow of influent to the treatment plant and its quality
-- the rate of discharge of effluent from it and its quality
-- the status of the process stages in the plant

Because these data are needed in real-time a telemetry system has to be utilized. Using a properly designed telemetry system also allows the control of pumps and adjustments to valves in plants to be made remotely. Control of pumps and adjustments to the rate of regulating water releases can also be made by remote control.

It is likely too, in Phase 2 of river basin development, that some stretches of the river itself will be more "critical" than others. These will be the first to be affected by variations in flow and quality. It is in such river sections that the much maligned automatic water quality monitor, respecified and redesigned and operated in accordance with a different philosophy has an important role to play.

By the careful setting of discharge consent conditions, the regulation of flow and monitoring the results in real-time, it may be possible to maintain a judicious balance of water quality within the stretch of river which will help to ensure the provision of water of acceptable quality at all times.

In the UK, general practice under the present laws relating to discharge of effluent limits the rate of discharge and its quality to rigid values. This practice prevents the local operational management from consciously varying the rate and quality of the discharge to take account of the assimilative capacity of the receiving water. Were the practice to be changed, a much more flexible management of effluent treatment plant and river section would be possible. The required water quality standards under this regime would be set for the receiving water rather than in the effluent itself.

When the river basin has been developed to an extent where integrated river basin management becomes necessary (Phase 3), a succession of local operational centers (LOCs), should be established. Each would be responsible for its own section of river, for the discharges to and abstractions from it, together with their associated treatment plants. The establishment of the LOCs should help ensure that the water in the system can be used intensively* and will be of a quality suitable for the variety of purposes for which it is to be used.

In addition to each LOC's real-time data gathering system for its own operational management purposes, communication between LOCs will become essential to manage the river system as a whole, under normal conditions.

Area operations centers (AOCs) should also be established whose purpose is to co-ordinate the activities of the LOCs for which it is responsible and to assume direct control of operations during extreme conditions of flow or quality. This order of management would be maintained for the duration of extreme conditions after which normal operations, (that is, with the LOCs in direct control) will be resumed.

To discharge these functions AOCs will have to be equipped with effective data/information gathering facilities and at all times will have to be in direct communication with the adjacent upstream and downstream centers. (It should be noted, however, that for many small river systems, one AOC will suffice.) They should also be able to provide forecasts of developing conditions for which they will need mathematical models; these will be used in a simulation mode.

The organization and information facilities outlined above are demonstrably the best for operational management and should enable the optimum use to be made of the resources of the basin. With these arrangements, the river flow may be regulated over most of its length by means of regulating reservoirs which may be of the impounding or pumped storage type, or, where it is available, by augmenting the flow of the river by groundwater pumped into it. This, together with a balance between the discharges of effluent made to the river and the abstractions made from it, will ensure that the quality of the water in the river will be suitable for the in situ uses that might be made of it. These will usually be recreational. In addition, level control structures such as weirs and sluices will frequently be introduced to provide in-river reservoirs at abstraction points and to control the spilling of river water to areas designated for that purpose, thereby reducing the risk of flooding in areas where danger and damage would be greater.

5. CONTROL POSSIBILITIES AVAILABLE TO OPERATIONAL MANAGEMENT

While the general concept described in the previous section is essential for good operational management, the extent to which

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* "Intensive water use" in this context is defined as the situation where water has to be abstracted for public supply (or other purposes) at all times regardless of the quality of the water available in the river. Conversely, "selective water use" describes a situation where it is possible to exercise some choice over when abstractions are made, thereby avoiding use of poorer quality water.

it is applied practically depends on the particular circumstances obtaining in each river basin.

Three generally important forms of water quality control suggest themselves--these are:

-- Source Control
-- Plant Control
-- In situ river treatment

5.1 Source Control

By its very nature, a present-day sewage treatment plant is not capable of effecting rapid and controlled changes in the quality of its effluent. New plant or extensions to existing plant take a considerable time and cost to construct and to bring into operation. For these reasons it is important to examine the possibilities of improvement in effluent quality at the sources of pollution.

It should be possible to treat or partially treat major effluents at source, that is, before they enter a sewer, thereby relieving the pollution load on the sewage treatment plant itself. Such pretreatment may consist simply of settlement, but could be much more sophisticated, particularly if this were to show cost benefit, such as the recovery of useful material from liquid wastes. Also, effluent may simply be stored in a buffering tank at the source so that it can be released to a sewer at a controlled rate.

5.2 Plant Control

Within sewage treatment plants it is usual to find spare storage capacity in the form of stormwater tanks. In many cases, it may be possible to use these as buffering influent tanks or as retention tanks for effluent polishing, or in some cases, as a combination of these uses.

It is also usually possible to vary the rate of aeration and the proportion of sludge return in the plant. By measuring influent flow and relating aeration and sludge return to it, an optimal operation of the treatment process may be achieved.

It is clear that a combined use of available air and/or effluent storage and the application of process control techniques to aeration and sludge return together constitute potentially powerful means to increase effluent handling capacity and to obtain a tighter control of effluent quality variation.

Prospects of yet further improvements include:

-- the use of oxygen instead of air
-- the chemical pretreatment of sewage at the treatment plant using, for example, lime

-- the use of low capital cost, high running cost treatment stages, but only when the works are heavily loaded, or when the river's dilution capability is low
-- use of bankside storage of treated effluent. This storage would be operated in the way suggested earlier for stormwater tanks but the capacity of such bankside storage can be expected to be substantial.

By the use of a combination of these methods, a significant enhancement in the management of the treatment capability should be possible. The sensitive nature of the biological process involved in sewage treatment must however be recognized and care must be taken in developing altered operational procedures of the types described.

5.3 In situ River Treatment

For short-term operational water quality management it can be argued that in situ river treatment offers greater scope to exert a positive influence on the quality of the receiving water, than alteration of treatment conditions. Three methods must be considered:

-- dilution
-- retention or
-- aeration

Dilution may be achieved in a number of ways; by releases from a regulating reservoir, by augmenting the flow from groundwater pumped into the river for that purpose or, in some cases, by using water brought in from outside the catchment altogether.

The speed of response of this method for water quality management depends largely upon the proximity of the discharge of effluent. However, more distant discharge points should not be discounted because the speed of propagation of the "front" of the diluting water is rapid when compared with the speed of the actual body of water released into the river.

An indirect way of altering the capacity for dilution of the river may be by reducing the abstraction of water at nearby abstraction points. This has the effect of leaving more water in the river for dilution purposes. Clearly, it may also be possible to use a mix of dilution methods to achieve the required result or, indeed, to operate dilution in association with retention or aeration.

Retention may be achieved by the diversion of the whole or part of the flow of the river through retention lakes which may be, for example, worked out gravel pits, or they may have to be purpose-built. Either way, the beneficial effects of retention (particularly on BOD and suspended solids) are well known.

It is possible to effect an improvement in quality in a river section by the introduction of direct aeration which may be achieved by the construction of a weir, by submerged sparge pipes through which air is pumped so that a diffused curtain of air is released across a section of the river or by the introduction of a surface aerator. Whichever method is chosen depends on the conditions obtaining at the proposed site. Aeration, of course, is not a panacea; many pollutants would remain unaffected by it, but the general "well-being" of the water would be improved.

Continuous management, or the partial control, of river water quality in these ways brings several benefits. With improved water quality, the flora and fauna of the river will become more abundant and diverse. Hence, the potential for recreational use may be improved. The downstream abstractors will benefit by having their treatment costs reduced. Lastly, and surely of equal importance, such control, though it is only partial, will produce a general improvement of the environment in the receiving water--a moral, if not legal responsibility of all those concerned with water management.

6. THE ROLE OF THE MATHEMATICAL MODEL

It is extremely difficult to make (and be seen to have made), the best possible decisions where large and complex systems of "men, machines, materials, and money" are involved (Beer, 1966). River basin management qualifies for this description, probably during Phase 2 of its development, but certainly in Phase 3.

It is then that the operational mathematical model can, if it is properly specified and constructed, become an indispensable aid to management. It is not just the model's ability to represent the large system in an abstract way that is important, but its ability to reduce the timescale that makes it so valuable. For example, in a simulation mode one can investigate in a matter of minutes the response of the system to a decision, not only for the time of making it, but also for successive days, weeks, months, or years whichever timescale seems to be appropriate. Anyone who finds difficulty in answering the question "what will happen if I follow this policy...or that?" should also ask himself whether he should invest in a model. The model will examine the results of the alternative possibilities quickly, conveniently and without interfering with the operation of the system itself.

Moreover, as has been explained elsewhere (Newsome, 1977), it is no exaggeration to say that the effectiveness and efficiency of management is largely dependent on the range and quality of the information available to it. To ensure the provision of high quality information, a good data gathering, processing, storage and retrieval service is a fundamental necessity.

However, data capture costs a great deal of money, the largest element of which is the cost of visits to sites. If, therefore, through modelling, the number of data collection sites and the frequency of visits to sites can be significantly reduced, it is arguable that the model will be cost effective on those grounds alone. But a model will do more than that. Given data for a few key sites, it may be used to generate data for other sites in the system thereby saving the cost of data capture at those sites altogether.

In general, water quality models may be conveniently classified under three broad heads: planning, operations and forecasting (both short- and long-term). They should, therefore, be capable of covering the entire spectrum of responsibilities of water quality management as defined in the introductory section of the paper.

(a) Planning. The two principal objectives of a water quality model used in this mode are (i) to plan in general terms a program to achieve the desired water quality in the system at some defined time in the future and (ii) then to optimize the quality of the effluents discharged to it so that the desired water quality is achieved at least cost.

For this purpose average concentrations of pollutants with, perhaps, some idea of the range of their variation about the average is sufficient to give a "feel" for the system as it would be under normal conditions. The model will not, however, be able to simulate the system under the extreme conditions of drought and flood.

Often, such variations in quality are buffered by the provision of bankside storage at the abstraction point before the water is fed into the treatment plant. If a model were employed to assist management in making its operational decisions, it could be postulated that the volume (and hence expense) of providing bankside storage could be reduced.

The accuracy of the "feel" for the system will be largely dependent on two factors (i) the validity of the assumptions that have to be made and (ii) the quality of the basic data fed into the model. It follows that the quality and quantity of the input data should be the best that the available resources of time and money can provide, bearing always in mind the desirable accuracy of the results.

(b) Operations. At present, the wholesomeness of water that has been subjected to pollution and which is to be abstracted for public supply is demonstrated by having a thriving fish population upstream of the abstraction point. Observations of the fish population are, of course, backed by frequent and regular chemical analyses. As has been suggested in an earlier section it would be an advantage to be able to control, partially at least, water quality in the river and thereby to reduce variations in it at the abstraction point. Practical methods of achieving such reduction were discussed. In a properly managed river section, the optimization of water abstraction, effluent discharge and the river condition itself are best achieved by the use of operational models.

Moreover, the output from such models could be used as the input to other models, for instance those used for the control of pumps feeding a pumped storage reservoir. This would enable the best quality water to be abstracted at the maximum rate subject only to the physical constraints of the system and to the provisions of the electricity tariff and the necessity to leave a minimum residual flow in the river.

Also, the model could provide warning of the impending arrival and perhaps duration of poorer quality water thus allowing abstraction to be minimized during the period of the passage of the poor quality water past the abstraction point. But this is beginning to stray into the third category of models.

(c) Forecasting. Forecasting may be short- or long-term. It is usual to base the short-term forecast on probabilities while long-term forecasts are based on the extrapolation of past trends, assuming that certain factors remain constant. While many models dealing with long-term forecasting have been developed, the use of short-term forecasting models is less widespread because the demand for an operational model has not existed hitherto. However, times and circumstances are changing and it can be prophesied (with caution!) that there will be a slow but steady increase in the demand for this type of model.

In summary, mathematical models of water quality with appropriately stated objectives, properly specified and with a clear understanding of the assumptions and constraints under which they operate are, or will become, an indispensable aid to the complex task of managing water quality in both the long- and short-term.

The modelling techniques are already available, the data have been or can be collected, all that remains is--and this may be the biggest hurdle of all--a crisis of confidence between the model maker and the model user. This is basically due to a lack of understanding of modelling techniques by the user, and, moreover, a distinct lack of desire to learn about them. It is also a failure, at least in part, by the model maker to explain in terms which are within the experience of the user (thereby enabling him to relate with the model) how his model is constructed and works.

7. CONCLUSIONS

The concept of time variable water quality management seems to induce one of two reactions in those who are currently involved in water quality management. Either they think that, while it has no relevance in their situation, they can appreciate its conceptual niceties, or alternatively, they claim that perhaps with slight extensions, it is no more than the setting out formally of what they practise intuitively or have arrived at through long years of experience. Either reaction amounts to a display of resistance to the acceptance of the different perspectives suggested in the total systems approach. This can only be overcome by patience and persistence (but not annoyance) and a readiness to seize any opportunity to implement the concept when the occasion arises.

If the approach advocated in time-variable water quality management is followed it will at least ensure that all possible avenues are explored in the exercise of operational water quality management; at most it will achieve much more.

The importance of the data gathering/information system necessary to make time-variable water quality management effective cannot be over-emphasized. Management should recognize the fundamental necessity of commissioning a reliable, robust data gathering, processing and retrieval system which will satisfy its needs for information and on which it can rely and act.

Time-variable water quality management is capable of producing beneficial effects in the river itself hence improving its recreational use potential. It may benefit downstream abstractors by minimizing the adverse effects on them of upstream discharges. Furthermore, it helps to discharge the moral, if not legal, duty of management to improve the quality of the environment whenever and wherever possible.

It is concluded that mathematical models have a valuable role to fulfill in assisting management to decide between alternative policies and strategies; that they can have a good benefit/cost ratio; that they can be of practical help to management and that mathematical models, appropriate for the purpose for which they are intended, should be a weapon in the armoury of all forward-looking management.

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INSTITUTIONAL AND PRACTICAL CONSTRAINTS ON TIME-VARIABLE WATER QUALITY MANAGEMENT

H. Fleckseder

1. INTRODUCTION

Let me start with some (very) personal remarks. I am a subscriber to the ideas of evolution, that is, that life as a unity and also the life of individuals has its past which determines to some extent the future of life, but which also allows actual decisions ("Chance and Necessity", Riedl, 1976). In relation to myself this means that I am Austrian by birth and grew up in Austria and Switzerland. My academic training as a civil engineer took place in Austria; I also hold an M.S. degree in Environmental Health Engineering from the University of Texas at Austin; I worked for my doctoral thesis--biological treatment of pulp mill effluents--in Austria; and now for roughly six years I have been interested--among other things--in "Planning of Water Quality Management" (in German: Gewässerschutzplanung). My working experience is bound to the region in which I reside (Austria, with contacts to FRG and Switzerland) and in addition, I have access to a number of international journals of my field (UK, USA).

Now you will surely ask: Why do you tell us all this? Is this necessary at all? In response, I would like to say: as I understand it, yes. If you would like to judge and understand how and why I subscribe to certain views, you have to have access to my personal past and the reverse must hold for me towards you and your views. By the same token, I am forced to shape my views according to your experience.

Regarding "Water Quality", I think I have learned that some basic concepts will apply in general, but that the individual features of any region will influence the "state of water quality" and that we have to describe these specific details before we are entitled to compare and judge actual situations. As my topic covers institutional and practical constraints, I am forced to put forward my basic views, but I am also forced to describe the specific, which is inherently linked with the basic.

The starting point for me therefore has to be how I view "Water Quality", what options there are open to "Water Quality Management" and its implementation in time, and what role "institutional constraints" do play at present, for example, in Austria. If you are of the view that my presentation comes from the "practical side", and if you compare or even contrast my views with, say, the ones in the "base paper" (Beck, 1980), it seems to me that "practical constraints" are covered in my paper. You will also recognize some differences in views from "the practical" versus "the theoretical". "Versus" for me, however, is used here not in the sense of "opposing" but "uniting".

2. WATER QUALITY

The wording "water-quality" implies that we project the "state of water(s)" (German: Gewässerzustand) towards a qualitative scale. Let me therefore differentiate between the "state of waters" and "water quality" (German: Gewässergüte). Furthermore, let me develop my views by a hypothetical concept which, as limnologists tell us, is not far from reality (Hynes, 1972). Let us first consider a stream from its origin high in the mountains to its discharge into the sea in an environment where man does not play as important a role in material cycles as he does today. Limnologists were able to observe such conditions and they tell us that the ecology in such a stream varies from the headwaters to the middle reaches and again down to the lower reaches. In the direction of flow there is enrichment with chemical constituents which, in a two-way fashion, influences and to some extent also determines the "state of waters". What we may learn from this concept is that it is hard to say what the "reference state" for "water quality" should look like, as there is change in the direction of flow. If we assume that the limnologists captured the "state of water(s)" along such a stream at a certain point in time of evolution, let us ask what the aim of evolution is in this respect. The answer we receive from ecologists is that evolution approaches a near-stable equilibrium state which is characterized by a minimum in production of entropy. Secondly, let industrialization and urban growth develop and allow for man's increasing dominance in geochemical cycles. From the point of view of global evolution, one may say that, fortunately, industrialization is not yet covering the whole of our globe. The interruption of existing material cycles (for example, disposal of human excreta) and the negligence of creating new ones (for example, disposal of industrial waste as well as disposal of products consumed) has led to the phenomenon of water pollution. Important for the present situation is that the threat to life in our waters is not so strongly related to the discharge of biodegradable matter or constituents determining phototrophic growth, but that compounds are released and dispersed into nature which in the long run may be mutagenic and may therefore completely alter the path of evolution. We should have in mind that no reliably controlled experiment is possible in this field and that only the passage of time will tell the outcome. These micro-pollutants, for which hardly any common measure exists, may have macroscopic effects; by the same token, the negative influence of biodegradable matter and of nutrients discharged to our waters is not denied and I am fully aware of the fact that appropriate countermeasures have to be conceived and, in fact, are at present already in operation (for example, source-load reduction and wastewater treatment). The picture is not yet complete. In order to conceive any countermeasure--that is, to "Manage Water Quality"--be it by technological or administrative paths, requires us to know not only what kind of substance will have what kind of effect, but we also have to know how and by what route that specific substance enters the water environment.

In Table 1 I again try to describe what discharges of matter exist, what sources and what effects in the receiving waters they have and what countermeasures are required at present. Figure 1, for which I am indebted to Roberts (1974), tries to show what interactions there are between man, man in nature and the existing institutional constraints. The more point sources are taken care of by technological solutions (for example, production process modification, wastewater treatment) the more important the influence of diffuse discharges on the "state of water(s)" becomes.

I think Table 1 is more or less self-explanatory and a reiteration of views just presented. However, bear in mind that chemical compounds of Group 2 are in nearly all catchments primarily linked with point source discharges, whereas the sources of compounds in Groups 1, 3 and 4 are also of "diffuse" origin in quite a number of catchments. Giger and Roberts,(1978) close an overview paper on "Characterization of Persistent Organic Carbon" by stating that

> ...In future work, emphasis should be given to obtaining quantitative data on compounds of suspected environmental or health significance rather than to expanding the already extensive list of compounds identified in waters. There is an urgent need for quantitative information concerning the occurrence, sources, pathways, and ultimate fates of selected organic micro-pollutants in the aquatic environment. Research of this sort is complementary to research on health and environmental effects... .

Moreover, it is important to realize that low levels of dissolved oxygen (DO), which in turn are caused by the introduction of biodegradable carbon and ammonia into flowing waters and by eutrophication (that is, in most cases excessive input of phosphorus) in lakes, is only one facet of "water quality". Thus, modelling DO-BOD-(algae)-interaction, for instance, constitutes only the modelling of one part of the overall unity of water quality. (We should therefore never equate "part" with "whole", yet we are always able to understand "the entire" only in its various "parts").

Table 1. Important parameters for the characterization of aquatic ecosystems and water quality (according to Wuhrmann, 1974, but altered somewhat by H. Fleckseder).

Class of chemical compounds	Examples/Sources	Dominant effects in the ecosystem 'water'	Requirements for elimination
1. Inorganic Most important nutritional ions and trace elements for phototrophic and lithotrophic organisms.	Resorbable compounds of N, P, K, Ca, Fe, Mn, and additional elements; carbonate, bio-oxidisable compounds (S^{2-}, Fe^{2+}, H_2, NH_4^+, NO_2^-). Domestic and industrial effluents, transport from land and via air.	Production of phototrophic and lithotrophic biomass. (The energy required by the organisms originates from the sun or chemical energy.)	The biomass formed can e.g. endanger the oxygen balance of lakes, estuaries and also seas, and therefore these compounds should be removed as far as possible.
2. Organic Substrates rich in energy; essential organic compounds.	More or less easily biodegradable compounds ('BOD'); vitamins. Domestic, industrial and agricultural sources. Degradation of dead phototrophic and lithotrophic biomass.	Organotrophic primary production of biomass (bacteria, fungi).	Effects on O_2-balance of waters; should be eliminated as far as possible.
3. Inorganic and organic Biologically active, but quantitatively without importance on the production of biomass. Partially not metabolizable.	Nonmetabolites governing pH and redoxpotential. Heavy metals and organic compounds with cumulative effects. Complexing agents. Direct (effluent) and indirect (application) industrial (in the broad sense) sources.	Alteration in the competition between species. Selective effects.	As far as possible and also complete elimination required.
4. Inorganic and organic Non-metabolites, biologically inert.	Biologically inert, recalcitrant compounds (salts and organic compounds). Domestic and industrial effluents, transport from land and via air.	Possibly without ecological effects. For the technical utilization of water, however, it is of importance.	The degree of elimination required depends on further water usage.

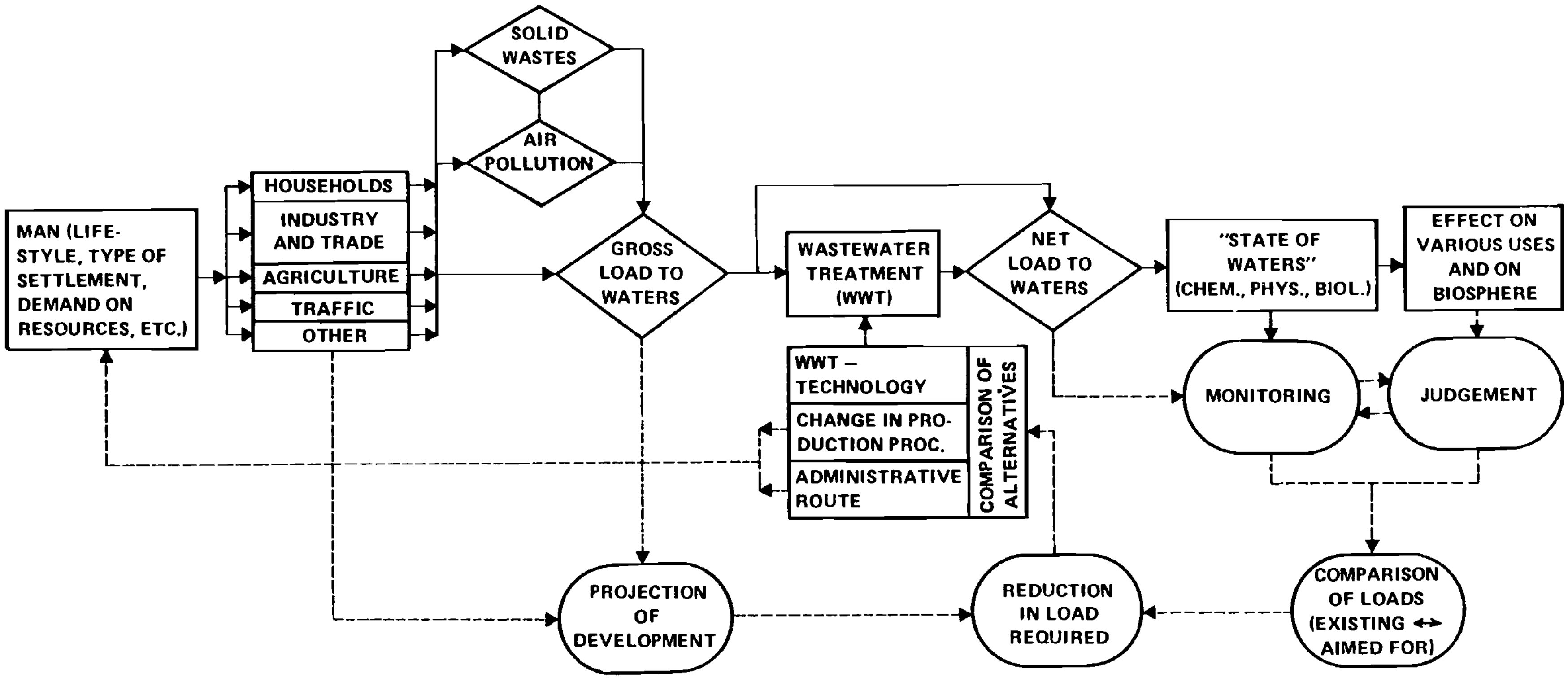


Figure 1. Interactions between man, man in nature, and existing institutional constraints (after Roberts, 1974).

This addition to Table 1 is also the main theme of Figure 1. Man, with his demand on the gifts of nature and his inability to directly recycle the matter he uses, discharges matter directly (via sewers) or indirectly (transport via air) into the waters of a catchment. The directly discharged materials can be reduced by wastewater treatment, while the indirectly discharged materials are reduced mainly by a change in behaviour.

3. WATER QUALITY MANAGEMENT

If "management" is understood as "the judicious use of means to accomplish an end", we find ourselves clearly at the center of the topic. The "end" is to attain a "state of waters" which approaches, to varying degrees, the state of "natural conditions", where again this last expression encompasses such a state in which the influence of man on geochemical cycles is greatly reduced. Why should this be so? The bioenergetic basis of ecosystem development has been documented by many ecologists (for example, Margalef, 1968; Odum, 1971). The more diversified a system is the more resistant it is towards external perturbations. The trend in (natural) evolution therefore goes from unstable to stable, from homogeneous to heterogeneous, from metabolic waste to metabolic economy, from few energy pathways to multiple ones, from a food chain to food webs, niches and symbiosis, and from high entropy to low entropy, despite the fact that production of biomass is high in both systems according to Stumm and Stumm-Zollinger (1971). They conclude their paper with the following:

> In the last hundred years, man has attempted to master his environment by applying ever increasing power, despite a lack of understanding. Appreciation of the various physical, chemical and biological factors that regulate the composition of natural waters provides a basis for a more general formulation of pollution. In view of man's inability to adapt to major environmental changes, pollution may be equated with disturbance in ecological balance and loss of stability. Because various kinds of disturbances cause similar and reasonably predictable changes in aquatic ecosystems, various means of water pollution control beyond those of waste treatment can be outlined. The stress imposed upon the environment results primarily from the fact that the western [today: "northern", HF] way of life is dependent on high energy utilization; but continued unlimited growth in energy dissipation is incompatible with maintenance of ecological stability and high quality of life. The ecological constraints demand the alteration of human, social and economic systems towards a stationary state, where matter has to be recycled as much as possible.

In a later paper, Stumm and Davis (1974) state in addition that the cycles cannot be completely closed and that in (total) recycling, the energy input necessary--both from a demand as well as from a dissipation (increase in entropy) point of view--limits recycling. However, recycling is a necessity. Georgescu-Roegen

(1971), an American economist of Rumanian origin, has for more than a decade now tried to tell his fellow economists that evolution, the entropy law and the economic process are inherently one whole and that the profession of economists should depart from staying within formal theories. He also concluded that, in contrast to present opinion, economics as a field of knowledge can only survive if economists shape their views on ecology, that is economics is in dialectical fashion "contained" in ecology.

Having discussed "the accomplishment of an end", I have to shift to "the judicious use of means", that is the tools of water quality management and their application in space and time. When I presented "water quality", I more or less automatically had to mention wastewater treatment, modification of production processes, administrative measures, the task of monitoring and judging the "(physical, chemical, biological) state of waters", of setting up permissible (point) source discharges, and other aspects such as these. Some additional measures of "Water Quality Management" are compiled in Table 2 (after Stumm and Stumm-Zollinger, 1971).

The application of these measures in space and time call for a topic that can be named "Management of Water Quality Planning". It seems to me that a general discussion of this topic is not meaningful. However, certain general features should be presented first before I describe under "Institutional Constraints" some problems from my experience.

In any comprehensive planning study, the subject of that study should be described first. Although not true in every case, one can say that in more densely populated areas the "(physical, chemical, biological) state of waters" and "water quality" are determined primarily by the loads of various kinds (matter, heat, radiation) that are discharged into the respective waters. In addition, every water body holds at certain points along its course both surface and subsurface drainage areas. For ease of presentation let us assume that both coincide. The loads are caused by "human activity and behaviour", and the consequence of this discharge is a deterioration of the "state of waters" as described previously. If we are charged with establishing a plan for managing water quality in any catchment, it is our task to transform "human activity and behaviour" into loads (matter, heat, radiation) that reach the water course and we have to check what countermeasures should be conceived and implemented. In applied work, we encounter now a first difficulty, namely, all statistical data available are grouped according to political boundaries. For water planning purposes, however, the boundaries to consider are those of the drainage area, and in the cases of lakes and inputs via air, one has to go beyond the boundaries of the drainage area in trying to locate the source of an input.

In reference to Figure 1 we have such a planning study to try to set up the loading within a drainage basin for a certain point in time t_o, and we would do well to distinguish between

Table 2. Some additional measures of water quality management.

Reducing Ecological Stability	Promoting Ecological Stability
Increase of Energy Flow by disposing of nutrients for heterotrophs and autotrophs by mixing (destratifying, sediment dredging, etc.) by heat disposal by imposing turbulence	P-R Balance Restoration by reducing waste input by harvesting or washing out of biomass by reducing relative residence time or by trapping of nutrients by mixing (bringing P and R together) by fish management by aeration
Exploitation of Adjacent Soil by crop growing, seeding, weeding and grazing by fertilizing and irrigating by deforestation by converting grass land into cropland by applying herbicides and pesticides	Conservative Land Management by reforestation by restricting monoculture productivity by zoning (maintaining zones adjacent to open waters which are kept free of fertilizers and of low net productivity) by controlling erosion by using detritus agriculture
Reduction of Structure by using algicides by destruction of niches (removal of reeds) by episodical physical perturbations (flushouts, temperature discharges, shock loadings) by excessive harvesting by disposal of strange chemicals by interfering with chemostasis	Enhancement of Biological Complexity by establishment of ecological niches (zones, waterfront development) by seeding diverse populations and recirculating certain organisms by maintaining relatively high biomass compatible with energy flow by maintaining stratification by selective harvesting by maintaining high chemical buffer intensity (weathering of rocks)

Note: P-R-Balance means "production-respiration-balance" and implies that the phenomena of pollution are not observable as long as production and respiration check one another.

gross loads (that is, all loads dischargeable, irrespective of wastewater treatment) and net loads (that is, all loads discharged, including those treated). Furthermore, we have to distinguish between various chemical parameters (say BOD_5, DOC, COD, TOC, total nitrogen, total phosphorus, total heavy metal(s) etc.) and we are obliged to assess all existing inputs. (We have to have in mind that effect alone, as observed by monitoring in a river, is not sufficient for cure; we also have to know the source and its pathways.) The next step is a transfer of the net loads at t_o into a concentration term, and at this stage the hydraulics and hydrology of the body of water concerned have to be specified. For most cases, drought conditions will be appropriate for dissolved components. (From observation on many rivers in (central) Europe that have been impounded for hydropower generation and navigation, however, we know that the worst total concentrations exist during the rising limb of a flood. This dynamic problem is, however, not yet amenable to a quantitative analysis.) The estimated (and maybe also observed) concentrations under low flow conditions have to be compared with the desired reference state and this comparison determines the action to be taken.

So much for general remarks. In order to discuss the present situation in central Europe (Austria, southern Germany, Switzerland), let me mention that dilution in the recipients is at low flow conditions in most drainage basins tenfold over the flow of waste waters discharged. In Austria we have succeeded in establishing full biological wastewater treatment (a sludge age of 4 days) as a general rule. Wuhrmann (1969) has shown in his work that dilution is absolutely no lasting solution for combating pollution and that the self-purifying capacity of a river is greatest in the most polluted, but still aerobic, reaches.

Stundl (1975) reported that in "Wassergüteklasse II" ("category of water quality 2"), according to the saprobic system used in Austria, the energy utilized by heterotrophs is 250 J/ (m^2 of wetted area of recipient) (day) whereas in "Wassergüteklasse IV", still under aerobic conditions, this figure is as high as 12,600 J/(m^2.day) and of the same size as the incoming radiation from the sun. This in turn means that if we would like to have clean recipients with life existing at a near-natural state, the self-assimilative capacity by the heterotrophic pathways is so small that it has to be neglected. A doubling in the effluent load discharged from a treatment plant will influence the direct downstream concentration by 10 per cent under such circumstances, and this figure seems to me to be in the order of accuracy of a monitoring network. Therefore real-time management of water quality under the conditions within most of the central European drainage basins will mean the gradual (year-by-year) approach towards a near-natural state of waters. The situation becomes drastically different as soon as the amount of flow available for dilution decreases. If the flow in the recipient equals the effluent discharged, a doubling of the effluent load will increase the concentration by 100 per cent and this figure can be detected very well by a monitoring network. The implementation of real-time management of water quality in such cases will therefore strongly be enhanced by a telemetered monitoring network that links the recipient with the hour-to-hour operation of wastewater treatment plants. The approach to a near-natural state of waters may be quite impossible.

Regarding wastewater treatment (which is a topic I have studied throughout my professional career) I hold the view that those methods should be applied that are as advanced as possible. But the next question is: which methods are really advanced? Antonucci and Schaumburg (1975) compared the primary, primary plus secondary, and finally primary through tertiary treatment requirements for energy and raw chemicals together with the various contaminants produced by the treatment processes specific to one million US gallons of the plant at South Lake Tahoe. They concluded that

> ...the advanced wastewater treatment facility at South Tahoe effectively removes organics and nutrients from domestic wastewater. It was found, however, that the application of these sophisticated treatment operations requires a significant input of energy and treatment chemicals. [Here let me add that in going from secondary to tertiary treatment, total energy use triples and the processed chemicals applied increase at least 50-fold, HF] Furthermore, several types of contaminants are discharged to the land and air phases of the environment as a result of the treatment operations. There are also secondary or indirect impacts associated with the production of treatment chemicals and the generation of energy by various support industries that are attributable to wastewater treatment at South Tahoe.

Although I stressed the importance of bioresistant pollution, I am of the opinion that the best way to avoid this is to try to generate as small an amount of bioresistant pollution as possible. What we have to be mindful of at present with sewage is the desire for a quite stringent reduction in organic carbon and phosphorus and the oxidation--if not also reduction--of nitrogen ($2NH_4\text{-}N \rightarrow 2NO_3 \rightarrow N_2\uparrow$). (Nitrification can in many cases be required due to the needs of the receiving waters, whereas controlled simultaneous denitrification will improve mainly the discharge of effluent suspended solids). All this can be accomplished by single and multi-stage biological-chemical treatment. Table 3 is intended to present some treatment sequences, the effluent quality thereby obtainable as well as the relative total cost for a plant size of 50,000 population equivalents. The base cost in Austria for process sequence (1) is at present AS 140 for average conditions. It includes construction (civil, 35 service-years; mechanical/electric, 12 years) at a preference rate of the national economy of 8 per cent per annum including inflation, operation (electricity, labor, materials) and maintenance. When looking at Table 3 it may be apparent that the process configuration (3) is less expensive that that under (2). Design (3) is basically a single-stage activated sludge system with a sufficiently long sludge age to provide for nitrification and built-in anoxic zones in which denitrification occurs.

Table 3. Treatment processes and effluent quality obtainable.

For 1 Population Equivalent	Susp.Solids g/d	BOD_5 g/d	TOC g/d	total N g/d	total P g/d	Relative Cost Estimates
Raw Water	90	60	32	10	4.0	-
(1) Effluent from "Full Biological Treatment" (Single-Stage AS, t_s=4 d)	4	4	4	7 (NH_4-N)	3.0	1.00
(2) Nitrified Effluent (Single-Stage AS, t_s=9 d)	4	3	3	7 (NO_3-N)	3.0	1.02 - 1.08
(3) Nitrified/Denitrified Effluent (Single-Stage AS, t_s=9 d)	4	3	3	1 (NO_3-N, NH_4-N)	3.0	1.00 (most cost-effective design among alternatives (1) through (3)).
(4) Nitrified/Denitrified Effluent with Simultaneous Precipitation (Single-Stage AS, t_s=9 d)	4	3	3	1 (NO_3-N, NH_4-N)	0.4	1.15
(5) (C+N+P)-Removal by Biological Means only Single-Stage AS, t_s=9 d)	4	3	3	1 (NO_3-N, NH_4-N)	0.4	1.15
(6) Nitrified/Denitrified Effluent with Simultaneous Precipitation + Contact Filtration (Single-Stage AS, t_s=9 d)	1	1	2	1 (NO_3-N, NH_4-N)	0.06	1.50

Operation occurs by "hiking on a ridge", that is, by simply providing for sufficient oxygen transfer for nitrification, but limiting supply such that denitrification is possible. The electron donor required for denitrification in this system is the incoming sewage; an internal high recycle in the aeration tank is necessary. Process configuration (5) is the same as (3), but includes anaerobic zones. Such plants are in operation in South Africa and excellent semifull-scale results have been reported from Israel, but at present it is an open question whether this configuration can be applied in every case. Its advantage over configuration (4) is that neither iron nor aluminium is required in the process, although the investment is higher. In configuration (6), finally, a rapid sand filter follows the single-stage AS system; the effluent from AS is subject to precipitation/flocculation before it enters the sand filter. The results shown relate to sewage as it is generated in central Europe. Where more bioresistant products are discharged, the effluent TOC (and also DOC) will be higher.

In design, construction and operation we are charged with conceiving plants that fulfill present requirements. In most locations in Austria, the present requirement is "full biological treatment". However, I can see that quite rapidly the need to have nitrification, P-removal and also denitrification will be demanded. Therefore, I think that the plant design and plant layout must already at present contain the features just described despite the fact that they will be constructed at a future point in time. Naturally we do not know at present the "exact" path of the future, but the often mentioned remark of "rapid change in technology" is in most cases not more than a step-by-step advance.

In concluding this section, let me state that

(i) Water "does not know" political boundaries.
(ii) Water quality objectives cannot be limited only to certain branches or reaches of a river system, but must reflect the river system as a whole together with the estuary or sea into which the waters discharge.
(iii) Water pollutants are not only transferred via "discrete" domestic and industrial effluents, but also from "diffuse" sources (soil, air).
(iv) Water quality parameters (in modeling: state variables) are multivectorial and no single vector alone represents "water quality".
(v) Proven and not too costly technology is available today to remove biodegradable organic carbon and the bulk of nitrogen and phosphorus from domestic and industrial point source effluents.
(vi) Refractory organic carbon and mutagenic compounds discharged are best regulated by source protection (if possible, to stop the discharge "completely"). In selected areas, treatment will have to include additional steps (for example, adsorption, reverse osmosis, etc.).
(vii) Only administrative countermeasures can be applied in the case of "diffuse" sources.

4. INSTITUTIONAL CONSTRAINTS

The term "Institutional Constraints" implies that there are institutions in the real world that exert forces which cause us to react in an other than rational fashion. "Rational" in this context is looked upon as the ability to comprehend the present and future path of the reality of evolution by reasoning. Again based on my personal experience, which is limited in space and time, there are at present in this (central European) region two groups of fallacies in water quality management.

One fallacy covers all inputs, goes to the heart of the question of quality management and can best be described by "engineering with BOD_5". Thus far water quality management in Austria, Germany and Switzerland is to a large extent equated with the design and operation of wastewater treatment plants. Basically, the civil engineering profession is in charge of designing the sewerage networks and the treatment plants. As I tried to show, wastewater treatment alone is not sufficient and "BOD_5" alone is not an appropriate parameter to describe water quality. In Switzerland, a reorientation of the priorities of water quality management started in 1973 through the input of EAWAG (Swiss Federal Institute on Water Pollution Control, Director Prof. W. Stumm). This reorientation in Switzerland has also come about through pressure from the public, since roughly 70-80 per cent of the Swiss population is serviced by biological treatment (mostly of the type of "full treatment"), yet water quality did not improve as markedly as expected. In the FRG, the "Abwasserabgabengesetz" (Law on Wastewater Levies) and its implementation (starting in the beginning of 1981) have created a tremendous discussion. The parameters taken into account (from point sources only) are settleable solids, COD and acute toxicity. In actual practice, BOD is substituted by COD. In the FRG, roughly 60-70 per cent of the population is serviced by biological treatment. The questions of P-removal are only considered in drainage basins of lakes, and N-removal is not thought to be necessary. Of all three states, the situation is least favorable in Austria, where at present only 40-50 per cent of the population and only a small number of industrial effluents receive biological treatment. Again P-removal is carried out in drainage basins of lakes, and N-removal, despite the developments that our "Institut" undertook at the Vienna-Blumental treatment plant, is not yet regarded as necessary by the authorities.

If you accept this "state of affairs", you will understand that dealing with "diffuse" sources has not yet started at all. The efficacy in practice of various water laws is at present fair to rather weak. As I tried to say in a previous section, it is hard to state in general terms what the contribution of non-point source pollution in every drainage basin is. For one specific case (Lake Neusiedl), we at our "Institut" were able to show that the non-point sources of total P had to be assessed and considered when a wastewater treatment policy on P-removal was formulated (Fleckseder et al, in press). The drainage basin is shown in Figure 2 and the outcome of the study in Figure 3. The estimate for total P from all diffuse sources is 90 t/a at present, of

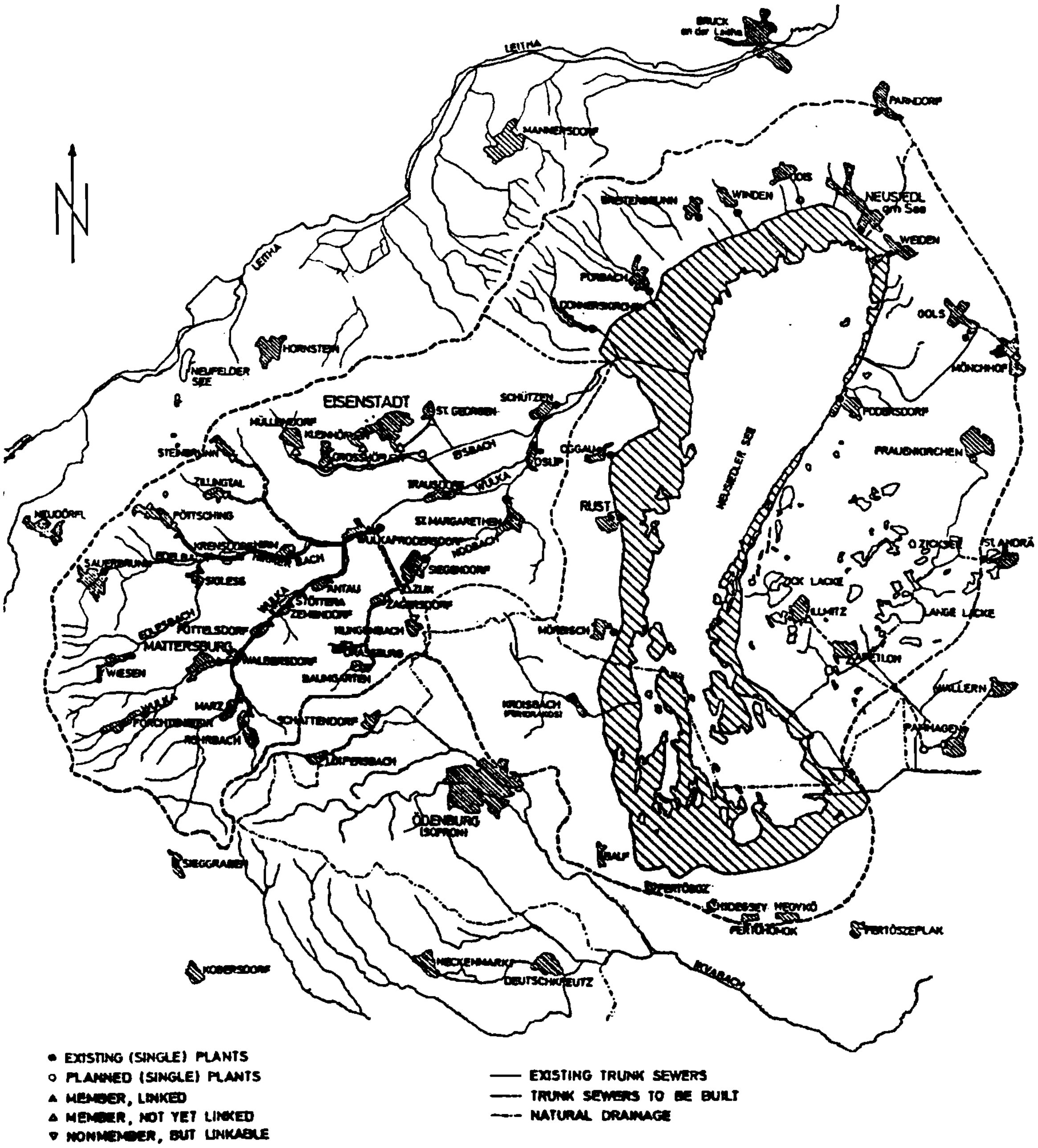
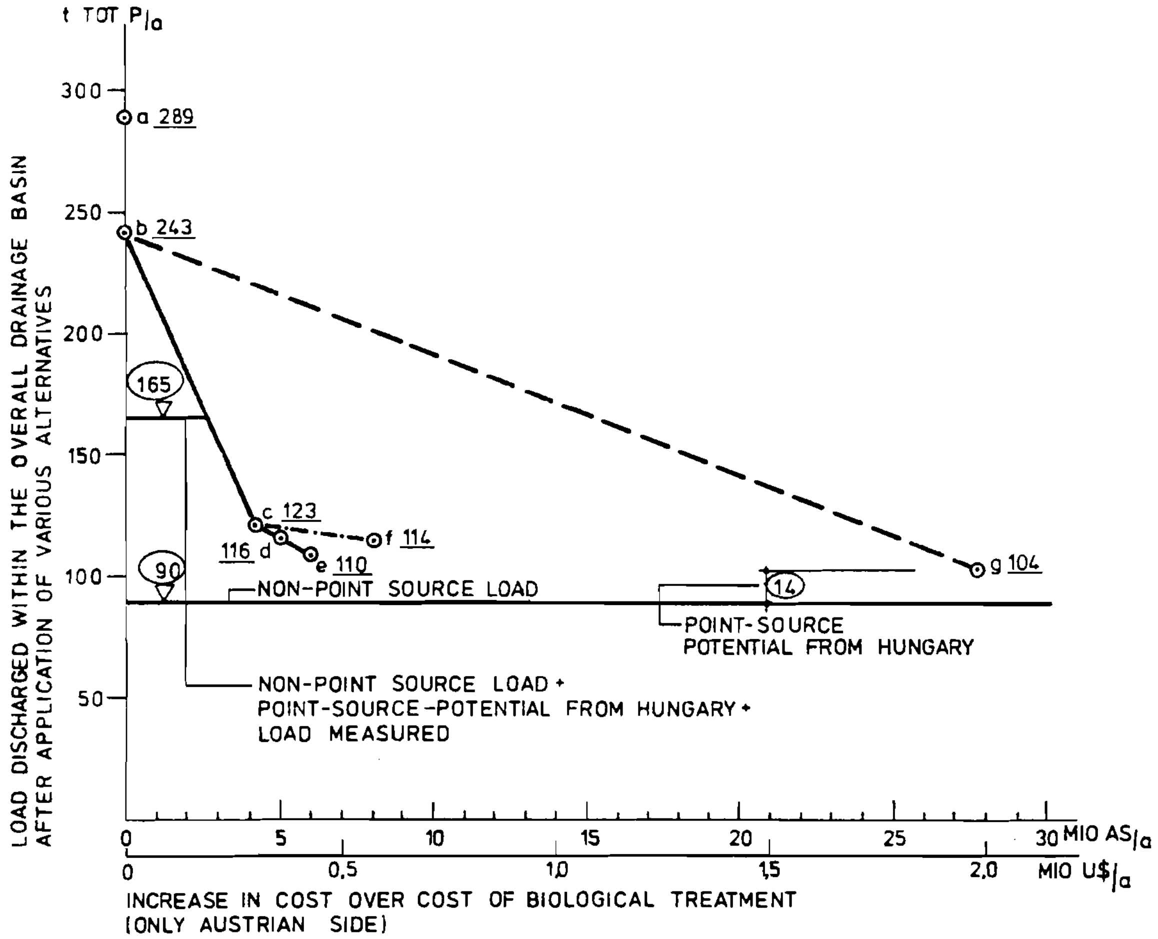


Figure 2. Drainage Basin of Neusiedlersee with Location of Wastewater Treatment Plants.



a GROSS POTENTIAL (POINT AND NON-POINT SOURCES)
b AFTER BIOLOGICAL TREATMENT
c AFTER BIOLOGICAL TREATMENT WITH SIMULTANEOUS PRECIPITATION
d AFTER BIOLOGICAL TREATMENT, SIMULTANEOUS PRECIPITATION AT ALL PLANTS AND HIGH Fe^{+}-DOSES AT REGIONALIZED PLANTS
e AFTER BIOLOGICAL TREATMENT AND SIMULTANEOUS PRECIPITATION WITH HIGH DOSES AT ALL PLANTS
f AFTER BIOLOGICAL TREATMENT, SIMULTANEOUS PRECIPITATION AND CONTACT FILTRATION AT REGIONALIZED PLANTS
g AFTER BIOLOGICAL TREATMENT AND BASIN TRANSFER TO RIVER LEITHA

Figure 3. Pollution Load Remaining over Increment in Cost for Various Alternatives of Advanced Wastewater Treatment in the Drainage Basin of Neusiedlersee.

which 57 t/a are supposed to reach the (very shallow) lake via air and 22 t/a are eroded from land via water. The point-source potential from Hungary was considered, but not included in the policy because this policy should apply only for plants within Austria. It is evident that "biological treatment only" is no option at all for P-removal. However, simultaneous precipitation at high doses of Fe^{+2}/P is a much better choice than, say, inter-basin transfer of the biologically treated effluent. This is because the former is much more cost-effective and much quicker to implement. Simultaneous precipitation has been installed, yet what is to be done in order to cut down the 90 t P/a from diffuse sources is at present still an open question. The causal relationships are not at all as easily understood as in the case of point source discharges. Lake Balaton in Hungary seems to be a similar case.

The second fallacy relates to large industrial discharges, both in the FRG and in Austria. (In Switzerland, despite her highly industrialized economy, large industrial discharges are quite rare). This second fallacy is the often asserted alternative (from industry) between process-linked (internal) and external (wastewater treatment) methods. Industry's statement "either process linked...or wastewater treatment" is moreover somewhat difficult to comprehend from a water quality management point of view because wastewater treatment technology is available, but process modifications still have to be developed. The main industry arguing in such a fashion, both in Austria and the FRG, is the pulp industry. (The human metabolism discharges waste; I cannot imagine that a production process with huge material and energetic inputs will--in one form or another--have an effluent without some matter in it.) Therefore I say that we need both urgently--process modifications as well as wastewater treatment. In implementation, certain process modifications have to be operational and one must be assured that (biological) wastewater treatment plant is not extremely underloaded in the future. However, from the financial point of view of the enterprise, it is better and completely rational that public loans with low interest rates be spent for improving the production process as a whole and for reducing the wasteload discharged to some extent, without having to pay for the running cost of an external wastewater treatment plant that yields no return on its investment.

In concluding this section and my paper, let me add that the human factor is for me the key element to the question of water quality management. When Bruce Beck states in his base paper that every treatment plant is as good as it is run, the same holds for water quality management as I see it. Our task is to realize man's position in evolution and the options we have available in order to comply with evolution. Whether a path chosen is correct or not can only be realized ex post (that is, whether is has been correct or not), and the ex ante decision (prediction) has to be founded primarily on faith.

Since dilution is no longer a solution to pollution, it is not possible to create any environmental quality we wish with the available technologies and energy usage; the energy degraded (an increase in entropy) will have its effects on climate. The questions of water quality are therefore only one side of a many-sided coin and the energy problem is a second side. However, we are forced to know all the sides of that coin and their interrelationships.

Is it not the case that systems synthesis is the task of our time, where synthesis is understood as an accumulated knowledge of these interrelationships? Therefore, let us become not only specialists but generalists as well; and let us try to speak a language (or languages) in which various specialists and generalists together can easily communicate.

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ON THE ECONOMICS OF TIME VARYING RIVER QUALITY CONTROL SYSTEMS

Y. Smeers

1. INTRODUCTION

The problem of river quality management has been discussed extensively in the literature (see Loucks (1976) and chapter 8 of Rinaldi et al (1979) for surveys of the problem). We shall only recall here the basic elements of the problem. A river is considered with a set of polluters who have to reduce their discharge in order to bring the quality of the river to a certain level. The problem is to find the least cost combination of pollution load reductions that will achieve that result. It is common, in such problems, to assume the pollution load to be measured in terms of biological oxygen demand (BOD) and the quality criterion to be expressed by the dissolved oxygen concentration (DO): the relation between dissolved oxygen and biological oxygen demand is usually represented by a system of two coupled linear differential equations of the Streeter-Phelps type (Streeter and Phelps 1925). Various simplifying assumptions are usually introduced in order to tackle the problem. Our objective in this paper is to concentrate on some of those assumptions more specifically related to the operation of the treatment system and to indicate how they could be relaxed at least in some simple cases.

It is common in river quality management models to assume that the treatment system is operated in a steady-state regime, and to require that it allows one to achieve the required quality level for specific low-flow conditions. This is usually done by considering the river model calibrated for such flow conditions: the dependence between oxygen deficit and biological oxygen demand is completely specified for those situations. Because the Streeter-Phelps model consists of a set of linear differential equations, the dissolved oxygen at different locations can be expressed explicitly as a function of the discharged loads using linear relations. A set of constraints is then derived that involves the various polluter discharge reductions and expresses the fact that the quality constraints are satisfied. A cost function is constructed that is the sum, over the set of polluters, of the costs of each individual discharge reduction. The system is then designed so as to minimize the total cost while taking those constraints into account.

This approach presents several defects that can be overcome by taking into account explicitly the time-varying operation of the treatment plants. We first note that the constraint set of the model considers only the treatment requirement during low-flow conditions and does not include any representation of the quality criterion during more favorable conditions. As a consequence it is impossible to take advantage in the model of the fact that, with a given set of treatment plants, the quality target can be achieved at a smaller operating cost during that period of the year when these more favorable flow conditions prevail. All plants are thus assumed to work at a given utilization rate throughout the year, which biases the economic choice of the whole system. An example of the consequence of this bias is that plants with small investment costs and high operating costs, which could be used to level off peak pollution conditions, will be systematically excluded from the analysis. It is also worthwhile to note that the treatment system obtained by the classical approach, while providing over-capacity during a fraction of the year, may also prove to be insufficient as soon as exceptional events occur, such as accidental discharges or forced overflows from some treatment plants. This brings us to the reliability problem, which to the best of our knowledge has never been investigated in relation to river quality management problems. More reliability can be built into the treatment system by installing additional capacity that can be expected to operate for only a small fraction of the year. This is again related to the problem of time-varying operations of the treatment system.

It is the purpose of this paper to introduce some basic notions related to the economic analysis of these problems and to show that time-varying operation in water quality control permits a significant enlargement of the scope of economic analyses of river quality management.

In order to make the presentation as simple as possible the discussion will be presented for a simple example that does not require any development of mathematical programming. Only elementary calculus and probability will be needed. The simplification introduced in this paper by no means implies that the problem discussed here always requires such drastic assumptions in order to be treated adequately. Many of the questions touched upon here can be formalized in a more general way and thus benefit from existing mathematical programming techniques for their analytical treatment. These aspects are discussed in more detail in a companion paper (Smeers 1980).

2. A SIMPLIFIED WATER QUALITY MANAGEMENT PROBLEM

We consider the usual classical river quality management problem where we assume that there exists only one polluter discharge along the river and the quality target is to be attained in one reach only. The problem of finding the best mix of pollutant discharge reductions is then reduced to finding the level of treatment to impose on the single polluter in order to achieve the required water quality in the reach. Clearly this problem does not require any use of mathematical programming techniques. Since the treatment of this elementary problem will constitute the cornerstone of our discussion, we shall dwell on it in some detail.

We suppose that a polluter and the river can be represented as in Figure 1. The dissolved oxygen concentration is assumed to be related to the upstream conditions and to the polluter discharge by a classical Streeter-Phelps model that we write as follows

$$\frac{db}{d\ell} = - K_1 b \quad , \qquad (1)$$

$$\frac{dc}{d\ell} = - K_2 b + K_3(c_s - c) + K_4 \quad , \qquad (2)$$

where - b and c respectively denote the biological oxygen demand and the dissolved oxygen concentration;
- c_s is the saturation concentration of dissolved oxygen;
- K_1, K_2, K_3, K_4 are coefficients;
- ℓ designates the distance from the discharge location to a point along the river.

It is well recognized that c_s and the K_i depend on external conditions such as the flow, the temperature, and the turbulence of the river. If we were to follow the classical approach adopted in water quality models we would assume that we are interested only in certain critical river conditions, and that the treatment system must be designed with respect to these conditions only. Let us assume that these conditions have been selected and that the corresponding K_i and c_s have been evaluated. The system of differential equations can be integrated for those values: let (c^0,b^0) and $(c(\ell),b(\ell))$ be respectively the values of c and b immediately below the discharge and at some point ℓ along the river. Integrating (1) and (2) with (c^0,b^0) as initial conditions, one can write after some obvious manipulations

$$c(\ell) = \alpha(\ell)c^0 + \beta(\ell)b^0 + \gamma(\ell) \quad . \qquad (3)$$

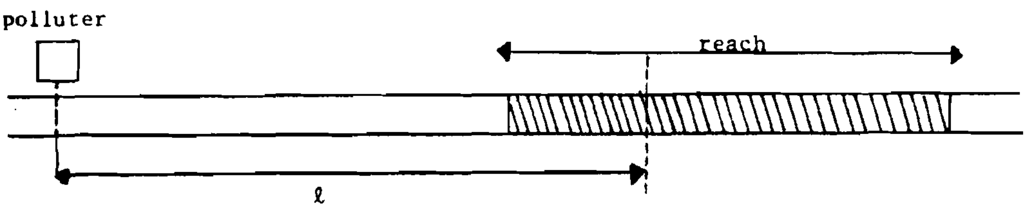


Figure 1. A simplified water quality problem configuration.

Assuming that the upstream biological oxygen demand and dissolved oxygen are known one can write c^0 and b^0 as linear expressions of the dissolved oxygen and BOD concentration of the wastewater discharge. Denoting the biological oxygen demand concentration in the discharge as b^d, (3) can be rewritten, after some minor notational changes as

$$c(\ell) = \alpha(\ell) + \beta(\ell) b^d \quad . \tag{4}$$

This expression directly relates the quality index at location ℓ to the control variable b^d.

The simplified river quality management model can then be stated as the problem of finding the least-cost reduction of b^d that permits $c(\ell)$ to remain above a certain lower limit throughout the reach.

Let ξ be the BOD removal rate at the treatment plant of the polluter and μ the residual BOD expressed as a fraction of the original influent BOD to the plant. Since the treatment cost is a decreasing function of μ, and $\beta(\ell)$ is negative (this can be seen by working out the integration of the model), it is obvious that the minimum cost solution corresponds to the maximum pollution load at the discharge that is compatible with the quality criterion imposed throughout the reach. This problem can be expressed mathematically as

$$\mu^* = \text{Max } \mu \quad ,$$

s.t.

$$\alpha(\ell) + \mu \; \beta(\ell) b^d \geqslant \underline{c} \quad \forall \ell \quad , \tag{5}$$

where $\underline{c}$ designates the minimum acceptable DO concentration in the reach.

The solution of this problem is given by

$$\mu^* = \underset{\ell}{\text{Max}} \frac{\alpha(\ell) - \underline{c}}{-\beta(\ell) \; b^d} \quad . \tag{6}$$

Many undirectional optimization procedures could be used for finding the maximum over ℓ. For practical purposes and for simplifying the presentation we shall assume that the quality criterion is imposed at a discrete set of points along the reach, say $\ell_1, \dots \ell_i, \dots \ell_n$. The optimal value of μ is then given as

$$\mu^* = \max_{\ell = \ell_1, \ldots \ell_n} \frac{\alpha(\ell) - \underline{c}}{-\beta(\ell)\ b^d} , \qquad (7)$$

and the corresponding maximum allowable residual load is equal to $\mu^* b^d$ or

$$\max_{\ell = \ell_1, \ldots \ell_n} \frac{\alpha(\ell) - \underline{c}}{-\beta(\ell)} . \qquad (8)$$

3. THE LOAD CURVE

The river is a dynamic system that can best be described by a set of coupled partial differential equations. In classical design procedures it is usual to adopt a simplified view of the river that singles out one steady-state regime, and to set up the corresponding set of coupled ordinary differential equations. In this paper we shall adopt an intermediate viewpoint and admit a representation of the river that consists of the set of its steady-state regimes: transient phenomena are thus still neglected but favorable flow conditions are represented simultaneously with bad flow conditions. Let ρ be the vector of parameters characterizing a steady-state regime of the river. To each regime ρ is associated a set of values of the river parameters, $K_i(\rho)$ and $c_s(\rho)$.

In the preceding section we have seen that one could compute, for each given steady-state regime, the maximum allowable load in the river as a function of $\underline{c}$. In this paper we shall assume $\underline{c}$ to be given: using the same reasoning as before one can then associate to each steady-state regime ρ the maximum allowable load L. Let $L(\rho)$ be this function. If we now describe the set of steady-state regimes by its distribution function

$$F(\rho^*) = \text{Prob } (\rho \leqslant \rho^*) , \qquad (9)$$

it is possible to describe the acceptable load in the river in probabilistic terms and to construct a curve $p(L^*)$ representing the probability that the acceptable load for the river is smaller than or equal to L

$$p(L^*) = \text{Prob } (L(\rho) \leqslant L^*) . \qquad (10)$$

$p(L^*)$ will be called the <u>distribution of the acceptable load</u> or, for notational simplicity, the <u>load curve</u>.

The simplest example of a load curve is the case where ρ consists of only one parameter such as the flow. In order to illustrate the construction of a load curve for this case, we consider the hypothetical river defined in Appendix 1 of this paper. This river is constructed on the basis of a case study given in Rinaldi et al (1979). Making the assumption that ρ consists only of the flow we define $\{\rho_j | j=1,...J\}$ to be the set of possible flows (see Table 1) and Π_{ρ_j} to be their probability of occurrence. To each ρ_j one can associate the maximum allowable load $L(\rho_j)$, which also occurs with probability Π_{ρ_j}. The load curve is then derived trivially from the definition. It is given in Figure 2 and additional relevant data are provided in Table 1. Flows are expressed in $10^3 m^3$/day and acceptable load in kg BOD/day.

The simplified load curve that we have just defined can be extended in several ways to include phenomena that are not usually taken into account in planning procedures.

Let us take as an example of these phenomena the uncertainty in the coefficients of the river model. A commonly heard criticism against the use of river models is their sometimes poor predictive power, which does not provide a sufficiently sound basis for design purposes. This criticism may lose much of its relevance if the design procedure explicitly takes into account this weakness of the models. In order to illustrate our point we shall assume that the defect of the river model arises from the uncertainty in its coefficients. We shall also assume that this uncertainty can be represented by the probability densities of the coefficient distributions. Taking again the Streeter-Phelps model we shall suppose that the $K_i(\rho)$ are only known in probability for each ρ. It is then clear that the $\alpha(\ell;\rho)$ and $\beta(\ell;\rho)$, which are explicit functions of the $K_i(\rho)$, are also random variables. Let $\bar{K}_i(\rho)$ be the expected value of the vector $K_i(\rho)$, and $\nu_i(\rho)$ be the random variable expressing the deviation of $K_i(\rho)$ with respect to $\bar{K}_i(\rho)$. We assume the $\bar{K}_i(\rho)$ and $\nu_i(\rho)$ to be known explicitly. Let $\nu(\rho)$ be the vector of the $\nu_i(\rho)$. To each pair $(\rho,\nu(\rho))$ is associated a maximum allowable load in the river. Let $L(\rho,\nu(\rho))$ be this load. If the distribution of $\nu(\rho)$ is known, it is possible to extend the preceding definition of the load curve so as to take into account the effect of the uncertainty in $K_i(\rho)$, and to define the function

$$p(L^*) = \Pr\ [L(\rho,\nu(\rho)) \leqslant L^*] \quad . \tag{11}$$

This describes the load acceptable by the river, taking sumultaneously into account the existence of several steady-state regimes for the river and the inevitable inaccuracy in the estimated model parameters.

Table 1. Characteristics of the hypothetical river.

	frequency	Π_{ρ_j}	Flow rate ρ_j $10^3 m^3/d.$	μ^*	L_ρ kg BOD/ day
1	6	.0333	36.12	75.68	2733.84
2	45	.250	49.55	68.21	3380.63
3	19	.1055	70.81	60.73	4300.76
4	11	.0611	88.64	56.49	5007.90
5	10	.0555	107.0	33.195	5691.91
6	4	.0222	129.32	50.087	6477.36
7	13	.0722	149.28	47.869	7145.90
8	9	.05	171.01	45.869	7844.15
9	7	.0388	190.62	44.339	8452.09
10	5	.0277	209.62	43.048	9023.76
11	10	.0555	228.972	41.886	9590.67
12	4	.0222	245.175	41.0106	10054.79
13	8	.0444	270.08	39.8075	10751.22
14	3	.0166	283.10	39.2367	11107.92
15	1	.0055	312.0	38.087	11883.27
16	3	.0166	331.66	37.3847	12339.015
17	2	.0111	351.30	36.7367	12905.63
18	3	.0166	368.30	36.2142	13337.72
19	3	.0166	388.56	35.6324	13845.33
20	2	.0111	417.65	34.8657	14561.41
21	3	.0166	432.13	34.5095	14912.60
22	1	.00555	472.90	33.589	15884.277
23	1	.00555	513.80	32.7673	16835.87
24	1	.00555	531.90	32.4313	17250.24
25	1	.00555	632.60	30.8082	19489.306
26	1	.00555	645.30	30.6283	19764.475
27	1	.00555	699.50	29.9109	20922.71
28	1	.00555	717.30	29.6915	21297.70
29	1	.00555	720.90	29.6479	21373.23
30	1	.00555	865.80	28.1075	24335.48

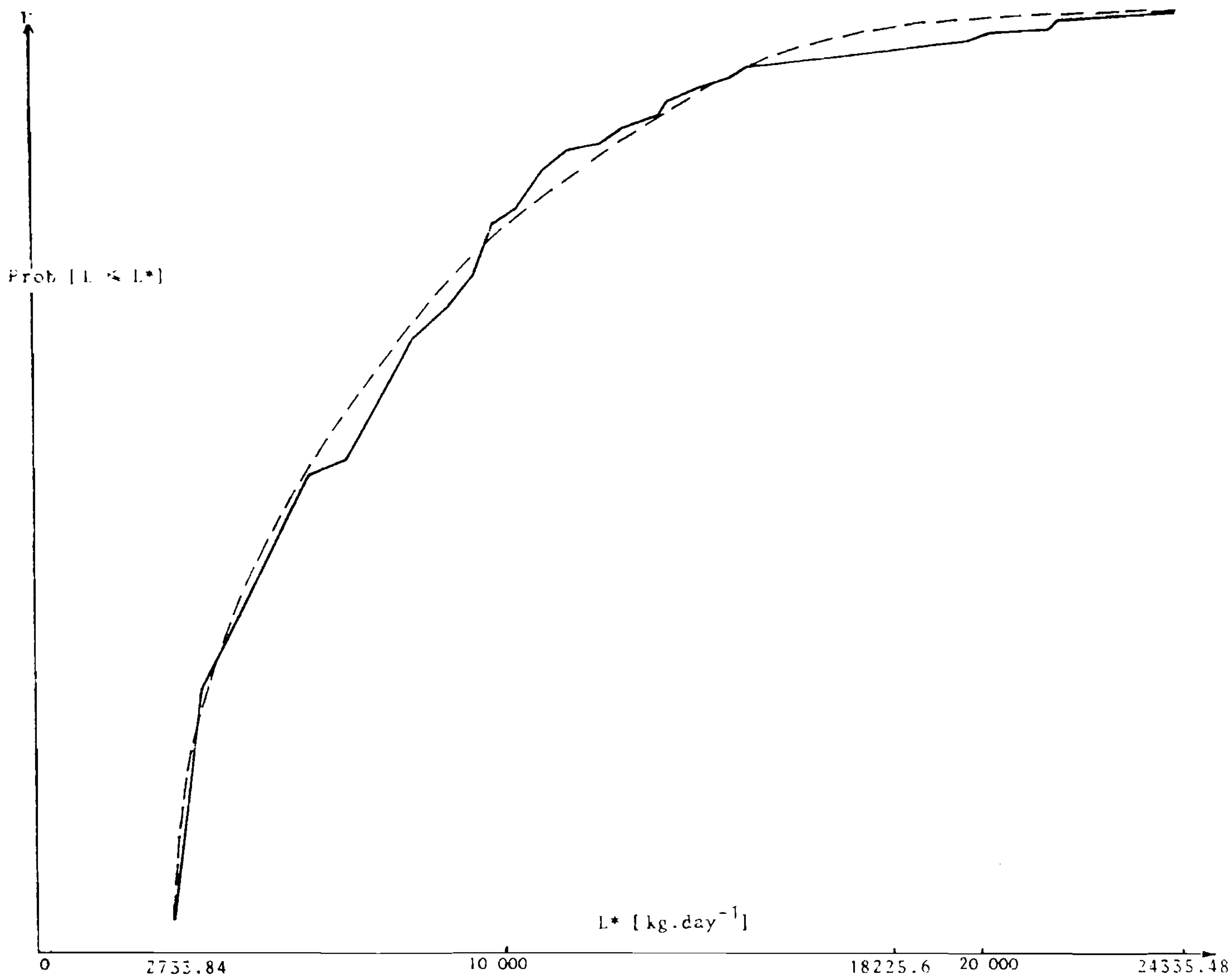


Figure 2. Load curve.

We shall now give an example of this construction based on the river model presented in Appendix 1. For our purpose we shall assume that $\nu(\rho)$ is a vector of independent normal variables of zero mean and given standard deviation. Because of the complexity of the analytical expressions it does not seem feasible to derive the distribution of the acceptable load analytically. We shall instead resort to a Monte Carlo simulation. A set of $\nu(\rho)$ has been selected at random and for each of them the acceptable load $L(\rho,\nu(\rho))$ has been computed. A conditional load curve,

$$p(L^*|\rho) = \Pr\ [L(\rho,\ \nu(\rho)) \leqslant L^*(\rho)] \quad , \tag{12}$$

can then be computed. The desired load curve is then obtained as

$$p(L^*) = \sum_{j=1}^{J} p(L^*|\rho_j)\ \Pi_{\rho_j} \quad . \tag{13}$$

This computation is illustrated in Figure 3. In this illustration, we have assumed a sample of one hundred different vectors $\nu(\rho)$ for each of the thirty flow regimes considered. The corresponding μ^* has been computed for the corresponding cases, and the load curve evaluated accordingly. Since the procedure is cumbersome, although straightforward, the details of this computation are not given here.

The reader will easily convince himself that other phenomena can be taken into account using the same framework. As a last example we shall consider the case of accidental discharges. Since Streeter-Phelps models are linear differential equations, discharges have additive effects as long as one remains in aerobic conditions. It is thus possible to represent any accidental discharge by an equivalent load at the outfall of the polluter. Let b_k, $k = 1, \ldots K$ be the equivalent loads of these accidental discharges and Π_{b_k} be their probability of occurrence. We define $k = 0$ to be the non-accident situation, and

$$\Pi_{b_o} = 1 - \sum_{k=1}^{K} \Pi_{b_k} \tag{14}$$

to be its probability.

As above, we can define a conditional load curve $p(L^*|b_k)$ that gives the distribution of the maximum acceptable pollution load in the river when the accidental load is b_k. We clearly have

$$p(L^*|b_k) = p(L^* - b_k) \text{ for } L^* \geqslant b_k \quad . \tag{15}$$

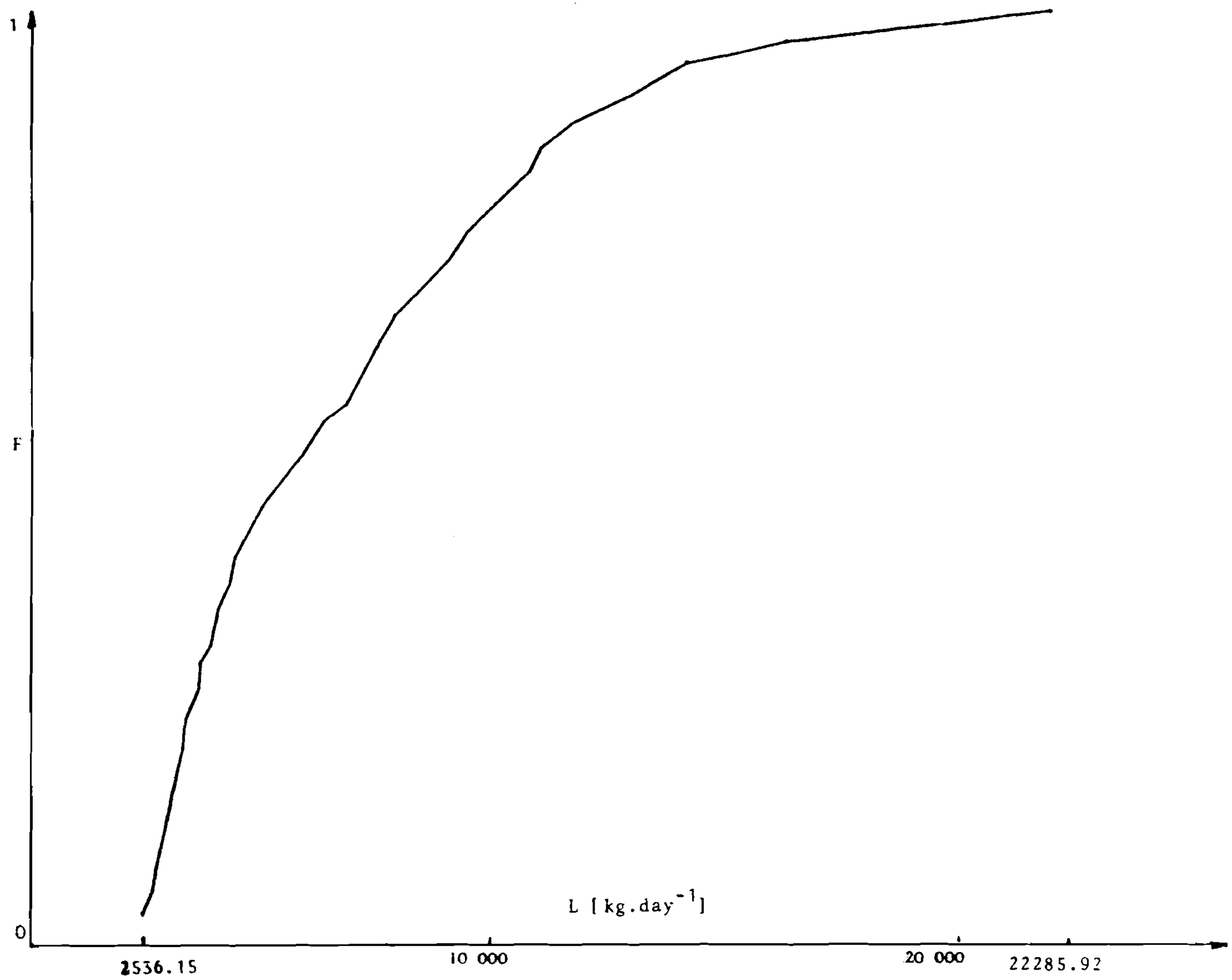


Figure 3. Load curve taking into account the uncertainty of the coefficients.

It is obvious that b_k may be such that the quality criterion cannot be guaranteed with certainty throughout the year. Let L^{min} be the maximum load that can be discharged without interruption throughout the year. (It can be noted from Figure 2 that in our example L^{min} is equal to 2734 kg/day.) It is clear that the quality criterion will be violated with a nonzero probability if

$$b_k > L^{min} \quad . \tag{16}$$

In those conditions the overall probability that the quality criterion will be violated because of discharge k is then

$$p(b_k)\ \Pi_{b_k} \quad . \tag{17}$$

Combining these expressions, we obtain for the new load curve

$$p(L^*) = \sum_{k=1}^{K} p(L^*|b_k)\ \Pi_{b_k} \quad , \tag{18}$$

and for the probability that the quality criterion be violated

$$\sum_{k|b_k > L^{min}} p(b_k)\ \Pi_{b_k} \quad . \tag{19}$$

An example of this construction is given in Figure 4 where we have computed the load curve associated with the two following accidental discharges: b_1 = 5000 kg/day of BOD with probability 1/10;

b_2 =10000 kg/day of BOD with probability 1/10.

It can be noted that the value of the function at the origin is the probability that the quality criterion will be violated, whatever the treatment at the polluter's outfall.

4. THE OPTIMAL TREATMENT SYSTEM

The simple problem defined in section 2 has an obvious solution when treated in the usual sense: the quality criterion corresponds to a maximum allowable pollution load and the plant must be designed so as to reduce the current discharge to that maximum tolerable level. The plant selected is the one that gives the minimum total investment and operating cost. We have seen previously that the classical formulation of the problem does not provide any information that permits an adequate

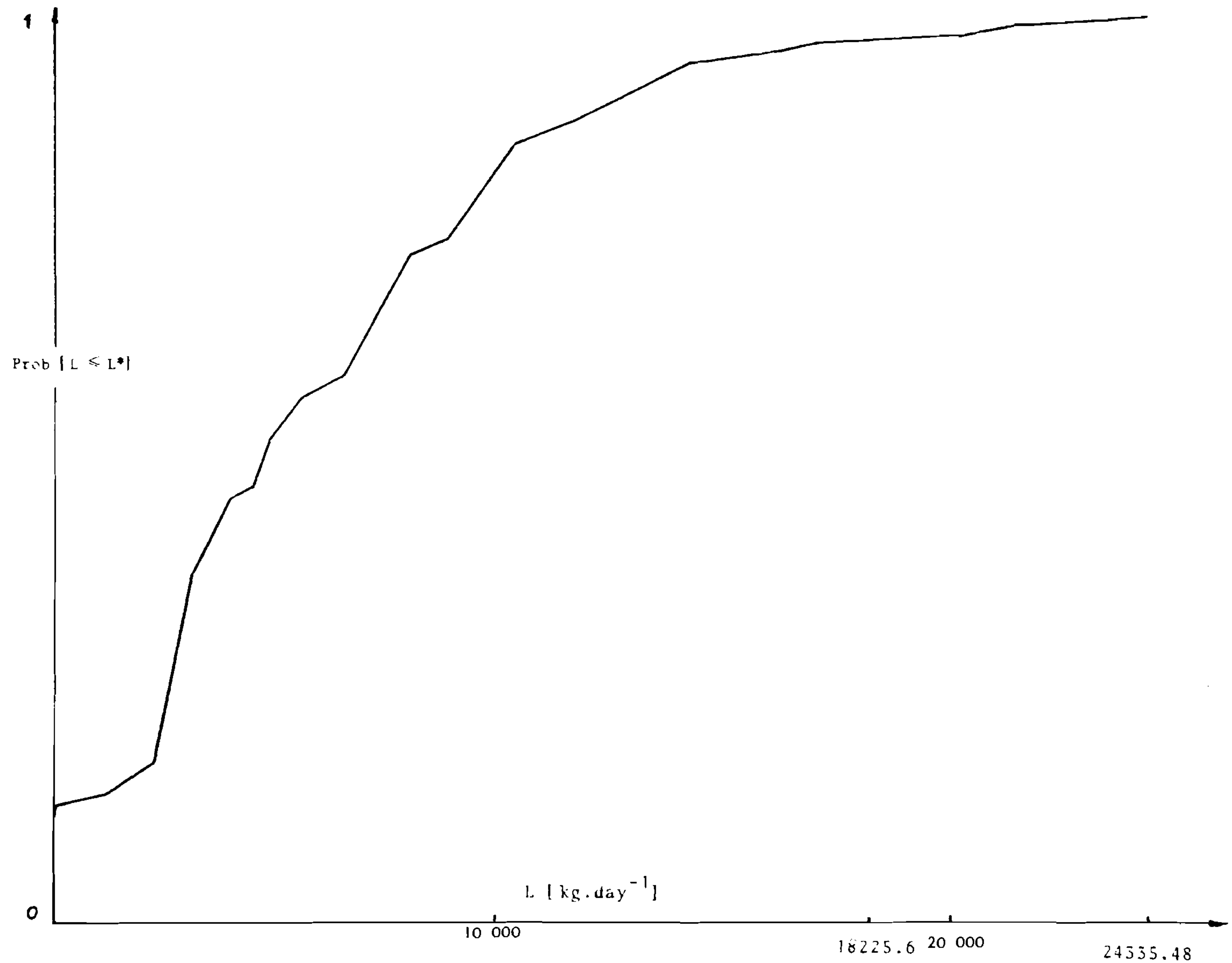


Figure 4. Load curve with accidental discharges.

evaluation of the operating costs. Assumptions must thus be introduced about the number of operating hours of the treatment plant in order to obtain an ad hoc estimate of the operating costs, and hence of the total cost. The choice of the system is then made on these costs, which are obviously somewhat arbitrary.

The problem is no longer as simple when we consider the more complete description of the maximum allowable pollution represented by the load curve. Indeed it is now explicitly recognized that the BOD removal rate required to guarantee the water quality target is no longer constant through time. Cost minimization will then require, at least to some extent, an evaluation of time-varying operation of the treatment plant. To the best of our knowledge, the economics of time-varying operation of treatment plants has never been investigated, and hence little information is available on which to base our reasoning. The following discussion deals with this question at a conceptual level, and a companion paper (Smeers and Tyteca, 1980) gives a more realistic investigation of the problem. A model of a treatment system allowing for time-varying operation must be constructed. The simplest situation is clearly that where one type of technology is available. The treatment plant is designed so as to permit the maximum treatment level represented on the load distribution curve, and cost minimization is achieved by always operating the plants at the minimum level compatible with the load that can be accepted by the river.

Various treatment technologies exist, however, and can be combined and operated in several ways. Since no model describing these different technological possibilities seems to be available yet, we shall adopt two conceptual representations of a treatment system. These representations are based on the combination of two technologies in various proportions. They are used here because of their tractability and not because of their realism.

Before going into this discussion we shall reformulate the load curve in a somewhat more usable form. We recall that L^{min} (when it exists) designates the maximum load that can be assimilated by the river throughout the year while maintaining the desired quality level. We let

$$L^{min} = \mu^{min} b^{d} \quad . \tag{20}$$

It is clear that the maximum removal rate required from the treatment plant is equal to

$$\xi^{max} = 1 - \mu^{min} \quad . \tag{21}$$

For our purpose we shall consider the load curve given in Figure 2. We recall that L^{min} is equal in this case to 2733.84

kg/day. As discussed in Appendix 1, we suppose that this load can be achieved after a maximum 85 per cent removal rate of the BOD in the influent sewage. We now introduce the reformulation of the load curve that will be used subsequently: Let T be the BOD to eliminate by treatment. We have

$$T + L = b^d \quad . \qquad (22)$$

The load curve can then be expressed with respect to the treatment T. We define

$$\bar{p}^T(T^*) \equiv \Pr\ [T \geqslant T^*] = \Pr\ [b^d - L \geqslant T^*] = \Pr\ [L \leqslant b^d - T^*]$$
$$= p(b^d - T^*) \qquad (23)$$

We shall define $\bar{p}^T(T^*)$ to be the treatment curve. In our illustrative case b^d is equal to 18225.6 kg/day of BOD. The corresponding treatment curve is derived from Figure 2 as indicated in Figure 5.

We now take up the question of the representation of the treatment plant. As discussed above, this representation is essentially conceptual, it is presented here because it provides a representation of time-varying operations and allows one to derive results analytically. We consider two technologies, namely, activated sludge and activated carbon. We assume that the activated sludge system can be combined with the chemical treatment. Two types of combinations are envisaged, which certainly do not represent the set of possible combinations that could be contemplated in a systematic investigation of the problem, but are chosen here because they lead to simple mathematical derivations.

Before discussing these combinations, we first briefly introduce some cost assumptions. Global annual costs of biological treatment plants are known to exhibit the form given in Figure 6 (see Deininger 1965). In the absence of a systematic investigation of the various elements constituting these costs, we shall assume that this amount consists of 65 per cent capital and fixed operating costs, and 35 per cent variable operating costs (see Appendix 2). More information on this is given in Smeers and Tyteca (1980). For the sake of simplicity, we shall assume the variable operating costs to be strictly proportional to the amount of BOD removed. We shall consider that the chemical plant involves only operating costs that are strictly proportional to the amount of BOD removed; no capital or fixed operating costs are thus envisaged for activated carbon. This is discussed further in Appendix 2.

The two structures of the treatment system considered can then be described as follows:

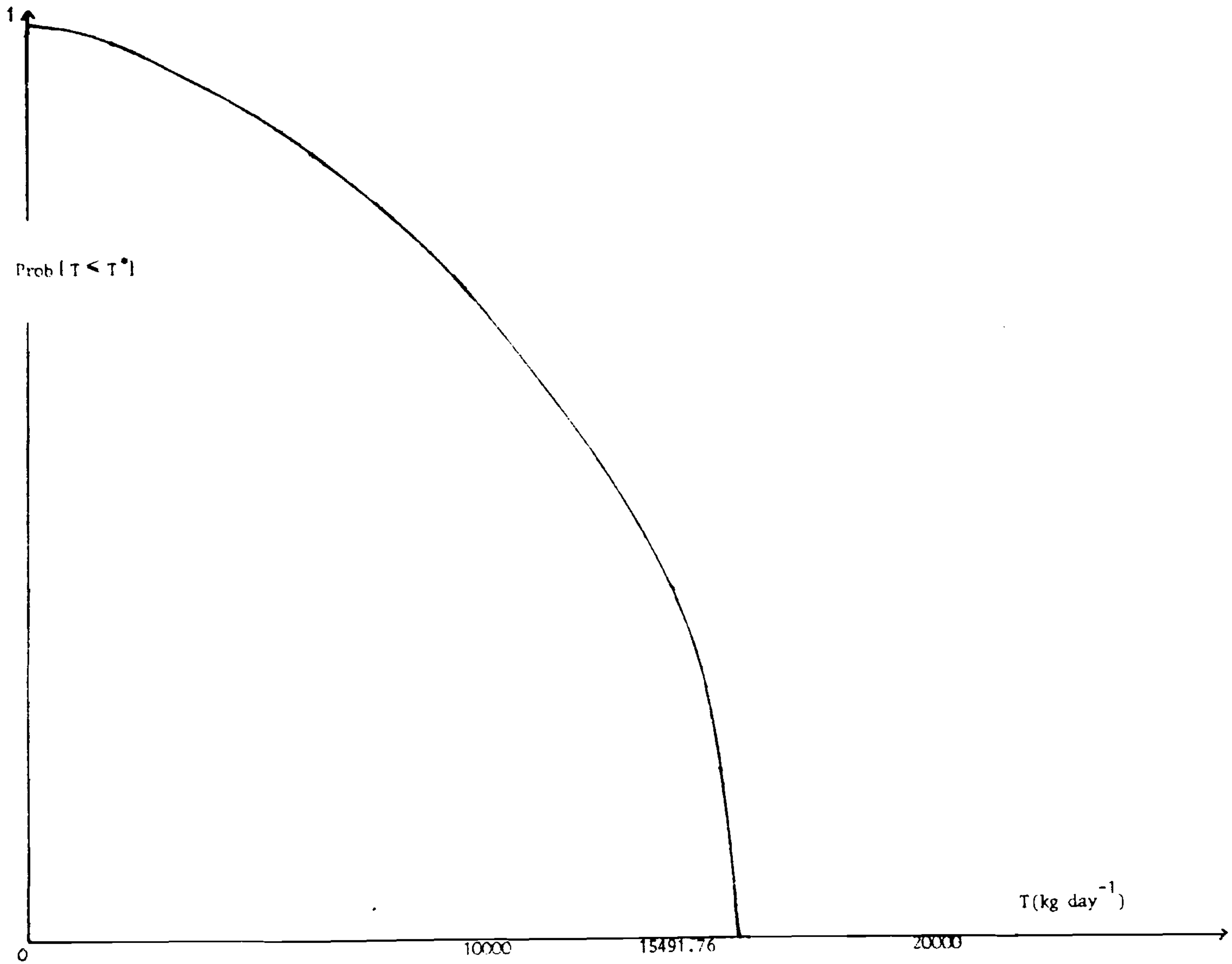


Figure 5. The treatment curve.

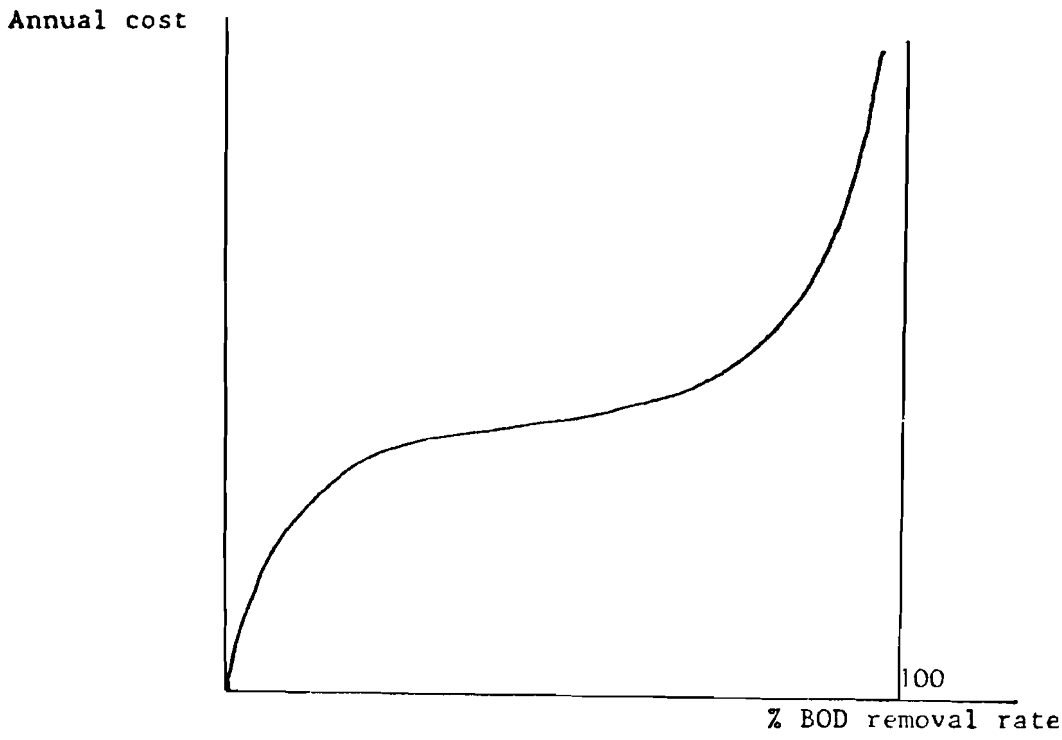


Figure 6. Annual cost as a function of the BOD removal rate.

- <u>Series-system</u>: The water is first conveyed to the biological plant, which is operated at a variable level as required. If the biological treatment is insufficient, chemical treatment is subsequently used to bring the discharged water to the required level.
- <u>Parallel-system</u>: the treatment system consists of a set of plants each of which treats a fraction of the wastewater flow. Each plant is composed of a mix of biological and chemical treatment in series. The total removal capacity is the same for all the plants, and is chosen to correspond to the maximum treatment demanded by the system, which in our case is a capacity of 85 per cent. The two plants differ according to the proportion of treatment effected by the biological process: the more important the biological process, the larger the annual investment cost and the smaller the operating cost (see Table A2.1).

These two structures permit, as we shall see, an easy analytical derivation of the optimal plant mix. They also form technically feasible alternatives.

The cost data are discussed in some detail in Appendix 2. We recall here the main assumptions leading to those costs. We consider a set of optimally designed biological plants with increasing removal rate, and distinguish their fixed and variable annual costs. We assume, for simplicity, that the variable costs of a treatment plant essentially consist of a proportional cost. Let $K(\xi)$ and $V(\xi)$ be respectively the fixed and variable annual costs of a plant with removal capacity ξ. Let ε designate the initial BOD concentration in the wastewater (in mg/ℓ), and Q_H the annual flow generated by each individual of the community served by the plant (in our case 150 x 365 ℓ). If we assume that the plant is continuously available at its rated removal capacity then $Q_H \varepsilon \xi$ units of BOD are removed annually from the water, which leads to a proportional cost of

$$c(\xi) = \frac{V(\xi)}{Q_H \varepsilon \xi} \tag{24}$$

for a biological plant of maximum removal capacity. Let v be the unit BOD removal cost of the chemical treatment. Numerical estimates of $c(\xi)$ and v are given in Appendix 2. The structure of the variable cost is then easy to define for both series and parallel systems.

Let us first take up the case of the series system. Let T^{max} be the maximum removal that will be required from the treatment system; T^{max} is the smallest T^* for which we have

$$\bar{p}^T(T^*) = 0 \quad .$$

Let ξ be the removal rate of the biological plant, and q the daily flow of wastewater; the annual variable cost of the biological plant will be equal to

$$- 365 \int_0^{q\varepsilon\xi} T\, c(\xi)\ d\bar{p}^T(T) + 365\, q\varepsilon\xi\, c(\xi)\, \bar{p}^T(q\varepsilon\xi) \quad . \tag{25}$$

Similarly the annual cost of the activated carbon system will be

$$- 365 \int_{q\varepsilon\xi}^{T^{max}} (T - q\varepsilon\xi)\ v\ d\bar{p}^T(T) \quad . \tag{26}$$

Assuming that $\bar{p}^T(T)$ is differentiable and defining

$$\phi(T) = - \frac{d\bar{p}^T(T)}{dt} \quad , \tag{27}$$

we can write for the total daily cost

$$\frac{1}{365}\left(\frac{q}{150}\right) K(\xi) + \int_0^{q\varepsilon\xi} Tc(\xi)\ \phi(T)dT + q\varepsilon\xi\ c(\xi)\ \bar{p}^T\ (q\varepsilon\xi) + \int_{q\varepsilon\xi}^{T^{max}} (T - q\varepsilon\xi)\ v\ \phi(T)dT \quad , \tag{28}$$

where (q/150) represents the design flow capacity expressed in population equivalents of the plant.

In order to simplify the presentation, we have chosen $c(\xi)$ to be constant (see Appendix 2). Relation (25) can then be rewritten as

$$\frac{1}{365}\left(\frac{q}{150}\right) K(\xi) + c \int_0^{q\varepsilon\xi} T\ \phi(T)dT + cq\varepsilon\xi\ \bar{p}^T(q\varepsilon\xi) + \int_{q\varepsilon T}^{T^{max}} (T - q\varepsilon\xi)\ v\ \phi(T)dT \quad . \tag{29}$$

In order to minimize this expression, we shall set its derivative equal to zero. This leads to

$$\frac{1}{365}\left(\frac{q}{150}\right) \frac{dK(\xi)}{d\xi} = (v - c)\ q\varepsilon\bar{p}^T(q\varepsilon\xi) \quad , \tag{30}$$

which has an immediate economic interpretation.

In the simple case considered in this paper the search for the best solution can be performed by simple enumeration. In order to simplify the presentation and, on the basis of the data given in Table A2.1, we have assumed that $\frac{dK(\xi)}{d\xi}$ is constant and equal to 700 BF. Since $\varepsilon = 0.3$ and $v - c = 0.17$ the optimal treatment is given by

$$\bar{p}^T(q\varepsilon\xi) = 0.25 \quad . \tag{31}$$

We can see from Figure 7 that this corresponds to a maximum removable load by the biological plant of 14855 kg day^{-1}. The shaded area on the surface is the portion that will be covered by the chemical treatment. It is easy to see that this portion increases as the unit cost of active carbon decreases. Figure 8 illustrates the same reasoning when accidental discharges are taken into account and using the same cost assumptions. It is easy to see here the relatively greater importance of the chemical treatment.

We now consider the parallel system. Let $\xi_\ell, \ell = 1, \ldots L$ be the BOD removal rates achieved in the biological components of the treatment plants constituting the parallel system. We assume the ξ_ℓ to be given, the only decision variables are then the design-flow capacities of the treatment plants of type ℓ.

The following assumptions are important for understanding the rest of the derivation. We shall suppose that all plants are designed so as to be able to remove a fraction ξ^{max} of the BOD contained in the influent sewage. Clearly the fraction of the load not removed by the biological component of the plant will have to be eliminated by an activated carbon unit. We shall assume that each plant ℓ always operates at its full removal rate capacity, but that it can operate on a fraction of the entering flow: a BOD removal rate smaller than the maximum achievable is then obtained by treating only a fraction of the flow entering the plant. Again this assumption is not introduced because it is necessarily realistic: it is only justified by the easy mathematical derivation that it permits. It also illustrates another type of control variable (the flows in the various parts of the treatment plant) that can be called upon in a systematic investigation of the problem of variable costs of a treatment plant. Let K_ℓ be the annual investment cost of a plant of type ℓ, designed for treating the pollution of a population equivalent and let C_ℓ be the cost of removing a fraction ξ^{max} of the pollution load from that flow. We assume that the plants are ranked so that

$$C_1 < C_2 < \ldots < C_L \quad ; \tag{32}$$

such a system is represented in Figure 9.

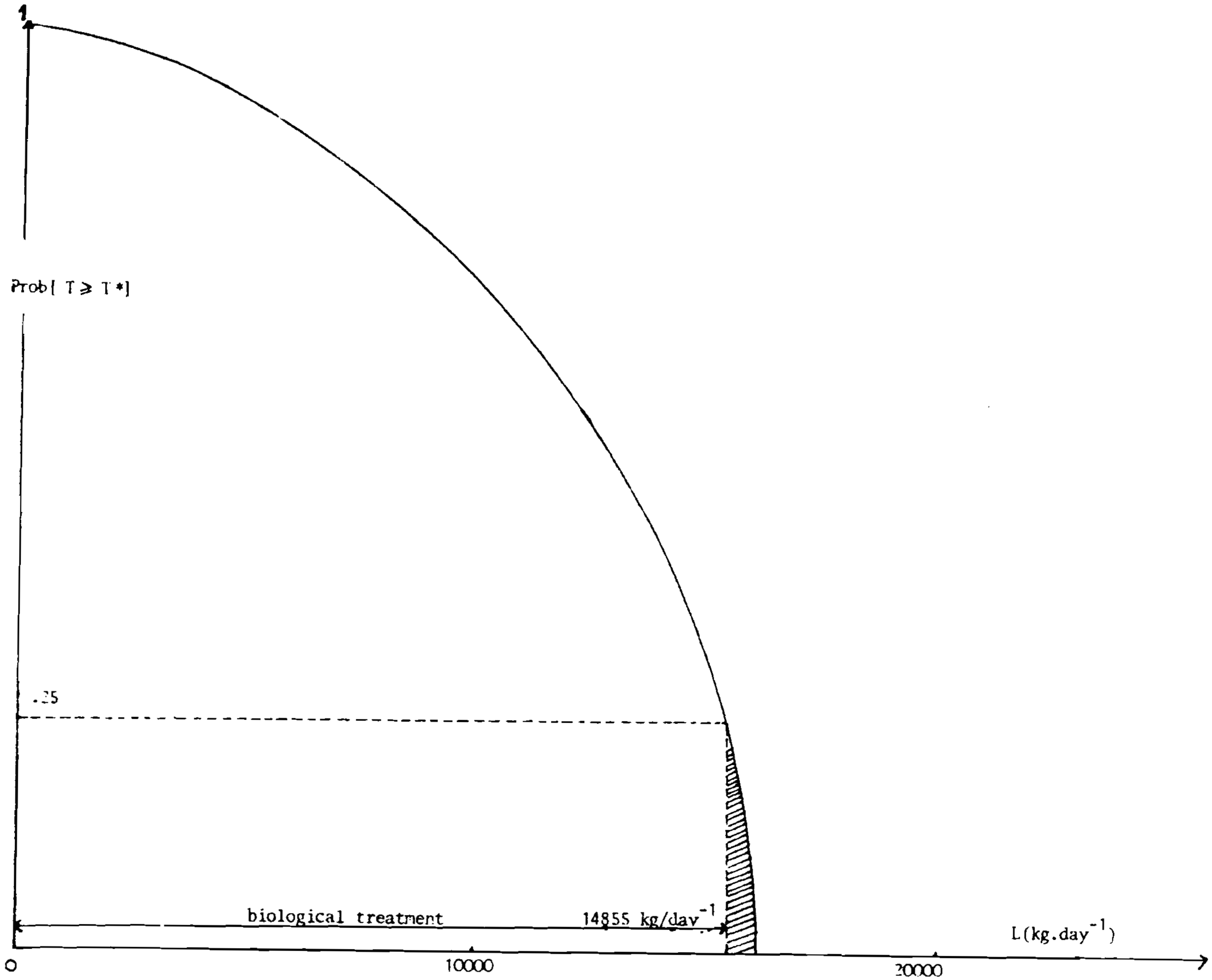


Figure 7. Optimal series treatment.

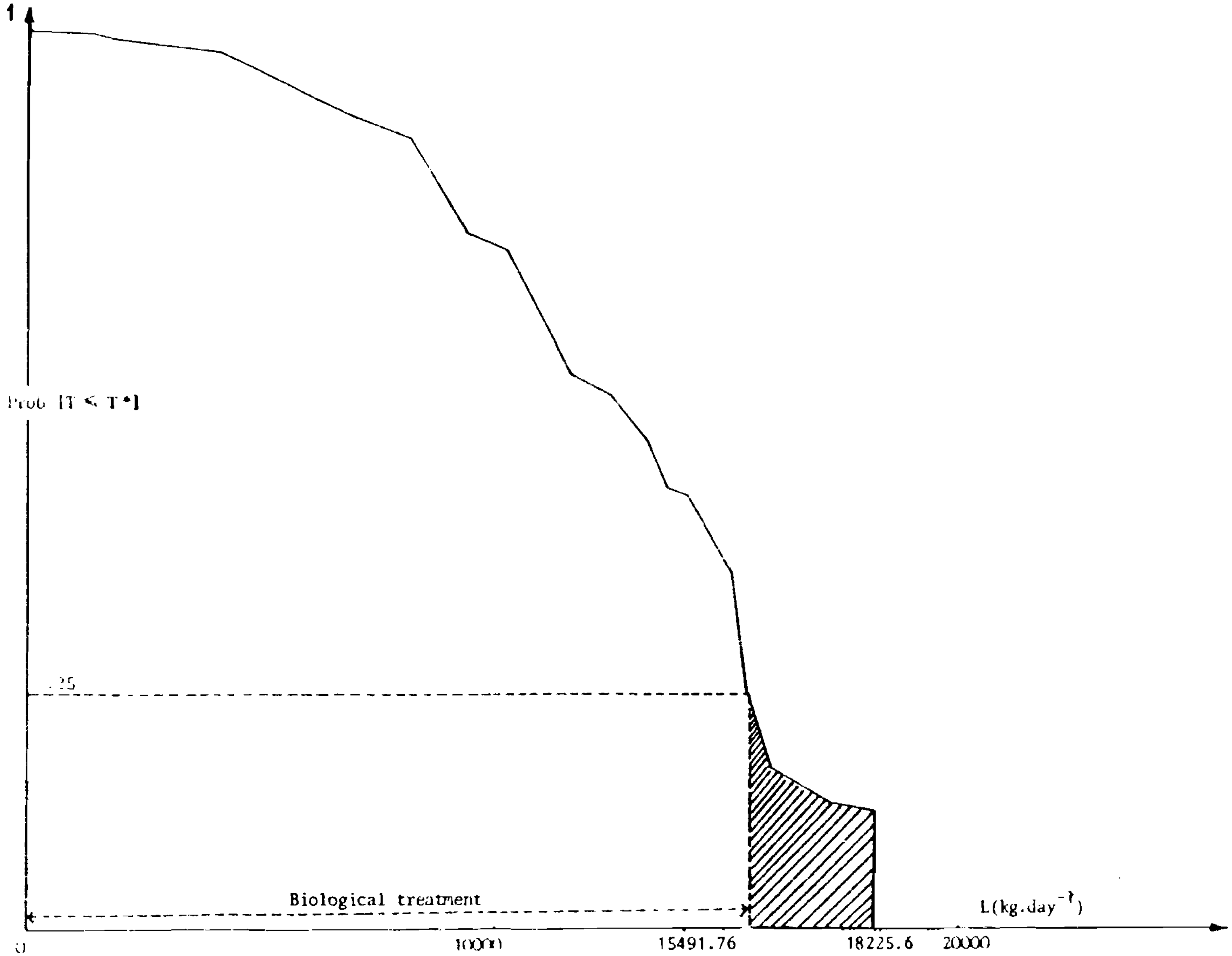


Figure 8. Optimal series system.

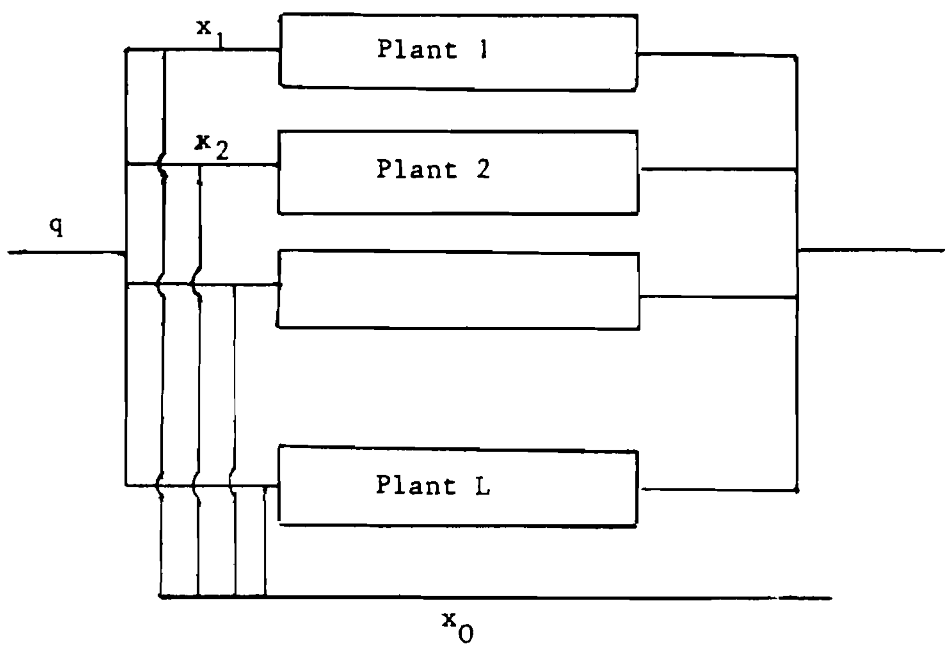


Figure 9. Representation of the parallel system.

The influent wastewater flow (measured in population equivalents) is partitioned into

$$q = x_0 + x_1 + x_2 + \ldots + x_L \quad , \tag{33}$$

where x_0 is the flow that is bypassed directly to the river and x_i is the flow that is sent to plant i. Since each plant provides a ξ^{max} rate of removal for the BOD contained in the influent sewage, the total BOD removed is then

$$150 \; \varepsilon\xi^{max}(x_1 + x_2 + \ldots + x_L) \quad , \tag{34}$$

and the operating cost is

$$(C_1 \; x_1 + C_2 \; x_2 + \ldots + C_L \; x_L) \quad . \tag{35}$$

Because the plants have a limited flow capacity we also have

$$0 \leqslant x_i \leqslant \bar{x}_i \quad , \tag{36}$$

where $\bar{x}_i$ is the design flow capacity of plant i.

It is easy to see in this model that the cheapest way of providing a given BOD removal is to successively load the different components of the plant in the order 1, ... L, until the BOD removal target has been attained. The optimal plant mix consists of finding the $\bar{x}_i$ such that the total investment and operating cost is minimized. This problem can be solved by resorting to a reasoning that has been used extensively in power generation problems for similar situations. This approach is illustrated in Figure 10. We first introduce a slight modification in the representation of the treatment curve: defining H to be a number of days between 0 and 365, we define TL(H) as the treatment level that will have to be provided during an expected number of days equal to H. This definition is equivalent to saying that

$$\bar{p}^T \; [TL(H)] = \frac{H}{365} \quad . \tag{37}$$

TL(H) is represented in Figure 10, which also gives a set of straight lines that represent the total annual costs of operating the treatment plants as a function of the number of days of operation. Let $H_o = 0$ and H_i represent the number of days for which the operation of plants i and i + 1 are equally expensive

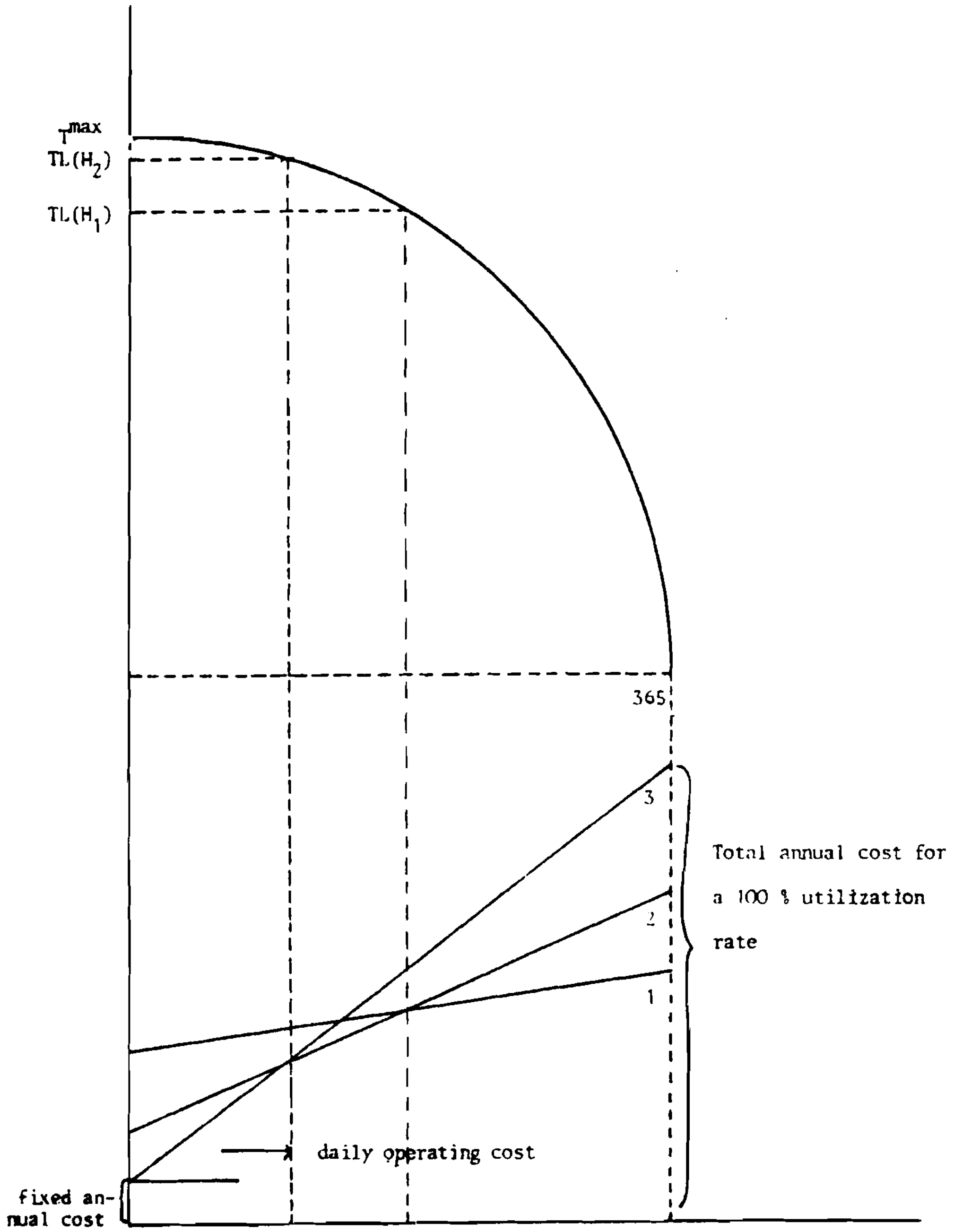


Figure 10. Optimal mix of a parallel treatment system.

on an annual basis. One can then show that plant i should provide a treatment capacity of

$$TL(H_i) - TL(H_{i-1}) \quad . \tag{38}$$

The optimal design flow of plant i is then

$$\frac{1}{\varepsilon \xi^{max}} \left[TL(H_i) - TL(H_{i-1})\right] \quad . \tag{39}$$

We now illustrate this discussion by an example. We first prepare our cost figures in a form that is more suitable for our purposes. We define the capacity of a plant to be the number of grammes of BOD that the plant is capable of removing in a day. Since our cost figures refer to plants designed for a maximum removal rate of 85 per cent and a flow of one population equivalent, the total number of grammes of BOD removed per day is equal to 38.25. The annual cost of a unit capacity, and the daily variable cost are then respectively given as $K(\xi)$ / 38.25, and $\overline{c+v}$ (see Appendix 2). This leads us to the values given in Table 2.

Table 2. Annual investment costs and operating costs for a parallel treatment system.

ξ	K_ℓ in Fr/gr/day	C_ℓ in Fr/gr
40 %	59.8	.22
50 %	62	.20
60 %	62.8	.18
70 %	64.4	.16
80 %	66.8	.14
85 %	67.9	.13

We illustrate this discussion for the situations described by the load curves represented in Figures 2 and 4. Figure 11 represents the total annual costs of the various plants considered as a function of their annual utilization rate. We recall that the intersection points of any two of these curves represent the number of days of utilization for which the corresponding plants are equally costly. Since the intersection points of these curves

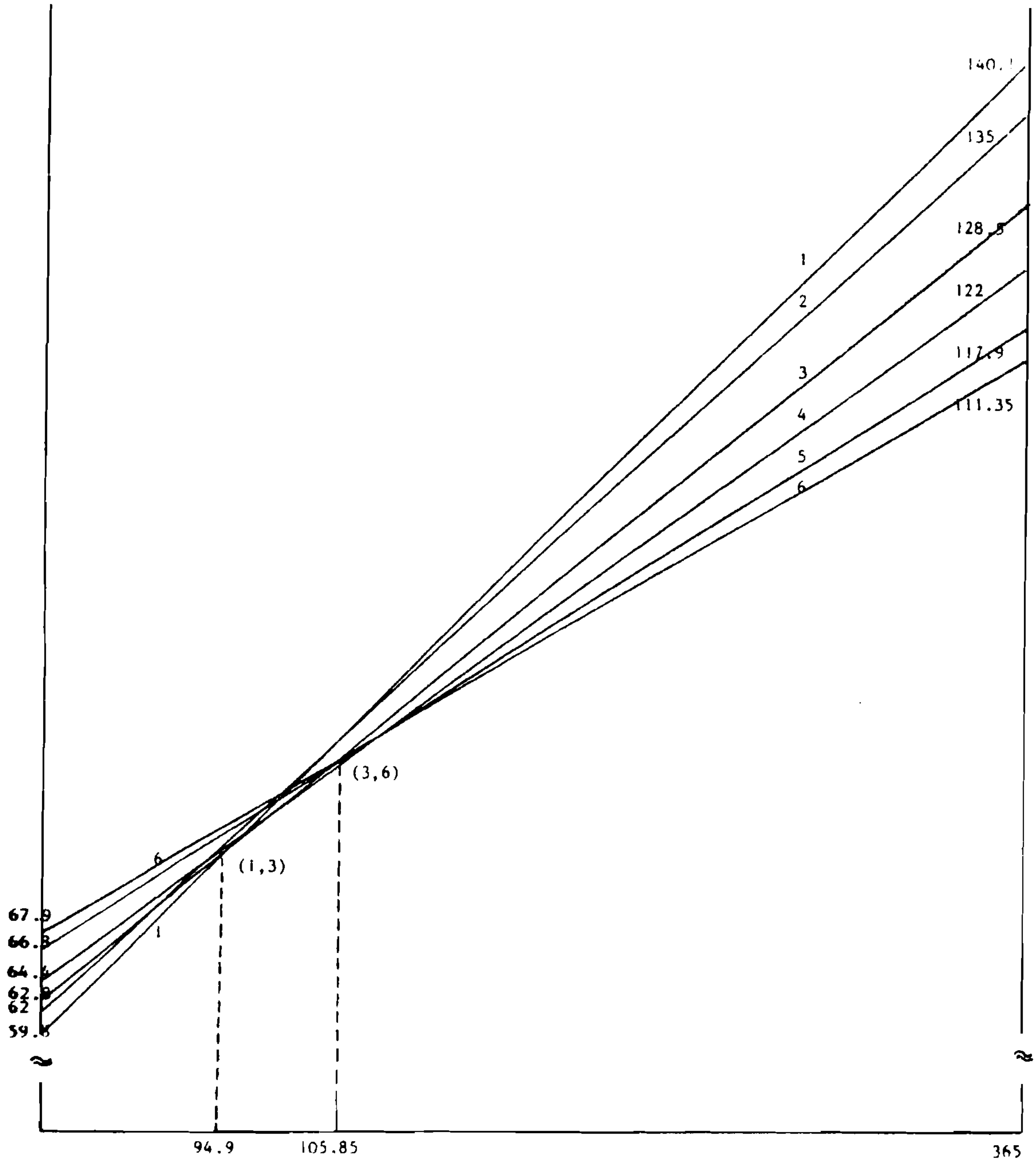


Figure 11. Annual cost as a function of the plant utilization.

are too clustered to be easily distinguishable we shall restrict ourselves to the plants 1, 3 and 6. The intersection of the cost curves (1,3) and (3,6) are indicated in Figure 11. These utilization rates are then used as shown in Figures 12 and 13 to arrive at the optimal capacity for the different plants.

5. INTRODUCING RESERVOIRS

Low flow augmentation can also be a part of a water quality management system. Although reservoirs may not be the cheapest means of attaining a water quality target, they may be used, among other things, to help alleviate pollution problems. Reservoir management can be looked at from several points of view. We shall take here the very simple case of a single reservoir, which we shall assume to be located upstream of the sewage outfall. In order to illustrate some of the approaches that can be followed we shall consider two cases that are of quite different complexity. In the first case a certain guaranteed low-flow target is set up and the reservoir must be designed in order to satisfy that goal. The treatment system is then built to bring the water of the resulting modified river to the desired quality target. In the second case, no intermediate guaranteed minimal flow is imposed on the system, and the operating rule for the reservoir must be found simultaneously with the best treatment system.

The first case presents the advantage that it allows one to partition the problem into two subproblems that can be solved separately: one first finds the reservoir capacity that allows one to satisfy the low-flow target. The flow of the regulated river is then taken as given and the treatment system is designed according to this flow pattern.

The problem of designing a reservoir so as to satisfy certain low-flow conditions with a given reliability is rather complex. It involves the simultaneous determination of the capacity and the operating rules for the reservoir; this is generally posed as a chance constraint problem (Eastman and Revelle 1973; Revelle et al 1969; Revelle and Kirby, 1969). In order to keep the discussion in this paper at a minimum level of complexity, we shall assume that the operating rule is given. More specifically, if R_t designates the reservoir level, C its capacity and $\underline{q}$ the guaranteed minimum flow, then the water release in period t, x_t, will be defined as

$$\begin{aligned} x_t &= R_t && \text{if } R_t \leqslant \underline{q} \;; \\ &= \underline{q} && \text{if } \underline{q} \geqslant R_t \leqslant C + \underline{q} \;; \qquad (40) \\ &= R_t - C && \text{if } R_t \leqslant C + \underline{q} \;. \end{aligned}$$

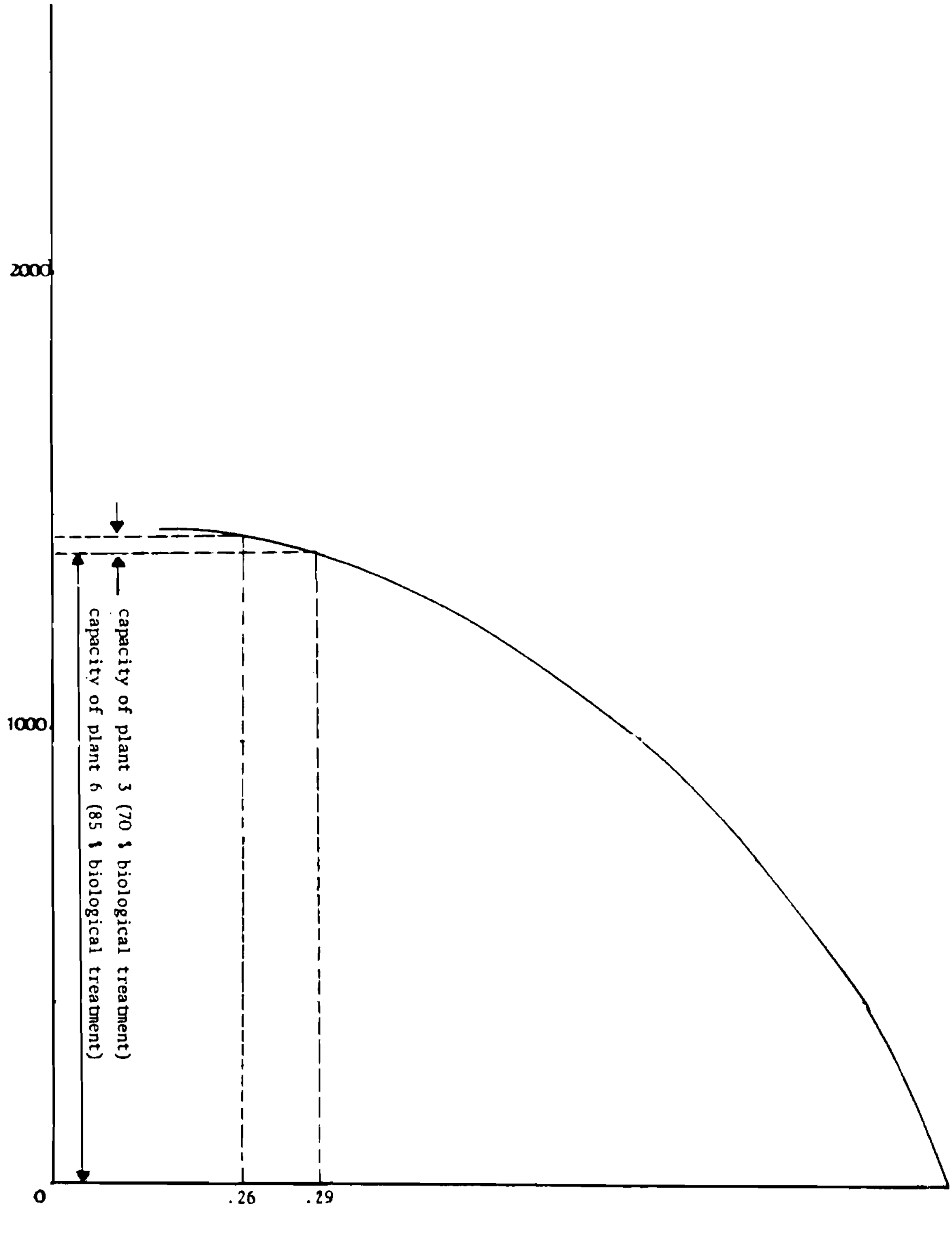
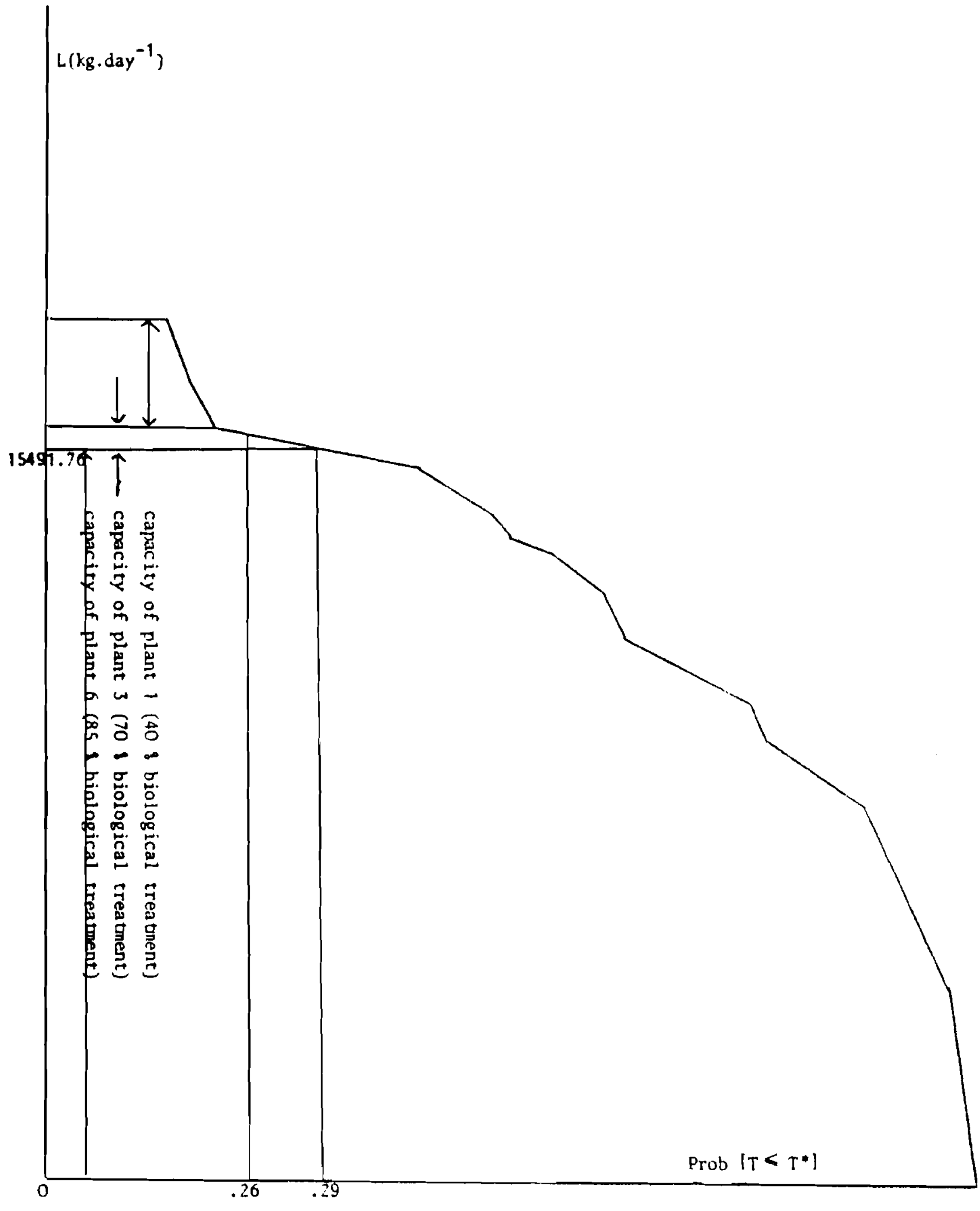

2000
1000
0
.26
.29
capacity of plant 3 (70 % biological treatment)
capacity of plant 6 (85 % biological treatment)

Figure 12.



L(kg.day^{-1})
15491.76
capacity of plant 1 (40 % biological treatment)
capacity of plant 3 (70 % biological treatment)
capacity of plant 6 (85 % biological treatment)
Prob [T ≤ T*]
0
.26
.29

Figure 13.

We shall not discuss further this operating rule; it is selected here for its simplicity. The problem of finding a reservoir that guarantees the required minimum flow $\underline{q}$ is then equivalent to finding the minimum C that will permit achieving the desired goal with the required reliability criterion. Let $x_t(R_t|C)$ designate in general the operating rule of a reservoir of capacity C; it is clear that the pair $[C\ ;\ x_t(R_t|C]$ defines a transformation of the distribution of the flow entering the reservoir into a distribution of the flow leaving the reservoir. The new distribution of the flow will thus clearly imply a different optimal treatment system. The trade-off between the reservoir cost and the treatment system can be studied accordingly. This first problem is illustrated in Figure 14, which shows the flow distribution before and after the reservoir has been constructed. The load curve of the regulated river is shown in Figure 15. The optimal series- and parallel-treatment systems are also represented in Figures 16 and 17 respectively.

A more complicated problem occurs when a guaranteed minimum flow is no longer specified for the reservoir, and one is asked to determine simultaneously the capacity of the reservoir, its operating rule and the associated treatment plant system. Determining an operating rule in a stochastic environment is always a complex problem that necessitates the construction of a model. If the problem has several time-periods and reservoirs this model is of a stochastic programming type and thus can be extremely difficult to solve. With one reservoir the problem can usually be cast in a dynamic programming formalism, which, although considerably easier to discuss and solve, would lead us much beyond the scope of this paper. In order to avoid completely any type of mathematical modeling we shall consider a drastically simplified situation. We shall first assume the problem to have only two time periods, of length T_1 and T_2 respectively: in the first period water is stored and then completely released in the second period. Water released in the second period can be used for regular low-flow augmentation but also for reducing the effects of accidental discharges. In order to limit ourselves to elementary calculations we shall assume that the incoming flow to the reservoir in the first period can take only two values Q_1 and Q_2, with probability p_1 and p_2 respectively. Similarly, the natural flow in the second period will be Q_3 and Q_4, with probabilities p_3 and p_4. These flows represent the number of cubic meters flowing through the river per day during the whole period. Flows in the second period are not correlated to flows in the first period. We obviously have

$$
\begin{aligned}
p_1 + p_2 &= 1 \quad , \\
p_3 + p_4 &= 1 \quad .
\end{aligned}
\tag{41}
$$

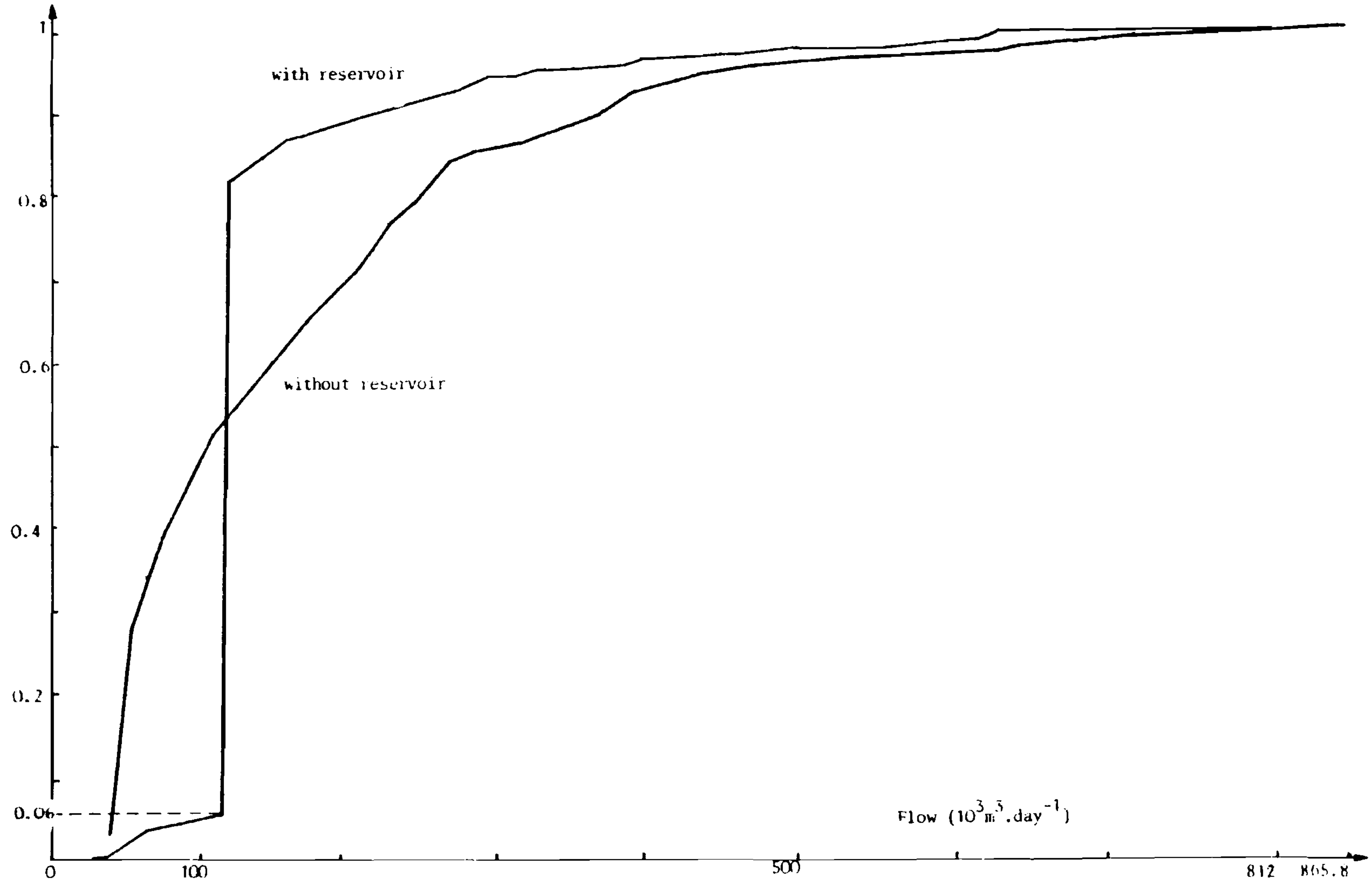


Figure 14. Distribution of the river flows.

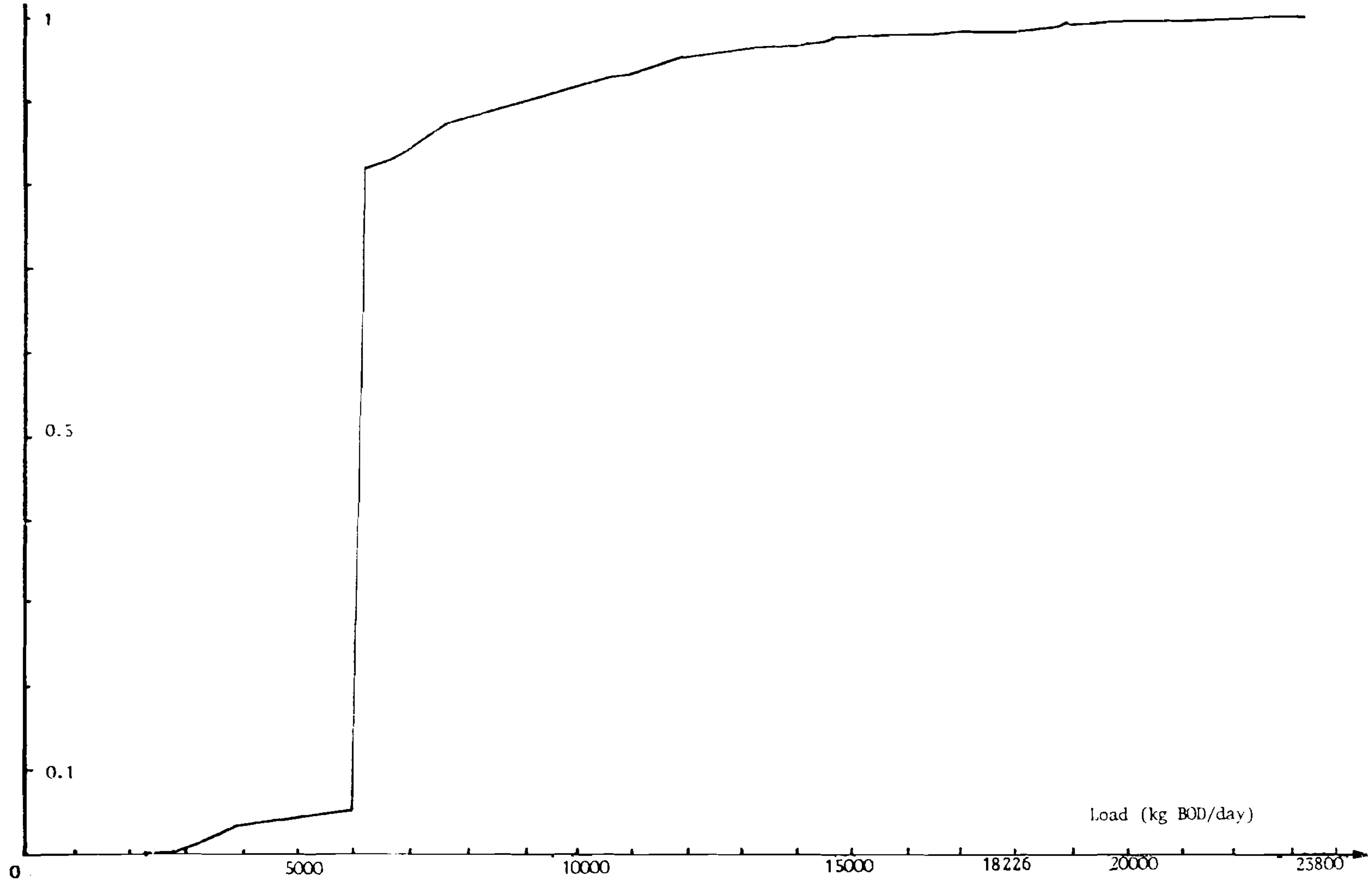


Figure 15. Load curve of the regulated river.

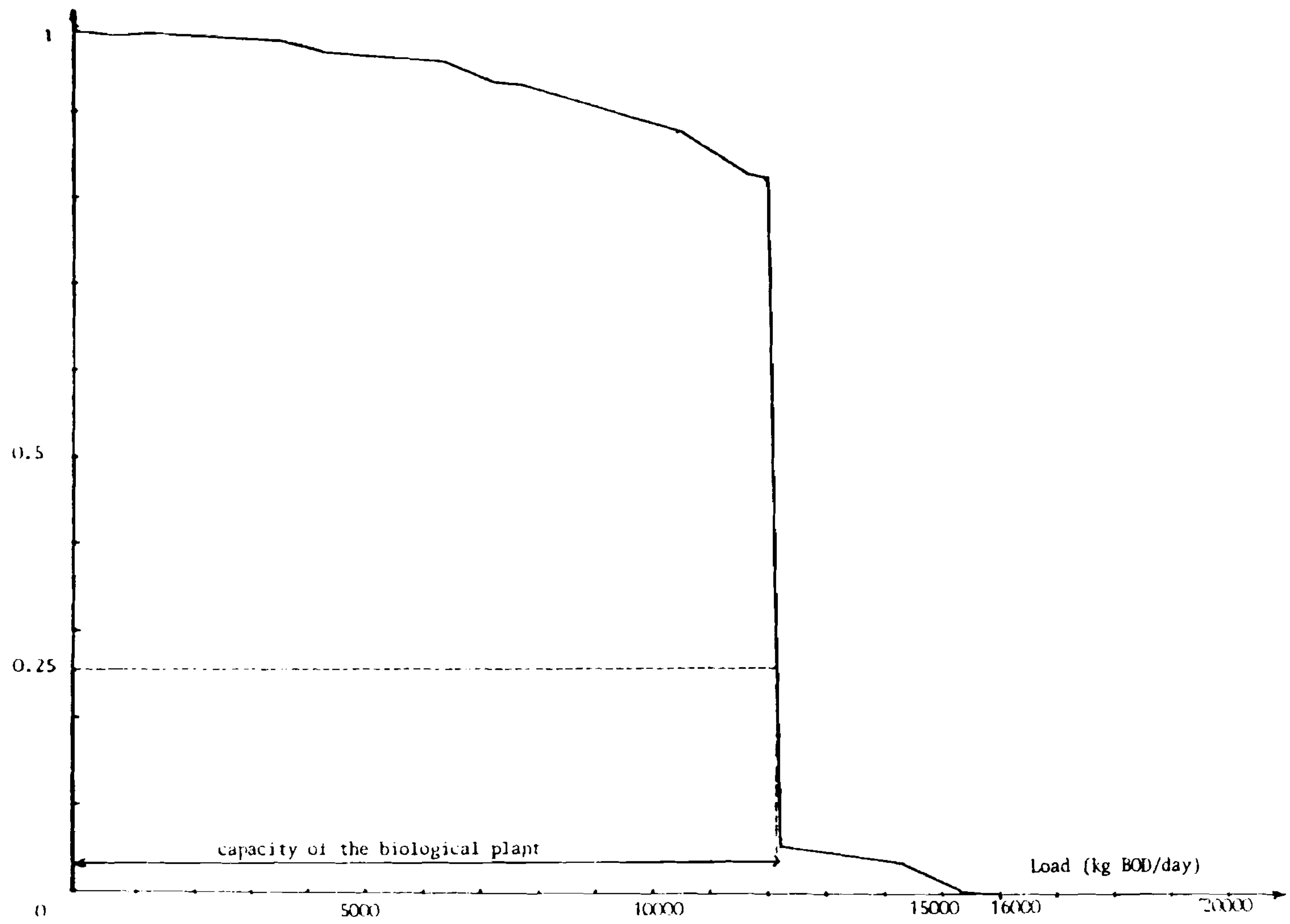


Figure 16. Optimal series system for the regulated river.

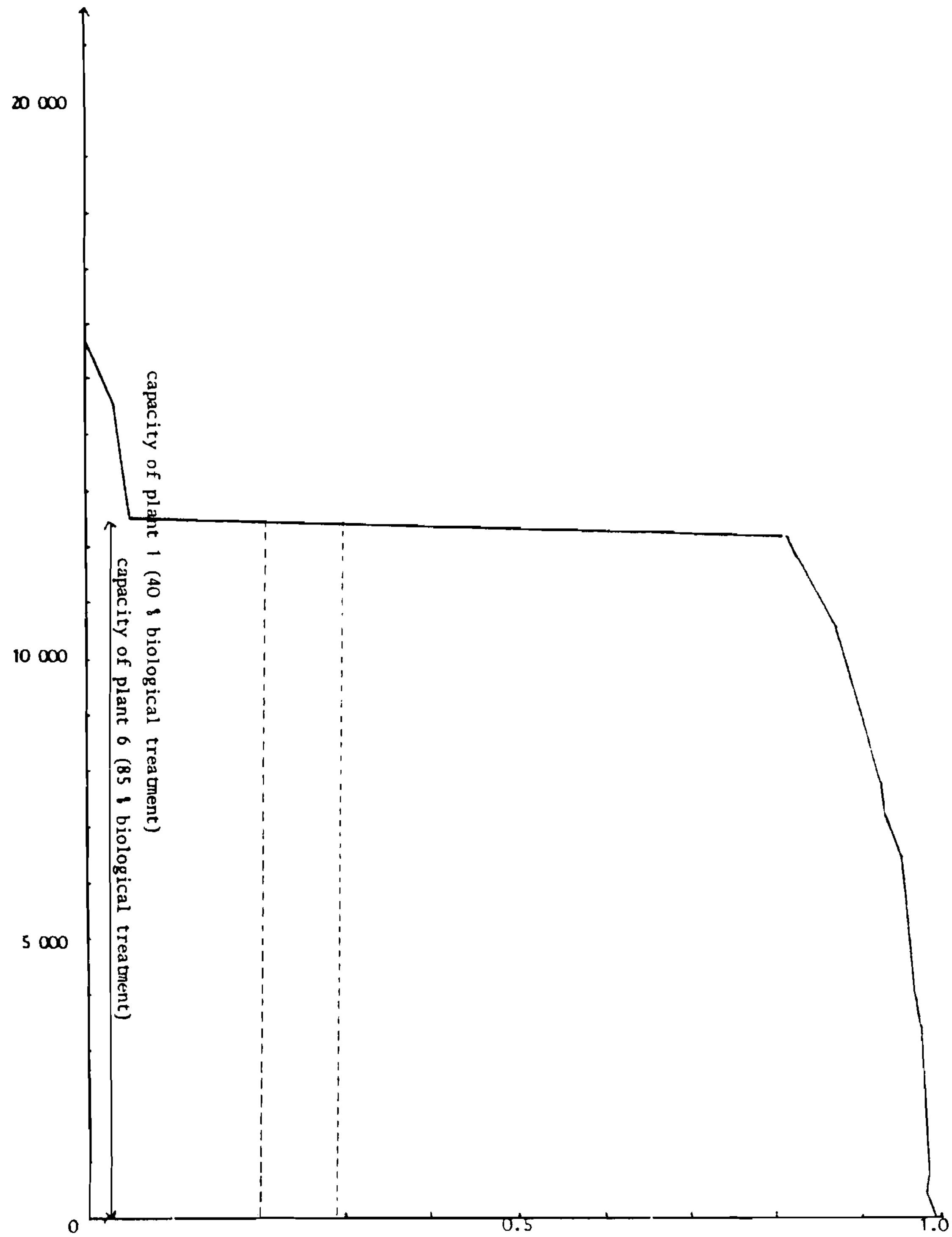


Figure 17. Optimal parallel system for the regulated river.

These assumptions lead to an extremely simplified reservoir management model that still allows us to consider the essential elements of more general problems.

We assume that accidental discharges can only occur during the second period. In order to restrict ourselves to two-period problems, we shall assume such accidental discharges to occur at the beginning of the period and to last a fraction f of this period. Let p be the probability of the accidental discharge. The reservoir manager is instantly informed of this accident and can release some of the water stored in the reservoir in order to improve the situation. As a simplification we shall assume the accidental discharge to be a known additional oxygen demand, and the probability of its occurrence to be known; we shall also impose the condition that the release during the accident be independent of the flow during that period. The operating rule of the reservoir can then be summarized as follows:

- First period : flow Q_1 store q_1 ;
  flow Q_2 store q_2 .
- Second period: If there is no accidental discharge, release the contents of the reservoir;
  If there is an accidental discharge, release $\bar{q}$ during the accident, and the remainder of the reservoir contents after the accident.

The total capacity of the reservoir is obviously equal to max (q_1, q_2). The problem is to select simultaneously the reservoir capacity and the appropriate treatment plant.

In order to investigate the economics of this problem, we first consider the set of possible flows and their probabilities as modified by the reservoir operating rule. During the first period the flows will be $Q_1 - q_1$ with probability p_1 and $Q_2 - q_2$ with probability p_2. During the second period, the flows occurring in the absence of accidental discharges will be

$$\left(Q_3 + \frac{T_1}{T_2} q_1\right), \left(Q_3 + \frac{T_1}{T_2} q_2\right), \left(Q_4 + \frac{T_1}{T_2} q_1\right), \left(Q_4 + \frac{T_1}{T_2} q_2\right)$$

with probability $(1-p)p_3p_1$, $(1-p)p_3p_2$, $(1-p)p_4p_1$ and $(1-p)p_4p_2$ respectively. (We recall that p denotes the probability of an accident.) If there is an accident, the situation is somewhat more complex: the flow is equal to $(Q_3 + \bar{q})$ and $(Q_4 + \bar{q})$ with probability pp_3 and pp_4 respectively, during a fraction f of the second period; after the accident it is equal to

$$Q_3 + \frac{\frac{T_1}{T_2} q_1 - f\bar{q}}{1 - \bar{f}} , \quad Q_3 + \frac{\frac{T_1}{T_2} q_2 - f\bar{q}}{1 - \bar{f}} , \quad Q_4 + \frac{\frac{T_1}{T_2} q_1 - f\bar{q}}{1 - \bar{f}} , \quad Q_4 + \frac{\frac{T_1}{T_2} q_2 - f\bar{q}}{1 - \bar{f}}$$

with probability pp_1p_3, pp_2p_3, pp_1p_4 and pp_2p_4 during a fraction (1-f) of this second period.

To each flow is associated a certain maximum load acceptable by the system. To each triplet $(q_1, q_2, \bar{q})$ one can thus associate the dimension of the reservoir (and hence its cost), and a treatment distribution curve (and hence the cost of the treatment system). By enumerating the possible values of $(q_1, q_2, \bar{q})$, the overall minimum can be found.

This discussion is illustrated in Figure 18, which gives the load curve before and after regulation and indicates the optimum parallel system. In order to simplify the discussion we did not consider the possibility of accidental discharges. The original flow distribution has been approximated as follows:

	Flow ($10^3 m^3$/day)	Probability
Dry season	47.73	.2684
	92.978	.1973
Wet season	168.52	.3268
	412.61	.2075

The operating rule has been selected as follows:

Store 50 when the flow is 168.52;
Store 200 when the flow is 412.61.

Since the wet and dry seasons are respectively of 195 and 170 days, we obtain the following distribution through flow regulation,

Flow	Probability
105.08	.1641
118.52	.3268
150.328	.1206
212.61	.2075
277.1399	.1042
322.3879	.0766

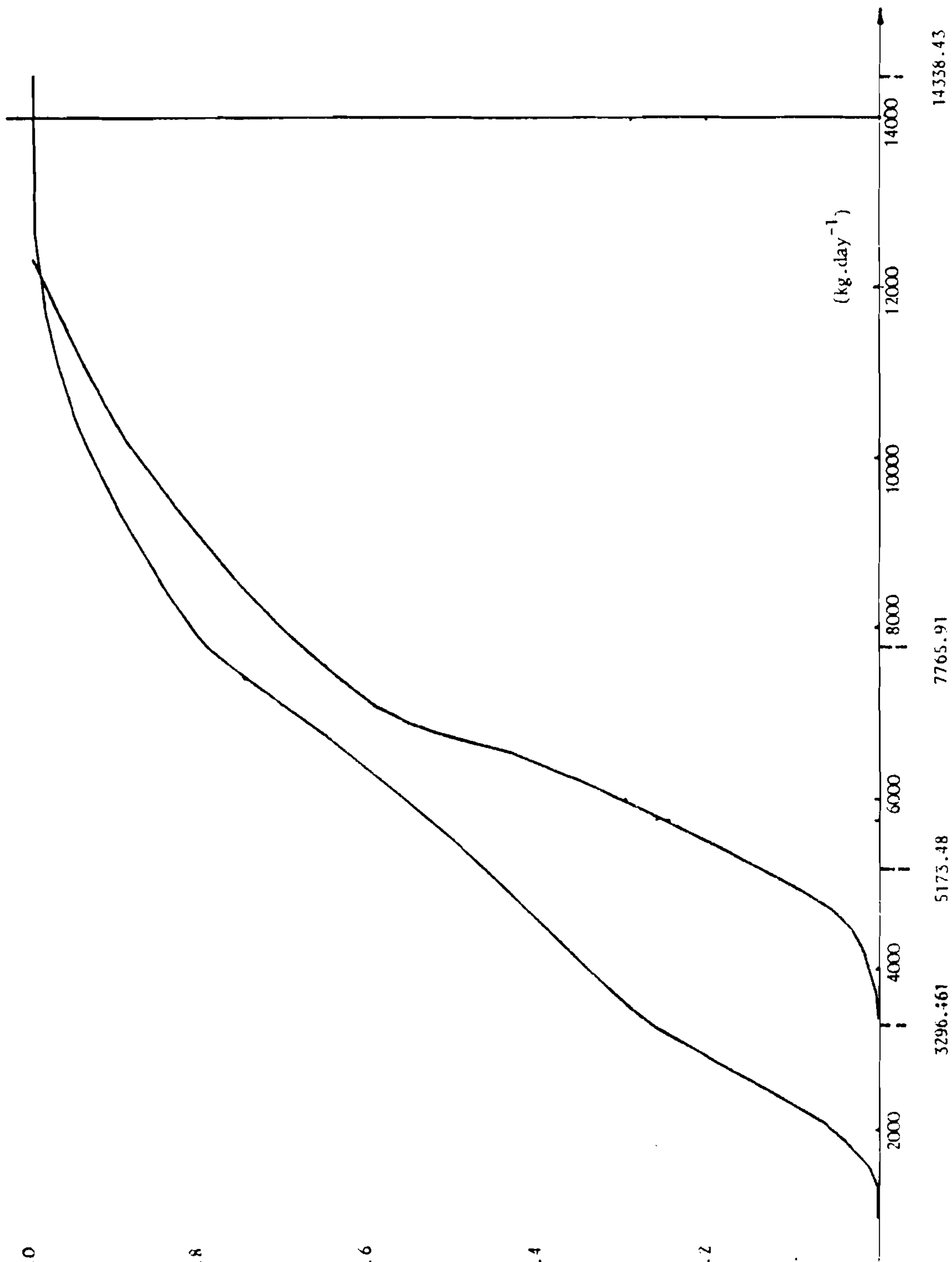

1.0
0.8
0.6
0.4
0.2
0
2000
3296.461
4000
5175.48
6000
7765.91
8000
10000
12000
(kg.day-1)
14000
14338.43

Figure 18.

The load curves corresponding to these flow distributions have been smoothed as indicated in Figure 18. The evaluation of the optimum parallel and series system can then be carried out as before.

6. TREATMENT PLANT FAILURES

The reliability of river quality management systems and wastewater treatment plants does not seem to have received much attention in the literature. This situation is somewhat strange if one considers that many treatment plants are certainly not always operating at their rated removal capacity. It would thus seem reasonable to take the possibility of plant unavailability into consideration in the design process and hence to collect data relevant for that purpose. In this section we introduce some notions related to the problem of evaluating the reliability of the treatment systems considered previously in this paper.

A comprehensive design procedure that directly takes into account reliability criteria seems difficult to imagine without requiring rather complex calculations at every step of the procedure. A second best to this ideal approach is to provide a first design of the system that does not take into account the uncertainty of the constituting components, and to correct this design at a second stage according to certain reliability measures. We shall show in this section how classical tools developed in the field of power-generation planning can be translated in order to apply to our problem.

We assume for the sake of simplicity that a treatment plant is either fully available or completely out of order: let p be the probability of a plant being forced out of operation. This assumption could obviously be modified for increased realism; it is made here because of its analytical convenience. Any reliability evaluation requires the definition of a criterion. The simplest evaluation of the failure of the system that can be considered here is the expected pollution load that should normally have been treated in order to achieve the quality criterion but which remains untreated because of the plant failure. We shall denote this criterion as the global failure of the system. More sophisticated criteria can be thought of: consider for instance a situation in which we have a safety system on stand-by that is only operated when the main system fails. The expected operating cost of this safety system is certainly a useful economic criterion to take into account in the design process. Both notions, global failure, and the incremental cost incurred in order to compensate the failure of the main system, are thus important decision criteria. In what follows we illustrate how they can be evaluated on the basis of the notions introduced above. As before, it should be clear that the discussion given here is only presented for illustrative purposes.

We first consider the series system, and we assume that the activated carbon treatment can be increased on request to provide full treatment when the biological plant goes out of normal operation. It is clear that the global failure of the system is then identically zero. The only remaining question is thus the evaluation of the additional operating cost of the activated carbon treatment due to its role as a safety mechanism. The solution of the problem is easy. The expected total operating cost consists of two terms:

- the normal annual operating cost when the biological plant is available--this cost is incurred with probability 1-p and is the one already evaluated;
- the cost of providing the full treatment with activated carbon only--this cost is equal to

$$v\int_0^{T^{max}} T\ \phi(T)\ dT \quad , \tag{42}$$

and is incurred with probability p.

The additional cost is then obtained by subtracting the cost evaluated under certainty assumptions from this new expected cost. The result is

$$p\left[\ (v-c)\int_0^{q\varepsilon\xi} T\ \phi(T)dT + v(q\varepsilon\xi)\ \bar{p}^T(q\varepsilon\xi)\right] \quad . \tag{43}$$

It should be noted that, in this case as before, an optimum choice of the treatment system could be made of both the regular and safety systems.

The reader can easily convince himself that more realistic assumptions on the unavailability of the plant will imply more complex evaluations. In particular the existence of several plants, or the representation of their availability by a model that is more complex than the simple binomial distribution which is used here, would lead to a more sophisticated evaluation. We illustrate this point with the case of the parallel system. In this system, the damage due to plant failure can be completely evaluated by the load which should normally have been treated by plants $\ell = 1,...L$, but remains untreated due to forced bypassing. Let T_F be this load: T_F represents the treatment capacity that is unavailable because of forced bypassing. As such it is a random variable that obviously depends on the structure of the treatment system. Its evaluation is straightforward under our assumptions, provided that we also suppose the availability of the various components ℓ of the plant at some period of time to be represented by independent random variables.

Let T be the demand for treatment during a given period of time; as discussed before T is represented by the treatment distribution curve, and we define the random variable

$$t = T_F + T \quad .$$

The distribution of t can be easily computed by convoluting the treatment distribution curve and the unavailable capacity distribution curve. We then construct the curve

$$\bar{p}_t(t^*) = \text{Prob}\ (t \geq t^*) \quad .$$

The availability of $\bar{p}_t(t^*)$ allows one to derive a considerable amount of information about the reliability of the whole system. Suppose first that we have no stand-by system: an interesting question is to determine the probability with which the quality of the river will be violated if no additional treatment capacity is installed. This is easily obtained as

$$\bar{p}_t(T^{max}) \quad .$$

The expected number of days per year that the quality criterion will be violated is then equal to

$$365\ \bar{p}_t(T^{max}) \quad .$$

The global failure of the system in the absence of additional capacity can also be found easily: it is equal to

$$- \int_{T^{max}}^{\infty} t\ d\bar{p}_t(t) \quad .$$

A more sophisticated criterion is the additional cost that the failure of some of the plants will entail for the system. This cost consists of two parts:

- o the additional activated carbon that will be used to supplement the lost treatment capacity;
- o the increase in the operating cost of the existing plants due to the fact that some plants with high operating costs will be operated more than expected because of the failure of other plants.

The first part of this cost is straightforward to obtain: it is equal to the global failure of the system multiplied by the cost of the active carbon necessary to eliminate one kg of BOD. The second part is more complex, and will not be discussed here. For our purposes, it suffices to say that it can be evaluated correctly on the basis of the function $\bar{p}_t(t)$. Details of the evaluation procedure can be found in Zahavi et al (1978).

7. CONCLUSIONS

In this paper we have presented several economic problems related to the time-varying operation of treatment plants, and we have shown that the consideration of time-varying operation greatly enlarges the scope of the planning process. Although the approach followed is extremely simplified, it leads to some interesting insights concerning the type of information that is needed for this kind of investigation.

In the first section it is shown that flow regimes different from low flow can be considered in the statement of the river quality planning problem. The economic evaluation is thus enlarged in order to take into account favorable as well as unfavorable river conditions. A requirement for proceeding this way is to have sufficient information on the flow in the river (which is very often available), and on the dependence of the parameters of the river model on the flow (which is more difficult to achieve). Loose estimates of the coefficients of the river model can also be taken into account if information about their relative inaccuracy is available. Special events such as accidental discharges can be included in the planning process, if they are quantified with sufficient accuracy. This quantification, although probably very difficult, is obviously an absolute requirement: it is indeed clear that one cannot design a system which would sustain every kind of accident, and hence that one must determine those situations that can be managed by the treatment system.

A second section deals with the choice of the optimal treatment combination. From this discussion, it appears important to have information about fixed and variable costs of treatment plants. It is also clear from the simple situation discussed that these costs will depend heavily on the operating modes of the plant, and hence that this problem must be studied with great care. What is needed here is a proper cost-accounting analysis of treatment plants.

Treatment systems can be combined with low-flow augmentation measures. It is shown that various situations can be contemplated, ranging from the case where the reservoir management problem and the pollution treatment can be completely decoupled to the more complex case where the two problems are completely merged. The second situation can obviously give rise to a whole class of specific models.

The last part of the paper deals with reliability evaluation. It is shown that various problems could be considered if the required information on plant availability existed. This information could be very crude, such as the binomial representation of plant availability given here, but it could also be much more sophisticated. Even with crude information, rather sophisticated reliability assessments can be made.

ACKNOWLEDGEMENTS

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APPENDIX 1: THE RIVER MODEL

The model used throughout this paper has been established for the Bormida River (Italy) by Rinaldi et al (1979); a full description of the model is given in that reference. The Bormida river model has been calibrated for a set of steady-state regimes, and the coefficients of the model expressed as functions of the flow. Referring to the expressions $K_i(\ell)$ introduced in section 3, the following relations have been found for the $K_i(Q)$.

$$K_2 \simeq K_1 = 0.2\ Q^{-0.43},\ K_3 = 16.4\ Q^{-0.8},\ K_4 \approx 0$$

where Q is measured in $10^3 m^3$/day and K in Km^{-1}.

In order to illustrate the use of imprecise estimates of the K_i in the derivation of the load curve we have supposed that for each flow Q the K_i have normal distributions with mean $K_i(Q)$ and standard deviations of 10 per cent of $K_i(Q)$.

The Bormida river is already regulated by a reservoir and thus no measure of the natural flow is readily available. Since one of our goals is to illustrate the modification brought about in the treatment system by the introduction of a reservoir, it is appropriate to assume flow regimes with sufficient variability throughout the year. In order to do so we have selected a flow distribution that follows the same pattern as a meridional river with a dry and a wet season.

The main pollution load in the Bormida river is due to an industrial discharge. For the sake of simplicity we did not consider the real characteristics of that discharge; we assumed instead that the load is equal to 18226 kg BOD/day, which represents 74.9 per cent of the maximum allowable load found in Figure 2.

Assuming this water to be similar to urban sewage (300 mg BOD/ℓ) this load corresponds to a flow of 60.7 $10^3 m^3$/day. There is obviously a contradiction in assuming such a discharge of wastewater that is larger than the minimum flow in the river (36.12 $10^3 m^3$/day). Because of the illustrative purpose of this text we did not take any action to eliminate this contradiction. In order to do so, it would suffice to increase the load of the wastewater. This would have forced us to recompute all our cost data for the biological plant.

APPENDIX 2: COST DATA FOR THE TREATMENT SYSTEM

Biological treatment: We consider activated sludge treatment plants achieving 40, 50, 60, 70, 80 and 85 per cent BOD removal rates. Other efficiencies could have been taken into account, but this would not have brought anything new to the reasoning. Using the model described in Tyteca and Smeers (1979), optimally designed treatment plants have been assumed leading to the evaluation of fixed and variable annual costs given in Table A.2.1. As indicated in the text variable costs have been assumed to be strictly proportional to the load removed. This allows us to derive a variable cost per gramme of BOD removed as indicated in Table A.2.1.

Table A.2.1. Costs of activated sludge treatment plants with different removal efficiencies; the influent flow corresponds to one population equivalent (150ℓ/day and 300 mg/ℓ BOD); 1 US dollar = 30 BF and 1 BF = 100 ct.

Efficiency	Fixed Annual Cost in BF/year	Variable Annual Cost in BF/year	Unit proportional Cost in ct/g BOD
40 %	2288	1248	18.99
50 %	2373	1304	15.878
60 %	2402	1311	13.30
70 %	2464	1395	12.13
80 %	2556	1455	11.07
85 %	2596	1502	10.76

For our purposes, and in order to simplify the computation, we have assumed an average cost of 13 ct/g BOD removed from the wastewater.

Activated Carbon Treatment: In order to develop a unit cost for activated carbon treatment, we have assumed that the treatment was applied to a fraction of the influent wastewater in order to arrive at a residual BOD concentration of 45 mg/ℓ. Any global BOD removal rate between 40 per cent and 85 per cent can then be achieved by varying the fraction of the flow that undergoes activated carbon treatment after the biological plant.

The amount of activated carbon required was computed using a Freundlich isotherm. More specifically, the following function has been chosen. Let M be the amount of carbon (in mg/ℓ) required and X (in mg/ℓ) the BOD eliminated by the treatment. We have

$$\frac{X}{M} = K\, C_f \quad ,$$

where C_f is the residual BOD concentration in mg/ℓ and the coefficients K and n are selected depending on the type of activated carbon used. For our purpose we took $K = 6.9(10^{-5})$ and $\frac{1}{n} = 1.8$. Since the residual BOD is 45 mg/ℓ we have

$$M = 15\ X \quad .$$

Consider now the fraction x of the water to be treated by activated carbon in order to obtain a concentration C_f given a concentration C_i in the effluent from the biological part of the plant. x must satisfy

$$x(45) + (1-x)\ C_i = C_f \quad ,$$

or

$$x = \frac{C_f - C_i}{45 - C_i} \quad .$$

The total quantity of activated carbon required per liter is then

$$15\ x\ (C_i - 45) \quad ;$$

hence the quantity required per mg of BOD removed in a liter of the water flowing out of the biological part of the treatment plant is

$$\frac{15 \times (C_i - 45)}{C_i - C_f} = 15 \text{ mg} \quad .$$

Taking a unit cost for activated carbon of 20 BF/kg we have a unit cost of 30 ct/g BOD removed per liter of wastewater. This leads us to state for the series system,

$$c = 13 \text{ ct/g BOD; } v = 30 \text{ ct/(g BOD/}\ell) \quad .$$

We now consider the parallel system. For each plant ℓ the unit cost of BOD removal is equal to

$$\xi\ 13 + (85 - \xi) \quad ,$$

which gives the figures of Table A.2.2.

Table A.2.2.

ξ	.40	.50	.60	.70	.80	.85
Unit cost $\overline{c+v}$	22	20	18	16	14	13

ξ is the BOD removal rate achieved in the biological part of the plant.

DESIGN AND OPERATION INTERACTIONS IN WASTEWATER TREATMENT

G. Olsson

1. INTRODUCTION

There is a strong relationship between process design and operation in wastewater treatment plants. This is more widely recognized now that operational control is becoming more common; and as operation and control has become more emphasized so new problems have come into focus. Many plants have been designed in such a way that control authority is too limited; this is due either to insufficient controllability of pumps, valves and compressors or to inflexible piping between the unit processes.

In Sweden sewage treatment plant construction has experienced a tremendous development during the last two decades. At first the requirements in performance were limited to maximum available BOD reduction, but have since been extended to include chemical precipitation in order to reduce the phosphorus content of the sewage. Since the 1960's both biological and chemical treatment have been required when granting permits for new construction of wastewater plants. Currently some 75 per cent of the population's sewerage is connected to combined biological and chemical treatment, 22 per cent to only biological while 3 per cent receive only primary treatment. This last group is usually connected to small works in sparsely populated areas.

Attention is gradually turning towards operation now that most of the facilities have been constructed. Maximum utilization has to be made of the plant design, operational costs have to be minimized and effluent quality has to be maintained and improved. The couplings between process design, recipient demand and operations have come to be more widely appreciated and it has been observed that plant design is often an obstacle limiting flexible and successful operation. A more flexible design (more piping, valves or instruments) is of course more costly. However, the increase in cost has to be balanced with the potential for saving operating costs.

The operational costs of wastewater treatment have risen from 1.0 Swedish kronor per cubic meter in 1971 to 3.5 kronor in 1978. The high cost of operations necessarily forces the emphasis to change from considerations of design to operation. Andrews et al (1979) have shown that similar conclusions can be made for conditions in the U.S. There the average number of years elapsed from the time a plant was put into operation to the time at which operation and maintenance costs total more than the initial investment is only 6.1 years.

Again, during the last few years other developments have taken place that will make possible significant improvements in operations. The most important developments are

-- computer developments
-- increased knowledge as represented by models
-- established control theory
-- new instruments

Today it is realistic from both a technical and an economical point of view to obtain standardized computer packages for specific tasks; the development of improved models has been significant; control theory has proven applicable in related areas, such as chemical engineering; and instrumentation has been improved. Even if there is still a gap between desired potential and actual availability of instruments, some probes have proven to be very useful. For example, dissolved oxygen probes are used on a routine basis and COD or TOC instruments have been successfully used for control purposes (Wells, 1979).

Thus for what reason are practical applications of control and operations still considered backward at many places? It has to be recognized, unfortunately, that significant incentives for good operation are lacking. Grant rules favour design as opposed to operation, one result of which has been an oversizing of plants in order to decrease operational costs. The consequences of not meeting the initially specified quality requirements are seldom clear and tangible. There is hardly any economic penalty for poor quality effluent and too little profit incentive to improve performance. The general lack of familiarity with on-line instrumentation and lack of education in dynamics and control are other obstacles.

A radically new attitude towards design and operation interactions has therefore to be adopted. New attitudes in education, consulting, legislation, grant rules, instrumentation, and so forth, are needed.

2. LONG-TERM CHANGES AND SHORT-TERM OPERATIONS

A wastewater treatment plant is never in a steady-state condition. Both the plant and control system designers have to be reminded of such an obvious fact. The time-varying nature of the plant and its input has consequences for tank design, actuator construction, piping flexibility, design of liquid sampling stations, instrumentation locations and control algorithms (Olsson, 1977). The term "dynamics" may sometimes be interpreted as meaning year-to-year changes and sometimes as hour-to-hour operations.

Let us distinguish between the concepts of automation and operational control. The former is concerned with the hourly or daily operations, while the latter may be human decisions in design, plant reconstruction or management.

Several long-term changes are such that the designer should take them into consideration from the very beginning. A couple of examples will illustrate the nature of year-to-year changes. First, input disturbance patterns may change significantly from year to year because of changes in industrial or agricultural establishments, new housing, etc. Both the hydraulic diurnal variation and the concentration and composition of the input may change. Therefore the plant has to be able to respond to varying hydraulic disturbance patterns, to new microbial disturbances, or to new risks of toxic inputs. Second, new regulatory demands may force the operation of the plant to be changed. Revised monitoring methods or new sensors for water quality may become relevant. Consequently the objectives for water quality can be specified differently such that not only yearly average quality values are stated but also peak values of the quality variables are related to standards. In Sweden nitrogen removal is generally not required. However, at the plant at Akeshov-Nockeby near Stockholm new regulatory specifications will demand a changed plant design since nitrification will be needed. The crucial question is how to adapt the design so that the specifications will be met at a minimum cost. Similarly, one can ask how easily can a plant be adjusted to satisfy new regulations? If BOD or suspended solids removal regulations become stricter, is the design flexible enough to allow for the new demands? Can by-passing be minimized in a more systematic manner?

Rising energy costs in the long-term have also changed the conditions for operation. For example, if the plant is supplied with digesters, methane production may be sufficiently profitable both for internal use and for commercial purposes. The use of dual-fuel engines ought to be considered. The goal for unit process operations depends on energy prices. Aerator operation is strongly coupled to digester performance and should be such that sludge transport costs are minimized and digester methane production is maximized.

Short-term changes appear in many different time scales--this includes seasonal to hourly operations. Nitrification illustrates well the seasonal variations since nitrification organisms are quite temperature sensitive and the effectiveness of nitrification is therefore different in summer and winter. In addition stream flows through the plant can be arranged differently in different seasons; recirculation as in the Kraus modification is one way of achieving better nitrification in cold climates.

In many Swedish plants the input organic load may be high in winter and low in summer. At the same time the heterotrophic organisms have larger growth rates in summer and therefore it may be desirable to use fewer aerators in summer than in winter. The settlers, however, should always be used to their full capacity. This demands a flexible piping system and such a flexible design will be more costly. On the other hand operational costs can be saved because, for example, there is a lower air demand or conditions for maintenance are better.

Too seldom plants are designed such that short-term disturbances can be handled successfully. Actuators have to be controllable, and a pump or motor ought thus to be supplied with variable speed control; a chemical dosage system would also be desirable.

Wastewater treatment plant dynamics include time constants within the range of minutes to several weeks. Consequently in evaluating real-time control on an hour-to-hour basis it is easy to make mistakes and to misinterpret the results. Dissolved oxygen (DO) control is a good example since it is relatively simple to control the DO concentration as a physical variable. Costs and savings can be estimated in a straightforward manner and comparisons can be obtained within a couple of days. The biological effects of DO control, however, will be noticed much later and it is necessary to make experiments over several months before a final evaluation of real-time control can be made. This has been clearly illustrated by Wells (1979).

3. MEETING FLOW DISTURBANCES

Hydraulic flows from municipalities are generally quite predictable and the composition of the wastewater does not radically change. On the other hand flows from industrial environments may vary more significantly and the same is true for flows resulting from weather changes. Both flow rate prediction (Beck, 1977) and hydraulic control are important for good operation. Here we mention a few design details that affect the control of hydraulic disturbances.

One can distinguish between external and internal disturbances; the former originate from the sewer system, and must be received by the plant, while the latter are created within the plant, for example by primary pumps or by recirculation between the unit processes. The pumping of raw wastewater is important for the whole plant operation. Hydraulic disturbances will affect both the aerators and the settlers and both the size of the flow and its rate of change will influence settling. It is therefore desirable to keep the flow-rate as constant as possible (Olsson, 1979). Pumps with variable speed control are thus important.

In order to equalize the sewage flow-rate large buffer volumes are required. Sometimes the trunk sewers can be used as equalization basins but the wastewater has to be kept only for a relatively short time in the sewer in order to avoid sedimentation problems. Undesirable septic conditions may also be encouraged by such practice. Sedimentation in the sewer may result in excessive load changes to the plant when the pump speed is increased.

Flow-rate measurements, it should be noted, are not at all trivial. Sometimes the level of the water in the sewer tunnel is measured and flow-rate is then calculated as the time-derivative of the level measurement. This measurement technique has to be used with great care since the accuracy of the derivative may be very sensitive to noise associated with the measurements. The application of magnetic flow meters is becoming more common and with better flow-rate measurements pump control can be made more accurate.

Step-feed control of the aerator is another means of meeting hydraulic disturbances, but note that this kind of control does not improve the BOD reduction under stationary conditions. It is, however, a control that is used in order to manage certain disturbances better, as reported in Busby and Andrews (1975). If a major hydraulic disturbance appears, the influent stream can be diverted to the tail end of the aerator. The return sludge flow-rate also has to be maximized so that the sludge can be stored at the head end of the aerator. For as long as the disturbance lasts the process performance may be poor but the process can at least be protected from the damaging effects of the disturbance. Without step-feed control there is no real possibility for handling such disturbances. Step-feed control can also be used to avoid bulking sludge problems or to cope with toxic disturbances. For the former it is possible to achieve a better F/M ratio in order to change the organic culture. For the latter it is too late to remove the toxic material once it has entered the plant but by step-feed control it is possible to avoid all the sludge organisms being killed.

For a flexible step-feed control controllable influent ports along the aerator are required. Moreover, if the flow-rates in the different influent ports are measurable, the chances for good step-feed control are much better.

It is also important that by-passing is minimized under all circumstances. Therefore the plant design should ensure that the by-pass valves are not accidently opened. This can be checked in different ways but both the effluent suspended solids concentration, the effluent dry-mass flow and the influent hydraulic load ought to be measured or estimated, (Gillblad and Olsson, 1978).

4. DISSOLVED OXYGEN CONTROL

The concentration of dissolved oxygen (DO) is a vital process variable in the activated sludge process. It has both an economic and a biological implication. Since a DO concentration exceeding a certain value (1-2 mg/l) does not help the growth of organisms, an increase of aeration merely unnecessarily increases the amount of energy consumed. Therefore the level of DO concentration maintained should be minimized but still be kept sufficiently high. For this control it is important to have a flexible design for the system of air supply; variable speed compressors are desirable so that energy can be saved by control.

As shown by Olsson and Andrews (1978) the DO spatial distribution is important in a non-homogeneous reactor. Ideally it should be possible to adjust not only the average DO concentration but also its spatial distribution. The total air demand could then be minimized to meet just the needs of the biological oxygen uptake rate while still satisfying the minimum mixing requirements of the aerator. At the design stage a preparation for flexible measurements ought to be made since the DO concentration has to be measured at several points along the reactor and it may also be important to measure the air flow-rate along the channel.

5. CHEMICAL PRECIPITATION

Chemical precipitation can be used for different purposes and not only to reduce the phosphorus content but also as an extra control variable during extreme loads to reduce the BOD and suspended solids content. This is important because most of the treatment plants (at least in Sweden) are already completed. A more flexible operational strategy can therefore be introduced and the different ways of using the available design can be thoroughly explored.

Part of the effluent BOD is in suspended form and can be settled by precipitation together with the phosphorus precipitate. Statistics from the Swedish Environmental Protection Board (1974) for a large number of plants showed that only a 78 per cent BOD reduction was achieved with biological treatment but a 95 per cent BOD reduction was possible when chemical treatment was added. Both the absolute reduction and the variability of the effluent quality were significantly improved by chemical precipitation. Such a result is discouraging from the point of view of biological process operation since these plants were not at all over-loaded. Part of the results is, however, encouraging in that chemical precipitation can improve a poor operation. Simultaneous precipitation has also been tested with good results. The investment costs are much less than those of post-precipitation since no special flocking or settler tanks are needed.

6. RECIRCULATION OF CHEMICAL SLUDGE

Thomas (1972) observed that already during the 1960's chemicals could be saved by simultaneous precipitation as the waste sludge was recirculated to the influent stream. The adsorbtion of phosphorus in the chemical sludge could be increased if the phosphorus concentration in the influent water was increased. Humenick and Kaufman (1970) made experiments on recirculating lime or aluminium sludge from post-precipitation to the aerator with similar results. Hultman (1978) has made a survey of different Swedish experiments on chemical precipitation. In these, sludge from post-precipitation has been recirculated either to the aerator or to the influent wastewater. The general experience is that a greater phosphorus reduction can be achieved with the same amount of chemicals.

7. NITRIFICATION COMBINED WITH CHEMICAL PRECIPITATION

Even if nitrogen reduction is not demanded, nitrification can be used to reduce the chemical dosage required for phosphorus reduction. In order to achieve nitrification the sludge age as well as the air supply have to be significantly increased compared to the demands for carbonaceous BOD removal. This gives an interesting optimization problem in which the increasing energy requirements for nitrification are compared to the savings of chemicals. One Swedish comparison (Grönqvist et al 1978) has shown that an increase of the sludge age from 5 to 20 days resulted in operating cost increases of 5-10 per cent.

In order to obtain optimal precipitation conditions the pH of the sewage has to be well defined and this can be achieved by using an extra dosage of chemicals. The size of the dosage depends on the water alkalinity, which can in fact be decreased by biological nitrification. This decrease corresponds to a bicarbonate decrease of 8.3 mg per mg oxidized ammonium-nitrogen. The combined use of nitrification and aluminium post-precipitation has been successfully tested at several Swedish wastewater works, for example, Himmersfjärden outside Stockholm and Örebro (Larsson, 1975; Isgård et al, 1974). At Örebro the aluminium dosage was reduced from 120 to 85 mg/l. At Huskvarna similar experiences are reported by Strandsäter (1979); there the total aluminium dosage was decreased from 135 to 89 mg/l. At the same time the effluent total phosphorus content decreased from 0.55 to 0.24 mg/l; overall plant operation was also improved and no risks for sludge bulking were noted.

8. INTERNAL COUPLINGS BETWEEN UNIT PROCESSES

The unit processes of a treatment plant are more or less strongly coupled to each other. In the design of a plant it ought to be considered as standard practice to take these couplings into consideration and particularly so for the feed-back streams. The main liquid and sludge streams create natural couplings in the system, such as the feed-forward coupling from the aerator to the settler. The coupling between the aerator operation and methane production has also already been mentioned. Some feed-back streams are thus now considered here.

The sludge supernatant from digesters or centrifuges can be returned to the influent main stream or directly to the aerators. This means that there is quite a significant load change for the aeration process. These operations can be scheduled such that the disturbances are used to compensate some of the influent load changes. Elsewhere the effect of chemical recirculation has been studied experimentally but so far little analysis of the results has been presented. Back-washing of deep-bed filters can further cause major hydraulic disturbances of the activated sludge process. Since the backwashing takes only a short time (a few minutes) the shock-wave can be significant and can upset the secondary settlers for a long time. Buffering of the back-washing water is therefore important.

9. CONCLUSIONS

Several consequences have to be considered when design and operation interactions are studied closely. The coupling between phenomena having different characteristic times has to be remembered because long-term decisions will affect the success of short-term operations and vice versa. Internal interactions between different unit processes must also be taken into account. Often operation of existing designs can be improved by redesigning the piping or by the feedback of streams. Operational goals must be optimized not only for each individual unit process separately but for the plant as a whole. The interactions between the wastewater treatment plant and the sewer system as well as the receiving water have to be considered, both in terms of operation and of plant design.

Better incentives for good operation must be created and this concerns both the system of grant rules and the monitoring of effluent quality. Education of operators, consulting engineers and designers must include a greater emphasis on an awareness of dynamical behaviour, instrumentation and computer technology.

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THE ROLE OF MICROPROCESSORS IN WATER QUALITY MANAGEMENT: Problems and Prospects

S. Marsili-Libelli

1. INTRODUCTION

Water quality monitoring and management entails complex sampling programs at a large number of locations across an entire catchment with a few delicate procedures to search for relevant water quality indicators. It has been demonstrated that even limited sampling programs may soon overwhelm the capacity of the local water authority workforce. In the case of real-time monitoring, with the purpose of water quality control, this burden is all the more intolerable and the establishment of a catchment-wide automatic monitoring network becomes necessary. The limitations of manual sampling programs have been clearly outlined in a recent study of the Bedford Ouse river system (Taylor, 1977) where a monthly sampling rate already exceeded the sample handling capacity allocated to the development of a water quality model. It should be recalled that even hourly variations may be significant in connection with the calibration and use of dynamic water quality models.

The aim of this paper is to highlight the potential for employing microprocessors within the context of a real-time water quality monitoring network. In this situation microprocessors are regarded as low-cost, flexible computing power which can be installed along the decentralized network to support a variety of activities: data acquisition and instrument management, data exchange with the central computer and communication-line management, peripheral process control and actuator management.

Emphasis is placed on the structural aspects of monitoring network and peripheral devices, rather than on algorithms for real-time processing of water quality data. Nevertheless, it should be stressed that the two issues are strongly inter-related and a few applications of advanced control algorithms have been made possible by the availability of economically attractive hardware. The influence of selecting a specific system architecture on overall performance will be examined together with the resulting tradeoffs between hardware and software.

Two major trends are now evident in computer installations for process control: the previous preference for a single large-scale central computer (Harrison, 1972) is gradually being superceded by the emerging philosophy of dividing the computational burden among a host of small subunits, each designed to carry out a specific set of tasks, and whose basic component is the microprocessor. Extremes in both directions should be avoided, the former since a failure in the central computer would be fatal for the whole plant, whereas the latter might result in a rigid architecture not easily amenable to subsequent modifications and unable to perform complex computational tasks given the inherent limitations of the individual decentralized microprocessor.

This report aims to present a unifying framework whereby the most essential features of control-oriented microprocessor systems in the environmental quality area can be analyzed and assessed by adapting the general concept of computer and communication science to this specific field of application. Since the basic concepts are discussed in detail elsewhere (Korn, 1978; Peatman, 1977; Doll, 1978) they will be used without further definition in the following.

2. DEFINING A WATER QUALITY INFORMATION NETWORK

Water quality monitoring may well entail locating sensors a long distance apart and covering a catchment of some hundred square kilometers. It is therefore unthinkable to design the network with a single large central computer receiving remote information by analog means. Conversely, what is envisaged here is a two-level digital communication network in which each remote station is equipped with a microprocessor performing peripheral tasks such as instrument polling, data acquisition, self-testing, data encoding and communication-line management. As to general system tasks and performance, a few options can be considered. Remote data may simply be stored onto mass memory to be retrieved later and to serve as a source of information for the local water authority in defining its water quality policy. The central computer can also be suitably equipped with algorithmic resources, such as decentralized, hierarchical control policies, to make use of two-way communication lines for feeding back control decisions to those remote stations which have control capabilities, such as those monitoring wastewater treatment plants or storage lagoons. The overall system is shown in Figure 1.

Before going into details of the various subsystems, a general assessment of the advantages introduced by distributed modular microprocessors can be stated:

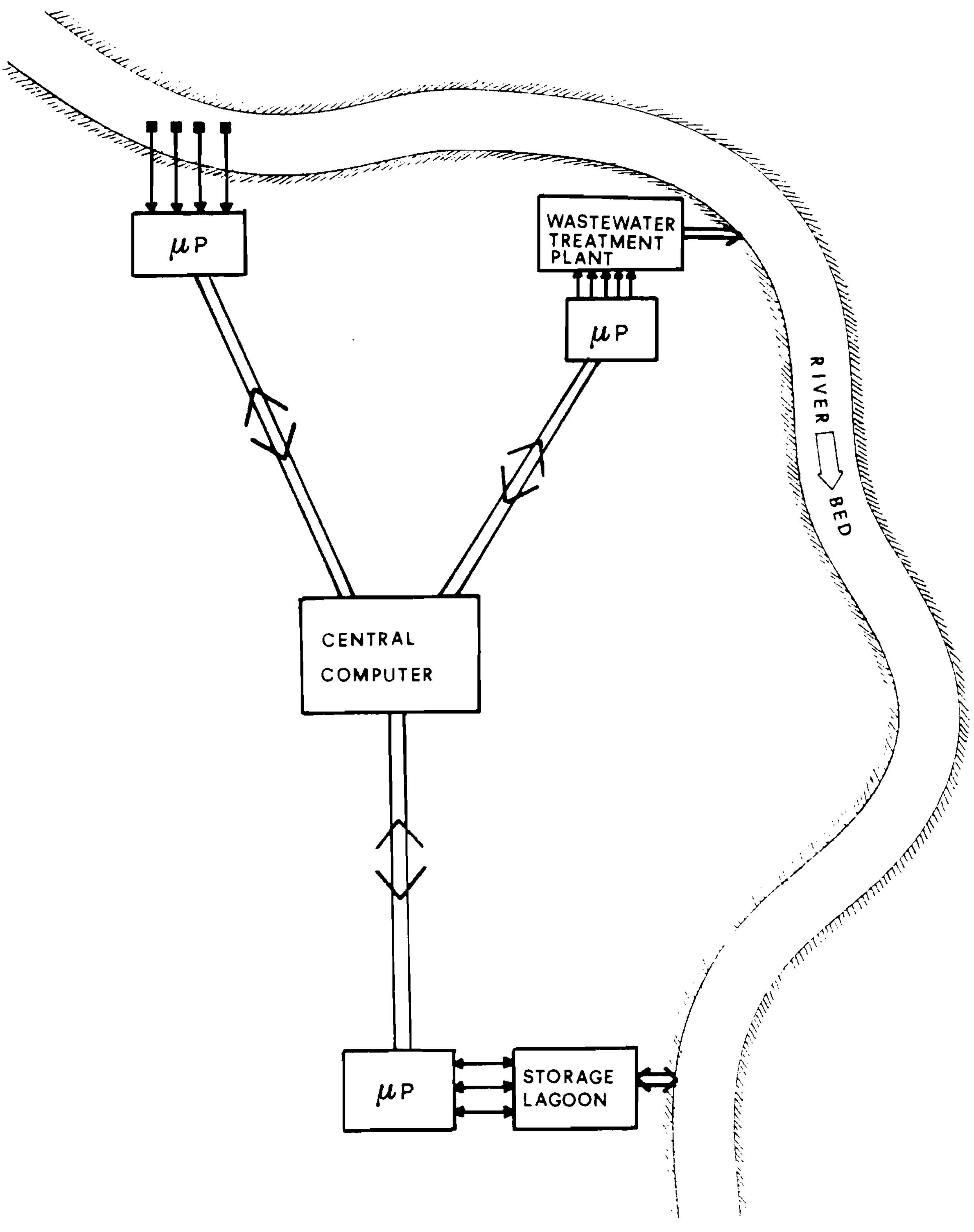

Figure 1. A scheme for a water quality monitoring network, showing peripheral stations (surveillance and/or control-oriented), the central computer and the digital communication links.

1. Software and/or firmware needed at each location can be tailored, tested and altered independently of the rest of the system. This eliminates complicated and costly operating systems required by a single large computer to supervise directly all the remote instruments.
2. A host of control and "housekeeping" functions such as instrument testing and calibration, local loop control, data filtering, can be assigned to the peripheral microprocessor, thus easing the requirements of the central computer and, therefore, its dimension and price.
3. Modularity within each microprocessor installation can be exploited. Different functions at different locations can be accomplished simply by imbedding specific software into the Programmable Read Only Memory (PROM), which can then be plugged into microprocessor motherboard sockets, whereas common problems such as communication-line management can be programmed once and for all for all the units. Such standardization reduces design time, enables the system to adapt easily to changing needs and requires less documentation, maintenance and personnel training.
4. Failure in a peripheral system will not impair the rest of the network. Furthermore, given the limited cost of microprocessors, backup duplication for improved reliability is economically feasible. Also, when the central computer is temporarily down some control functions can be relieved by peripheral microprocessors; collected data can be temporarily stored in local low-cost mass memory, such as cassette magnetic tape, and communicated later after the central computer has resumed control of the network.

Following this broad appraisal of a decentralized monitoring network, the specific tasks of microprocessors within a remote sensing station are now examined in detail. The system architecture of Figure 2 is assumed with the microprocessor regarded as an intelligent interface between the analog and digital worlds.

2.1 Water Quality Parameters

Water quality is intrinsically related to water quantity, and therefore quality monitoring stations should comprise flow-gauging devices. In addition, however, many more quantities contribute to the definition of water quality. Those for which automatic instrumentation is available are briefly examined with regard to their role in defining the state of water quality.

- *Dissolved Oxygen:* represents key information about water pollution and is also an important control parameter. Its measurement is quite simple and reliable whenever a minimum of maintenance is provided, especially maintenance of the probe.

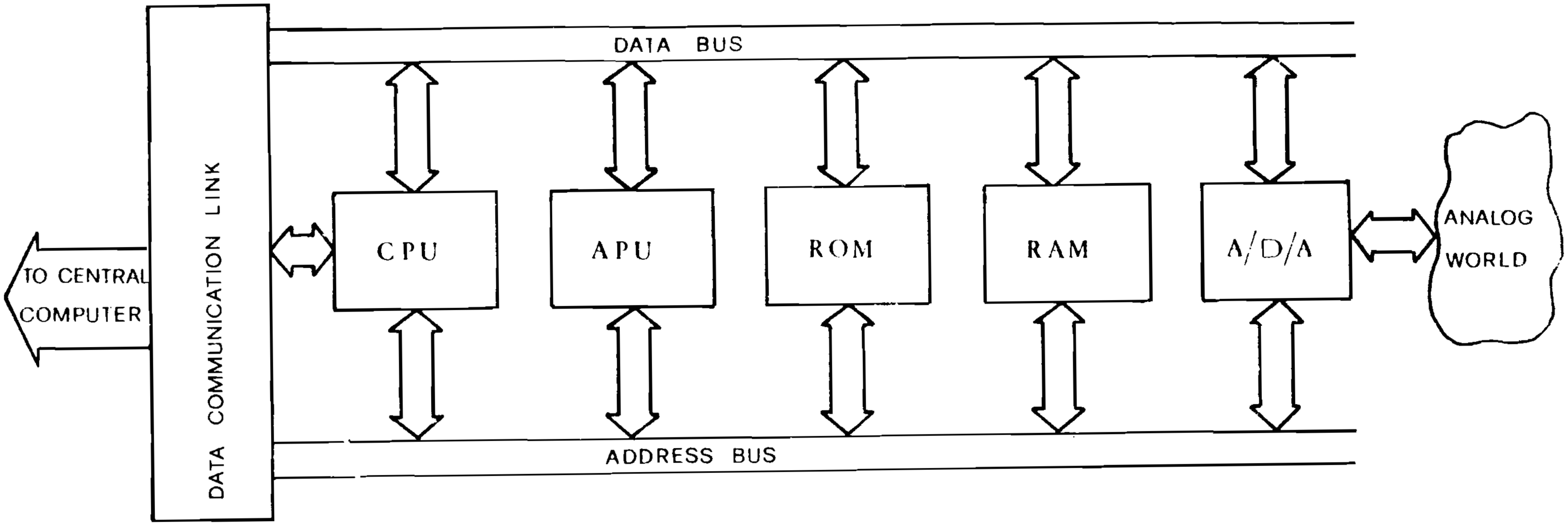

Figure 2. General architecture of a microprocessor-based station. The analog world and the digital communication link can interact via the microprocessor, which in addition to conventional components (CPU, ROM, RAM) features an Analog/Digital/Analog two-way converter and an Arithmetic Processing Unit for hardware floating-point processing (see section 3)

- *Temperature:* is necessary for determining the dissolved oxygen saturation level and, therefore, the oxygen depletion due to pollution. Simple and reliable process instrumentation is available, usually provided together with dissolved oxygen probes.

- *Conductivity:* is an indirect measurement of ion concentration in water due to a dissolved electrolyte. In freshwater, conductivity can be related to total dissolved solids, providing a quick quality check. Reliable conductivity cells are available requiring little maintenance.

- *pH:* water purification processes are influenced by this index. Glass electrodes can be employed wherever turbulence is negligible. Instrumentation with process output, commonly voltage, is widely available.

- *Redox:* oxidation-reduction potentials give an indication of the amount of self-purifying reactions taking place in the stream. In wastewater treatment a link has been shown to exist between redox and the extent of treatment. Only the net potential is detected, unless a specific metal/metal salt electrode is used instead of a noble metal. Redox measurements should always be performed in connection with pH and temperature measurements, these being two factors affecting redox value.

- *Residual Chlorine:* this is always monitored at the output of a tertiary treatment unit after chlorine has been added to water for disinfection. The iodine substitution method is widely used in process instrumentation.

- *Solar Radiation:* silicon cells are employed to measure the amount of solar light received by the water body. This quantity is important in relation to algal growth and photosynthetic oxygen production.

- *Turbidity:* optical process equipment measures the amount of light passing through a quartz jar filled with a sample of the water under test. This simple optical test yields a voltage proportional to the turbidity. Finely dispersed media, although inert, may constitute a relevant pollution factor acting as a shelter for bacteria and reducing the effects of solar radiation. In addition settling creates a slime layer impairing normal benthic processes.

- *Nitrate:* the ion NO_3^- can be determined by ultraviolet absorption, with a peak at 203 and 257 nm wavelength. Related instrumentation is highly sophisticated and requires ancillary equipment and trained personnel for maintenance. Properly used, its indication may be valuable.

- *COD & TOD:* both Chemical Oxygen Demand (COD) and Total Oxygen Demand (TOD) determinations have recently been transformed into sophisticated process instruments, where cathalitic bed oxidation and zircon dioxide oxygen emitting cells play a key role. Their cost is extremely high, and their reliability is debatable. A certain degree of maintenance is required as well as some environmental protection, thus making these devices suitable only for manned surveillance stations or for wastewater treatment plants, where they can be used to monitor the influent organic load.

2.2 Microprocessor Interactions with the Analog World

Depending upon the type of the remote station it supervises, each microprocessor may have control over several closely located instruments and/or actuators. For instance, surveillance stations along the river are intended for data collection only, whereas a station supervising a wastewater treatment facility should be capable of control actions in accordance with local information and remotely sent commands regarding the rest of the system under control. In either case instruments communicate with the microprocessor by means of data and address busses, as shown in Figure 2 where the basic microprocessor system is depicted for the present field of application. Interface functions are many, including analog signal conditioning, sample/hold circuitry, conversion control logic, digital encoding of analog quantities, buffering the system data bus. A specific interface architecture suitable for process control is depicted in Figure 3 for the A/D section and in Figure 4 for the D/A counterpart. Particularly, the use of three-state buffers (Korn, 1978; Peatman, 1977) enables high quality 12- or 16-bit converters to be matched with a low-cost 8-bit microprocessor, since the result of conversion can be loaded into memory (with two successive LOAD cycles) from the temporary storage represented by the buffer. Interconnections with the microprocessor are reduced to essentials, with only timing being provided in addition to busses and a single line serving as a backward link. The conversion takes place as follows: since process instrumentation can be regarded as "slow" with respect to the microprocessor time-scale, no sophisticated interrupt system is needed. By contrast, instrument polling is initiated by the program simply by addressing the required device; the address decoder both selects the correct analog input and initiates the conversion procedure by means of the START OF CONVERSION command. Upon completion of the conversion procedure an END OF CONVERSION flag is sent to the processor status register. The sampling routine periodically tests the appropriate bit in the status register and initiates the loading phase when the flag is set. With this kind of arrangement, requiring minimum hardware, polling a set of eight instruments may require one second. This time may be intolerable for fast process applications, but is thought to be reasonable for water quality sampling. On the other hand, such a solution seems particularly convenient when interfacing microprocessors with complex instrumentation such as automatic COD/TOD equipment, where the processing of a single sample may take some minutes to perform. In such cases the microprocessor is left available for other tasks and service of the COD/TOD analyzer is

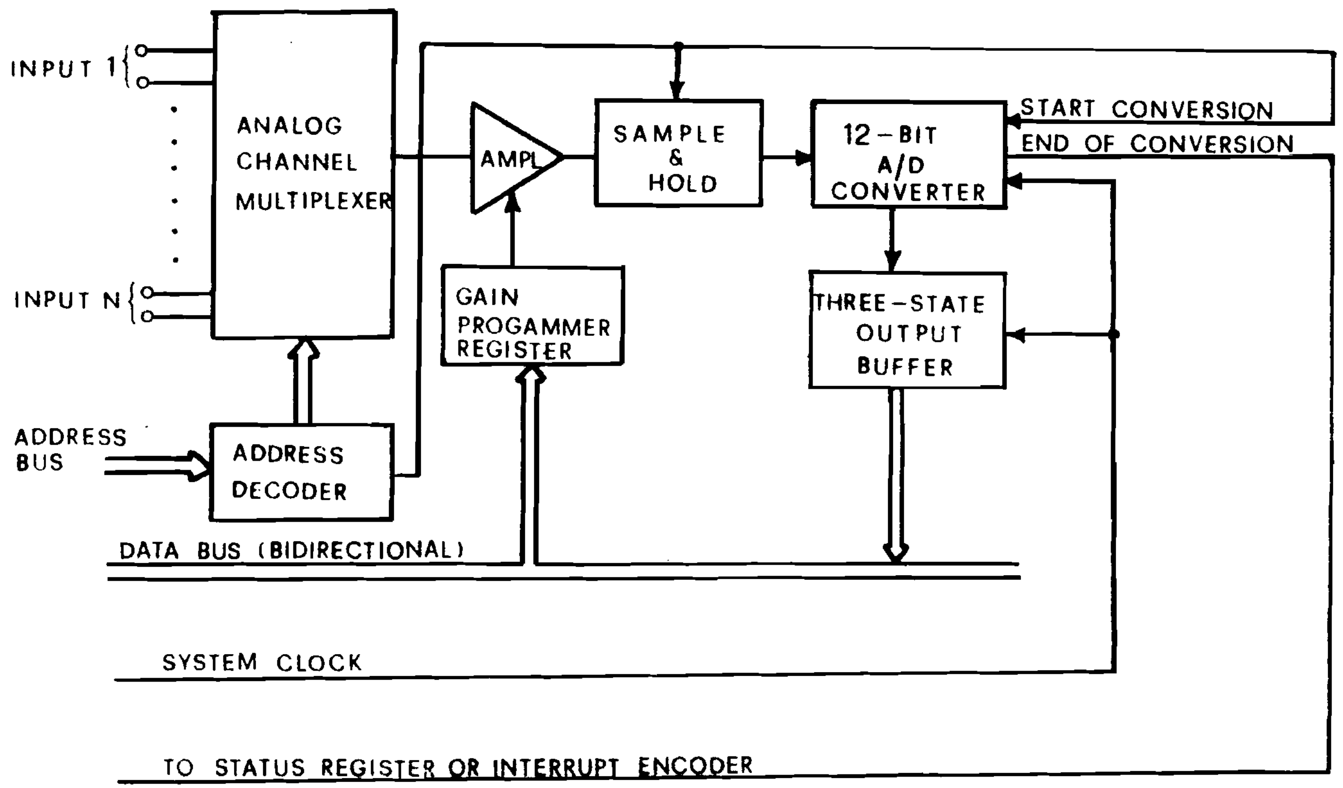

Figure 3. Schematic diagram of the Analog/Digital converter. The input multiplexer selects the channel to be sampled through the address bus decoding device. The end of conversion pulse is interpreted by the microprocessor as an interrupt request or a flag bit (according to the required speed of response). To service the device, the microcomputer enters a data-acquisition routine which loads the content of the three-state buffer into memory via the data bus.

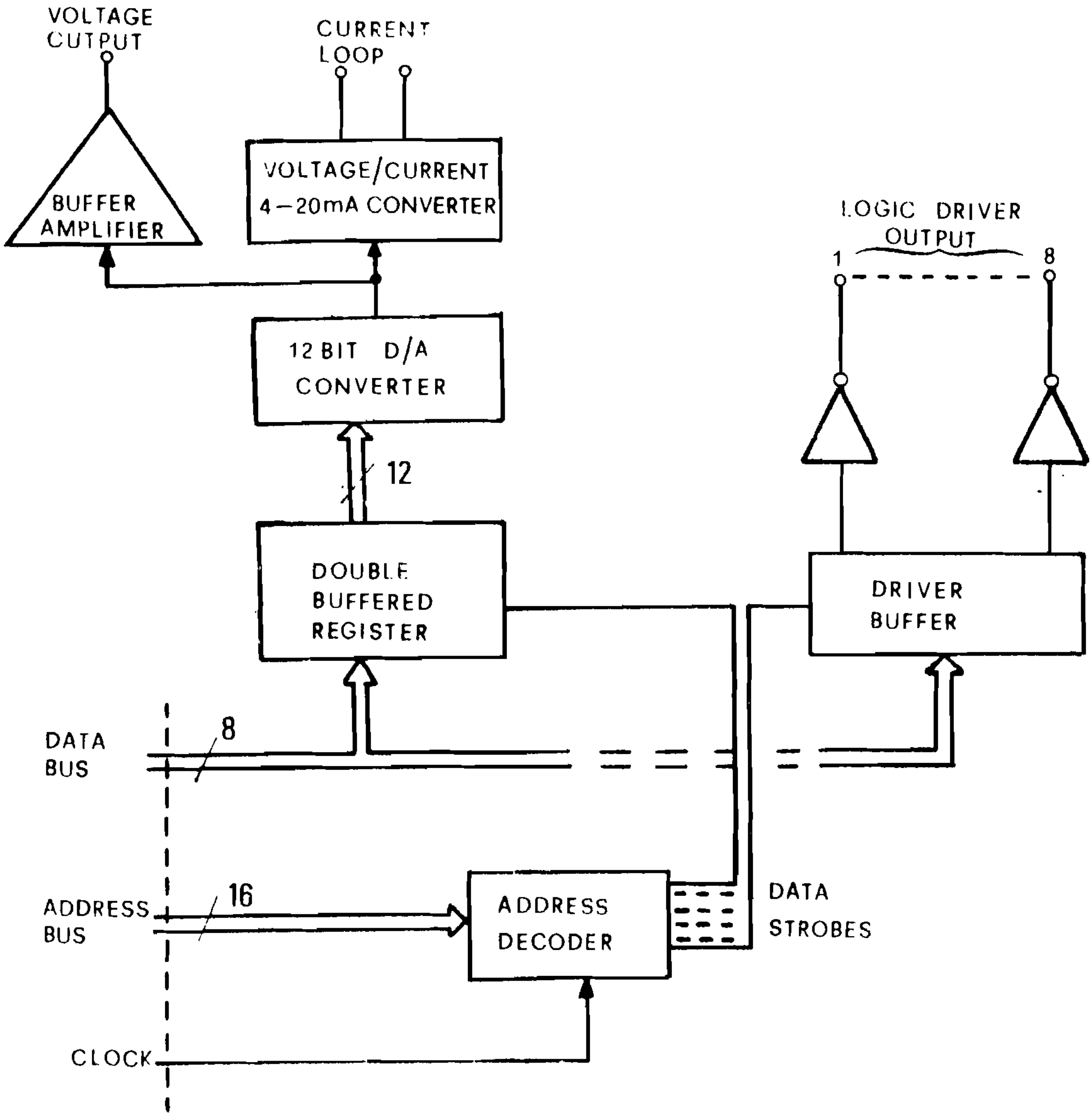

Figure 4. Schematic diagram of a Digital/Analog converter. The particular output port is selected via the address bus and a timed decoding circuit. Buffered registers are required to load 12-bit variables via an 8-bit data bus. Voltage and current outputs should be provided in case current-loop actuators have to be driven. Logic output is also useful in the case of stepping devices, for example, when stepping motors are provided as actuators.

requested by a status flag being set upon measurement completion. This avoids the use of dedicated circuitry for interrupt priority encoding, such as is shown in Figure 5 and of special interrupt servicing subroutines. Thus if only fast-response instrumentation is employed, the microprocessor can poll them sequentially and therefore only one line is necessary to feed the flag or interrupt command to the microprocessor.

Instruments with their own digital output can be considered as another option. In this case communication with the microprocessor takes place completely at the digital level using "handshaking" control lines (Peatman, 1977) whereby the device signals to the microprocessor when data are available on the data bus, receiving a "data acknowledged" signal when the data are successfully accessed by the microprocessor and transferred into memory. The highest degree of sophistication is currently represented by the complex handshaking protocol proposed by the Hewlett-Packard Company and named IEEE488 (Peatman, 1977).

With regard to the measurement resolution, all the instruments considered provide a process output (in addition to a visual display), which is usually a low impedance voltage port capable of a full scale of 100 mv. This means that using 12-bit converters the resolution is 24.4 μV. Moreover, the analog side of the interface should provide differential, isolated inputs so that no two instruments have a common ground loop or any common path for bias current. This ensures decoupling of disturbances and the minimization of common mode errors.

2.3 Protocol Definition and Data Link Efficiency

Specifying a protocol for communication with the central computer is largely influenced by the type of data and physical channel being used. For the latter there is a choice between radio relay systems and leased telephone lines. The former is widely used in connection with water quantity monitoring, where rain gauges transmit rainfall data with no provision for repetition in the case of wrongly received data. In this situation error correction occurs automatically, since rainfall is instrinsically an integral measurement and the next measurement simply compensates for the missing previous measurements. Moreover, in rainfall monitoring there are bottlenecks during heavy rain periods, when the transmission pace from all the rain gauges increases. In this situation polling becomes prohibitive and fast acquisition modes must be used, otherwise provision for error correction is ceded. In contrast water quality data collection does not present this kind of problem, since data variability is not linked to any specific meteorological event. Moreover, the instantaneous value of the quantities is of importance rather than their cumulative distribution and therefore error minimization of a single sample should be sought. Subsequent data will contain no inherent provision for past data correction. These points lead to the conclusion that a simple relay network may have limitations due to the lack of two-way communication and the difficulty of communication--the stations

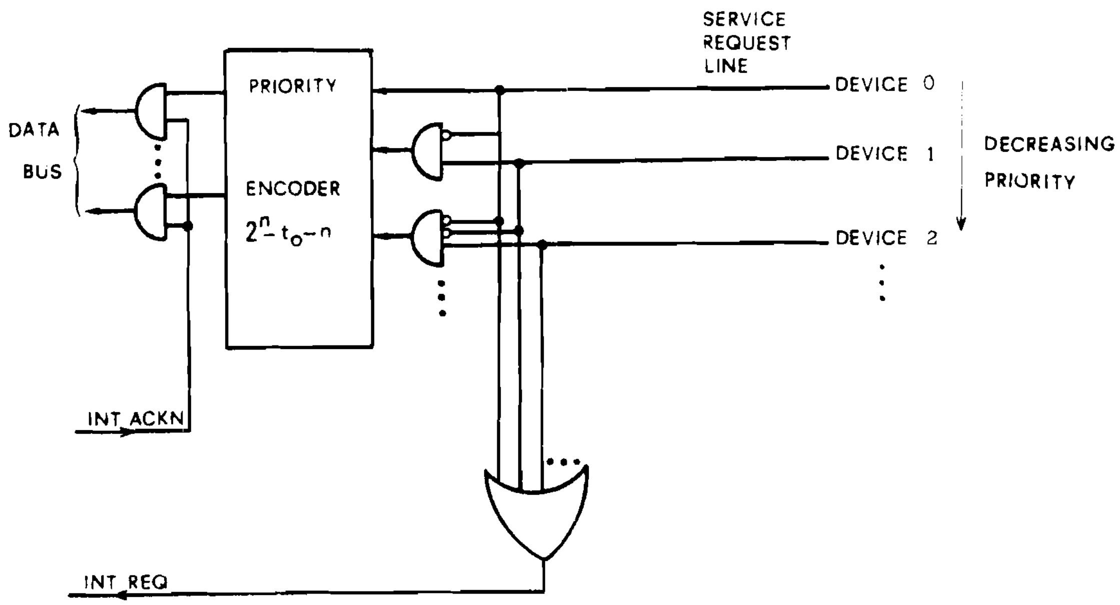

Figure 5. A simple way to create priorities among a number of interrupt lines. Interrupt philosophy is preferred when peripheral servicing is assigned a high preference, otherwise flag bit testing may represent a simple way of servicing a great number of peripherals.

are positioned along the river course at the bottom of the valley and there will be obstacles such as hills, buildings, and trees that impair signal propagation. The alternative of leased telephone lines is now being examined with respect to this system's two-way communication capability which allows for handshaking control of data acquisition and two-way information flow.

Several protocols exist for very complex data links, such as the Binary Synchronous Communication (BSC) or Synchronous Data Link Control (SDLC) (Doll, 1978); these are available from computer vendors and are certainly too complex for the present application. The following, instead, is intended as a guideline for specifying a simple communication protocol for environmental quality monitoring networks.

Since data validity has priority over sampling speed, a *Stop-and-Wait, Automatic Request for Repeat* (ARQ) protocol is considered, whereby the message correctness is checked immediately after transmission of each data block. The channel organization takes the form of Figure 6, with the backward line from the central computer to the remote microprocessor carrying the acknowledge signal pertaining to correct data reception; if data are incorrectly received, a message repetition is immediately requested. For this reason the microprocessor data-buffer interfacing with the communication link must have dimensions sufficient to save the message being transmitted until successful completion of the handshaking procedure.

This arrangement determines the time interval between one block transmission and the next, which is required by the handshaking procedure, as follows:

$$\Delta T = t_{fp} + t_{rd} + t_{rp} + t_{cm} + t_{rr} \qquad (1)$$

where

t_{fp} = forward propagation time delay

t_{rd} = receiver detection time

t_{rp} = reverse propagation delay

t_{cm} = control message transmission time

t_{rr} = receiver reaction time

Line protocol formating will be different for microprocessor and central computer messages. A possible scheme is shown in Figure 7(a) for the microprocessor and in Figure 7(b) for the central computer.

The header control initiates the handshaking procedure which resets the receiver buffer and error decoder; then a station status flag is transmitted followed by the station and

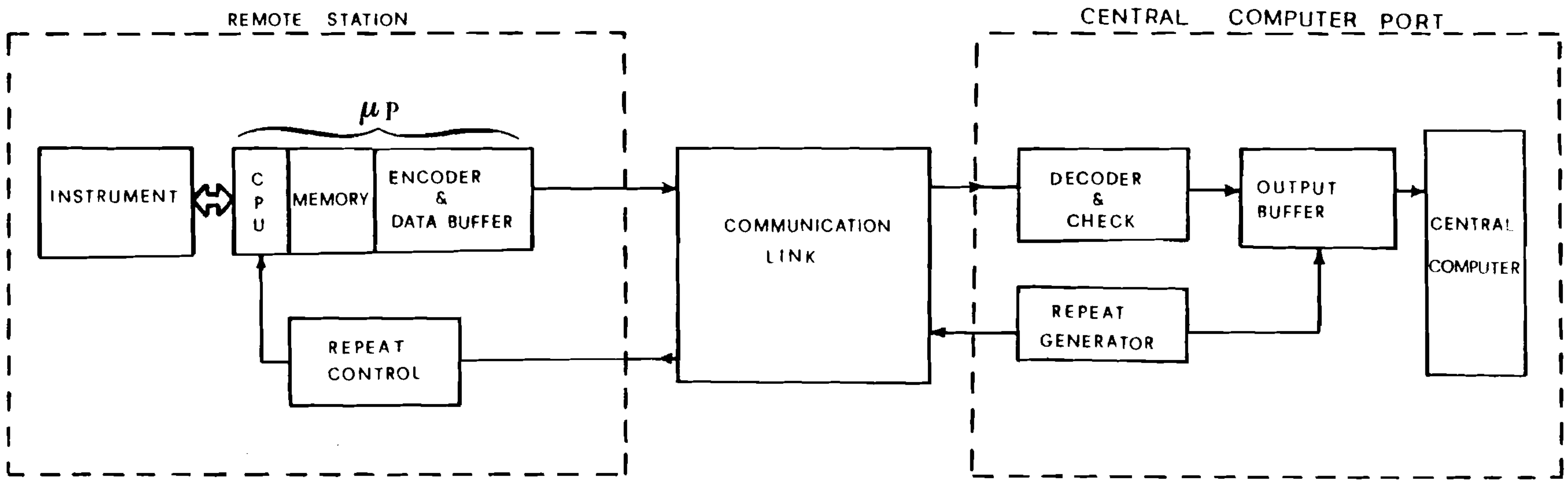

Figure 6. Block diagram of the communication link between each remote station and the central computer, in the full-duplex fixture. Whenever a wrong message is detected, immediate repetition is requested. For this reason the message being transmitted is saved in the microprocessor data buffer until central computer acknowledgement is received.

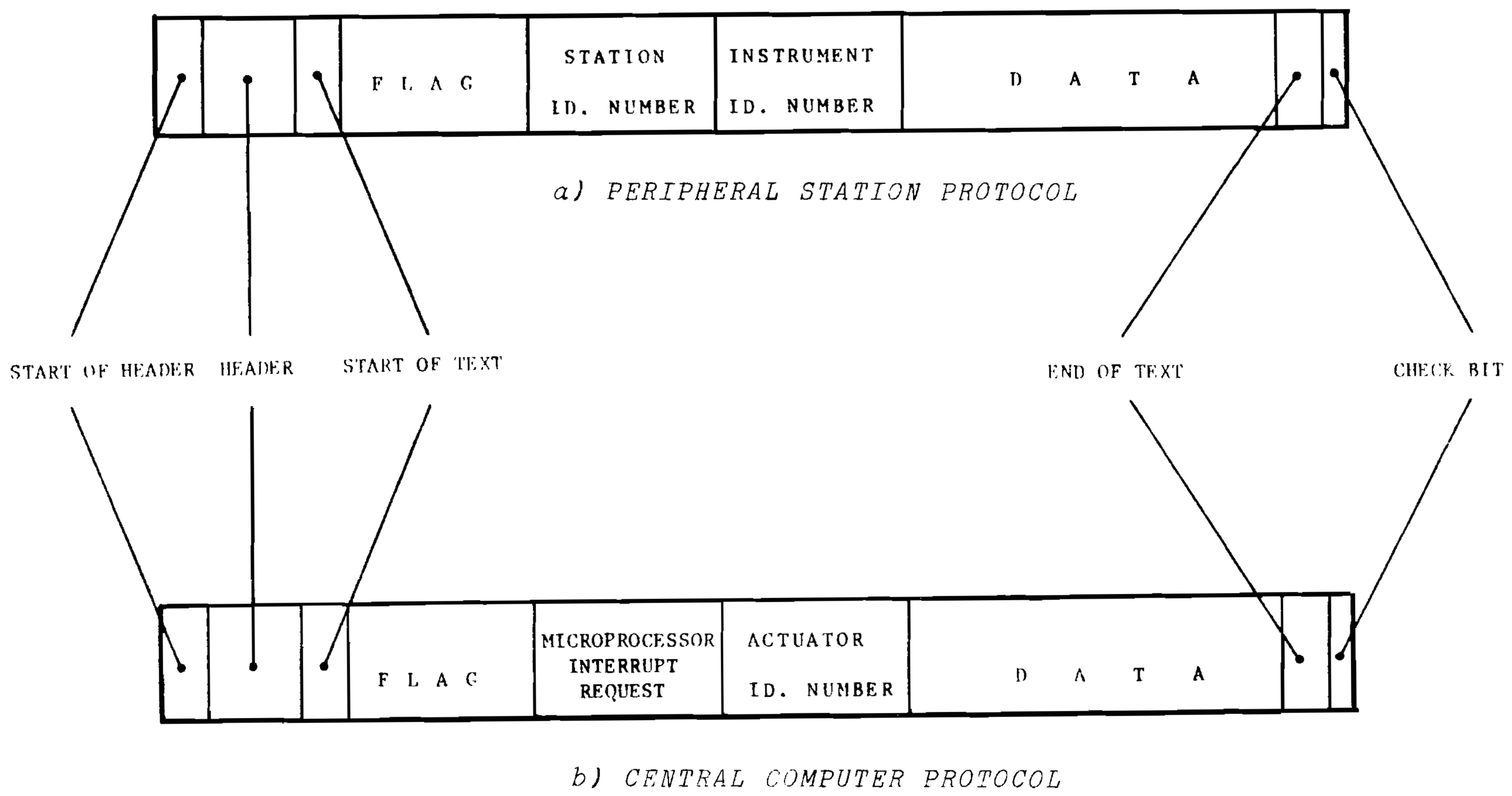

Figure 7. Communication line protocol for the proposed monitoring/control network. Message formats have been reduced to a minimum, in order to produce an efficient protocol, suitable for low cost, sub-voice grade, leased lines.

measurement identification numbers. It is noted in passing that complex identification labels, such as those proposed in Taylor (1977) can be avoided, since all the information concerning station and measurement features can be stored permanently in the central computer and retrieved using a single key such as the identification number. This 16-bit word can be used as an addressing aid if the central computer is equipped with a Direct Memory Access (DMA) facility, so that data acquisition can be interleaved with normal CPU activity. End-of-text and check bits are used where needed. With word lengths as indicated 255 stations can be connected in the same network and accessed either by sequential polling or in a random fashion with exchange data in both directions.

The message format for the central computer is shown in Figure 7(b) where the header control characters complete the handshaking procedure towards the microprocessor while clearing its buffer and the "interrupt disable" status bit. Thus the peripheral system is switched to other tasks upon successful reception of the previous data block. Conversely, if an erroneous message is detected a repeat request is issued, which in turn produces a different header to maintain the "disable interrupt" status and initiates a new transmission of the old buffer content. In this case the following flag field is such that it inhibits decoding of the trailing message fields.

Commands from the central computer may also be sent towards peripheral stations as a result of centralized control algorithms, for example, to change major control loop set-points, whereas minor control loops are entirely under local microprocessor control. Whenever a control message is issued it affects normal microprocessor operation, hence the interrupt request field specifies request priority. After the interrupt request has been acknowledged, the actuator identification number and control data are acquired as input parameters of suitable interrupt service subroutines.

Having defined the line protocols, the requirements of the transmission link can now be stated in terms of bandwidth and efficiency. Since speed is not the crucial factor, sub-voice grade leased lines can be used, for example, the Series 1000 channels with a rate of 150-bit/sec, whose monthly charge does not exceed $100. This fixture provides full duplex communication, with reliable modern equipment being available. The channel rate determines the actual single bit time slot, which in this case is 6.67 msec. Finally, the link efficiency can be evaluated by computing the Transfer Rate of Information Bits (TRIB) (Doll, 1978).

$$\text{TRIB} \triangleq \frac{\text{number of information bits accepted by receiver}}{\text{total time required to get the bits accepted}}$$

which can be specified as

$$\mathrm{TRIB} = \frac{(M-C)(1-P)}{M/R + \Delta T} \qquad (2)$$

where

M = message block length (bits)

C = average number of non-information bits per block

P = probability of block retransmission

R = line transmission rate (bit/sec)

ΔT = guard time between blocks, as defined by (1)

For the protocol defined above, the following values hold

$M = 51$ bits $\quad C = 15 \quad P = 0.1$ (worst case)

$R = 150$ bit/sec $\quad \Delta T = 0.5$ sec

yielding $\quad \mathrm{TRIB} = 38.5$ bit/sec .

This means that it takes little more than one second to transfer a single sample onto the central computer. This time is considered sufficient in view of the type of data being transmitted. In this respect a rainfall monitoring network would require more stringent specifications, since during heavy rain periods time gaps between consecutive messages may be reduced significantly and to the extent of requiring much higher TRIB and bandwidth values. For this reason radio relay links are preferred in rainfall monitoring.

Conversely, a constant sampling time is assured when dealing with water quality variables. For example, consider a system with 30 stations each equipped with 10 different instruments. In the worst case polling of this entire network requires 5 minutes, an extremely short time compared with the time-scale of self-purification or pollution propagation phenomena. Yet sampling in connection with steady-state models, such as that referred to by Taylor (1977), requires measurements to be taken in the sequence imposed by the flow-time delays between successive stations, which are at least of the order of one hour. Therefore, the proposed scheme has a sufficiently high overhead to avoid the clustering situations typical of rainfall measuring systems.

3. UPGRADING PERIPHERAL MICROPROCESSOR PERFORMANCE

The structural arrangement of the peripheral station, as shown in Figure 2,deserves further comment. The microprocessor is regarded as a local manager for instruments and communication links. But more tasks may be performed locally and without affecting the execution of central computer tasks. As an example, identification programs for tuning the parameters of a local process is best performed locally, without burdening the communication line with an extra load of data. The architecture of Figure 2 is a rather conventional one in the sense that a Central Processing Unit (CPU) has control of both data and programs and is supported by either Random Access Memory (RAM) and Read Only Memory (ROM) for storage and retrieval of data and/or programs during the execution of a task. But in addition an Arithmetic Processing Unit (APU) has been added to enhance the microprocessor capabilities of stand-alone computing power. The following considerations explain how and why the use of an APU may considerably expand the range of problems that a small amount of computing power can tackle.

In most control applications higher numerical accuracy is required than that which can be achieved by the single integer arithmetic normally employed in standard microprocessors. Floating-point routines, on the other hand, cannot be efficiently programmed given the limited hardware resources of a microcomputer. This results in inefficient codes both for memory requirements and execution time. APU represents an effective alternative to software-supported floating-point computation. Being marketed as an independent chip it can be connected with the rest of the system via the data and address busses and it is regarded merely as a memory location in which the operands are "stored" and from which the results are "read". Figure 8(a) shows the basic interconnections involving busses and control lines from the CPU. Using APU leaves the memory free for application programs and provides a dramatic decrease in execution time. From the point of view of logic, the interconnections between APU and the rest of the system require four bytes of memory that will be termed as follows, for mnemonic convenience:

TOAPCO	:	to APU command
TOAPDA	:	to APU data
FRAPDA	:	from APU data
APST	:	APU status

These four bytes are addressed as normal memory locations, whereas the decoding circuit of Figure 8(a) provides selection of the APU device and its required functions whenever the appropriate address is present on the address bus. Figure 8(b) depicts the logical communication scheme between APU and CPU. As an example, suppose that a certain operation between two operands has to be performed using APU. The following program segment can then be defined using the labels defined above:

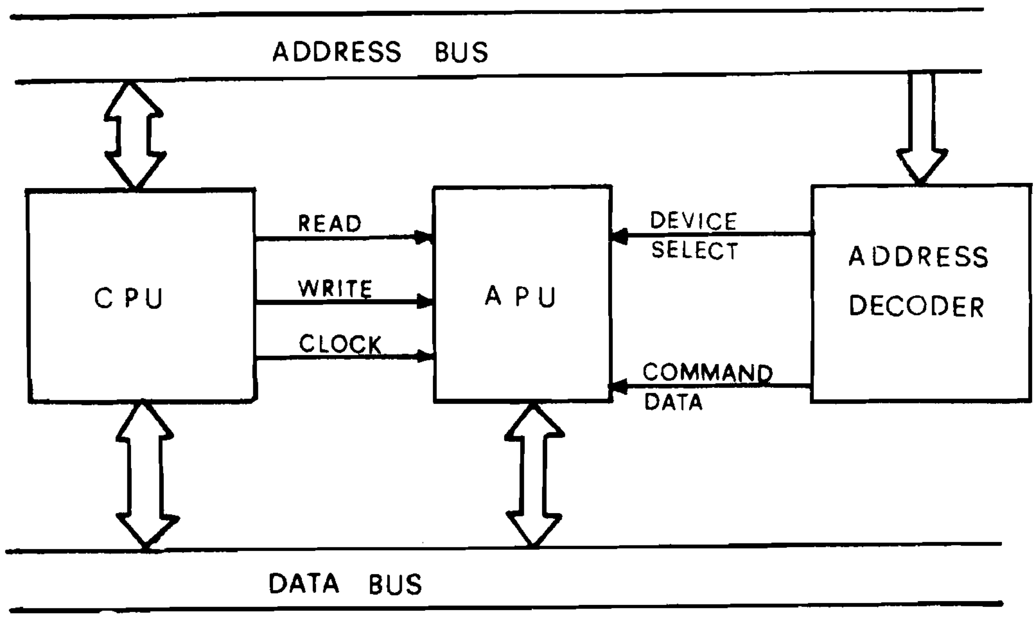

Figure 8a. System wiring to interconnect APU with the rest of the microcomputer system. Both system buses are involved in addition to a few control lines.

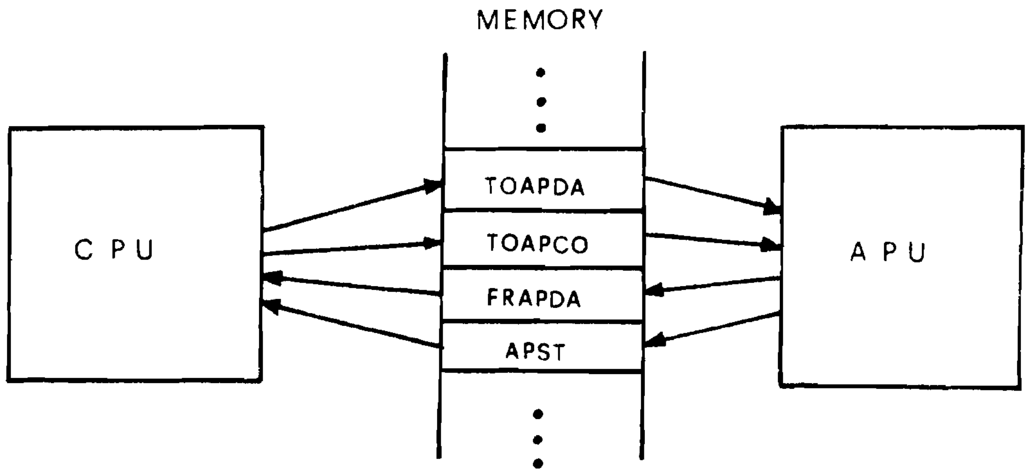

Figure 8b. Logical communication paths between CPU and APU. Data/Command exchange occurs via four virtual memory locations, depending on the kind of exchange. Both commands and data can be sent to APU, whereas data and APU status can be read back. Actually, data to and from APU involve access to the top location of the APU stack structure.

```
         code                      comments

         LDA A                     Load operand A into accumulator
         STA TOAPDA                Load APU stack with operand A
         LDA B                     Load operand B into accumulator
         STA TOAPDA                Load B into APU stack (A is
                                    pushed down)
         LDA OPER                  Load into accumulator the code of
                                    operation
         STA TOAPCO                Transfer command to APU
    WAIT LDA APST                ) Wait loop to test APU status bit
         ASL ACC                 { for completion of operation
         BSC WAIT                )
         LDA FRAPDA                Load into accumulator the result
```

It should be emphasized how neatly such complex operations can be handled. The above program segment is quite general--only the OPER variable needs to be changed according to the kind of operation to be performed. This modularity allows the programmer to merge such segments wherever required while storing into appropriately labeled memory locations the code numbers of the various operations. Table 1 represents a simple benchmark comparing APU versus subroutine-supported floating-point processing.

Table 1. Comparison of APU with subroutine-supported floating-point processing

OPERATION	APU		SUBROUTINES	
	memory bytes	exec. time	memory bytes	exec. time
+/-	40	168 μs	192	190 μs
×	40	80 μs	236	750 μs
÷	40	82 μs	244	780 μs

4. UPGRADING PROGRAMMING EFFICIENCY

Microprocessors usually lack software support in terms of high-level language compilers. As a result, programs have to be developed using assembly language, thus making it cumbersome to mechanize algorithms of even moderate complexity. Some microprocessor firms do supply ROM resident BASIC interpreters thus easing the programming effort, although the resulting code has very poor memory and time efficiency. One way out of this stalemate is represented by *macroprocessors* (Brown, 1973) as buffer packages that accept as inputs codes which are written in a user-defined high-level language, and produce translations in assembly language. A general purpose macrogenerator has recently been implemented (Pelacani, 1979) using APL as a metalanguage, whereby the user can define his own source language and a set of programs (macrodefinitions) each defining an operation with any desired degree of complexity. Once these programming tools have been defined, each program statement within a source language program will be analyzed, interpreted and replaced by the corresponding macrodefinition, taking into account possible looping and branching. Notice that macrodefinitions can be defined at more than one level, only the lowest of which need be written in assembly language of the host microprocessor. Thus intermediate-level macros can still be defined in terms of high-level language statements. During program translation and code generation, replacement of high-level statements is made by the corresponding macros, thus expanding the source code into a single-stream assembly code. This represents an alternative to subroutine branching, since macro substitution (avoiding parameter passing procedures) is preferred for reasons of time efficiency, whereas memory efficiency can be optimized by careful formulation of macrodefinitions.

One of the assets of this approach is the freedom in defining the high level language, possibly making it transparent to some hardware features which it may be helpful to retain for efficient programming. For example, preserving the stack structure of APU enables the programmer to write programs using Reverse Polish Notation (RPN) thus resulting in efficient codes which can even be tested beforehand using pocket computers.

Two common algorithms, representing benchmarks in progress, have been implemented: a three-term discrete-time controller and a least-squares estimator, using the following algorithms

a) Three-term controller

$$u_t = \sum_{\sigma=1}^{n} a_\sigma u_{t-\sigma} + \sum_{\sigma=1}^{n} b_\sigma (y^{sp} - y_{t-\sigma}) \qquad (3)$$

where

u_t = control value

y^{sp} = set-point of the regulated variable

y_t = actual value of regulated variable at time t

a , b = numerical weighting coefficients

b) Least-squares estimator

$$\hat{\underline{\theta}}_t = \hat{\underline{\theta}}_{t-1} + (y_t - \underline{U}_t^T \hat{\underline{\theta}}_{t-1}) P_t \underline{U}_t \quad (4)$$

$$P_t = P_{t-1} - P_{t-1}\underline{U}_t (1 + \underline{U}_t^T P_{t-1} \underline{U}_t)^{-1} \underline{U}_t^T P_{t-1} \quad (5)$$

where $\hat{\underline{\theta}}_t$ = vector of estimated parameters at time t

$\underline{U}_t$ = vector of past process inputs and output

y_t = process output at time t

Both algorithms were easily coded using the mentioned macrogenerator. The source programs resulted in 17 and 57 statements respectively, yielding assembly codes of 86 and 268 lines. These automatically generated codes when compared with handwritten, optimized assembly codes, have an efficiency loss of less than 3 per cent. Thus, automatic program generation seems an ideal tool for systematic and efficient program translation for a microprocessor. Of course, a large computer should be available on which the macrogenerator can be permanently located. The central network computer could serve in this capacity and the resulting assembly codes could be loaded into peripheral microprocessors using the communication links.

CONCLUSIONS

The aim of this appraisal was to outline the potential and benefits of using microprocessors in water quality monitoring networks. It has been shown how the widespread trend of decentralized computation and the increasing availability of low-cost computing power could be exploited to establish a reliable monitoring network. An attempt has been made to define some of the most basic features of such a network and to point out its differences with respect to systems for rainfall gauging stations. Emphasis has been placed on defining the kind of instrumentation with which each remote station should be equipped and on how the peripheral microprocessor could be employed to run the routine tasks of the station and to manage the communication line with the central computer. Moreover, a quantitative appraisal of line protocol and its capabilities has been presented, together with some hardware and software tools that might render the use of the microprocessor more systematic and reliable in the process industries in general. Intensive research is being conducted to obtain a deeper understanding of the capabilities of the ideas discussed in sections 3 and 4.

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MODELING AND FORECASTING WATER QUALITY IN NON-TIDAL RIVERS: THE BEDFORD OUSE STUDY

P.G. Whitehead

1. INTRODUCTION

In addition to being the major sources of water, river systems are used as the principal disposal pathways for waste material from man's activities. Such waste material alters the concentration of many chemical substances in water and impairs the quality and thus the usefulness of that water. Moreover, the variety of pollutants generated by a highly industrial society appears to grow continuously and, as discussed by Stott (1979), 'the problems of water quality are now more difficult and demanding than water quantity'.

While, in general, average water quality in the UK has tended to improve, in certain respects there have been grounds for concern. For example, some water authorities have been observing progressively increasing levels of nitrates in their system. The mechanisms governing these increases are not wholly understood and, as a result, strategies for the management of nitrate levels have not been fully identified. In particular, nitrate levels in the River Thames and the River Lea have increased dramatically over the past ten years with the average concentration increasing from 4 mg N/l in 1968 to an average of 11.1 mg N/l in 1977 in the River Lea (Thames Water Statistics, 1978). This level is close to the WHO limit of 11.3 mg N/l and at certain times of the year nitrate levels in the Lea have in fact exceeded the WHO limit, thereby preventing the abstraction of water for potable supply. Moreover, the observation that certain acceptable limits of quality are exceeded from time to time indicates that desirable stream quality is not only quantified in terms of, say, yearly average indices. Transient, intermittent deterioration of quality is also important, and may be of growing concern for the future.

In this paper water quality models developed during the recent Bedford Ouse Study (Bedford Ouse Study, 1975, 1979; Whitehead et al 1979, 1980) are briefly described and applied to assess the impact of effluent on the river system. Concern over the future water quality in the Bedford Ouse has led to the development of an extensive automatic water quality monitoring and computer controlled telemetry system. Water quality models are included in the mini/micro computer system and provide forecasts for operational management. In the paper models of ammonia and dissolved oxygen are developed using the extended Kalman filter (EKF) technique applied to data obtained from the automatic monitors; the utility of such forecasting schemes is also discussed.

2. MODELING FOR WATER QUALITY MANAGEMENT

There has been a tendency in recent years to categorize water quality models as either planning or operational management aids. However, such a breakdown is not strictly correct since planning models provide the "steady-state" or annual average water quality conditions and identify measures which alter the natural distribution of water quality in time and space in accordance with an overall development objective. Steady-state planning models do not account for the uncertainties in the system, such as errors associated with sampling measurement and the imprecise knowledge of system mechanisms and provide only a rough guide to likely future water quality levels.

By contrast operational management is concerned with short-term (hourly or daily) behaviour of water quality; models are thus required for selecting optimal operating rules and control procedures and for providing real-time forecasts of water quality in river systems.

A third intermediate stage between planning and operational models is required during the detailed design of a water resource system. Here, there must be some consideration of risk, and information on the day-to-day changes in river quality is required, since it is the transient violation of water quality standards that creates particular problems. The approach of digital simulation provides a convenient method of analysing systems during this design phase; historic and synthetic inputs can be simulated and information on the distributions of water quality used to assess risk. If the model is to be useful for the purpose of design it should possess the following properties:

(i) It should be a truly dynamic model, being capable of accepting time-varying input (upstream) functions of water quality which are used to compute time-varying output (downstream) responses.

(ii) The model should be as simple as possible yet consistent with the ability to characterize adequately the important dynamic and steady-state aspects of the system behaviour.

(iii) It should provide a reasonable mathematical approximation of the physico-chemical changes occurring in the river system and should be calibrated against real data collected from the river at a sufficiently high frequency and for a sufficiently long period of time.

(iv) It should account for the inevitable errors associated with laboratory analysis and sampling, and account for the uncertainty associated with imprecise knowledge of the pertinent physical, chemical and biological mechanisms.

3. AN INTEGRATED MODEL OF FLOW AND WATER QUALITY

Mathematical models that satisfy these four properties have been developed during the recent Bedford Ouse study (Whitehead et al, 1979, 1980) and the principal interactions between flow and water quality components of the model are illustrated in Figure 1. The underlying hydrology of a river system is modeled using a deterministic non-linear storage model in order to relate flow variations at downstream points in the system to input flows at the upstream system boundaries. Having accounted for most of the flow variations with the deterministic streamflow model, the residual between the deterministic model output and the observed downstream flow is modeled using stochastic methods of time-series analysis (Whitehead, 1979). The stochastic times-series models represent the residual flow variations due to rainfall and runoff effects. As shown in Figure 1, information on flow is transferred to physico-chemical models of water quality, which contain the principal mechanisms governing water quality behaviour and are based on a mass balance over the reach.

The structure of these models is based on a transportation delay/continuously stirred reactor (CSTR) idealization of a river (Beck and Young, 1976). The mathematical formulation of this model is in terms of lumped-parameter, ordinary differential equations and draws upon standard elements of chemical engineering reactor analysis, e.g. Himmelblau and Bischoff (1968). As indicated by Whitehead, Young and Hornberger (1979), this idealization can be shown to approximate both the analytical properties of the distributed-parameter, partial differential equation representations of advection-dispersion mass transport and experimentally observed transport and dispersion mechanisms (Whitehead 1980).

The principal advantages of this model over the equivalent partial differential equation descriptions are:

(i) the simplified computation required to solve the lumped-parameter differential equations;

(ii) the availability of statistically efficient algorithms for model identification and parameter estimation that can only be readily applied to the lumped-parameter form;

(iii) the availability of extensive control system methods which may be used for management purposes and are most suited to the ordinary differential equation model.

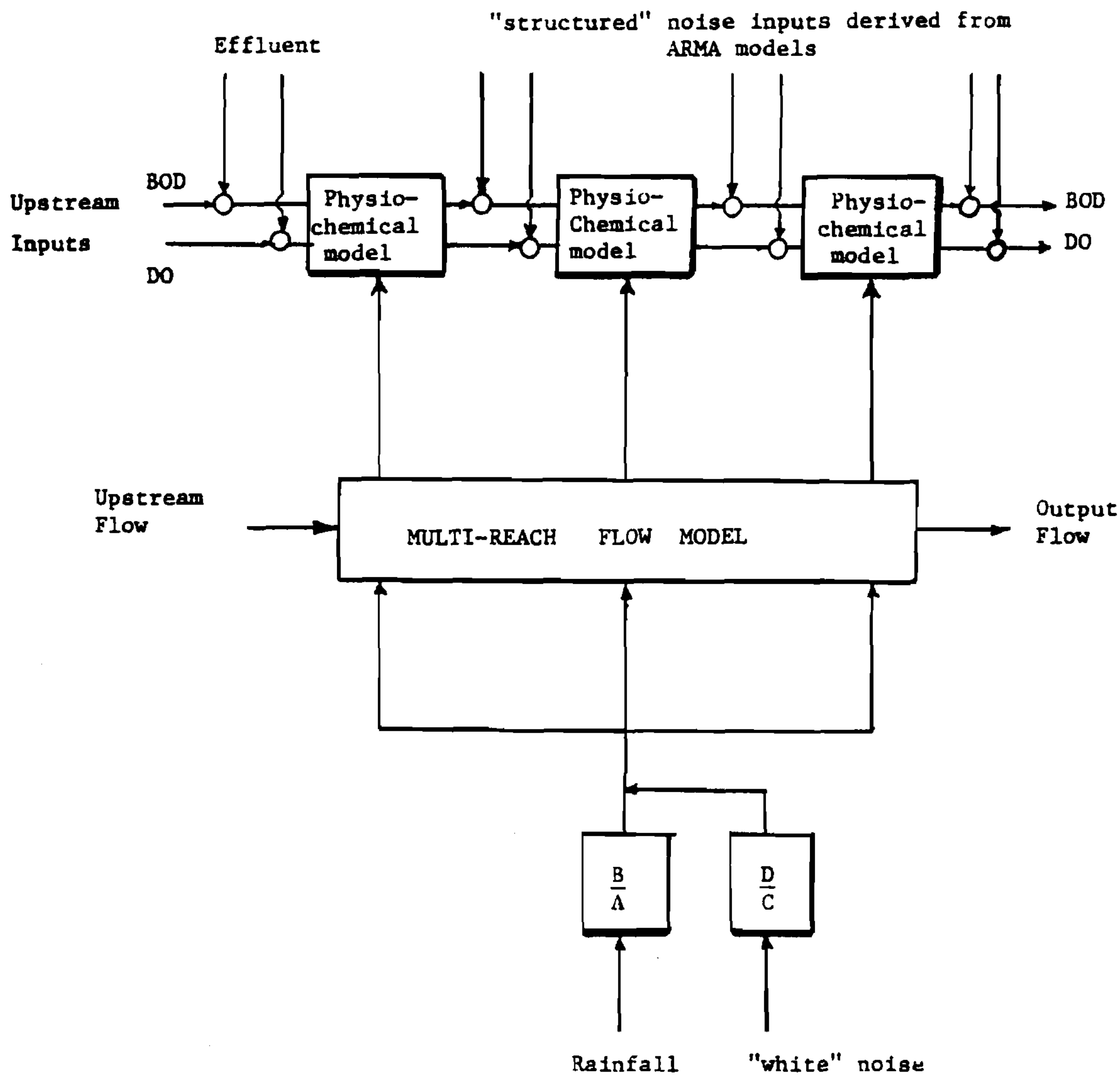


Figure 1. Interaction between Hydrological and Water Quality Models

The mathematical form of the model is derived from a component mass balance:

For the CSTR,

$$\frac{d\underline{x}(t)}{dt} = \frac{Q(t)}{V}\underline{\tilde{u}}(t) - \frac{Q(t)}{V}\underline{x}(t) + \underline{S}(t) + \underline{\zeta}(t) \qquad (1)$$

and for the transportation delay,

$$\underline{\tilde{u}}(t) = \underline{u}(t - \tau(t)) \quad ,$$

where

$\underline{u}(t)$ is the vector of input, upstream component concentrations (mgl^{-1}),
$\underline{\tilde{u}}(t)$ is the vector of time-delayed input, upstream component concentrations (mgl^{-1}),
$\underline{x}(t)$ is the vector of output, downstream component concentrations (mgl^{-1}),
$\underline{S}(t)$ is the vector of component source and sink terms ($mgl^{-1}day^{-1}$),
$\underline{\zeta}(t)$ is the vector of chance, random disturbances affecting the system ($mgl^{-1}day^{-1}$),
$Q(t)$ is the stream discharge (m^3day^{-1}),
V is the reach volume (m^3),
$\tau(t)$ is the magnitude of the transportation delay element (day),
t is the independent variable of time.

The errors associated with the laboratory analysis and sampling are included in the observation equation,

$$\underline{y}(t) = \underline{x}(t) + \underline{\eta}(t) \quad , \qquad (2)$$

in which,

$\underline{y}(t)$ is the vector of observed (measured) downstream component concentrations (mgl^{-1}), and
$\underline{\eta}(t)$ is the vector of chance measurement errors.

Equations (1) and (2) provide the basic description of the conceptual water quality model. The identification and estimation of these models against water quality data is given in detail elsewhere (Whitehead et al, 1979, 1980; Beck and Young, 1976).

4. THE BEDFORD OUSE STUDY

The Bedford Ouse Study was initiated in 1972 by the Great Ouse River Division of the Anglian Water Authority and the Department of the Environment. The objective of the study was to develop and utilize water quality models in the planning, design and operational management of the Bedford Ouse River system in central eastern England. In particular the development of the new city of Milton Keynes (see Figure 2) is likely to have a considerable impact, and effluent from the city is discharged some 55 kilometres upstream of an abstraction plant supplying water to Bedford.

The research has therefore been directed towards obtaining models of water quality which could be used to investigate the impact of effluent on the aquatic environment. Details of the Bedford Ouse Study are given elsewhere (Bedford Ouse Study, 1975, 1979; Whitehead et al, 1979, 1980) and the integrated models of flow and water quality discussed in the previous section have been extensively applied to the Bedford Ouse River system. For example, a typical simulation of flow based on data from the upstream flow gauging stations and the daily rainfall in the area is given in Figure 3. This shows the simulated river flow superimposed on the observed flows together with a plot of the residual error. The mean percentage error of 8.6 per cent is within the accuracy of the flow gauging stations estimated at 10 per cent by the Great Ouse River Division. In addition, the model explains 99 per cent of the variance of the original flow series and the errors are within 10 per cent of the observed flow for 70 per cent of the time. The model has been validated using several years' data and it appears that the combination of a deterministic flow routing model and stochastic rainfall-runoff model provides a satisfactory representation of the system.

4.1. Assessing the Impact of Effluent on River Water Quality

Water quality models for the Bedford Ouse have been developed for chloride, dissolved oxygen, biochemical oxygen demand, total oxidized nitrogen and ammonia.

A typical simulation for nitrate over 1974 is given in Figure 4 and again upstream water quality information can be used to simulate downstream behaviour reliably. In addition, since the models are based on mass balance principles, it is possible to assess the impact of effluent in the river system. Figure 4 shows the effect on downstream nitrate levels assuming an effluent flow from Milton Keynes of 114,000 m^3 day^{-1} with nitrate levels of 10 mgl^{-1}. During high flow conditions the impact of the effluent is minimal because of dilution effects, and upstream sources of nitrogen and runoff effects predominate. In this situation nitrate treatment at Milton Keynes would have relatively little effect and alternative methods of overcoming the high nitrate levels are required, such as blending with groundwater or reservoir water at the abstraction plant at Bedford.

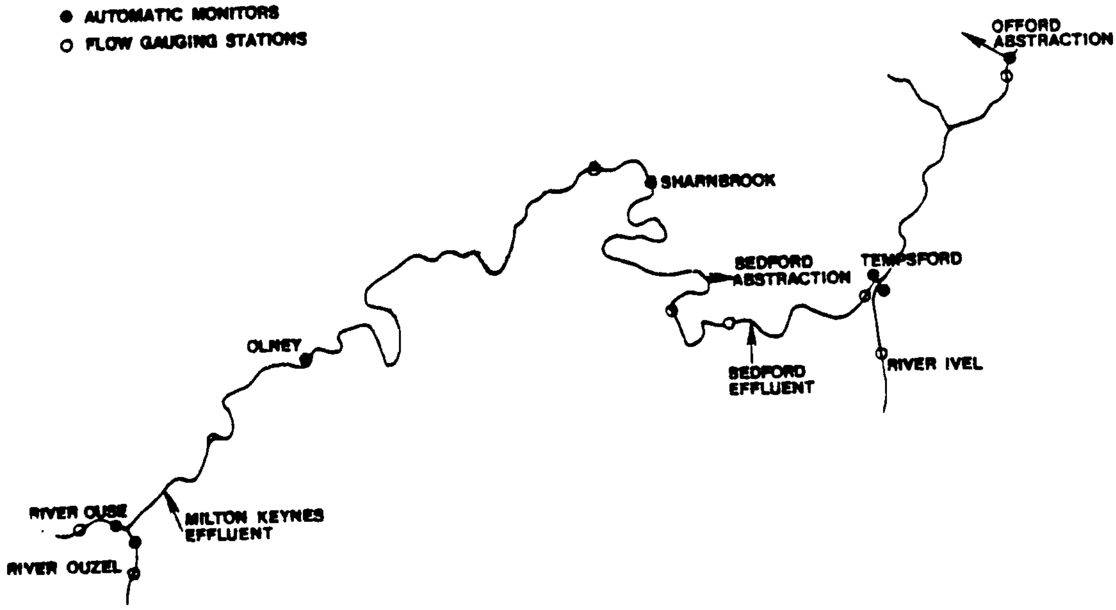
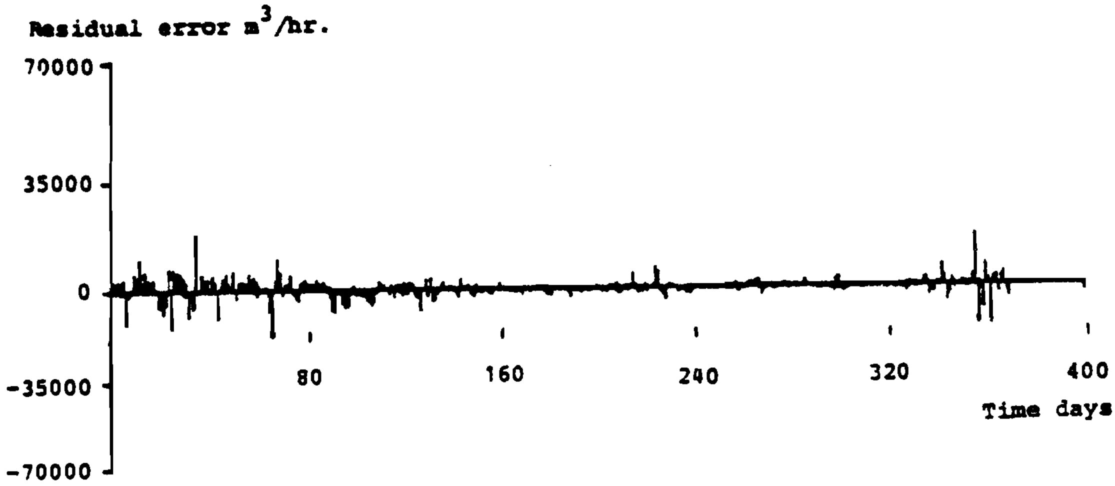


Figure 2. The Bedford Ouse River System



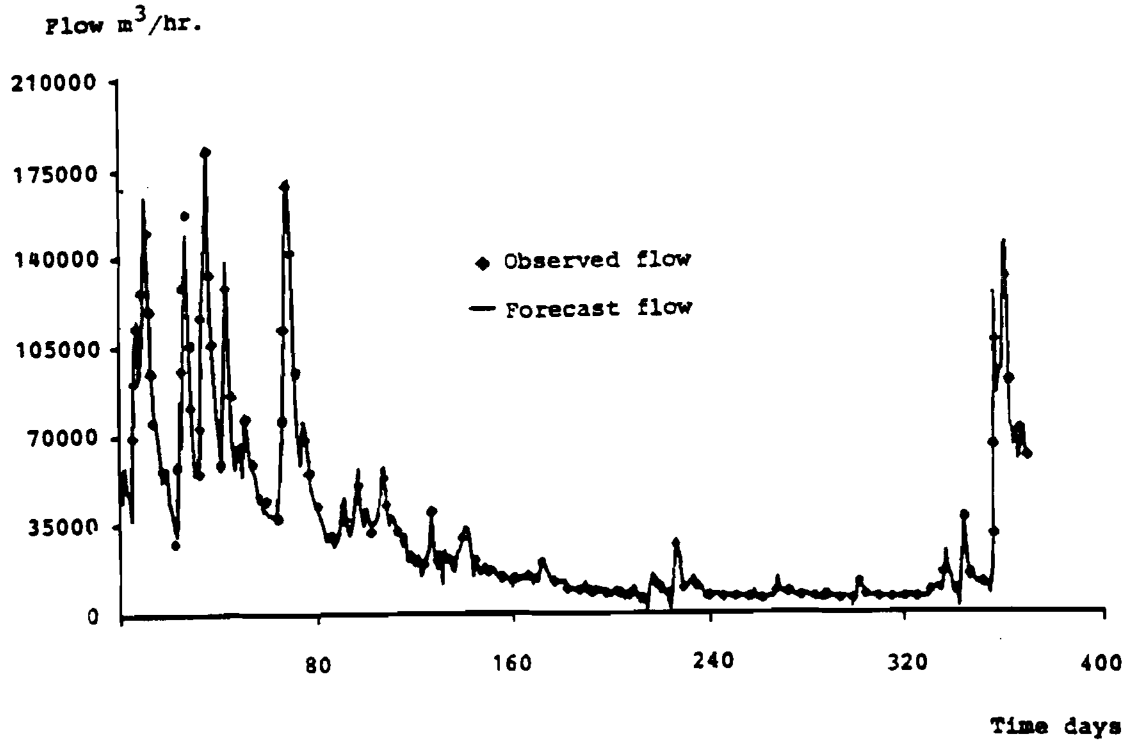


Figure 3. Simulated, Observed and Residual Flows on the Bedford Ouse over 1972

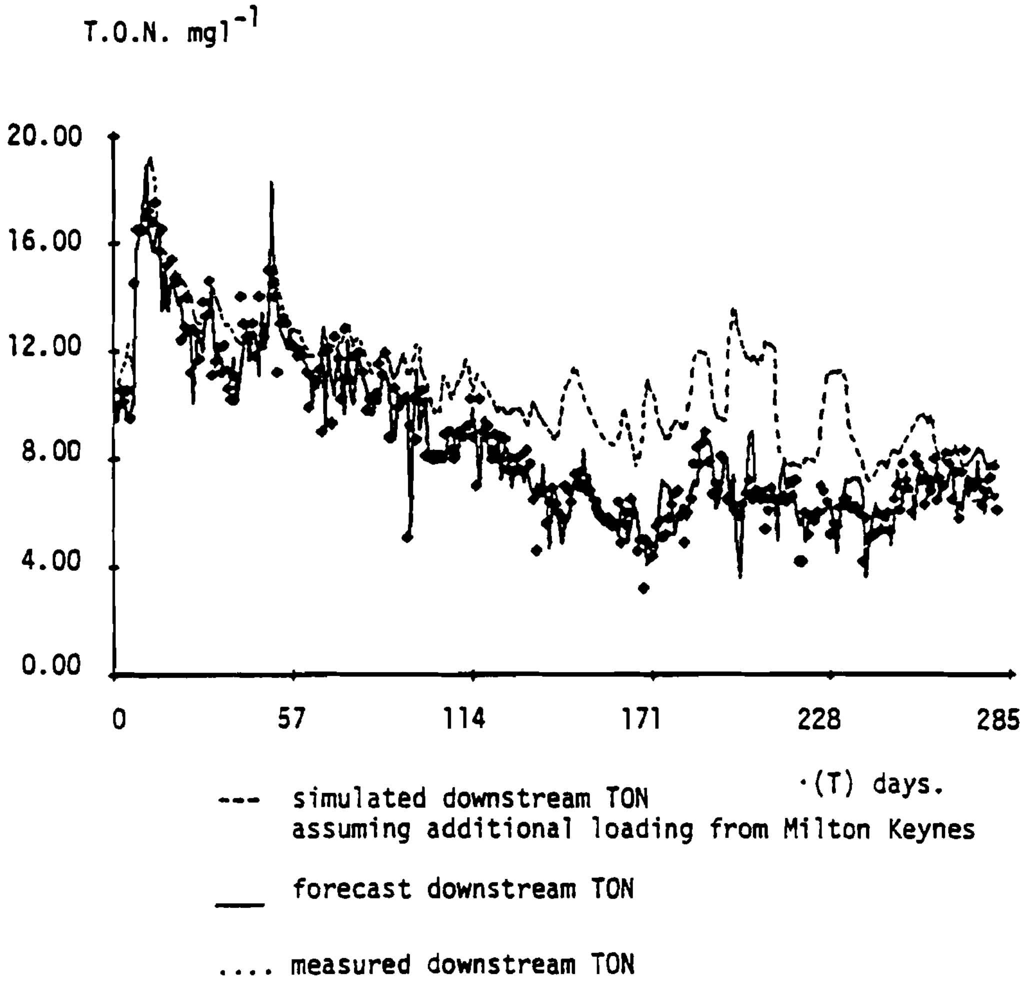


Figure 4. Simulated and Observed Daily TON Concentrations on the Bedford Ouse during 1974

During low-flow conditions and increased temperature levels during summer, the background levels of nitrogen fall, and the effluent effect is more significant.

In addition to providing time-varying concentrations at the downstream point, the models may be used in a Monte Carlo simulation study to provide predictions directly in terms of probability distributions rather than exact values (Whitehead and Young, 1979). The stochastic simulation approach is extremely useful where analytical solutions are difficult or even impossible to obtain, as is often the case with reasonably complicated dynamic systems. The system calculations (usually simulations) are performed a large number of times, each time with the values for the stochastic imputs or uncertain parameters selected at random from their assumed (i.e. estimated) parent probability distributions. Each such random experiment or simulation yields a different result for any variable of interest and when all these results are taken together the required probability distribution can be ascertained to any degree of accuracy from the sample statistics. The degree of accuracy of the probability distribution function estimated in this manner is, of course, a function of the number of random simulations used to calculate the sample statistics, but it is possible to quantify the degree of uncertainty on the distribution using non-parametric statistical tests such as the Kolmogorov-Renyi statistics.

Monte Carlo simulation is a flexible, albeit computationally expensive tool with which to investigate certain design problems. For example, the water quality standards proposed in the Bedford Ouse Study (1979) are presented in terms of the percentage of time that a water quality level is exceeded, and, therefore, provide a reference against which the water quality can be tested. It would be possible to perform Monte Carlo simulation analysis using the water quality models developed for the study section of the Bedford Ouse together with various assumptions about future levels of effluent input. The outcome of such an analysis would be probability density functions for the water quality states that could be compared directly with the water quality standards. Such information would be extremely useful in assessing the impact of effluent on the system and in determining the degree of treatment necessary at Milton Keynes in order to ensure satisfactory water quality at the downstream abstraction point.

An initial assessment of the impact of Milton Keynes effluent on the aquatic environment may now be obtained using Monte Carlo simulation, details of which are given by Whitehead and Young (1979). Altogether three effluent conditions were considered at different flow rates and BOD levels, as shown in Table 1.

Table 1.

	Flow Rate m^3/sec	BOD Concentration in Effluent mg/l	Variance of BOD levels
Case 1	0.1	5	1
Case 2	0.4	10	4
Case 3	1.0	10	4

It was assumed that the effluent has no dissolved oxygen present--a condition that represents the worst situation but which is not unrealistic as the effluent is to be pumped direct from the treatment works via a 4-km pipe into the river. Effluent BOD levels fluctuate in practice and a stochastic component defined by a noise signal of variance 1, 4 and 4 $(mg/l)^2$ respectively was added to the three BOD levels shown in Table 1. The distributions of BOD and DO at Bedford given these three effluent conditions are compared with the present situation in Figure 5. At low discharge conditions there is relatively little effect on the aquatic environment. At the 1 m^3/s condition, however, the mean BOD level has risen to 4.5 mg/l, the mean DO level has fallen to 6.5 mg/l, and the DO distribution ranges from 4.5 to 9 mg/l. These distributions represent only an initial assessment of the impact of Milton Keynes effluent and an updated prediction based on a re-estimated model in two years' time may indicate an improved situation. On the other hand the DO levels may be adversely affected by the changing biological nature of the river and some form of control action may be necessary to improve the DO distribution.

5. THE REAL-TIME MONITORING SCHEME FOR THE BEDFORD OUSE

In the short-term operational management of water resource systems a major requirement is for information on the present condition of the river system and on future changes in water quality. Operational managers must be able to respond quickly to emergency situations in order to protect and conserve the river and maintain adequate water supplies for public use. Moreover, the costs of water treatment and bankside storage are particularly high and there are therefore considerable benefits to be gained from the efficient operational management of river systems from the viewpoint of water quality (Beck, 1980; Rinaldi et al, 1979; Whitehead, 1978; Young and Beck, 1974).

In recent years there has been some progress towards providing more efficient operational management by the installation of automatic, continuous water quality monitors on river systems. These monitors measure such water quality variables as dissolved oxygen, ammonia, and temperature and, if combined with a telemetry scheme relaying information to a central location, provide

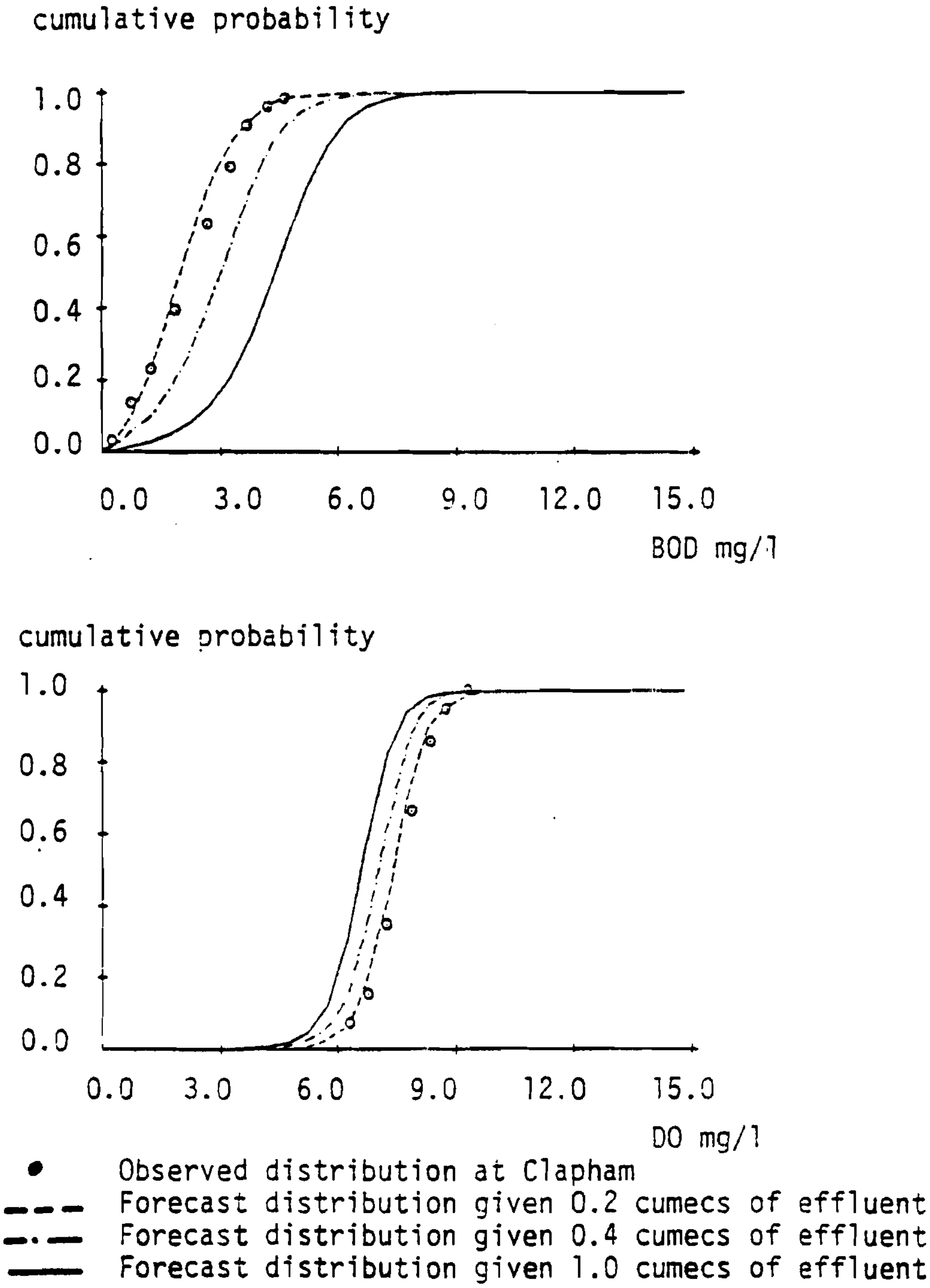


Figure 5. Distributions of DO and BOD at Clapham obtained from the Monte Carlo Simulation Study

immediate information on the state of the river for pollution officers. Whilst the reliability of such schemes is still rather poor there is now an opportunity to use this information together with mathematical models for making real-time forecasts of water quality.

The practical problems associated with the continuous field measurement and telemetering of water quality data have largely limited the application of on-line forecasting and control schemes. Continuous flow of water past sensors for measuring water quality gives rise to severe fouling of optical and membrane surfaces, thereby drastically reducing the accuracy of the data produced. In recent years, however, there have been several studies and applications of continuous water quality monitors (Briggs, 1975; Kohonen et al, 1978). Most UK water authorities have established monitoring and telemetry schemes (Hinge and Stott, 1975; Cooke, 1975; Caddy and Akielan, 1978) and report reasonable reliability provided the monitors are regularly maintained. More recently, Wallwork (1980) describes an application on the River Wear in north east England where a continuous monitor is used to protect an abstraction point.

The application of particular interest in this paper is an extensive monitoring and telemetry scheme that has been developed along the Bedford Ouse River system. As indicated in Figure 6, automatic water quality monitors have been installed at several sites along the river and data on dissolved oxygen, pH, ammonia, and temperature are telemetered at four-hourly intervals to the central control station located in Cambridge. It is proposed to extend this telemetry scheme to include information on flow and variables such as rainfall and solar radiation and to use a mini/micro computer located in Cambridge to analyse the data on-line. The system will provide rapid information on the present state of the river and will incorporate a dynamic water quality model for making real-time forecasts of flow and quality at key locations along the river system.

The data from the automatic monitors are telemetered at four hourly intervals to the central master station in Cambridge and in order to assess and to model the short-term behaviour data has been obtained for the monitoring stations located at Sharnbrook and Tempsford (see Figure 1) for the period of July to November, 1978. The stretch of river between these two sites is of particular interest to the Anglian Water Authority because of the location of the Bedford Water Division's abstraction plant at Clapham, the discharge of effluent from Bedford Sewage Works and the abstraction of water at Offord just downstream of Tempsford.

Data have been obtained for dissolved oxygen, ammonia, flow, temperature, and solar radiation together with data on the quality of effluent from Bedford Sewage Works. A plot of dissolved oxygen at the upstream site is given in Figure 7 and shows clearly the daily oscillations of dissolved oxygen, caused by oxygen production and consumption processes, and the longer-term fluctuations that are due to other variables such as temperature and streamflow.

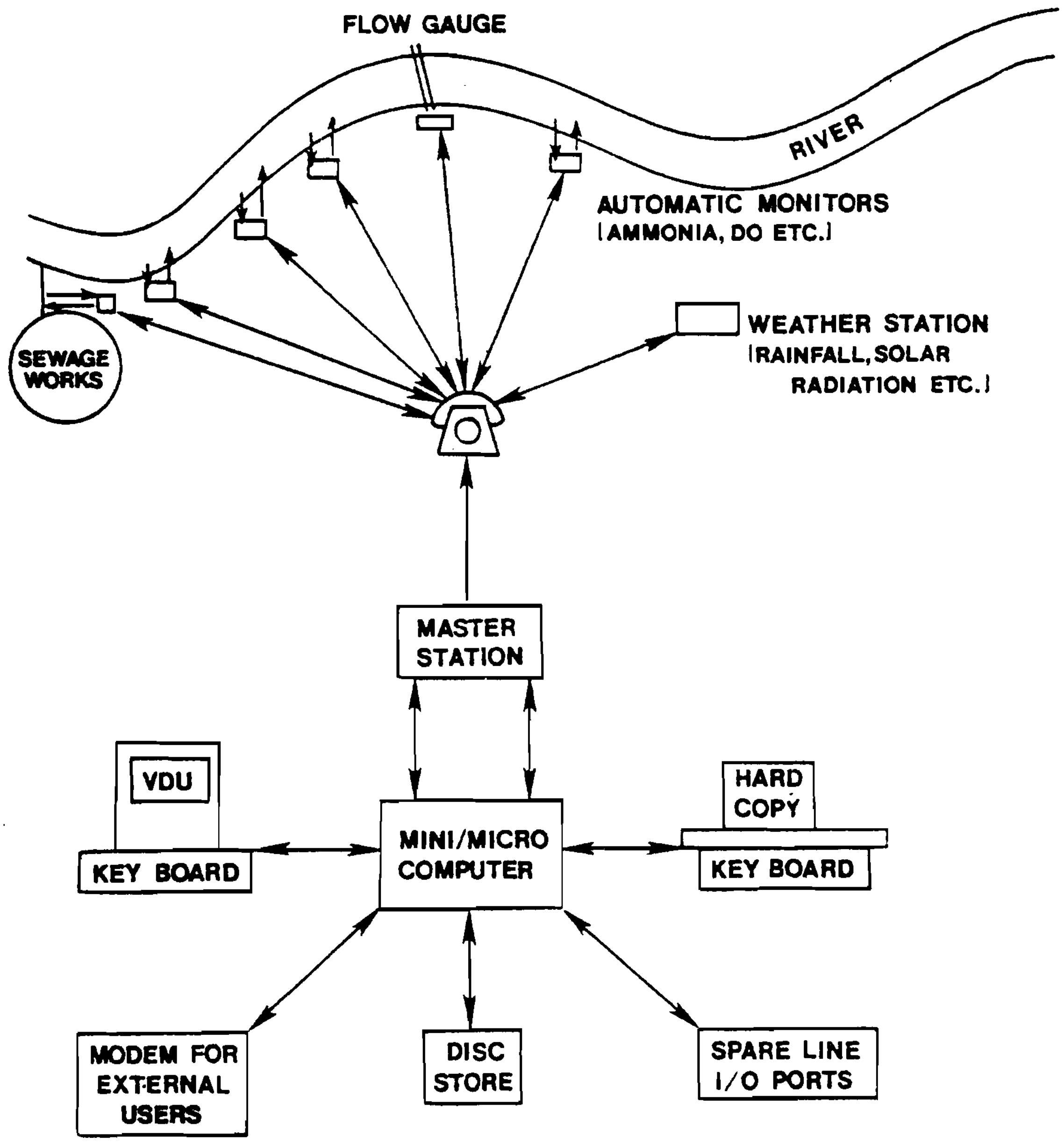


Figure 6. Monitoring, Telemetry and mini/micro Computing System Operational Management

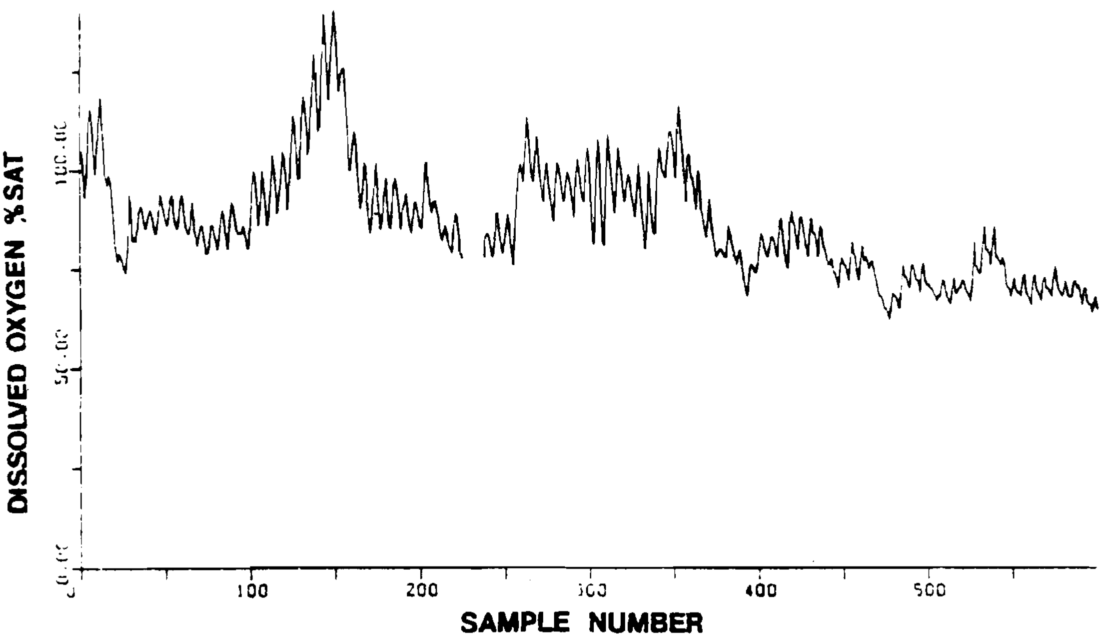


Figure 7. Continuous DO data at Tempsford on Bedford Ouse

Initially, analysis of these data has been restricted to the first 108 samples (18 days), since this period corresponds with a major storm event and high levels of ammonia in the river downstream of the sewage works.

6. AMMONIA AND DISSOLVED OXYGEN MODELS

The model of ammonia and dissolved oxygen is based on the mass balance description of equation (1) but contains additional terms to describe source and sink processes such as the nitrification of ammonia and the production of oxygen by photosynthesis. The river between Sharnbrook and Tempsford has been divided into four reaches with reach boundaries corresponding to the abstraction plant at Bedford, the Bedford Sewage Works and an intermediate point between the sewage works discharge and the Tempsford monitor. The upstream ammonia concentrations are particularly low (< 0.05 mg/l) and therefore the ammonia model has been formulated for just the two reaches below the sewage works. The models identified using the EKF are as follows:

Dissolved Oxygen

$$\frac{dx_1}{dt} = \frac{Q}{V_1} u_1 - \frac{Q}{V_1} x_1 + k_1 S - k_2 \quad , \qquad (3)$$

$$\frac{dx_2}{dt} = \frac{Q}{V_2} x_1 - \frac{Q}{V_2} x_2 + k_1 S - k_2 \quad , \qquad (4)$$

$$\frac{dx_3}{dt} = \frac{Q}{V_3} x_2 - \frac{Q}{V_3} x_3 + k_1 S - k_3 - 4.33 \frac{k_4}{Q} x_5 \quad , \qquad (5)$$

$$\frac{dx_4}{dt} = \frac{Q}{V_4} x_3 - \frac{Q}{V_4} x_4 + k_1 S - k_3 - 4.33 \frac{k_4}{Q} x_6 \quad , \qquad (6)$$

Ammonia

$$\frac{dx_5}{dt} = \frac{Q}{V_3} U_e - \frac{Q}{V_3} x_5 - \frac{k_4}{Q} x_5 \quad , \qquad (7)$$

$$\frac{dx_6}{dt} = \frac{Q}{V_4} x_5 - \frac{Q}{V_4} x_6 - \frac{k_4}{Q} x_5 \quad , \qquad (8)$$

where x_1, x_2, x_3 and x_4 represent DO at the downstream boundaries of the four reaches (mgl^{-1}),

x_5, x_6 are the ammonia concentrations at the downstream boundaries of the third and fourth reaches (mgl^{-1}),

u_1 is the upstream DO concentration entering the first reach at Sharnbrook (mgl^{-1}),
U_e is the ammonia in the effluent discharge calculated as the effective instream ammonia level (mgl^{-1}),
Q is the flow rate measured at Bedford ($m^3 day^{-1}$),
S is a sunlight term to account for addition of oxygen by photosynthesis,
V_1, V_2, V_3 and V_4 are the reach volumes (m^3),
k_1 is the rate constant associated with oxygen production by photosynthesis ($days^{-1}$),
k_2 is the loss of dissolved oxygen caused by biochemical oxygen demand upstream of Bedford ($mgl^{-1}day^{-1}$),
k_3 is the loss of dissolved oxygen caused by biochemical oxygen demand downstream of Bedford ($mgl^{-1}day^{-1}$),
k_4 is the nitrification rate ($days^{-1}$).

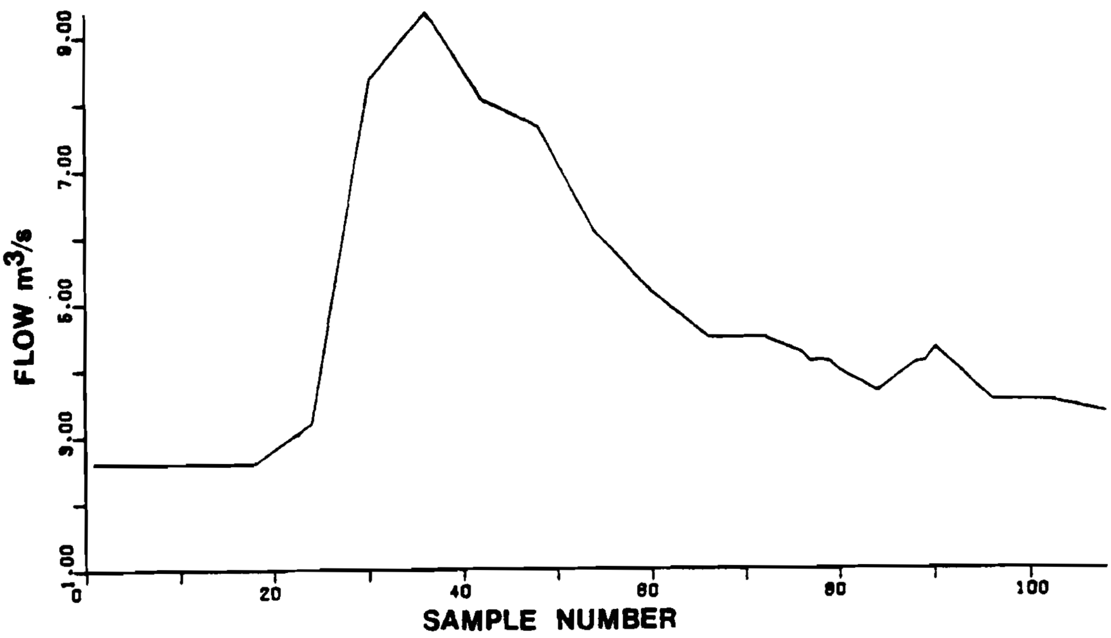
The sunlight term , S, is a function of solar radiation, S_r, (see Water Pollution Research Laboratory, 1968) and is determined as

$$S = S_r^{0.28} \quad .$$

The constant 4.33 in equations (5) and (6) represents the mass of oxygen removed from the water for each unit mass of ammonia nitrified.

One feature of particular interest in this model is the inclusion of the flow term, Q, into the ammonia nitrification expression in equations (5) to (8). The flow is included to account for the lower nitrification rate occurring under high flow conditions (Garland, 1978). During the initial EKF runs the flow term was not included and the parameter k_4, when estimated recursively, appears to be inversely proportional to the flow, Q (see Figure 8). Inclusion of the flow term and re-estimation k_4 produced an essentially constant or slowly-varying parameter, as shown in Figure 9. The higher flows tend to flush the reach of the nitrifying bacteria, which are responsible for the conversion of ammonia to nitrite and nitrate, and hence reduce the nitrification processes. The EKF is particularly useful in identifying this behaviour and in reducing an essentially time-varying parameter model to a model which is time-invariant (Whitehead, 1979).

The other parameters in the dissolved oxygen model do not vary significantly over the sampling period, as shown in Figure 9, although the parameter k_1 increases slightly during estimation. This is most probably due to the presence of large algal populations in the river that have not been explicitly included in the model. During the Bedford Ouse study (Whitehead and Young, 1975) the sunlight term was modified to account for the algal populations using chlorophyll-a concentrations as a measure of the oxygen producing matter in the river. In the present study,



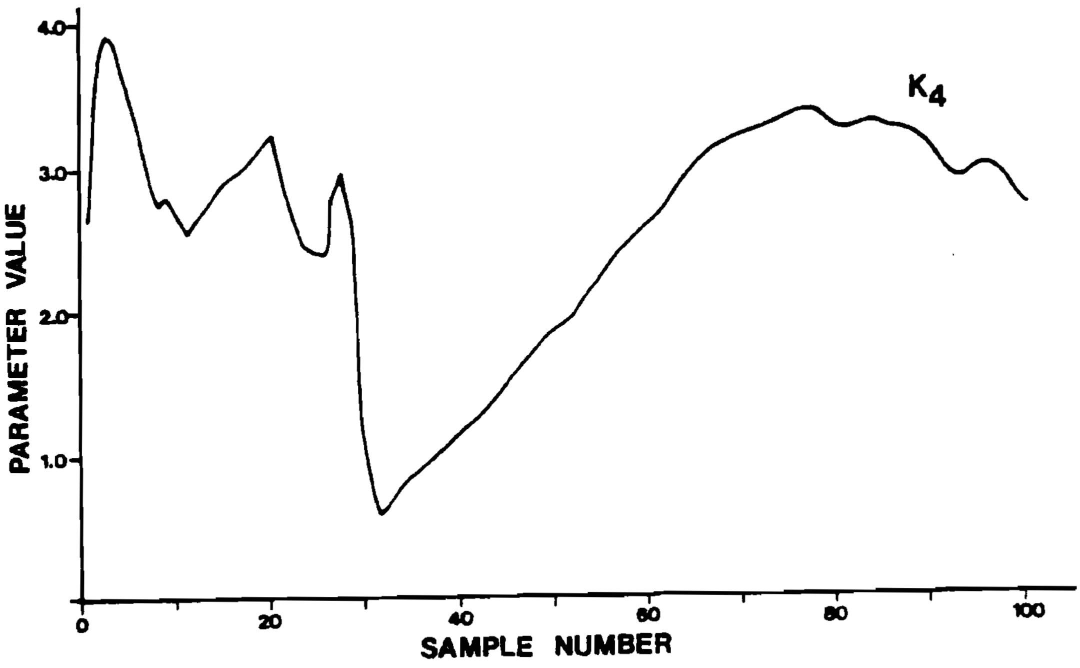
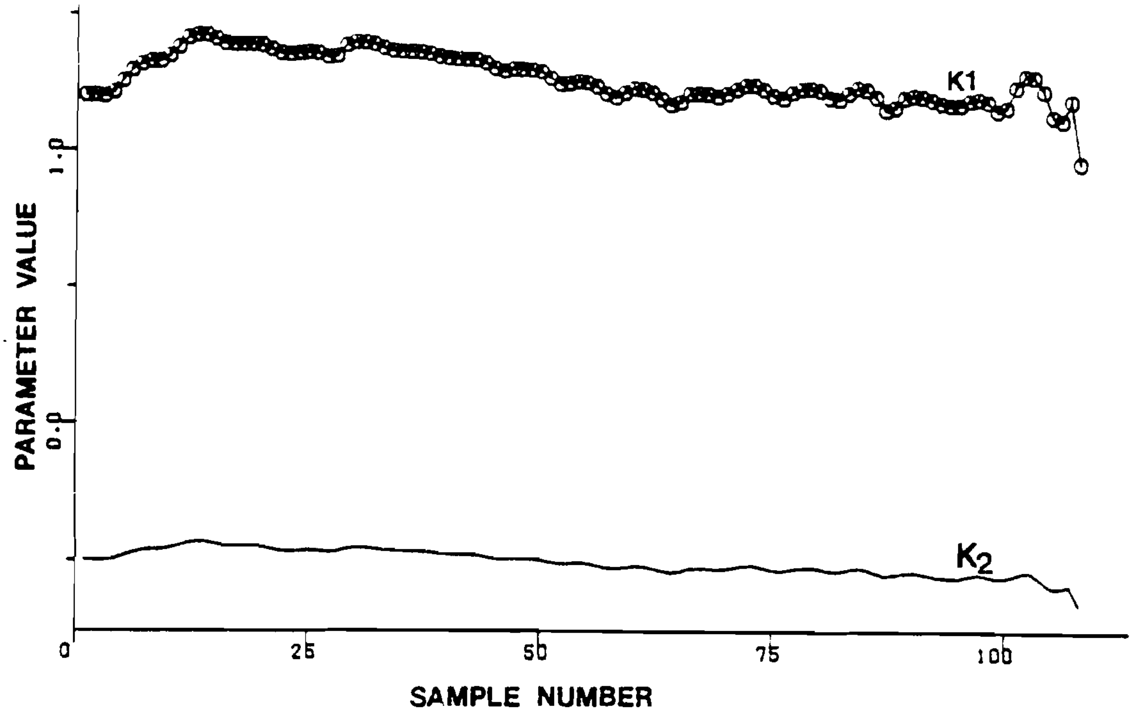


Figure 8. Recursive Estimate of Ammonia Decay Coefficient and Measured Flow at Tempsford



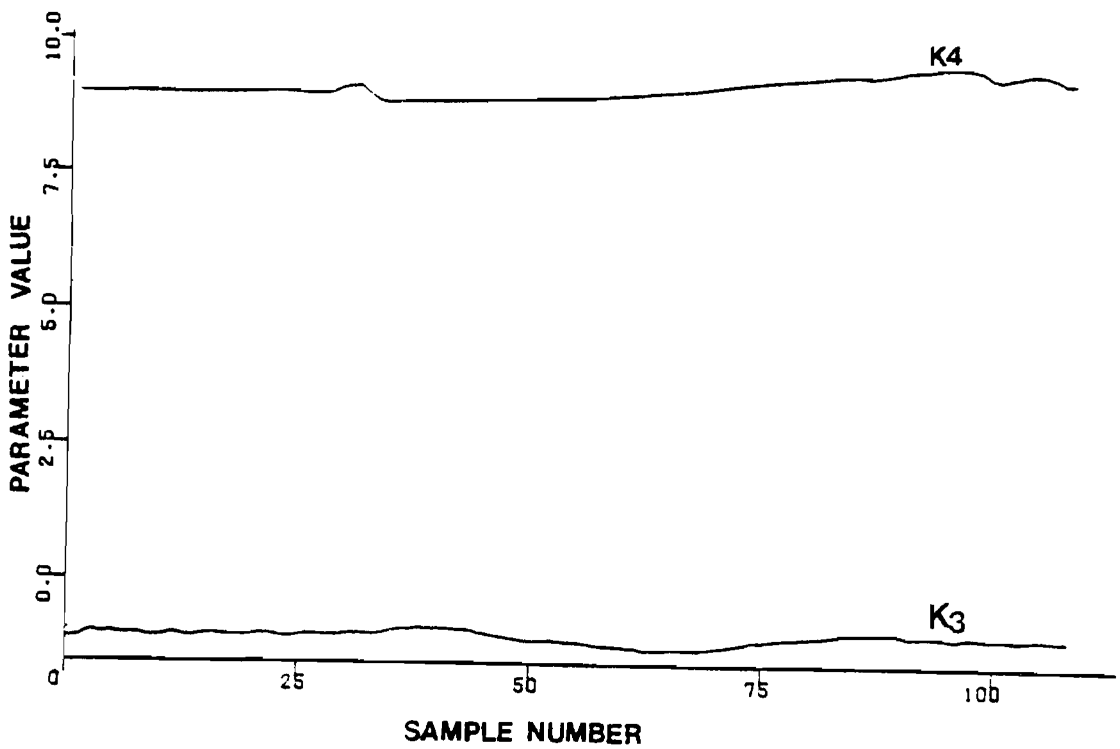


Figure 9. Recursive Estimates of Parameters

chlorophyll-a data is not available and the sunlight term is therefore dependent on solar radiation only. As shown in Figure 10, there are large diurnal variations in dissolved oxygen which are indicative of algal activity and further work incorporating the algal components is therefore required.

The simulated responses of dissolved oxygen and ammonia, as shown in Figure 10, are reasonable, although the peak of the ammonia is considerably underestimated. This may be due to the inaccurate measurement of effluent flow from the sewage plant during the peak of the storm or to the additional inputs along the reach from agricultural and urban runoff.

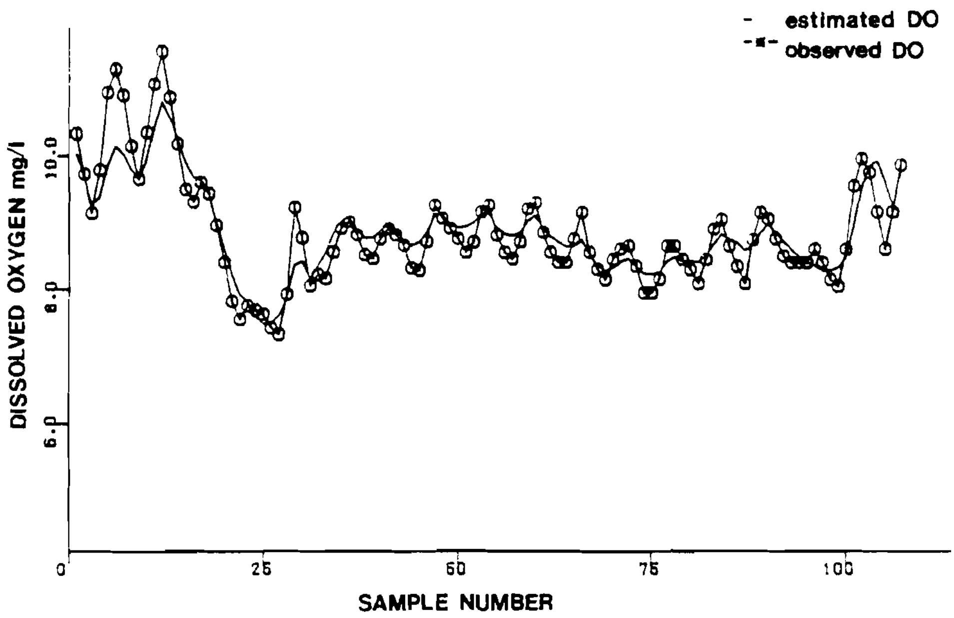
7. CONCLUSIONS

The design of a water resource system from the viewpoint of water quality has conventionally been based on 'steady-state' models that provide information about annual, average conditions. However, for many design problems detailed information on the transient behaviour of water quality is required together with a description of the stochastic aspects of water quality. Such information can be obtained using the integrated models of flow and water quality developed during the Bedford Ouse Study. In this paper the models have been used to assess the impact of effluent on the Bedford Ouse River.

In recent years continuous water quality monitoring schemes have been developed in conjunction with telemetry systems to provide real-time information for operational management. The rapid development in microcomputers has enhanced such schemes by providing considerable analytical power for on-line data processing at a relatively low cost. The application of real-time forecasting and control of water quality along critical stretches of river systems is therefore an option available to operational management. Such an application has been considered for the Bedford Ouse river system and this scheme is currently being implemented by the Anglian Water Authority and the Institute of Hydrology.

ACKNOWLEDGEMENTS

The results presented in this paper reflect the opinions of the author and are not necessarily the views of the Anglian Water Authority. The author is particularly grateful to Dr. D. Caddy of the Great Ouse Division of the Anglian Water Authority for the provision of water quality data and collaboration in establishing the water quality study.



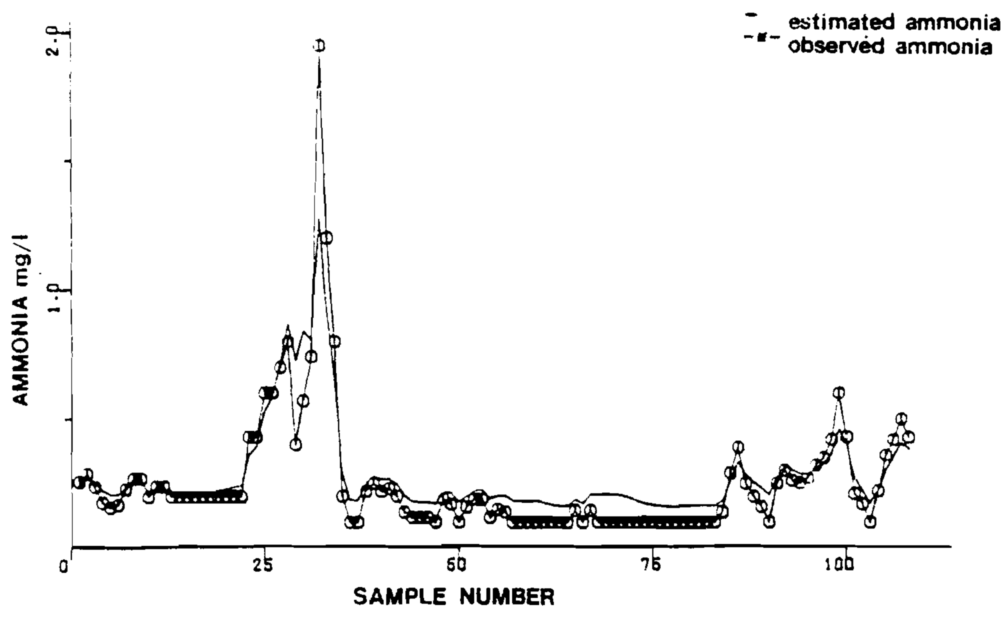


Figure 10. Simulated and Observed DO and Ammonia Concentrations at Tempsford

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REAL-TIME WATER QUALITY MANAGEMENT IN FINLAND: CURRENT RESEARCH AND SOME COMPUTER-BASED APPLICATIONS

A. Halme

1. INTRODUCTION

In Finland water courses are relatively large in area but generally contain little water. The mean depths of lake basins are small and the turnover of water is slow. Since in addition the long winter stops biological production of oxygen almost completely for 3-4 months a year, the ability to withstand pollution loads is generally relatively poor. Taking care of water quality is thus almost as great a problem in Finland as it is in many highly populated central European countries.

The principal origin of pollution in Finland is industrial, being mainly from the pulp and paper industries, whose share of total BOD-load is about 70 per cent. The corresponding share of municipal sources is only about 6 per cent and the remainder comes as scattered loads from agriculture and so forth. The communities are in many cases, however, of considerable importance as local polluters. Because industry and population are concentrated in southern Finland, the problems are more pronounced in this part of the country.

In this paper the aim is to describe briefly some research projects and technical developments that have been recently completed, or are still continuing, in relation to systems analysis and/or control of water systems in the broad sense. All the applications are aimed at the operational level of water quality management. Both water purification and wastewater treatment are considered for the communities and pollution load monitoring is considered with respect to the receiving water bodies. All the activities described have taken place in the 1970's, mainly after 1974, and they are in one way or another of current interest. The purpose here is to review rather than to describe in detail. With this experience in mind some conclusions and discussion have been made concerning how these and similar results in other countries might be used in real-time water quality management in the future.

2. ACTIVITIES RELATED TO WATER PURIFICATION AND WASTEWATER TREATMENT

Since 1974 there have been several research projects conducted in Finland in which wastewater treatment plants have been analyzed by the methods of systems analysis with a view to finding new methods and means to improve plant operation and design. This year SITRA (The Finnish National Foundation for Research and Development) started a two-year master project called YVY (Community-Water-Environment-project), the purpose of which is to initiate research programs aimed at improving municipal waste treatment (both liquid and solid wastes). In one large research project and two minor projects the whole municipal sewer system (network + treatment plants) has been studied. In addition to systems analytical studies, undertaken mainly by the universities, a few firms have carried out development work to produce microprocessor-based monitoring and control systems for treatment plants. In the industrial waste treatment field corresponding research has not been carried out as actively and a similar master project started by SITRA in 1978 has initiated research programs aimed primarily at improvements in process technology.

In the field of water purification and distribution there is one particularly interesting development project that has led to the realization of a computer-based management system that is motivated both by the use of modern technology and by considerations of energy conservation.

2.1 VITMO-project

VITMO is an abbreviation of the Finnish expression for "model development for the consideration, dimensioning and control of sewer systems". This project was conducted during the years 1976-78 as a commission from The Academy of Finland. It was preceded by two minor research studies, one of which (VISA) was concerned with the application of dynamical models to the analysis of an activated sludge plant and the other (SIMU) was concerned with the introduction and application of the U.S. EPA's SWMM model (Storm Water Management Model). In the VITMO project itself the whole sewer system was investigated so that the total discharge, including both the plant effluents and overflows, could be considered. The general goal was to develop those systems engineering models and methods that could be used as tools to assist in decreasing the total pollution load and unit treatment costs of a sewer system. Because the basic features of the different process models had already been widely studied both abroad and in Finland, it was thought reasonable to include case studies and to try to obtain experience of the difficulties that arise in practical applications. Typical questions to which answers were sought were:

-- How does a combined sewer network behave dynamically under runoff loadings from heavy rainfall? How can the time, place, quantity and quality of overflows be anticipated?
-- How can a study of process dynamics be utilized for design when, for example, defining the dimensions and locations of storages?
-- Is it possible to identify dynamical parameters in practice?
-- Is it possible to decrease the total discharge and to allocate it to different locations in an optimal manner by controlling the inner pumping and overflow dams of the network?
-- If disturbances in the treatment plant are taken into consideration, how much rainwater can be reasonably kept running through them without increasing the total discharge?
-- Is it possible to have relevant models for a typical biological treatment plant and to identify the corresponding parameters in practice?
-- Where can one affect to the best advantage increases in efficiency and/or decreases in operational costs?
-- What possibilities and limitations do current instrumentation and computer technology have in sewer systems?

The project was actually divided into two subprojects, one of which was concerned with the sewer network and the other with the treatment plant. In both subprojects a set of dynamical models and corresponding program packages were developed (FORTRAN V language, UNIVAC 1108 computer). For the case studies experimental programs were carried out in co-operation with three towns (Helsinki, Lahti, Tampere). The sewer network experiments were made in a combined sewer in the metropolitan area of Helsinki. A measuring system consisting of six level meters and two magnetic flow meters was installed in the area. The amounts of precipitation were measured with ordinary rainfall gauges. Observations were made over a period of nine months, including both wet and dry periods. The treatment plant experiments were made at a pilot-scale and a full-scale plant. The experiments included several 3-4 day periods when the aim was to estimate the parameters for dynamic models and to observe changes in the dynamic state of the processes. By interviewing operating personnel in all of the larger treatment plants in Finland the state-of-the-art of instrumentation and automation was surveyed; the results were compared to similar studies made outside Finland. The publications resulting from the project are unfortunately mainly written in Finnish or Swedish. Those papers written in English are listed in the references [1],...,[7]. Since finishing the project there has been an interest in utilizing the results in practice in two different ways. The simulation programs have been used by a consultant for designing sewer networks and by the experimental plant personnel who calculated optimal steady-state conditions for their plant. The results for the activated sludge process have been applied directly in the development of additional features for a microcomputer-based monitoring and control system.

2.2 Activities Related to the Development Work in Industry

A couple of firms have shown an active interest in developing monitoring and/or control systems for water systems. Besides the VESKU-project, considered in more detail later, this activity has been related either to water supply or to wastewater disposal processes, with the latter being the more active field. The aim has been to develop commercial computer- or microprocessor-based automation systems oriented towards these special applications. The projects have been mainly financed by SITRA or KTM (Ministry for Commerce and Industry), the former following a royalty principle while the latter covered up to 50 per cent of all costs in this kind of development work.

For monitoring and control of activated sludge processes two firms (Labko, Ulmaelectro) have developed a microcomputer application, both using an Intel 8080 processor. In both systems basic variables such as flow, pH, conductivity and dissolved oxygen are measured. Other operations include simple signal analysis, alarms, reporting and DDC control loops, of which dissolved oxygen control is the most important. Figure 1 shows the design of one of the systems. Both systems are being developed at the moment in the direction of distributed systems with video monitors. They are also marketed more widely for small-scale unit process control applications in industry. Currently there are four systems in operation and a further three are being delivered to treatment plants. All except one system have been installed in medium- or large-scale plants (in Finnish terms this means greater than 30 000 m^3/day).

In the above systems the only advanced feature thus far has been the dissolved oxygen control. Research, however, is being undertaken to develop methods and programs for real-time estimation of sludge growth and the inlet BOD-load. Based on this kind of information the objective is to improve process operation by a more accurate control of sludge wasting. The leading principle in estimation is to use the whole aeration basin as a respirometer, for which only an operational dissolved oxygen control is required.

Minicomputer systems intended for centralized plant monitoring and control have not been developed or applied in wastewater treatment plants in Finland. The reason is probably that the plants are relatively small in size when compared with those applying such systems abroad. There is, however, some interest in these systems because integrated monitoring and control of the whole sewer system in some larger cities, especially Helsinki, seems feasible for the future.

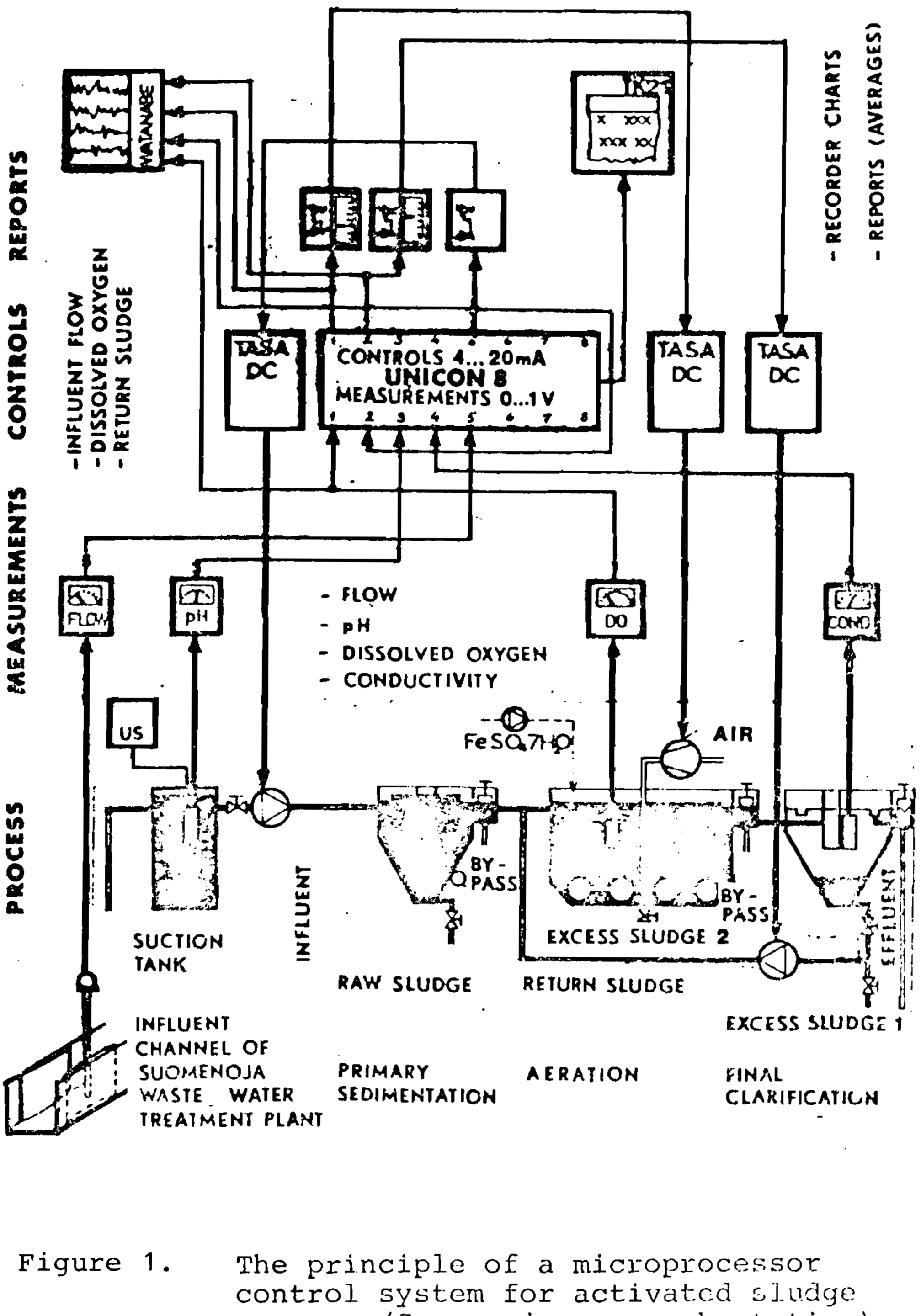

Figure 1. The principle of a microprocessor control system for activated sludge process (Suomenoja research station).

In supplying, treatment and distribution of pure water an interesting computer application has been recently developed and applied in Helsinki. With this system (developed by the Outokumpu Company) water storages, treatment processes and distribution are supervised and controlled from one centralized control station. Besides this central station, the system includes several substations at the treatment plants and pumping stations. The system is based on a PDP 11 computer and color videos are used with good effect for operator communication. Methods and programs are currently being developed to optimize pumping policies on a daily and weekly basis where the criterion for optimization is the energy cost of pumping. Because the price of electricity varies during the day it is expected that a considerable amount of money can be saved by using an optimal pumping policy; at the same time electrical load variations can be balanced. The principle for solving the problem is to use one week as the time-period for an LP-problem which is then solved repeatedly and sufficiently often. The scale of the LP-problem is very large and the best way to obtain a solution is currently under investigation.

3. AN AUTOMATIC POLLUTION LOAD MONITORING SYSTEM

The National Board of Waters, in co-operation with a company (Nokia), has developed a pollution load monitoring system that consists of automatic measurement stations connected to a central computer. The development project, called VESKU, has been part of a larger project (the KTV project) financed by the World Bank [9]. Various research programs have been included, for instance, the development of ecological models for inland waters and an assessment of the impacts of industrial pollution. The first version of the pollution load monitoring system was implemented in 1976 on the Kokemäenjoki River.

In its initial configuration (Figure 2) the system comprised three river monitoring stations, one sited upstream of the Nokia Pulp and Paper plant, one immediately downstream and the third a further 100 km downstream. A total of nine measurement stations were located on the plant site, four in the sewer discharges and five within the plant limits on the waste effluent line to the treatment plant. The river monitoring stations perform the following measurements: temperature, pH, conductivity, dissolved oxygen, turbidity and flow--this last measurement at two stations only. The sewer stations monitor temperature, pH, conductivity, turbidity and flow, and the stations within the plant measure temperature, conductivity, fibre content and flow. The central computer (a PDP 11/35)--located at the treatment plant--polls each point in sequence for the measurement data, compares the values to alarm limits stored in the computer memory, writes an alarm report if the limits are exceeded, and issues a sampling command whenever necessary. The system also includes a printer terminal located at the Tampere Water District Office, which prints out alarms and their termination, together with daily, monthly, and yearly reports showing average and extreme values, fractiles and total discharges.

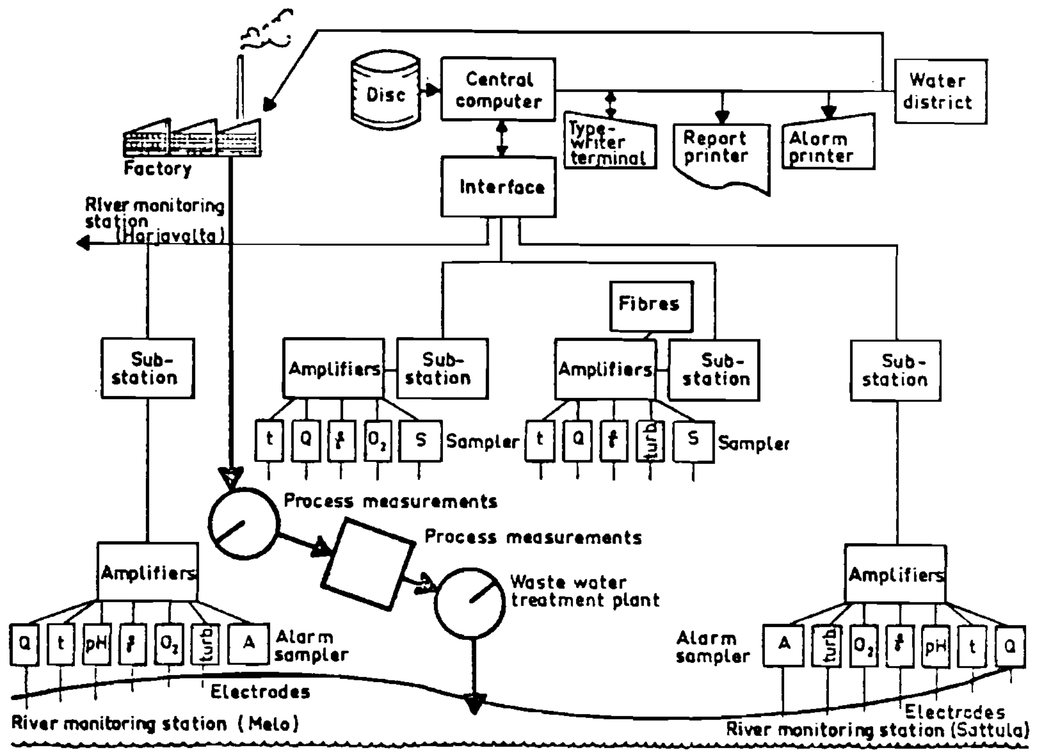

Figure 2. Automatic water quality monitoring system on the Kokemäenjoki River [9]

Another corresponding system was applied about a year later on the Kymijoki River. The central computer in this system is located at the Helsinki office of the National Board of Waters, and data transfer from the river stations takes place twice a day via telephone lines.

The problematic parts of the above systems are the measurement stations. Considerable effort has been put into the development work but reliable operation is still a problem, especially in places where the water contains large amounts of suspended solids (as just downstream from a paper mill). At the stations (made by Phillips and Ulmaelectro) water has been pumped into a chamber where the measurement electrodes are situated (Figure 3). The problem has been that the chamber accumulates solids and it is difficult to keep it clean by automatic means. Development is now going on to make all the measurements in situ with submerged electrodes. The measurement stations usually contain their own microcomputer systems which handle the measurement operations, data storing and communication with the master computer.

4. CONCLUSION AND DISCUSSION

The studies and systems described here are examples of the methods of systems engineering that can be applied in water quality management at an operational level. Corresponding studies have been done and associated systems implemented in many countries during the last decade. When considering real-time management automated computer-based systems are essential tools. Given the rapid developments in micro-electronics and computer technology it is unlikely that even the field of water quality management can avoid an increasing use of such systems in the future. Our experiences to date seem to be quite consistent and may be summarized as follows:

1. Technical difficulties, especially problems related to automatic measurements are still considerable but can be solved in most important cases.
2. Technical readiness to utilize more advanced monitoring and control systems in treatment plants is in general good (only the motivation is lacking).
3. To obtain more benefits from pollution monitoring systems considerable effort should be made in developing methods and programs to analyze the data and to predict the effects of pollution.
4. Compared with other industries the "water industry" uses automation generally to a very low degree. A basic reason for this is that water as a product or raw material either has no price at all or else price is not quality-dependent. This makes the profit incentive ill-defined except in those clear cases where direct conservation of energy or chemicals can be demonstrated. Another reason is that the people working in this field are not usually very accustomed to automation technology or to systems analytical methods and therefore are opposed to them ("it is better to invest in concrete than computers").

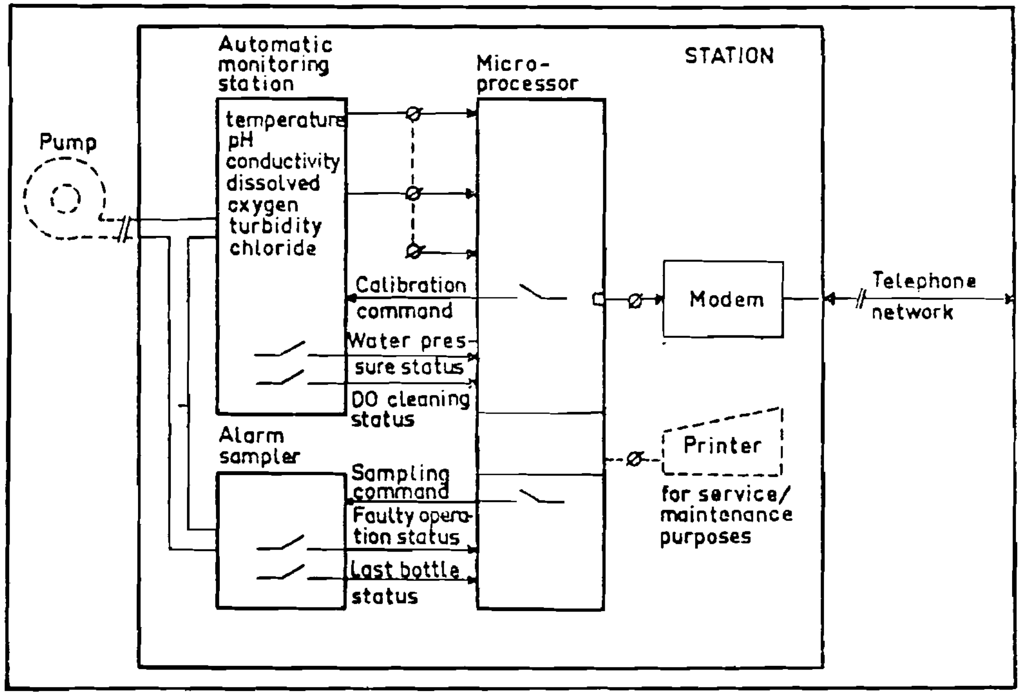

Figure 3. Principle of an automatic quality monitoring station (Philips)

Having these experiences in mind the realization of integrated real-time systems for regional water quality management seems to be a matter of the next century. Basic readiness, however, exists and much depends on whether problems will get worse in the future. Real-time management in this field generally needs considerable changes in attitude, because real-time operation means (by definition) that the action to an input should be fast enough to solve the problem caused by this input.

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APPLICATION OF COMPUTER SYSTEMS FOR REAL-TIME WATER QUALITY MANAGEMENT IN JAPAN

M. Ohnari

1. INTRODUCTION

Almost all cities and towns in Japan have developed beside water courses and they have used these rivers as a resource for drinking water, irrigation, fishing, transportation, and as recreational areas. Longer-term trends in water quality in public-use water areas are shown in Figure 1. Although the rate of noncompliance with the water pollution standards shows a slight trend of improvement over this period, citizens have argued for a long time in favour of restoring river water quality. Both national and local governments have guided manufacturing industries with regulations and subsidies in order to reduce wastewater discharges to rivers.

2. MEASURES AGAINST WATER POLLUTION IN JAPAN

The Japanese Environment Agency has specified measures against water pollution in a White Paper on the Environment as follows (Environment Agency, Japan, 1979):

> As measures against water pollution, after the enactment of the Water Quality Conservation Law and the Factory Effluent Control Law in 1958, problem water areas were individually designated and factory effluent regulations were applied to each. In 1970, with the enactment of the Water Pollution Control Law, provision was made for the establishment of uniform effluent standards for all public water bodies. The standard values set in 1971 (for BOD, a daily mean of 120 ppm) were designed to reduce the pollution load due to factory effluent by

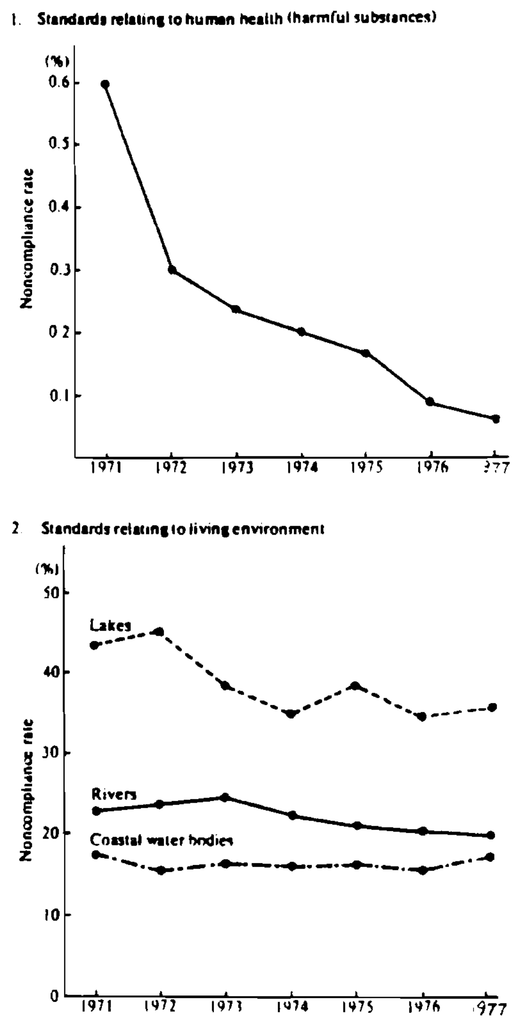

Figure 1. Changes in rate of noncompliance with water quality standards (ratio of samples exceeding the standards)--after Environment Agency, Japan (1979)

about 60 per cent as compared to the untreated condition. In the case of factory effluent, the measures began with primary treatment such as solid-liquid separation.

For water areas where it is difficult to attain the environmental standards by means of the uniform nationwide standards alone, the local government is empowered to set stricter supplementary standards by ordinance, and such supplementary regulations are presently in effect in all prefectures. Further, with the amendment in 1978 of the Water Pollution Control Law, the regulation of total effluent has come into effect in 1979. The regulation of total effluent aims to maintain water quality in the wide closed water areas where at present water is badly polluted. It will be realized by reducing total effluent pollution load which is composed of pollutant from upstream areas, domestic effluent, etc.

A problem remaining unsolved in recent years is that of water pollution due to domestic effluent in areas of high population density. This type of pollution is typically caused by discharge of untreated effluent into water bodies, due to the slow progress of sewer construction, as evinced by the pollution of agricultural water accompanying urbanization. In order to prevent water pollution by domestic effluent, the importance of urban sewer construction need hardly be emphasized. Although efforts have been made in recent years to promote rapid construction, the progress is still inadequate due to the absolute inadequacy of the existing sewerage facilities; as of the end of FY 1976, only 24 per cent of the total population were supplied with this service. Sewer construction works are in progress with the aim of raising the sewer reticulation ratio to 40 per cent by the end of FY 1980.

A further important problem is the restoration of river flow volume by the reduction of water-use per unit production and introduction of water purification. Although the growth of the volume of industrial water intake has slackened markedly, with the ratio of recycled water to total fresh water use reaching 67 per cent in 1975, the volume of water supplied to city water services, etc. (which are centered on domestic use), continues to grow due among other factors to the increasing installation of flush toilets.

The resulting intake of large volumes of river water at points upstream has led to impairment of the rivers' diluting and self-purifying capacities. Rationalization of water use is important not only from the viewpoint of water supply and demand in the future, but also in preventing environmental effects such as ground subsidence and water pollution.

3. APPLICATION OF COMPUTER SYSTEMS IN JAPAN

In the field of water resources management, many computers are now used in Japan for management and control (policy decisions, planning of facilities and operations). Several of these applications are described below and in the accompanying papers* with special reference to water quality management.

Consideration of water quality in a water supply control system (Matsumoto et al, 1980). A total system for water control is in operation in Yokohama City. For this system control computers are used to predict the demand and supply of water, to prepare a schedule of water distribution and to control the flow and pressure of water in a pipe network. These functions are performed with the aid of a three-level hierarchical scheduling model. The primary objectives are to minimize the costs of water transportation and chemical dosages. From the viewpoint of water quality management the total system functions so as to take in a maximum quantity of good quality raw water and to allow the operators to intervene at any level of the control scheme in the case of an accidental contamination.

Mixing and dilution control algorithm for sewer systems (Shioya et al, 1980). In the combined type of sewerage used mainly in Japan sewage inflow and pollutant concentration vary widely with time depending upon the local conditions of the sewer network area involved (residential, commercial or industrial). Rainfall-runoff is superimposed on these site-specific variations of inflow and pollutant concentrations. Some sewage treatment plants receive a large proportion of industrial wastes with high pollutant concentrations and during periods of peak loading they may receive too much sewage for their proper functioning.

To prevent such situations several methods of mixing and dilution of sewage are under development. Within the sewer networks it is useful to combine raw sewage between sewer lines in order to balance the variations in quality of the sewage entering the treatment plant. In an individual sewer line highly concentrated sewage can be stored temporarily by closing the gate of a pumping station and then diluted by the less concentrated sewage that subsequently mixes with the already-stored sewage.

Water quality control in a wastewater treatment plant (Tanuma, 1980). A hierarchical water quality control system for a wastewater treatment plant has been developed. In this system mixed liquor suspended solids (MLSS) and dissolved oxygen (DO) controllers at the lowest level are co-ordinated for stabilizing the activated sludge process. A total sludge quantity control function at the middle level controls the sludge quantity in the whole process and ensures process stability in the longer term. An operating-guide function at the highest level of the controller assists operators in searching for optimum operating conditions by using mathematical models.

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* Fujita and Ozaki, 1980; Matsumoto et al, 1980; Shioya et al, 1980; Tanuma, 1980.

The DO controller consists of a DO control loop and aeration rate control loops. The former computes desired values of the aeration rate based on the deviation of the measured values from the desired value of DO. Aeration rate is controlled by adjusting valve openings at the exit sides of blowers or suction valves.

Two types of MLSS control are under investigation, return sludge control and dynamic sludge reserving control. In the return sludge control, return sludge flow-rate is regulated such that the amount of suspended solids that flows from the aeration tank equals the amount supplied to the tank. Dynamic sludge reserving control uses a gate installed in the upstream part of the aeration tank for regulating the flow-rate of sewage to the head of the tank as the input control variable. When sewage flow-rate decreases and MLSS becomes high, so the controller closes the control gate and stores return sludge at the head of the aeration tank. When sewage flow-rate increases, the controller opens the gate and releases the stored sludge downstream in order to prevent changes in MLSS.

From the results of analyses of activated sludge process dynamics, it is found that the control of waste sludge flow-rate plays a very important role. Total sludge quantity control consists therefore of three functions: calculation of the desired value of total sludge quantity from the selected index for sludge quantity (for example, sludge age, or F/M ratio); estimation of the present value of sludge quantity based on measured MLSS, measured sludge blanket level, and so on; and adjustment of waste sludge flow-rate based on the deviation of sludge quantity from the desired value.

The operating-guide system, which can predict variations in water quality by using mathematical models is very effective for the operation of the activated sludge process whose responses to process inputs are very slow.

On-line water quality monitoring system (Fujita and Ozaki, 1980). Monitoring of rivers and pollution sources, such as factories and sewage treatment plants is essential for implementing the regulation of total effluent discharges. The on-line water quality monitoring system discussed here monitors automatically water quality and effluent quantity, obtains continuous data on pollution conditions, and computes the effluent pollution load.

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TOTAL SYSTEM FOR WATER SUPPLY CONTROL

K. Matsumoto, S. Miyaoka, M. Ohnari,
K. Yamanaka, and T. Kanbayashi

1. INTRODUCTION

Owing to the growth of the Japanese economy and the increase in the nation's standard of living, the demand for water will continue to increase. In fact, it will increase so much that shortages in the total volume of water are predicted for the long-term future. The quality of river water has gradually been improved, but overall pollution levels have not yet been reduced sufficiently. In order for the water authority to perform successfully, that is, in supplying water of good quality whenever needed in the required quantity and at the required pressure, it is necessary to exert comprehensive management and control by treating the supply and demand characteristics of water supply in a dynamic manner and by regulating demand accordingly. Such a total control system can only be realized through the integration of applications software for water operations and with the use of computers for supervisory control. Yokohama City Waterworks Bureau was the first in Japan to introduce a total system for water supply control of this kind.

The primary objective of the total control system is to manage water quantity. In this paper, however, we shall focus on the on-line scheduling model from the viewpoint of water quality management. This model plays an important role in the system. The water system of Yokohama has three intake points; the raw water quality at each point depends on its location along the river. In order to produce water of good quality at a low cost, it is necessary to utilize a larger volume of water from that intake point which supplies the best quality raw water. In addition to the average differences in water quality at each intake point accidental contamination of the raw water may occur because of algal growth or the discharge of toxic substances to the river.

In an on-line scheduling model it is necessary to consider the quality of the water as well as its quantity and pressure. In the model used for Yokohama City the difference of water quality at each intake point is expressed as a difference in cost; it is thus possible to use a cost minimization method for the network flow so that raw water of good quality can be used efficiently. In order to cope with accidental contamination the model is designed to allow man-machine interaction so that operators can make suitable decisions easily whenever such accidents occur.

2. ON-LINE SCHEDULING MODELS FOR A LARGE WATER SUPPLY SYSTEM

In order to have an optimum operating schedule for a large water supply system the objectives listed below must be considered:

(i) *To secure sufficient volume of water*. The most important role of the system is to take in raw water and to distribute purified water over a wide area in order to satisfy the given demand.

(ii) *To use raw water of good quality effectively*. The cost of chemical dosage in water treatment plants will increase, if the quality of raw water deteriorates. Therefore, it is necessary to maximize the intake amount of good quality water in order to reduce these costs.

(iii) *To use water transported by gravity effectively*. Transportation costs can be reduced if the water is transported not by pumping but by gravity.

(iv) *Stable control of facilities*. Reducing frequent changes of operations at intake stations and water treatment plants makes it possible to control the system easily and to prolong the life of the control equipment.

(v) *Efficient and safe operation of reservoirs*. Reservoirs must be used to absorb demand fluctuations; at the same time any storage imbalance among reservoirs must be prevented for security reasons.

(vi) *To maintain service pressure*. Maintenance of the pressure at demand nodes at an adequate level is necessary for the servicing of users.

(vii) *Reduction of water leakage*. In order to reduce water leakage pressure in a pipe network must be kept lower than its design level.

(viii) *Security control against contingencies*. It is necessary to cope with contingencies such as accidental contamination and failure of facilities.

If we were to develop a single-level scheduling model that would satisfy all the objectives given above, such a model would surely be very large and complicated; it would also be difficult for operators to judge whether the schedule derived from the model would be adequate or to make corrections if necessary.

We have, therefore, divided all the functions necessary for the scheduling model into three levels and have developed a hierarchical model as shown in Figure 1.

At the first level intake schedules are determined; at the second level operation schedules for water treatment plants are determined; and at the third level operation schedules for reservoirs are determined. From the viewpoint of water quality management, objective (ii) above, "To use raw water of good quality effectively", is realized at the second level. If an accidental contamination is detected, a counter-measure can be taken immediately by exploiting the characteristics of the model for man-machine interaction. Each level has the following functions:

1. First level: planning of abstractions at intakes based on the predicted demand for water over the whole area.
2. Second level: planning of water treatment plant operation based on the predicted demand at each treatment plant. At this level the whole area is divided into several zones, each of which includes a water treatment plant and several reservoirs. Zones are connected to each other by pipes. The zone network of Yokohama City is shown in Figure 2. The minimum cost flow for the zone network is calculated by an optimization technique for network flows called the primal-dual method. The schedule is made in order to reduce frequent changes of operation at treatment plants together with a reduction of costs.
3. Third level: planning of reservoir operation based on the predicted demand at each reservoir. This level has many types of facility configuration for purified water transportation. To overcome this problem of variety a concept of modularity is introduced. Calculation modules for purified water transportation systems have been designed to include the non-linear characteristics of the flow and pressure relationship. All the modules required to describe the systems are shown in Figure 3; using these modules schedules can be prepared for any specific water transportation system.

The scheduling is carried out sequentially from the first level down to the third level, where the results of a higher level are considered as constraints for any lower level. Operators can intervene in the calculation procedure through a CRT display at any level and whenever necessary.

With regard to computational time requirements, it usually takes less than 10 minutes to obtain a schedule from the model on a HIDIC 700 (Hitachi control computer) and this is therefore suitable for real-time operations with the system.

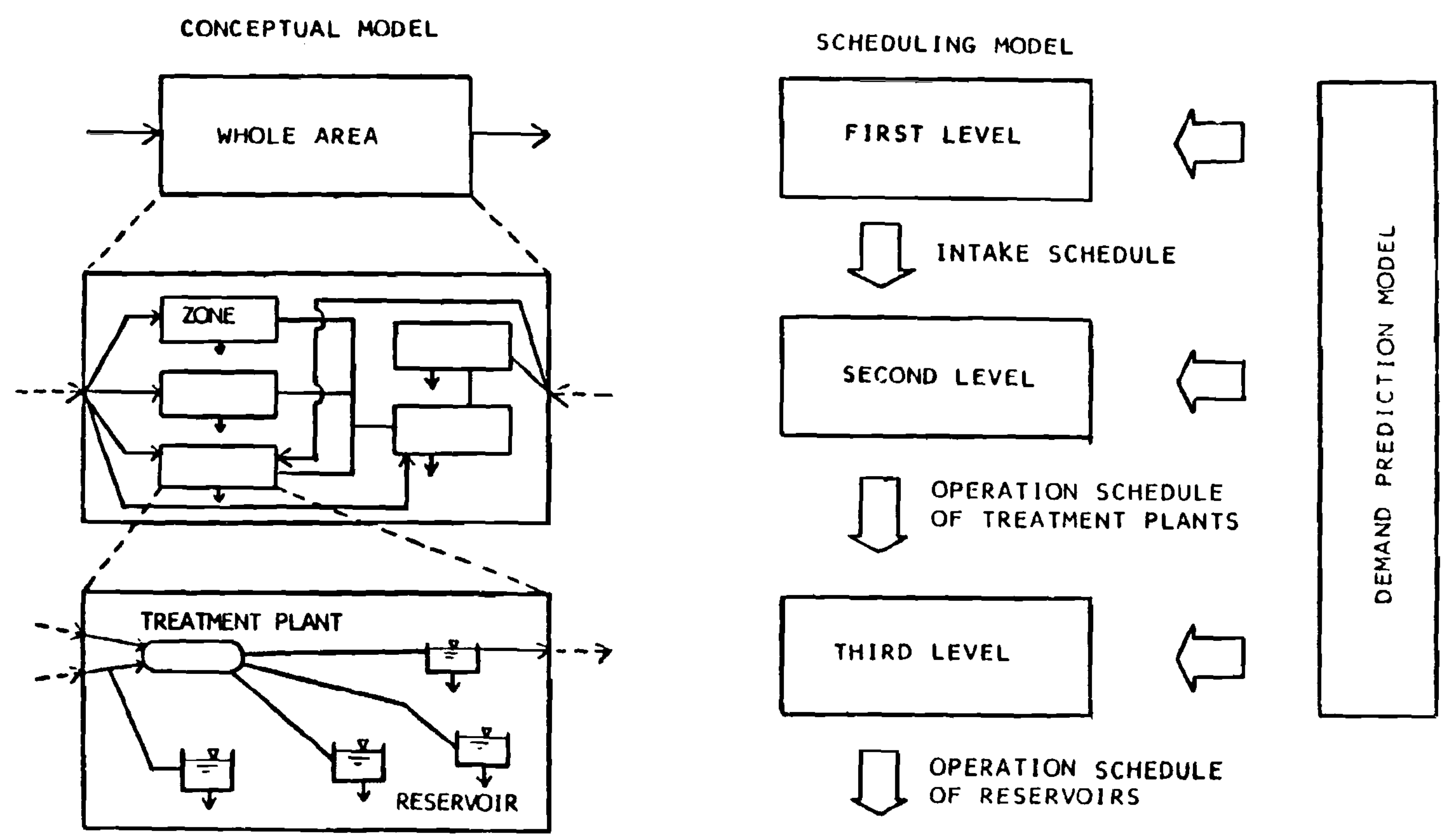

Figure 1. Hierarchical Scheduling Model

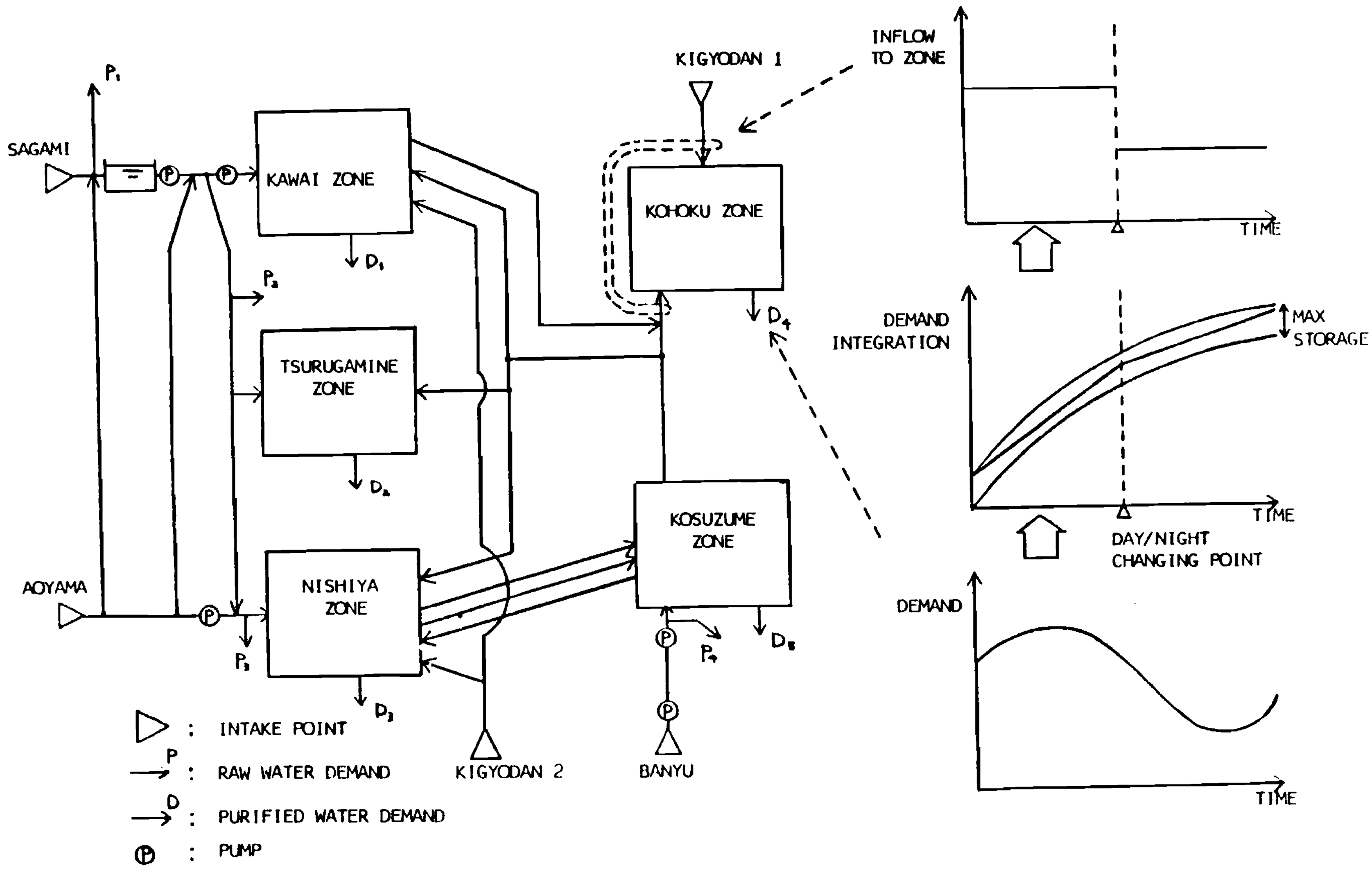

Figure 2. Zone Network of Yokohama City

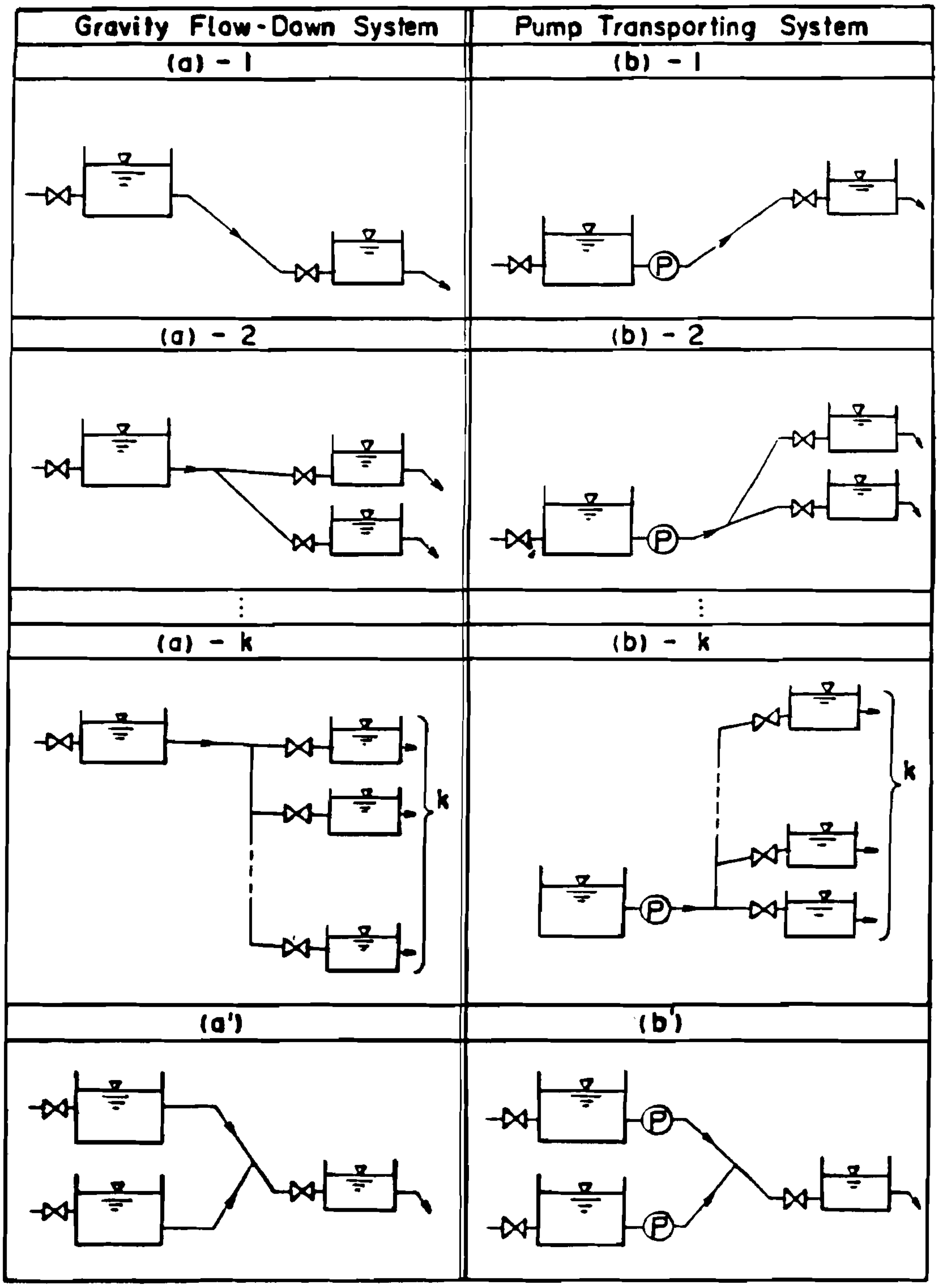

Figure 3. Calculation Modules for a Water Transportation System

3. CONCLUSIONS

We have described the total system for water supply control in Yokohama City; the main aim of the system is to secure a sufficient volume of water. This is the first such system to be operated in practice in Japan.

From the point of view of water quality management the total system functions so as to take in a maximum quantity of good quality raw water and to allow operators to interact with the computer at any level and at any time. In the case of toxic spillages, the system is required to prohibit immediately the abstraction of polluted raw water, to increase the amount of water abstracted at other points, and to convey this water to the zone where abstraction has been prohibited. Such an emergency action can be taken by operators communicating through a CRT display with the scheduling models of the computer system.

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DEVELOPMENT OF A MIXING AND DILUTION CONTROL ALGORITHM FOR SEWER SYSTEMS

M. Shioya, M. Ohnari, and S. Shimauchi

1. INTRODUCTION

The amount and quality of raw sewage in a sewer main vary with the time of day and with the type of area served, that is, a residential, commercial, or industrial area. Some treatment plants therefore receive a high proportion of industrial wastes with a high pollutant concentration; indeed during periods of peak load the treatment plant may receive too much sewage for a proper functioning and the quality of the discharged water is lowered. To prevent these situations of overload it is necessary to combine raw sewage between mains in order to even out variations in the quality of the sewage entering the treatment plant and to attenuate the peak loads. In this paper we present a mixing and dilution algorithm for sewer systems together with an example of its application.

2. MIXTURE DILUTION

2.1 Algorithm

For mixing and dilution control diluent water or highly concentrated raw sewage is stored at a pump station or bypass pipe where the flow can be controlled. The mixing and dilution takes place during storage of the diluent, after which the mixture is released. Another method is to release the sewage in a carefully timed sequence and then to dilute it downstream at the point where it meets another main line. There are six different methods of mixing and dilution control; these differ according to the place of dilution, to the substance temporarily stored prior to dilution, and to the use or non-use of a bypass pipe. The methods are listed in Table 1.

Table 1. Types of mixing and dilution control methods.

Method	Bypass pipe use	Dilution method		Control method
		place	substance stored	
1	not used	sewer line at pump station entrance	highly concentrated sewage	prior storage of concentrated sewage
2			diluent water	prior storage of diluent
3		junction with another main	highly concentrated sewage	control of amount of concentrated sewage
4			diluent water	control of amount of diluent
5	used	bypass to same main		storage in bypass pipe
6		bypass to different main		control by flow route change

The diagrams shown in Figure 1 illustrate these methods and Table 2 lists their respective advantages and disadvantages.

<u>Method 1</u>. <u>Prior storage of highly concentrated sewage</u>

Upon detection of a highly concentrated sewage, the gate of the pumping station is closed and the highly concentrated sewage is detained at the intake of the pumping station. The sewer water which subsequently flows in is used as the diluent. After mixing and dilution to a specified level of concentration the mixture is released. It is necessary only to monitor the concentration of sewage coming into each pumping station and to close the gate when the concentration reaches a certain level. Control is thus easy. This method is especially suited to sudden changes in water quality due to accidents. However, since dilution takes place in the sewer line where the wastewater is stored, mixing is likely to be uneven unless the water is stirred mechanically. And since the wastewater cannot be released until dilution is complete, the process must be carried out in many stages if the storage capacity of the sewer line is insufficient. Extreme changes might also result in the downstream flow-rate and load.

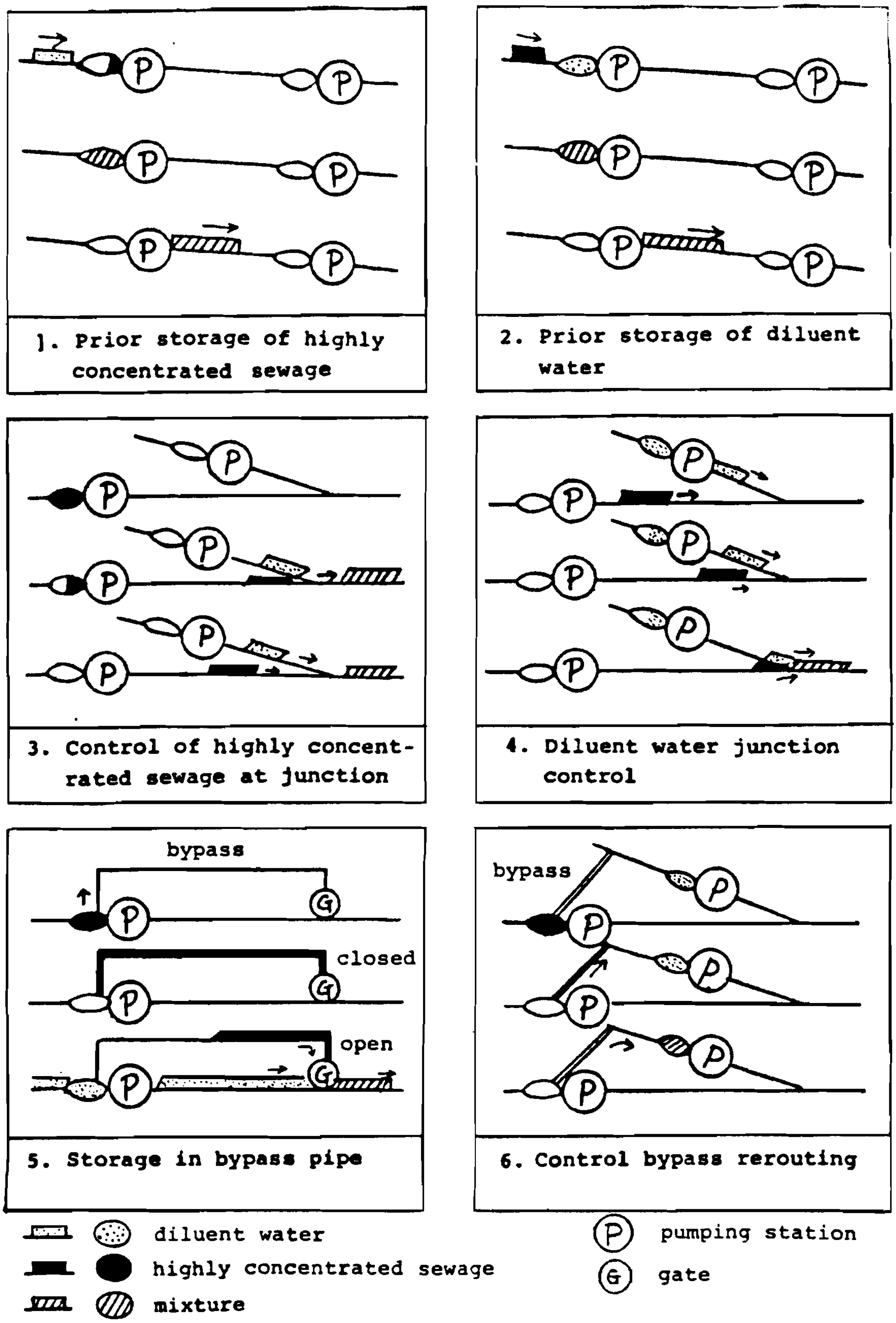

Figure 1. Diagrams of the Mixing and Dilution Control Methods

Table 2. Advantages and disadvantages of mixing and dilution methods.

Method	Advantages	Disadvantages
1. Prior storage of highly concentrated sewage	o simplified control o can cope with accidents and emergencies	o uneven mixing o extreme load changes o multiple stages necessary
2. Prior storage of diluent water	o load changes controllable o can be used to smooth load under normal conditions	o uneven mixing o necessary to predict inflow of concentrated sewage o cannot cope with accidents and emergencies o necessary to predict inflow of rainwater
3. Control of highly concentrated sewage volume	o uniform dilution and mixing o can cope with accidents and emergencies	o timing control necessary o extreme load changes
4. Control of diluent water volume	o uniform dilution and mixing o can be used to smooth load o can cope with accidents and emergencies	o timing control necessary o difficult to keep diluent water o extreme load changes
5. Storage in bypass pipe	o easy control	o limitations on dilution capability depending on capacity of bypass pipe o construction costs
6. Control by flow rerouting	o easy control	o construction costs

Method 2. Prior storage of diluent water

When an influx of highly concentrated sewage is expected, the concentration and rate of flow may be computed and the necessary amount of diluent water then stored at a downstream pumping station. Since the diluent water may be accumulated gradually without stopping altogether the flow of water from the pumping station, changes in flow-rate and load can be controlled to a limited extent. This method can also be used to smooth out the flow-rate under normal conditions. However, as with the first method, it is difficult to obtain a uniform dilution of water and this method is not well suited to coping with accidents or emergencies. Further, in stormy weather it is necessary to store less diluent water than nominally computed in order to prevent an overflow at the pumping station.

Method 3. Control of highly concentrated sewage volume

Highly concentrated sewage is stored at the intake of the pumping station and at the same time diluent water is stored in another line. At the appropriate time water is released from both sides for dilution to take place at the junction. Mixing and dilution is uniform and, like method (1), this method is well suited to handling accidents. It is necessary, however, to calculate the desired timing for release of the concentrated sewage and the diluent; there is also a possibility of extreme changes in flow-rate and load.

Method 4. Control of diluent water volume

The diluent water is stored at the pump station intake and released with the proper timing to meet and dilute wastewater from another line at the junction. Clarified water, river water, or well water may be used as diluent. With this method too uniform mixing is possible and, if some diluent water is always stored, accidents can be handled. As with method (2), the load can be smoothed under normal conditions. However, as with method (3), timing control is necessary and changes in flow-rate due to dilution control can be extreme. In addition, both methods (3) and (4) require the use of mains without a flow of concentrated sewage in which to store the diluent; this may not be possible in some cases.

Method 5. Storage in bypass pipe

Highly concentrated sewage is stored in a bypass pipe and the gate is opened and closed to mix this sewage with diluting water flowing along the main line. This is an easy method of control, although the absolute volume of possible dilution is limited by the bypass pipe capacity and extra construction costs are necessary for laying the bypass pipe.

Method 6. Control by rerouting the flow

Two lines are joined by a bypass pipe and when concentrated sewage flows into one line it is diverted to the other and thereby diluted. Like method (5) this method permits easy control but requires additional construction costs.

2.2 Study of Actual Application

Now let us consider an application of the methods. For this example, methods (5) and (6) are excluded from consideration because of the cost needed for laying the bypass pipe. Methods (3) and (4), which make use of the flow from another line, are more suitable because they can obtain uniformity of dilution. However, there are few lines in a sewer system in which there is sufficient water with a low enough concentration of pollutants to serve as a diluent. In comparing methods (1) and (2), which use the water in only one line, method (2) has more flexibility for dilution control in daily use because the diluent water is always available for use. We will therefore examine method (2).

We must consider first the problems associated with this method: overflow due to rain water; uneven mixing and dilution; and poor response to sudden accidents. If there is precipitation while diluent water is being stored, it will be necessary to discharge the stored water before the rainfall runoff enters; this will be necessary even if the line entering the pumping station and the rainwater pump have a large capacity. Incoming runoff has a large pollutant load at the beginning of the storm and prediction of runoff flow should be used effectively to prevent discharge of this water to rivers and streams. Supplementary dilution at a downstream junction (method (3)) is one way of making the mixing and dilution uniform. Simultaneous use of dilution at a junction also assists in obtaining sufficient storage capacity at the pumping station intake. This is also helpful in dealing with accidents and in storing diluent water below the point where abnormal water quality resulting from the accident is detected. In general, maximum dilution should be carried out at each pumping station. Special consideration should then be given to those stations and time periods where acceptable concentrations are exceeded and those stations and time periods for which concentrations are low. By releasing water from certain stations with the correct timing the overall concentration can be controlled within acceptable limits.

3. CONCLUSION

An algorithm has been developed for mixing and dilution of sewage in and between mains in a sewer system. The objective of the control is to minimize interference with the receiving sewage treatment plant and to prevent lowering of the quality of water discharged due to the inflow of highly concentrated sewage. Six methods are included in the algorithm with variations in (i) the place where dilution occurs (pumping station intake, junction with another line), (ii) the substance stored (concentrated sewage, diluent), and (iii) the use of a bypass pipe.

We examined the possible application of one of these, the "diluent prior storage" method, to an actual sewer system. In this method, the water flowing in a particular line is stored at a pumping station intake and subsequently mixed with highly concentrated inflowing sewage.

In the event of an accidental spillage of toxic material this system for mixing and diluting highly concentrated sewage in one or between two sewer lines can be used to keep the concentration of sewage within acceptable limits for protecting, for example, the activated sludge process. The treatment plant can continue to operate without interruption and with no significant decrease in the quality of the effluent discharged. This method can also be used to even out the flow and quality of water entering the treatment plant and to attenuate peak loads, thus increasing the effective average plant capacity. In addition, such control could serve in the future as an important element in a comprehensive total system for control of the entire sewer system, as shown in Figure 2.

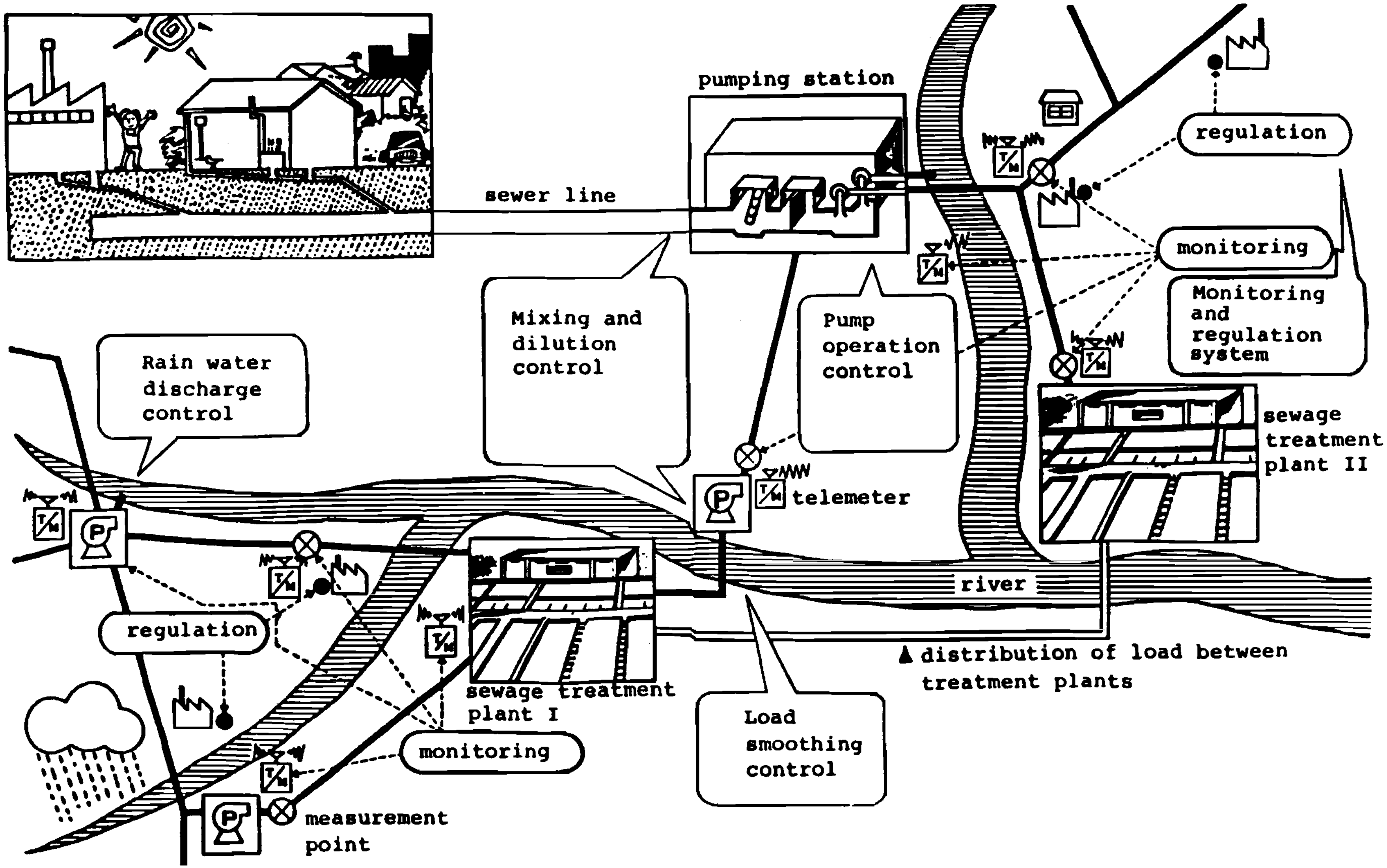

Figure 2. Total System Control for the Entire Sewer System

WATER QUALITY MANAGEMENT IN A WASTEWATER TREATMENT

M. Tanuma

1. INTRODUCTION

Recently many wastewater treatment plants have been constructed in Japan under the 4th sewer construction plan of the Ministry of Construction. At the same time regulations limiting the organic matter content of effluent discharges from treatment plants have been strengthened. These measures have improved the water quality of rivers and coastal areas but there are still some problems, such as a shortage of skilled operators, an increase in labor costs, an increase of treatment costs in general, and so on. In order to solve these problems a computer control system has been developed for an activated sludge process and has been used for pump control, process monitoring and data logging.

In this paper control algorithms and some experiences of practical applications of a control system for wastewater treatment (developed by Hitachi Ltd.) are presented.

2. OUTLINE OF THE CONTROL SYSTEM

2.1 Control System of a Hierarchical Type

A schematic diagram of the wastewater treatment processes to be considered in this paper is shown in Figure 1. Although these processes are managed in order to maintain a good quality effluent, it may still occur that organic matter concentration (BOD) in the discharge exceeds the limit value. Such deterioration of water quality can be classified roughly into two types according to whether the deterioration occurs over a short period or over a long period of time. Short-term deterioration may be caused by

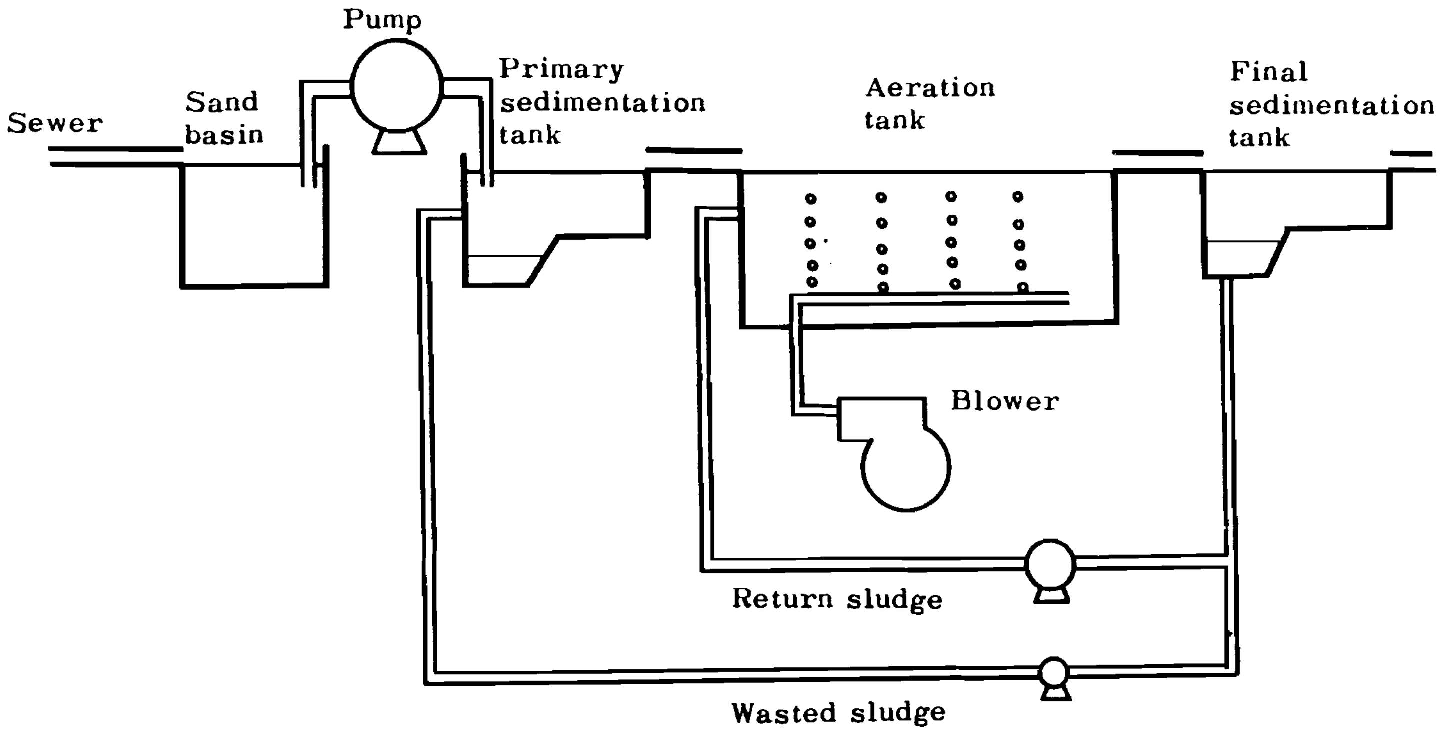

Figure 1. Schematics of wastewater treatment process

diurnal variations in the flow-rate and organic matter concentration of the influent sewage. In this case the quality of the effluent can be maintained by keeping process variables such as MLSS (Mixed Liquor Suspended Solids), DO (Dissolved Oxygen) and so on, at constant values and by having controllers for these purposes available. On the other hand, deterioration in performance in the long-term is caused by inappropriate management of the process. In this case improvements using an automatic controller are limited because the relation between effluent quality and other process variables is not well understood at present.

Based on these considerations a hierarchical control system, shown in Figure 2, has been developed by Hitachi Ltd. An MLSS controller and a DO controller at the lowest level assist in stabilizing the process. Total sludge quantity control,at the middle level, regulates the amount of sludge in the whole process and ensures process stability in the long term. An operating guide system at the top level assists operators in finding optimum operating conditions with the aid of mathematical models. This hierarchical control system has many advantages, in particular, a high degree of flexibility and reliability.

2.2 Sensors used for Control

A list of sensors used for control is shown in Table 1. Flow meters are installed in all plants since the quantity of sewage treated must be reported to the Ministry of Construction. The number of plants installing sensors for water quality has increased in the last few years. For example, DO meters and return sludge concentration meters are used in more than 60 per cent of the wastewater treatment plants; MLSS and turbidity meters are used in more than 30 per cent of the plants. However, TOC or UV (ultra violet) meters that can measure organic matter concentration are used in very few plants, since these meters have problems of reliability. This prevents both the development of sophisticated control systems and the development of mathematical models for the activated sludge process. Nevertheless, it can be expected that the regulation of the total quantity of organic matter in the effluent discharge will be a strong motivation for improving the reliability of related sensors.

3. DO CONTROL SYSTEM

A schematic diagram of the system for DO control at a specific point in the aeration tank is shown in Figure 3. The system consists of a DO control loop and air discharge control loops. The DO control loop computes desired values of air discharge to the aeration tanks based on the deviation of the measured value of DO from its desired value. There are two ways of controlling air discharge, either by adjusting valve openings at the exit side of the blowers or by adjusting suction valves. In Japan, the former is more popular. When outlet control valves are used, control loops for discharge pressure are needed.

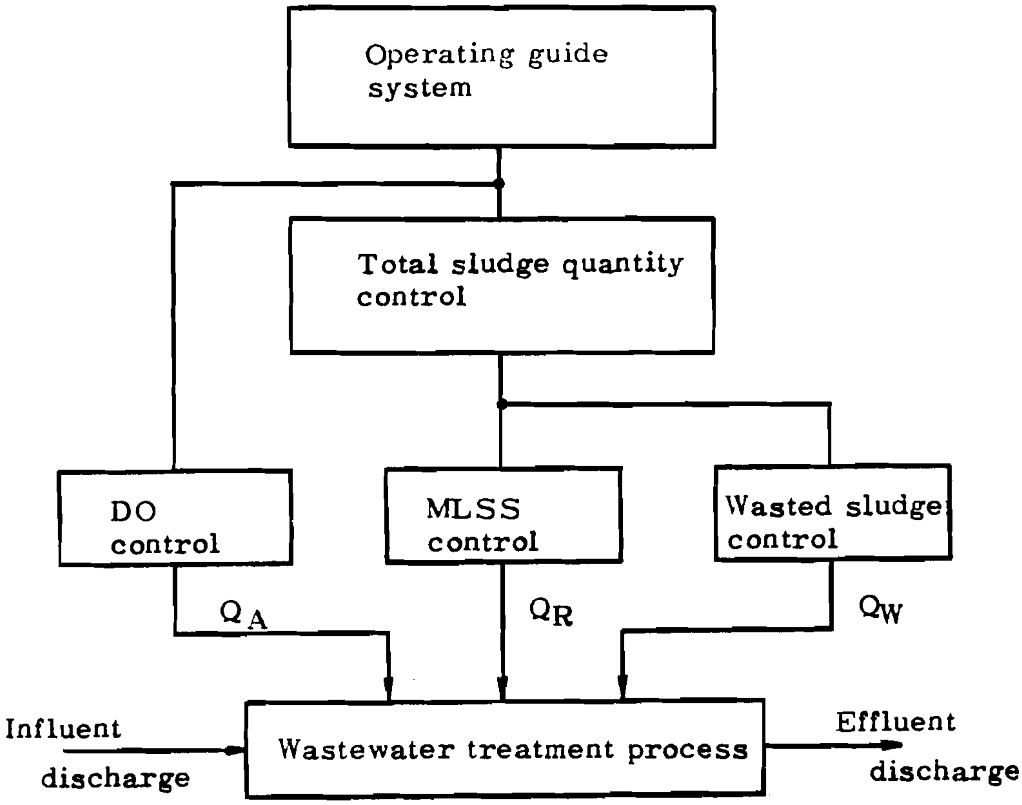

Figure 2. Organization of the wastewater treatment control system

Table 1. List of sensors used for water quality control

sensors		
Flow rate meter	Influent discharge	all plants
	Return sludge	
	Wasted sludge	
	Air discharge	
PH meter		
Thermometer		
DO meter		many plants
SS meter	Mixed Liquor in Aeration Tank	
	Return sludge	
	Effluent discharge	
Sludge blanket level meter (Final sedimentation tank)		a few plants
Sludge volume index meter		
Organic matter concentration meter*	Influent discharge	very few plants
	Effluent discharge	

(* TOC or Ultra violet)

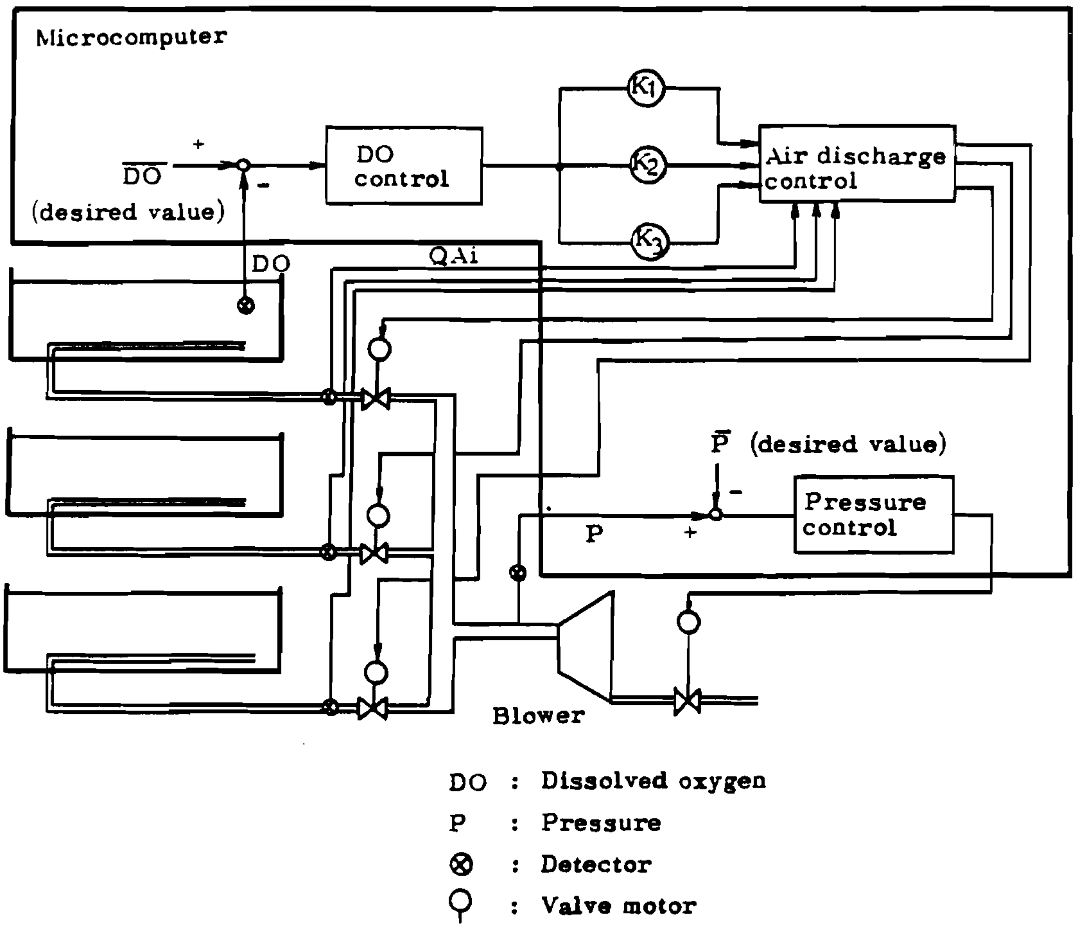

Figure 3. Block diagram of DO control

Analog or digital equipment can be used for the hardware of the DO control system. From our experience it can be said that the digital controller is superior to the analog controller since the former provides the following advantages:

(i) noise in the measured data can be easily removed by a digital filter;
(ii) nonlinearities existing in the relations between valve opening and air flow-rate can be compensated by using a nonlinear function in a microcomputer.

Control results of a DDC (Direct Digital Control) system are shown in Figure 4, where it is found that the DO controller contributes to stabilizing the aeration tank behaviour since deviation of the DO from its reference value is reduced to ± 0.5 mg/l. It is expected that the DO controller can contribute to energy savings as well as to improvement of effluent quality. An analysis of three months'data is summarized in Figure 5, which shows that the reduction in air flow-rate (for automatic as compared to manual operation) is 10 per cent when DO is kept at 4 mg/l. This reduction of air flow brings about a 5 per cent cost saving.

Although implementation of DO control is relatively easy, problems can arise from a narrow range of variation for air flow-rate in a blower and from the performance of the DO meter.

4. MLSS CONTROL

4.1 MLSS/Return Sludge Control System

Figure 6 presents a block diagram of an MLSS control system using return sludge flow-rate for maintaining MLSS at a constant level. In this system return sludge flow-rate is adjusted according to

$$Q_R = Q_O(\bar{S}-S_O)/(S_R-\bar{S})$$

where Q_R is the return sludge flow rate (m^3/h), $\bar{S}$ is the desired value of MLSS (mg/l), S_R is the return sludge concentration (mg/l), Q_O is the sewage flow rate (m^3/h), and S_O is the sewage suspended solids concentration (mg/l). This equation is derived from a mass balance equation, in which the amount of suspended solids supplied to the aeration tank equals the amount that flows from the tank.

In experiments of return sludge control at a large plant, the controller can reduce variations in MLSS to 50 per cent of the variations under manual operation, that is, about ± 500 mg/l. These results are worse than expected. A study of the experimental data reveals that a sufficiently variable range of return sludge flow-rate for MLSS control cannot be obtained because running gutter siphons are installed in the secondary sedimentation tanks to remove sludge. Thus, it can be said that careful

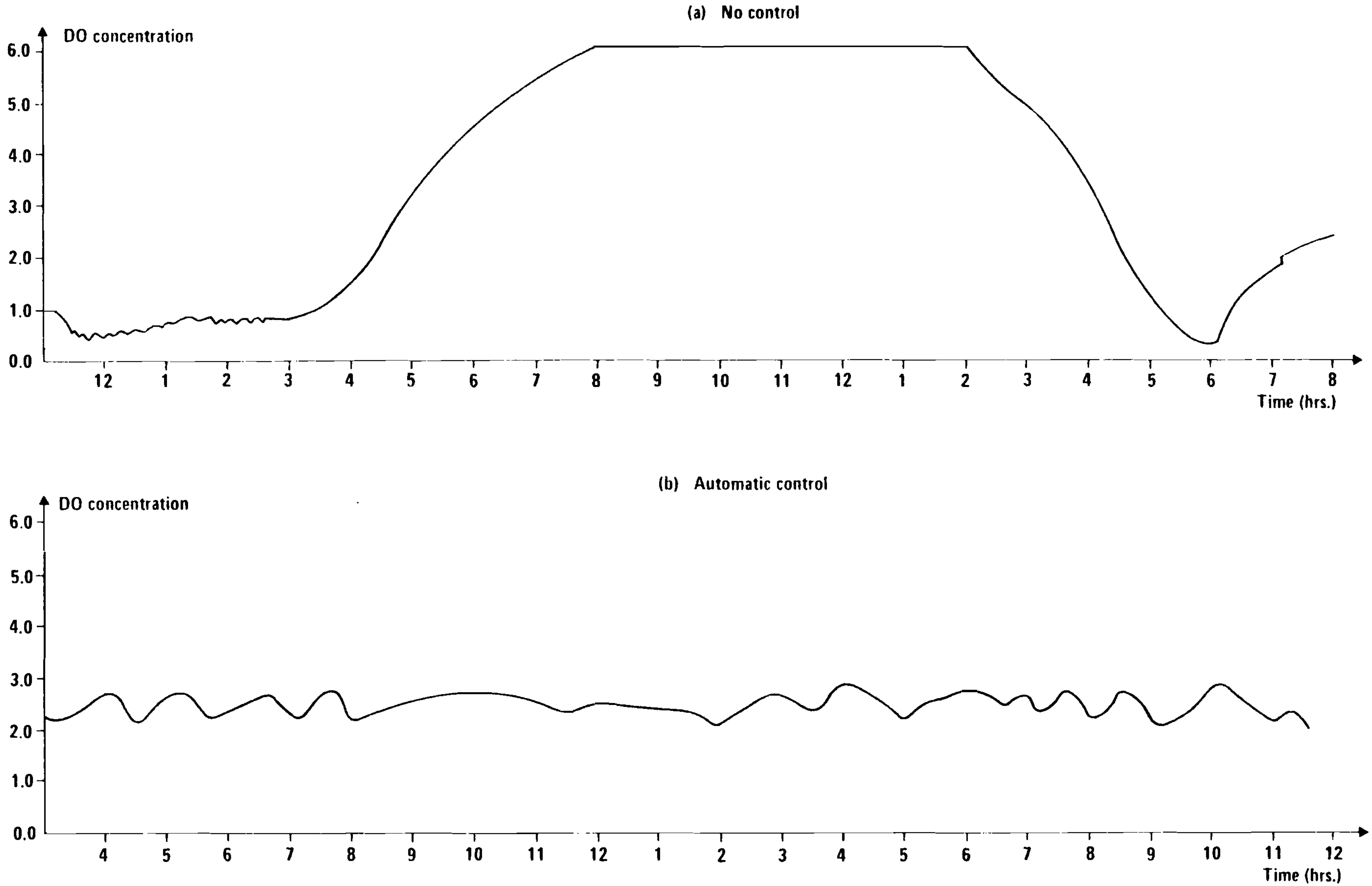

Figure 4. Variations in dissolved oxygen (DO) in aeration tank under manual and automatic operation.

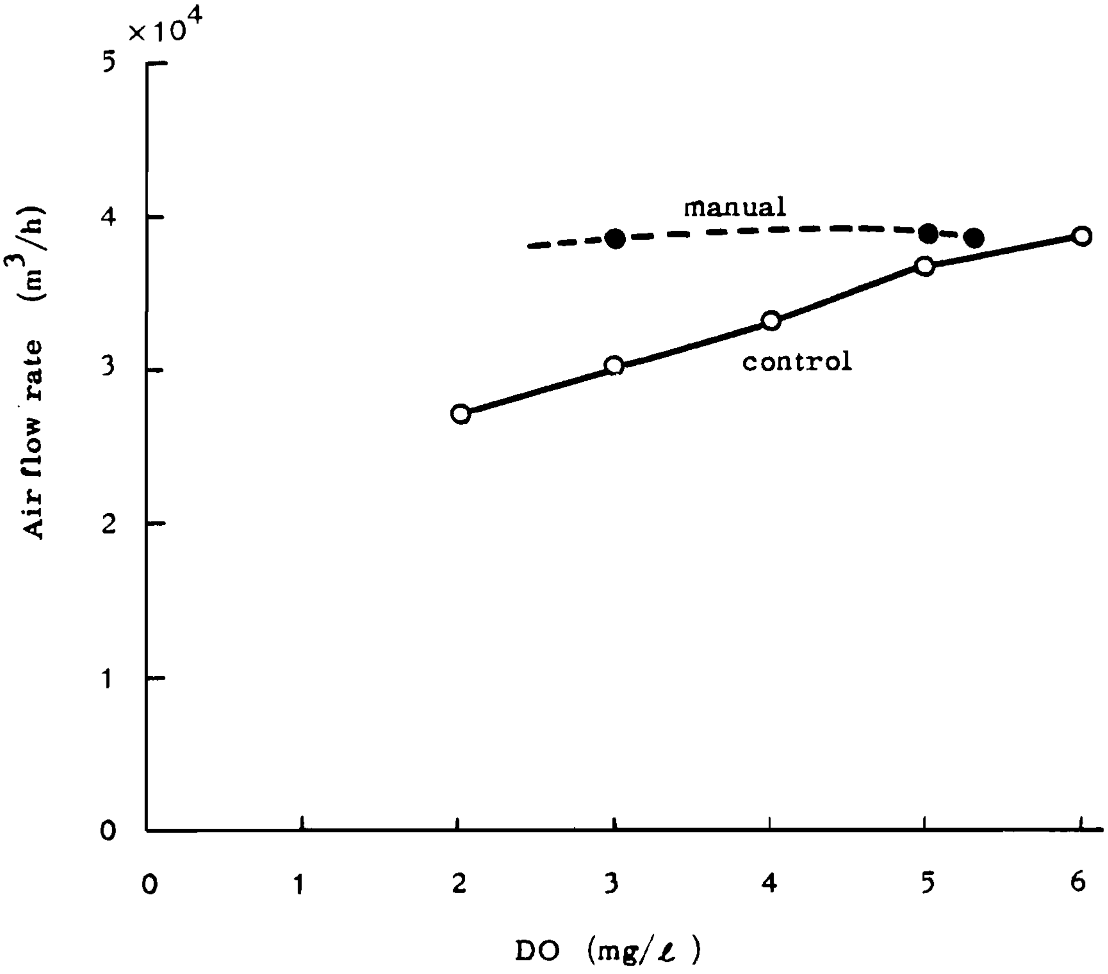

Figure 5. Effect of DO control on air flow rate reduction

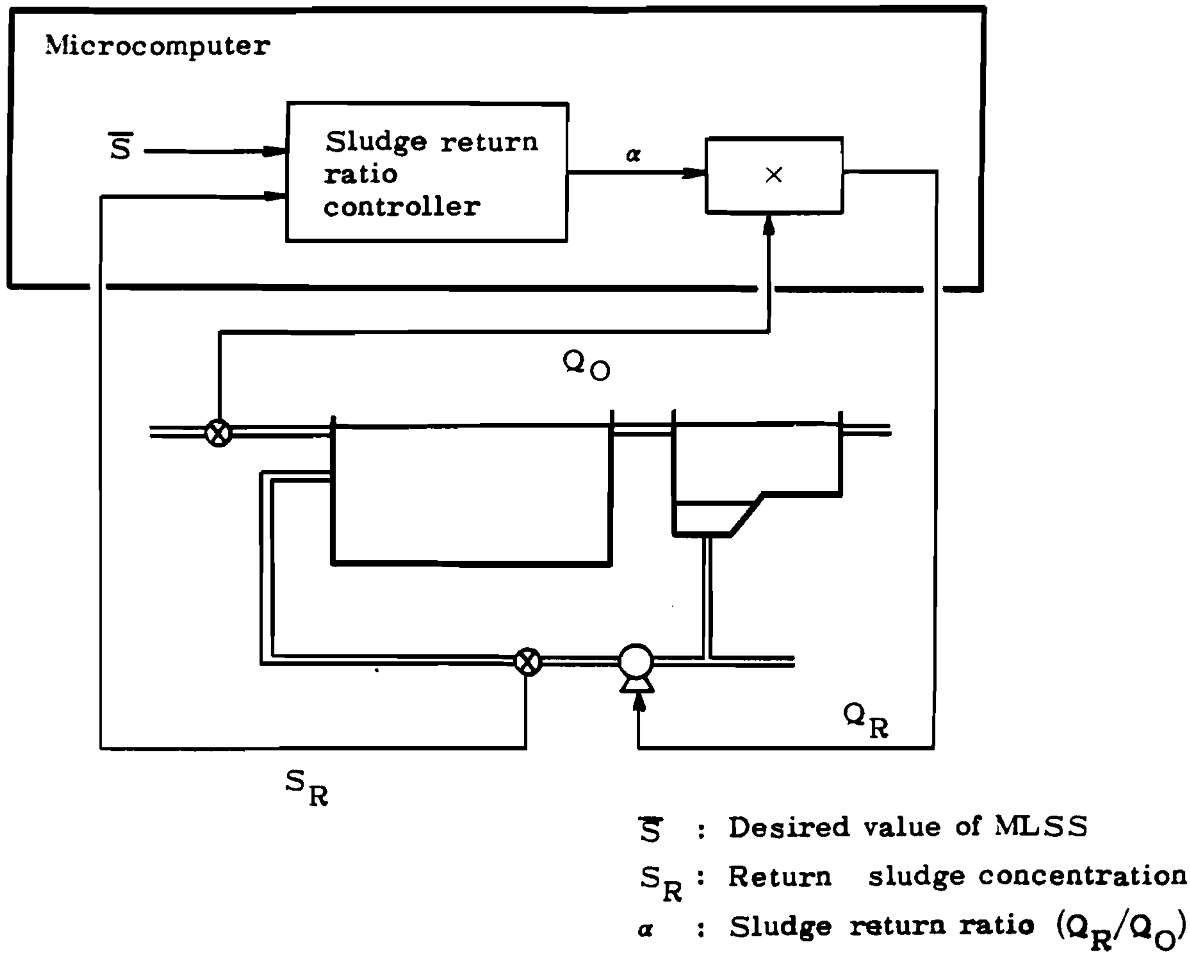

Figure 6. Block diagram for MLSS controller

prior studies of the feasibility of return sludge control in a full-scale process are needed.

4.2 MLSS/Dynamic Sludge Reserving Control System

Construction of a sludge reserving tank resolves the problem of a shortage or excess of return sludge in MLSS control. However, many costs and considerable space are needed for the sludge reserving tank and may make it impractical to construct the tank.

A block diagram of a new MLSS control system--the dynamic sludge reserving system which stores return sludge in a part of aeration tank--is shown in Figure 7. This MLSS control system uses a gate for regulating the flow-rate of sewage to the head of the aeration tank as a manipulating variable. When sewage flow-rate decreases and MLSS becomes high, the control system closes the control gate and stores return sludge in the head of the tank. When sewage flow-rate increases, the control system opens the gate and sheds the stored sludge downstream in order to prevent MLSS changes. In practice the dynamic sludge reserving system provides a feedback control function that adjusts the opening of the gate according to the deviation of the measure MLSS from its desired value. One of the advantages of this control system is that it can be implemented merely by installing a small motor for the control gate.

Experiments with the dynamic sludge reserving system have been performed in large operational plants and satisfactory results obtained. As shown in Table 2, variations in MLSS under such control are less than 10 per cent of the variations under manual operation. MLSS stabilization also brings an improvement of some 2 mg/l in the effluent COD.

5. TOTAL SLUDGE QUANTITY CONTROL SYSTEM

Controlling the quantity of total sludge in the unit, as well as stabilizing diurnal MLSS variations, is also very important for maintaining a high water quality. For example, when the settling characteristics of the activated sludge deteriorate because of organic overloading, the most important thing is to increase sludge quantity in the unit. This can be accomplished only by reducing wasted sludge flow-rate.

From the results of a dynamic analysis for the activated sludge process and from studies of operation at actual plants, it is found that control of the wasted sludge flow-rate plays a very important role. Based on these studies the total sludge quantity control system shown in Figure 8 has been proposed. This system consists of three control functions: the function of calculating the desired value of total sludge quantity ($\bar{S}_T$) from the selected index for sludge quantity (sludge age, F/M, for example); the function of estimating the present value of sludge quantity based on the measured MLSS, the measured sludge blanket level and so on; and the function of adjusting wasted

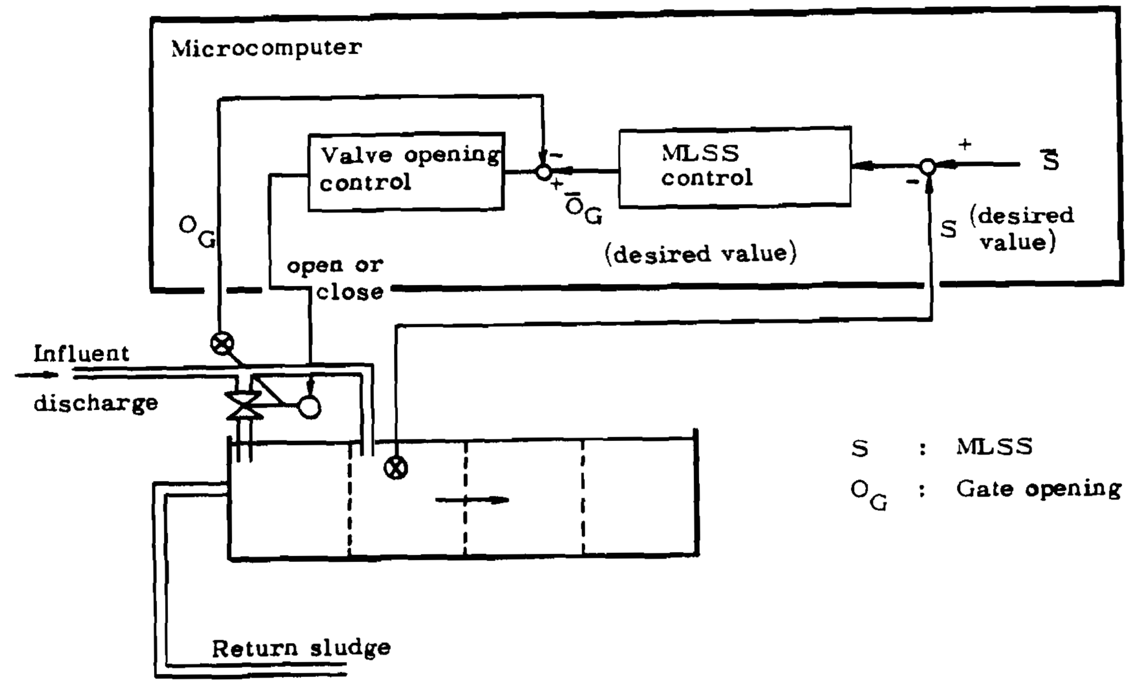

Figure 7. Block diagram of dynamic sludge reserving system

Table 2. Effect of dynamic sludge reserving control

	No control	Control
Variations in MLSS(for a day)	630 mg/l	50 mg/l

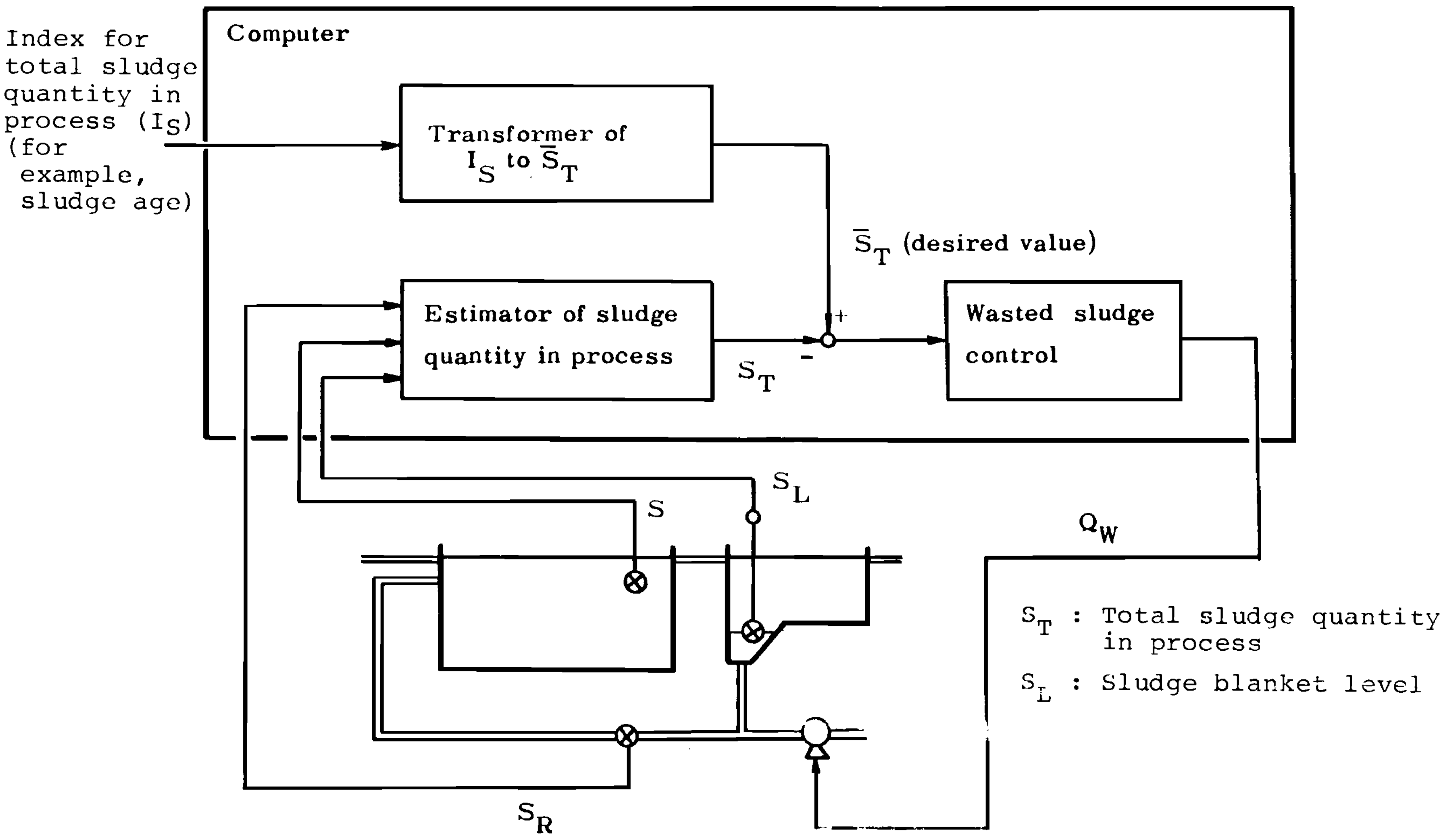

Figure 8. Block diagram of total sludge quantity control

sludge flow-rate based on the deviation of sludge quantity from its desired value. The advantages of this control system are as follows:

(i) problems of organic overloading can be avoided by controlling sludge quantity and this brings improvement in the settling properties of the activated sludge;
(ii) the system can be widely applied and several types of sludge control, such as sludge age control, F/M control and so on, can be effected without changing the structure of the controller.

6. OPERATING GUIDE SYSTEM

The operating guide system, which can predict variations in water quality by using mathematical models, is very effective for operation of the activated sludge process since the response of this process to input disturbances is very slow. In this section the development of mathematical models for computer control and an operating guide system are presented briefly.

6.1 Mathematical Model Development: Data Collection

From June 1975 to December 1976 process data were logged with a computer at a large-scale wastewater treatment plant under the control of the Sewage Bureau of the Tokyo Metropolitan Government. Figure 9 illustrates the computer system used for data logging. A HIDIC-500 control computer (with a 24k word core) processed 25 sets of analog data and 48 sets of digital data at intervals of five minutes through the process I/O and stored them on magnetic tape (M/T). The data on the M/T were then transferred to a master tape by means of a large computer and subsequently analyzed by the large computer.

The following data were logged for the purposes of developing mathematical models. The sewage flow-rate, MLSS, DO, water temperature and pH were measured at the aeration tank outlet. The return sludge concentration and wasted sludge flow-rate were measured automatically at the final clarifier and the air discharge-rate for aeration was also measured. Chemical oxygen demand (COD) and transparency of the influent and effluent were measured manually. For logging data in wastewater treatment processes the following should be considered:

(i) Water quality data should be gathered continuously for a long period of time because of the slow dynamic components of the activated sludge process.
(ii) The difficulty of obtaining data concerning organic matter concentration of the influent and effluent obstructs the development of mathematical models. In our study COD was measured manually once every two hours for one day in each month; problems of analysis may occur because of this small amount of data. Sensors that can measure

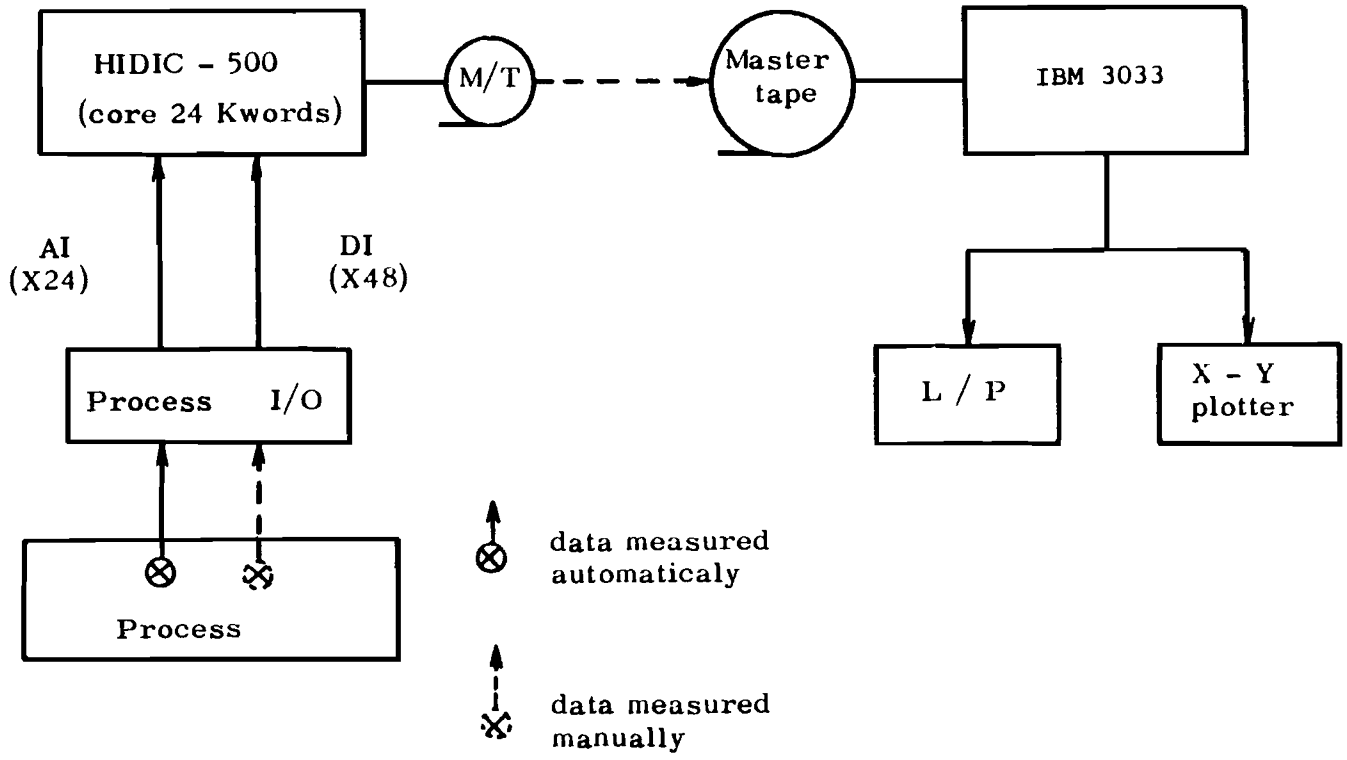

Figure 9. Data logging system

organic matter concentration and turbidity in sewage would therefore be very useful in developing accurate mathematical models.

(iii) Data showing the distribution of variables such as DO, MLSS, and COD in the aeration tank, are important for examining process behaviour.

6.2 The Model

The aeration tank and the final clarifier are integral components of the plant. As shown in Figure 10, we studied mathematical models for the aeration tank that allow representation of the variations in MLSS, DO and COD, and we studied models for the final clarifier that allow representation of the variations in COD discharged from the clarifier. An on-line mathematical model has been developed with particular reference to the following:

(i) The submodels shown in Figure 10, that is the MLSS model, the DO model and so on, may be developed individually. One of the reasons for this is that water quality data are not homogeneous (for example, MLSS is measured continuously while COD is measured intermittently) and this makes the simultaneous construction of two models very difficult.

(ii) A simplified model that can predict water quality on the basis of easily measured process variables should be developed.

From simulation results, it is found that sewage quality in the activated sludge process can be predicted with an error of less than 15 per cent.

6.3 Operating Guide System

The computer introduced for plant operation incorporates rather simple functions, such as data logging and process monitoring. However, the development of mathematical models enables the computer to offer a more sophisticated control function.

A schematic diagram of the operating guide system is shown in Figure 11. The mathematical models are used to predict the quality of the effluent discharge one week in advance; this is achieved on the basis of historical sewage data and values chosen for the process manipulating variables by the operator. The results of predicted quality variations are displayed to the operator on a cathode ray tube (CRT) and if the predicted values do not satisfy the water quality standards, the manipulating variables are reselected and the simulation is repeated. By this process of iteration the optimum operating conditions can thus be determined.

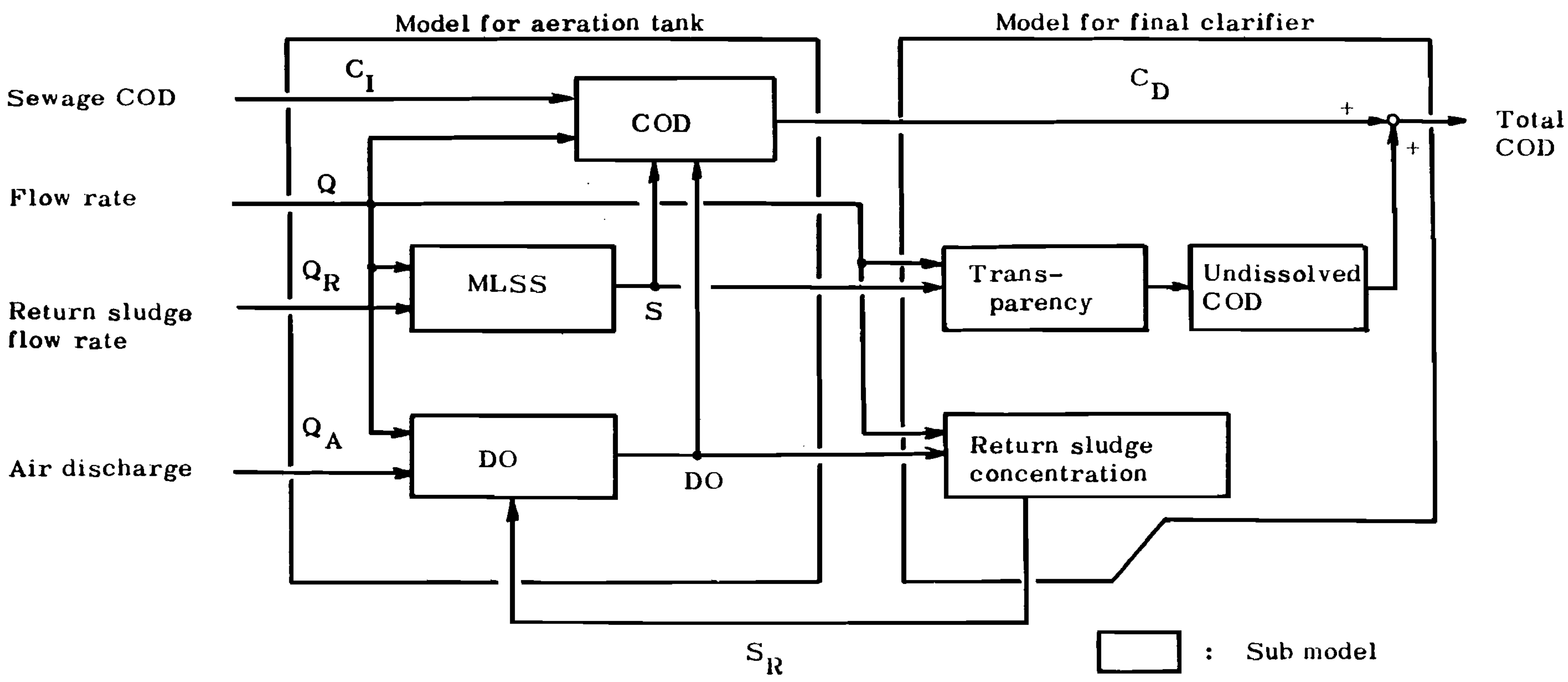

Figure 10. Organization of mathematical model

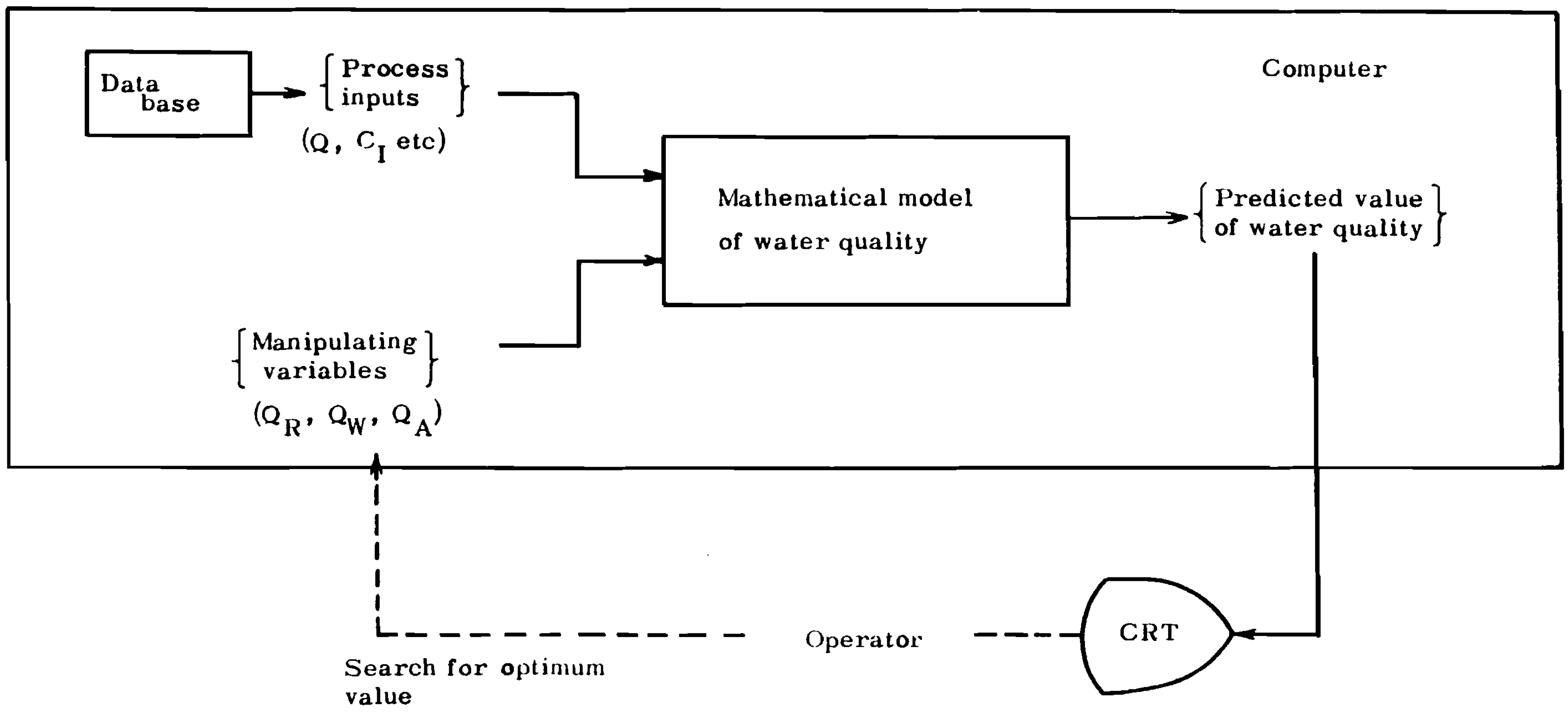

Figure 11. Schematics of computer assisted control system

7. CONCLUDING REMARKS

The current status of a wastewater treatment control system is reported here. So far we can conclude that the approach has passed from the basic research stage to a stage of more practical development. Based upon our experience it can be said that the following are required for further progress:

(i) More data should be gathered for the analysis of process characteristics. Data and the development of a general mathematical model, whose effectiveness can be demonstrated by reference to the data, are very important for future control applications.

(ii) Making the activated sludge process controllable is also necessary. From the point of view of process automation, the wastewater treatment plant suffers from problems arising from the structure of unit processes that were designed without consideration of automation. It is necessary to establish procedures for design that give consideration to the possibility of future automation.

ON-LINE WATER QUALITY MONITORING SYSTEM AND ITS APPLICATION IN OSAKA

M. Fujita, and M. Ozaki

1. INTRODUCTION

The quality of water in Japanese rivers and other public water areas has improved since the mid-1970's following the implementation of effluent standards and pollution control measures. However, concentrations of pollutants related to the living organic environment (BOD, COD, and so forth) still exceed the environmental quality standards in rivers flowing through urban areas of high population density and in large enclosed bodies of water that have little interaction with the open sea. This is mainly because controls on permissible pollutant concentrations at effluent outlets were imposed in 1970 as a measure against water pollution and these controls have suffered from the following limitations:

(i) They attempt to maintain environmental quality standards in the coastal water areas of each prefecture separately. Therefore, they cannot effectively deal with either wide areas of water covering several prefectures or pollution generated from the prefectures where the headwaters are located.

(ii) Previous standards regulate factories and business entities and do not have sufficient influence on those domestic effluents which may create excessive loading of the existing (and inadequate) sewage treatment facilities.

(iii) Concentration standards can be met by diluting the effluent but without reducing the overall load of pollution.

2. REVISION OF WATER POLLUTION CONTROL LAW FOR REGULATION OF TOTAL EFFLUENT

In order to maintain water quality in large enclosed water areas, a partial revision of the Water Pollution Control Law was made in June, 1978. This introduced total effluent controls for reduction of the total pollution load from all sources in inland and coastal prefectures. This revision went into effect in June, 1979.

This is a regulation of the actual amount of pollutants entering public water areas. For the present this regulation covers three main water areas in which there is a limited circulation of water to and from the open sea. They are Tokyo Bay, Ise Bay, and the Seto Inland Sea (also regulated by the Seto Inland Sea Conservation Law). COD is used as a pollution index. The schedule for implementation of the regulation of total effluent is given in Figure 1.

3. WATER QUALITY MONITORING SYSTEM

Monitoring of rivers and pollution sources such as factories and sewage treatment plants is essential for implementing the regulation of total effluent. The required system should automatically monitor water quality and effluent quantity, obtain continuous data on pollution conditions 24 hours a day, and transmit this data to a central monitoring station by means of a telemetry network. At the central station, hourly, daily, and monthly reports should be produced on-line by computer and all types of data would have to be processed to provide important information for reducing the pollution load. The Environment Agency of Japan has announced a policy of assisting the local governments (prefectures and designated cities) affected by the regulation of total effluent in implementing water quality monitoring systems. Co-operation and a subsidy were given to Osaka City in 1978 as a model program and will be offered to a number of other districts from 1979 onwards.

4. THE OSAKA WATER QUALITY MONITORING SYSTEM

4.1 Process of Implementation

Osaka obtained a subsidy from the Environment Agency of Japan in 1978 to introduce a water quality monitoring system. The system was constructed by Hitachi, Ltd., and actual operation began in April, 1979. Osaka is the central city of western Japan with a population of 2,700,000; it contains a variety of industries located both inland and alongside the ocean. The city instituted a "Clean Water Plan" in 1973 for restoration of the waters of the adjacent rivers and coastal zones to prevent further deterioration of water quality. Osaka now has the highest sewer reticulation ratio in Japan (97.3 per cent as of April, 1974) and has taken many other pollution control measures. It is this background that encouraged and stimulated the construction of the first such water quality monitoring network in Japan.

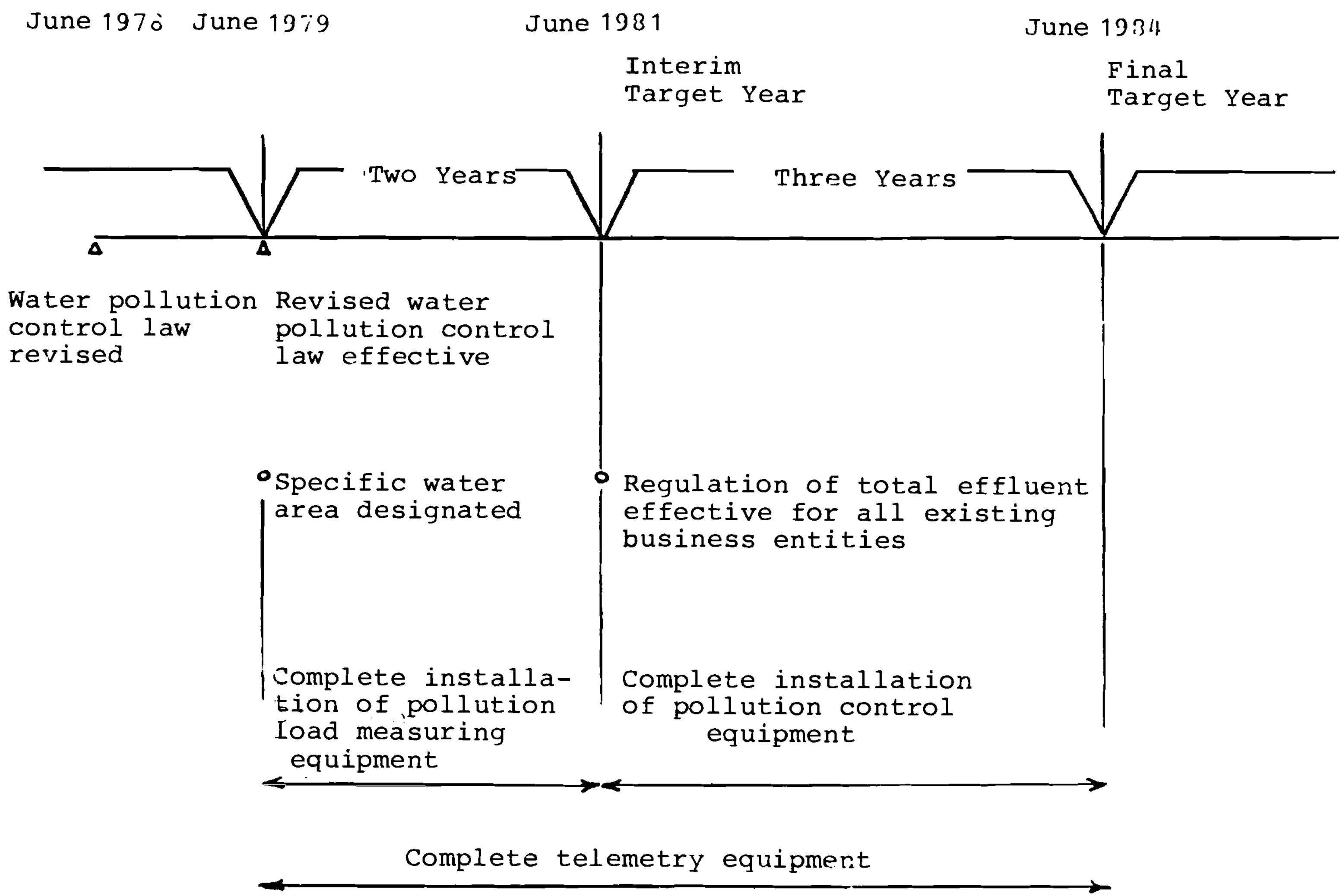

Figure 1. Schedule for implementation of the regulation of total effluent

4.2 Structure and Functions of the System

The structure of the system is shown in Figure 2. Automatic monitoring of the variables listed in Table 1 is carried out at factory monitoring stations, sewage treatment plant monitoring stations, and river and stream monitoring stations. The data are transmitted by telemetry equipment at each branch station to the central monitoring station where a computer (complete with memory and output terminals) displays pollution data from all the monitoring stations on a data display panel. On-line, real-time processing and batch processing of the data are also provided. The system has the following functions:

- (i) Automatic analysis of water quality and monitoring of effluent quantity;
- (ii) Computation of effluent pollution load;
- (iii) Collection of data with telemetry equipment;
- (iv) Preparation of various types of reports;
- (v) Data display;
- (vi) Graphic representation of data (with X-Y plotter and CRT display);
- (vii) Compilation of data and statistical analysis;
- (viii) Transmission of data to related institutions.

The locations of the branch and central monitoring stations are shown in Figure 3.

4.3 Effect of Implementing the System

The monitoring equipment in the system had a high rate of reliable operation and provided continuous and effective monitoring. The results obtained with the COD and UV meters had a very high correlation with the COD value obtained manually by the JIS standard method of analysis, which serves as the index for the regulation of total effluent.

The data measured and compiled (COD, COD load) is printed out in the form of daily totals, weighted averages and maximum and minimum values. Thus it is easy to observe the amount of pollution produced each day by each factory. It is also easy to check whether measurements at any location have been omitted. Approximately 30,000 business entities in the city of Osaka discharge effluent into the sewer system. There are only 120 factories that discharge their effluents directly to rivers or the ocean and thus come under the effluent regulations for public water areas. Among these, there are 10 factories whose effluent discharge rate exceeds 1,000 $m^3 day^{-1}$. The government assumes that by establishing monitoring stations at these factories and at the 13 sewage treatment plants in Osaka, the major portion of the pollution load produced in the city can be monitored effectively.

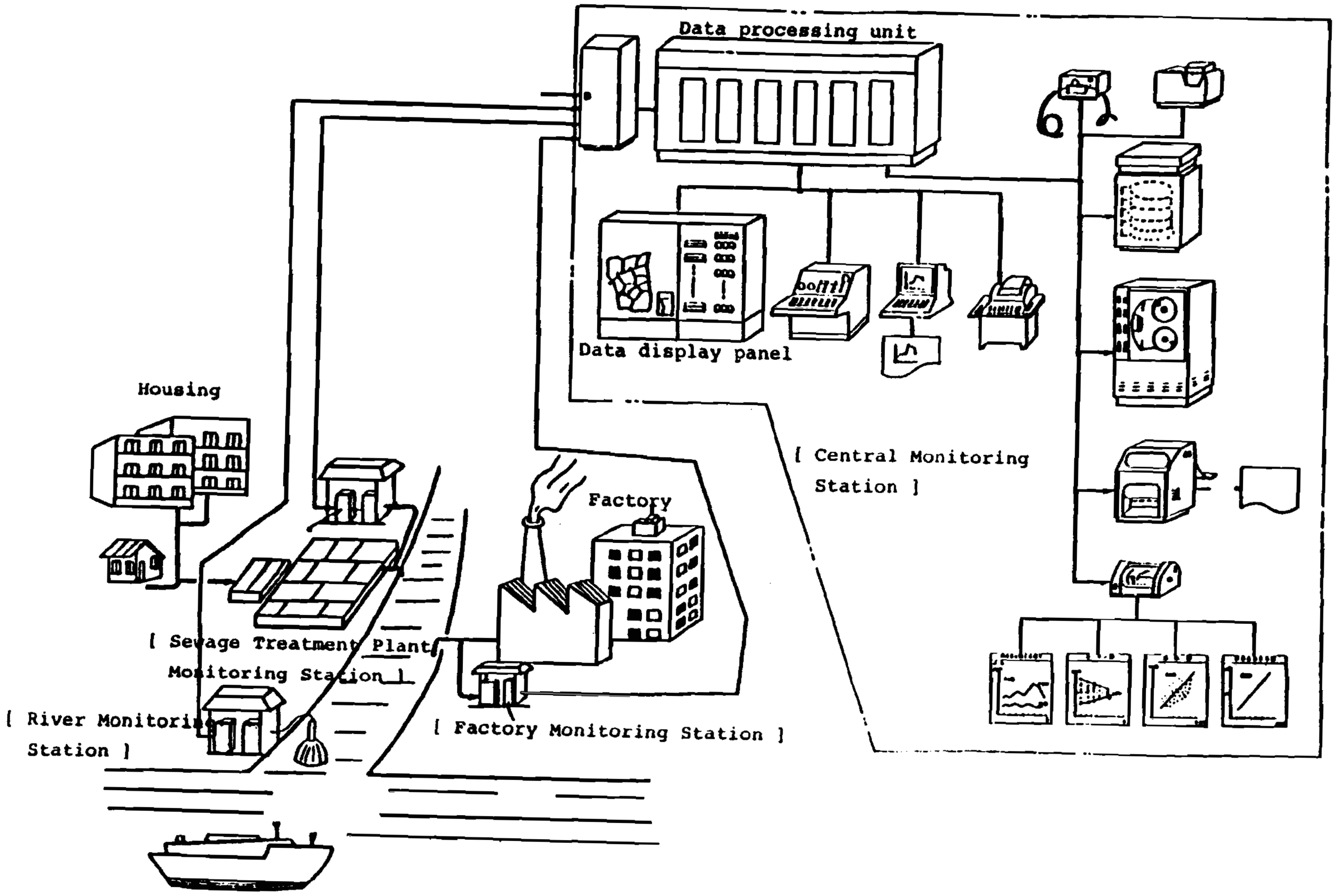

Figure 2. Configuration of water quality monitoring system

Table 1. List of variables monitored at each station

Station	Variables Monitored
River Monitoring Station	COD, DO, water temperature, pH, electrical conduction rate, turbidity, oxidation-reduction potential
Factory Monitoring Station	effluent volume, COD, UV absorption rate, COD load or UV load
Sewage Treatment Plant Monitoring Station	COD, UV absorption rate, COD load or UV load, effluent volume

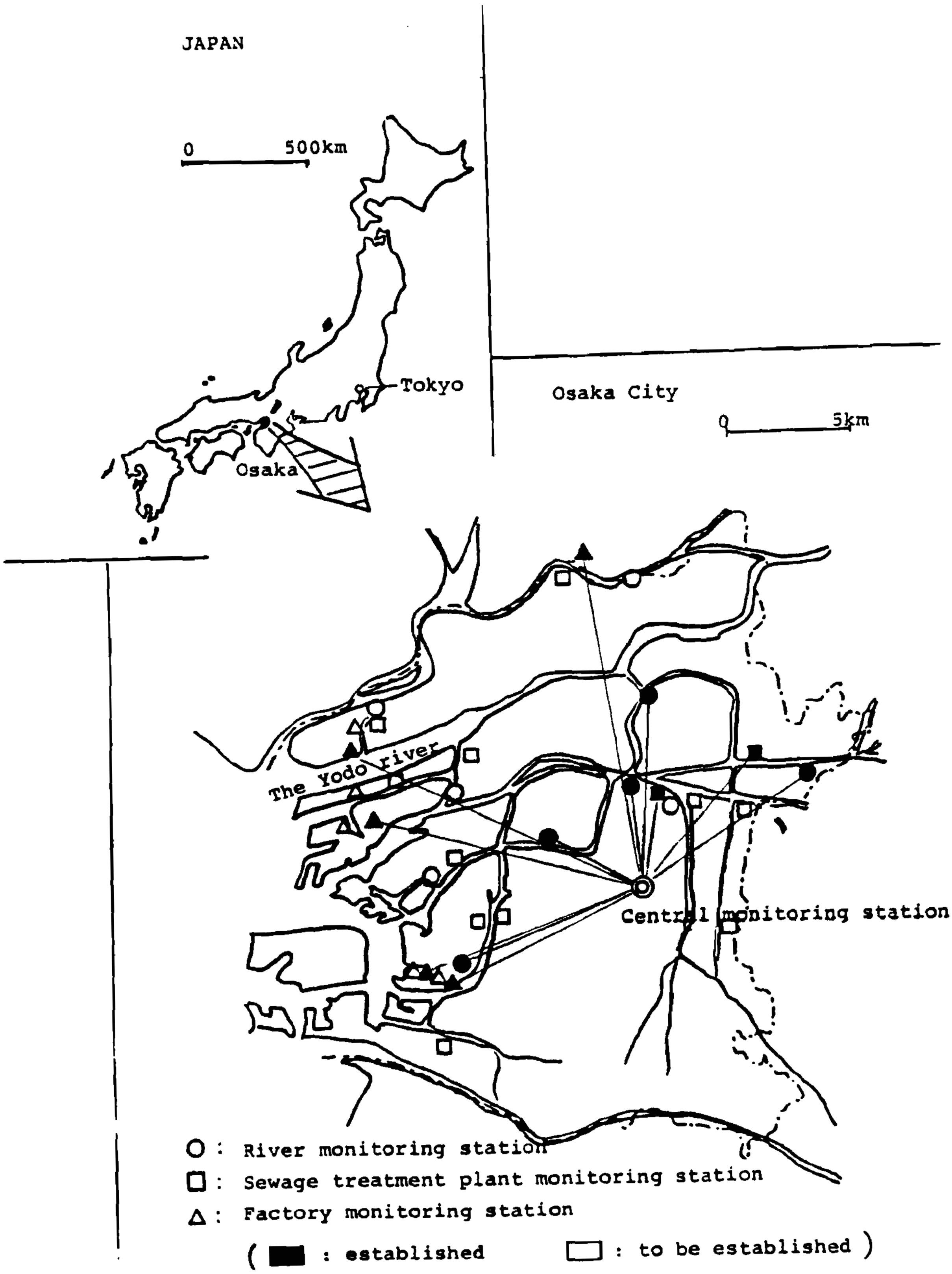

Figure 3. Location of branch and central monitoring stations in the Osaka network

APPENDIX A: LIST OF CONTRIBUTORS TO THE TASK FORCE AND PARTICIPANTS IN THE MEETING (MARCH 12-14, 1980)

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APPENDIX B: AGENDA FOR THE TASK FORCE MEETING (March 12-14, 1980) ON REAL-TIME WATER QUALITY MANAGEMENT

Wednesday March 12

8.30 - 9.00	Registration (Conference Secretariat on First Floor)
9.00 - 9.45	Introduction (B. Beck) (i) Objectives of the Task Force Meeting (ii) Expected results -- the Executive Report and other publications (iii) Discussion of Agenda
9.45 - 10.30	Institutional and Practical Constraints on Time-variable Water Quality Management (H. Fleckseder)
COFFEE BREAK	
11.00 - 11.45	Energy Conservation in Wastewater Treatment (J. Andrews)
11.45 - 12.30	Design and Operation Interaction in Wastewater Treatment (G. Olsson)
12.30 - 14.00	*LUNCH*
14.00 - 14.45	Operation of a Stream Water Quality Monitoring Network (P. Whitehead)
14.45 - 15.30	Microprocessors in Water Quality Management (S. Marsili-Libelli)
COFFEE BREAK	
16.00 - 16.45	Real-time Water Quality Management in Finland -- Current Research and Some Computer-based Applications (A. Halme)
16.45 - 17.30	Application of Computer Systems for Real-time Water Quality Management in Japan (M. Ohnari)
17.30	Depart for "Heuriger" in Baden

Thursday March 13

9.00 - 9.45	Economics of Time-variable Water Quality Management (Y. Smeers)
9.45 - 10.30	Additional presentations
COFFEE BREAK	
11.00 - 12.30	Specification of Working Groups (see attachment)
12.30 - 14.00	*LUNCH*
14.00 - 17.30	Working Groups

Friday March 14

9.00 - 10.30	Working Groups
COFFEE BREAK	
11.00 - 12.00	Closing Session (1) -- Reports from Working groups for preparation of the Executive Report
12.00 - 13.00	*LUNCH*
13.00 - 14.30	Closing Session (2) -- Conclusions and specification of extensions to the project