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WATER QUALITY MAINTENANCE AND CONTROL THEORY

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ABSTRACT.

River pollution control, or water quality control to use less emotive language, really needs no introduction to the chemists and biologists who have nurtured the subject since its emergence with the Industrial Revolution. In contrast, the control engineer has begun only recently to contemplate the application of his particular expertise and knowledge to this sphere of research. It is intended, therefore, that this report should review the component features of water quality control and locate those areas where control and systems theory may provide useful results; in this respect it is furthermore advantageous to show where coordinated research is required between the control engineer and members of other sciences such as biology, ecology, hydrology and economics. Indeed, water quality control is a field which denies the strict classical separation of scientific research into well-defined disciplines and faculties.

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1. INTRODUCTION.

It is probably true of all countries that national requirements for potable and municipal water supply are increasing; and, similarly, with expanding population and industries the production of waste material from society is also increasing. The combination of these two events places a great strain on the maintenance of river water quality and requires more sophisticated techniques for the management of water resources in general. With specific reference to the United Kingdom, one might define the problem as not so much a case of the traditional diminishing resource of finite quantity, but rather one of finite retrieval of fresh-water in terms of reservoirs and impoundments; rising prices and increasing competition for land use have generated considerable interest in an alternative to fresh-water reservoirs, namely the use and re-use of water courses for the purification of effluents and the abstraction of potable water supplies.

Thus, given a situation where the problem of planning and control of river water quality is too complex to be considered outside the realms of relatively advanced mathematical and engineering methods, control and systems theory may offer the techniques to solve many of the current problems. Nevertheless, it should not be overlooked that the control engineer is naturally dependent upon many other disciplines of science in order to approach the subject with any hope of success in <u>practical</u> terms. As will become evident in the present discussion, control theory has advanced far beyond the current needs and available technology of waste water treatment; thus it is unfortunate that published material suggests that the control theoreticians have tended to assume too high a level of technology in water pollution studies, which belies a requisite minimum intimacy with the system to which they have chosen to apply their knowledge.

2. GENERAL ASPECTS OF RIVER WATER QUALITY CONTROL.

2.1. The Degradation of Water Quality.

Principally, polluting materials enter a water course through effluent discharges, although water quality can be significantly impaired by agricultural chemicals in surface water run-off and land drainage and by power station cooling water. The effects of the latter two inputs are mainly indirect in the sense that they provide nutrients and higher temperature conditions, respectively, which can increase the growth rate of certain components of the aquatic ecology, e.g. algae, thus causing an undesirable imbalance in the system.

The numbers and types of pollutant substances are many and varied, but first let us make a distinction between conservative and non-conservative substances by the following definitions: a non-conservative substance can be degraded or altered by biological and chemical processes in the stream, whereas a conservative substance is unaffected by such action. To the control engineer the interaction of soluble non-conservative matter with the aquatic environment is the more challenging topic since the underlying physico-chemical and biochemical mechanisms are complex and dynamic variations are quite pronounced.

2.2. Waste Water Treatment Technology.

Ultimately, the maintenance of river water quality is dependent to a large extent on the technology and design of sewage treatment plants. Currently available techniques of waste water treatment conform to a comparatively standardized pattern and are oriented towards the removal of two indices of pollution level: (i) suspended solids; (ii) biochemical oxygen demand (BOD), an aggregate or macro-measure of the degradable organic waste content of the effluent. Usually the quality of the final effluent is specified as a maximum permissible level of suspended solids and BOD related to a given effluent /stream dilution ratio.

The design of a waste water treatment plant for efficient operation depends essentially upon the regulation of a constant volumetric flow through the biological oxidation process of a percolating filter or activated sludge stage. At present, therefore, the automation of the plant is usually a function of routing the flow according to pre-specified schedules based on the design flow. Possibly because of its hitherto relatively insignificant economic importance, the waste water treatment industry has not been subjected to a wealth of technological innovation; the application of control theory to the unit process involved, e.g. activated sludge treatment [8] and chemical precipitation, is merely in its infancy. Generally, only a few local controllers are currently used for operation and the introduction of further on-line control is hampered by the considerable effort required to develop suitable and reliable instrumentation [23] as we shall see later.

Thus, a truly variable control of waste water treatment is not available at present and it is simply not possible to regulate either the effluent flow or quality in a manner which can maintain prescribed in-stream conditions on a day-to-day operational basis.

2.3. Water Quality Monitoring and Instrumentation.

In contrast to the process industries, the monitoring of water quality is severely encumbered by the accessibility problems associated with rivers and the multitude of variables to be observed; it is often difficult to place a monitor in a suitable position owing to the nature of the river bank or bed and even then the retrieval of data can be delayed by the long distances over which it must be transmitted to the processing centre. The technology of the instrumentation is limited and integrated monitoring systems with reliable, robust equipment are few and far between; clearly, it is not feasible to produce an automatic system capable of monitoring all the physical, chemical and biological variables that might at some time be significant [7].

However, sensors have been developed for the determination of temperature, dissolved oxygen (DO) concentration, pH value, conductivity and turbidity; more recently, ion-selective electrodes for the measurement of nitrate, sulphide, ammonia, and cyanide, for example, have been made available, but are only at the evaluation stage [7]. Suffice it to say that, in the majority of cases, the observation of water quality variables is a matter of manual or automatic sampling followed by laboratory analysis; indeed, experience shows that it is an extremely tedious affair.

With respect to control applications the difficulty in obtaining suitable data cannot be emphasised too strongly. Many locations for monitors prevent the use of a mains power-supply and the alternative is beset by recurrent failure of batteries; in addition the sensory equipment requires continual maintenance to prevent fouling and the loss of calibration. Such problems in conjunction with the laboratory analysis of samples make the data collection procedure a labour-intensive operation which can only be accomplished in an arduous manner and with a certain dedication to duty. The net result is a debilitating lack of data in the published studies.

2.4. Water Quality Standards.

It should be understood that in the course of most water quality studies one encounters the vexed question of specifying standards for acceptable stream conditions; as yet, no-one has solved the problem of establishing suitable and socially-fair levels of quality to be maintained and nor is there an effective characterisation of the benefits to accrue from the amenity value of water courses. In the case where stream quality holds the balance between the competing demands of effluent disposal and potable water abstraction it is more a mathematical problem to formulate the cost-benefit analysis; however, amenity values are less easy to cost objectively and the problem formulation tends to stray into the less tangible sphere of politics.

2.5. The Control Problem.

The water quality control problem can best be defined by reference to Figure 1; briefly, it divides into three separate categories:

(i) On-line automatic control for waste water treatment plants (WT);

(ii) On-line automatic control for potable water abstraction plants (PWA);

(iii) On-line control of water quality in reaches $j = 1, \ldots, m$ to be consistent with pre-specified standards for the stream.

As will become evident in Section 3 of the report, the majority of control theory applications have examined category (iii), either for the single reach case or multi-reach case where $j = 1,\ldots,m$; it is, in general, true that control (iii) will be dependent upon (i), which is invariably assumed to be available in order to obtain solutions for (iii). Other areas of active research have been confined mainly to the control of one of the unit processes in waste water treatment (i), namely the activated sludge stage [8]. However, the synthesis of a control system for the combined operation of (i) + (iii) or (i), (ii) + (iii) has not been attempted to the best of the author's knowledge.

3. CONTROL AND SYSTEMS THEORY APPLICATION TO PROBLEMS OF WATER QUALITY CONTROL.

A cursory review is given here of those aspects of water quality maintenance which have proved amenable to the application of control and systems theory. The discussion is not exhaustive, since it is largely restricted to considerations of dissolved oxygen as a specific index of water quality, and should be read as a collection of example problems and their modes of solution.

3.1. System Identification and Estimation of Parameters. In-stream water quality modelling.

What is really required of a water quality model is that it be able to predict the effects of a multitude of pollutant materials on, and their interactions with, the aquatic environment. However, for the purposes of the present discussion, the problem is simplified by the conservative nature of many pollutants, where independent component mass balances and time-series analysis of the associated system inputs and outputs at various fixed spatial locations can be applied to obtain models.

On the other hand, the dynamic variations of non-conservative pollutants are more difficult to characterise since they interact with the aquatic life system in a complex biochemical or biological manner. Historically one particular index of water quality, DO *), has received

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*) Appropriately so, since DO level reflects the general health and balance of the aquatic life; BOD is the principal non-conservative substance interacting with DO and hence the tendency to refer to BOD-DO models in the literature.

much attention [9], [13], [26], although the major research effort has been directed towards the development of theoretical models for use in a steady-state, deterministic parameter estimation context. Unfortunately, steady state is the exception rather than the rule for river systems and the more realistic problem of identifying a dynamic BOD-DO model in the presence of system and observation noise has been tackled using the extended Kalman filter [3]; it was first necessary, however, to identify the system approximately by deterministic simulation, where it was found that the complexity of the model should be extended to include explicit representation of the effects of algae [2].

The emergence of algal growth and decay as important constituents of the BOD-DO balance raises the intriguing issue of the control engineer's ability to model ecological systems in general. Although preliminary steps have been taken already in this direction [1], it would be reasonable to suggest that data collection for verification purposes could prove to be quite restrictive.

Stream flow modelling.

The synthesis of stream flow data plays an integral part in the prediction of water quality variations, since the flowrate of a river affects the dispersive and retention time properties of each reach. An example of recursive time-series analysis (see e.g. Young [33]) applied to this kind of problem is the rainfall-flow modelling work carried out recently in connection with a systems analysis study of water quality in the Bedford-Ouse river system [4], [35]. The flow model of a 55 km stretch of the river between the site of the new city of Milton Keynes and Bedford uses a combination of lumped-parameter differential-difference equations to characterise the deterministic variations in flow, and a time-series model to account for stochastic variations resulting from rainfall and run-off effects. These latter time-series models have been developed using an Instrumental Variable - - Approximate Maximum Likelihood (IV-AML) approach [5], [6] and seasonally adjusting the rainfall data to account for varying rates of evaporation [30]. Similar studies besides that of the Bedford-Ouse system have also used recursive time-series analysis techniques to model rainfall-run off relationships [18].

3.2. Control System Synthesis: In-Stream Water Quality Control.

The general approach to the in-stream water quality control problem has been to assume largely unverified dynamic models of BOD-DO interaction and the availability of a method of on-line waste water treatment plant control.

Single-reach control.

The single-reach case may be thought of as a subset of the multireach problem discussed below; however, the concern of hierarchical strategies, in particular, with the optimisation of the global system and their assumption of sub-optimal or optimal singe-reach controllers, shows a surprising, and almost total, disregard in the literature for more simple dynamic control investigations.

There are two basic alternative approaches to the local (i.e. single-reach) control of, for instance, in-stream dissolved oxygen level:

(i) artificial aeration of the stream;

(ii) regulation of an effluent discharge to the stream.

Tarrasov et al [28] have provided optimal control surfaces for the solution of (i) by operation of a series of submerged pipes and diffusers attached to the river bed, but it is (ii) which would appear to be the more immediately practicable of the two methods. Thus, in an attempt to place a lesser demand on the possible technological advances in this field, a preliminary examination employing simple <u>algebraic techniques of state-space control system synthesis</u> has demonstrated the initial feasibility of approach (ii) [34]; this study was oriented specifically towards the use of field data primarily collected for identification purposes [2], [3]. Adequate control can be achieved by either of two state-variable feedback laws: (i) assuming a variable treatment process the <u>BOD concentration</u> of the effluent is controlled in a prescribed manner; (ii) for a fixed treatment process the <u>effluent flow</u> is detained in storage lagoons or tanks and subsequently discharged to the river in accordance with the control law.

Multi-reach control.

Several investigators have tackled the optimal or near-optimal control of a multi-reach system and adjacent treatment plants; by multi-reach it is assumed that it is possible to decompose the global river system into a series of sequential, discrete reaches (usually defined in terms of the physical placement of treatment plants, tributaries and weirs) as in Figure 1. Recent work has shown that methods of hierarchical-multilevel control are appropriate for the solution of the operational problem [12], [24], [25], [27], although other suboptimal procedures have been suggested [19]. The structure of the hierarchical strategy requires a "first-level" local controller, which computes the optimal control trajectories for each reach, while a "second (or higher) level" controller co-ordinates this information to be consistent with an optimal or near-optimal control law for the global system.

3.3. Long-Term Planning and Investment Analysis.

For a long time capital investment in the necessary facilities has dominated the economic evaluations of water resources management; indeed, operational costs are so traditionally thought of as negligible that for this reason, and, in addition, the lack of a clearly defined "final product" specification, the automatic control of waste water treatment has remained somewhat of a backwater in the stream of technological advance.

However, in the broadest setting, investment policies need to consider a multitude of objectives for supply and demand of water; in the United Kingdom the precursor for this type of large-scale study has been the Trent Research Programme *) [14], [15]. A steady-state model describing many indeces of water quality is a fundamental part of this analysis, which examined the complex problem of assessing the different ways in which water from the Trent and its tributaries can be used for domestic, industrial, agricultural and amenity purposes. The problem is constructed in a manner whereby the costs and benefits of each facility can be evaluated to determine the most efficient solution using a dynamic programming routine. Similar approaches have been used by Dysart [10] and Futagami [11], for example, to solve the less ambitious problem of optimising future investment needs for a series of sewage treatment plants.

The more general principles of water resources management have been formulated by several people in the USA; in particular, Thomann [29] has provided a review of systems analysis application and Kneese (see e.g. [20]) has contributed much to the advance of economic theory in this area.

The omissions of this review section are a reflection of the general absence of control and systems theory application to the water quality maintenance problem. However, we have not considered the identification and control system synthesis for waste water treatment plants, since the review by Olsson et al [23] illustrates the many problems to be addressed in that respect; neither is men-

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*) It is worth mentioning in passing that the Trent Research Programme is a comprehensive survey which has hypothesised several interesting methods of obtaining potable supplies from moderately polluted river water, e.g. sandstone aquifer recharging, and naturally filtered water from alluvial gravels.

tion made of the technological progress required for the on-line control of potable abstraction plants, where it can be assumed that latent control problems exist, although this area is outside the previous experience of the author. And finally, since the discussion has been limited to water quality as opposed to water resources in the wide sense, it is interesting to observe that reservoir systems, for example, are not immune to simple control analysis [16], [17], [31].

4. A CRITICAL APPRAISAL OF SOME ASPECTS OF CONTROL APPLICATIONS.

There are several general criticisms to be made of the current tenor of control applications in water quality systems. Firstly, by virtue of their distributed-parameter nature they are an example problem for the formulation of estimation techniques with partial differential equations [21], [22]; however, these studies, either merely assembling the optimal state estimation equations [21] or "verifying" a stochastic approximation technique with synthetic data [22], while they may indicate the initial viability of an approach, have tended to overlook practical considerations in order to obtain theoretical completeness. The very limiting constraints of field data collection, where the most intensive sampling programmes so far published in the literature are a maximum of some eighty daily samples from the author's experimental work, and, more recently, a further block of seventy daily samples from the Bedford-Ouse study, seem to indicate a certain naïvety in discussing unbiased parameter convergence over several hundred iterations of daily samples [22]. And in any case, it is not necessarily true that partial differential equation models are the best representation of quality and flow dynamics in a river; certainly, the lumped-parameter differential-difference equations used for deterministic simulation of BOD-DO interaction [2] and rainfall-flow prediction [30] adequately account for the majority of variations observed.

Secondly, since a river system can be decomposed into a sufficiently complex sequential, discrete, multi-reach problem it has become popular to apply techniques of hierarchical or multi-level control in this area, again, largely as a convenient example formulation. Experience shows that even a simple PI controller on the DO level in a river is difficult to justify unequivocally in an economic context; thus, hierarchical, multi-reach control solutions tend to meet with implacable refusal, on behalf of the practising profession, to admit the feasibility of on-line control in any form whatsoever. It seems, therefore, that some subtlety is required of the control engineer and he should proffer more immediately practicable solutions to the problems of water quality control. At the very least he should be able to demonstrate that operational costs are not negligible or that the introduction of on-line control could reduce capital investment costs.

Yet, in making such criticisms of hierarchical control applications in this field it is not denied that such studies can provide useful references against which the performance of less sophisticated control systems can be judged; moreover, they may be of significance in the possible extensions to the simple local control schemes when emergency situations require co-ordinating action between individual reaches and their controllers. However, it should not be forgotten that we are, after all, dealing with the solution of essentially practical problems and in this case it should be a matter of the problem specifying an applicable technique rather than a piece of theory searching for justification in an applications sense.

5. FUTURE PROBLEMS FOR IDENTIFICATION AND CONTROL.

Some of the points which have been reviewed are developed further here since they give an insight to the control engineer of the type of complexities involved and they also define the peripheral areas where he may be required to make compromise solutions in view of the intricate biological and biochemical nature of water quality systems.

Let us take as our example the BOD-DO interaction discussed previously and although we shall consider in-stream aspects of the relationships they may well apply to similar processes occurring during the treatment of effluent before discharge to the stream. Superficially it would appear that we are concerned with chemical constituents interacting in a manner which can be described largely by the rate kinetics of purely chemical and physical phenomena. However, without giving too much detail, which may confuse the issue at present, the very definition of BOD and its "decay" properties, i.e. the oxidation of degradable material, are a crude, but nevertheless viable, approximation of complex biological processes by first-order chemical reaction kinetics. Thus, from the outset the most basic mathematical descriptions of BOD-DO interaction are considerable simplifications of the true dynamics of the system.

Furthermore, when it was found necessary to include the effects of algal growth and decay in the model [2], [3] the identification problem moved into the more mathematically nebulous area of describing the interplay between components of an ecological system. Algal population kinetics are dependent upon sunlight intensity, and the concentrations of nitrogen- and phosphorus-bearing chemicals; their particular importance lies in their ability to expand their numbers suddenly under so-called "bloom" conditions, thus completely disrupting the balance of the aquatic life structure. Indeed, algae have been the subject of much research effort in connection with the eutrophication *) of lakes and reservoirs (see e.g. [32]), which, as is indicated below, may be of importance in waste water treatment control system synthesis. However, for the purposes of a mathematical BOD-DO model there exists a large gap between the macroscopic needs of a control engineer and the microscopic details which can be provided by a biologist; one may compare the requirements of the situation to those of a bilateral international meeting without an interpreter!

Ultimately, in view of limited data, the compromise solution was to predict algal growth and decay by a pseudo-empirical relationship which low-pass filtered the hours of sunlight incident on the system each day. Quite obviously, it would be preferable to augment the BOD-DO equations with properly identified state-space equations for algal population dynamics, since this would be more theoretically satisfying and it may provide a more easily manipulable control variable than sunlight intensity, e.g. phosphate or nitrate concentration. However, it is now appropriate that we make mention of the other principle non-conservative substances in a stream, namely those bearing nitrogen in their structure; in fact, the <u>nitrogen cycle</u> interacts with the BOD-DO balance by the processes of nitrification and denitrification **), while the corresponding fluctuations in nutrient concentration

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**) Nitrification is the oxidation of ammonia products, for example, through nitrite to nitrate compounds; denitrification is the reverse process.

*) i.e. nutrient-rich; nitrates and phosphates etc. are nutrients in this sense.

influence the growth rates of algae. It is hoped that a combined BOD-DO, algae, and nitrogen-cycle model can be identified from data currently being analysed at the Control Division, University of Cambridge Engineering Department, in connection with the Bedford-Ouse River study.

Thus, there is much to be accomplished in the modelling of water quality dynamics, but the problem will probably be constrained by the availability of suitable data and the interpretation of complex biological information into a tractable mathematical form. On the other hand, for control system synthesis it may be adequate to make several approximations, although it seems reasonable to assume here that nitrate and phosphate removal at the treatment stage may eventually be closely linked to that of BOD. In particular, the feasibility of lagoon detention schemes for effluent control (see Section 3.2) rests upon the suppression of eutrophication and the subsequent possible transmission of large, active algal populations to the stream.

6. CONCLUSIONS.

The problems of water quality maintenance are no different in nature from those in many other systems; rather, it might be concluded that they are more emphasised. For instance, data are particularly difficult to obtain, the technology of the plant is currently not amenable to control application, cost-benefit analyses are difficult to formulate and there is a lack of clearly-defined "final product" specifications for stream quality control and potable water abstraction.

All the possible control applications cannot be reviewed, since many of them are only in a nascent form and others will emerge as further research is undertaken. But the necessary investigations should not assume the appearance of running before they can walk, so to speak, and even the most elementary control theory may be genuinely useful before the implementation of more sophisticated techniques.

7. Footnote.

This report is based on research *) carried out by the author in the Control Division of the University Engineering Department, Cambridge between October, 1970, and October, 1973. During the final year, from October, 1972, a three-year project was commenced on the modelling and control of water quality in the Bedford-Ouse river; part of this study is the responsibility of Dr. Peter C. Young and Paul Whitehead of the Control Division at Cambridge and to whom the author is indebted for many useful discussions.

The author would also like to express his appreciation of the advice and comments on this report given by Professor G. Olsson of the Lund Institute of Technology, Division of Automatic Control.

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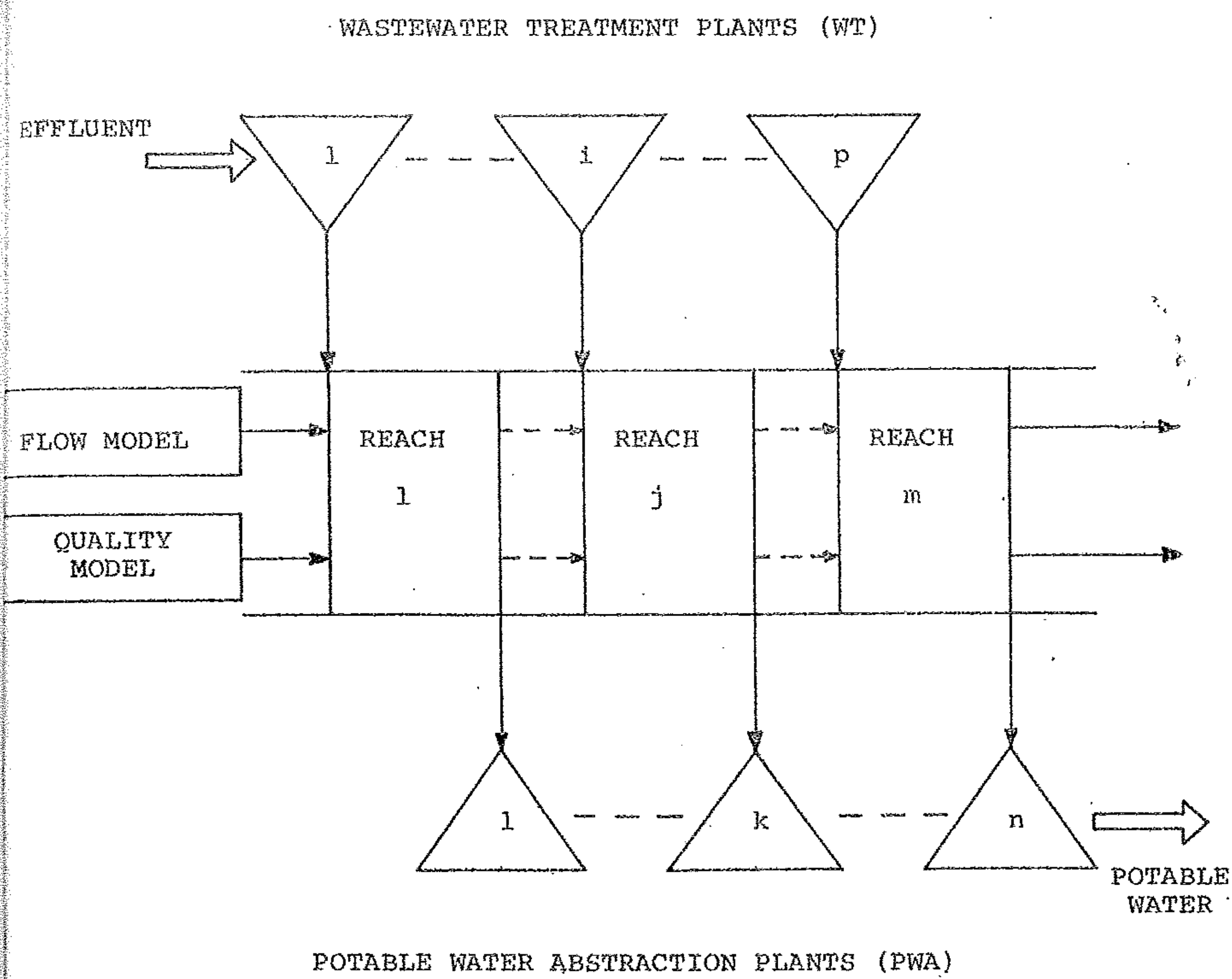

Figure 1. A Schematic Diagram of a River System and Adjacent Treatment and Abstraction Facilities.