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ANALYSIS AND CONTROL OF NONPOINT NITRATE POLLUTION OF MUNICIPAL WATER SUPPLY SOURCES

K.-H. Zwirnmann

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PREFACE

The Resources and Environment Area (REN) of IIASA is dealing with, among other problems, pollution of water resources caused by agricultural activities. For example, nitrate pollution of water resources is very dangerous in many water supply regions. In April 1980, an exploratory study on nonpoint nitrate pollution of municipal water supply sources was initiated as a collaborative study between REN and several institutions from the IIASA National Member Organization countries. The first objective of the study is to explore approaches to analysis and control of the problem in question. The second objective is to generate a methodological outline focusing on the integration of the most relevant results of the exploratory phase. Based on this, the overall direction of further REN research can be established more clearly, which is the third objective.

This paper summarizes the work concerning the first two objectives done at IIASA between April and October 1980. The paper is based mostly on source material kindly furnished by the cooperating organizations from the NMO countries. It has been structured largely according to the main topics of a related Task Force Meeting which will be held at IIASA in February 1981. In doing so, the paper is intended to serve as a basis for the discussion at this meeting on the attainment of the study objectives mentioned above.

Dr. Janusz Kindler
Chairman
Resources & Environment Area

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K.-H. Zwirnmann

INTRODUCTION

In many developed and developing regions throughout the world, a steadily increasing demand for water is confronting water supply and management agencies. Water supply is usually constrained by natural, technological, and economic conditions. This limit on the quantity of water which can be tapped grows more severe because deteriorating water quality necessitates even more complex utilization constraints. Operating with this in mind, regional water managers attempt to satisfy different supply interests, especially when these interests conflict with each other. In particular, the competing interests of agriculture, environment, and municipal water supply develop increasing importance. For example, in recent years water supply agencies have become progressively more concerned by high nitrate levels in municipal water supply sources. This is because many studies carried out in several countries (including some pursued at IIASA), show that agricultural nonpoint pollution sources are the major cause of rapid increase in nitrate concentrations in water resources, despite the tremendous variety of nitrogen sources in the environment which contribute to water pollution.

So far, research at IIASA related to nitrate pollution has been concentrated mainly in the Task "Environmental Problems of Agriculture" of the Resources and Environment Area. This work dealt in particular with agricultural-environmental processes related to crop production and thus provided insight into the important role of agriculture in the nitrogen cycle (Golubev and Shvytov, 1980). Moreover, the research was concerned with modeling agricultural nonpoint source pollution and analyzing economic-environmental tradeoffs between the intensification of agricultural production and the possible deterioration in environmental quality (Haith, 1980; Gum and Oswald, 1980).

Yet another aspect of the problem remains to be considered, that of water supply and management. The specific concern about nitrate pollution of municipal water supply sources stems from the hazard to public health caused by the toxic effects of nitrates in drinking water. On the other hand, nitrate removal from water supplies cannot be accomplished by using conventional treatment procedures. Consequently, there is a clear necessity to clarify the potential extent and severity of the situation in order to understand constraints imposed by nitrate pollution on water supply planning and to identify feasible control strategies. Taking into account the variety of nitrogen pollution sources, the control can only be achieved when the phenomenon of nitrate pollution of water supplies, a complex interdisciplinary problem, is attacked as a whole, by the adoption of some type of systems approach. This paper represents a preliminary attempt in this direction. Although the main concern here focuses on agricultural nonpoint pollution sources, and in particular on the use of inorganic fertilizers, the author attempts to formulate an approach generally suitable for most other relevant types of pollution. This is done by placing nonpoint nitrate pollution control in the general framework of water quality management, and reflected throughout the paper by the complementary and largely synonymous use of the terms control and management.

The first section of the paper tries to identify the various mechanisms by which the water resources of a region and the inputs and outputs of nitrogen to and from the water resource system interact. Based on this analysis, a conceptual system for control of nonpoint nitrate pollution of municipal water supply sources is outlined. After having dealt with important features of both the system to be controlled and the control system itself, the subsequent sections analyze the components of the control system. The discussion of the management objectives and alternatives for pollution control will be followed by a section on methods of analysis to be applied in the planning phase of pollution control. In order to establish clearly the conflict needing resolution, agriculture is dealt with as an internal control factor in the two problem areas of management objectives and alternatives. However, it is far beyond the scope of this paper to deal comprehensively with both agricultural production planning and water quality management planning. Attention is therefore devoted to the latter, with particular reference to planning processes such as water quality monitoring (including data management), water quality impact analysis, and the analysis of management alternatives. Agricultural production is taken into account as an external constraint. In dividing the discussion into sections on management objectives, management alternatives, and methods of analysis, some overlapping among the sections is unavoidable and even desirable.

NITRATE POLLUTION OF WATER RESOURCES: SOURCES AND CONTROL

The initial step in developing options for control of nonpoint nitrate pollution of municipal water supply sources is the analysis of the physical system to be controlled. The interactions of various components of the system, such as the water resources of a region, or the inputs and outputs of nitrogen to and from the water resources system, need to be identified. Then a control system can be outlined.

Nitrogen and Water Resources

The schematic representation of the inputs and outputs of nitrogen to and from a regional water resource system (Figure 1) conceptualizes, in a highly simplified manner, the physical system requiring control.

The amount of nitrate present in water supply abstraction is determined by the amount of nitrogen lost from the system as regional outflow. However, it is basically controlled by the various processes taking place in the nitrogen cycle, particularly by the interaction of water with the soil-plant system. Consequently, the system to be controlled has been divided into three generalized parts: surface water, groundwater, and the soil-plant system.

The major inputs of nitrogen to this system are:

- waste sources such as domestic and industrial effluent, and animal wastes;
- atmospheric sources, such as nitrogen delivered in rainfall, and biological fixation;
- inorganic fertilizers.

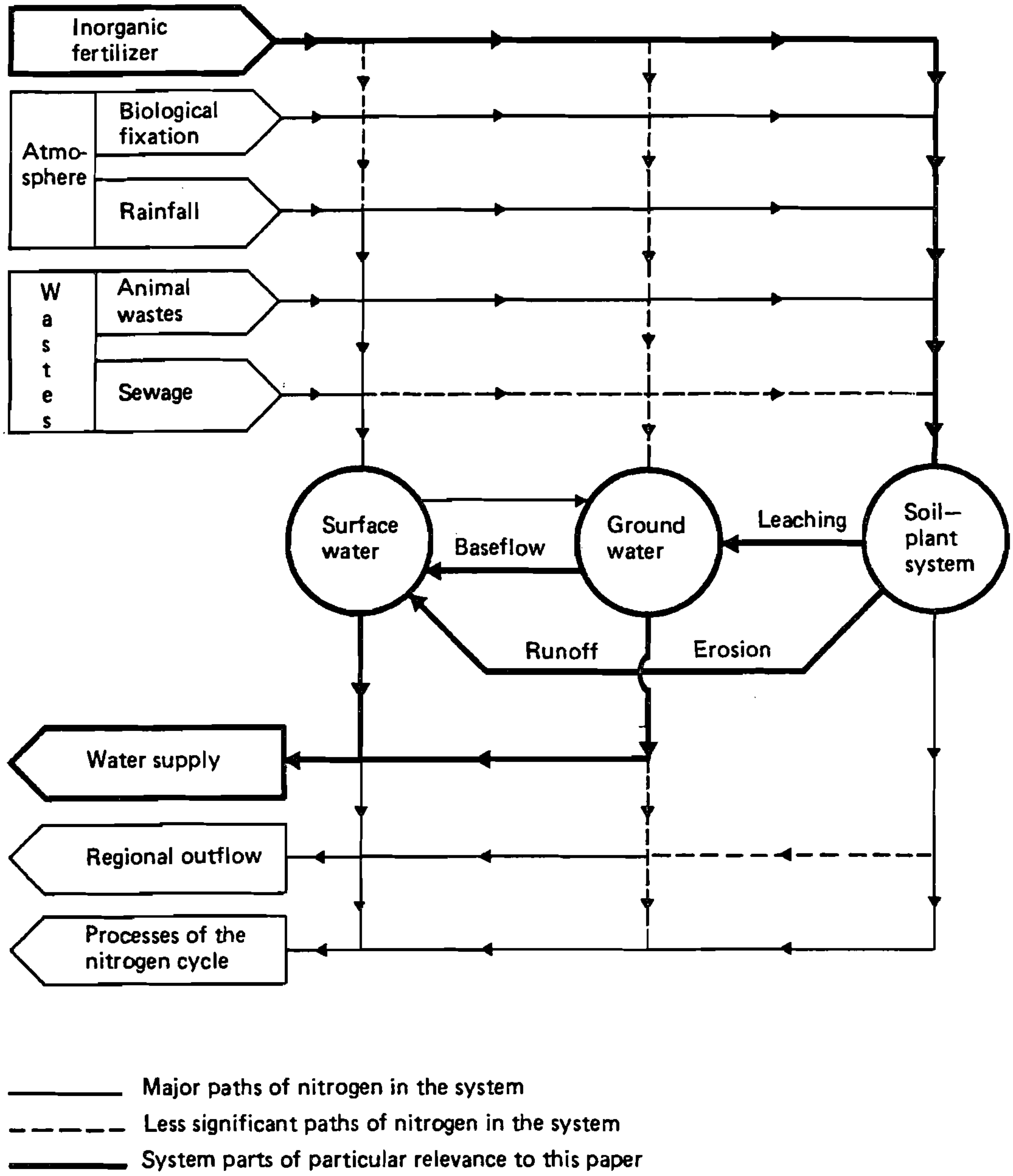


Figure 1. Schematic representation of the inputs and outputs of nitrogen to and from a regional water resources system. (Source: adapted from Reeves, 1977)

In addition to these sources, the indigenous nitrogen potential of the water resource system and the soil-plant system must be taken into account.

Waste makes up most of the point source pollution, but can be transformed into nonpoint pollution when used in large-scale land treatment (as fertilizers, sewage farming) or when there is septic tank drainage. Atmospheric sources and inorganic fertilizers used in agriculture create typical nonpoint pollution sources.

When relating the nitrogen sources to the water resource system, the following becomes evident:

-- sewage effluent enters the system primarily through the surface water courses; direct entry to the soil is possible only when there is land treatment of sewage or septic tank drainage; the entry to the groundwater system through losses from surface waters (see diagram) may be more common than direct entry, but the latter cannot be ruled out.

-- rainfall enters the system either as direct runoff to the surface waters, or through the soil and thereafter to the groundwater system; the direct entry to the groundwater system is unusual.

-- biological fixation, i.e.,nitrogen fixation by bacteria from the air, is mainly associated with agricultural crops cultivated on the soil;

-- animal wastes and inorganic fertilizers enter the system mainly through their application as fertilizers to the soil; direct losses to the surface water or groundwater system are believed to occur only in cases of accidental spillage.

After having reached the water resource system, nitrogen is subject to various chemical and biological processes composing the nitrogen cycle. The interactions among these processes, associated mainly with the soil-plant system and the surface water system, are complex and need not be described in more detail here. Moreover, as water is the transfer vector for transporting mobil nitrogen from the soil-plant systems to the surface and groundwater resources, nitrogen is subject to the physical processes of the hydrological cycle. Processes such as leaching (deep percolation) or surface and subsurface runoff, erosion, and baseflow (Figure 1) illustrate this.

Figure 2 shows the relative importance of nitrogen sources for England and Wales and their development from 1935-1970. It can be seen that, on an annual basis, atmospheric sources provide the greatest amount of available nitrogen, followed by waste sources, and fertilizers. However, it should be noted that the total amount of nitrogen available annually has steadily increased since 1938 and that inorganic fertilizers account for most of this increase. This is due to expanding food requirements of growing populations; these two factors help explain the increase in the amount of human and animal wastes. Nonagricultural users of inorganic fertilizers, such as the forestry

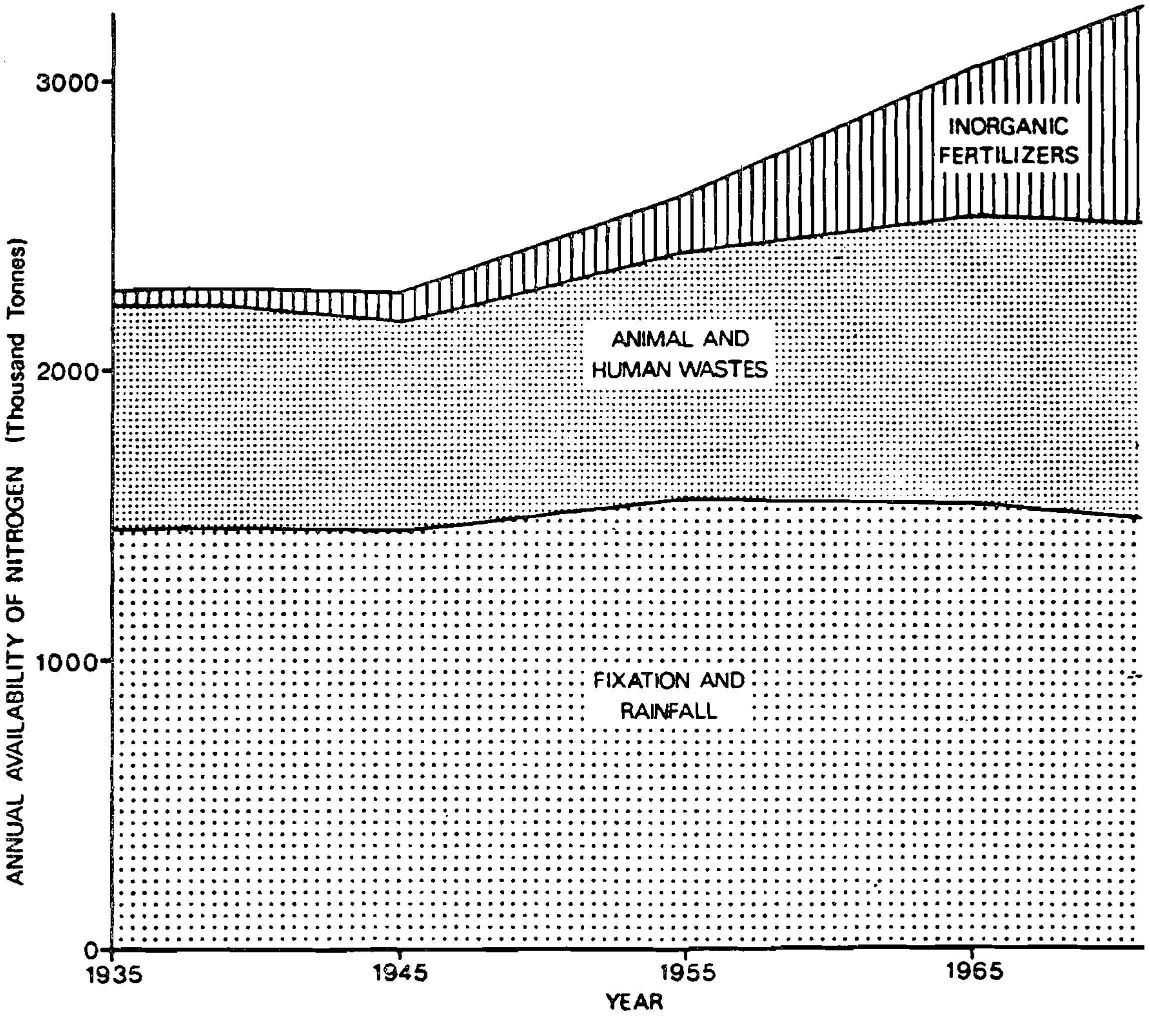


Figure 2. Relative importance of nitrogen sources.
(Source: Central Water Planning Unti, 1977.)

industry, further account for the increase. Although forests have a higher nitrogen elimination potential compared to agricultural lands, they do contribute to nitrate pollution of water resources.

Although the contribution of agricultural fertilizers to water pollution depends very much on specific climatic, soil, and land use conditions in a region, there is abundant evidence proving that the situation depicted in Figure 2 applies to many other developed countries or regions. For example, Golubev (1980) concluded from a global survey that water pollution by nitrates is of more concern on a nationwide basis for countries of Western and Central Europe with dense populations and the highest levels of fertilizer application. However, the nitrates problem is also important on a regional basis in large countries, such as the USA and the USSR, which have lower fertilizer loads and are less densely populated.

The relative importance of water supply sources (rivers, lakes, reservoirs, and aquifers) generally depends on the natural conditions of a given region. It is important to note that for those countries identified as having a particularly high potential for nitrate pollution, groundwater resources play a key role in drinking water supply. For instance, the percentage of groundwater versus total drinking water is roughly 98% in Denmark and Austria, 93% in Italy, 71% in the German Democratic Republic, the Federal Republic of Germany, and Belgium, 70% in Luxemburg and Switzerland, 65% in the Netherlands and the CSSR, 50% in France, and 31% in the United Kingdom (Huisman, 1976; Lauterbach et al., 1976; Fried and Zampetti, 1979; Stibral, 1979). Moreover, Golubev (1980) proved that the hazard of nitrate leaching is particularly high for these countries because of their general climatic features. Often, the effect of this natural situation is compounded by the use of supplemental irrigation, a factor which intensifies agricultural crop production.

Because of the above situation, groundwater resources deserve special attention, especially as there is an important difference between groundwater and surface water pollution and their respective management strategies. While the decision to purify river water is made with the knowledge that water quality can be restored relatively quickly after having removed the pollution source, the same does not apply to lakes, reservoirs, or particularly to aquifers where pollutants may be retained for decades or even centuries. Nevertheless, examination of the effects of fertilizer nitrate water pollution in a regional context usually requires a conjunctive consideration of the groundwater and surface water resources of a region.

Outline of a Control System

The physical system considered so far is now ready to be fit into a more general management system for the control of nitrate pollution in municipal water supply sources. As seen from the preceeding analysis, the major concern in outlining such a system is controlling nonpoint pollution sources in agriculture, such as organic and inorganic fertilizer, with most importance given to the latter. Hence, the system must provide a framework for the analysis of the various factors affecting regional water resources management, considering the interests of the competing users of soils and waters. In order to understand how water supply and management is influenced by increasing nitrate concentrations in water resources and how to ensure a safe drinking water supply, management must link land use and water supply development. The framework for analysis carried out in the subsequent sections of this paper therefore follows the concept of a decision making process based on the control system shown in Figure 3. The major components considered are:

a) the system to be controlled, encompassing
   -- the municipalities (representatives of the general public) which are supplied with water and agricultural commodities and govern the overall control system by setting the management objectives; they also contribute to nitrate pollution of municipal water supply sources through the disposal of human and industrial wastes;
   -- the environment, especially the atmosphere, which provides the background load of nitrogen to the two environmental subsystems of interest, the soil-plant system, and the water supply sources;
   -- the water supply and management agencies managing the municipal water supply sources and responsible for ensuring a safe drinking water supply;
   -- the agricultural production sector which strives to achieve production goals, causing nitrate pollution of water supply sources as a side effect of technological activities of crop production and waste disposal to the soil-plant system;

b) the management objectives of the overall control system which should be accomplished through management measures appropriate for the specific system;

c) the management subsystem, where management objectives are achieved through planning and implementation of management measures not only in the field of water supply and management, but also in the agricultural sector.

The components of the system to be controlled (the municipalities and the environment, with its subcomponents of the water resource system and soil-plant system) are physically connected by mass flows (nitrate polluted water, drinking water, agricultural commodities) and constitute the basis and target for decision making. In contrast, components of the management subsystem are linked by the flow of information. The conjunction

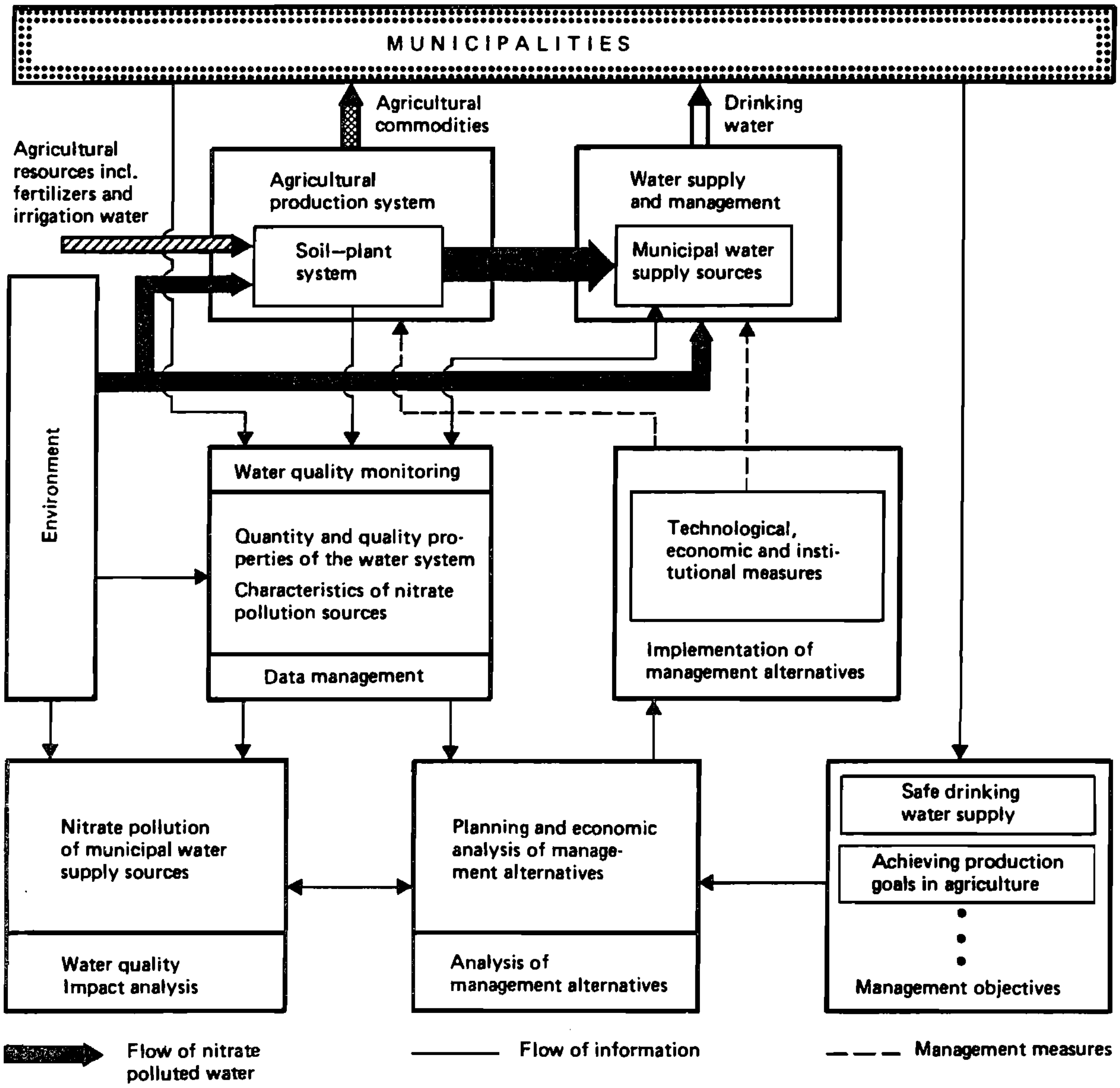


Figure 3. The system for control of nonpoint nitrate pollution of municipal water supply sources.

between these two main parts of the overall control system is provided through the implementation of management measures.

MANAGEMENT OBJECTIVES FOR CONTROL

In discussing the establishment of management objectives for a complex nitrate pollution control system as shown in Figure 3, it must first be noted that the actual control problem is multiobjective. That is, in order to manage the system optimally, objectives other than a safe drinking water supply must be taken into account, including agricultural production goals, industrial development, public health, eutrophication control, utilization of resources, etc. This paper does not consider in depth this multiobjective feature of the overall control problem; rather, an attempt is made to deal with the two objectives relating to water supply and agricultural production.

Particular attention is paid to the basic objective of water supply engineers, meeting the nitrate concentration limit set for drinking water standards. Many water systems managers are, however, skeptical of these limits and often express the opinion "I don't know where these magic numbers come from." (Eaton, 1978). Clearly, a widespread attitude exists that the nitrate limits set for drinking water standards are higher than necessary. Consequently, one might conclude that no real "nitrate problem" exists and that the most feasible "management alternative" for pollution control would be to set new, i.e., higher (less restrictive) standard limits.

Safe Drinking Water Supply

Earlier, the analysis and hygienic relevance of the nitrate content in drinking water were considered in conjunction with the ammonia and nitrite content. This situation changed when Comly in 1945 proved that the nitrate content is the cause of methemoglobinemia; the direct cause is actually nitrite, the compound produced by nitrate-reducing bacteria in the child's gastrointestinal tract. Nitrite oxidizes hemoglobin to methemoglobin, which is unable to carry oxygen to the tissues, and the child can succumb to cellular anoxia. However, since nitrate is at the root of methemoglobinemia, the WHO set nitrate limits for drinking water. The 1971 WHO International Standards for Drinking Water (WHO, 1971) recommended a maximum level of 45 mg per liter of NO_3; above this level, infants less than one year old were considered to be at risk. The first edition of the WHO European Standards gave a value of 50 mg NO_3 per liter, but the second edition revised this to:

> Nitrate concentrations should be less than 50 mg NO_3/l, but concentrations up to 100 mg NO_3/l are acceptable, providing that the local doctors are informed and are therefore aware of problems with infants; water with nitrate concentrations higher than 100 mg NO_3/l are not recommended for drinking water supply (WHO, 1970).

National regulations adopted on the basis of WHO standards reach from 5 mg NO_3/l (Mexico 1953 cit. from Höring, 1979) to 100 mg NO_3/l (Carlson, 1973).

In developed countries, the actuality is that well water methemoglobinemia of infants is rare. For example, in the UK, only one case of death was reported for the period 1950-1975 (Wild, 1977). Furthermore, methemoglobinemia is hardly found in older children and adults (Gruener, Toeplitz, 1975).

However, the discussion on the importance of nitrate toxins in drinking water and food has recently been regenerated because nitrites can react with secondary and tertiary amines in the food to form nitrosamines which are potentially carcinogenic, teratogenic, and mutagenic. It is of interest that about one half of the total amount of nitrate and nitrite consumed by human beings is supplied by food.

According to Höring (1979), no definitive evidence exists proving the carcinogenic effects of N-nitroso compounds on man. But it is difficult to prove such effects using epidemiological methods. The complex and combined influence of summation toxins on man often makes it impossible to identify the consequences of a single factor in the overall effect. Consequently, Höring (1979) only stated that much circumstancial evidence indicates that the nitrate contained in food and drinking water participates in forming harmful amounts of carcinogenic nitrosamines after ingestion by the human organism. He further argued however, that the knowledge presently available remains insufficient for estimating the nitrate concentration in drinking water which produces no adverse health effect.

This somewhat uncertain assessment of the effects of nitrates on human health has led to criticism of the limits set for safe concentrations of nitrate in drinking water. Hence, while hardly anyone would agree that "there is no evidence to support the WHO limits..." (Wild, 1977), scientists are inclined to concur with another of Wild's conclusions:

> An 'oversafe' limit will increase the costs of purifying drinking water and of sewage treatment quite unnecessarily, and might bring unreasonable pressure on farmers to restrict the use of fertilizers... As a society we have to balance the health risk of nitrate in water (and food) against the cost of any requirement to reduce the concentration.

In agreeing with Wild's remarks one must place the hygienic issue of nitrates in drinking water within the context of water supply protection benefit considerations. Asking the question of whether there are health risks, one is inclined to ask if the benefits of protection are worth the cost. Even when using some kind of benefit-cost analysis for answering this, the most important problem is assessing the health risk from nitrates, which governs all considerations on benefits and costs of a safe municipal water supply. Rather than using quantification in a benefit-cost analysis to determine the harm done, including death caused by nitrates in drinking water, it is necessary to establish consistent criteria for safe (low risks) limits of nitrate concentration in drinking water. To reduce uncertainties, more toxicological or epidemiological studies should consider factors such as size and susceptibility of population exposed, number of water systems involved, relative dose in water compared with total burden, positive response of nitrate in carcinogenic, teratogenic, and mutagenic tests etc.

Until such consistent criteria have been established, water supply engineers must rely on the present arguments provided by hygienic studies. For example, Höring (1979), in reference to the GDR Drinking Water Standard, which proposes a nitrate limit concentration of 40 mg NO_3/l and a guide concentration of 20 mg NO_3/l, summarizes:

> The lowering of high nitrate concentrations of drinking water to and below the guide concentration must be considered a real prophylactic measure, although at present the dose-time-effect-relation is unclear and the proportional decrease of the total loading with carcinogenics as well as other harmful substances seems to be rather less.

Such an attitude is also stressed by Tate (1978), when discussing results of a study carried out by the National Academy of Sciences of the United States;

> The NAS study indicated that available evidence tends to confirm a value near 10 mg/l nitrate-nitrogen (i.e., about 45 mg/l nitrate) as maximum no observed-adverse-health-effect level, but this is also the value of the interim standard (i.e., the the EPA Standard), implying a safety factor of one. Therefore, it seems that the nitrate standard should be reexamined for possible lowering in the revised drinking water regulations.

In summary, despite the uncertain evidence about the carcinogenic effects of nitrosamines in water, general safety considerations suggest lowering rather than raising the present standard limit of the recommended nitrate concentration in drinking water. This recommendation is based both on the incidence of methemoglobinemia and the fact that other health risks are unforeseeable.

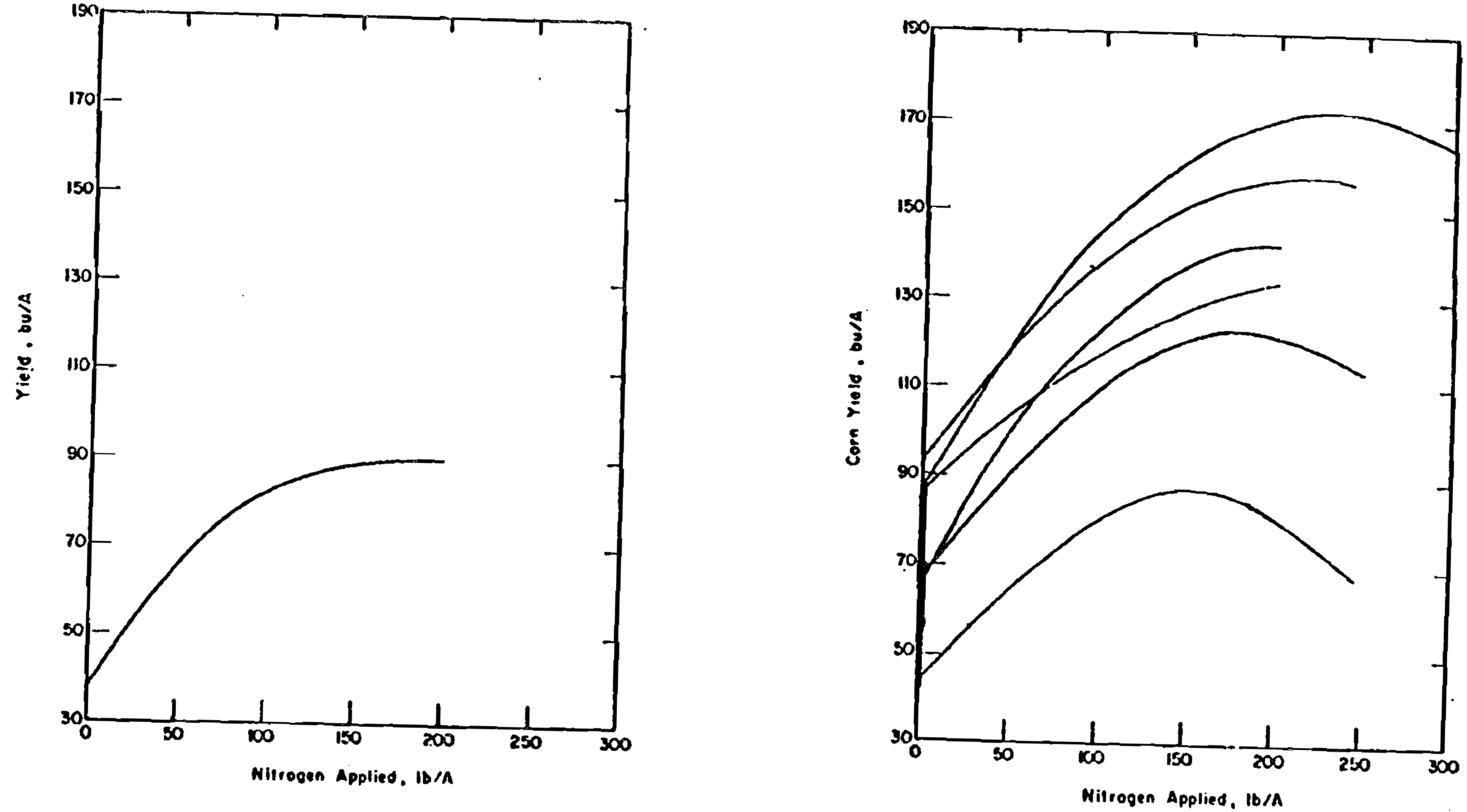
Attainment of Agricultural Production Goals

Supplying food to a steadily growing population requires high yields in agriculture and a high quality in agricultural products. Hence, the management of agroecosystems is usually production oriented. This means that the agricultural output and necessary management practices are determined by production policy decisions of national and regional bodies and farm operators. As Haith (1980) says:

> These decisions may be mixtures of tradition, rational planning, and responses to economic stimuli. Regardless of their origin, however, agricultural policies are shaped primarily by their perceived effects on food and fiber production.

There are at least two matters of interest in discussing such agricultural production policies. First, due to increased animal production, animal wastes have become of real concern when devising waste disposal strategies in many regions. Large livestock breeding farms are often the main concern in this connection. In terms of water pollution control, they are often considered to be point pollution sources, at present often badly controlled because of a technological dearth in methods for waste disposal. This may lead, for example, to uncontrolled land treatment of slurry around livestock farms, which must be considered "intentional" water pollution impact. A second and even more important fact with respect to nonpoint pollution control is the input of chemical fertilizers and pesticides to crop production, which have proved efficacious for increasing yields. In addition, the control of water inputs through irrigation has become a major factor in sustaining the efficiency of agroecosystems. Unfortunately, agricultural policies encouraging irrigation and the use of chemicals have not only increased efficiency, but also produced, among other environmental impacts, a degraded water quality.

However, in contrast to the waste issue discussed above, these water pollution impacts are largely "unintentional." Figure 4 illustrates this assumption. As shown in the hypothetical nitrogen fertilizer-yield response function of Figure 4a, when applying fertilizers to crops, an initial part of the application contributes to a considerable increase in yield, generally several tens of percent in comparison with unfertilized crops. Above a certain value, however, the increments in yield grow smaller and smaller until there is no further increase in yield despite the larger applications of fertilizer. Accordingly, the superfluous fertilizer eventually passes, possibly in modified form, to surface and groundwaters. The difficulties in controlling this process are depicted in Figure 4b, which shows quite different corn yield responses to nitrogen fertilization for six experimental fields of the same region. Obviously, only effective operational management of agricultural fertilization practices which account for regional features can meet the requirements of a controlled yield increase.



(a) Hypothetical response function

(b) Response functions of experimental fields

Figure 4. Nitrogen fertilizer - agricultural yield response functions. (Source: Taylor and Swanson, 1973.)

To summarize, it is manifest that agricultural production must be intensified at an ever increasing rate, because water and food are indispensible to human life. Agricultural management policies based on intensive use of land, water, and chemicals have greatly increased the efficiency of food production. On the other hand, present technologies are relatively inefficient in utilizing agricultural resources such as chemical fertilizers, because they produce environmental pollution hazardous to human health and natural ecosystems. Hence the remaining unanswered question is, how can agricultural production systems be managed so that negative side effects are avoided or at least minimized? When dealing with nonpoint source pollution control, it is important for researchers, practitioners, and policy makers to realize that only a beginning has been made. While the control of point source discharges of wastewaters is based on over a hundred years of research and testing, continued investigations into nonpoint source control are necessary to establish a comparable level of technology (Haith, 1980).

MANAGEMENT ALTERNATIVES FOR CONTROL

As indicated in the control scheme shown in Figure 3, the management objectives, among them safe drinking water supply, are generally attained through an integrated implementation of technological, institutional, and economic measures. According to the system to which they refer, two general alternatives for water supply pollution control can be distinguished: controlling potential pollution sources and/or treating polluted water and taking special measures to ensure water supply. In terms of Figure 1, this means differentiating between control measures taken before nitrogen reaches the water resource system and measures taken before injecting water into the municipal supply system. While the first method is carried out through various pollution control strategies implemented in the environmental and political sectors encompassing the pollution sources (e.g., municipal and industrial wastewater treatment, agricultural production, air pollution control), the second involves either no treatment measures or treatment measures taken in municipal water supply.

As for the specific case of nonpoint nitrate pollution control measures used in the agricultural sector to manage fertilizer application, animal waste disposal, and runoff, erosion and leaching (nontreatment) are generally preferred to nitrate elimination by water purification. This is because there is a high probability of having to treat toxic chemicals other than nitrate, and the cost and risk of technology depend on the actual pollution source (sewage, slurry, fertilizers). Treatment should therefore only be considered after having proved that nontreatment is insufficient or too slow in being effective.

Such an approach appears closer to the meaning of the term "pollution control," which is often understood as preventing, or at least minimizing water pollution. However, in reality, due to the advanced state of water pollution, one has to consider problems facing municipal water supply in the short run, for example, the need for alternative supply sources, new water treatment technology, or special supply measures. On the other hand, the preventive feature of the term "control" also comprehends the mutual interest of the water supply industry and agriculture in nitrate pollution control. The amount of nitrogen which pollutes water resources constitutes an uneconomical loss of a valuable production resource, which must be overcome by better management practices in agriculture.

Consequently, the most effective management of nonpoint nitrate pollution results from control of fertilizer application, irrigation, and other agricultural practices including proper land use management. The development and application of new kinds of fertilizers and inhibitors for controlling fertilizer release or transformation also must be considered. In addition to the measures discussed so far, other institutional, legal, and economic actions for implementing management alternatives have to be considered. Special attention should be given to the fact that practical implementation of pollution control strategies strongly depends on the existence of regional authorities and their capabilities.

To deal comprehensively with all of these aspects would require a separate study. In the following pages, therefore, only a few technological and institutional aspects of management alternatives in municipal water supply or agriculture will be discussed.

Nitrate Pollution Control in Agriculture

As already stated, nitrogen, like all other nutrients, is moved by water from agricultural lands through leaching, direct runoff, and with sediment from erosion. A large body of literature exists on the subject of agricultural pollution control practices for these processes. But, because of the variations in climate, soils, vegetation, and agricultural practices in different regions, no single group of control measures can be recommended for every region. Stewart et al. (1975, 1976) have, however, elaborated in an instruction manual the methods for developing specific guidelines for localized areas. Table 2, taken from this manual, illustrates general practices for the control of nutrient loss from agricultural applications. While it is obvious that the control strategies chosen from the technological alternatives should be appropriate for local conditions and acceptable to the farmers, nonpoint source pollution control programs should provide general information and education to assist farm operators (Evans et al., 1980). This is most important with respect to the first practice listed in Table 2, developed to eliminate excessive fertilization, considered the basic control alternative in agriculture.

Table 2. Nutrient Control Practices.

Nutrient Control Practice	Practice Highlights
Eliminating excessive fertilization	May cut nitrate leaching appreciably; reduces fertilizer costs; has no effect on yield.
	Leaching Control
Timing nitrogen application	Reduces nitrate leaching; increases nitrogen use efficiency; ideal timing may be less convenient.
Using crop rotations	Substantially reduces nutrient inputs; not compatible with many farm enterprises; reduces erosion and pesticide use.
Using animal wastes for fertilizer	Economic gain for some farm enterprises; slow release of nutrients; spreading problems.
Plowing-under green legume crops	Reduces use of nitrogen fertilizer; not always feasible.
Using winter cover crops	Uses nitrate and reduces percolation; not applicable in some regions; reduces winter erosion.
Controlling fertilizer release or transformation	May decrease nitrate leaching; usually not economically feasible; needs additional research and development.
	Control of Nutrients in Runoff
Incorporating surface applications	Decreases nutrients in runoff; no yield effects; not always possible; adds costs in some cases.
Controlling surface applications	Useful when incorporation is not feasible.
Using legumes in haylands and pastures	Replaces nitrogen fertilizer; limited applicability; difficult to manage.
	Control of Nutrient Loss by Erosion
Timing fertilizer plow-down	Reduces erosion and nutrient loss; may be less convenient.

Source: Stewart et al., 1975.

Beer et al. (1980) report on the experience gained with a computer-aided advisory system for fertilizer application used in the centrally planned agriculture program of the GDR. The system has been developed by the Agrochemical Investigation and Advisory Service of the Academy of Agricultural Sciences of the GDR. This institution and its regional branches are responsible for advising the regional Agrochemical Centers in charge of supplying and applying mineral fertilizers to farms. The advisory system fulfills two major objectives:

- planning the demand for mineral fertilizers (amount, type) on farms, in districts, and in regions, taking into account the availability of organic manure;
- determining type of fertilizer used and timing, rate, splitting, and technological method of fertilizer application.

Figure 5 provides a schematic overview of the entire advisory system, including the input and output information.

Concerning inputs, the system accounts for a large variety of crops and soil types. Moreover, in order to consider varying climatic conditions, the entire country has been divided into four macroclimatic regions derived from meteorological parameters such as sea level, precipitation, temperature, and aridity index. For determining the actual fertilization periods, four phaenological regions have been established according to different vegetation periods.

The advisory system itself consists of two major components--the planning model system and the operational adaptation system. The first is structured into three submodels used in developing recommendations for

- organic fertilization,
- mineral fertilization--macronutrients (N,P,K,Mg,Ca),
- mineral fertilization--micronutrients (B,Cu,Mn,Mo,Zn).

In order to be employed for fertilizer demand planning, the model system must be run in the summer of the year preceeding the application of fertilizer. A procedural step then has to be incorporated into the process which modifies the recommendations of the planning model so that they are operational for the specific field conditions. While the precise determination of the rate of the first nitrogen application is largely based on the inorganic nitrogen content of the soil, the amount of precipitation during winter, and soil climatic conditions, the nitrogen content of plants at the time of shoot (spring) up forms the basis for determining the second rate of nitrogen application to winter cereals. The entire adaptation procedure requires many intensive field tests.

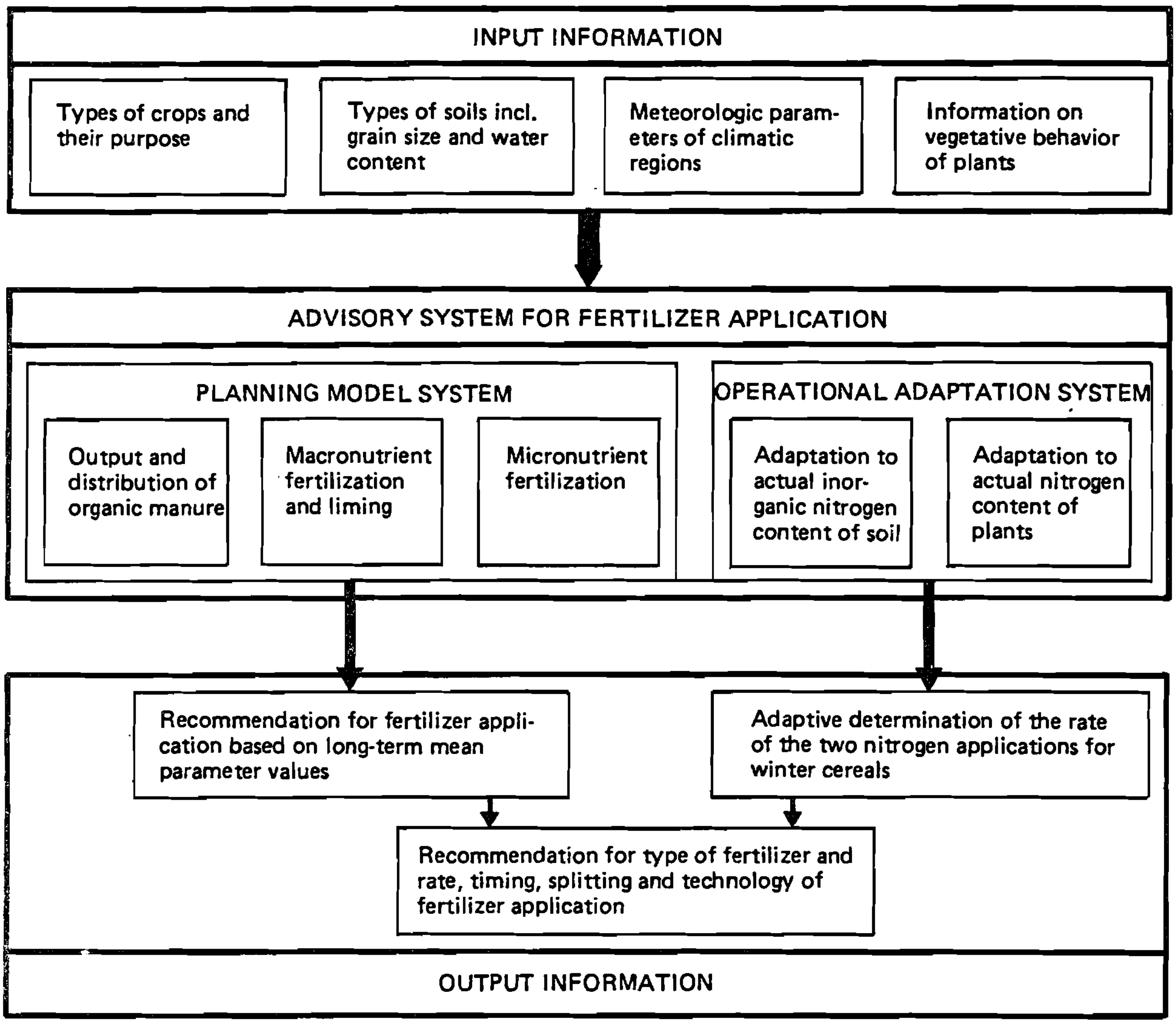


Figure 5. Advisory system for fertilizer application.

The lessons learned from using such an advisory system for fertilizer application can be summarized as follows:

- the output information of the system is only a set of recommendations to farmers; even if it were made illegal to exceed the upper limits of application, the problem of administering such regulations would remain;
- the system itself is overloaded with uncertainties due to the roughness of the models and procedures used; to compensate for the generality of the planning model system, an operational adaptation system capable of more precise simulation of the soil-water-plant relationships within the yearly nitrogen cycle would be required.
- to produce efficiency in controlling nitrate pollution from agricultural nonpoint sources, fertilization control must be operated jointly with control systems for pest management and irrigation.

Some general conclusions on controlling nonpoint source pollution in the agricultural sector need to be drawn. An arbitrary agricultural crop production system might consist of a field, a region, or a river basin. Several inputs and outputs affect such a system; the inputs can be divided into controlled or uncontrolled ones. Within the agricultural sector, complete control is possible only over the inputs made by man (seed, fertilizer, pesticides, management, labor, etc.). It is the inputs of nature, such as precipitation and solar radiation, which remain uncontrolled and cause the stochastic nature of the outputs. Since the outputs can be changed only by varying the inputs or the system itself, the overall control problem is very complex. It is trifold, comprising the interactions among agricultural production resources, technologies, and the environment. Further research is required to quantify this interaction so that more efficient agricultural management practices can be developed which will ensure pollution control.

Nitrate Elimination in Municipal Water Supply

The preceeding discussion demonstrates how far complex agricultural systems are from being controlled efficiently enough to prevent water pollution by nitrates from agricultural sources. Consequently, the water supply industry faces and will continue to face a nitrate problem. As nitrate is not removed through conventional water treatment, alternative solutions must be found in municipal water supply. Treatment and nontreatment alternatives can be distinguished. Treatment measures refer either to technologically supported denitrification in waters, especially surface waters, or to drinking water purification in waterworks.

As to the latter, Scholze et al. (1978) consider three basic procedures--

- the biochemical-bacteriological procedure,
- the biochemical-macrophytic prodedure, and
- the physico-chemical procedure

as the best available technologies for nitrate elimination in drinking water purification. They are technologically implemented in water treatment using

- anaerobic filters with fillings,
- slow sand filters with grass cover,
- an ion exchanger.

While the biochemical-bacteriological technique is basically a promising procedure, there are still unsolved problems. There is the assessment of the importance of toxins in the nutrient solutions applied (methanol, fat acids), as well as the subsequent treatment of the anaerobic effluent containing harmful amounts of bacteria and remainders or metabolites of the applied organic carbon sources. Furthermore, the continuous operation of the plant, regeneration of the fillings, and the sludge problems still have to be investigated. As in all biological procedures, careful control and continuous operation are required in order to maintain the population of the denitrificants. Consequently, this procedure can only be safely applied in large waterworks equipped with advanced control systems.

The biochemical-macrophytic procedure is based on the capability of higher plants to assimilate nitrate by utilizing solar energy. The plants are usually cultivated in infiltration basins and must be harvested. The elimination rate of such systems is determined by the autotrophic nitrate assimilation within the macrophytes and the nitrate dissimilation of the heterotrophic soil bacteria. Besides the harvest of the plants, the operation of the system in the winter period is problematical. During this time, when nitrate leaching peaks, the macrophytes do not assimilate nitrogen.

According to Wiegleb (1980), among the physico-chemical procedures, ion exchange has several advantages, even after considering electrodialysis and reverse osmosis. These advantages are:

- the safe treatment effect,
- relatively low capital and prime costs,
- a high operation reliability,
- the possibility of real-time control of the operating system.

Disadvantages include:

- the output and subsequent disposal of wastewater with high chloride concentration from regenerating the ion exchange plants,
- the low efficiency in treating raw water with a high sulfate concentration, fortunately a rather unusual procedure.

When considering these disadvantages, it must be remembered that only ion exchange can be considered a safe treatment technology for any kind of municipal water supply sources. On the other hand, Wiegleb (1980) estimates that the additional cost for nitrate elimination by ion exchange almost equals the cost for the complete conventional treatment of medium polluted raw water.

Considering the tremendous expenses outlaid for eliminating nitrates in waterworks, it is worthwhile to look at the alternative of nontreatment. A municipality can usually choose among three nontreatment alternatives:

- developing an alternative supply source,
- blending two or more water supplies, or
- connecting up with an approved water supply.

Sorg (1979) listed the advantages and disadvantages of these nontreatment alternatives as shown in Table 3.

Table 3. Nontreatment Alternatives.

ALTERNATIVE	ADVANTAGES	DISADVANTAGES
Development of a new water supply.	Less expensive. Short time implementation.	Modifications to distribution system. Water quality may change.
A blend of two or more water supplies.	Less expensive. Short time implementation.	Extensive modifications may be required for blending.
Connection to an approved water supply.	Less expensive. Short time implementation. Few modifications.	No control over water supply. Dependent on another utility.

Source: Sorg (1979).

While the underlying assumption for the first two alternatives is the existence of a nitrate free supply or supply source with low nitrate content, the third alternative assumes the readiness of a municipality to give up control over its drinking water supply and become dependent on another utility.

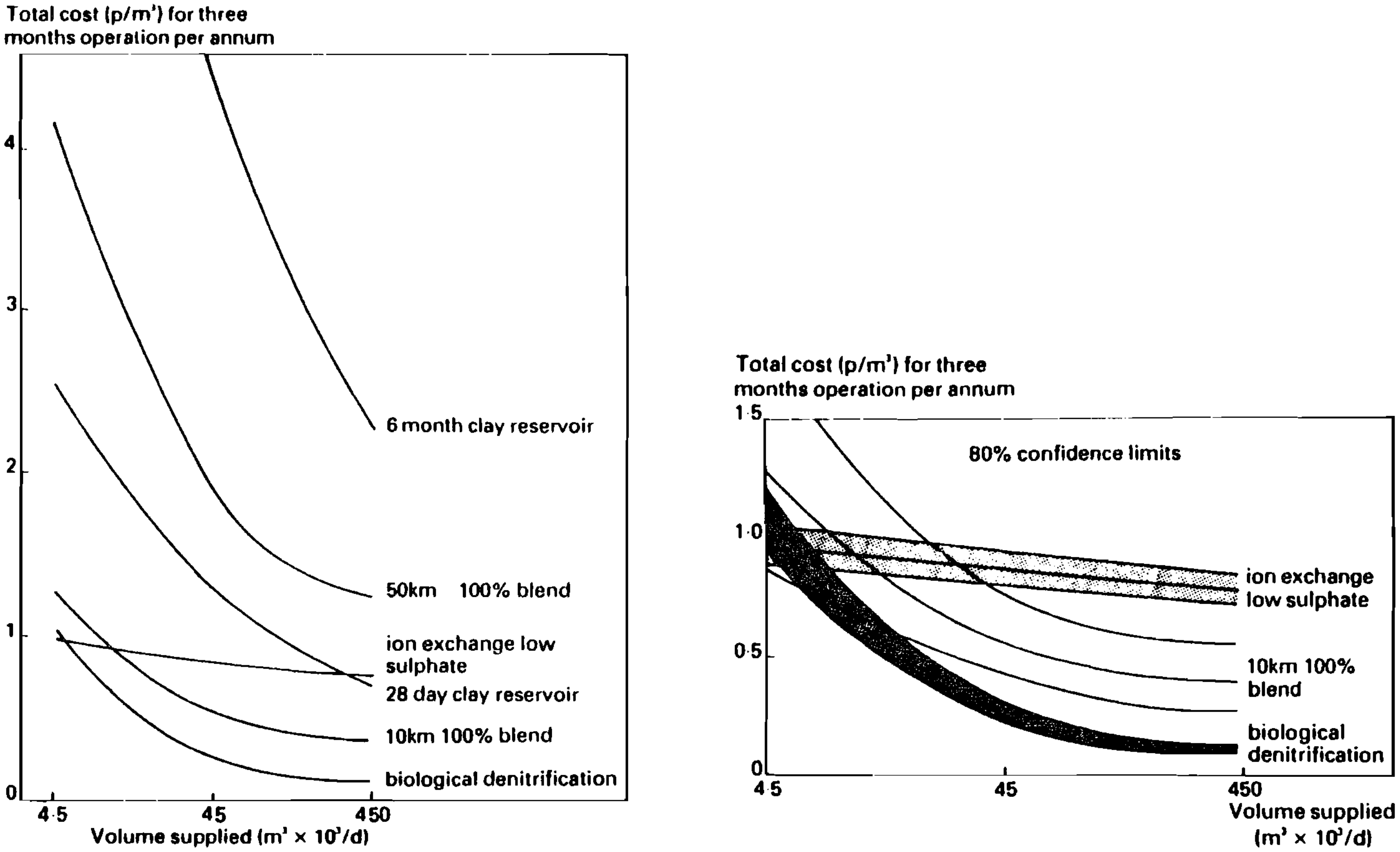
Nicholson (1979) discussed several alternatives for overcoming the problem of high nitrate concentrations in river waters, assuming that a serious problem exists only during the three month period of autumn and winter when a river reaches an acme of nitrate concentration. In such a situation, blending might be the most obvious practical solution in switching to alternative sources, while raw water storage could ensure the supply of low nitrate water. Nicholson also includes biological denitrification of abstracted river water, effected with a technology using an addition of a carbon and energy source, such as methanol. The costs for blending and denitrification have been estimated and compared to those of ion exchange, assuming full installation required for blending, storage, or treatment. As Nicholson indicates, no attempt has been made to offset the costs of blending or storage by allowing for benefits, other than control of nitrate, which may accrue from the provision of these facilities. The cost schemes depicted in Figure 6 are only cited in order to allow rough comparisons to be drawn between treatment in waterworks and other measures. No detailed discussion of Nicholson's simplified assumptions for estimating the costs is made, because the local conditions in each situation may substantially affect the comparisons.

The final alternative measure to be taken when high nitrate concentrations are present in municipal water supplies, is the provision of bottled water for infants. This kind of supply cannot be considered a real alternative by the water industry because according to Nicholson (1979), "it begins to call into question the wholesomeness of water supplies at other times." Nevertheless, it remains the only practical solution if all other possibilities fail.

In closing, it must be noted once more that water purification technologies for nitrate elimination cause a tremendous increase in expenditures to the water industry. Even when neglecting the long-term requirements of water supply protection, short-term social benefits can only be received through the overall control system when the benefits gained from intensified agricultural production outweigh the additional costs of municipal water supply.

METHODS OF ANALYSIS

This section of the paper concerns the planning component of the management subsystem contained within the overall control scheme depicted in Figure 3. For analytical purposes, this subsystem is then divided into three categories: water quality monitoring, water quality impact analysis, and integrated physical-economic analysis of management alternatives. In accordance with the overall objective of the paper, the subsequent discussion does not mainly focus on methods for detailed analysis of the physical, chemical, and biological processes constituting the behavior of nitrogen in water resources. It is rather intended to show how such means as monitoring and modeling can support the decision making process in nitrate water pollution control management with particular reference to nonpoint source pollution.



(a) Without confidence limits

(b) With 80% confidence limits

Figure 6. Estimated costs for three months operation per annum of management alternatives. (Source: Nicholson, 1979.)

Since the management and control of water pollution depends first of all on an appropriate assessment of the state of the water quality, the discussion begins with water quality monitoring. It is based on the following definition of this process given by the U.S. Environmental Protection Agency (Meyer, 1973):

> Monitoring of water quality might be defined as a scientifically designed program of continuing surveillance, including direct sampling and remote quality measurements, inventory of existing and potential causes of change, and analysis of the cause of past quality changes and prediction of the nature of future quality changes.

Two aspects of this definition are unusually interesting. First, when considering monitoring in a water pollution control management context, ambient trend and pollution source monitoring should be included. Second, the definition also encompasses water quality impact analysis in order to promote an understanding of water quality changes as space and time dependent processes. A thorough grasp of this concept and its mathematical description is obligatory for proper use in forecasting. The problem of effectual management of the data accrued in the monitoring process must also be taken into account. From the point of view of monitoring, nitrate is, of course, only one among numerous water quality variables. The discussion therefore focuses more on methodological aspects of water quality monitoring than on nitrate monitoring itself.

Although there are methodological approaches for considering data analysis, some even using advanced mathematical models, the methods are still considered only as specific activities of monitoring (Zwirnmann, 1977; Ward, 1979). However, modeling has virtually become an independent field of analysis to be particularly discussed. The typical objectives of models describing environmental impacts of nitrogen fertilization in crop production include estimating nitrogen losses or loadings from cropland to water bodies, assessing water quality impacts of nitrogen loadings, and determining economic effects of control practices.

Accordingly, Haith (1980) divided models into the following categories:

- chemical and sediment loading models,
- water quality impact models,
- agricultural planning and management models.

Models of the first and third category have been described elsewhere (Haith, 1980; Frissel and Van Veen, forthcoming; Golubev and Shvytov, 1980) and need not be discussed here. The second type of models is a priori not unique to nonpoint sources since it is in general designed to describe the response of a water body to any kind of pollution. The question of how these models can be employed in water quality management planning in regions where nonpoint source pollution is singularly important therefore holds interest in the ensuing discussion. Their integration with economic planning models applied at a higher level of decision making constitutes a second topic. The viewpoint adopted throughout is that land use management remains the most effective pollution control alternative in the long run.

In pursuing this concept the discussion does not, of course, aim at any state-of-the-art analysis of water quality modeling. Rather, it provides preliminary information on models developed at several institutions collaborating with the Resources and Environment Area of IIASA. One exception is the discussion on modeling nitrate pollution of groundwater systems, which is largely based on a model review conducted by the author for a lecture on groundwater quality modeling (Zwirnmann, 1979).

Water Quality Monitoring

According to WHO (1977), a basic requirement in establishing a system of safeguards for water supply is a monitoring network which ascertains the water quality state. This ensures that the water quality remains safe and suitable for the required purposes. Langbein (1977), in overviewing a conference on hydrologic data networks, drew conclusions highlighting some basic concerns of this paper. He stated:

> Looked at along different lines, the conference dealt with subject matter in this order: quantity of precipitation, streamflow, water quality, and groundwater, but with virtually no attention paid to soil moisture or to quality of precipitation. In contrast to precipitation and streamflow the treatment of water quality and groundwater appeared rudimentary. This order reflects no more than recent history in working with data programs and not the hydrologic or economic importance. ...We need breadth rather than deeper penetration of older subjects.

It seems worthwhile to consider more thoroughly the shortcomings found by Langbein, perhaps thereby furthering the prospects for their resolution.

Methodology

Tinlin and Everett (1978) proposed a groundwater quality monitoring strategy encompassing 15 procedural steps to be followed in chronological order. The stepwise procedure considers both ambient trend and source monitoring, but stresses the latter. This makes it suited, with some adaptations, to the concern of this paper. The steps are listed as follows:

Step 1 -- Select area of basin for monitoring.
Step 2 -- Identify pollution sources, causes and methods of pollutant disposal.

Step 3 -- Identify potential pollutants.
Step 4 -- Define water usage.
Step 5 -- Define hydrometeorologic, hydrologic, and hydrogeologic situation.
Step 6 -- Study existing water quality.
Step 7 -- Evaluate infiltration potential for pollutants at the land surface.
Step 8 -- Evaluate mobility of pollutants from the land surface to the water supply sources.
Step 9 -- Evaluate attenuation of pollutants in the water supply sources.
Step 10 -- Prioritize sources and causes.
Step 11 -- Evaluate existing monitoring programs.
Step 12 -- Establish alternative monitoring approaches.
Step 13 -- Select and implement the monitoring program.
Step 14 -- Review and interpret monitoring results.
Step 15 -- Summarize and transmit monitoring information.

The first four steps identify the purpose of a particular monitoring program. They are defined at the outset of a pollution control program as they constitute the basis for formulating the control objectives. For example, the discussion in Section II on nitrogen and water resources has essentially been based on such a concept. Some additional comments on the subject would be useful now.

Specifying the region to be monitored is usually done according to the jurisdiction of the management agency. Since the agency might be structured according to political districts, it might be necessary to divide the jurisdiction into smaller areas for physiographic reasons or the requirements of data utilization methods. Water usage is a key factor in developing priorities for monitoring needs. In this paper, the a priori interest is drinking water, for which intensive monitoring is generally deemed necessary. While the second a priori consideration restricts the paper's concern to nitrate as the potential pollutant, it should be noted that there are a number of other components, such as phosphorus and pesticides, which must be in agricultural nonpoint pollution. Chloride, as a good indicator of the extent of nitrate pollution, must also be taken into account. Moreover, if pollution sources other than agricultural ones are involved, as is usually the case, it might be necessary to isolate an accompanying constituent not found in the other sources. As to step 2, inorganic fertilizers have been identified as the primary pollution source, although other sources contribute to nitrate pollution as well. In considering monitoring as a means of pollution control, it is extremely important to identify quantitatively the relative contribution of these sources. Only in this way can the management agency prioritize sources and causes as defined in step 10.

Implementation of Monitoring Programs

Having completed step 10, the monitoring programs (steps 11 to 15) need to be implemented. In order to support water pollution control by management agencies, monitoring must have a regulatory function. Since Ward (1979) has developed an approach which comprehensively addresses general monitoring issues of interest to this paper, his method is summarized:

> Regulatory water quality monitoring has evolved to the point where it is a rather complex system encompassing many monitoring purposes and involving many monitoring activities. Lack of a system's perspective of regulatory monitoring hinders the development of effective and efficient monitoring programs to support water quality management.

Ward distinguishes two general classifications of monitoring purposes. The first, the legal classification, relates the purposes to the "location" of the water to be monitored. For example, laws such as the Federal Water Quality Act (U.S.P.L. 89-234), the Federal Water Pollution Control Act Amendments (U.S.P.L. 92-500), or the Safe Drinking Water Act (U.S.P.L. 93-523), have established the need for routinely monitoring water quality in three general "locations": surface water, groundwater, and effluents. Each of the different locations requires a specific monitoring system. The second classification arises from different data needs. While there is a need to obtain trends (means) in water quality for management functions such as planning, there is also a need to obtain extremes in water quality for other functions, such as operational control or enforcement of water quality standards.

The legislative activity in the United States cited above has resulted in routine monitoring programs for surface water, groundwater, and effluents from point sources. With regard to nonpoint pollution control, emphasis has been placed on special surveys scheduled on a periodic basis. Additionally, unscheduled surveys are often conducted for future regulatory actions in any type of pollution control. Thus, Ward (1979) has identified five general purposes of regulatory monitoring:

- routine surface water monitoring,
- routine groundwater monitoring,
- routine effluent monitoring,
- special surveys scheduled on a periodic basis,
- special surveys performed during a pollution event.

As also discussed elsewhere (Zwirnmann, 1977; Zwirnmann et al., 1980), monitoring purposes represent only one dimension of a monitoring system.

A second important dimension is that associated with operational activities involved in the acquisition and utilization of data. According to Ward (1979), data acquisition consists of network design, sample collection, and laboratory analysis, in that order. There is no doubt that designing a data acquisition system is difficult. In the past, much research and operation efforts have been devoted to that subject. However, an even larger problem in establishing a sound data acquisition system within a monitoring program, is the need for achieving an adequate level of data utilization.

The main function of this process is to convert objective pieces of data into information which is then used in a rather subjective manner to assist decision makers (Ward, 1979). Hence, it involves two basic steps. First, appropriate data storage must provide easy retrieval and manipulation of data. Second, the data analysis techniques chosen must generate information meeting two major requirements. These are:

- matching the ability of data to yield information with confidence,
- matching the expectations of the decision makers.

Translated into more practical terms, data utilization consists of three major activities, namely data handling, data analysis, and information utilization.

The six activities identified in the process of data acquisition and utilization are shown in their operational setting (Fig. 7). As can be seen, the operational activities link the water quality to the respective decision making process. The major activities depicted in Figure 6 encompass numerous subactivities or functions. For example, network design requires the determination of the location of sample stations, the parameters to be monitored, and the sampling frequency. In Figure 8, the interaction of the two dimensions of monitoring, its purposes and activities, are visualized in a monitoring system matrix as proposed by Ward (1979). This matrix, creating some thirty major combinations of monitoring purposes and activities, can serve as a decision framework for allocating the resources (e.g., money, personnel) of an agency in designing pollution control monitoring systems.

Before concluding the discussion on water quality monitoring. it must be remembered that steps 5 through 9 of the monitoring methodology must still be dealt with. Carrying out this part of the methodology provides an accurate description of the physical setting in which the monitoring program will operate. Steps 5 and 6 help to quantify the pollution potential, mobility, and attenuation of pollutants. For example, considering nitrate leaching as depicted in Figure 1 would require evaluation of the infiltration potential of nitrogen into soil as well as the mobility of nitrogen in the unsaturated zone, and the attenuation of nitrate in the saturated zone of the groundwater system. Mathematical analysis and modeling have become of great importance

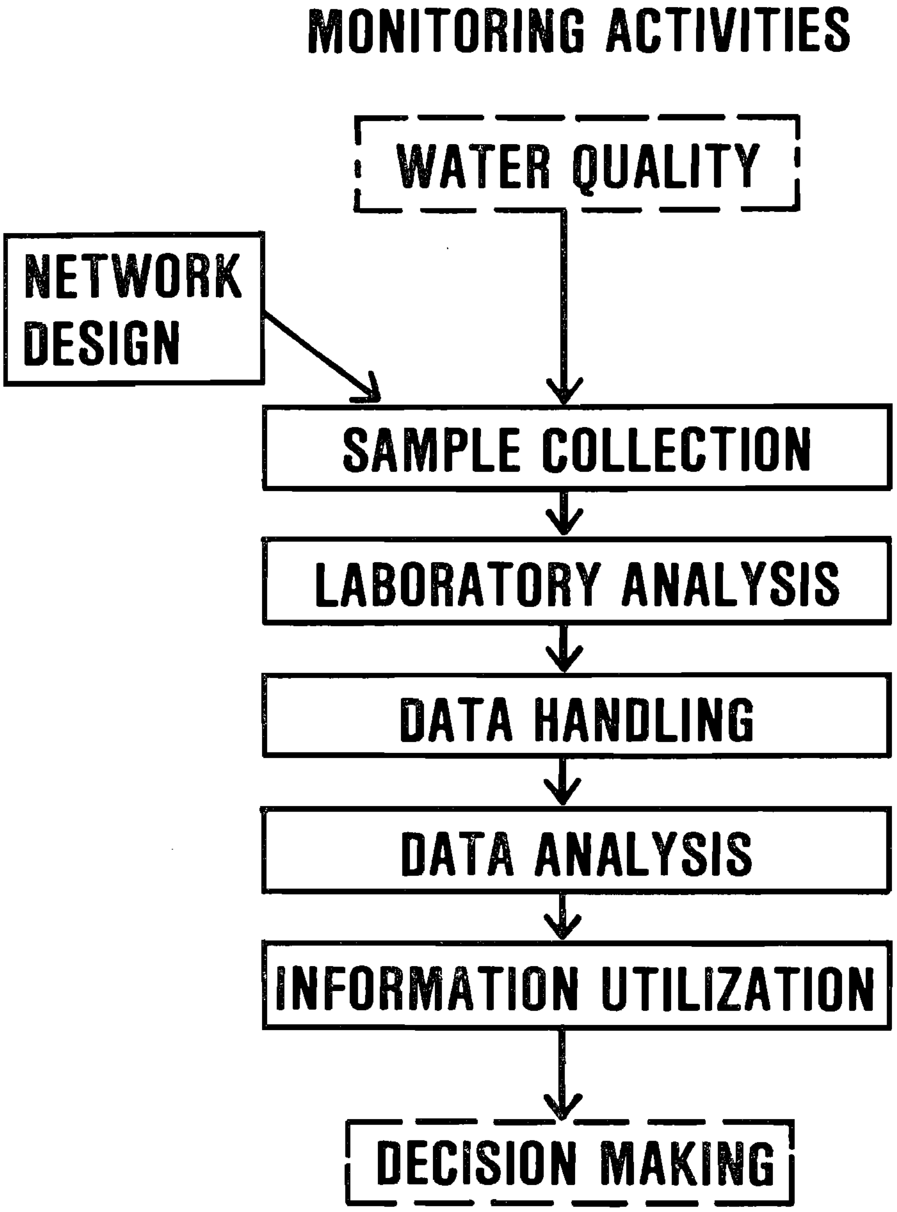


Figure 7. Water quality monitoring activities in a decision making context. (Source: Ward, 1979.)

MONITORING PURPOSES	ROUTINE MONITORING			SPECIAL SURVEYS	
MONITORING ACTIVITIES	SURFACE	GROUND	EFFLUENT	SCHEDULED	UNSCHEDULED
NETWORK DESIGN 1. STATION LOCATION 2. PARAMETER SELECTION 3. SAMPLING FREQUENCY					
SAMPLE COLLECTION 1. SAMPLING POINT 2. FIELD MEASUREMENTS 3. SAMPLING TECHNIQUE 4. SAMPLING PRESERVATION 5. SAMPLE TRANSPORT					
LABORATORY ANALYSIS 1. ANALYSIS TECHNIQUES 2. OPERATIONAL PROCEDURES 3. QUALITY CONTROL 4. DATA RECORDING					
DATA HANDLING 1. DATA RECEPTION a. LABORATORY b. OUTSIDE SOURCES 2. SCREENING AND VERIFICATION 3. STORAGE AND RETRIEVAL 4. REPORTING 5. DISSEMINATION					
DATA ANALYSIS 1. BASIC SUMMARY STATISTICS 2. REGRESSION ANALYSIS 3. WATER QUALITY INDICES 4. QUALITY CONTROL INTERPRET 5. TIME SERIES ANALYSIS 6. WATER QUALITY MODELS					
INFORMATION UTILIZATION 1. INFORMATION NEEDS 2. REPORTING FORMATS 3. OPERATIONAL PROCEDURES 4. UTILIZATION EVALUATION					

Figure 8. Monitoring System Matrix.
(Source: Ward, 1979.)

in dealing with the water quality impact analysis making up steps seven through nine.

Water Quality Impact Analysis

A water management agency needs at least three types of information before strategic planning decisions for pollution control can be taken. These information needs are:

- identification of the relative importance of nitrogen sources and those supply sources most at risk from nitrate pollution,
- predictions of likely future levels of nitrate concentration in supply sources,
- identification of implications to water supply development plans by assessing the effects of management alternatives to be taken.

Several methods of mathematical analysis and modeling are available for providing such information. Some of these models used for management purposes will be described, although without attempting to develop a comprehensive theoretical framework. After focusing on the modeling of nitrate pollution of groundwater resources, an example study on modeling nitrate pollution in a complex water resource system will be discussed.

Modeling Nitrate Pollution of Groundwater Resources

As evident from the literature, groundwater quality modeling in general is still in a developmental stage. Translating the discussion of Section II into modeling terms, a flow model must be coupled to a water quality model in order to predict the concentration of pollutants in an aquifer. Such coupled flow-water quality models are usually classified as distributed parameter models or lumped parameter models. Several models of the first type have even been used for predicting the effects of alternative management strategies for point pollution control, but it is difficult to trust completely the predictions. The two major reasons are first, the uncertainties involved in determining the input data, particularly dispersivities, and second, the numerical difficulties in solving the basic equations. However, while there is a need for complex distributed parameter models of the advection-dispersion type in detailed studies of pollutant migration from point sources, there is also a need for simpler conceptual and operational nonpoint source pollution models for use in regional size problems. For example, Gillham et al. (1978) concluded that the application of advection-dispersion models to the study of nonpoint nitrate water pollution "may not be a useful endeavor."

Lumped parameter models neglecting the dispersion phenomena have been successfully used in modeling nonpoint source pollution of groundwater systems when spatially averaged concentration values are an appropriate output, as is often the case in planning and management. Like the distributed parameter models, lumped parameter models are based on a mass balance calculation. But instead of modeling a series of cells, the entire modeled area is represented by what in essence is a single cell for which mass balance equations for water flow and pollutant movement are written. This concept is quite similar to the concept of a well-mixed linear reservoir where outflow water contains pollutants at the same concentrations as the reservoir. Figure 9 is an attempt to depict schematically the most important features of the different model types discussed above.

At present, only relatively simple chemical processes such as adsorption and radioactive decay have been considered by most pollutant transport models. Referring to nitrate pollution of groundwater resources, Kaufman (1974) noted that

> ...although the literature is replete with case studies dealing with the occurrence of nitrate pollution, and the general theory of the nitrogen cycle in nature has been understood for many decades, the coupling of theory and field experience in a manner to permit the engineering of management systems is sadly lacking.

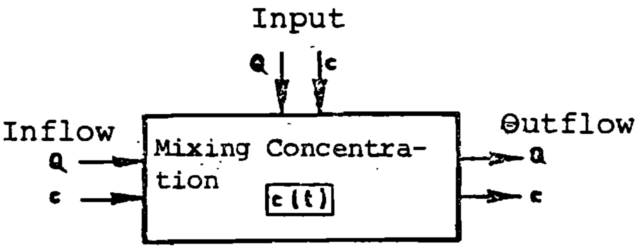
In the meantime, several attempts have been made to overcome this situation. The three attempts discussed below, with reference to the three basic information needs listed previously, show the progress made.

Reeves (Central Water Planning Unit, 1977) analyzed nitrate pollution of water resources on a national basis for England and Wales, giving particular attention to groundwater. The entire study area encompasses 60 hydrometric areas. There are two major aquifers, the Chalk and the Permo-Triassic sandstone aquifers. Four major nitrogen sources were considered--rainfall, atmospheric fixation, animal and human wastes, and inorganic fertilizers. The study uses a mass balance approach not only to quantify the amount of mobile nitrogen leached from the soil into surface water and groundwater, but also to predict the sensitivity of the leached material to changes in the various input sources of nitrogen to the soil. The model applied was divided into two parts, a soil leaching model and an aquifer recharge model. While the first provides an estimate of leached nitrogen, the second combines nitrogen and water, imposing delays in transit, and representing the dilution effects of aquifer storage. The leaching part of the model is shown in Figure 10. All processes depicted in this figure and also those of the aquifer recharge model, are modeled by a series of empirical equations. These were solved for more than 6000 elements representing the area under consideration and use a one year time-step for the period between 1938 and 1972. The model simulation for obtaining regional trends and differences agrees closely with observed nitrate levels and trends in aquifers.

While Reeves (1977) only used his model to identify the nitrate leaching potential of soils, or in other words, to identify those regions where supply sources are most at risk from nitrate pollution, Young et al. (1979) went a step further by studying the impact of agricultural practices on the nitrate content

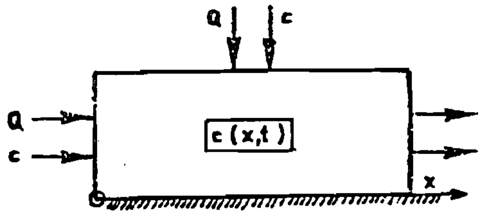
Lumped Parameter Model:

Assumption:
Fully mixed concentration within the whole cell considered



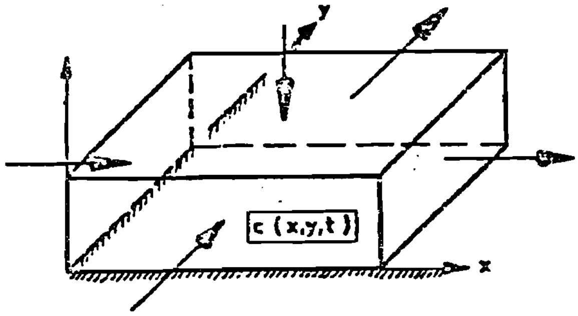
Distributed Parameter Models:

One-Dimensional Model:
one-dimensional coefficient of dispersion D_x required



Two-Dimensional Model:

two-dimensional coefficient of dispersion D_x, D_y required



Three-Dimensional Model:

three-dimensional coefficient of dispersion D_x, D_y, D_z required

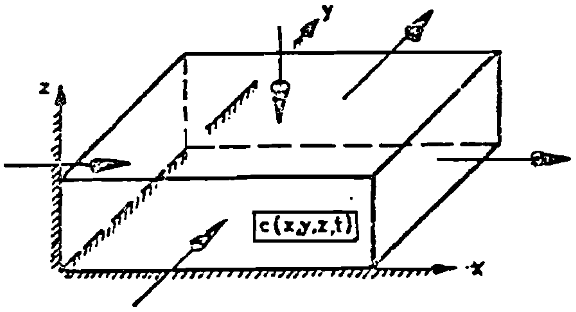


Figure 9. Types of groundwater quality models.
(Source: Damrath et al., 1979.)

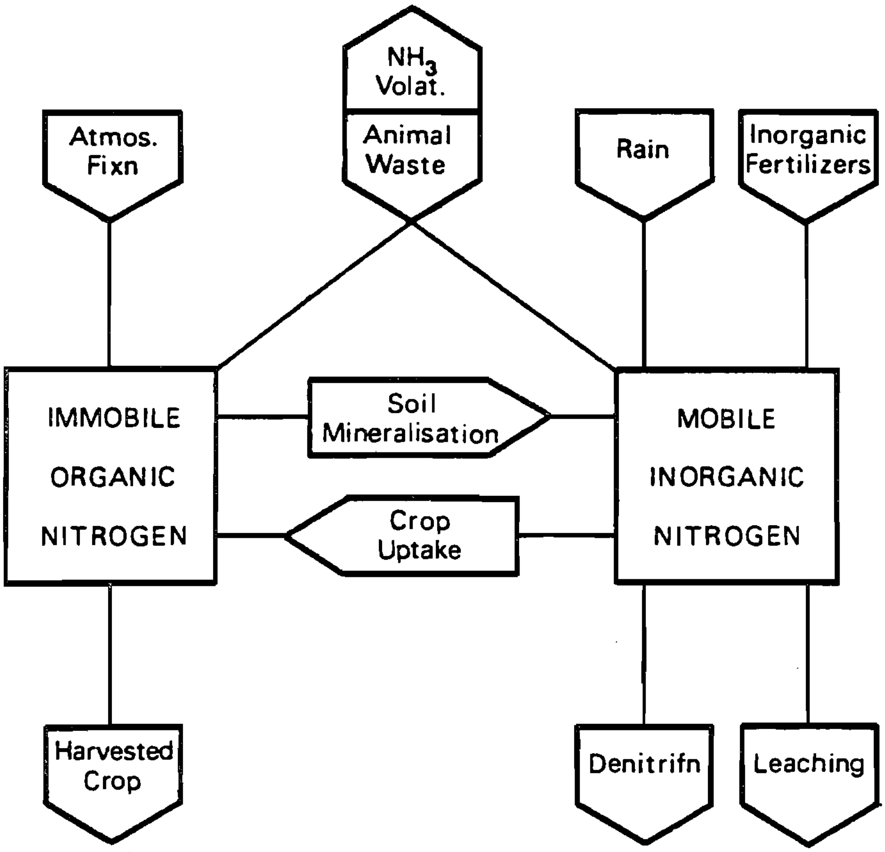


Figure 10. Schematic representation of a mass balance model for nitrogen leaching from the soil. (Source: Reeves, 1977.)

of groundwater in the principal aquifers of the United Kingdom. Similar to Reeves' approach, the model is structured into a vertical flow model and a catchment model. The first model describes nitrate leaching from the soil with a rate that depends on the infiltration and pore water content of the rock, taking into account land use history and fertilizer application rates for the simulation period. A model referred to as the catchment model monitors nitrate movement in the saturated zone of the aquifer and uses the leached nitrate generated by the vertical flow model as input. In fact, this model is one of a fully mixed single cell type model. The catchment area was structured into 500 m and 500 meter squares and the model was run from the year 1800 up to the year 2000, assuming present levels of fertilizer application will be maintained in the future. A typical model output for one catchment is shown in Figure 11, where a rather good agreement exists between the predictions and the few available measured values. The model predictions were found to be relatively insensitive to future trends in land use and fertilizer application, because of the long transit period (typically 25 to 30 years) through the unsaturated zone in the catchment in Figure 11. This might be even more important in a management context than the excessive rise of the nitrate concentration because it clearly illustrates the main feature of groundwater pollution control, in general the slow response of the system to be controlled.

Another comprehensive study on nitrate pollution control and management of groundwater systems was conducted by Mercado (1976). This study goes several steps further than the two other studies, because it considers the uncertainties involved in the model predictions and uses the model for investigating different management alternatives for pollution control. The result of this approach is an output of information which largely fulfills the previously stated requirements, such as matching the ability of data to yield information with confidence and matching the expectations of decision makers.

Mercado (1976) also used a single cell model which integrates pollution sources on the land surface, hydrologic parameters of the aquifer and unsaturated zone, and variations of nitrate concentration distribution in pumping supply wells. Complicated hydrologic and biochemical processes in the unsaturated zone are simplified and represented by two basic parameters, transit time from land surface to the aquifer and nitrogen losses in the soil. In doing so, it was assumed that linear relationships exist between the amount of nitrogen released in the soil and the amount reaching the water table. The effective volume of groundwater in the mixing zone of the aquifer, interpreted from concentration variations of chlorides, was used to determine other parameters of the nitrogen terrestrial cycle. Five potential nitrogen sources were considered for a region of roughly 100 km^2, namely inorganic fertilizers, sewage, livestock excretions,sanitary landfills, and rainwater.

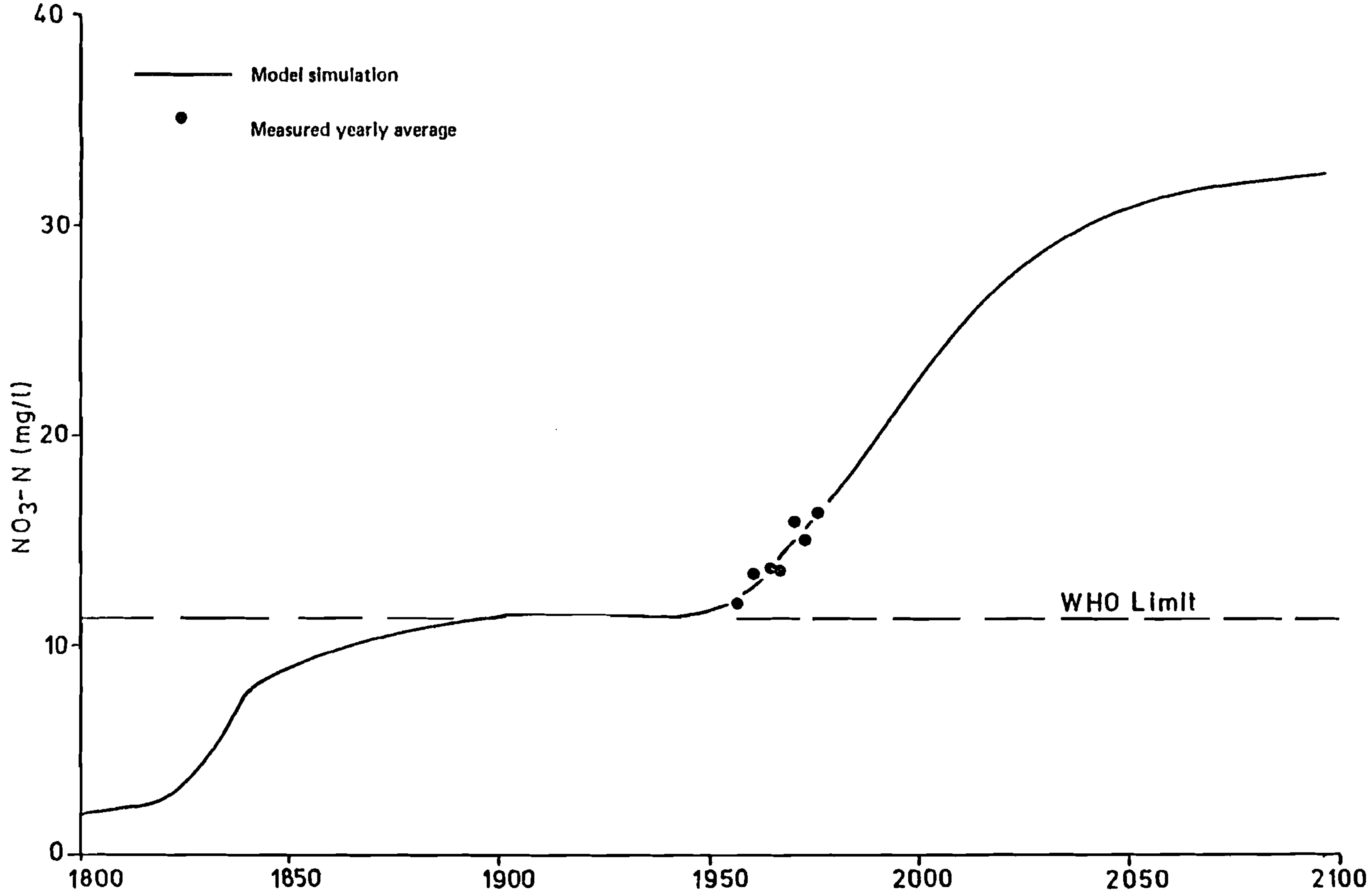


Figure 11. Catchment model simulation--prediction of nitrate concentrations in pumped discharge and comparison with measurement. (Source: Young et al., 1979.)

In order to predict average nitrate concentrations as a function of time, the uncertainties in defining the pollution mechanism and difficulties in calibrating the model parameters were dealt with. As shown in Figure 12, a probabilistic expression was given to the uncertainties by using the Monte Carlo technique for determining the range of predicted groundwater concentrations. (According to Mercado, the maximim permissable concentration of nitrate in waters was raised to 90 ppm in Israel following recent epidmiological research.) Mercado examined thirteen management alternatives for pollution control, including advanced treatment of sewage water prior to its recharge to the aquifer, reduction of fertilizer dosage to crops, and exchange of nitrate polluted groundwater by low-nitrate surface waters. Figure 13 provides an overview on four mixes of alternatives compared to predictions based on present nitrogen loads and hydrologic regime. At least two interesting management aspects have to be noted. First, there is again a considerable time lag of about 10 years (Figure 13b) in the aquifer response to fertilizer reduction. Second, alternative 14, which is obviously not the optimal alternative with respect to its effect on the nitrate concentration development, has been found by Mercado to be the most satisfying practical solution to pollution control. By combining the three basic alternatives, such as fertilizer reduction, sewage treatment, and groundwater exchange, it enables the 1975 nitrate concentration to be virtually frozen. The percentage of disconnected wells can be kept as low as 10-20%.

Since groundwater pollution can obviously be decreased by any of the three basic controls, Mercado developed exchange relationships which can even be used for evaluating economic criteria for nitrate pollution control. The relationships shown in Figure 14 clearly illustrate the way in which the preferred combination of controls was found through consideration of the following extreme cases (Mercado, 1976):

- rejection by farmers and municipalities of any attempt to decrease the nitrogen load would require a continuous groundwater exchange of 33.3 $10^6 m^3/yr$;
- considered as the only protective measure, fertilizer doses to crops would have to be reduced to to about 15% of the present level;
- even the most advanced sewage treatment ($\Sigma_s = 0$) cannot, under any circumstances, serve as the only measure for freezing existing nitrate concentrations.

The optimal combination of these control measures is, of course, subject to multicriteria optimization which was not dealt with by Mercado.

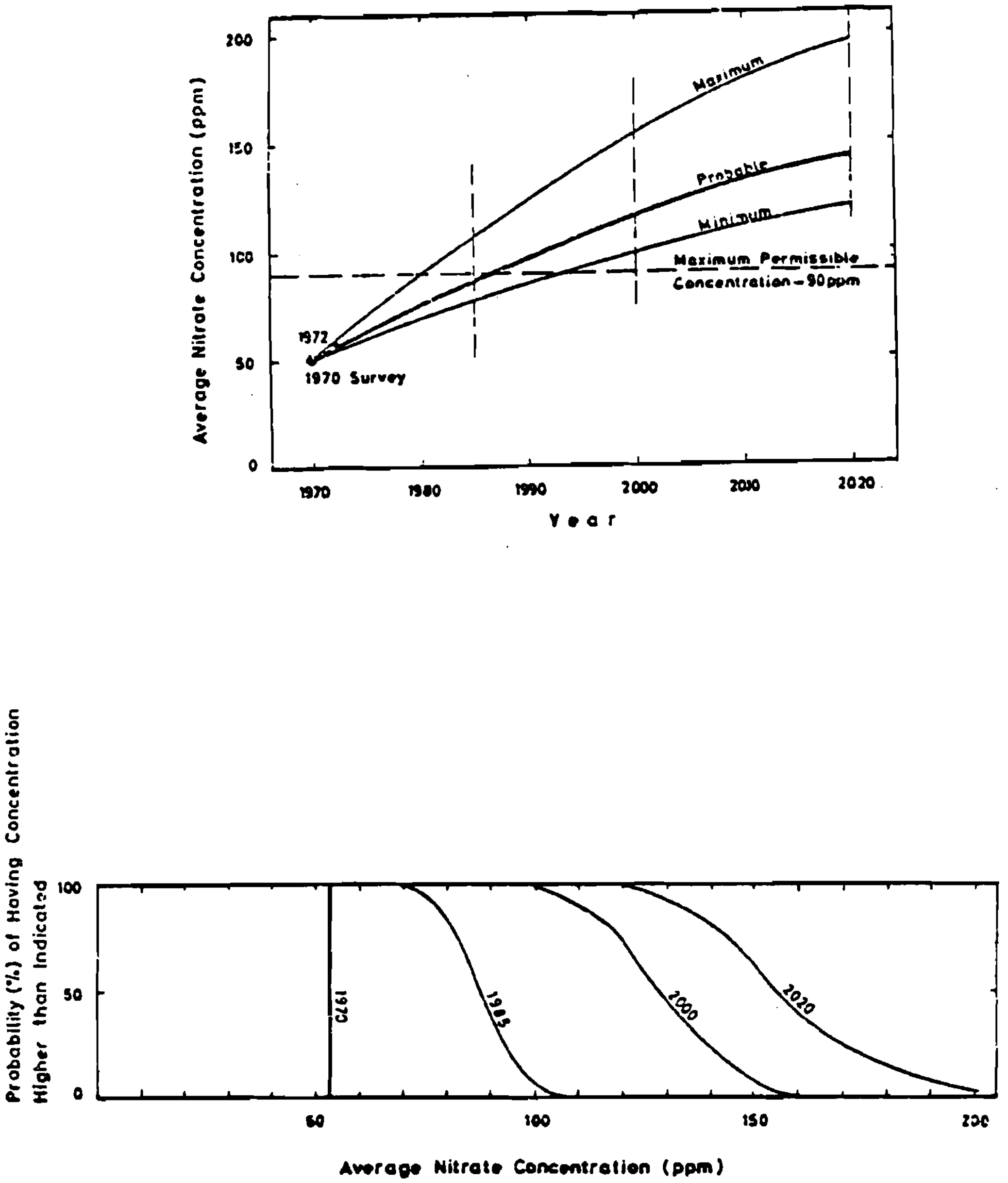


Figure 12. Predicted average nitrate concentrations as a function of time. (Source: Mercado, (Source: Mercado, 1976.)

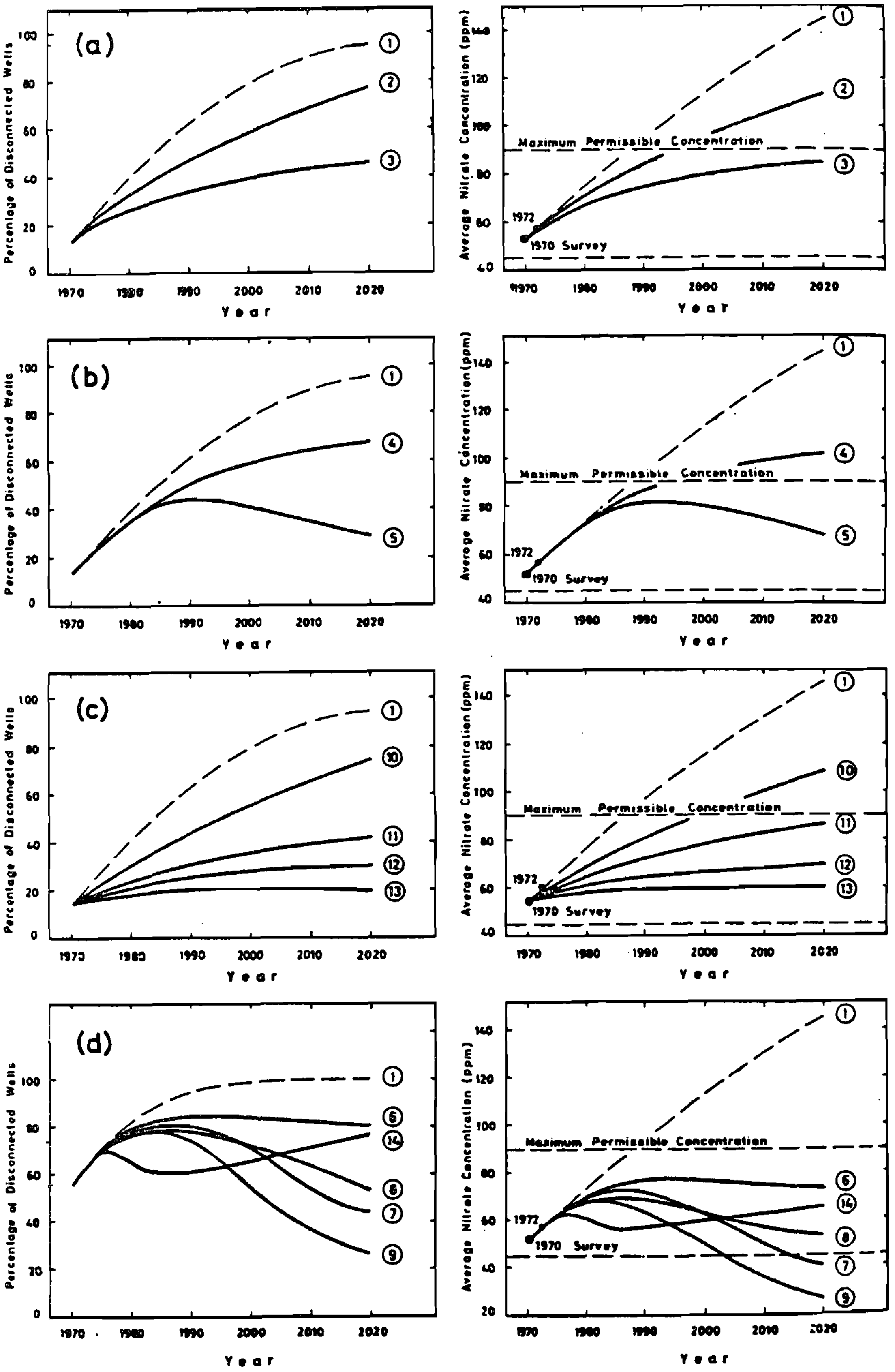
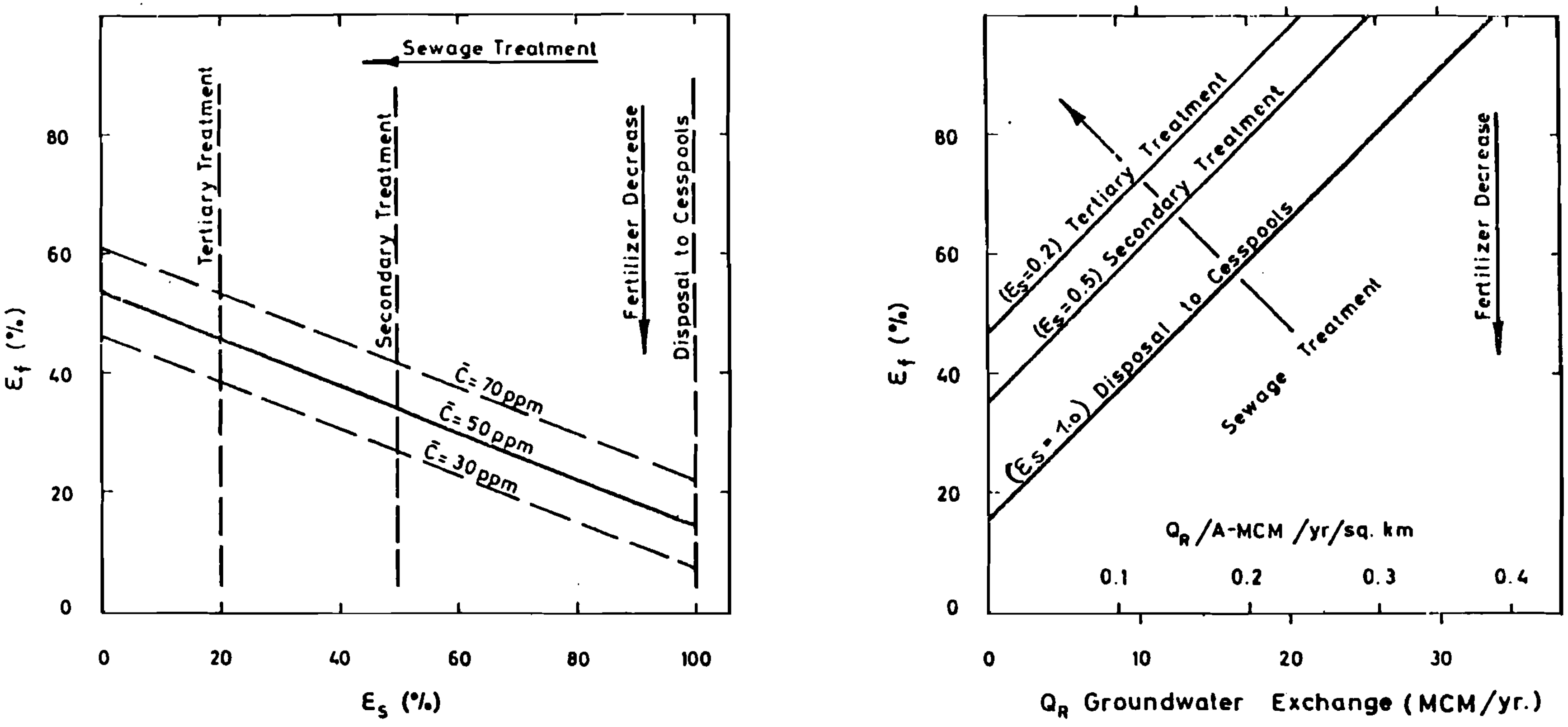


Figure 13. The effect of alternative protection measures on future average nitrate concentrations and expected disconnection of nitrate-contaminated wells. Disconnection estimates were based on the maximum permissible nitrate concentration of 90 ppm. (a) Removal of 80% of sewage nitrogen (alternative 2) and export of 90% of sewage waters to the south (alternative 3). (b) Reduction of fertilizer quantities to one half (alternative 4) and to one tenth (alternative 5) of existing application. (c) Exchange of contaminated groundwater by low-nitrate surface water at the rates of 10, 20, 30, and 40 $10^6 m^3/yr$ (alternatives 10, 11, 12, and 13, respectively). (d) Combined alternatives: alternative 6, a combination of 2 and 4; alternative 7, a combination of 2 and 5; alternative 8, a combination of 3 and 4; alternative 9, a combination of 3 and 5; alternative 14, the same as alternative 9 with the addition of groundwater exchange of 25 $10^6 m^3/yr$ between 1975 and 1985.

(Source: Mercado, 1976.)



(a)

(b)

Figure 14. Exchange relationships between protective measures to prevent nitrate pollution. (Source: Mercado, 1976.)

Modeling Nitrate Pollution in Water Resource Systems

As already discussed in Section II of this paper, nitrate pollution control for ensuring water supply usually requires joint consideration of all water supply and pollution sources of a region as well as the integration of water supply and demand. A comprehensive example for such a situation is the River Thames basin which comprises some 13100 km^2 and supports a population in excess of 11.8 million. The average daily quantity of water supplied is 3.5 x $10^6 m^3$/day of which at present nearly 60% is met by surface water abstraction, the remainder being abstracted from groundwater. The Thames Water Authority, responsible for water supply, sewage disposal, and river management in the whole basin, has been pursuing a three-phase approach to the nitrate pollution problem. The first was the identification phase where the magnitude and timing of the problem was assessed. Now, a methodology for examining counteractive measures is under development. Based on this, an effective solution has to be implemented in a third phase (Sexton and Onstad, 1980; Thames Water Auth., 1980, personal comm.).

In the identification phase, three main sources of nitrate in the Thames were found to be significant: sewage effluents, groundwater, and surface runoff. Omitting effluents, the concentrations of which remain relatively constant from year to year, the nitrate content of the Thames is the direct consequence of the agricultural activities in the river basin. Hence, Onstad and Blake (1979) developed a transfer function model for describing the relation between historical, agricultural, and river trends, and for predicting the expected future river nitrate concentrations.

While the output series was the mean annual flow weighted river nitrate concentration, the input series was derived using historical agricultural data on land use, inorganic fertilizer use, animal production, and crop yields. This input series, representing the total amount of nitrate available for transport to the Thames, is the product of the rate per unit area of nitrate availibility and the total area over which the rate applies. Although it is important to consider hydrological factors, they were omitted because of the difficulty of including them in the model concept based on an annual time step.

Box's and Jenkins' (1970) technique was used to develop a transfer function relating the input and output series. The model built has two moving average terms and one autoregressive term. The first two terms represent the quick reaction of land runoff, overland flow, and shallow subsurface drainage to input variation, as well as the delayed response of the unsaturated and saturated zones of the aquifers. The autoregressive term considers the integrating effects on the outputs at a large, complex catchment. These effects are caused by dispersion or diffusion phenomena of the soil and the aquifers as well as being due to mixing which occurs as surface water channels intercept the aquifers at various locations and at different depths. Since the coefficient of determination and the standard error for the model were 78 percent and 0.63 mg N/l respectively, the model was considered adequate for relating the input and output series for planning purposes. Nitrate trends in the Thames were forecasted by extrapolating the input series, such as the nitrogen rate per unit area and the crop area itself. To extrapolate these series, several variables affecting food demand and supply to the year 2000 were taken into account. These variables were population growth, level of national self sufficiency, growth of real disposable income and annual agricultural production growth rate. Afterwards, the model was run for a variety of projected crop areas to obtain mean annual nitrate concentrations in the Thames up to the year 2000. For example, Figure 15 shows the resulting curves for the 1.5 percent growth rate.

After having established that the Thames Water Authority is likely to have a serious nitrate problem within the next 20 years, the agency is proceeding with a simulation approach to produce a regional nitrate model compatible with the water resource model already in existence (Thames Water Authority, 1980). The model is considered a tool for the investigation and evaluation of alternative strategies for managing nitrate pollution in the main rivers and reservoirs of the Thames basin, taking into account a range of nitrogen inputs from agricultural activities. To compute economically, the model is divided into two submodels as shown in Figure 16.

Submodel A, representing the regional hydrological system on a subcatchment basis, will receive all inputs of nitrogen to that system and corresponding components of flow from the water resource model (WRM). It will deliver as output the total daily flows and concentrations of all main inflows to all Thames and Lea reaches. Besides the outputs of submodel A, submodel B will receive as inputs demands on the river and reservoir system according to the water resource model. It will output the nitrate concentrations of all water supplied under a particular management strategy. Each submodel consists of several component models and a synthesis section, modelling their combined output. Data and interface requirements for each component and submodel are indicated in the structure diagram shown in Figure 16.

In applying the model, each submodel will be run under a range of conditions. Combining their outputs will provide a stepwise simulation of the regional system. Finally, control alternatives aimed at a reduction of nitrate levels can be included to test their denitrification capabilities.

Even when incorporating management alternatives into mathematical models like those developed by Mercado (1976) or the Thames Water Authority (1980), nitrate pollution control is still dealt with on a level of physical modeling which largely contributes to water quality impact analysis. Recalling the outline of the general control system in Section II, the need remains for considering the control problem in a broader context of decision making, which would link the agricultural production sector with the public sector in decisions regarding land use and water supply

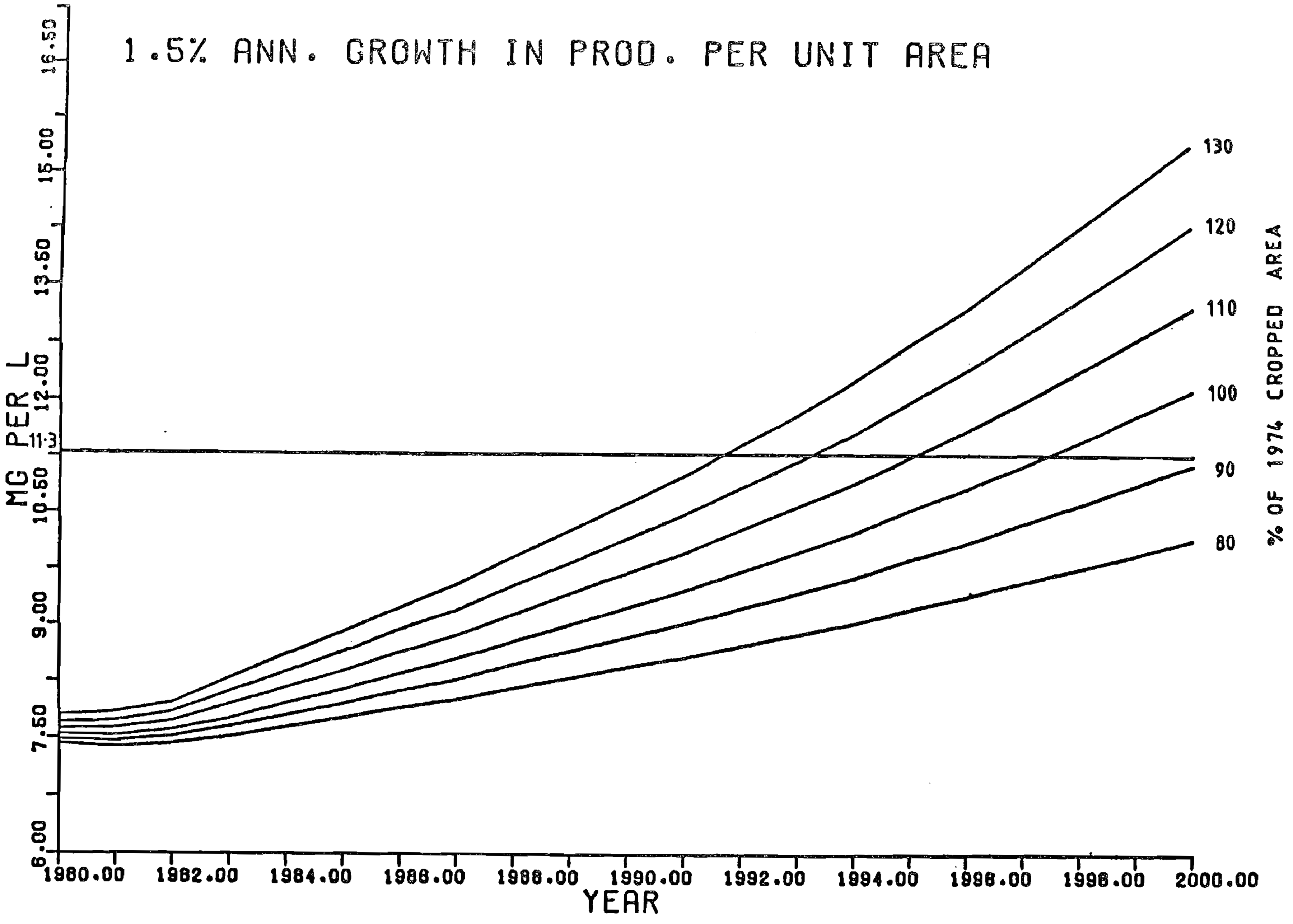


Figure 15: Forecast average annual nitrate concentrations (mgN/l)--1.5% growth rate. (Source: Onstad and Blake, 1979.)

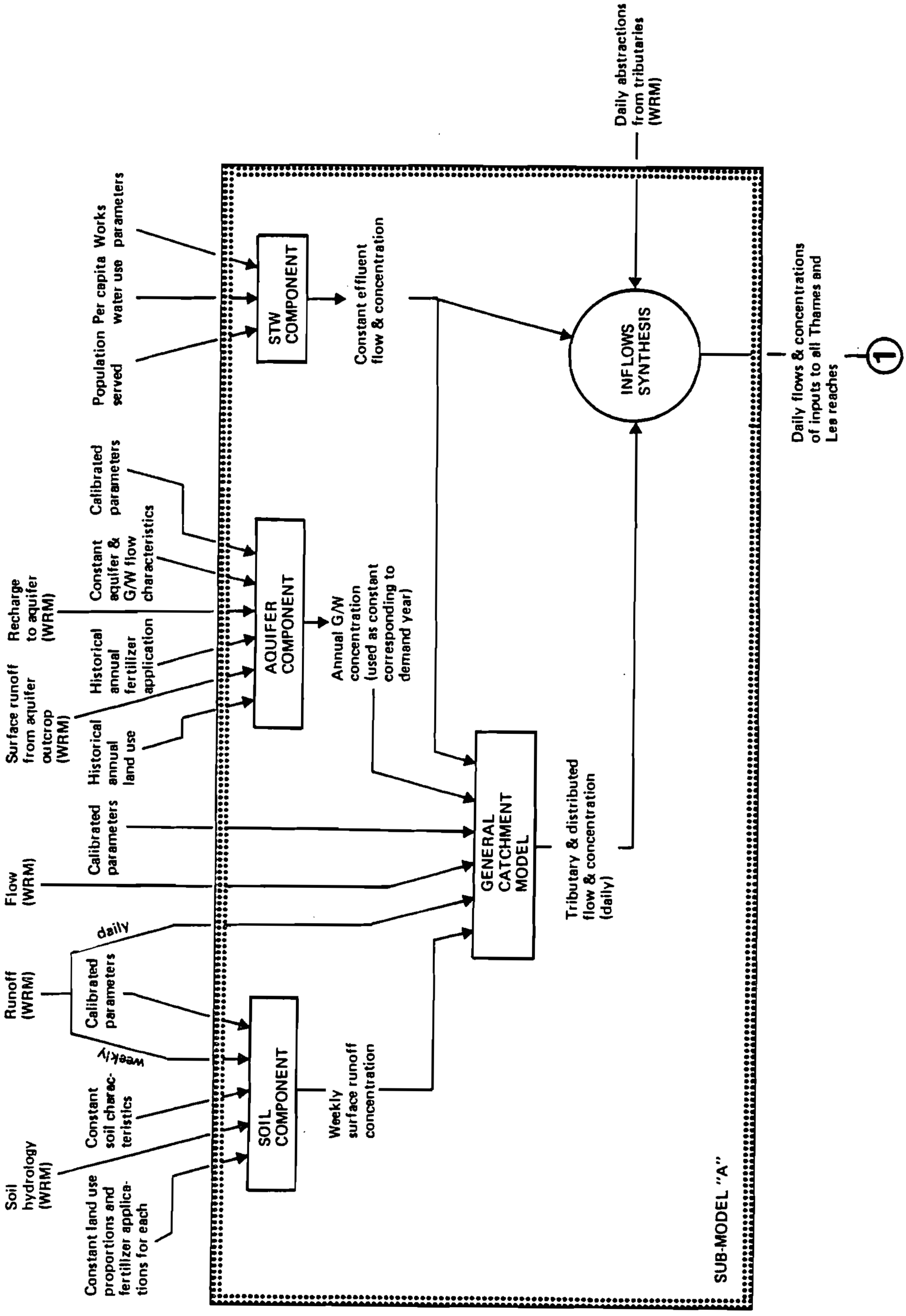


Figure 16a. A regional nitrates model.
Source: Thames Water Authority, 1980.

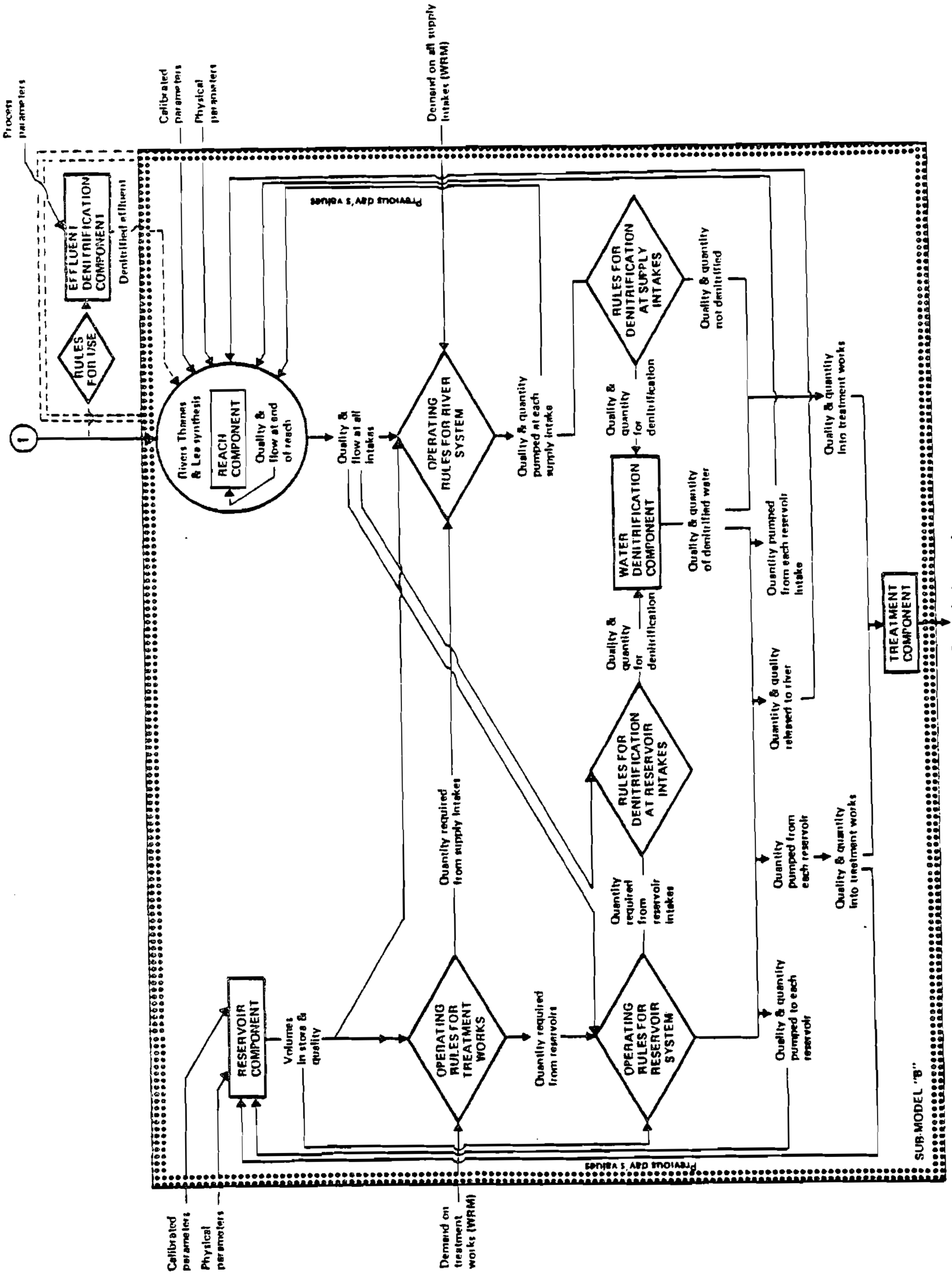


Figure 16b. A regional nitrates model.
Source: Thames Water Authority, 1980.

development. Mathematical methods capable of integrating physical and economic analysis of nonpoint nitrate pollution control are needed.

Integrated Physical-Economic Analysis of Management Alternatives

Social benefits can only be gained from the overall control system outlined in Figure 3 if the benefits received from intensified agricultural production outweigh the additional costs of municipal water supply. This statement suggests the need for identifying the interdependence between the economic and physical systems so that the effect of public policy decisions on natural resource use and environmental quality can be determined. From the viewpoint of resource economy and planning, it can be said that water pollution control must be coordinated with water resource development and land use planning to achieve a better allocation of the natural resources. With respect to this paper, Horner and Dudek (1979) reported on a study dealing with such a complex setting of agricultural nonpoint pollution control.

The study begins with the requirements of the U.S. Federal Water Pollution Control Act Amendments of 1972 (P.L. 92-500), especially the planning requirements of Section 208. These encompass the identification of agriculturally related nonpoint sources of pollution and the specification of procedures and methods for feasible control of such sources. Such control procedures are termed "Best Management Practices" (BMP) to contrast them with the traditional conservation and production practices in agriculture. A traditional practice can become a "Best Management Practice" if certain criteria are fulfilled. For example, Bower et al. (1977) suggested the following criteria for evaluating alternative environmental management strategies:

- environmental or physical effects,
- economic effects,
- institutional effects.

It is obvious that the ultimate criteria is the degree to which a management strategy can improve the quality of resources. On the other hand, as shown throughout this paper, the relationship between changes in agricultural fertilization practices and water quality is very hard to measure for a broad set of physical conditions. Determining the environmental effectiveness of BMPs therefore requires consideration of this uncertainty.

Economic effects can be categorized into direct and indirect ones. Direct benefits from improved water quality can be measured by reduced or avoided water treatment costs, reduced medical costs etc. Direct costs, which can even include reduced agricultural production, are those incurred by farmers as a result of pollution control. Other direct costs include the cost to municipal water supply agencies of providing water treatment facilities. It should, however, be noted that indirect effects, resulting from the sensitivity of the highly intradependent national economy to production changes, can exceed direct costs and benefits to a single producer. Generally, the distribution of benefits and costs is accepted as the most important effect of pollution control.

Other important effects relating to the institutional aspects of implementing control strategies which, as shown in the discussion on monitoring, usually require additional accounting, monitoring, reporting, supervision, enforcement, and management. Moreover, to be effective, a control strategy must be flexible enough to adjust to changing economic and physical conditions. Another feature of BMPs is that they are subject to competing interests in the approval process. Since each interest group will certainly weigh the effects of each BMP on the goals of that group, compromise BMPs will probably result from the decision making process.

To contribute to the decision making process, Horner and Dudek (1979) developed a model for optimal natural resource allocation in irrigated agriculture which accounts for nonpoint nitrate pollution. Concerning land and water resource problems, the model is based on the economic theory of exhaustible resources, while the physical processes are represented as conjunctive management problems. The theoretical model framework is conceptualized as a dynamic optimization problem in optimal control. Since data requirements prevented the practical use of such an analytical system, static models with appropriate sequential and recursive techniques were included in the methodology. The four basic economic concepts considered by the model are commodity demand, commodity supply, resources demand, and resource supply. These concepts have been identified as flows of information between different components of the analytical system, consisting of a land use and a water quality model (Fig. 17). Water quality management alternatives can be simulated to determine their environmental and economic effects.

The land use model has three component models--a projections model, a regional linear programming model, and a linear quadratic control model. This structure represents the authors' assumption of a bilevel decision making process. Agricultural firms are presumed to optimize land use, given their resources and the policy variables dictated by the projections model. On the other hand, the regional model presumes some rational central resource allocation planning from a social welfare point of view. Hence, aggregate firm behavior is simulated by the regional linear programming model, while the linear quadratic control model simulates the central planning authority.

The water quality submodel utilizes resource use-stocks and commodity prices as inputs from the land use submodel. Within the submodel itself, two location specific linear programming models are used to derive an optimal cropping pattern, select water application technologies, specify water and fertilizer use, and predict the resulting surface runoff for the basin. The resulting production patterns serve as input to the physical model

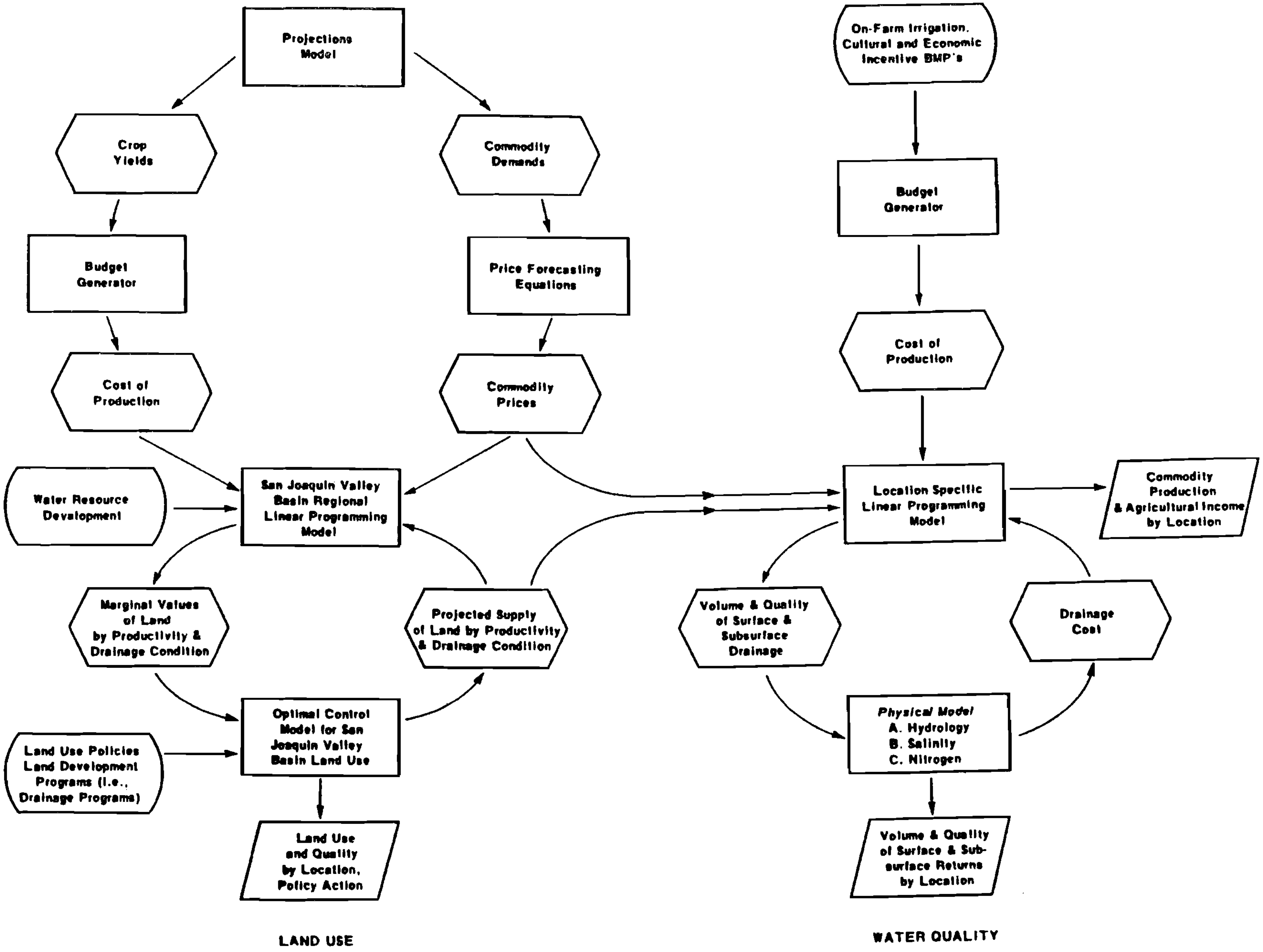


Figure 17. Integrated land use, water resource and water quality analytical system. (Source: Horner and Dudek, 1979.)

which has three interdependent submodels to analyze the hydrology, salinity balances, and nitrogen concentrations in the basin. For example, the nitrogen submodel is based on a steady state mass balance model. The concept of this model which neglects complex soil-nitrogen reactions, is based on the long-run effects of plant efficiency in utilizing the nutrient.

The analytical model system discussed above can be considered a useful tool to evaluate nonpoint water pollution control alternatives in terms of their environmental and economic effects. Since the scope of analysis is not restricted to the farm level, but is concerned with the agricultural economy of river basins, the problem is dealt with at the level where policies are implemented. To date, the analytical systems developed by Horner and Dudek (1979) are important means for developing and evaluating integrated resource use and environmental plans. Broad practical application of such analytical tools is clearly needed because the following critical conclusion of the U.S. General Accounting Office in 1978 appears typical for other countries than the United States:

> Planning is not being done comprehensively under Section 208 of Public Law 92-500 as envisioned by the Congress. Water quality management planning needs to be comprehensive if the nation's water quality problems are to be solved in the most cost-effective manner.

SUMMARY

It has been proved that for many regions, particularly in developed countries, water supply and management is increasingly constrained by nitrate pollution of water resources. This is because of the public health hazard due to the toxic effects of nitrates in drinking water. For example, methemoglobinemia in infants led the World Health Organization to set nitrate limits in drinking water standards. The present situation, at least in developed countries, is such that this symptom is rarely found. On the other hand, nitrates metabolize into nitrosamines which are potentially carcinogenic, teratogenic, and mutagenic. However, because no final evidence is available to prove these effects, it is sometimes argued that the present standard limits are oversafe. Nevertheless, since these arguments also lack conclusive proof, there is virtually no reason to believe that any change of the standard limits will occur. Despite the conflicts, it still seems necessary to establish consistent criteria for safe (low risk) limits of nitrate concentration in drinking water. More toxicological and/or epidemiological studies are needed to dispel uncertainties by accounting for such factors as size and susceptibility of population exposed, number of water systems involved, relative dose in water compared with total burden, positive response of nitrate in carcinogenic, teratogenic, and mutagenic tests etc.

There is a tremendous variety of nitrogen sources in the environment contributing to water pollution. However, among the major sources of nitrogen to water supplies, chemical fertilizers are the dominant cause of the recent rapid increase in nitrate concentrations in water resources. Fertilizer nitrate pollution is a typical case of nonpoint source water pollution. In the past, point source pollution of industrial and municipal origin received most attention in water management. While control of this kind of pollution is generally characterized by known cost and has already demonstrated its effectiveness, this does not hold true to the same extent for the management of agricultural nonpoint source pollution. Due to the many variables involved in this process, it is not a straightforward problem to solve, especially because developing recommendations for management, including cost estimates, is not an easy one.

When applying fertilizers to crops, an initial part of the application contributes to a considerable increase in yield, generally several tens of percent in comparison with unfertilized crops. Beyond a certain value, however, the increments in yield grow smaller and smaller until there is no further increase in yield despite the increasing application of fertilizer. Accordingly, the excess amount of fertilizer is not utilized by plants and will eventually, possibly in modified form, pass to surface and groundwaters. There is no question of the necessity for increasingly intensified agricultural production, because both water and food are indispensible to human life. Agricultural management policies based on intensive use of land, water, and chemicals have greatly increased the efficiency of food production. On the other hand, the present technologies are inefficient in utilizing agricultural resources, such as chemical fertilizers, because they result in environmental pollution hazardous to human health and natural ecosystems. Hence, the question remains: how can agricultural production systems be managed such that negative side effects are avoided or at least minimized?

To answer the question of how water supply and management are influenced by increasing nitrate concentrations in water resources and how a safe drinking water supply can be ensured, requires coordinating goals of the agricultural production sector with public decisions regarding land use and water supply development, and the surface water and groundwater systems. Therefore, water pollution control management must be based on an effective planning procedure. Water quality monitoring, water quality impact modeling, and joint physical-economic modeling of management alternatives should form an integrated system of analysis. In order that strategic planning decisions for pollution control are taken in time, the analysis must meet the following information requirements:

- identification of the relative importance of nitrogen sources and those supply sources most at risk from nitrate pollution,
- predictions of likely future levels of nitrate concentration in supply sources,

- identification of implications to water supply development plans through assessment of the physical and economic effects of the chosen management alternatives.

The tools applied in the analytical process must be capable of matching both the ability of data to yield information with confidence and matching the expectations of the decision makers.

Water management objectives are generally achieved through an integrated implementation of technological, institutional, and economic measures. Depending on the system to which they refer, two general alternatives for water supply pollution control can be distinguished: 1) controlling potential pollution sources, 2) treating polluted water and taking special measures to ensure water supply. Nonpoint nitrate pollution control measures used in the agricultural sector to manage fertilizer application, animal waste disposal, runoff, erosion, and leaching are generally preferred to the elimination of nitrates by water purification. This is because there is a high probability of having to treat toxic chemicals other than nitrate, and the cost and risk of technology depend on the actual pollution source (sewage, slurry, fertilizers). Treatment should therefore only be considered after having proved that nontreatment is insufficient or too slow in being effective.

Such an approach appears closer to the meaning of the term "pollution control" which is often understood as preventing, or at least minimizing water pollution. However, in reality, due to the advanced state of water pollution, one has to consider problems facing municipal water supply in the short run, for example, the need for alternative supply sources, new water treatment technology, or special supply measures. On the other hand, the preventive feature of the term "control" also comprehends the mutual interest of the water supply industry and agriculture in nitrate pollution control. The amount of nitrogen which pollutes water resources constitutes waste of a valuable production resource which must be overcome by better management practices in agriculture.

Consequently, the most effective management of nonpoint nitrate pollution results from control of fertilizer application, irrigation, and other agricultural practices including proper land use management. The development and application of new kinds of fertilizers and inhibitors for controlling fertilizer release or transformation also must be considered. In addition to the measures discussed so far, other institutional, legal, and economic actions for implementing management alternatives have to be considered. Special attention should be given to the fact that practical implementation of pollution control strategies strongly depends on the existence of regional authorities and their capabilities.

The management policies pursued by such authorities must recognize that water purification technologies for nitrate elimination cause a tremendous increase in expenditures to the water industry. Even when neglecting the long-term requirements of water supply protection, short-term social benefits can only be received through the overall control system when the benefits gained from agricultural production outweigh the additional costs of municipal water supply. Moreover, when dealing with nonpoint source pollution control, it is important for researchers, practitioners, and policy makers to realize that only a beginning has been made. While the control of point source discharges of wastewaters is based on over a hundred years of research and testing, continued investigations into nonpoint source control are necessary to establish a comparable level of technology.

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