THE MANAGEMENT ALTERNATIVES FOR CONTROL OF NONPOINT NITRATE POLLUTION OF MUNICIPAL WATER SUPPLY SOURCES

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PREFACE

Regional water management aims at satisfying different supply interests, where these interests are often conflicting. In particular, the competing interests of agriculture, the environment, and municipal water supply, are becoming increasingly important. In this setting of regional water management, nonpoint nitrate pollution of municipal water supply sources is one of the most severe problems. At present, this problem is particularly acute in developed regions with high levels of fertilizer application, but undoubtedly in the future, regions which are now in a developing stage will also face the same problem.

So far, related research at IIASA has been concentrated in Task 3 of the Resources and Environment Area on "Environmental Problems of Agriculture." This work has dealt in particular with agricultural-environmental processes as they are related to crop production and thus has also provided insight into the important role of agriculture in the nitrogen cycle.

Yet another side of the problem remains to be considered, and this is related to water supply and management. This paper therefore proposes a study on management alternatives for control of nonpoint pollution of municipal water supply sources. The study aims at integration of the already initiated studies on "Environmental Problems of Agriculture" with IIASA's water management research. At the same time, due to the role of agriculture in this study, the study will be integrated with IIASA's Food and Agriculture Program investigations. Moreover, because of the need for modelling techniques in analyzing the problem in question, the study will utilize the research results of IIASA's activities on ecological and water quality modelling and the research pursued by the Systems and Decision Sciences Area at IIASA.

Due to the importance of the problem for the majority of IIASA's National Member Organizations an international study involving IIASA and several institutions of different NMO countries is proposed. Therefore, the paper has been written in a specific form and is to be considered a tentative plan for collaboration within and outside IIASA in order to achieve more comprehensive research results. We would therefore like to ask our readers for any comments, remarks, or suggestions that could help to improve the course of our future activities.

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IDENTIFICATION OF THE PROBLEM

In many developed and developing regions throughout the world, a steadily increasing demand for water is confronting municipal water supply agencies. The water resources available for supply are often already heavily utilized, but are also generally limited either because of insufficient quantity or quality of water.

One of the most severe problems concerning the quality of water supply is that of nitrate pollution, because it creates a health hazard due to the toxic effects of nitrates in drinking water. For example, a high concentration of nitrate may cause methaemoglobinaemia, which can lead to the death of infants. Moreover, nitrate can be metabolized into nitrosamine, a potential carcinogen. These implications for public health have led the World Health Organization to set standards for nitrate concentrations in drinking water. In its standards, the WHO recommends that nitrate concentrations should be less than 50 mg NO_3/l, but concentrations up to 100 mg NO_3/l are described as acceptable, providing that local doctors are informed and are therefore aware of problems with infants. Water with nitrate concentrations higher than 100 mg NO_3/l is not recommended for drinking water supply (WHO, 1970).

Atmospheric sources (including rainfall and biological fixation), waste sources such as animal, human, and industrial activities (mainly in the form of manure or sewage effluent), and chemical fertilizers constitute the major inputs of nitrogen to the water environment. The relative importance of these inputs differ from region to region. Nevertheless, many studies carried out in several countries, including some pursued at IIASA, have shown that

chemical fertilizers are the major cause of rapid increases in nitrate concentrations in water resources within recent years. Also taking into account the dependence of manure availability, biological fixation, and even rainfall-related hydrological processes on agricultural practices, the important role of agriculture in the nitrogen cycle becomes fully evident.

Fertilizer nitrate pollution is a typical case of nonpoint source water pollution. In the past, point source pollution of industrial and municipal origin has 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 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 and the development of recommendations for management, including cost estimates, is not an easy one. Nevertheless, there is no doubt that the regional effects on water resources caused by nonpoint source pollution cannot be controlled by technological water treatment measures alone. More emphasis must be placed on precautionary actions based on economic and institutional measures than on restoration of the water resources once they are already polluted.

The water supply sources of a region are rivers, lakes, and storage reservoirs, as well as groundwater aquifers. All of them are more or less threatened by depletion and pollution. Consequently, the relationships between groundwater and surface water, as well as between water quantity and quality, have to be considered in regional water resources management planning. One of the questions to be answered is how water supply and management are influenced by increasing nitrate concentrations in water resources and how a safe drinking water supply can be ensured.

All these facts demonstrate the need for regional systems for management and control of nonpoint nitrate pollution of municipal water supply sources. Such systems must be capable of considering the dynamic relationships between water supply, its management, and the agricultural sector.

OBJECTIVES AND EXPECTED RESULTS OF THE STUDY

The main objective of the study is to develop an approach to analysis and evaluation of management alternatives for control of fertilizer nitrate pollution of municipal water supply sources. Since no specific case study is planned for the time being at IIASA, the main concern is to explore analytic approaches already pursued in IIASA's NMO countries and to generate a methodological outline of an approach focusing on the integration of all the relevant aspects of the problem. The main deficiency of existing approaches is that usually only single components of the overall management system are dealt with. But in reality, the system encompasses the natural water resources to be managed, the respective management measures both for agriculture and water,

and the economics of feasible management alternatives. The study is therefore to be based on the concept of a decision making process encompassing the whole system as shown in Figure 1.

The major components to be considered are:

- the municipalities (as representatives of the public in general), to be supplied with water and agricultural commodities, govern the whole system by setting the management objectives to be achieved; at the same time they also contribute to nitrate pollution of municipal water supply sources by the disposal of human and industrial wastes;
- the agricultural sector causing nitrate pollution of water resources as a side effect of its activities in achieving production goals in agriculture;
- the system of municipal water supply sources such as rivers, lakes, storage reservoirs, and aquifers, and its relations with the environment, which provides the natural background load of nitrogen to water resources; this subsystem is managed by agencies responsible for a safe water supply to municipalities;
- the management subsystem encompassing the planning component (water quality monitoring, including data management, analysis of water supply sources, and management alternatives) and the implementation of management alternatives by technological, economic, and institutional measures in the field of water supply and management as well as in the agricultural sector.

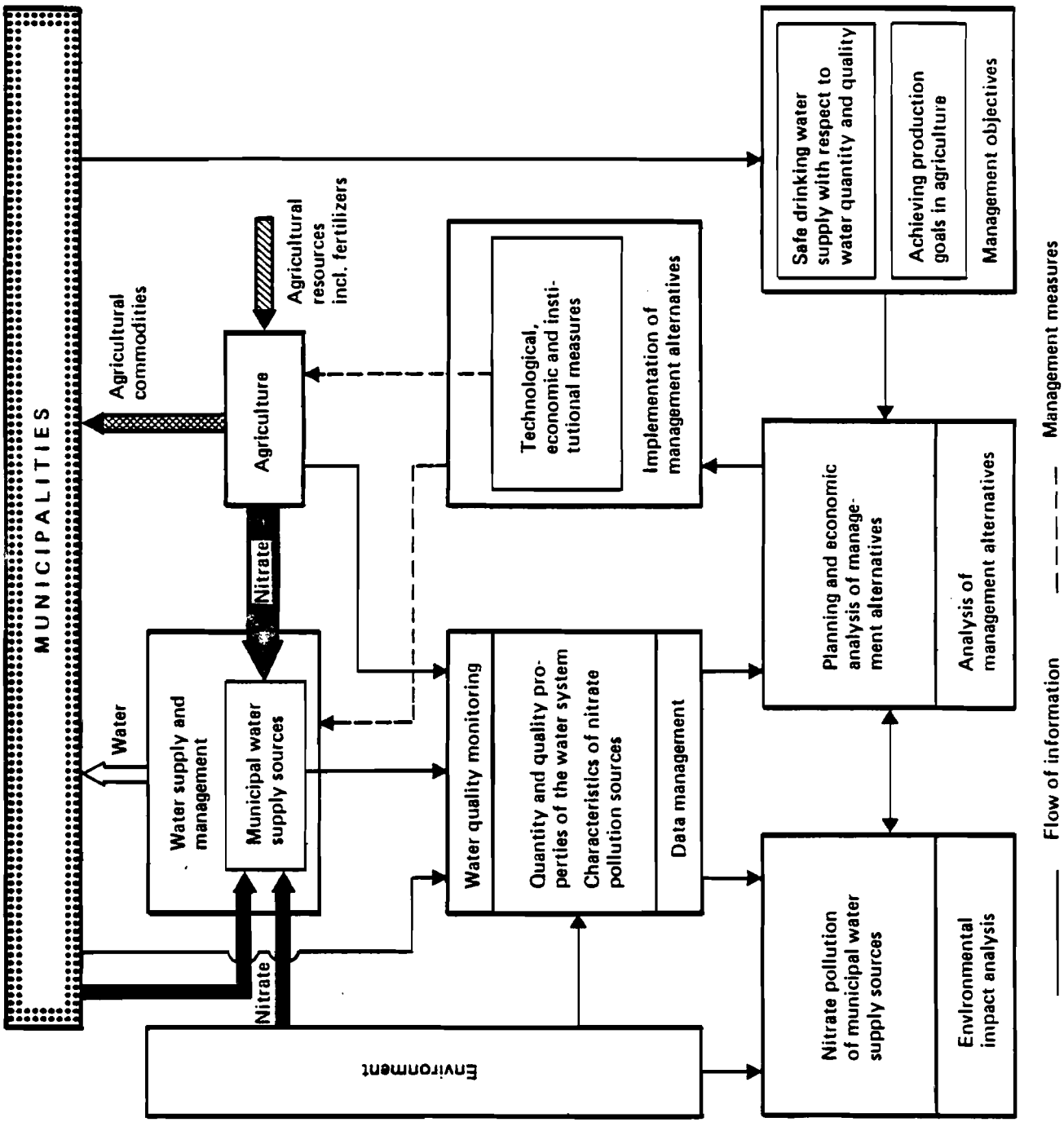
While the subsystems of environment, water supply sources, agriculture, and municipalities are linked by mass flows (water, agricultural commodities, nitrate) and constitute the basis and the target for decision making, components of the planning subsystem are linked by the flow of information. The linkage between these two main parts of the system is provided by the implementation of management alternatives through the respective measures to be taken.

The expected results of the study are twofold. First the methodological outline is to be developed as a basis for applying appropriate methods to a real case study which might be initiated at IIASA in 1981. For the time being, the methodological problems associated with the management of nitrate pollution of water resources should be demonstrated by brief case histories from different regions. By approaching the problem in this way, it is hoped that timely assistance can be given to decision makers. Consequently, the study will provide results of scientific and practical importance to the majority of IIASA's National Member Organizations.

SCOPE OF THE STUDY

The study will deal with the system shown in Figure 1 as far as its components relate to the process of water quality management. According to Wilson et al. (1976), such a process encompasses the

Figure 1. The system of management and control of fertilizer nitrate pollution of municipal water supply sources.



following steps:

- establishment of water quantity and quality objectives;
- analysis of the water quantity and quality factors playing decisive roles in the specific region, e.g., analysis of the municipal water supply sources and the nitrogen sources in the environment;
- analysis of the capability of the region to fulfill objectives without any planning action, e.g., through water quality monitoring and environmental impact analysis;
- formulation of feasible management alternatives to achieve the objectives;
- analysis of each management alternative, together with evaluation of its environmental impacts and the degree of achievement of objectives, e.g., through the joint use of environmental impact analysis and economic analysis of management alternatives;
- selection of the management alternative that ensures the most satisfactory degree of achievement of the objectives;
- plan implementation, e.g., in the field of water supply and management as well as in the agricultural sector.

Taking into account the major steps of this process, a more detailed framework for dealing with the system as shown in Figure 1 is outlined below.

Management Objectives

The management objectives to be achieved within the framework of the system presented in Figure 1 relate to the supply of water in sufficient quantity and quality as well as to the achievement of production goals in agriculture. The municipalities are very sensitive to failures in achieving the above objectives; such failures lead to public health hazards and/or restrictions in the production of agricultural commodities. There is no doubt however, that they have a strong interest in finding solutions to the emerging conflict between permanently deteriorating quality of municipal water supply sources and a simultaneous need for intensification of agricultural production. Both the municipalities and the public can decisively influence the setting or changing of management objectives.

It is not the intention here to consider in depth the debate on the WHO nitrate standards, which determine the upper limit of nitrate concentration in drinking water, especially as different national regulations indicate a nonuniform attitude to this problem. The study will, however, consider health impact aspects of nitrate pollution. This also includes the analysis of possible changes in standard limits. Moreover, variables having effects on agricultural production as well as changes in the standards must be taken into account.

Nitrogen Sources in the Environment

The study has to clarify the relative importance of various nitrogen sources in the environment. In particular, agriculture, as the main cause for nitrate pollution, will be dealt with.

Food supply to a steadily growing population requires high yields in agriculture and a high quality of agricultural products. These aims are achieved by using modern agricultural technologies, among which the use of chemical fertilizers is very important. About 50% of the increments of crop yields in recent years are ascribed to the application of fertilizers (International Association of Hydrogeologists, 1979) and the world production of fertilizers is steadily increasing, as shown in Table 1.

Table 1. Annual world production of nitrogen fertilizer, 1966-1976.

Year	1966-1967	1967-1968	1968-1969	1969-1970	1970-1971	1971-1972	1972-1973	1973-1974	1974-1975	1975-1976	1976-1977
Production of Nitrogen Fertilizers (million tons)	22.4	25.5	28.4	30.2	33.0	35.0	37.8	40.4	42.5	43.8	45.9

Source: Annual Fertilizers Review, of FAO, 1976,1977, 1978.

To feed the current population of the world with protein at today's level of protein consumption for developed countries, would require about 500 million tons of nitrogen fertilizers (White-Stevens, 1977). Projections indicate a rise in fertilizer production in spite of the growing cost of energy.

When applying fertilizers to crops, an initial part of the application contributes to a considerable increase in yields, generally several tens of percent in comparison with unfertilized crops. Above a certain value, however, the increments in yield become smaller and smaller and finally 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.

Municipal Water Supply Sources

The relative importance of water supply sources (rivers, lakes, reservoirs, and aquifers) depends mainly on the natural conditions in the given region. Nevertheless, groundwater resources play a key role in drinking water supply for many countries. Given the dominant influence of nonpoint nitrate sources on groundwater pollution, particular attention is to be paid here to these resources. In doing so, we also keep in mind that there is an important difference between groundwater and surface water pollution and their respective management strategies. While the decision to restore surface water is made with the knowledge that surface water quality can be restored relatively quickly, the same is not true for groundwater where pollutants may be retained for decades or even centuries. Nevertheless, we fully recognize the fact that examination of the effects of fertilizer nitrate pollution on groundwaters requires consideration of the relationships between groundwater and surface water resources of the region.

Planning of Water Quality Management Alternatives

The management and control of water quality depends first of all on an appropriate assessment of the state of water quality. For example, the U.S. Environmental Protection Agency has developed a comprehensive definition of this process for monitoring in the context of management and control (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.

Based on such a definition, water quality monitoring with particular reference to the pollution of groundwater by nitrates will be considered. Needs, objectives, and constraints of monitoring; and purposes, design, and operation of observation networks, as well as monitoring methods, will be dealt with. The problem of managing the data gained in the process of monitoring must also be taken into account because water quality management and control cannot be fully effective without establishing some kind of data management system.

Environmental impact analysis and economic analysis of management alternatives constitute the core of planning for water pollution control. For optimal planning the joint use of these two types of analysis is required.

With regard to environmental impact analysis two main objectives have to be achieved:

- identification of the problem in order to assess its magnitude and timing; this requires macroscopic information on temporal and spatial variations of nitrate pollution;
- understanding of water quality changes as space and time dependent processes, including their mathematical description, to be used for forecasting purposes.

While the first objective relates primarily to the process of water quality monitoring and data management, the second contributes more to the analysis of management alternatives.

In discussing the use of mathematical models, usually two classes of techniques, optimization and simulation, are distinguished. Due to the complexity of water resources systems, the direct use of optimization techniques for determining the best alternatives is often not advisable. More often, simulation models have to be used to test the alternatives. These models therefore play, and will continue to play, a primary part in water quality management. Such models have to be assessed according to the scale of the problem (field, region) and according to the time scale (short-term and long-term) required for water quality management. As indicated above, this requires joint consideration of groundwater and surface water.

Provisionally the simulation models to be used for environmental impact and economic analysis may be grouped into agricultural nonpoint pollution models, groundwater quality models, and water resource system models that are capable of integrating all the individual components of a catchment for overall planning purposes. The aim of the proposed study is not to develop new models but to assess the available models relating to the nitrate pollution problem and to prepare guidelines for their integration and practical use. Of particular interest is the conjunctive use of decision oriented models and process oriented models describing environmental impacts of man's activity, physical processes, etc. Special attention will be paid to elaborating a framework for multiobjective decision making in water quality management and control.

Implementation of Management Alternatives

The management objectives are usually achieved through an integrated implementation of technical, institutional, and economic measures. Two general alternatives for water quality management can be distinguished: one is related to the concept of controlling potential pollution sources; the other relates to the treatment of polluted water and special measures to protect water supply.

Problems facing municipal water supply in the short run, for example, the need for alternative sources, new water treatment procedures, or special supply measures, create additional costs. However, the most effective management of fertilizer nitrate pollution results from control of fertilizer application, irrigation,

and other agricultural practices as well as proper land use management. The development and application of new kinds of fertilizers and inhibitors for controlling fertilizer release or transformation also have to be taken into account.

The study will examine different practices for the control of fertilizer loss from agricultural applications. In particular, the effects of restrictions on the use of nitrogen fertilizer and their economic consequences will be considered. Equal emphasis will be given to control measures to be taken in the field of water supply. Feasible counter measures will be examined and assessed, including cost estimates.

In addition to the measures mentioned so far, other institutional, legal, and economic measures for implementing management alternatives will be considered. Special attention will be given to the fact that practical implementation of pollution control measures depends strongly on the existence of regional authorities and their capabilities.

ORGANIZATION OF THE STUDY

A methodological outline on "The Management Alternatives for Control of Nonpoint Nitrate Pollution of Municipal Water Supply Sources" will be written. This report will tentatively consist of four major parts dealing with the following topics:

- the problem:
  causes and consequences (e.g, municipal water demand and supply, the health hazard issue of nitrate pollution, nitrogen sources in the environment, the need for water quality management);
- analyzing the problem:
  methods of analysis (e.g., water quality monitoring and data management, environmental impact analysis, economic analysis of management alternatives, simulation techniques, and multiobjective decision making);
- solving the problem:
  planning and implementation of management alternatives (e.g., technological measures in water supply and management, control of fertilizer losses from agricultural applications, institutional, legal, and economic measures);
- case histories.

In closing, the report will examine possible recommendations addressed particularly to those dealing operationally with the problem in question.

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