Water Quality Problems and Control Strategies for the Water Supply of Tianjin City

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Abstract

Water supply development must be concerned with both the quantity and quality of water required to meet the needs of man in an efficient and economical manner. The diversion of water from the Luan River into Tianjin is a vast urban water supply project. There are some obvious and potential pollution hazards for the drinking water supply, especially eutrophication is a serious problem and results in treating difficulties at the water supply plant. This paper attempts to provide information on this issue and to discuss the program of water quality conservation and management for the water supply of Tianjin based on various treatment techniques used in the basin, the reservoir and the water treatment plant.

Introduction

Surface water sources are being used increasingly to supply a growing population, industry, and agriculture. In some areas the water supply falls far short of today's demand. This results in the necessity for these continuously growing communities to look elsewhere for a water supply to meet people's continuously growing demand. At the present time many cities in the world transport water over a long distance at great costs. Obviously, the diverted water would provide good conditions for city development and spur on the economy. Often some problems of water quality arise due to the environmental impact of diversion or new pollution problems appear. Sometimes the water resource may be in danger of being lost if the water quality is unsatisfactory. We must remember that water supply development must be concerned with both the quantity and quality of water required to meet the needs of man in an efficient and economical manner. Neither factor can be neglected. The usefulness of the water supply is determined to a large extent by its quality.

Tianjin is the third largest city in China. After the 1970's, the inadequacy of the water supply posed great difficulties to the development of the national economy and the life of the people. With the approval of the Chinese government, the project of diverting the water of the Luan River into Tianjin was started in May 1982 and completed in Sept. 1983. The diversion system has already been used for four years and it has provided a steady water supply for developing Tianjin. Many people have been pleased and satisfied with the sufficient water quantity. But experiences with

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water quality in the Tianjin water supply during the four years after completion of the diversion project showed that the water supply is not safe. Water quality problems related to the diversion project itself include the excessive growth of algae and aquatic plants in storage reservoirs, rivers and open channels; excessive coliform groups and other bacteria; periodical high concentrations of iron and manganese; organic wastes and so on. Eutrophication of rivers and reservoirs due to the diversion project was serious and resulted in treating difficulties at the water supply plants. This paper attempts to provide information on this issue and discusses the conservation and control strategies for the Tianjin water supply.

Diversion Project of Tianjin

The diversion of water from the Luan River into Tianjin was a vast urban water supply project. It extended across provinces, cities and river basins, with a complete system of channeling, conveying, storing, treating and distributing water. Crossing six counties, the system has a total length of 234 km. A tunnel 11 km long had to be dug, and as many as 215 construction projects had to be completed such as pump stations, reservoirs, waterworks, underground and above ground channels, piping systems, reverse siphons, sluice dams and power stations (see Fig. 1). The people of Tianjin completed the entire diversion project within a year and four months. The water source of the project is the Pan Reservoir with a capacity of 29×10^8 m^3, which is an impoundment of the Luan River. The reservoir dam is over 107.5 m high. As shown in Figure 1, the water from the Luan River released from the Pan Reservoir flows down to the Daheiting Reservoir, which is shallow and has a storage capacity of 3×10^8 m^3. From there, water reaches the beginning of the diversion system. From that point, water is transported by means of a tunnel, which is 11.2 km long and 3.5 m in diameter, across the mountains at a flow rate of 80 m^3/s, then released into the original channel of the Li River in the Tianjin area. The water follows the 57.4 km channel at a rate of 65 m^3/s to the Yuqiao Reservoir which is shallow with an average depth of about 3.8 m and a total capacity of about 4.2×10^8 m^3. The water leaves the reservoir at 40 m^3/s and turns south to flow in a 56 km river and a 64.2 km diversion channel. There are three pump stations for transporting water along the open channel. After the third pump station, the water enters two underground pipelines which are 2.5 m in diameter and which carry the water to the Tianjin water supply treatment plant at a flow rate of 10 m^3/s. A small reservoir for pre-storage of the water, with a capacity of 0.45×10^3 m^3, was constructed near the last pumping station.

This is the largest diversion project in China. In normal years, an annual supply of a billion cubic meters is available. This greatly relieves the city's water demand and promotes its functions.

Water Quality Problem

A comprehensive water quality program was undertaken for monitoring water from the Luan River to the Tianjin water supply plant by some environmental and

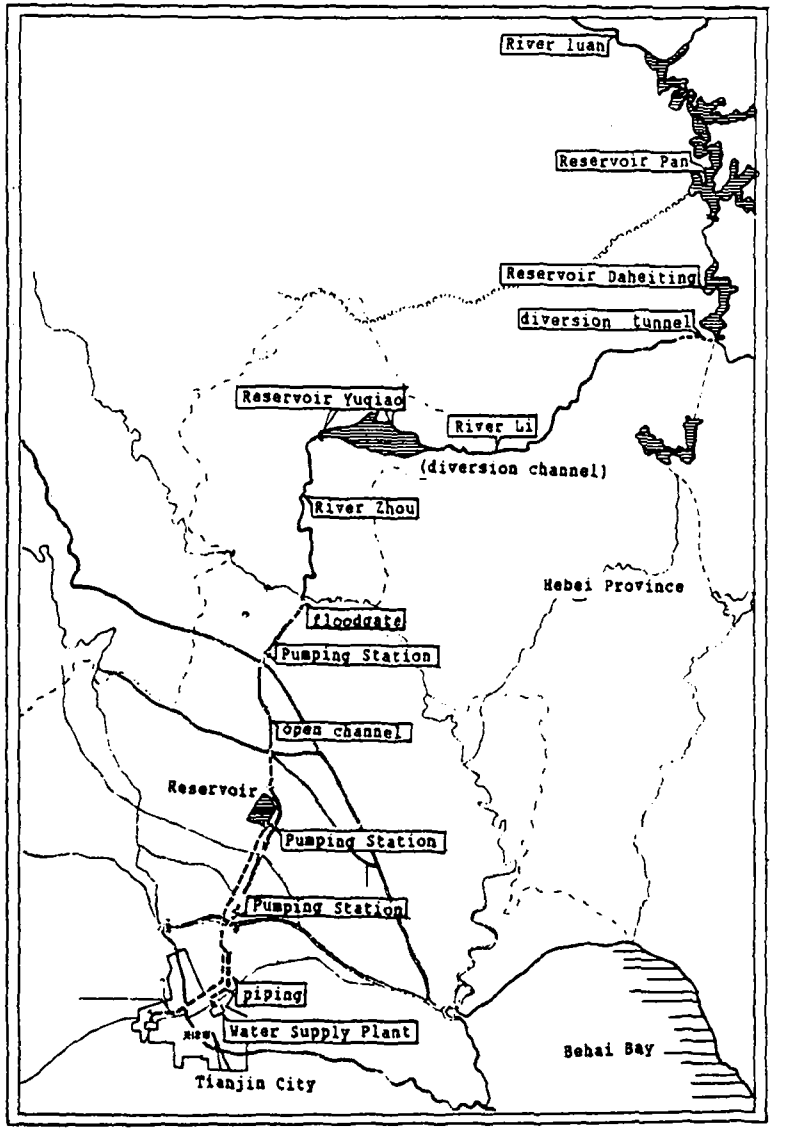

Figure 1. Ouline of the diversion work of leading the water of River Luan into Tianjin

hydrological stations and institutes. Based on the average monthly assessments of water quality, it was found that most of the water quality standards for surface water were met.

As the water was transported through this complex system of storage areas and transport pathways over a long distance, water quality was modified from upstream to downstream due to various nutrients, as shown in Figure 2.

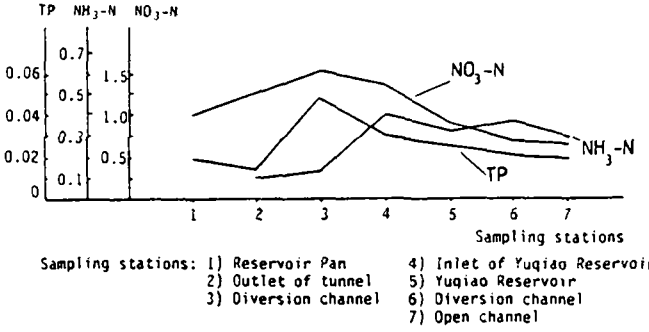

Figure 2. Nutrient concentrations variance in the water along the diversion work

It was clear that the concentrations of some nutrients in the water were higher downstream than in the Pan Reservoir, and this may be related to the effect of the diversion channels which carry the water, the internal nutrient cycle in the reservoir, chemical, physical and biological processes, and finally an adjustment which occurred in the water body itself. The main water quality problems of the diversion project are analyzed subsequently.

Eutrophication of the Yuqiao Reservoir

The Yuqiao Reservoir was impounded in 1960 for purposes of irrigation. After completion of the diversion project it became a very important storage and regulating reservoir as well as the drinking water source for Tianjin. The area of the basin is about 2060 km^2 with three tributaries: Sha River (largest in the basin), Lin River and Li River (which also forms part of the diversion channel). The annual input from the three tributaries is about 4 x 10^8 m^3. About 1 billion cubic meters of water from the Luan River enter the Yuqiao Reservoir via the Li River after completion of the diversion project. Thus some changes in the hydrology and loading conditions occurred in the Yuqiao Reservoir, as shown in Table 1.

	Before diversion work	After diversion work
influent flows	4x10^8 m^3	14x10^8 m^3
effluent flows	3x10^8 m^3	10x10^8 m^3
detention time	1.4 Years	0.42 Years

Table 1. Changes of limnology conditions of Yuqiao Reservoir

Before the diversion work in 1976 and in 1982 – 83, a chemical and biological examination of the Yuqiao Reservoir was undertaken. It was shown that the concentrations of nitrogen and phosphorus were higher than usual and thick algal growth was present in the Yuqiao Reservoir in spring and autumn. Most of the algal species were blue-green algae. A large number of macrophytes was found in the middle and upstream areas. Temperature and dissolved oxygen stratification was particularly pronounced in the summer and severe anoxic conditions were present near the reservoir bottom in the summer months. The Secchi Disk reading was only 0.5 m in summer. It was obvious that the Yuqiao Reservoir was on its way to becoming a eutrophic reservoir.

Some people expected the trophic state of the reservoir to improve due to the higher flushing rate and shorter detention time in the reservoir after completion of the diversion project. In fact, transparency was increased to 1.2 m in summer, 3 to 5 m in winter; the concentration of total phosphorus in the water had decreased to 0.02 to 0.04 mg/l. Some algal species and some macrophytes decreased, but some also increased because of the higher light intensity in the water due to increased water transparency. The stratification of temperature and oxygen in the reservoir changed slightly, but anoxic conditions near the bottom remained. See Figure 3.

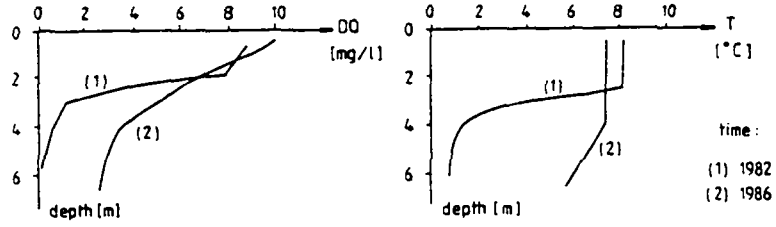

Figure 3. DO stratification of Yuqiao reservoir

Excessive Growth of Macrophytes

There were many species of macrophytes growing in the Yuqiao Reservoir, including emergent, floating-leaf and submersed varieties. Biomass was very high and in some parts of the reservoir the plants formed a thick forest which hindered movement of the boat. In addition to the macrophytes found in the reservoir, there were also plants downstream in the old and new channels. Some had been flushed from the reservoir, others grew there. The biomass of the macrophytes was surprisingly high in the growing season, causing decreased water flow and raising the water level significantly so that strong pressure affected the channel banks. A surprising event took place in the spring of 1985: macrophytes in the open channel had clogged the screen of the Chaobei pumping station. About 100 people stood on these aquatic plants, and their density was so high that no one fell into the water! It was necessary to harvest these macrophytes day and night during the growing season.

Other Water Quality Problems

Other water quality problems associated with the diversion project were as follows:

1) Periodically, high concentrations of iron and manganese were present in the reservoir and channel.
2) The populations of coliform groups and other bacteria were very large, above the national standard, upstream as well as downstream of the diversion system.
3) High concentrations of chloride were present in some parts of the open channel for short periods, and were due to the effect of salt land near the open channel.
4) The COD in the water in the diversion channel ranged from 3 to 6 mg/l, sometimes exceeding the national standard for surface water. Phosphate concentrations were often higher than 0.5 mg/l.

Water Treatment in the Tianjin Water Supply Plants

The Tianjin water supply plants have the obligation to provide potable water which is chemically and bacteriologically safe for human consumption and which is of an adequate quality for industrial users. Three plants provide 106 m^3 per day for Tianjin City. Before the diversion project, the plants received water from the Hai River which had a high chloride concentration due to the sea water. The diversion project ended the unpleasant history of people drinking salt water and provided sufficient quantity and better water quality for Tianjin.

The largest and most important of the three plants is called the Jieyan water supply plant, and was built in the 1930's but has been expanded since then. The design capacity of the plant is 5×10^5 m^3 per day. The plant consists of 2 horizontal flow basins, 2 tube settlers and 8 rapid sand filters. The treatment process consists of pre-chlorination, addition of chemicals, rapid mixing, coagulation, precipitation, filtration and chlorination. The water conditions and dosage of chemicals were as follows: water temperature 20 to 32°C, turbidity 20 to 40 mg/l, $FeSO_4$ dosage 5 to 6 mg/l (in summer) and 3 mg/l (in winter), chlorination 3 to 5 mg/l.

The treated water discharged from the plant met most of the national standards for water quality. But there were many problems with treatment due to the eutrophication of the water source, however, after completion of the diversion project. The problems encountered in the Tianjin water supply plant included: rapid clogging of filters by algae, unpleasant tastes and odors, risk of increased bacterial growth in the drinking water due to the fouling of the distribution network and the nutrient content. In order to counteract these problems, twice the amount of chemicals was added, which increased the frequency of filter backwashing. This led to a reduction in the water production. It is clear that the eutrophication problem at the water source has caused expensive and time-consuming treatment problems.

Control Strategies

The diversion project has played the most important role for improving people's lives in Tianjin and for economic development. We must take effective protective measures and use conservation strategies to ensure safe water transport and a developing economy for a long time.

Eutrophication is one of the most important water quality problems worldwide. Solving this problem will entail more advanced technology, high costs and detailed management planning. In spite of the economic conditions in our developing country, we cannot ignore the economic and political realities in favor of a technical approach.

The final decision on an appropriate control strategy must be based on the relevant social, technical, economic and ecological aspects.

We have proposed a research program for selecting effective strategies for controlling eutrophication of the Tianjin water supply. This program is based on the analysis of the following problems:

1) The water quality of the Pan Reservoir (Luan River impoundment and the water source of the diversion project) is better than that of the Yuqiao Reservoir. There are no obvious problems except the high concentrations of nitrogen produced by soil erosion.
2) All the areas through which the diverted water passes are agricultural areas without developed industry. The emphasis on pollution control is therefore in controlling nonpoint sources.
3) Since the water is transported over a long distance, it is affected by different storage areas and channels which are in turn affected by ecology, limnology and land use. A system of control strategies is needed for water quality conservation, which must be regarded either as a special problem or one for which the whole state carries a responsibility.

The research program is primarily concerned with control measures in five major categories:

1) Control of nutrient sources in the watershed
2) Treatment of the tributaries which feed into the Yuqiao Reservoir
3) Eutrophication control in the reservoir itself (biological methods)
4) Intensifying the treatment process in the Tianjin water supply plant
5) Legislation for and management of the watershed

Nutrient Source Control in the Watershed

Experience has shown that the most effective approach is to treat the most readily-controllable cause of the problem. In this case it is the input of excessive quantities of phosphorous and nitrogen from the drainage basin into the water. The control program must be directed towards the major sources of these nutrients in the drainage basin.

According to the examination of pollutant load inputs along the route of the diverted water, approximately 80% of the loads were contributed by the tributaries of the Yuqiao Reservoir.

A detailed investigation of nutrient loading into the reservoir was carried out in 1982 to 1984 simultaneously with investigations of water quality and quantity. The amount of phosphorus and nitrogen was estimated for each storm event and for each month of the year.

The results of total nutrient flux including runoff, precipitation and ground water into the Yuqiao Reservoir showed that:

1) Runoff from nonpoint agricultural sources was the main source of these nutrients
2) The nutrients input during the flood season were over 80% of the total annual load.
3) Approximately 50% of the annual nitrogen load comes from point sources. There are two fertilizer plants upstream of the Yuqiao Reservoir near the diversion channel. Another 50% comes from nonpoint sources. Almost all the phosphorus comes from nonpoint agricultural sources.

Two major approaches were undertaken in attempting to reduce the potential impact of agricultural activities on the eutrophication of the Yuqiao Reservoir:

1) Application of natural and mineral fertilizer in a manner that inhibits their transport into water bodies.
2) Maximum prevention of soil erosion.

The nutrient flux data indicated that the concentration of solids and suspended solids from agricultural runoff reached over 5000 mg/l in the Yuqiao Reservoir. The sediment mass flux was estimated at 24 x 10^4 tons per year, which played a major role in the eutrophication of the reservoir. Therefore, it is necessary to control the input of sediment in order to protect the reservoir and its water quality. Some typical management practices that should be adopted are as follows:

1) Contour farming to reduce erosion
2) Leaving buffer strips of trees and shrubs along streams to reduce soil erosion
3) Grass seeding or other vegetation to stabilize areas near the stream and reservoir banks particularly to reduce flushing of soil and erosion
4) Use of culverts and other engineering structures to control water flow and thereby reduce erosion
5) Nutrient management practices including the formulation of a fertilizer application rate, application technique and timing of the applications
6) Pesticide management practices including application methodology, timing and rate of application.

The total surface area of the Yuqiao Reservoir was 104 km^2 at normal water levels. The loads of total phosphorus and total inorganic nitrogen in the reservoir were 0.71 g/m^3 yr and 4.31 g/m^3 yr, respectively. It is clear that these loads are much higher than those recommended by Vollenweider. As noted above, the external nutrients came mainly from the agricultural nonpoint sources in the catchment area.

Treatment of Tributary Influent Waters

Pre-reservoir. The use of pre-reservoirs as bioreactors for phosphorus elimination has been investigated and applied successfully to some lakes and reservoirs around the world.

The elimination of phosphorus in the pre-reservoir is related to an enhancement of bioproductivity. The phosphorus is fixed in the increased algal and macrophyte biomass in the pre-reservoir and is thus largely retained there via sedimentation.

The Yuqiao Reservoir already seems to act as a pre-reservoir. Upstream of the reservoir, approximately 25% of the total surface area was covered with macrophytes which helped to absorb nutrients and increase the retention time of the water. The area is about 30 km^2 with depths of 0 to 3 m. These were good conditions under which to construct a pre-reservoir although it was provided by nature and had not required extensive planning.

In order to build an effective pre-reservoir, the following questions must be answered through research:

1) What retention time is required in order to ensure bioproductivity?
2) How can the pre-reservoir project be completed taking into account the natural conditions, and how efficient will it be for phosphorus elimination?

The research plan for the Yuqiao reservoir is shown in the form of a flow chart in Figure 4.

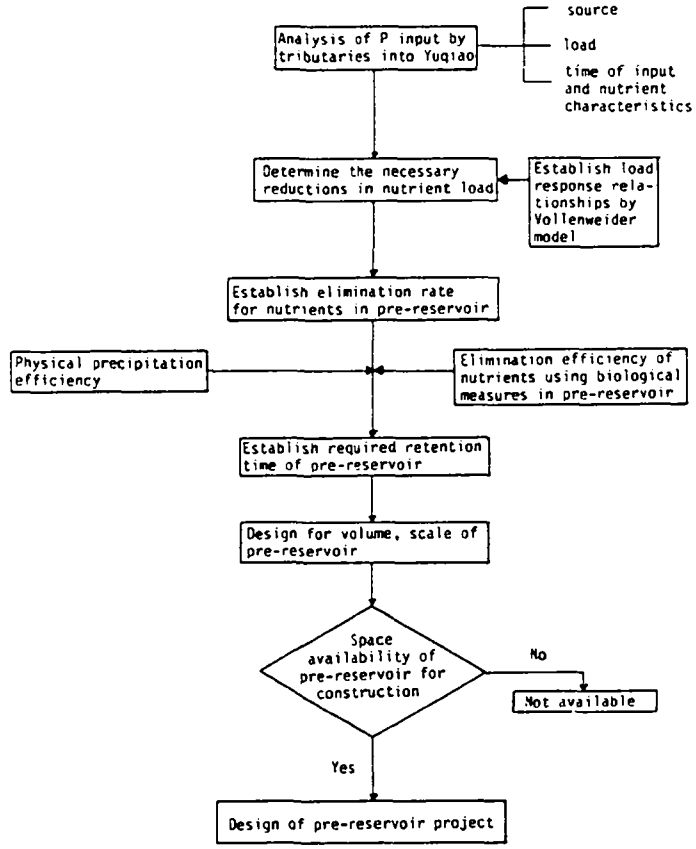

Figure 4. Research procedure for pre-reservoir of Yuqiao reservoir

Direct Addition of Phosphorus Precipitating Chemicals to the Influent Waters. The shallow Yuqiao Reservoir has three main tributaries. The large phosphorus load is contributed by the tributaries in a short period of 3 summer months. If the water is allowed to reach the treatment plant, pre-treatment is too expensive and this method cannot be used throughout the year. Thus, it seems reasonable to add the chemicals directly at the point where the water flows into the reservoir. The following questions must be answered through research:

1) Can addition of phosphorus-precipitating chemicals be correlated with the actual water flow and the concentration of phosphorus in the tributaries entering the reservoir?
2) What amount of chemicals must be used? What should be done about silting in the reservoir due to the precipitating phosphorus?

Eutrophication Control in the Reservoir Itself

Growth of the macrophytes in the Yuqiao Reservoir was prolific, covering the area at a depth of 0 to 3 m from April to November. If these plants are not removed from the water, they can function as a nutrient "pump" which transports nutrients from the sediments back into the water. This may result in an increase in nutrients in the reservoir and progressive eutrophication. We should determine the feasibility of harvesting macrophytes for the removal of nutrients from the reservoir and develop ways for reusing the biomass as raw materials and animal fodder.

Intensification of the Treatment Process at the Tianjin Water Supply Plant

Although significant progress has been made concerning the water supply in Tianjin, in many cases the water service is not nearly as good as it could and should be. Some aspects of water quality fell short of present daily standards. Monitoring, operator and manager training and water research do not stand up to today's requirements.

In order to counteract the eutrophication problem at the water source, management and conservation practices must be strengthened to achieve adequate surface water quality in the catchment area. On the other hand, in order to intensify the treatment processes at the water supply plant, research must be undertaken in the following areas:

Improvement of Water Treatment Processes. When water is supplied from rivers, this normally requires the most extensive treatment facilities and greatest operational flexibility. The water treatment plant must be capable of handling day-to-day variations and anticipate changes in quality. The Tianjin water treatment plant receives its water from rivers and reservoirs which are eutrophic. Rivers and reservoirs are subject to seasonal changes. Algal blooms frequently occur in early spring and late summer. Heavy algal growth, particularly that which includes certain species of blue-greens, produces tastes and odors which are difficult to remove. In order to deal with these changes in water quality at the source, the operator should

have the means to change the point where certain chemicals are added. For example, chlorine feedlines are normally provided for pre-, intermediate and post-chlorination. Multiple chemical feeders and storage tanks should be supplied so that various chemicals can be employed in the treatment process.

Development of New Techniques. We should energetically pursue the development of new techniques in water treatment to improve treatment efficiency and to satisfy the increasing demands for high water quality. For example, proper instantaneous and thorough mixing of chlorine, and treatment which provides better disinfection; the use of granular activated carbon for removing trace organic compounds and for complete color removal and taste and odor control; the use of biological treatment to eliminate algae; the use of polymers to improve coagulation, flocculation and settling; the use of methods for continuously monitoring and controlling water treatment processes and other methods.

Legislation for and Management of the Watershed

Since Tianjin's water supply is transported over a long distance, across provinces and river basins, water quality is governed by processes in these basins, ecological characteristics and human activities. For example, deforestation, the excessive use of chemicals and fertilizer, the industrialization of agricultural regions, fish farming, irrigation practices, precipitation, and soil erosion, etc. may contribute to an increase in the nutrient and pollutant load which leaves the basin and promotes eutrophication of the water. Thus, in order to obtain a long-term reliable and good water supply, management and planning for efficient conservation, development and utilization of the water resource must be undertaken from the standpoint of the range of the watershed. The Tianjin Diversion Project Management Agency was established in 1984, and is responsible for managing and protecting the water supply. Although the transport of water and regulation of the quantity of the water are fairly simple tasks, implementation of the eutrophication control program is difficult due to its division among several administrative regions, range of responsibility and power. Control of eutrophication may contain some conflicting elements, for example, the Yuqiao Reservoir belongs to the Tianjin area but its basin to Hebei Province. Implementation of this control must involve limiting industrialization and excessive use of fertilizer and increasing forest cover in the upstream basin of Yuqiao Reservoir, among other things. The government of Hebei Province does not welcome this program, however, because it does not benefit them.

The first step, therefore, is to establish a single agency which has jurisdiction over the environmental management program in the national government, or through a cooperative hierarchical framework with the national government and local governmental entities.

Secondly, legislation and regulation should be examined as a necessary component of a pollution control program.

Research Plan for Decision Strategies

Summarizing the research plan, the basic approach for achieving the above-mentioned objectives consists of the following steps, shown in Figure 5:

- Identify water quality problems and establish management goals
- Assess how much information is available on the watershed
- Identify the options for managing water quality
- Analyze all costs and expected benefits of alternative management and control options
- Evaluate the adequacy of the existing institutional and regulatory framework for implementing alternative management strategies
- Select desired control strategies
- Submit progress reports on the control program to the government periodically.

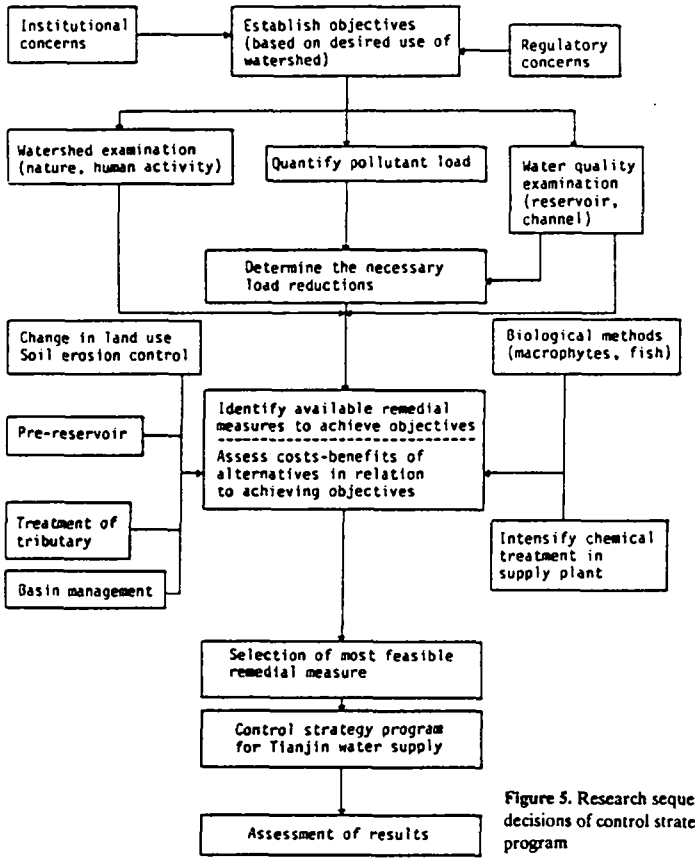

Figure 5. Research sequence for decisions of control strategies program

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