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Water pollution control planning for the Taizi River watershed

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Abstract—Water pollution control planning for the Taizi River watershed, a typical Chinese case study, is presented in this paper. Based on comprehensive analysis, water quality in the watershed was assessed and predicated; water quality models for the river and reservoir were built; and function of water bodies and environmental assimilative capacity were determined; and then the planning for industrial pollution sources and concentrated sewage treatment were made respectively.

Keywords: water pollution control planning; water quality model; benefit-cost analysis.

1 Introduction

The Taizi River watershed, which is situated in the middle part of Liaoning Province and runs through three cities——Benxi, Liaoyang and Anshan, is not only a main base of the Chinese steel and petro-chemical industries, but also an important grain- producing area of Liaoning Province where there is a developed economy and concentrated population. With the development of the economic construction in the watershed, the discharge capacity of industries and cities is rapidly increasing, which results in a gradual deterioration of water environmental quality and limits directly the development of industrial and agricultural production, and affects the ecological balance and human health in the area. The study is an important task for controlling water pollution and improving and protecting the natural ecological environment in the watershed.

The planning objectives are to control water pollution and to improve water quality of the main river sections in the short- term (1995); and to improve water quality of the entire watershed and to coordinate environment and socio-economic development in the long-term (2000).

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By means of systems engineering, the relationships among all river watershed factors of water pollution control system are to be analyzed and coordinated. The effects of the coordinated factors on the overall objective are simultaneously considered, so that the optimum control of the overall environmental problems may be explored.

The task is divided into three levels to be studied (Fig. 1).

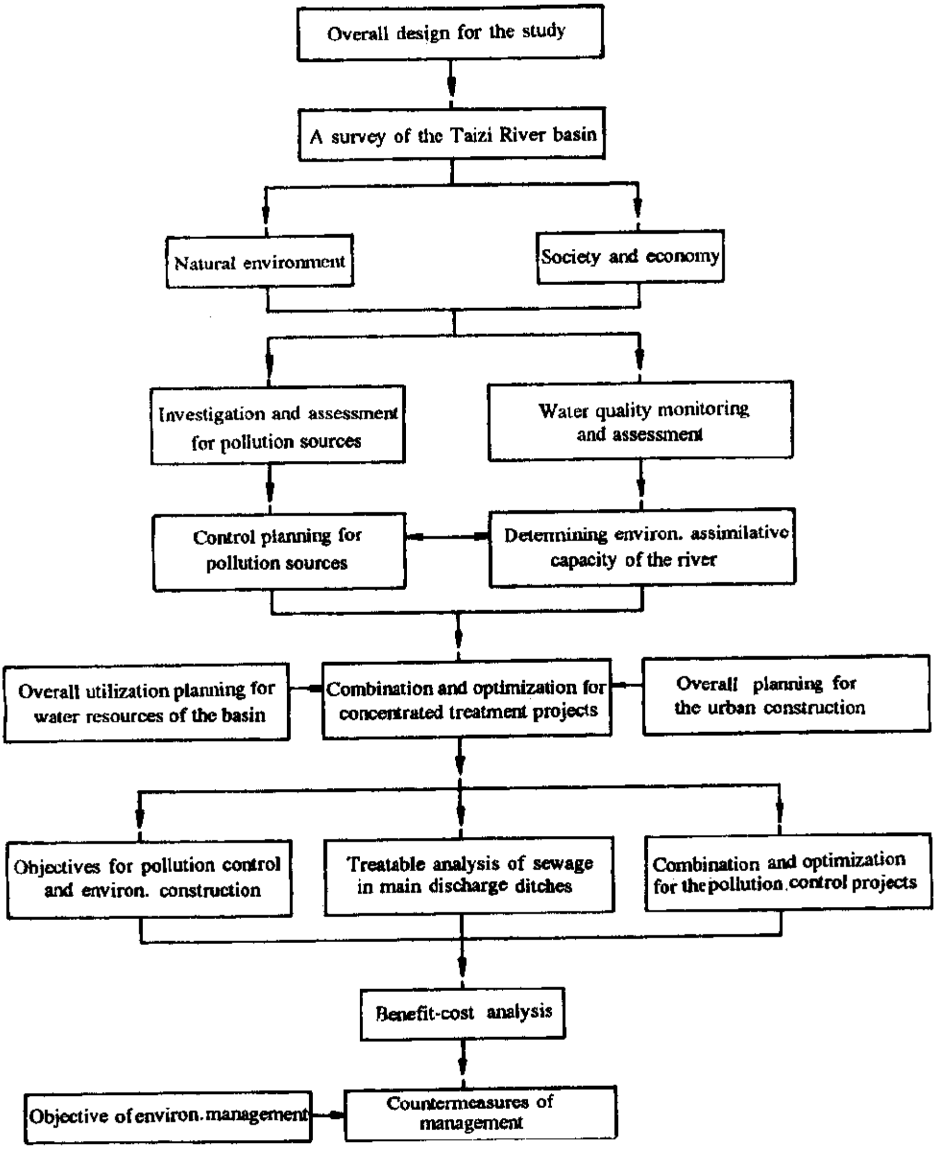


Fig. 1 Procedure of water pollution control planning study for the Taizi River watershed

2 A survey of the Taizi River watershed

The Taizi River watershed is 313 km in length with an area of 13883 km^2. It is located in the East Asia monsoon area in the continental climate zone with extremes of heat and cold.

Mean annual temperature and precipitation are 7.8℃ and 800mm, respectively. Winds blow mainly from the east, south and southwest with an average speed of 2.8m/s.

Two tributaries from south and north at the source of the Taizi River flow together at Jiucaiyuanzi in Benxi County, which then passes through the urban district of Benxi City from northeast to south and runs through Liaoyang City. The river then joins with the Hun River becoming the Daliao River at Haicheng County(Fig. 2).

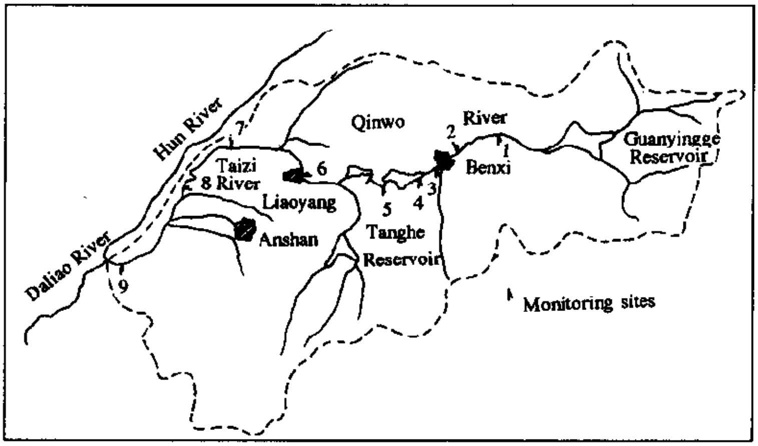


Fig. 2 Diagram of the Taizi River basin

According to hydrological statistical data for the last eleven years at Benxi Hydrologic Station, the minimal and maximum average flow of the Taizi River each year are 21.7m^3/s and 92 m^3/s, respectively; the minimum winter flow and perennial low-flow are 3.97m^3/s and 1.61m^3/s, respectively.

The basin population was 5.97 million in 1989 including a 2.91 million urban population and 3.06 million rural population. Three industrial cities had 3897 factories and enterprises including 39 large enterprises, of which the main factors were metallurgy excavation, energy resources, petro-chemicals. The total output values was 2.18×10^{10} RMB Yuan. The total agricultural output value was 30.57×10^8 RMB Yuan in 1989.

3 Assessment and prediction of water quality for the Taizi River watershed

3.1 Water quality monitoring and assessment

Nine sections were set up based on the original sections(Fig. 2). The selected monitoring items included water temperature, pH , DO, BOD_5, COD, phenol, total CN^-, petroleum oil, NH_3-N, NO_3-N, NO_2-N and so on.

Based upon the original materials of three cities, 224 major enterprises of discharge sewage were initially chosen and investigated. It turns out that discharge capacities of 143 enterprises possessed of more than eighty percent of total amount of the watershed, which were screened out as key pollution sources.

Major pollutants of the key pollution sources in each section of the Taizi River were as follows:

Upper reaches of Benxi section: COD, SS, BOD_5, NH_3-N;

Lower reaches of Benxi section: SS, phenol, CN^-, COD, sulphite, NH_3-N, Cu, P, BOD_5, petroleum oil.

Liaoyang section: COD, BOD_5, phenol, petroleum oil;

Anshan section: petroleum oil, COD, BOD_5, CN^-, Zn, phenol.

3.2 Prediction of discharge sewage for key industrial pollution sources

Based on the material from 1987, the predictions included the short-term (1995) and long-term (2000). The prediction methods adopted prediction models of Gongpazi and grey system.

The prediction results indicated that the growth rates of total amount of discharge sewage in the short-term and long-term were 1.6% and 2.47% respectively; the spread of pollution zone of excess standard would constitute a serious threat on water quality of the Qinwo Reservoir.

4 Water quality models for the Taizi River watershed

4.1 Water quality models for the watershed

According to the principle of linear accumulation and the relationship of multiple sources and reaches input, the model including six parameters: COD, BOD_5, NH_3-N, phenol, CN^-, oil was built as follows:

$$C=C_0\exp(-kt)+\sum_{j=1}^{n} N_j/86.4Q_j\times 1/\exp(-kt).$$

Where, C is pollutant concentration in control site of some reaches, mg/L; C_0 is pollutant concentration in initial site of some reaches, mg/L; t is flow time of river water from initial site to control site of some reaches, h; n is number of discharge ditches in some reaches; N_j is discharge capacity of pollutant for discharge ditch j in some reaches, kg/d; t_j is flow time of river water from discharge ditch j to control site in some reaches, h; Q_j is flow of river water at discharge ditch j in some reaches, m^3/s; K is overall decomposed coefficient of pollutants, 1/h.

Streeter-Phelps model for multiple sources and reaches:

$L_1=(L_0-k_1\cdot t_{0-1}),$

$L_2=(L_1+N_1/86.4Q_1)\cdot\exp(-k_1\cdot t_{1-2}),$

$L_3=(L_2+N_2/86.4Q_2)\cdot\exp(-k_1\cdot t_{2-3}),$

…

$L=(L_{n-1}N_n/86.4Q_n)\cdot\exp(-k_1\cdot t_n),$

$O_1=O_s-(O_s-O_0)\exp(-k_2\cdot t_{0-1})+k_1\cdot L_0/(k_1-k_2)\cdot[\exp(-k_1\cdot t_{0-1})-exp(-k_2\cdot t_{0-1})],$

$O_2=O_s-(O_s-O_1)\exp(-k_2\cdot t_{1-2})+k_1\cdot(L_1+N_1/86.4Q_1)/(k_1-k_2)[\exp(-k_1\cdot t_{1-2})-\exp(-k_2\cdot t_{1-2})],$

$O_3=O_s-(O_s-O_2)\exp(-k_2\cdot t_{2-3})+k_1(L_2+N_2/86.4Q_2)/(k_1-k_2)[\exp(-k_1\cdot t_{2-3})-\exp(-k_2\cdot t_{2-3})]$,

…

$O=O_s-(O_s-O_n)\exp(-k_2\cdot t_n)+k_1\cdot(L_n+N_n/86\cdot 4Q_n)/(k_1-k_2)[\exp(-k_1\cdot t_n)-\exp(-k_2\cdot t_n)]$,

Where, L_0 is BOD_5 concentration in river water at discharge ditch j of some reaches, mg/L; $L_j(j=1-n)$ is BOD_5 concentration in river water at discharge ditch j of some reaches, mg/L; L is BOD_5 concentration in river water at control site of some reaches, mg/L; O_0 is DO concentration in river water at initial site of some reaches, mg/L; $O_j(j=1,\ldots,n)$ is DO concentration in river water at discharge ditch j of some reaches, mg/L; $N_j(j=1,\ldots,n)$ is BOD_5 discharge amount at discharge ditch j of some reaches, kg/d; $Q_j(j=1,\ldots,n)$ is flow of river water at discharge ditch j of some reaches; t_{0-1} is flow time of river water from initial site to first discharge ditches in some reaches, h; t_{1-2} is flow time of river water from first discharge ditch to second discharge ditch, h; t_{2-3} is flow time of river water from second discharge ditch to third discharge ditch, h; t_n is flow time of river water from n-th discharge ditch to control site, h; O_s is saturated DO concentration in river water, mg/L; k_1 is BOD decomposed coefficient, 1/h; k_2 is aeration coefficient, 1/h.

4.2 Reservoir water quality model

Considering effects of the Qinwo Reservoir on the watershed, a two-dimensional linear regression model was adopted:

$$Y=a+b_1X_1+b_2X_2,$$

where, Y is pollutant concentration of the reservoir output, mg/L; X_1 is total pollutant amount of the Xi River input, kg/d; X_2 is total pollutant amount of the Taizi River input, kg/d; a is constant; b_1, b_2 is regression coefficient.

4.3 Parameter estimation

The rivers were dealt with in generalities since the discharge ditches and water catchments concentrated on the Taizi River watershed. According to the observed values of some sections, parameter estimation was divided into two steps. The first step was to estimate overall decomposed coefficient and aeration coefficient of pollutants in each hydrological period; the second step, based on the estimation of step one and the flows and temperatures of river water for relevant hydrological period, was to calculate coefficients $K_{(20)}$, θ_1, θ_2, θ_3, θ_4 and θ_5 using gradient method (Table 1).

$$K_1(T)=K_{(20)}\theta_1^{(T-20)}$$

$$K_2(T,\theta)=\theta_2+\theta_3\cdot\theta_4\cdot\theta_5^{(T-20)},$$

where, T is temperature of river water, ℃; θ is flow of river water, m^3/s; $K_{(20)}$ is overall decomposed coefficient of pollutants at temperature 20℃ in river water, 1/h; $\theta_1-\theta_5$ are constants.

Table 1 Parameters $\theta_2-\theta_5$ in water quality model for the Taizi River

Areas	Reaches	Parameters			
		θ_2	θ_3	θ_4	θ_5
Benxi	Section 1 to 2	0.0357	0.0423	0.0284	1.0599
	Section 2 to 3	0.0461	0.0795	0.1881	1.1415
	Section 3 to 4	0.2548	0.0462	0.0530	1.0645
Liaoyang	Section 5 to 7	0.0129	0.0153	0.0254	1.0655
	Section 7 to 8	0.0270	0.0389	0.0383	1.0460
Anshan	Section 8 to 9	0.0253	0.0293	0.0198	1.0600

Less than 10% of the average errors between the calculated value and observed value of water quality parameters was 78% in each monitoring section, the relative errors of less than 10% was about 74%, of which precision could satisfy the requirement of water quality simulation.

5 Functional division of water bodies and environmental assimilative capacity for the Taizi River

5.1 Functional division of water bodies and determination of water quality criterion

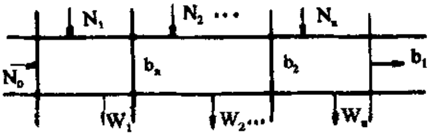
According to information of the present investigation and prediction of urban development, the function of water bodies and water quality goal in the main stem were determined by means of the built water quality model, which had considered the technological and economic conditions based upon making repeated simulations and feasible analysis.

The basic principles are as follows: first, the upper reaches of Benxi section in the Taizi River, which are the first-class protected zone for drinking water source, belong to the area of key protection and strictly controlling pollution. Second, based upon protecting water resources the Qinwo Reservoir is one of relatively large reservoirs on the watershed, which has to be changed from the present water quality of excess class 5 in the short-term and has to be obviously improved for water environmental quality in the long-term for the middle and lower reaches of the Benxi section (from section 2 to section 4). Third, the present water quality in the reaches of Liaoyang is superiors to that in the reaches of Benxi and Anshan. However, water quality control for the reaches of Liaoyang should be strictly demanded according to the requirements of the usage and protecting water quality. Finally, the reach of Anshan, a lower reach of the Taizi River's stem, is extremely important in water quality control for the requirement of its own environmental quality and for alleviating pollution of the Taizi River. Therefore, water pollution should be generally controlled in the short-term and water quality should be improved to some extent in the long-term for the reach of Anshan.

5.2 Environmental assimilative capacity in each reach of the Taizi River

The design flow of each control section was calculated by using 90% guarantee ratio and the lowest flow of thirty days.

A sketch for the input and output of an one-dimensional river is as follows:



where, N_j is the maximum permissible discharge of pollutant at discharge ditch j, kg/d; W_j is the amount of drawing pollutant at water catchment j, kg/d; N_0 is the amount of pollutant input at initial section, kg/d; b_j is the water quality goal for control section j, mg/L.

A mathematical model for calculating maximum permissible discharge is as follows:

Objective function: Max $\sum_{j=1}^{n} N_j$

Restrained condition:

$$\begin{cases} \alpha_{11}N_1+\alpha_{12}N_2+\cdots\alpha_{1n}N_n\leqslant b_1-\alpha_{10}N_0+\beta_{11}W_1+\beta_{12}W_2+\cdots\beta_{1n}W_n \\ \alpha_{21}N_1+\alpha_{22}N_2+\cdots\alpha_{2,n-1}N_{n-1}\leqslant b_2-\alpha_{20}N_0+\beta_{21}W_1+\cdots+\beta_{2,n-1}W_{n-1} \\ \cdots \\ \alpha_{n1}N_1\leqslant b_n-\alpha_{n0}N_0+\beta_{n1}W_1 \end{cases}$$

where, α_{ij} is the effect coefficient of discharge ditch j on source intensity of control section i; β_{ij} is the effect coefficient of water catchment j on control section i; α_{10} is the effect coefficient of the input of the upper reaches of initial section on source intensity of control section i.

Effect coefficient of source intensity accords with the decomposition reaction of the first order kinetics:

$$\alpha_j=\frac{1}{86.4(Q_0+q_j)}e^{-ktj} \qquad \beta_j=\frac{1}{86.4(Q_0-q_j)}e^{-ktj}$$

where, Q_{O3} is flow of the upper reaches at discharge ditch j (or water catchment), m^3/s; q_j is flow of discharge ditch j, m^3/s; k is overall decomposed coefficient of pollutants, 1/h; t is flow time of river water from discharge ditch j to calculated section, h.

The method of single step and the computer were adopted to analyze and calculate the above mentioned questions. According to the maximum permissible discharge and the predicted amount of pollutants in planning period, reduced demand and developable demand of pollutants at the discharge ditch can be estimated. First of all, the pollutants in industrial pollution sources should be reduced, and then the pollutants in municipla sewage can be concentrated and lowered if the reduced goal of the pollutants in industrial pollution sources can not be achieved. Moreover, the self-purification capacities should be fully utilized for the discharge ditches and streams with developable potentialities.

6 Water pollution control planning for the Taizi River watershed

6.1 A plan for the key industrial pollution sources

The guiding ideology of the planning was to excavate with the maximum limit the potentiality of reduced pollutants in industrial pollution sources under the conditions of a rational economy and practicable technology . Therefore, two kinds of planning methods had been determined, of which one adopted the method for dispersed planning to allot optimally the demand of reduced pollutants for water quality goal of the discharge ditches can control the key industrial pollution sources; the second adopted the method for a comparison between multiple options and objectives to screen out the treatment programs with a fine environmental benefit and lower treatment expense for water quality goal of the discharge ditches can not control the key industrial pollution sources.

According to the principles of pollution control planning, based upon multiple investigations and analysis, a few alternative treatment projects were initially provided and then optimally screened. The proposed projects in the short-term were divided into three classes according to their extent on water quality pollution.

Class 1: The projects, which will cause extremely serious effects on water quality in the watershed, urgently need to be treated in the short-term planning.

Class 2: The projects, which will cause relatively serious effects on water-quality, need to be treated in the short-term planning.

Class 3: The projects, which will cause certain effects on water quality in the watershed, need to be paid attention to in the short-term planning.

6.2 A plan for concentrated sewage treatment

Based on the determined environmental assimilative capacity of the reaches and the control planning of the pollution sources, the concentrated treatment was adopted for water pollution of the watershed and provided with systematization and rationalization for the transportation, treatment and discharge of sewage.

According to possibility, necessity and treatable analysis of the dam sewage, four dam sewage projects were determined through multiple studies with the departments for urban construction and urban planning. Based on the above works and practical survey, eight projects of concentrated sewage treatment were further provided. Those projects consist of remove nitrogen method, oxidation pond, primary and second treatment of sewage and land treatment and so on.

Qualitative policy-making for the combined projects adopted Hierarchical Analytical Process. The calculated results are listed as follows:

$A-D_1= 0.10127$

$A-D_2= 0.10127$

$A-D_3= 0.10659$

$A-D_4= 0.12261$

$A-D_5= 0.14313$

$A-D_6= 0.12274$

$A-D_7= 0.14206$

$A-D_8= 0.16032$——The optimum project

Projects 8, 5 and 7, which were three projects of relatively high weight values in the priority order of the combined projects determined by qualitative policy-making, were used as the alternative projects to carry out quantitative policy-making using matrix methods. The state variables were first estimated, and then the values of benefit and cost were calculated according to the above results. Finally, the policy-making was carried out using the expected value of the benefit and cost, of which results indicated that project 8 was the optimum project of the concentrated treatment.

According to the order of importance and urgency of environmental issues and saving financial resources, the classification and investment of the project in the combined projects were determined.

Class 1: The projects are extremely important and should be urgently invested in the short-term.

Class 2: The projects are obviously important and should be invested in the short-term.

Class 3: The projects are relatively important and may be considered to invest in the long-term.

6.3 Benefit-cost analysis of the project

Construction investment and operation and management expenses of the treatment projects are listed in Table 2, of which total construction investment is 901.4 million RMB Yuan.

Table 2 Cost analysis of water pollution control projects in the watershed

Areas	Planning period	Concentrated treatment		Key pollution sources		Total
		Investment of projects	Operation expenses	Investment of projects	Operation expenses	
Benxi	Short-term	94100000	8713300	99822000	—	
	Long-term	179772900	18730000	35900000	—	
Liaoyang	Short-term	31000000	2616700	54670000	—	
	Long-term	50461600	5050000	62780000	—	
Anshan	Short-term	73720000	4736700	147710900	—	
	Long-term	69530000	10570000	1936400	—	
Σ		498584500	—	402819300	—	901403800

The method for shadow price was adopted to set a price on the function of environmental protection in the water pollution control project. The direct benefit, which equals the investment of building a large reservoir of 1.2×10^{9} m^{3}, reaches 8.87×10^{8} RMB Yuan which was estimated by referring to the investment about the control expenses of total investment in the project of the Guanyingge Reservoir. According to the principle of public welfare and efficacy measure, the indirect benefit will be 1.25×10^{8} RMB Yuan. The direct and indirect benefit sum reach 10.12×10^{8} RMB Yuan.

7 Conclusion

The total benefit is more than the total expenses in the water pollution control project for the watershed, which is, therefore, economically rational and should be listed in " the blue water" plan of Liaoning Province. The project should be implemented as soon as possible by vigorously opening up a path of fund raising, which will be very valuable in improving environmental quality and alleviating lack of water resources.

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