A GREY SYSTEMS ANALYSIS OF WATER QUANTITY ALLOCATION AND QUALITY PROTECTION IN XIAMEN, CHINA

by

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B.Sc., Peking University, 1982

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
in the Department
of Geography

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SIMON FRASER UNIVERSITY

August 1991

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ABSTRACT

This study was designed to introduce the concepts of grey systems theory into water resources management as a means for accounting for uncertainty, and to conduct a grey systems analysis of the tradeoffs between meeting water quantity/quality objectives and maximizing economic income in the specific case of Xiamen, China.

The literature on water resource systems analysis was reviewed to arrive at an understanding of how water quantity and quality problems were analyzed and incorporated, how uncertainty was accounted for, and what cases have been studied in water quantity and quality management. The literature revealed that (1) previous studies of water quantity and quality management were related to river or lake basins, and none was about a canal basin with strict water quality requirements; (2) none of the studies in China combined both quantity and quality problems in an optimization framework; and (3) no previous study attempted to communicate uncertain messages directly into optimization processes and solutions.

This study has developed a grey linear programming (GLP) model for water quantity allocation and quality planning, and advanced a new solving approach which can effectively incorporate uncertain messages into the optimization framework. This method has been applied to water quantity and quality management in a water delivery canal in Xiamen, China. Results of the case study indicate that the derived decision schemes are feasible for the study area. When the canal water quality has precedence, the scheme for lower limit of objective function has to be adopted. Under this alternative, less cropping area, manure application and livestock numbers, and no fertilizer application are programmed. When agricultural income has precedence, the scheme for upper limit of

objective function can be adopted. Under this alternative, more cropping areas, manure application and livestock numbers, and some fertilizer application are programmed. Therefore, decision makers can adjust the grey decision variables (including cropping area, manure and fertilizer applications and livestock numbers) within their grey intervals according to the detailed situations.

Reliability of the method has been proved through sensitivity tests of the impacts of pollutant loss constraints on agricultural income, the costs of reducing pollutant losses, the impacts of water quantity constraints on agricultural income, and the effects of grey inputs on grey outputs.

ACKNOWLEDGEMENT

Completion of this study was only possible through the generous assistance of many individuals and agencies. My thanks are especially extended to Dr. R. Dan Moore, my supervisor, for his excellent supervision. No word can sufficiently express my thanks for his providing me kind guidance, assistance and encouragement.

I am deeply grateful to Dr. John T. Pierce for his insight and farsighted advices, and Dr. Hong-Quan Yang for his assistances and comments. Thanks are also due to Dr. S. Tuck Wong for his guidance and understanding.

I also thank Dr. Ian Hutchinson who has kept giving me assistance since I began the M.Sc. study.

Xiamen Research Institute of Environmental Protection (XRIEP) and Xiamen Environmental Protection Bureau (XEPB), Xiamen, China, were very instrumental in making the study a success and were at all time very supportive of my efforts. My thanks are especially extended to Ms. S. Sun, Dr. Z. Wu, Dr. Z. Liu, and Mr. C. Lin.

I am particularly grateful to the Department of Geography at Simon Fraser University for providing scholarships for my M.Sc. study. I also appreciate the support provided by Dr. Y. Yin for his critical evaluations and Mr. Y. Guo for his drafting assistance.

My wife, Chunling, and daughter, Wanzhi, are appreciated for their understanding.

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CHAPTER 1
INTRODUCTION

The objective of water resource management can be described in simplest terms as having the right amount of water available with the right quality for a particular use. Having too much, too little, or poor quality of water is poor management because too much water for a particular use will cause waste, too little may hinder socio-economic or ecological activities, and poor water quality will not be feasible for certain uses. Water uses include aesthetic and recreational uses, aquatic life habitat, domestic use, irrigation, and industrial use. Each of these uses has specific requirements for water quantity and quality.

Water resource systems are complex, because the supply of, demand for and quality of water can be affected by human, socio-economic, biophysical, and other indirect factors. There is often an insufficient supply of water to meet all demands, and some economic activities (e.g., farming, industry) can reduce the value of water for some uses. Therefore, water resource management normally involves decisions regarding the tradeoffs between the costs and benefits of alternative water allocation schemes and management of related economic activities.

Because of the complexity of water resource management, systems analysis methods have been applied with increasing frequency for identifying plans, policies or decision schemes that achieve to the greatest extent possible the needs, goals, and aims of those who plan, play for, and make use of, or are affected by water resources facilities and management plans. Systems analysis was defined as "techniques for applying the ways of thinking and working commonly used by scientists to the problems confronted by the decision makers in governments, businesses, and other institutions" (Rogers et al. 1978).

Over the past 30 years systems analysis applied to the planning and operation of water resource systems has "grown from a mathematical curiosity to a major specialty" (Rogers & Fiering 1986). Most of the systems analysis techniques were quantitative mathematical approaches, such as mathematical programming, dynamic programming, control theory, multivariate analysis, and simulation, which can incorporate all relevant variables into a mathematical expression, and their solutions may be directly related to practical problems. However, some systems analyses were qualitative, and no general mathematical expression was developed to incorporate all impact factors although quantitative methods may be used individually (e.g., Adiguzel and Coskunoglu 1984).

Table 1.1 shows a summary of literature review of water resource systems analysis. The table indicates that five types of analytical method were commonly used: (1) mathematical programming, including linear programming and nonlinear programming; (2) dynamic programming; (3) goal programming; (4) statistical techniques; and (5) game theory. Linear and nonlinear programming, dynamic programming and goal programming are analytical optimization techniques. They usually incorporate quantitative relationships to describe the interactions among variables of the system, and display an analytical structure which promotes the optimal solution. Linear and nonlinear programming are optimization methods for single objective and single stage decision making. They differ as to whether the relations between decision variables in objective functions and constraints are linear or nonlinear. Dynamic programming is an optimization technique which was commonly used for multistage or multilevel water resource decision making. Goal programming was used for the resolution of water problems involving multiple and conflicting objectives and for systematic investigation of various alternatives. Statistical techniques include multivariate analysis and inference (e.g., factor, principal component, and discriminant analysis). They

Table 1.1 Literature list of water resource systems analysis

		Research Focus													
		Water Quantity & Quality Management		Analytical Technique								Situation of Study Areas			
Year	Author	Quantity Manag.	Quality Manag.	Linear Progr.	Non-Linear Progr.	Dynamic Progr.	Goal Progr.	Statistical Techniq	Game Theory	Multi-Object. Progr.	Others	River Basin	Lake Basin	Agricultural System	Canal Basin
1955	Griffith	x						x				x			
1955	Maffitt	x						x				x			
1956	Ferguson	x	x								x			x	
1958	Wilcox	x	x					x						x	
1958	Krause		x					x			x	x			
1959	Leopold	x						x			x	x			
1960	Pavelis et al.	x		x											
1965	Wallis	x						x							
1968	Revelle et al.		x	x											
1968	Diaz et al.	x						x							

Table 1.1 (continued) Literature list of water resource systems analysis

Year	Author	Research Focus													
		Water Quantity & Quality Management		Analytical Technique								Situation of Study Areas			
		Quantity Manag.	Quality Manag.	Linear Progr.	Non-Linear Progr.	Dynamic Progr.	Goal Progr.	Statistical Techniq	Game Theory	Multi-Object. Progr.	Others	River Basin	Lake Basin	Agricultural System	Canal Basin
1968	Wallis	x						x							
1969	Stephenson	x		x										x	
1969	Butcher et al.	x				x									
1969	Rogers	x							x			x			
1970	Gisser	x		x								x		x	
1970	Young &Pisan	x			x										
1970	Cochr &Butch	x				x									
1971	Muspratt	x		x										x	
1971	Heidari	x				x									
1971	Morin et al.		x			x								x	

Table 1.1(continued) Literature list of water resource systems analysis

Year	Author	Research Focus													
		Water Quantity & Quality Management		Analytical Technique								Situation of Study Areas			
		Quantity Manag.	Quality Manag.	Linear Progr.	Non-Linear Progr.	Dynamic Progr.	Goal Progr.	Statistical Techniq	Game Theory	Multi-Object. Progr.	Others	River Basin	Lake Basin	Agricultural System	Canal Basin
1971	Anderson et al	x						x						x	
1972	Jacoby et al.	x		x								x			
1972	Graves et al.		x	x											
1972	Bargur	x				x									
1973	Zand et al.	x			x							x			
1973	Young et al	x		x										x	
1974	Mawer &Thorn	x				x								x	
1975	Taylor et al.	x								x					
1975	Heady &Nicol	x	x					x		x				x	
1976	Biswas	x		x											

Table 1.1 (continued) Literature list of water resource systems analysis

Year	Author	Research Focus: Water Quantity & Quality Management		Analytical Technique								Situation of Study Areas			
		Quantity Manag.	Quality Manag.	Linear Progr.	Non-Linear Progr.	Dynamic Progr.	Goal Progr.	Statistical Techniq	Game Theory	Multi-Object. Progr.	Others	River Basin	Lake Basin	Agricultural System	Canal Basin
1976	Hipel et al.	x							x						
1976	Goicoech et al	x								x		x			
1976	McBean	x								x					
1977	Hochm et al.		x	x								x			
1977	Narayana et al	x		x											
1977	Pratishthanada	x			x										
1977	Bishop		x				x								
1978	Potter et al.	x		x											
1979	Ciecka et al.		x					x					x		
1980	Duckstein		x							x			x		

Table 1.1 (continued) Literature list of water resource systems analysis

Year	Author	Research Focus													
		Water Quantity & Quality Management		Analytical Technique								Situation of Study Areas			
		Quantity Manag.	Quality Manag.	Linear Progr.	Non-Linear Progr.	Dynamic Progr.	Goal Progr.	Statistical Techniq	Game Theory	Multi-Object. Progr.	Others	River Basin	Lake Basin	Agricultural System	Canal Basin
1980	Haimes et al.	x						x		x					
1980	Guitjen et al.	x	x								x	x		x	
1981	Tubbs &Haith		x								x			x	
1981	Mandl	x	x	x										x	
1981	Guariso et al.	x						x						x	
1981	Stone	x		x								x			
1981	Rydzewsk et al	x		x										x	
1981	Bras et al.	x		x										x	
1982	Lindsay et al.	x		x										x	

Table 1.1 (continued) Literature list of water resource systems analysis

Year	Author	Research Focus													
		Water Quantity & Quality Management		Analytical Technique								Situation of Study Areas			
		Quantity Manag.	Quality Manag.	Linear Progr.	Non-Linear Progr.	Dynamic Progr.	Goal Progr.	Statistical Techniq	Game Theory	Multi-Object. Progr.	Others	River Basin	Lake Basin	Agricultural System	Canal Basin
1982	Long	x	x					x							
1982	Khan	x						x			x			x	
1983	Jenq et al.		x	x										x	
1983	Delwic &Haith		x								x			x	
1983	Greis	x						x				x			
1983	Chapra et al.		x					x					x		
1983	Ogg et al.		x	x										x	
1984	Haimes	x								x		x			
1984	Jenq et al.		x	x									x		
1984	Simonov et al		x					x						x	

Table 1.1 (continued) Literature list of water resource systems analysis

Year	Author	Research Focus													
		Water Quantity & Quality Management		Analytical Technique								Situation of Study Areas			
		Quantity Manag.	Quality Manag.	Linear Progr.	Non-Linear Progr.	Dynamic Progr.	Goal Progr.	Statistical Techniq	Game Theory	Multi-Object. Progr.	Others	River Basin	Lake Basin	Agricultural System	Canal Basin
1985	Clark	x	x					x							
1985	Burn & McBean		x								x			x	
1986	Graham et al.	x									x			x	
1986	Krzysztofowicz	x									x			x	
1987	Heatwo et al		x								x			x	
1987	Milon		x					x						x	
1987	Wenger &Rong		x								x			x	
1987	Haith		x					x			x			x	
1987	Su	x						x						x	
1987	Huete	x		x									x		

Table 1.1 (continued) Literature list of water resource systems analysis

Year	Author	Research Focus													
		Water Quantity & Quality Management		Analytical Technique								Situation of Study Areas			
		Quantity Manag.	Quality Manag.	Linear Progr.	Non-Linear Progr.	Dynamic Progr.	Goal Progr.	Statistical Techniq	Game Theory	Multi-Object. Progr.	Others	River Basin	Lake Basin	Agricultural System	Canal Basin
1987	Allam	x									x	x		x	
1987	Ormsbe et al.	x	x			x								x	
1988	Houghtal et al	x				x								x	
1989	Walker JF et al		x								x		x		
1989	Wood et al.	x						x						x	
1989	Walski et al.	x						x						x	
1989	Kessler &Sham	x		x										x	
1989a	Lansey et al.	x		x							x			x	
1990	Fujiwara et al.	x									x				
1990	Camera et al.	x									x		x		

have had numerous applications in aspects of water resource planning and decision making, primarily to describe recorded phenomena associated with river basin runoff and water quantity management. The purpose of game theory was mainly to establish a framework for water resource decision making under multiple criteria or under conflict. Among all these methods, linear programming was most commonly used because it is easier to be solved and its solutions are directly related to decision schemes (Gisser 1970; Hochman et al. 1977; Lindsay et al. 1982; Narayanan et al. 1977; Revelle et al. 1968). Methods of multiobjective programming were also developed (e.g., Haimes et al. 1980; Goicoechea et al. 1976).

A limitation inherent in many optimization methods is that only phenomena quantifitable by some standard (e.g. monetary value, and energy expenditure) can be included. Intangibles cannot be properly accounted for in mathematical programming frameworks. For example, in the systems analysis of water quantity and quality management of Little Bear River, North Utah, a mathematical programming model was employed to devise a plan that would provide maximum net benefits from water resource development and management, and would present specific recommended measures to be undertaken. However, many social benefits (e.g., public health, aestheletic benefits) of improving river water quality were excluded from the calculation of net benefit, because of the difficulty of quantifying these benefits (Hendricks, et al. 1970).

Previously, applications of systems optimization in water resources decision making mainly included (1) decision making of the trade off between environmental quality requirements and economic developments, and (2) decision making of the allocation of insufficient water supply for achieving maximum economic return. However, some studies have tried to combine both quantity and quality management in the optimization frameworks (e.g., Guitjens 1980; Mandl 1981; Long 1982; Ormsbee et al. 1987). However, all these previous studies were related to soil conservation or land use planning

(Heady and Nicol 1975; Karmeli 1978; Mandl 1981; Pizor 1984; Lauwaert 1985), and river or lake basin management (Guitjens 1980; Long 1982; Ormsbee 1987). None was about a canal, involving multiple uses, various human activities and strict water quality requirements, connected to a drainage basin.

In China only a few studies of water resource systems analysis have been conducted (Liu et al. 1985a). Of those related directly to decision-making, some focused on the qualitative analysis of multiobjective water resource development problems (Chen 1985; Hou et al. 1988; Liu et al. 1985b; Lo et al. 1985), while others were concerned with either quantity (Lou 1985; Liu et al. 1985b) or quality (Wang 1985) management. None analyzed the quantity-quality issues in an optimization framework.

Therefore, an optimization analysis of water quantity-quality problems of a canal basin would expand our knowledge of the complexities of water resource management and planning, and a case study in China, where high population density, overload utilization of natural resources, great quantities of agricultural nonpoint source pollutant losses, and serious water pollution problems are involved, would fill in the gap in the integration study of water quantity and quality management in China.

Water resources management has an important influence on agriculture, forestry, geography, watershed management, political science (water law and policy), economics, and sociology; and it has practical applications in structural design, water supply, waste-water disposal and treatment, irrigation, drainage, hydropower, flood control, navigation, erosion and sediment control, salinity control, pollution abatement, recreational use of water, fish and wildlife preservation, insect control, and coastal works. Because of the complicated nature of water resource management, we cannot have perfect knowledge of all relevant phenomena and their relationships. Uncertainties will be associated with the physical phenomena, socio-economic interactions, environmental response, pollutant effects on health, and other situations where our understanding is limited. The definition of uncertainty therefore is a phenomenon where the value of a specific realization is not known precisely.

In water resources systems analysis, problems of uncertainty can be divided into input data uncertainty, parameter estimation uncertainty, model specification uncertainty, and uncertainty of solution errors in simulation, impact assessment, and optimization models. The existence of uncertain messages can affect the systems analysis results and the formation of water policies and decisions. Therefore, quantifying these impacts is an important step toward a more robust decision making process.

Table 1.2 summerizes the literature on analyses of uncertainty in water resource systems. The table indicates that most previous studies of uncertainties in water resources systems analysis were related to simulations or impact assessments. Only a few tried to incorporate elements of uncertainties in optimization analyses for decision making (Burn and McBean 1985; Fontaine and Lesht 1987; Lansey 1989; Morgan 1983; Segerson 1988; Smith 1979). However, all of these previous studies employed uncertainty analysis methods which were unable to communicate uncertain messages directly into optimization processes and solutions, and none of them considered both quantity and quality problems in its uncertainty analysis framework.

Two problems therefore arise based on the above review:

(1) In water resource systems analysis, there have been very few studies trying to connect water quantity allocation with water quality protection in an optimization

Table 1.2 Literature list of water resource systems analysis under uncertainty

		Research Focus										
Year	Author(s)	Water Quantity & Quality Management		Area of Uncertainty Study				Situation of Study Areas				
		Quantity Management	Quality Management	Simulation	Impact Assessment	Optimization * A	Optimization * B	River Basin	Lake Basin	Agricultural System	Canal Basin	Others
1970	Upton		x	x			x					
1972	Thomas et al.	x					x					
1974	Bogardi et al.	x		x								
1974	Shamir	x					x			x		
1978	Kaynor	x					x	x				
1979	Goicoechea	x			x							
1979	Smith	x		x			x			x		
1981	Clark DA et al.	x		x								
1982	Duckstein et al.		x	x					x			

* A means that the optimization analyses can reflect uncertain messages into optimization processes and solutions; and B means that the optimization analyses cannot reflect uncertain messages into optimization processes and solutions.

Table 1.2 (continued) Literature list of water resource systems analysis under uncertainty

		Research Focus										
Year	Author(s)	Water Quantity & Quality Management		Area of Uncertainty Study				Situation of Study Areas				
		Quantity Management	Quality Management	Simulation	Impact Assessment	Optimization * A	Optimization * B	River Basin	Lake Basin	Agricultural System	Canal Basin	Others
1982	Finney et al.		x	x				x				
1982	Thomann		x	x								x
1982	O'neill et al.		x	x				x				
1982	Walker		x	x					x			
1982	Mahamah & Bhagat		x		x							
1982	Rao & Jessup		x	x						x		
1982	Chadderton et al.		x	x								
1982	Goicoechea et al	x			x							
1983	Morgan		x				x					

* A means that the optimization analyses can reflect uncertain messages into optimization processes and solutions; and B means that the optimization analyses cannot reflect uncertain messages into optimization processes and solutions.

Table 1.2 (continued) Literature list of water resource systems analysis under uncertainty

Year	Author(s)	Research Focus										
		Water Quantity & Quality Management		Area of Uncertainty Study				Situation of Study Areas				
		Quantity Management	Quality Management	Simulation	Impact Assessment	Optimization * A	Optimization * B	River Basin	Lake Basin	Agricultural System	Canal Basin	Others
1983	Spear & Hornberg		x	x				x				
1983	Reckhow		x	x					x			
1984	Dewey		x	x								
1984	Jaffe & Parker		x	x								x
1984	Huson		x	x								
1984	Fedra		x	x								x
1984	Haimes	x					x					
1985	Burn & McBean		x				x					

* A means that the optimization analyses can reflect uncertain messages into optimization processes and solutions; and B means that the optimization analyses cannot reflect uncertain messages into optimization processes and solutions.

Table 1.2 (continued) Literature list of water resource systems analysis under uncertainty

Year	Author(s)	Research Focus										
		Water Quantity & Quality Management		Area of Uncertainty Study				Situation of Study Areas				
		Quantity Management	Quality Management	Simulation	Impact Assessment	Optimization * A	Optimization * B	River Basin	Lake Basin	Agricultural System	Canal Basin	Others
1985	Dandy		x		x							
1986	Riboudo et al.		x		x							x
1986	Warwick & Cale		x	x				x				
1987	Fontaine & Lesht		x	x			x		x			
1988	Segerson		x	x						x		
1989b	Lansey et al.	x		x								
1990	Melching et al.	x			x			x	x			

* A means that the optimization analyses can reflect uncertain messages into optimization processes and solutions; and B means that the optimization analyses cannot reflect uncertain messages into optimization processes and solutions.

framework. Of these, no study has performed an analysis in a basin with an open water supply canal, involving multiple uses, various human activities, and strict water quality requirements, and no study in China combined both quantity and quality problems in an optimization framework. An optimization analysis of water quantity allocation and quality protection in such an area (canal basin, China) would therefore be helpful for fully understanding the complex nature of water resource management and planning in a basin-wide context.

(2) Uncertainty is a common problem in water resource management. However, most previous studies tended to pay attention to the uncertainties in simulations or impact assessments. Very few studies tried to consider uncertainties in optimization analyses, and none communicated uncertain messages directly into the optimization processes and solutions. Consequently, a study of an effective approach which can reflect uncertainties in optimization processes and solutions will be very important for sound water resources decision-making.

Therefore, the objective of this study is to do a grey systems analysis of water quantity allocation and quality protection under uncertainty in a canal basin in Xiamen, China. This objective entails:

(1) a systems analysis of the tradeoffs between meeting water quantity and quality objectives and maximizing economic income in the specific case of Xiamen. It will include: assessment of the factors that determine water quantity and quality management; examination of the conditions that can lead to maximum net income under the relevant constraints; identification of relationships between water quantity and quality considerations; and the formation of an optimal scheme for decision-making.

(2) introducing the concepts of grey systems theory into water resources management as a means for accounting for uncertainty. A grey linear programming (GLP) model will be developed and applied, which can incorporate elements of uncertainty within its optimization processes and solutions through the use of grey numbers and the concepts of topological space and state. These concepts will be presented in detail in Chapter 3. A new approach for solving the GLP model will also be advanced.

The remainder of this thesis is organized in six chapters. Chapter 2 will describe the regional geography of the study area. Chapter 3 will present the methodology, model construction, and the method of solution of a grey linear programming (GLP) model. A detailed discussion of the characterization of relevant coefficients and parameters in the model, including agricultural, economic, resource and environmental factors, based on the data from each basic division, is presented in Chapter 4. Chapter 5 will provide the results of optimization analysis, and examine the applicability of the derived decision schemes. Chapter 6 gives sensitivity analyses of the optimization analysis, including tests of impacts of pollutant loss constraints on agricultural income, costs of reducing pollutant losses, impacts of water quantity constraints on agricultural income, and the effects of grey inputs on grey outputs. The last chapter will be devoted to an appraisal of the new approach of water resource management, and some areas for further research will be suggested. Figure 1.1 shows a general flow chart of the research framework.

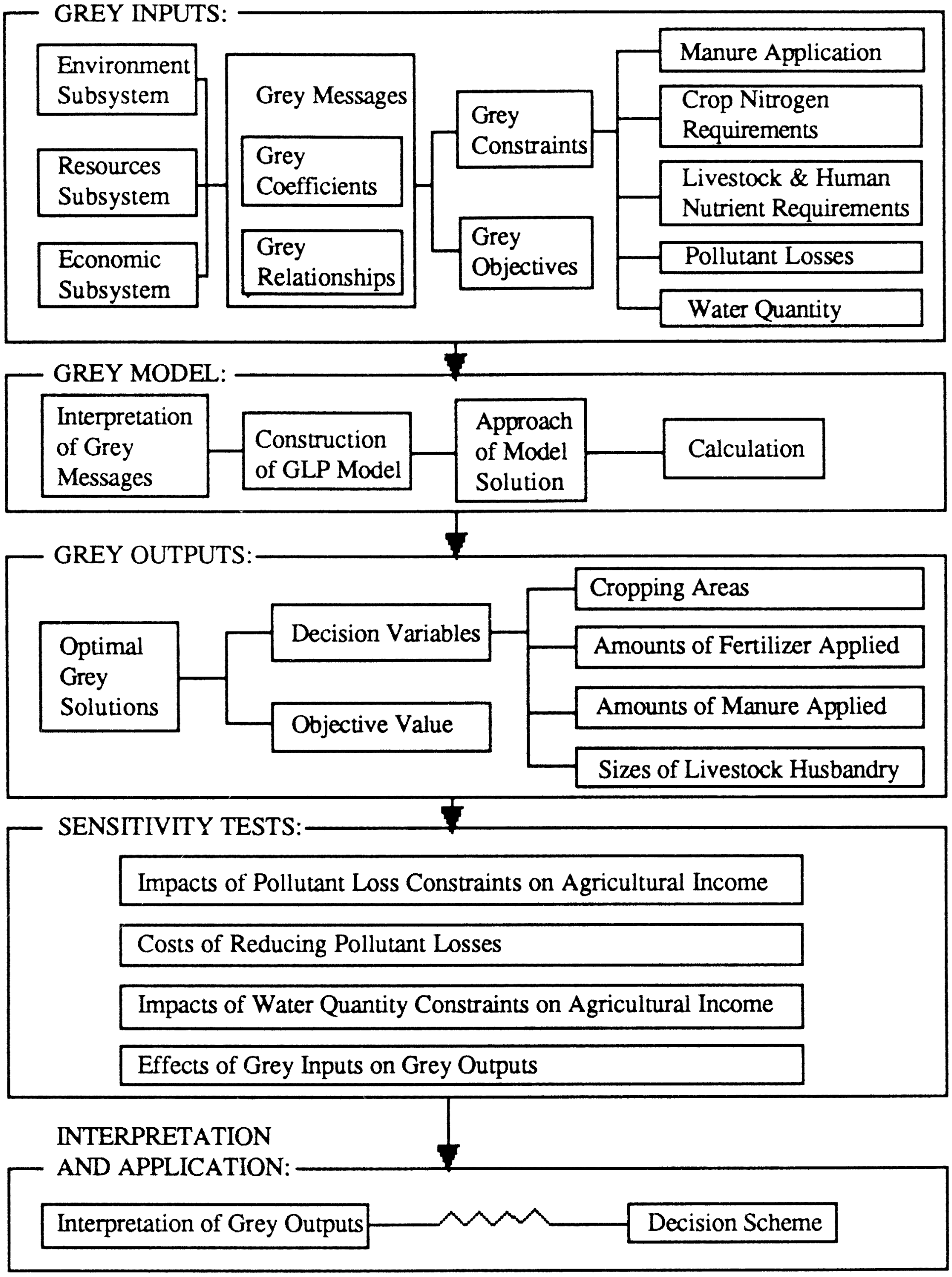


Figure 1.1 General flow chart of the research framework

CHAPTER 2
THE STUDY AREA

1. Xiamen Area (XA)

Xiamen Area is located in the southeast of Fujian Province, China. It is composed of Xiamen City (XC) and Xiamen Suburban Area (XSA), with an area of 754.7 km^2 (Figure 2.1).

(1) Xiamen City (XC)

Xiamen City is located on an island (130.2 km^2). It is one of the five special economic zones (SEZs) of China (the other four are Shenzhen, Zhuhai, Shantou and Hainan), and is the most important city in South Fujian Province.

The city became a SEZ in 1980, and has been developed on the basis of active foreign participation and run in ways different from the rest of the country. It has three special characteristics: first, its economy is mainly based on the free-market system; second, foreign investment is actively promoted, and has become the dominant source of investment within the city; and third, the city constitutes open systems of high technology and management skills and as such serves as China's nodal point for the transfer of technology (Jao and Leung 1986).

Industry, tourism, commerce and housing are the main functions of the city. The main industries are food, textile, chemical, mechanical, shipbuilding, building materials,

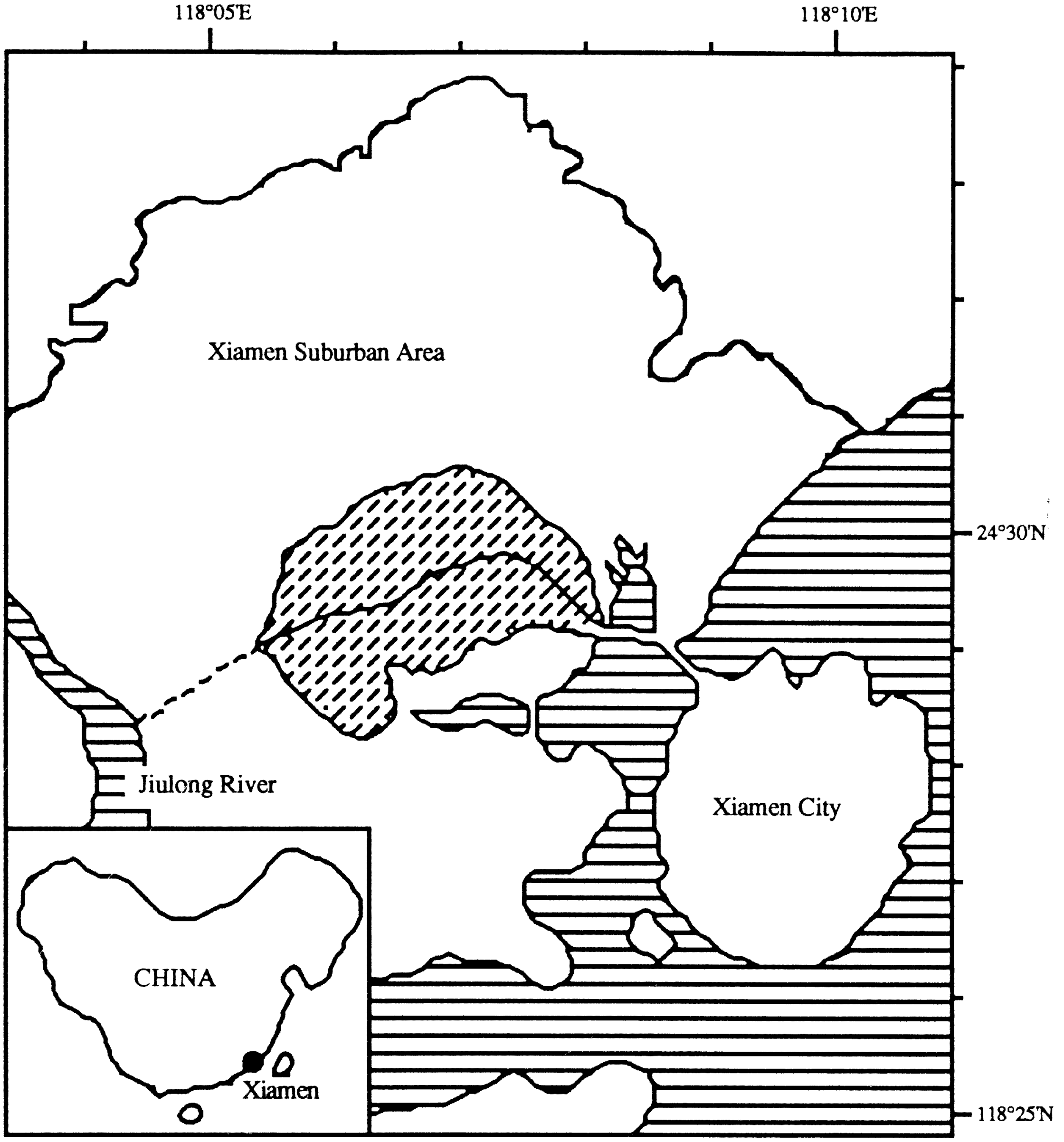


Figure 2.1 Xiamen City and Xiamen Suburban Area

pharmacy, printing, power, and electronic industries. Of them, food, textile, chemical, and electronic industries play a leading role. Since 1980, when the city became a SEZ, more than 800 foreign enterprises have invested in industries here, which brought about a great advance in the industrial economy. The gross value of industrial output in 1989 was about $7.80 billion, which is over 6 times that in 1980. Table 2.1 compares the gross values of industrial output of the four leading industries in 1980 and 1989 (XSB 1981 & 1990).

The city is the largest tourist centre in Southeast China. Mountains, islets, beaches, subtropical vegetation, and hot springs attract tourists from all over the world. About 1.5 million tourists visited the city in 1989 (XSB 1990).

Xiamen is also a commercial centre. Many trading corporations and shopping centres are distributed over the city. As an 'economic open city', it trades with many other countries based on a free-market system. The volume of import and export trades in 1989 was about $210 million (XSB 1990).

Along with the development of industry, tourism, and commercial activities, increasing requirements in both quantity and quality of housing has become a problem. About 400,000 to 600,000 m^2 of new floor area have been built per year since 1984. The average per capita housing floor area has been increased from about 6 m^2 in 1980 to about 10 m^2 in 1989. This floor area standard is comparatively higher than that of most other Chinese cities. In addition, thousands of new hotels, factories, office buildings and service buildings have been built since 1980 (XSB 1981 & 1990).

Table 2.1 Gross values of industrial output of the four leading industries in Xiamen City in 1980 and 1989

Leading Industries	Food	Chemical	Electric	Textile
1980 ($10,000)	26477	19772	18874	12882
1989 ($10,000)	82997	74652	345271	29339
Ratios (1989/1980)	3.13	3.78	18.29	2.28

(2) Xiamen Suburban Area (XSA)

The primary role of Xiamen Suburban Area (XSA) is to supply agricultural products to the Xiamen Area. Its area is 624.5 km^2. There are about 332 km^2 of tillable land (58.0% of the total area of XSA), including 203 km^2 of wet soil (rice soil) and 159 km^2 of dry soil, in the area. The main crops are rice, wheat, sweet potato, and vegetables (Liu et al. 1989).

Besides crop farming, livestock husbandry and fishery also contribute to the agricultural economy. The main livestocks are ox, sheep, pig and domestic fowls (chicken, duck, goose and turkey), and fishery production exists along the coastal zone in the south and east of the area (Liu et al. 1989).

In 1989, the gross value of agricultural output was about $229.28 million. Table 2.2 shows the agricultural output values of crop farming, livestock husbandry, and fishery in 1989, respectively. It demonstrates that crop farming contributed the most (62.1% of the gross value) to the agricultural economy. Livestock husbandry and fishery contributed only 24.8% and 9.5% of the gross value, respectively (GXSA 1990).

2. The Study Area

(1) Location and Division

The study area is situated in Xiamen Suburban Area, and the northwestward of Xiamen City (Figure 2.2). It is 6.5 km west of Jiulong River, which is the largest river in South Fujian Province. Its area is 143.7 km^2, containing three townships and a population

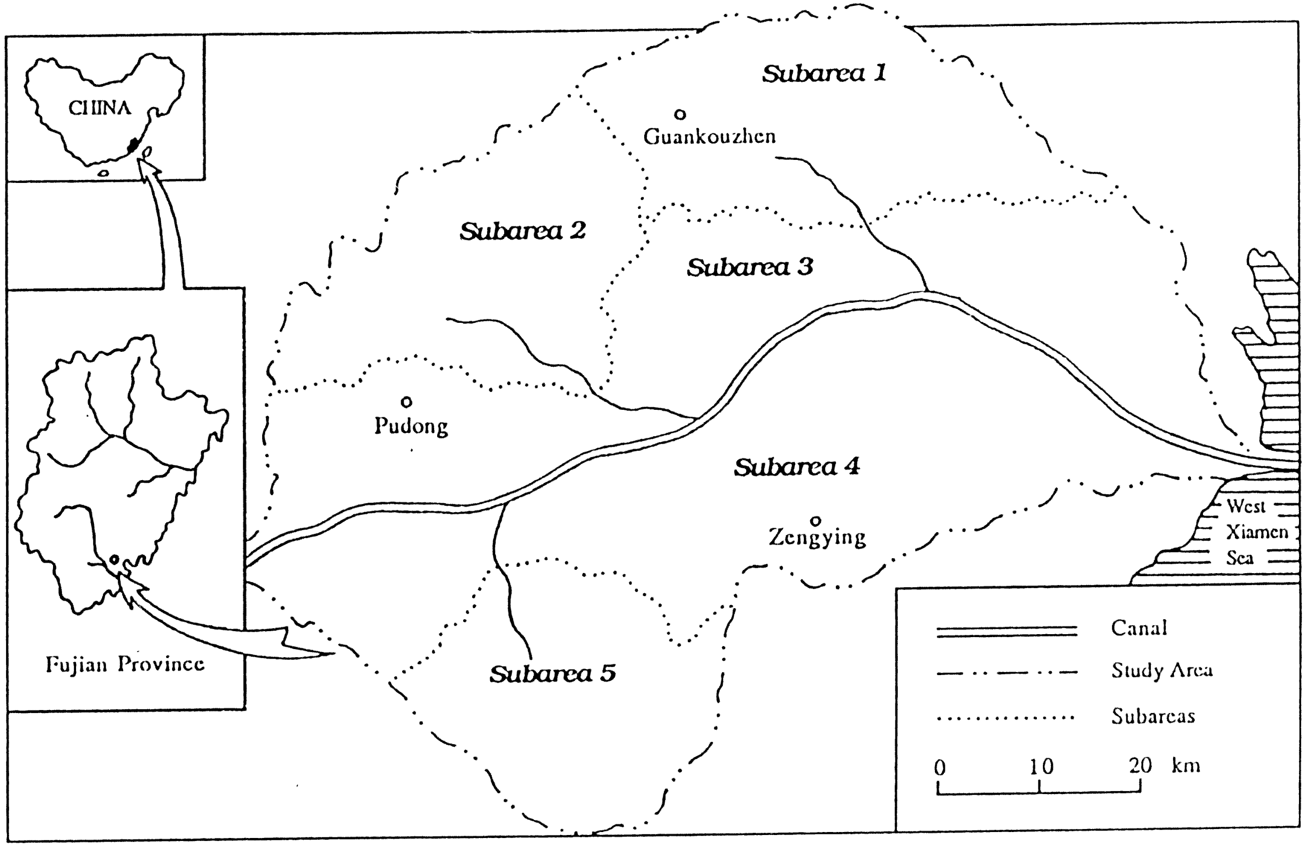


Figure 2.2 The study area

Table 2.2 Distribution of agricultural output values in Xiamen Suburban Area in 1989

Activities	GAOV*	Crop Farming	Livestock Husbandry	Fishery	Others
Output Values ($10,000)	22,928	14,242	5,687	2,181	818
Percentages (%)	100	62.1	24.8	9.5	3.6

* GAOV means gross agricultural output value;

of 32,400 (1989). The three townships are Xinglin, Guankou, and Dongfu. Their areas are 57.1, 48.6 and 38.0 km^2, respectively (GXSA 1990).

A water delivery canal stretches across the basin with a length of 23.2 km. It supplies water to Xiamen City for industrial, domestic and recreational water uses, and the basin area for agricultural irrigation. The water is pumped from Jiulong River, maintaining a constant flow of 12.5 m^3/s (D. Chen 1989).

The area is divided into five subareas with different ways of drawing water for irrigation and different soil-crop distributions. Subarea 1 is located in the north of the basin area, subarea 2 in northeast, subareas 3 and 4 stretch along the canal, and subarea 5 is in the south. Three ditches (subcanals) were built for transferring water to subareas 1, 2 and 5 because they are too far away from the canal (Liu et al. 1989; GXSA 1990).

(2) Natural Environment

A. Topography

The study area is a drainage basin. A water delivery canal, built upon a little river in the 1970's, flows through the basin westerly. Flat terraces are distributed over both sides of the canal.

On the north is a narrow strip of hilly and rocky lands of varying width, which are the extension of the hilly areas in the northwestern XSA. Elevations here are as high as 60 m above sea level. Immediately to the east, the relief becomes quite moderate. The elevations rarely reach over 20 m high. On the southeast, the terrain is generally rough and rocky, but unlike the north, there is no mountain here. The terrain in the western and southwestern boundaries of the basin area is generally mountainous. The highest peaks of the basin are located here with elevations ranging from 70 m to over 90 m. The highest peak (91.3 m) is Dongping Mountain (Xu et al. 1988).

B. Climate

Xiamen Area is located in the southern subtropics. It has a South-Subtropical Monsoon Type of Maritime Climate. The climate is generally warm and wet, with sufficient solar radiation, frequent monsoon, and highly varied precipitation (Tregear 1980).

(a) Air Temperature

Neither extremely hot summer nor cold winter is the general characteristic of air temperature in Xiamen Area. According to data from Xiamen Meteorological Observatory (XMO), the yearly average temperature in the area is 20.9 °C. The highest temperature in the period 1950-1989 was 38.5 °C (15th August, 1979), and the lowest 2.0 °C (12th February, 1959). January is the coldest month with an average temperature of 11.2 °C, and August the hottest, with an average temperature of 27.9 °C (XMO 1989 & 1990). Table 2.3 shows the temperature variation of Xiamen Area in 1985-1989 (XMO 1989 & 1990).

(b) Precipitation

Over the 1950-1989 period, the average annual precipitation in Xiamen Area was 1143.5 mm, ranging from 747.2 mm in 1954 to 1771.3 mm in 1973. Spatially, precipitation decreases progressively from southeast (coastal areas) to northwest (mountainous areas). Temporally, over 75% of annual precipitation falls from May to

Table 2.3 Temperature variation of Xiamen Area in 1985-1989 (°C)

Years	1985	1986	1987	1988	1989	Average
January	12.0	12.6	11.6	10.5	12.0	11.7
February	12.6	12.1	11.0	10.8	12.3	11.8
March	16.0	14.9	13.2	13.4	12.5	14.0
April	19.9	17.3	19.4	17.1	17.8	18.3
May	21.4	23.1	23.0	21.2	23.7	22.5
June	24.7	24.4	26.2	26.5	24.8	25.3
July	27.4	27.2	28.4	28.1	26.5	27.5
August	28.3	27.5	27.8	27.3	27.0	27.6
September	25.8	26.1	27.2	25.2	25.8	26.0
October	22.6	23.9	24.4	22.3	23.7	23.4
November	17.7	20.0	18.0	19.8	18.9	18.9
December	13.3	13.8	12.7	13.8	13.6	13.4
Yearly Average Temperature	20.1	20.2	20.2	19.7	19.9	20.0
Highest Temperature	36.7	35.7	35.1	37.0	36.7	36.2
Lowest Temperature	3.6	5.7	3.3	2.6	3.8	3.8

August (the wet season), while in the dry season (from September to April of the next year), precipitation is less than 25% of the annual value. Table 2.4 shows the monthly and annual precipitation of Xiamen Area in 1985-1989 (XMO 1989 & 1990).

(c) Wind

The prevailing wind direction in Xiamen Area is easterly. Northeast wind is most frequent between September and February, and east and southeast winds between March and August. The yearly average wind speed is 3.4 m/s. However, from July to September, the area is frequently affected by typhoon. Wind speed in the typhoon season can exceed 25 m/s. Table 2.5 shows the wind speeds and directions of Xiamen Area in 1985-1989 (XMO 1989 & 1990).

(d) Other Meteorological variables

The yearly average solar radiation intensity is 5300.4 MJm^{-2}, the average annual sunshine time is 2233.5 hours, and the average annual pan evaporation is 1910.4 mm. The yearly average air pressure is 1006.9 mb, maximum air pressure 1025.1 mb, and minimum 973.0 mb. The yearly average relative humidity is 77.0%, and absolute humidity 20.4 g/m^3 (XMO 1989 & 1990).

C. Soils and Vegetation

(a) Soils

Soils of South Fujian Province in general are Subtropical Udults and Ustults. They are high in iron and aluminum contents, and usually low in phosphorus and nitrogen

Table 2.4 Monthly and annual precipitation of Xiamen Area in 1985-1989 (mm)

Years	1985	1986	1987	1988	1989	Average
January	4.2	5.6	5.6	10.2	29.6	11.0
February	40.7	21.8	14.5	20.5	8.8	21.3
March	33.8	87.1	40.3	63.4	13.9	47.7
April	32.5	98.5	49.2	61.3	109.8	70.3
May	107.1	110.7	345.4	229.6	106.7	179.9
June	349.6	282.0	319.8	151.1	322.0	284.9
July	334.5	206.8	238.8	321.2	121.4	244.5
August	161.1	147.4	380.8	112.6	216.3	203.6
September	15.9	104.7	60.4	25.6	39.1	49.14
October	68.5	3.3	0.8	24.1	70.1	33.36
November	8.7	14.4	1.7	20.8	38.4	16.8
December	32.9	4.0	21.8	2.1	23.7	16.9
Annual Precipitation	1189.5	1086.3	1479.1	1042.5	1099.8	1179.4
Rainy Days (Day)	153	157	164	133	132	148

Table 2.5 Wind speeds and directions of Xiamen Area, 1985-1989

Years	1985	1986	1987	1988	1989
Average Wind Speed (m/sec)	3.9	3.7	3.8	3.7	3.5
Maximum Wind Speed (m/sec)	27.0	22.1	24.3	19.1	17.7
Most Frequent Wind Direction	E	E	E	E	E
Second Frequent Wind Direction	ENE	NE	SSE	NE	ENE

contents (Tregear 1980). According to a general survey of agricultural resources and productions, there are mainly four kinds of farming soil in Xiamen Area. They are rice soil, solonchak, sandy loam, and loam (XASI 1989).

Solonchak soils are rare in the study area. They are scattered along coastal zones, and rather poor for cultivation. Rice soil, sandy loam, and loam are distributed over most of the basin area, especially the flat terraces beside the canal. Some of them are the best agricultural soils in Xiamen Area.

The agricultural soils can be generally classified into two categories: dry soil and wet soil. Solonchak, sandy loam, and loam are dry soils, where wheat, sweet potato and vegetables are planted. Rice soil is the wet one, including two types: salinized and permeable rice soils (XASI 1989).

(b) Vegetation

The primeval regional vegetations in the Xiamen Area were classified as South Fujian Wet-Hot Subtropical Rainforest (Tregear 1980). The primeval forests have vanished as a result of human activities over thousands of years. The present forests are human-made or secondary. They can be classified into six categories: evergreen broadloaf forest, evergreen conifer forest, mixed forest, economic forest, mangrove forest, and bush/grass (Lin and Lu 1988).

There are 114 families, 292 genus, and 708 species of vegetation in Xiamen Area. They are composed of over 400 species of arbors, over 200 species of bushes, and nearly 100 species of herbs (Lin and Lu 1988). However, crops, including rice, wheat, sweet potato and vegetables, are the dominant vegetation in the study area (canal basin). A very small area in the west is occupied by forests extending from the northwestern mountain forests of XSA.

D. Hydrology

(a) Land

The water delivery canal is a major hydrological entity in the study area. It stretches across the area with a length of 23.2 km. The water is pumped from Jiulong River, maintaining a constant flow of 12.5 m^3/s (D. Chen 1989). Jiulong River is the largest river in southern Fujian Province. Its drainage area is 13000 km^2, and annual runoff 12 billion m^3. Its average annual flow is 259.7 m^3/s, maximum 1230 m^3/s, and minimum 37.3 m^3/s (JRHS 1989; Chen, D. 1989).

Groundwater is scarce in the area, and highly affected by marine water. Its chemical characteristic is Coastal Cl-Na type with high salt content, and it is not suitable for drinking or irrigation (Xu 1988).

There are two reservoirs, namely Xinglinwan Reservoir and Maluanwan Reservoir, near the study area. They were built upon little gulfs for fishery and salt production in the 1950's. The contents are seawater.

(b) Marine

The study area is near both West Xiamen Sea (WXS) and East Xiamen Sea (EXS). WXS is situated south of the area. It has an area of 52 km^2 and depths of 6-25 m. EXS lies east of the study area. It has an area of 42 km^2 and depths of 5-10 m. The sea areas are all located in the inner gulf where wave power is minimal.

The tidal pattern is semidiurnal. The highest tide height is 4.53 m, and the lowest -3.30 m. The average height of high water is 2.39 m, and that of low water -1.53 m. The average sea level in the Xiamen Area is -0.32 m (Chen et al. 1987).

(3) Social Environment

A. Population and Settlement Features

The total population of Xiamen Area in 1989 was 0.84 million with 0.71 million in Xiamen City and 0.13 million in Xiamen Suburban Area (XSB 1990). The study area, situated in XSA, has a population of about 32,480, with 12,090 in Xinglin Township, 10,730 in Guankou, and 9,660 in Dongfu. This population is only 3.86% of that of Xiamen Area, but its area amounts to 19.0%.Therefore, the population density of the area (226 /km^2) is lower than that of Xiamen Area (1,110 /km^2), and much lower than Xiamen City (5,470 one/km^2). Among the three townships, Dongfu is the most densely populated (254 /km^2) followed by Guankou (221 /km^2). Xinglin has the lowest population density (212 /km^2). However, their differences are very little (less than 42 /km^2).

The yearly average population growth rate of the study area in 1989 is 14.38 per thousand population, which is higher than that of Xiamen Area (12.91 per thousand population). Table 2.6 shows the population distribution and growth rate of Xiamen Area in 1989 (XSB 1990).

There are only three small towns, namely Zengying, Guankouzhen and Pudong, in the study area. They are the capitals of Xinglin, Guankou and Dongfu Townships,

Table 2.6 Population distribution and growth rate of Xiamen Area in 1989

Areas*	XA	XC	XSA	Study Area	Xinglin	Guankou	Dongfu
Population in 1988 (10^3)	831	704	127	31.94	11.91	10.56	9.49
Population in 1989 (10^3)	841	712	129	32.41	12.09	10.73	9.66
Percentages in 1989 (%)	100	84.66	15.34	3.86	1.44	1.28	1.14
Population Density in 1989 (10^6/km^2)	1.11	5.47	0.207	0.226	0.212	0.221	0.254
Growth Rate in 1988-89 (‰)	12.03	11.36	15.75	14.72	15.11	16.10	17.91

* XA means Xiamen Area; XC means Xiamen City; and XSA means Xiamen Suburban Area.

respectively. Their importances lie in their acting as trading centres for agricultural products.

Thirty-two villages are scattered throughout the area. Among them, 13 villages are in Xinglin Township, 10 in Guankou, and 9 in Dongfu. Table 2.7 shows the population distribution of the towns and villages in the study area (GXSA 1990).

B. Agriculture

Crop farming is the primary activity in the study area. Farmlands are distributed throughout the area. There are 98.35 km^2 of tillable land in the study area, 38.51 km^2 in Xinglin, 32.43 km^2 in Guankou, and 26.91 km^2 in Dongfu. Table 2.8 shows the farmland distribution in Xiamen Suburban Area (GXSA 1990).

According to data from the Government of Xiamen Suburban Area (GXSA), the major crops are rice, wheat, sweet potato (camote), and vegetables. Vegetables grown in the area include cabbage, Chinese cabbage, carrots, onions, bean, pepper, soybean, tomato, and rape. Rice, the main crop, is grown on rice soils distributed all over the area except the mountainous west. The area of rice soil is 41.9% (41.19 km^2) of that of tillable soil in the study area. The rice yield was 14.39 million kg with an output value of $5.91 million in 1989 (GXSA 1990).

The other crops are grown on dry soils, and all have lower yields and output values than rice. The yields of wheat and sweet potato were 3.91 and 6.99 million kg, and their output values were $1.92 million and $2.10 million in 1989, respectively.

The output value of vegetables was $8.33 million in 1989. In 1989, 97.7% (96.09 km^2) of the tillable land was cultivated, and 95.0% irrigated, which suggests that

Table 2.7a Population distribution of Xinglin Township in 1989

Villages	Population (1,000)	Area (km^2)	Population Density ($1,000/km^2$)
Zengying Town	2649	6.2	427.3
Waizhai	698	2.9	240.7
Zhaishang	908	4.6	197.4
Kechu	1011	6.0	168.5
Guochu	532	3.2	166.3
Weiying	682	3.4	200.6
Sitong	927	5.0	185.4
Sizhuang	638	2.2	290.0
Dianhou	729	4.1	177.8
Hubian	431	2.5	172.4
Binnei	1020	5.3	192.5
Aoguang	766	3.9	196.4
Tiandian	552	4.1	134.6
Shengtao	450	3.7	121.6

Table 2.7b Population distribution of Guankou Township in 1989

Villages	Population (1,000)	Area (km^2)	Population Density (1,000/km^2)
Guankouzhen Town	2041	6.1	334.6
Koutie	1175	4.2	279.8
Fangzhuang	973	3.8	256.1
Guokeng	595	2.9	205.2
Shuikou	967	4.3	224.9
Huxi	602	4.3	140.0
Luoxi	1087	5.0	217.4
Qianxi	545	2.5	218.0
Shipu	952	3.9	244.1
Weichun	884	5.7	155.1
Shanqian	909	5.9	154.1

Table 2.7c Population distribution of Dongfu Township in 1989

Villages	Population (1,000)	Area (km^2)	Population Density (1,000/km^2)
Pudong Town	2159	5.2	415.2
Yingchun	636	2.8	227.1
Fengdan	1190	3.4	350.0
Waiyang	792	2.3	344.3
Laizhai	845	5.0	169.0
Shunchun	652	3.6	181.1
Qianzhen	809	4.7	172.1
Qitou	675	4.1	164.6
Biangou	1023	4.3	237.9
Tianli	877	2.6	337.3

Table 2.8 Farmland distributions in Xiamen Suburban Area (XSA)

Areas	XSA	Study Area	Xinglin	Guankou	Dongfu
Farmland Area (km^2)	362.1	98.35	38.51	32.43	26.91
Percentage (%)	100	27.16	10.64	8.96	7.43
Percentage of Total XSA Area (%)	58.0	15.75	6.17	5.19	4.31

agricultural land use is very intensive in the area. Table 2.9 shows the crop farming achievements of the study area in 1989 (GXSA 1990).

Animal husbandry is the secondary activity of the area. Table 2.10 shows the livestock husbandry achievements in 1989. It indicates that the main livestocks are ox, sheep, pig, and domestic fowls. Ox contributed the most in the output value of animal husbandry although domestic fowls had the highest yield (GXSA 1990).

C. Traffic

Traffic conditions are efficient in the study area, benefiting from the advanced traffic network in Xiamen City. Ying-Xia Railway (from Xiamen to Yingtan, Jiangxi Province), Fu-Xia Highway (from Xiamen to Fuzhou, Fujian Province), and Zhang-Xia Highway (from Xiamen to Zhangzhou, Fujian Province) all go through the area. All towns and villages are linked up by railway, highways or roads (XSB 1990).

(4) Water Quantity and Quality Problems

Since crop farming is the primary activity of the study area, agricultural production needs water for crops to grow and generates nonpoint source pollutants by fertilizer and manure applications. Therefore, water quantity and quality problems arise.

A. Water Quantity Problem

Xiamen City needs about 8.4 m^3/s of water for industrial (5.4 m^3/s), domestic (3.0 m^3/s), and recreational (0.001 m^3/s) water uses. These demands must be satisfied

Table 2.9 Crop farming achievements of the study area in 1989

Crops	Farmland Area		Average Yields (10^3 tonne /km^2)	Total Yields (10^3 tonne)	Output Value	
	Area (km^2)	% of Total Area			Values (10^6 ¥)	% of Total Value
Rice	41.11	41.80	0.350	14.39	5.91	31.66
Wheat	21.78	22.15	0.180	3.91	1.92	10.28
Vegetables	11.69	11.89	1.549	18.11	8.33	44.62
Sweet Potato	21.19	21.55	0.330	6.99	2.10	11.25
Others	0.32	0.33	/	/	0.41	2.20

Table 2.10 Livestock husbandry achievements of the study area in 1989

Livestock	Yield (10^3)	Output Value (10^6 ¥)	Percentage (%)
Ox	5.80	8.60	26.22
Sheep	7.25	0.76	4.63
Pig	12.82	6.03	62.99
Domestic Fowl	101.20	0.98	5.98
Others	/	0.03	0.18

according to the Water Management Regulation of Beixi Canal (GXSA 1987). This is based on two considerations. First, the main function of the canal was designed to supply drinking water to Xiamen City when it was built in the 1970's. Second, the output value per m^3 of water consumption in Xiamen City (¥ 29.44/m^3) is over 70 times that in the study area (¥ 0.41/m^3) in 1989, which indicates that it is more efficient to supply sufficient water for Xiamen City than for the study area.

After the demands in Xiamen City are met, the remaining 4.1 m^3/s (include evaporation loss) is not sufficient for agricultural production in the basin area. Some farmers draw water from the canal wantonly for agricultural uses, which sometimes (in dry seasons) can produce water shortages in Xiamen City. Therefore, the first problem is how to solve the conflict between limited water supply and the increasing water demand for agricultural development.

Since the 1980's, studies of water quantity management in the study area have been conducted by local and national institutions because water supply is an important prerequisite for the development of Xiamen Special Economic Zone (D. Chen 1989; Jao and Leung 1986). Xiamen Hydrographic Station has observed the canal flow for many years. Xiamen Hydraulic Bureau has conducted some measures to reduce soil and sand sedimentation, and to increase canal flow (D. Chen 1989). Xiamen Agricultural Bureau has made some regulations of canal water uses (XAB 1989). However, no study dealt with a systems analysis of water quantity allocation for agricultural irrigation in the basin area.

B. Water Quality of the Canal

XEMS has monitored water quality of the canal six times per year (twice in June, October and December, respectively) regularly since 1980. Water samples were taken between 11:00 to 12:00 AM. Five monitoring stations were set up (Fugure 2.3), and over ten chemical items monitored.

Tables 2.11 to 2.14 (see Appendix V) show the monitoring results of the canal water quality in 1989, and Tables 2.15 to 2.18 (see Appendix V) are their WQIs (water quality indices). WQI is a comparison of water quality with the SDWS. WQI = C/P, where C is pollutant concentration, and P is the SDWS of the pollutant. When WQI < 1, the pollutant concentration can meet the SDWS, and WQI > 1 means that the concentration exceed the SDWS. Fugure 2.4 (see Appendix V) shows pollutant concentrations, and Fugure 2.5 (see Appendix V) shows the distribution of the WQI values (Sun et al. 1990).

The results indicate that the canal water quality deteriorates as the water flows through the basin area. The yearly average NO_3^--N concentrations (Table 2.14) increase from 0.45 mg/l in Station 1 (source) to 0.99 mg/l (2.2 times of that in Station 1) in Station 5 (canal outlet); NO_2^--N concentrations increase from 0.013 mg/l in Station 1 to 0.069 mg/l (5.3 times of that in Station 1) in Station 5; NH_3-N concentrations increase from 0.13 mg/l in Station 1 to 0.53 mg/l (4.1 times of that in Station 1) in Station 5; and Total Phosphorus concentrations increase from 0.005 mg/l in Station 1 to 0.038 mg/l (7.6 times of that in Station 1) in Station 5. Other pollutants have similar trends. The results indicate that the canal basin, where nonpoint source pollutants are discharged from agricultural production, has the main responsibility for the deterioration of canal water quality.

Station 1 has the best water quality (all pollutant concentrations can meet the SDWS), followed by Station 2 (most of pollutant concentrations can meet the SDWS in October and December). Most of the higher concentrations are found at Stations 4 and 5. Station 4 has the highest concentrations of NO_3^--N (1.11 mg/l, WQI = 0.11) and NO_2^--N (0.091 mg/l, WQI = 4.55), followed by Station 5 (NO_3^--N and NO_2^--N concentrations are 0.99 mg/l (WQI = 0.10) and 0.069 mg/l (WQI = 3.45), respectively); Stations 3 and 5

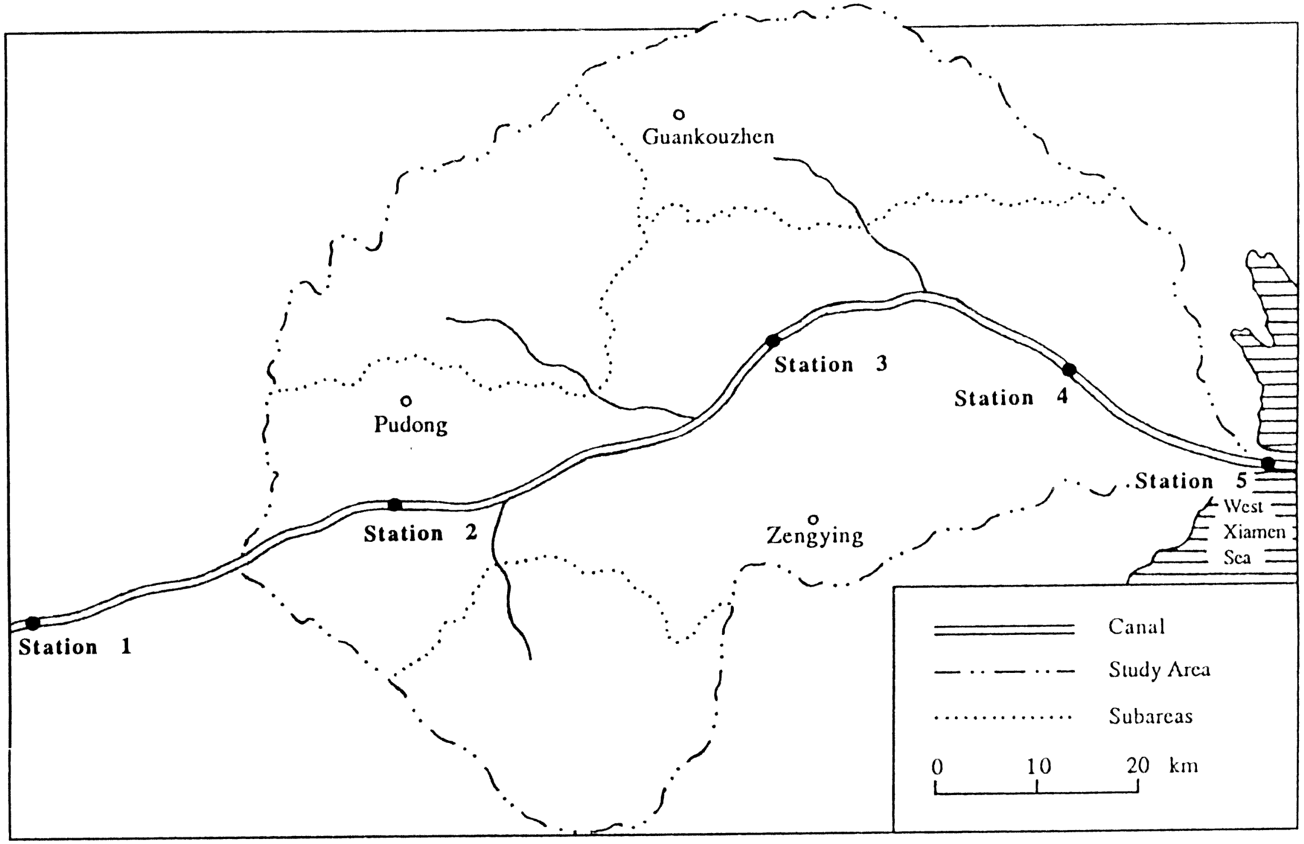


Figure 2.3 Distribution of canal water quality monitoring stations

have the highest NH_3-N concentrations (0.66 mg/l (WQI = 3.30) and 0.53 mg/l (WQI = 2.65), respectively); and the highest Total Phosphorus concentrations are found at Station 5 (0.038 mg/l, WQI = 1.90) and 4 (0.029 mg/l, WQI = 1.45). The results indicate that water quality is worst near the canal's outlet (NO_2^--N, NH_3-N and Total Phosphorus concentrations greatly exceed the SDWS).

The major pollutants are NO_2^--N and NH_3-N, followed by Total Phosphorus. The yearly average concentrations of NO_2^--N and NH_3-N at Station 2, 3, 4 and 5 all exceed the SDWS, and their yearly average WQIs at Station 3, 4 and 5 all exceed 2.0. The yearly average Total Phosphorus concentrations at Station 3, 4 and 5 also exceed the SDWS (WQI > 1.0). Nitrogen compounds can hardly be treated by waterworks, and excessive nitrogen can cause health effects (i.e., methaemoglobinaemia). Therefore, high nitrogen concentration at the canal's outlet is a very serious problem facing the government.

Water quality in June is much worse than in October or December. In June, NO_2^--N, NH_3-N and Total Phosphorus concentrations at Station 2, 3, 4 and 5 all exceed the SDWS. At Station 5, WQI of NO_2^--N is 8.45, that of NH_3-N is 6.10, and that of Total Phosphorus is 2.55. The results demonstrate serious pollution problem in this season (wet season).

In October, NO_2^--N concentrations exceed the SDWS at Station 4 (0.023 mg/l, WQI = 1.15) and 5 (0.027 mg/l, WQI = 1.35); NH_3-N concentration exceed the SDWS at Station 2 only (0.302 mg/l, WQI = 1.51); and Total Phosphorus concentrations exceed the SDWS at Station 4 (0.034 mg/l, WQI = 1.70) and 5 (0.038 mg/l, WQI = 1.90). The lower WQI values and less stations with high pollutant concentrations indicate better water quality in this season.

In December, NO_2^--N concentrations reach the SDWS at Station 4 (0.020 mg/l, WQI = 1.00) and meet the SDWS at other stations; NH_3-N concentrations exceed the

SDWS at Station 4 (0.401 mg/l, WQI = 2.01) and 5 (0.220 mg/l, WQI = 1.10); and Total Phosphorus concentrations exceed the SDWS at Station 3 (0.030 mg/l, WQI = 1.50) and 5 (0.025 mg/l, WQI = 1.25). The results are comparable to those in October. The reasons of the above temporal variance of water quality are that in wet season (June), greater runoff and soil loss can carry more pollutants from croplands to the canal.

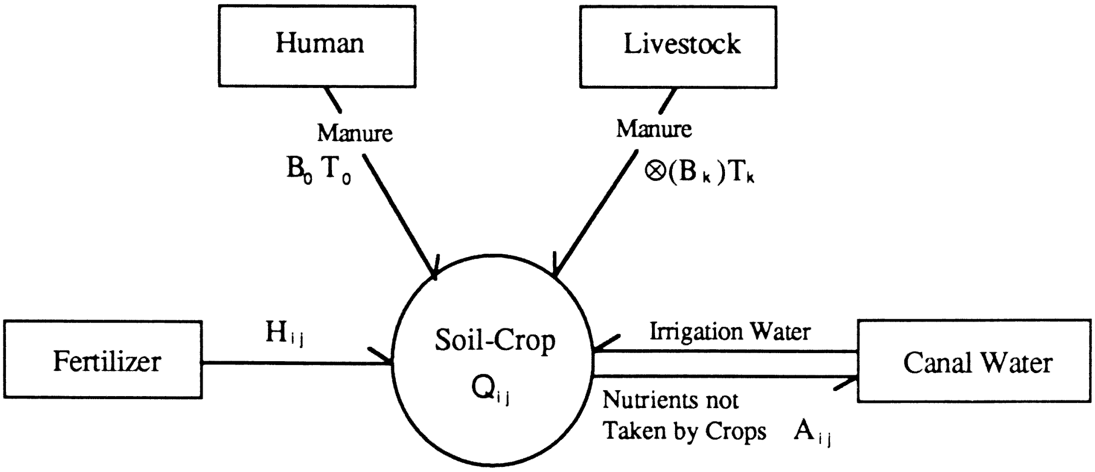
C. Water Quality Problems

Since a large amount of fertilizer and manure is spread on the croplands every year, agricultural nonpoint source pollutants (mainly nitrogen and phosphorus) can enter the canal through a number of dispersed and often poorly defined drainage paths.

Nonpoint source losses of soil, nitrogen and phosphorus are due to land erosion and the wash away of unused nutrients from fertilizers and manures. Since crops need nitrogen and phosphorus for growth, farmers usually supplement the natural sources of these nutrients in the soil with fertilizer and manure applications. The applied nutrients, not taken up by crop as "wastes", can leave crop land through runoff and percolation. Both nitrogen and phosphorus may move with runoff in dissolved forms or in solid-phase or particulate forms associated with the canal sediments. Dissolved nutrients can also be transported by percolation. Therefore, the canal water quality is closely related to fertilizer and manure applications in the canal basin. Table 2.19 and Fugure 2.6 show the relations between the amounts of fertilizer and manure spread and yearly average nitrogen and phosphorus concentrations at the canal's outlet during 1987-1989. It is indicated that as the amount of manure spread increased from 2.08×10^6 tonnes in 1987 to 2.96×10^6 tonnes and 2.51×10^6 tonnes in 1988 and 1989, nitrogen and phosphorus concentrations increased correspondingly (the average nitrogen content of manure is 7.5 kg/tonne, and manure was applied to supply most of crop nitrogen requirement in the study area). NO_3^--

Table 2.19 Amounts of manure and fertilizer spread in the canal basin and yearly average nitrogen and phosphorus concentrations at the canal's outlet during 1987-1989

Year	Amounts of manure Spread (10^6 tonne)	Amounts of fertilizer Spread (tonne)	NO_3^--N Concentration (mg/l)	NO_2^--N Concentration (mg/l)	NH_3-N Concentration (mg/l)	Total Phosphorus (mg/l)
1987	2.08	3.71	0.89	0.039	0.48	0.031
1988	2.96	3.66	0.96	0.038	0.48	0.032
1989	2.51	3.92	0.99	0.069	0.53	0.038



Where:

$$\sum_i \sum_j A_{ij} = \sum_i \sum_j [(1 - p)(H_{ij} + r \sum_k (\otimes(B_k)T_k) + r B_0 T_0) - Q_{ij}]$$

H_{ij} = the fertilizer nitrogen applied to soil i planted to crop j;
r = nitrogen content of manure;
$\otimes(B_k)$ = the amount of manure discharged by livestock k;
T_k = the numbers of livestock k in the study area;
B_0 = the amount of manure discharged by human;
T_0 = the number of man in the study area;
Q_{ij} = the nitrogen requirement of crop j on soil i;
p = the percent of the applied nitrogen lost to the atmosphere because of ammonia volatilization and denitrification;
i = the type of soil;
j = the type of crop;
k = the type of livestock.

Figure 2.6 Relations between manure and fertilizer applications and the canal water quality

N concentrations increased from 0.89 mg/l in 1987 to 0.96 mg/l in 1988 and 0.99 mg/l in 1989, NO_2^--N concentrations increased from 0.039 mg/l in 1987 to 0.069 mg/l in 1989, NH_3-N concentrations increased from 0.48 mg/l in 1987 to 0.53 mg/l in 1989, and Total Phosphorus concentrations increased from 0.031 mg/l in 1987 to 0.032 mg/l in 1988 and 0.038 mg/l in 1989. Although the amount of manure spread in 1989 was less than that in 1988, nitrogen and phosphorus concentrations in 1989 were higher than those in 1988, possibly because some unused nitrogen and phosphorus from fertilizer and manure applied after the wet season of 1988 could also be washed away and contribute to the canal water pollution in the wet season of 1989.

Table 2.20 shows the relations between the amounts of fertilizer and manure spread and crop yields in the study area during 1987-1989. It is indicated that as the amount of manure spread increased from 2.08×10^6 tonnes in 1987 to 2.96×10^6 tonnes and 2.51×10^6 tonnes in 1988 and 1989, yields of rice, wheat, and vegetables increased correspondingly. rice yields increased from 13.51×10^3 tonnes in 1987 to 14.27×10^3 tonnes in 1988 and 14.39×10^3 tonnes in 1989, wheat yields increased from 3.80×10^3 tonnes in 1987 to 3.91×10^3 tonnes in 1989, and vegetable yields increased from 16.09×10^3 tonnes in 1987 to 18.11×10^3 tonnes in 1989. The only exception was sweet potato. Its yields decreased from 7.10×10^3 tonnes in 1987 to 6.93×10^3 tonnes in 1988 and 6.99×10^3 tonnes in 1989.

High nitrogen and phosphorus concentrations can lead to eutrophication of water. In addition, nitrogen, in the form of nitrates such as NO_3^--N, NO_2^--N, and NH_3-N, can contaminate water and make them unsafe for drinking. According to data from Xiamen Environmental Monitoring Station (Sun et al. 1990; Huang, et al. 1988), water quality at the canal's upper reach accords with the Standards for Drinking Water Sources (SDWS) issued by Xiamen Environmental Protection Bureau (XEPB 1988), while that at the canal's outlet does not meet with the standards. Concentrations of some pollutants (NO_2^--N,

Table 2.20 Amounts of manure and fertilizer spreads and crop yields in the canal basin during 1987-1989

Year	Amounts of manure Spread (10^6 tonne)	Amounts of fertilizer Spread (tonne)	Crop Yields			
			Rice	Wheat	Vegetables	Sweet Potato
1987	2.08	3.71	13.51	3.80	16.09	7.10
1988	2.96	3.66	14.27	3.82	17.82	6.93
1989	2.51	3.92	14.39	3.91	18.11	6.99

NH_3-N, BOD, and COD) increase progressively along the canal, and greatly exceed the SDWS at the canal's outlet. Therefore, the main responsibility of water pollution is the discharge of agricultural nonpoint source pollutants from the canal basin.

In recent years, many measures, such as setting regulations, cutting down fertilizer disposal, and soil/water conservation practices, have been conducted. However, pollution overload still remains. It is also impossible to construct a new canal or pipe network in the future as the distance is long and the investment is costly (D. Chen 1989). Therefore, the problem is a conflict between agricultural development for economic growth on the one hand, and water quality protection for public health reason on the other.

Since the 1980's, studies of water quality protection of the canal have been conducted for supplying water with satisfactory quality to Xiamen Special Economic Zone (D. Chen 1989; Jao and Leung 1986). Xiamen Environmental Monitoring Station has monitored the canal water quality since 1980, and conducted time series analysis of pollution trends (Sun 1988; Sun et al. 1990; Huang et al. 1988). Water pollutant sources from runoff and soil erosion were investigated, and canal water quality was predicted (Sun et al. 1987 & 1988; Li & Xu 1988; Wu et al. 1989; Wu et al. 1988; Zhuang 1988). Xiamen Agricultural Science Institute has made a general survey of agricultural resources and agricultural production (Liu et al. 1989). Systems analysis of water pollution control in the area has also been conducted. Agricultural factors relating to water pollution, including cropping areas, types of soil-crop combinations, manure and fertilizer application rates, and livestock husbandry, but excluding the factor of water availability, were analyzed and adjusted to realize the objective of maximum net income under the constraints of water quality requirements. The results have been used for directing farming operation planning. Some regulations and local standards of canal water protection were also made according to the results (Sun et al. 1987 & 1988; Huang 1986). However, no study until now has integrated both water quantity and quality management in a systems analysis model.

Therefore, an optimization analysis of water quantity-quality problems is necessary to fully understand and effectively manage the complex water problems in the canal basin.

CHAPTER 3
METHODOLOGY AND MODEL CONSTRUCTION

1. Introduction to Grey Systems and Grey Linear Programming

Grey systems theory was developed by Dr. J. Deng in the 1980's to deal with the problem of uncertainties in systems analyses (Deng 1984a and 1984b). Previously, most of reports on the developments of applications of the theory were published in Chinese, and very few of them were in English. This study is to introduce the grey systems theory to water resource management under uncertainty, and try to propose a new method of solution for grey linear programming (GLP) model.

(1) Grey Systems

In grey systems theories, all systems are divided into three categories: white, grey, and black systems. A white system has certain and clear messages (e.g., water quality records), and black systems have unknown messages (e.g., mechanism of human body, and temperature field of human body). A grey system has both known and unknown messages (e.g., effects of water pollution, fates of pollutants in water body).

In the real world, many problems are uncertain (grey problems). These uncertain problems have usually been expressed by certain numbers. A certain number, in fact, can only represent one of the infinite whitening values of a grey number (an uncertain problem). Therefore, it is incomplete to use certain numbers to express uncertain problems, especially in systems analysis.

Open sets of a topological space play an important role in space topology. An open set means that its bounds are uncertain. A number, whose real value cannot be determined with certainty, but whose open interval where this number located is known, is called a grey number (Deng 1985a; Huang 1987). For example, let $\otimes(a)$ be a grey number, we have $\otimes(a) = [\underline{\otimes}(a), \overline{\otimes}(a)]$, where $\overline{\otimes}(a)$ is the upper limit of the grey number, and $\underline{\otimes}(a)$ is the lower limit of the grey number. Therefore, the grey number $\otimes(a)$ represents a number (or an interval) which can have the maximum value of $\overline{\otimes}(a)$ and minimum value of $\underline{\otimes}(a)$. Any white number (certain number) with the value between $\underline{\otimes}(a)$ and $\overline{\otimes}(a)$ is defined as a whitening value of the grey number $\otimes(a)$. Thus, we can say that an open set is a grey number. In space topology, the neighbourhood of a point is a set of points which lie "close" enough to that point. Usually, a neighbourhood is an extension of a grey number, or, in other words, neighbourhoods imply that some close elements are located around a key element. According to the theory of grey systems, a key element is one of the whitening values of a grey number (Deng 1986).

A decision model containing grey parameters is defined as grey decision model. The process of a grey decision can be described as:

(i) an event occurs;

(ii) there are many games (options) for dealing with the event;

(iii) the effects (results) vary with games;

(iv) the ultimate aim is to obtain the optimal effect.

Therefore, four components are included in a grey decision process: event, game, effect, and aim. A combination of event(s) and game(s) is defined as state(s).

State is an essential concept of grey system theory. A set of states, including event(s) and game(s), is the essential element of grey decision making. For example, in agricultural production, it is a problem of decision making which crops should be chosen for farming in order to achieve the highest possible yields under different situations of water supply. In this case, different situations of water supply are the events, and different crops are the games.

Let event 1 and 2 are the situations of sufficient and insufficient water supply, respectively, and game1 and 2 are rice and wheat, respectively. Thus we have four primary states:

State 1 = (sufficient water supply, rice)
State 2 = (sufficient water supply, wheat)
State 3 = (insufficient water supply, rice)
State 4 = (insufficient water supply, wheat)

Furthermore, different games can be combined to achieve new games. For example, rice and wheat can all be cropped under sufficient water supply. Thus we have:

State 5 = (sufficient water supply, rice + wheat)

Also, these games can be arranged in different proportion, and then combined to achieve new games. For example, let the proportion of rice is 70%, and that of wheat is 30%. We have:

State 6 = (sufficient water supply, 70% rice + 30% wheat)

Similarly, we can have:

State 7 = (sufficient water supply, 60% rice + 40% wheat)

State 8 = (sufficient water supply, 30% rice + 70% wheat)

.
.
.

Therefore, the number of the states can be infinite. As a general rule, the effects of a state can vary with games under the same event. Therefore, the ultimate aim of decision making is to obtain a set of satisfactory states, where a key state is included, according to the effects. All satisfactory states, which consist of the neighbourhood of the key state, will abut on the key state in accordance with the given objectives and constraints, and are called a grey target of decision making (Deng 1987).

(2) Grey Linear Programming (GLP)

Grey linear programming (GLP) is an important area of grey systems theories. It is a development of the traditional linear programming (TLP) method.

In a TLP model, all variables and coefficients are certain numbers, and the solution is unique. The TLP method has two disadvantages. First, many variables and coefficients are uncertain in the real world. They cannot be expressed by certain numbers. However, TLP model is static, and can only deal with certain messages. Second, solutions of TLP models are often very sensitive to even very small changes of coefficients, which can affect the effectiveness of the programming.

The GLP method can overcome the two disadvantages. In a GLP model, grey numbers are introduced to express uncertain messages, which can be contained by the GLP model. Grey messages are then communicated into the optimization processes, and, thereby, yield grey solutions, i.e., from grey inputs, by GLP model, to grey outputs (solutions). Planners can analyze the whitening values in the grey solutions to achieve the feasible realizations of the required objectives.

2. Model Construction

The objective of the proposed research will be achieved via a GLP model. The studied canal basin will be considered as a general grey system. Three components, namely soil-crop, livestock, and human activities, will be analyzed based on the consideration of water quantity allocation and quality protection (Figure 3.1). Their contributions to ecological, environmental, economic, and social efficiencies will be evaluated.

Water pollution is generated by nonpoint source losses of sediment, nitrogen, and phosphorus from farm lands due to land erosion and the washing away of unused nutrients from fertilizers and manures. Water allocation for irrigation is related to farming activities, channel flows, and economic returns.

(1) Decision Variables

The basic grey decision variables in the water resources system are cropland areas, manure and nitrogen fertilizer application rates, and the size of livestock husbandry. The objective is to achieve the maximum of net income, and the constraints include all the relations between the decision variables and the quantity-quality restrictions.

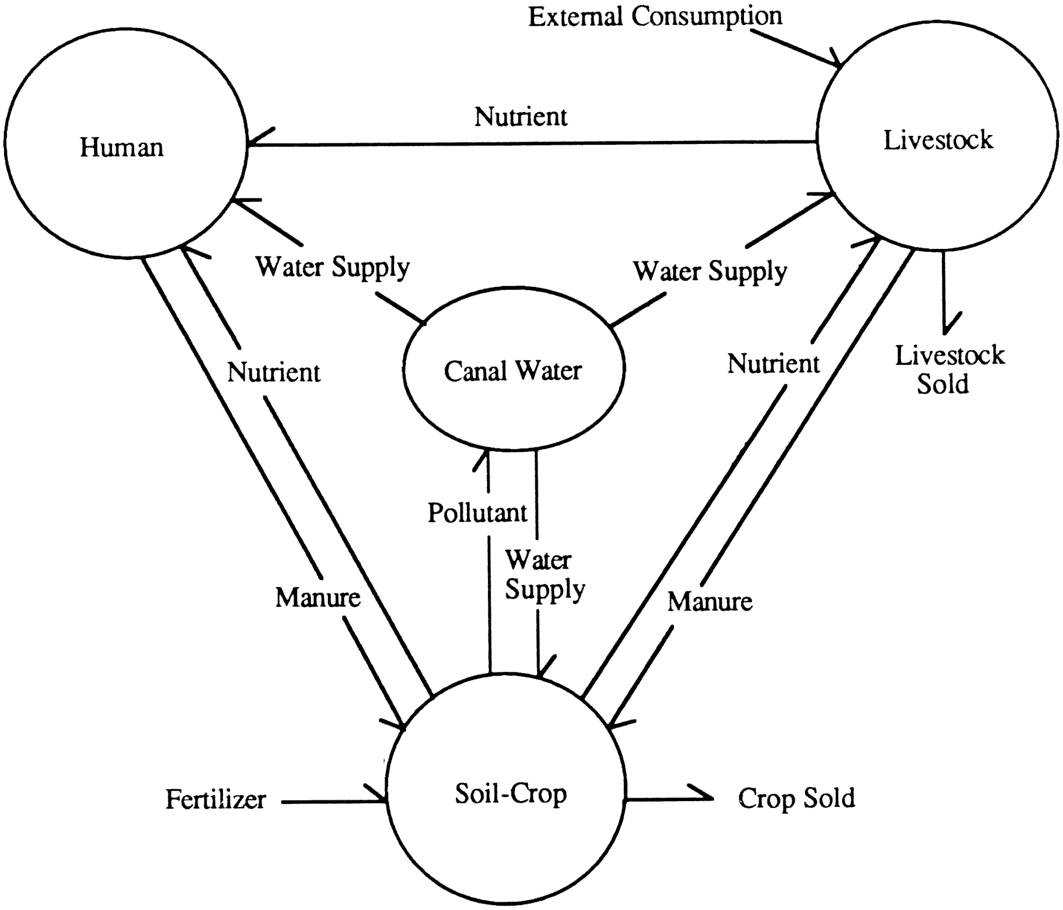


Figure 3.1 Three agricultural components in the study area

Let there be m type of soils, n kind of crops, and l kind of livestocks in the study area. Since only certain soil/crop combinations are feasible in the area, we have:

$$(1 - SC_{ij})S_{ij} = 0 \qquad \forall i, j \text{ ---------------} \quad (1)$$

where

$SC_{ij} = 1$ if the soil/crop combination (i, j) is permitted and zero otherwise.

S_{ij} is the area of soil i planted to crop j (km²);

Manure spreading may not be allowed in all cases, and:

$$(1 - MS_{ij})F_{ij} = 0 \qquad \forall i, j \text{ ---------------} \quad (2)$$

where

$MS_{ij} = 1$ if manure can be spread on S_{ij}, and zero otherwise.

F_{ij} is the amount of manure spread on soil i planted to crop j *(tonne);*

A second constraint on manure spreading is required to assure that $F_{ij} = 0$ whenever $S_{ij} = 0$:

$$-10000S_{ij} + F_{ij} \leq 0 \qquad \forall i, j \text{ ---------------} \quad (3)$$

The "10000" on the left side of the constraint is an arbitrary large number greater than the maximum possible manure spreading rate (tonne/km²).

(2) Manure Application

The manure spread on soil-crop component is from both human and livestock components (Figure 3.2). Thus a manure mass balance is given by:

$$\sum_{i=1}^{m} \sum_{j=1}^{n} F_{ij} - \sum_{k=1}^{l} \otimes(B_k)\, T_k - B_0\, T_0 = 0, \quad \text{---------------} \quad (4)$$

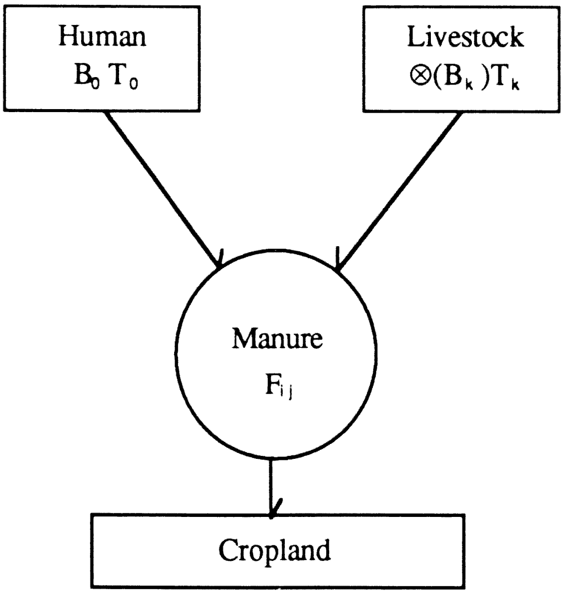
where

$\otimes(B_k)$ and B_0 are the amount of manure discharged by livestock k and human, respectively (tonne/one). $\otimes(B_k)$ is a grey variable controlled by the grey properties of the agricultural system, $\otimes(B_k) = [\underline{\otimes}(B_k), \overline{\otimes}(B_k)]$, where $\underline{\otimes}(B_k)$ is the whitening value of the lower limit of $\otimes(B_k)$, and $\overline{\otimes}(B_k)$ is the whitening value of the upper limit of $\otimes(B_k)$ (Deng 1984b & 1985b); B_0 can be the total amount of manure discharged by human divided by the population.

T_k and T_0 are the numbers of livestock k and people in the area, respectively.

The sizes of livestock may be constrained to some maximum numbers (T_{max}) based on the available housing facilities or other considerations. Therefore:

$$T_k \leq T_{max} \qquad \forall k \quad \text{---------------} \quad (5)$$



Where:

$\otimes(B_k)$ = the amount of manure discharged by livestock k;
T_k = the numbers of livestock k in the study area;
B_0 = the amount of manure discharged by human;
T_0 = the number of man in the study area;
F_{ij} = the amount of nitrogen spread on soil i planted to crop j;

Figure 3.2 Manure mass balance

(3) Crop Nitrogen Requirements

A crop nutrient balance is constructed for nitrogen only. Potassium is not considered a potential water pollutant, and the total amount of phosphorus in the soil is generally not affected by fertilizer or manure applications (Haith 1984). Crop needs for potassium and phosphorus are not ignored, however, since the costs of these fertilizers are included in the model's objective function.

The nitrogen requirement of crop j on soil i is specified by Q_{ij} (kg/km^2). The nitrogen requirement will vary with soil fertility, and hence Q_{ij} is the requirement for the crop over and above the nitrogen provided by mineralization of soil organic matter. Thus, in order to supply the crop nitrogen requirements, we have the soil nitrogen balance (Figure 3.3):

$$(1 - p_1/100)\, r F_{ij} + (1 - p_2/100)\, H_{ij} - Q_{ij} S_{ij} \geq 0, \qquad \forall i, j \text{ ---------------- } (6)$$

where

r is nitrogen content of manure (kg/t);

H_{ij} is the fertilizer nitrogen applied to S_{ij} (kg);

p_1 and p_2 are nitrogen volatilization/denitrification rates of manure and nitrogen fertilizer, respectively (%).

(4) Livestock and Human Nutrient Requirements

On energy and digestible protein requirements, although livestocks and humans need many different nutrients, the onfarm crops are grown principally to help supply their

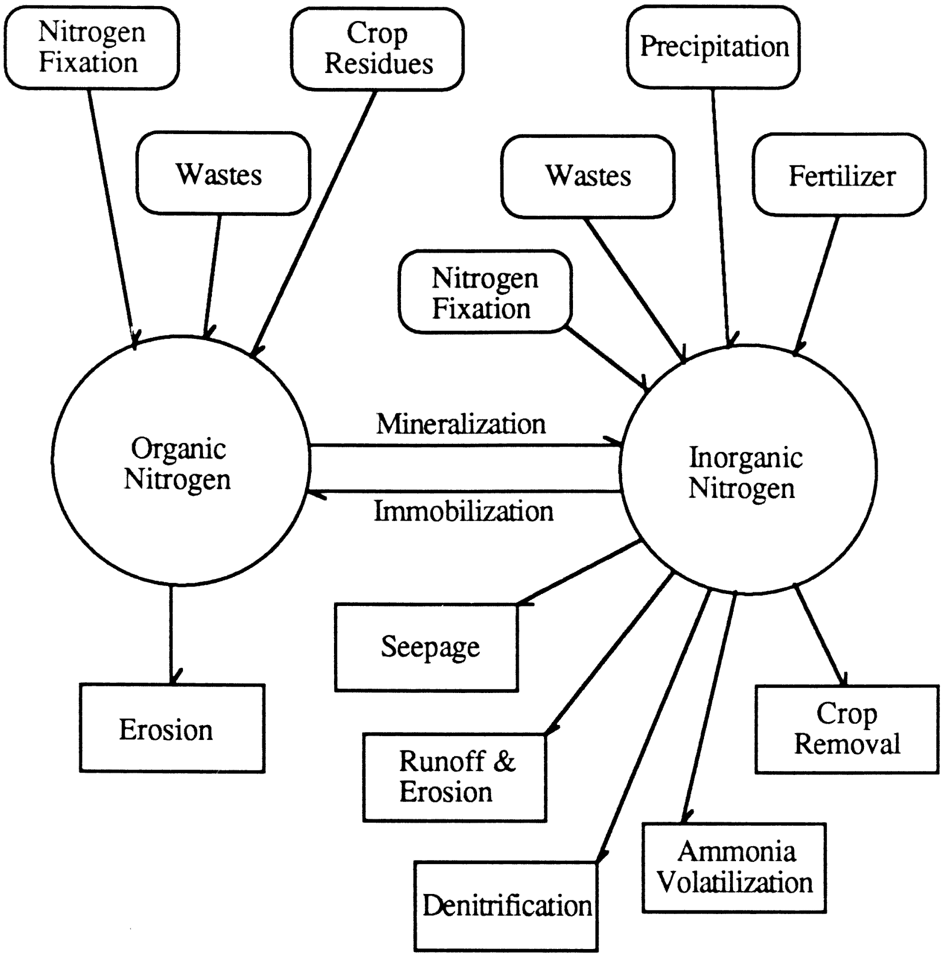


Figure 3.3 Soil nitrogen budget

(livestocks and human) net energy and digestible protein requirements (Figure 3.4 and 3.5). Therefore, we have net energy and digestible protein balances:

$$\sum_{i=1}^{m}\sum_{j=1}^{n} C_{ij}\,\alpha_{ij}\,S_{ij} - \sum_{k=1}^{l}(E_k - \otimes(e_k))\,T_k - (E_0 - \otimes(e_0))\,T_0 \geq 0, \quad \text{---------------} \quad (7)$$

$$\sum_{i=1}^{m}\sum_{j=1}^{n} C_{ij}\,\beta_{ij}\,S_{ij} - \sum_{k=1}^{l}(D_k - \otimes(d_k))\,T_k - (D_0 - \otimes(d_0))\,T_0 \geq 0, \quad \text{---------------} \quad (8)$$

where

E_k and E_0 are the energy requirements of livestock k and human to be satisfied from onfarm crops, respectively (kcal/one);

C_{ij} is the yield of crop j on soil i (kg/km^2);

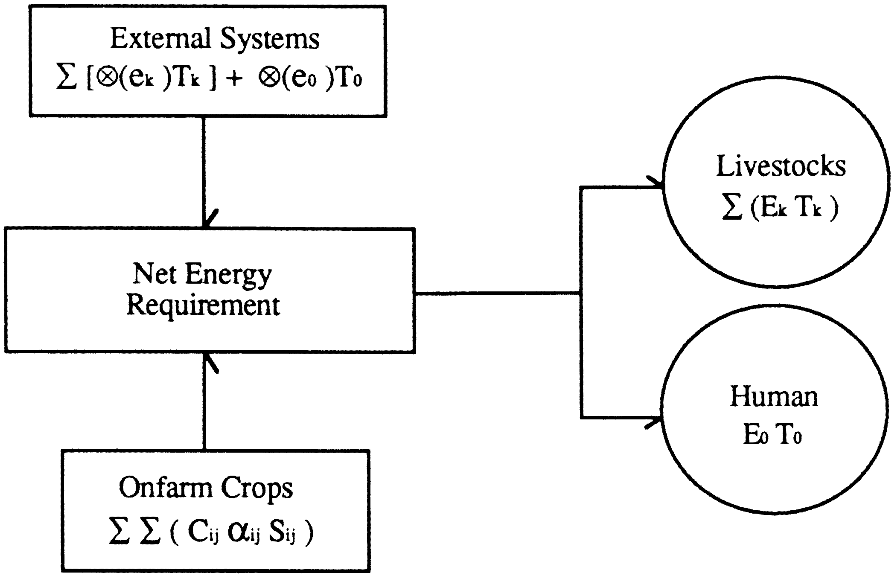
α_{ij} is the net energy content of C_{ij} (kcal/kg);

$\otimes(e_k)$ and $\otimes(e_0)$ are the net energy absorbed by livestock k and human from external systems, respectively (kcal/kg), where $\otimes(e_k) = [\underline{\otimes}(e_k), \overline{\otimes}(e_k)]$, $\otimes(e_0) = [\underline{\otimes}(e_0), \overline{\otimes}(e_0)]$;

D_k and D_0 are the digestible protein requirement of livestock k and human to be satisfied from onfarm crops, respectively (kg/one);

β_{ij} is the digestible protein content of C_{ij} (%);

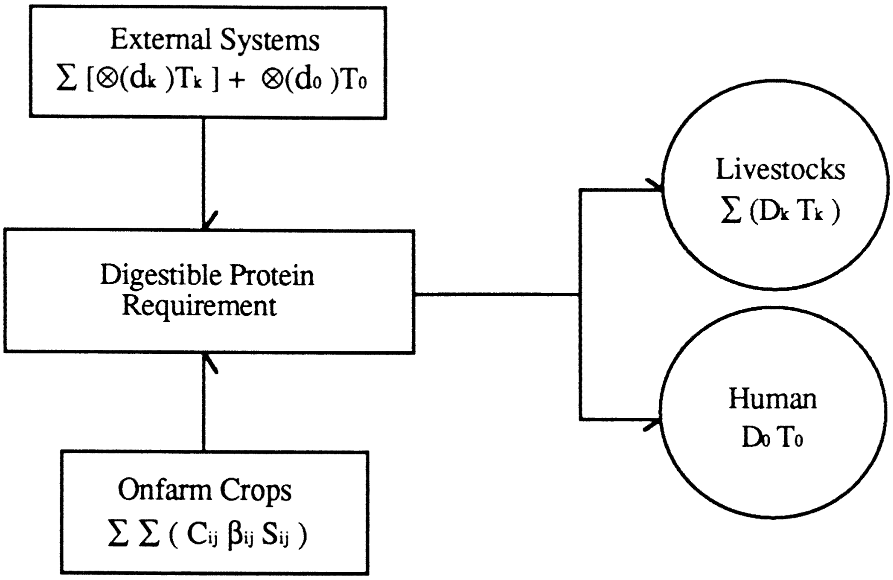
$\otimes(d_k)$ and $\otimes(d_0)$ are the digestible protein absorbed by livestock k and human from other systems, respectively (kg/one), where $\otimes(d_k) = [\underline{\otimes}(d_k), \overline{\otimes}(d_k)]$, $\otimes(d_0) = [\underline{\otimes}(d_0), \overline{\otimes}(d_0)]$.



Where:

$\otimes(e_k)$ = net energy absorbed by livestock k from external systems;
$\otimes(e_o)$ = net energy absorbed by human from external systems;
T_k = the number of livestock k in the study area;
T_o = the number of people in the study area;
E_k = energy requirement of livestock k to be satisfied from onfarm crops;
E_o = energy requirement of human to be satisfied from onfarm crops;
C_{ij} = the yield of crop j on soil i;
α_{ij} = the net energy content of C_{ij};
S_{ij} = the area of soil i planted to crop j;

Figure 3.4 Net energy supply and demand



Where:

$\otimes(d_k)$ = digestible protein absorbed by livestock k from external systems;
$\otimes(d_o)$ = digestible protein absorbed by human from external systems;
T_k = the number of livestock k in the study area;
T_o = the number of people in the study area;
D_k = digestible protein requirement of livestock k to be satisfied from onfarm crops;
D_o = digestible protein requirement of human to be satisfied from onfarm crops;
C_{ij} = the yield of crop j on soil i;
β_{ij} = the digestible protein content of C_{ij};
S_{ij} = the area of soil i planted to crop j;

Figure 3.5 Digestible protein supply and demand

(5) Pollutant Losses

The following environmental parameters are related to the canal water quality:

1. Total nitrogen losses
2. soil loss
3. solid-phase nitrogen and phosphorus losses
4. dissolved nitrogen and phosphorus losses

Each loss can be restricted to a maximum average annual value per km².

Let *a* and *b* be the maximum allowable total nitrogen and soil losses, respectively (kg/km²), which are controlled by the objectives of drinking water quality. The objectives are related to many grey factors, including upper stream water quality (external grey systems), diffusivity of canal water (environmental grey sub-system), local sanitary standards of drinking water (legal grey sub-system), and environmental/economic tradeoffs (economic grey sub-system). Therefore, *a* and *b* should be considered grey parameters $\otimes(a)$ and $\otimes(b)$ in order to reflect the effects of many grey factors, where $\otimes(a) = [\underline{\otimes}(a), \overline{\otimes}(a)]$, $\otimes(b) = [\underline{\otimes}(b), \overline{\otimes}(b)]$. Thus, we have:

$$\sum_{i=1}^{m}\sum_{j=1}^{n}(r F_{ij} + H_{ij} - Q_{ij} S_{ij}) \le \otimes(a) \sum_{i=1}^{m} K_i \ , \quad \text{----------------} \quad (9)$$

$$\sum_{i=1}^{m}\sum_{j=1}^{n} L_{ij} S_{ij} \le \otimes(b) \sum_{i=1}^{m} K_i \, , \quad \text{----------------} \quad (10)$$

$$\sum_{j=1}^{n} S_{ij} \le K_i \, , \qquad \forall i \quad \text{---------------} \quad (11)$$

where

K_i is the tillable area of soil i (km^2);

L_{ij} is the soil loss from S_{ij} (kg/km^2).

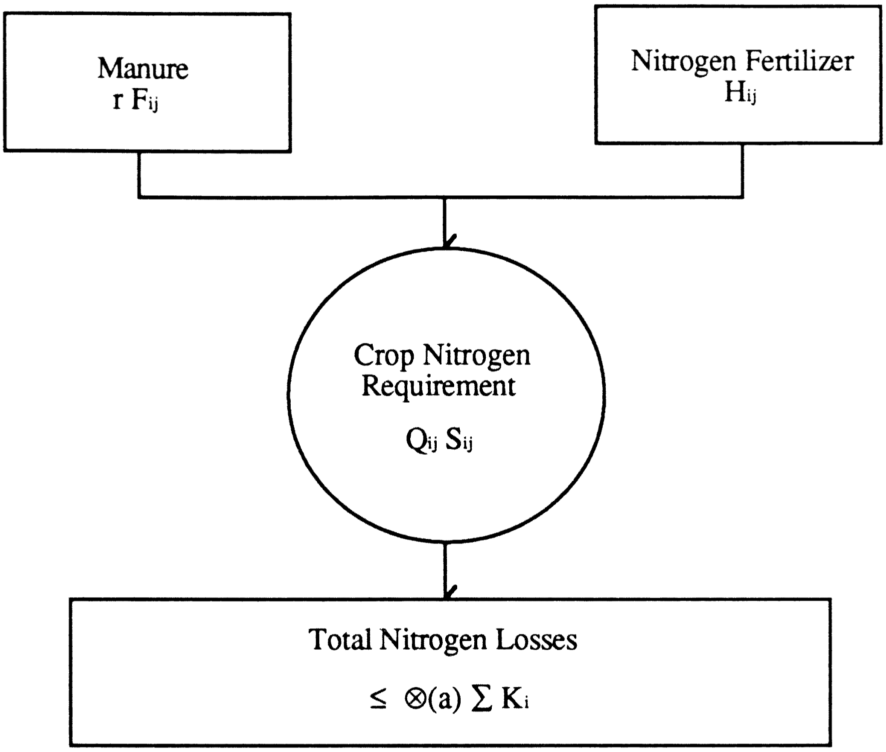
Figure 3.6 is a description of Constraint (9) of total nitrogen losses.

On the losses of solid-phase and dissolved nitrogen and phosphorus, the quantities of solid-phase nitrogen and phosphorus in the soil are not greatly affected by cropping, manuring, or fertilizer practices. However, these nutrients vary significantly with soil type (Haith 1984). Runoff losses of dissolved nitrogen and phosphorus can be estimated as the product of runoff and dissolved nutrient concentrations in the runoff. These concentrations are primarily influenced by crop selection, and the concentrations in dry and wet seasons are often substantially different.

Let c_1 and c_2 be the maximum allowable solid-phase nitrogen and phosphorus losses, respectively (kg/km^2), and f_1 and f_2 be the maximum allowable losses of dissolved nitrogen and phosphorus by runoff, respectively (kg/km^2). Similarly, c_1 , c_2 , f_1 and f_2 should also be considered grey factors $\otimes(c_1)$, $\otimes(c_2)$, $\otimes(f_1)$, and $\otimes(f_2)$, where $\otimes(c_1) = [\underline{\otimes}(c_1), \overline{\otimes}(c_1)]$, $\otimes(c_2) = [\underline{\otimes}(c_2), \overline{\otimes}(c_2)]$, $\otimes(f_1) = [\underline{\otimes}(f_1), \overline{\otimes}(f_1)]$, and $\otimes(f_2) = [\underline{\otimes}(f_2), \overline{\otimes}(f_2)]$. Thus, we have:

$$\sum_{i=1}^{m} \sum_{j=1}^{n} h_{i1} L_{ij} S_{ij} \le \otimes(c_1) \sum_{i=1}^{m} K_i , \qquad \text{---------------} \qquad (12)$$

$$\sum_{i=1}^{m} \sum_{j=1}^{n} h_{i2} L_{ij} S_{ij} \le \otimes(c_2) \sum_{i=1}^{m} K_i , \qquad \text{---------------} \qquad (13)$$



where: F_{ij} = the amount of manure applied to soil i planted to crop j;
H_{ij} = the fertilizer nitrogen applied to soil i planted to crop j;
r = nitrogen content of manure;
Q_{ij} = the nitrogen requirement of crop j on soil i;
S_{ij} = the area of soil i planted to crop j;
$\otimes(a)$ = the maximum allowable total nitrogen losses
K_i = tillable area of soil i.

Figure 3.6 Constraint of total nitrogen losses

$$\sum_{i=1}^{m}\sum_{j=1}^{n}(R_{1ij}N_{1j}+R_{2ij}N_{2j})\,S_{ij} \le \otimes(f_1)\sum_{i=1}^{m}K_i\,, \quad \text{---------------} \quad (14)$$

$$\sum_{i=1}^{m}\sum_{j=1}^{n}(R_{1ij}P_{1j}+R_{2ij}P_{2j})\,S_{ij} \le \otimes(f_2)\sum_{i=1}^{m}K_i\,, \quad \text{---------------} \quad (15)$$

where

h_{i1} and h_{i2} are nitrogen and phosphorus contents of soil *i*, respectively (%).

R_{1ij} and R_{2ij} are wet and dry season runoff from S_{ij}, respectively (mm);

N_{1j} and N_{2j} are dissolved nitrogen concentrations in wet and dry season runoff from land planted to crop *j*, respectively (mg/l);

P_{1j} and P_{2j} are dissolved phosphorus concentrations in wet and dry season runoff from land planted to crop *j*, respectively (mg/l).

(6) Water Quantity Requirements

On water quantity management, let the quantity of irrigation water required (including losses during irrigation) per km^2 of crop *j* on soil *i* in subarea *t* (suppose there are *p* subareas in the research area, $t = 1, 2, \ldots, p$) be designated as $\otimes(W_{ijt})$, $\otimes(W_{ijt}) = [\underline{\otimes}(W_{ijt}), \overline{\otimes}(W_{ijt})]$ (m^3/km^2). Thus the total quantity of water required by each S_{ij} in each subarea *t* is:

$$\otimes(QW_{ijt}) = \otimes(W_{ijt})S_{ijt}\,, \qquad \forall\ i, j, t \quad \text{---------------} \quad (16)$$

$$S_{ij} = \sum_{t=1}^{p} S_{ijt} \quad \text{----------------} \quad (17)$$

where S_{ijt} is the area of soil i planted to crop j in subarea t (km^2).

The total quantity of water required in the study area (QW_0) therefore is:

$$\otimes(QW_0) = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{t=1}^{p} \otimes(W_{ijt}) S_{ijt} \quad \text{----------------} \quad (18)$$

Let the total quantity of water required by Xiamen City be QW_1, we have the water quantity balance (Figure 3.7):

$$\otimes(QW_0) + QW_1 \leq CC\ , \quad \text{----------------} \quad (19)$$

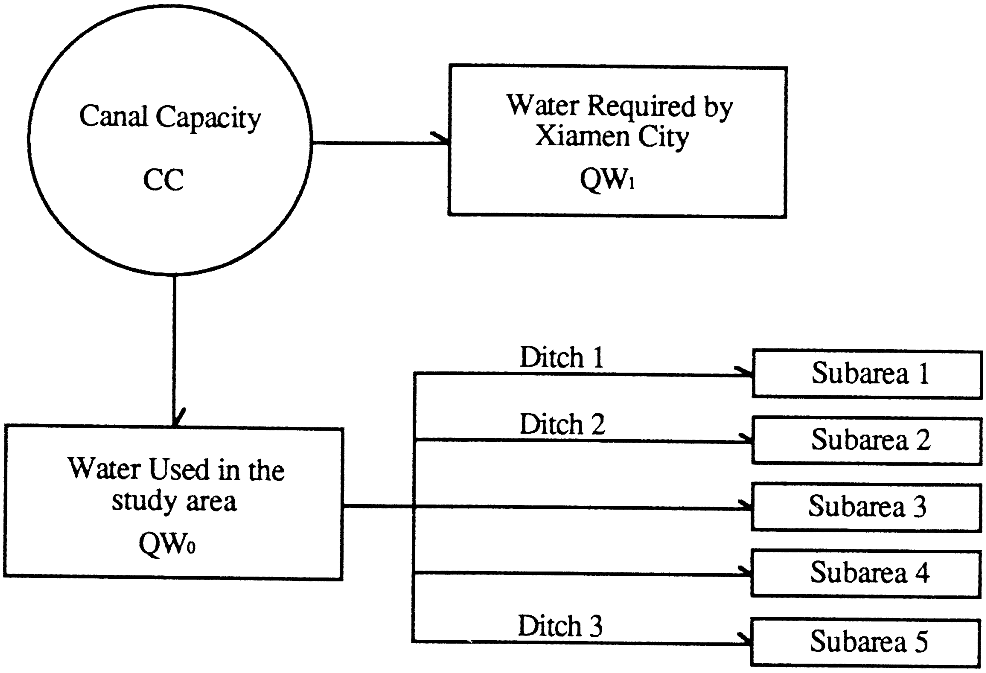
where CC is the canal capacity (m^3).

To deliver the water $\otimes(QW_0)$ to subarea t, we have:

$$\sum_{i=1}^{m} \sum_{j=1}^{n} \otimes(W_{ijt}) S_{ijt} \leq q_t\ , \qquad t = 1, 2, 5 \quad \text{----------------} \quad (20)$$

where q_t is the channel capacities within subarea t.

The costs of water (Ω_{ij}) for each S_{ij} in subarea t may include the portion to obtain and transport water to the basin area, $\otimes(U)$, associated with the canal capacity. The cost will also include the fraction $\otimes(v_t)$ of the costs of delivering the water to Subarea t with ditch capacity q_t. In addition, there are variable costs associated with each water allocation QW_{ijt}. These variable costs include the cost to obtain and allocate water to each S_{ijt}.



where:

CC = canal capacity;
QW_0 = total quantity of water required by the study area (include evaporation loss);
QW_1 = total quantity of water required by Xiamen City.

Figure 3.7 Water quantity constraint

Denoting the variable costs per unit quantity of surface water as $\otimes(X_{ijt})$, $\otimes(X_{ijt}) = [\underline{\otimes}(X_{ijt}), \overline{\otimes}(X_{ijt})]$, the total cost of water for each S_{ij} is (Figure 3.8):

$$\Omega_{ij} = \sum_{t=1}^{p} [\otimes(U) + \otimes(v_t) + \otimes(X_{ijt})]\otimes(W_{ijt})S_{ijt}, \qquad \forall\ i,\ j. \text{ ---------------} \qquad (21)$$

(7) Agricultural Income

For the purpose of this study, it is assumed that the farmer's objective is to maximize net income. Therefore, the objective function for the optimization model is (Figure 3.9):

$$A = \sum_{i=1}^{m}\sum_{j=1}^{n} \otimes(\delta_j)\, C_{ij}\, S_{ij} + \sum_{k=1}^{l} [\otimes(\sigma_k) - \otimes(q_k)]\, T_k - \sum_{i=1}^{m}\sum_{j=1}^{n} \otimes(G_{ij})\, S_{ij} -$$

$$- \otimes(G_f) \sum_{i=1}^{m}\sum_{j=1}^{n} F_{ij} - G_h \sum_{i=1}^{m}\sum_{j=1}^{n} H_{ij} - \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{t=1}^{p} [\otimes(U) + \otimes(v_t) + \otimes(X_{ijt})]\otimes(W_{ijt})S_{ijt}, \quad (22)$$

where

$\otimes(\delta_j)$ is the price of crop j (¥/kg), $\otimes(\delta_j) = [\underline{\otimes}(\delta_j), \overline{\otimes}(\delta_j)]$;

$\otimes(\sigma_k)$ is the average net return of livestock k (¥/one), $\otimes(\sigma_k) = [\underline{\otimes}(\sigma_k), \overline{\otimes}(\sigma_k)]$;

$\otimes(q_k)$ is the average consumptions from external systems by livestock k (¥/one),
$\otimes(q_k) = [\underline{\otimes}(q_k), \overline{\otimes}(q_k)]$;

$\otimes(G_{ij})$ is the farming cost on S_{ij} (¥/km^2), $\otimes(G_{ij}) = [\underline{\otimes}(G_{ij}), \overline{\otimes}(G_{ij})]$;

$\otimes(G_f)$ is the cost of manure disposal (¥/t), $\otimes(G_f) = [\underline{\otimes}(G_f), \overline{\otimes}(G_f))]$;

G_h is the cost of nitrogen fertilizer (¥/kg).

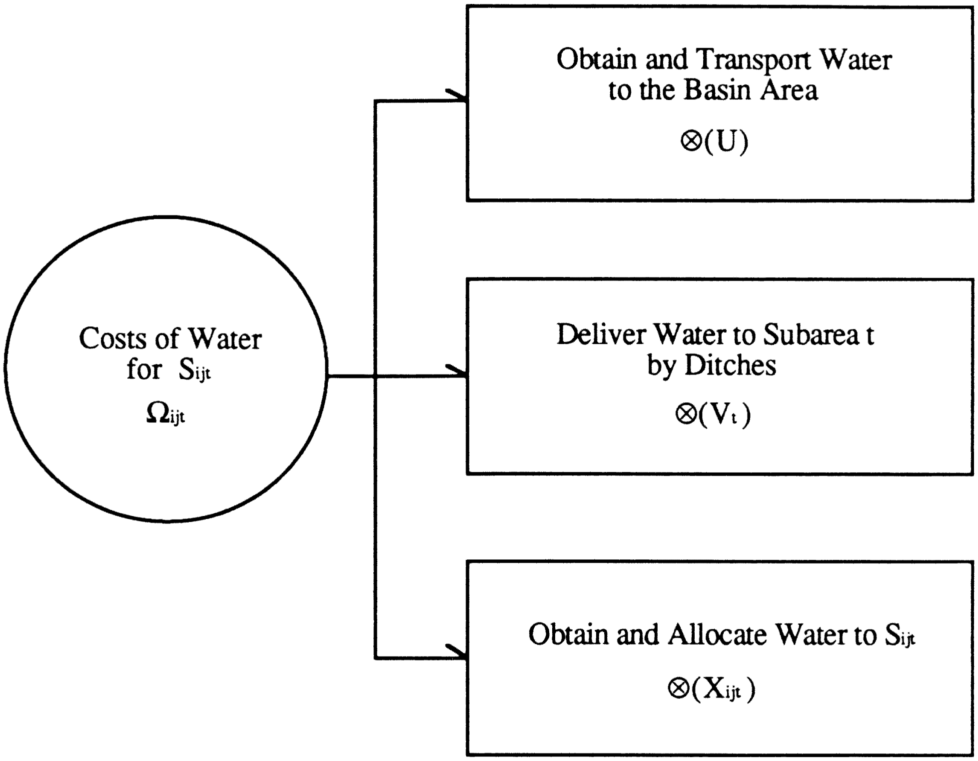


Figure 3.8 Costs of water for each soil-crop-subarea combination

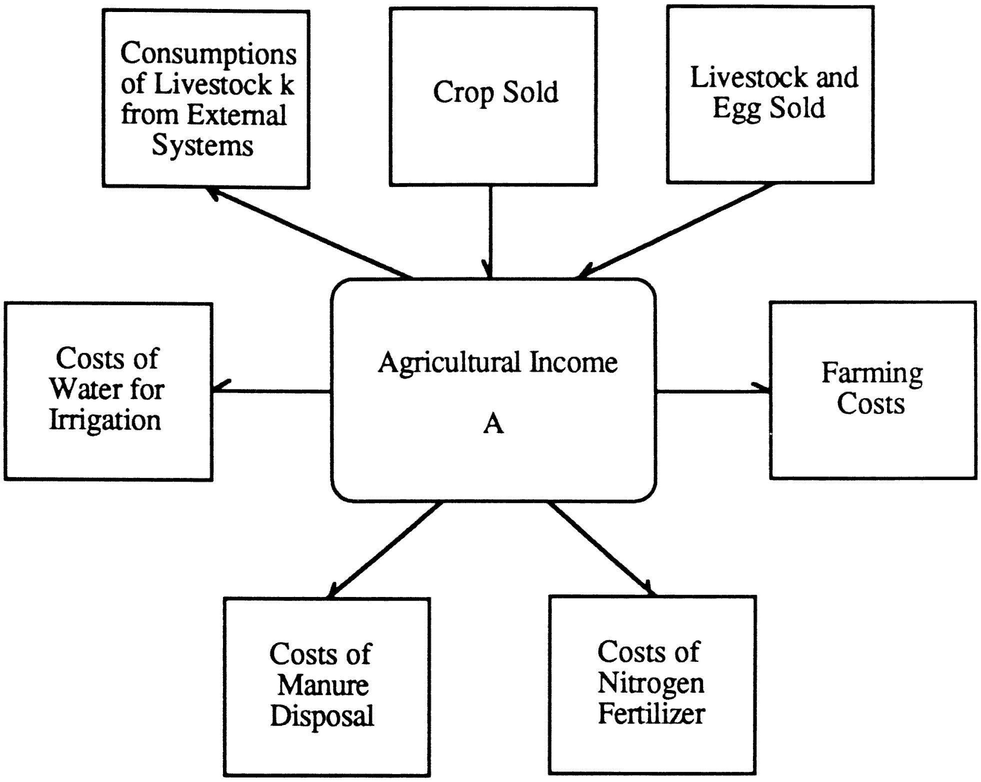


Figure 3.9 Agricultural income of the general system

(8) Optimization Model

Thus, the optimization model is:

$$
\begin{aligned}
&Max\ A \\
&\text{subject to } (1) \text{ to } (20) \\
&S_{ij},\ F_{ij},\ H_{ij},\ Q_{ijt}\ \geq 0, \qquad \forall\ i, j, t \\
&T_k \geq 0, \qquad \forall\ k, \qquad\qquad \text{----------------} \quad (23)
\end{aligned}
$$

where S_{ij} , F_{ij} , H_{ij} , Q_{ijt} and T_k are decision variables, and other parameters are determined by practical investigations.

This is a grey linear programming (GLP) model which needs a new solving approach different from the approach for traditional linear programming model.

3. Method of Solution

Optimization model (23) can be transferred into a standard format of grey linear programming model:

$$
\begin{aligned}
&Max\ f = \otimes(\mathbf{c})\ \boldsymbol{x} \\
&\text{subject to } \otimes(A)\ \boldsymbol{x} \leq \boldsymbol{b} \\
&\boldsymbol{x} \geq 0, \qquad\qquad \text{----------------} \quad (24)
\end{aligned}
$$

where $\otimes(\mathbf{c}) = [\otimes(c_1), \otimes(c_2), \ldots, \otimes(c_m)]$, $\boldsymbol{x}^T = (x_1, x_2, \ldots, x_m)$, $\boldsymbol{b}^T = (b_1, b_2, \ldots, b_n)$,

$$\otimes(A) = \begin{bmatrix} \otimes(a_{11}) & \otimes(a_{12}) & \dots & \otimes(a_{1m}) \\ \otimes(a_{21}) & \otimes(a_{22}) & \dots & \otimes(a_{2m}) \\ \vdots & \vdots & & \vdots \\ \otimes(a_{n1}) & \otimes(a_{n2}) & \dots & \otimes(a_{nm}) \end{bmatrix} \qquad \text{----------------} \quad (25)$$

For grey vector $\otimes(\boldsymbol{c})$ and grey matrix $\otimes(A)$, we have:

$$\otimes(c_i) = [\underline{\otimes}(c_i), \overline{\otimes}(c_i)], \qquad \forall\, i \quad \text{----------------} \quad (26)$$

$$\otimes(a_{ij}) = [\underline{\otimes}(a_{ij}), \overline{\otimes}(a_{ij})], \qquad \forall\, i, j \quad \text{----------------} \quad (27)$$

Since some grey parameters exist in the objective function and constraints of the grey programming model, the optimal solutions of model (24) should be:

$$\otimes(f^*) = [\underline{\otimes}(f^*), \overline{\otimes}(f^*)], \qquad \forall\, i \quad \text{----------------} \quad (28)$$

$$\otimes(x^*) = [\otimes(x_1^*), \otimes(x_2^*), \dots, \otimes(x_m^*)], \quad \text{----------------} \quad (29)$$

$$\otimes(x_i^*) = [\underline{\otimes}(x_i^*), \overline{\otimes}(x_i^*)], \qquad \forall\, i \quad \text{----------------} \quad (30)$$

Although some solving approaches of GLP model have been proposed, they were limited in solving the model by defining and testing "creditabilities". Creditability is defined as f_a / f_{max}, where f_{max} is maximum possible objective value (upper limit); α is defined as a grey coefficient, and its value is between 0 and 1, i.e. $\alpha \in [0, 1]$ (when $\alpha = 0$, the grey coefficients in objective function and constraints will take their lower limits, but decision variables will reach their upper limits; and when $\alpha = 1$, the coefficients will take their upper limits, but decision variables will reach their lower limits); and f_t is the solution of objective value under the grey coefficient α (see Appendix IV for details) (Deng 1986; Huang 1988). The "creditability" method does not communicate uncertain messages into optimization processes and solutions, and therefore cannot fully reflect the effects of grey factors. Therefore, a new approach for solving $\otimes(f^*)$ and $\otimes(x^*)$ is developed and described below.

(1) Whitening Solution of the GLP Model

Model (24) can be whitened as:

$$\begin{aligned} &Max\ f = \otimes_m(\mathbf{c})\ \mathbf{x} \\ &subject\ to\ \ \otimes_m(A)\ \mathbf{x} \le \mathbf{b} \\ &\mathbf{x} \ge 0, \qquad \text{----------------}\ (31) \end{aligned}$$

where:

$$\otimes_m(\mathbf{c}) = [\otimes_m(c_1), \otimes_m(c_2), \ldots, \otimes_m(c_n)], \qquad \text{----------------}\ (32)$$

$$\otimes_m(A) = \begin{bmatrix} \otimes_m(a_{11}) & \otimes_m(a_{12}) & \ldots & \otimes_m(a_{1m}) \\ \otimes_m(a_{21}) & \otimes_m(a_{22}) & \ldots & \otimes_m(a_{2m}) \\ \vdots & \vdots & & \vdots \\ \otimes_m(a_{n1}) & \otimes_m(a_{n2}) & \ldots & \otimes_m(a_{nm}) \end{bmatrix} \qquad \text{---------------}\ (33)$$

or:

$$\otimes_m(\mathbf{c}) = (\otimes_m(c_i)), \quad \forall\ i$$

$$\otimes_m(A) = (\otimes_m(a_{ij})), \quad \forall\ i, j$$

where $\otimes_m(c_i)$ *and* $\otimes_m(a_{ij})$ are the whitening values of $\otimes(c_i)$ *and* $\otimes(a_{ij})$, respectively.

Thus, we have:

$\otimes_m(c_i) \in [\underline{\otimes}(c_i), \overline{\otimes}(c_i)]$, where $\underline{\otimes}(c_i)$ is the whitening value of the lower limit of $\otimes(c_i)$, and $\overline{\otimes}(c_i)$ is the upper limit of $\otimes(c_i)$;

$\otimes_m(a_{ij}) \in [\underline{\otimes}(a_{ij}), \overline{\otimes}(a_{ij})]$, where $\underline{\otimes}(a_{ij})$ is the lower limit of $\otimes(a_{ij})$, and $\overline{\otimes}(a_{ij})$ is the upper limit of $\otimes(a_{ij})$.

Usually, whitening mean values are chosen for calculation.

A set of whitening solutions $\otimes_m(f^*)$ and $\otimes_m(\mathbf{x}^*)$, which are included in the optimal grey solutions $\otimes(f^*)$ and $\otimes(\mathbf{x}^*)$, can be derived by solving model (31).

(2) Optimal Grey Solution $\otimes(f^*)$ and $\otimes(\mathbf{x}^*)$

For m grey coefficients $\otimes(c_i)$ $(i = 1, 2, \ldots, m)$ in the objective function, if k_1 of them are positive, and k_2 are negative, let the former k_1 coefficients $\otimes(c_i) \geq 0$ $(i = 1, 2, \ldots, k_1)$, and the latter k_2 coefficients $\otimes(c_i) < 0$ $(i = 1, 2, \ldots, k_2)$, where $k_1 + k_2 = m$. Thus, we have:

$$\begin{aligned}\overline{\otimes}(f) = {} & \overline{\otimes}(c_1)\otimes_u(x_1) + \overline{\otimes}(c_2)\,\overline{\otimes}(x_2) + \ldots + \overline{\otimes}(c_{k_1})\,\overline{\otimes}(x_{k_1}) + \\ & + \overline{\otimes}(c_{k_1+1})\,\underline{\otimes}(x_{k_1+1}) + \ldots + \overline{\otimes}(c_m)\,\underline{\otimes}(x_m), \qquad \text{--------------} \quad (34)\end{aligned}$$

$$\underline{\otimes}(f) = \underline{\otimes}(c_1)\,\underline{\otimes}(x_1) + \underline{\otimes}(c_2)\,\underline{\otimes}(x_2) + \ldots + \underline{\otimes}(c_{k_1})\,\underline{\otimes}(x_{k_1}) +$$
$$+\ \underline{\otimes}(c_{k_1+1})\,\overline{\otimes}(x_{k_1+1}) + \ldots + \underline{\otimes}(c_m)\,\overline{\otimes}(x_m). \quad \text{---------------} \quad (35)$$

Based on equation (34), relevant constraints can be given as:

$$\underline{\otimes}(a_{i1})\,\overline{\otimes}(x_1) + \underline{\otimes}(a_{i2})\,\overline{\otimes}(x_2) + \ldots + \underline{\otimes}(a_{ik_1})\,\overline{\otimes}(x_{k_1}) +$$
$$+\ \overline{\otimes}(a_{ik_1+1})\,\underline{\otimes}(x_{k_1+1}) + \ldots + \overline{\otimes}_u(a_{im})\,\underline{\otimes}(x_m) \le b_i, \quad \forall\, i \quad \text{---------} \quad (36)$$

Similarly, based on equation (35), relevant constraints are:

$$\overline{\otimes}(a_{i1})\,\underline{\otimes}(x_1) + \overline{\otimes}(a_{i2})\,\underline{\otimes}(x_2) + \ldots + \overline{\otimes}(a_{ik_1})\,\underline{\otimes}(x_{k_1}) +$$
$$+\ \underline{\otimes}(a_{ik_1+1})\,\overline{\otimes}(x_{k_1+1}) + \ldots + \underline{\otimes}(a_{im})\,\overline{\otimes}(x_m) \le b_i, \quad \forall\, i \quad \text{----------} \quad (37)$$

For whitening solutions $\otimes_m(x^*)$, we have $\otimes_m(x^*) \in \otimes(x^*)$. Therefore:

$$\overline{\otimes}(x_i) \ge \otimes(x_i^*), \qquad i = 1, 2, \ldots, k_1,$$
$$\underline{\otimes}(x_i) \le \otimes(x_i^*), \qquad i = k_1 + 1, k_1 + 2, \ldots, m, \quad \text{---------------} \quad (38)$$

$$\overline{\otimes}(x_i) \ge \otimes(x_i^*), \qquad i = k_1 + 1, k_1 + 2, \ldots, m,$$
$$\underline{\otimes}(x_i) \le \otimes(x_i^*), \qquad i = 1, 2, \ldots, k_1. \quad \text{---------------} \quad (39)$$

Thus, Model (24) can be divided into two models:

$$\begin{aligned}&Max\ \overline{\otimes}(f)\\&\text{subject to (36) and (38)}\\&\underline{\otimes}(x_i) \geq 0, \qquad i = k_1 + 1, k_1 + 2, \ldots, m, \quad \text{---------------} \quad (40)\end{aligned}$$

$$\begin{aligned}&Max\ \underline{\otimes}(f)\\&\text{subject to (37) and (39)}\\&\underline{\otimes}(x_i) \geq 0, \quad i = 1, 2, \ldots, k_1. \quad \text{---------------} \quad (41)\end{aligned}$$

Models (40) and (41) are linear programming models with a single objective function. Therefore, $\overline{\otimes}(f^*)$, $\overline{\otimes}(x_i^*)$ ($i = 1, 2, \ldots, k_1$) and $\overline{\otimes}(x_i^*)$ ($i = k_1 + 1, k_1 + 2, \ldots, m$) can be solved by Model (40), and $\underline{\otimes}(f^*)$, $\overline{\otimes}(x_i^*)$ ($i = k_1 + 1, k_1 + 2, \ldots, m$) and $\overline{\otimes}(x_i^*)$ ($i = 1, 2, \ldots, k_1$) can be solved by model (41). Thus, the solutions of the GLP model (Model 40) are:

$$\otimes(f^*) = [\underline{\otimes}(f^*), \overline{\otimes}(f^*)], \quad \text{---------------} \quad (42)$$

$$\otimes(x_i^*) = [\underline{\otimes}(x_i^*), \overline{\otimes}(x_i^*)], \qquad \forall\ i \quad \text{---------------} \quad (43)$$

4. Interpretation of Solutions

Solutions of the GLP model include decision variables $(\otimes(x_i^*),\ \forall\, i)$ and the relevant objective $(\otimes(f^*))$. The solutions of decision variables are expressed as $\otimes(x_i^*) = [\underline{\otimes}(x_i^*),\ \overline{\otimes}(x_i^*)],\ \ \forall\, i$, which means that the maximum possible value of $\otimes(x_i^*)$ is $\overline{\otimes}(x_i^*)$ (upper limit), and the minimum is $\underline{\otimes}(x_i^*)$ (lower limit). The solutions can be directly applied to decision making. Their values can be adjusted within their grey intervals in the final decision scheme.

The solution of objective function is important for assessing decision efficiencies. It is expressed as $\otimes(f^*) = [\underline{\otimes}(f^*),\ \overline{\otimes}(f^*)]$, which means that the maximum objective value is $\overline{\otimes}(f^*)$ (upper limit), and the minimum is $\underline{\otimes}(f^*)$ (lower limit). The upper and lower limits of objective value are corresponding to different distributions of decision variables. The adjustment of decision variables within their grey intervals will lead to the variation of objective value within its grey interval correspondingly.

The following is an example explaining the practical significance of the GLP model and its solutions. First, set a GLP model:

$$Max\ \ f = \otimes(a_1)X_1 - \otimes(a_2)X_2$$

Subject to

$$\otimes(b_{11})X_1 + X_2 \leq 150$$

$$6X_1 + \otimes(b_{22})X_2 \leq 280$$

$$X_1 + \otimes(b_{32})X_2 \leq 90$$

$$\otimes(b_{41})X_1 - 10X_2 \leq -1$$

where $\otimes(a_1)$, $\otimes(a_2)$, $\otimes(b_{11})$, $\otimes(b_{22})$, $\otimes(b_{32})$ and $\otimes(b_{41})$ are grey coefficients. Let

$\otimes(a_1) = [50, 60],$

$\otimes(a_2) = [70, 90],$

$\otimes(b_{11}) = [4, 6],$

$\otimes(b_{22}) =[5, 7],$

$\otimes(b_{32}) = [3, 4],$

$\otimes(b_{41}) = [1, 2],$

where $\otimes(a_1) = [50, 60]$ means that the maximum value of $\otimes(a_1)$ is 60 (upper limit), and the minimum is 50 (lower limit); and so on for the others. We can then solve the GLP model by the former proposed approach. The solutions are:

Decision variables:

$X_1 = [24.18, 36.56],$

$X_2 = [3.76, 4.94],$

Objective value:

$f = [764.71, 1930.73],$

where X_1 = [24.18, 36.56] means that the maximum possible value of X_1 is 36.56 (upper limit), and the minimum is 24.18 (lower limit); X_2 = [3.76, 4.94] means that the maximum possible value of X_2 is 4.94 (upper limit), and the minimum is 3.76 (lower limit); and f = [764.71, 1930.73] means that the maximum objective value is 1930.73 (upper limit), and the minimum is 764.71 (lower limit).

The solutions of decision variables X_1 and X_2 can be directly applied for achieving the optimal objective value, and the solution of objective function f can be used for evaluating the final decision scheme. Under the scheme for upper limit of objective, X_1 should take the upper limit value ($\overline{\otimes}(X_1) = 36.56$), and X_2 the lower limit ($\underline{\otimes}(X_2) = 3.76$);

and under the scheme for lower limit of objective, X_1 should take the lower limit value ($\underline{\otimes}(X_1) = 24.18$), and X_2 the upper limit ($\overline{\otimes}(X_2) = 4.94$). Therefore, the final decision scheme of X_1 and X_2 can be adjusted within their grey intervals, i.e., from 24.18 to 36.56 for X_1, and from 3.76 to 4.94 for X_2. Higher X_1 and lower X_2 can be programmed for achieving higher objective value, and lower X_1 and higher X_2 can be chosen for lower objective value.

CHAPTER 4
SPECIFICATION OF COEFFICIENTS AND PARAMETERS

1. Agricultural Data Sets

The study area contains generally two soil types: dry soil and wet soil. Table 4.1 is their general natures (Liu et al. 1989). There are mainly four crops grown in the area. They are rice, wheat, vegetables and sweet potato. Rice is grown on wet soil (rice soil), and wheat, vegetables and sweet potato on dry soils. The possible soil-crop combinations are listed in Table 4.2 (GXSA 1990).

Nutrients produced from the crops are given in Table 4.3. They are obtained by multiplying average yields of a crop in 1989 by nutrient contents of the crop (Liu et al. 1989; GXSA 1990). Crop nitrogen requirements (Table 4.4) are obtained from a soil survey in 1988 (Liu et al. 1989; XAB 1989).

The area is divided into five subareas with different ways of water drawing for irrigation and different soil-crop distributions. Table 4.5 shows their tillable land areas (Liu et al. 1989; GXSA 1990).

The main livestocks are ox, sheep, pig and domestic fowls. Livestock nutrient requirements and manure production are shown in Table 4.6 (GXSA 1990; Zhang et al. 1988). The table indicates that most of the nutrient requirements are supplied by the area itself.

Table 4.1 Soils of the study area

Soils	Tillable Area K_i (km^2)	Nitrogen Content h_{i1} (%)	Phosphorus Content h_{i2} (%)
Dry Soil*	68.16	0.20	0.030
Wet Soil **	41.19	0.25	0.056

* Dry soil includes Solonchak, sandy loam, and loam;
** Wet soil includes salinized and permeable rice soils.

Table 4.2 Possible soil/crop combinations*

Soil	Rice	Wheat	Vegetables	Sweet Potato
Dry Soil	0	1	1	1
Wet Soil	1	0	0	0

* 1 means that the combination is possible, and 0 otherwise.

Table 4.3a Net energy produced from the crops

Crop	Rice	Wheat	Sweet Potato	Vegetables
Net Energy Content * $\otimes(\alpha_{ij})$ (kcal/kg)	[908, 917]	[560, 569]	[166, 176]	[480, 489]
Average Yield * $\otimes(C_{ij})$ (10^3 kg/km^2)	[339, 362]	[159, 181]	[150, 172]	[300, 332]
Net Energy Produced $\otimes(C_{ij}\,\alpha_{ij})$ (10^6 kcal/km^2)	[308, 332]	[89, 103]	[249, 302]	[144, 162]

* the ranges of investigated values from GXSA.

Table 4.3b Digestible protein produced from the crops

Crop	Rice	Wheat	Vegetables	Sweet Potato
Digestible Protein Content* $\otimes(\beta_{ij})$ (%)	[11.6, 11.8]	[16.5, 16.7]	[0.49, 0.52]	[8.3, 8.6]
Average Yield * $\otimes(C_{ij})$ (10^3 kg/km^2)	[339, 362]	[159,181]	[150, 172]	[300, 332]
Digestible Protein Produced $\otimes(C_{ij}\,\beta_{ij})$ (10^3 kg/km^2)	[39.18, 42.56]	[26.23, 30.30]	[7.42, 9.00]	[24.84, 28.52]

* the ranges of investigated values from GXSA.

Table 4.4 Crop nitrogen requirements

Crop	Rice	Wheat	Vegetables	Sweet Potato
Nitrogen Requirement Q_{ij} (10^3 kg/km^2)	1.80	1.11	1.10	1.00

Table 4.5 Tillable land areas in five subareas

Subarea	Subarea 1	Subarea 2	Subarea 3	Subarea 4	Subarea 5
Area (km^2)	23.00	20.26	40.31	40.74	19.39
Tillable Land Area (km^2)	16.23	17.91	23.84	25.64	14.73
Percentage (%)	70.57	88.40	59.14	62.94	75.97
Dry Soil Area (km^2)	12.12	13.57	10.97	9.93	10.57
Wet Soil Area (km^2)	4.11	4.34	12.87	15.71	4.16

Table 4.6 Livestock nutrient requirements and manure production

Livestock	Ox	Sheep	Pig	Domestic Fowls
Energy Requirement $\otimes(E_k)$ (10^6 kcal/one)	[1.58, 1.76]	[0.538, 0.562]	[1.05, 1.32]	[0.098, 0.120]
Energy from External Systems $\otimes(e_k)$ (10^3 kcal/one)	[28, 34]	[1.0, 1.2]	[130, 170]	[13.5, 18.0]
Digestible Protein Requirement $\otimes(D_k)$ (kg/one)	[70, 90]	[12, 16]	[17, 23]	[3.8, 4.8]
Digestible Protein from External Systems $\otimes(d_k)$ (kg/one)	[3.8, 8.2]	[0.85, 1.34]	[4.8, 7.9]	[0.91, 1.13]
Manure Produced $\otimes(B_k)$ (tonne/one)	[117, 143]	[22.5, 27.5]	[82.8, 101.2]	[3.42, 4.18]

2. Human Activities

The study area has a population of 32,400, and a population density of 226/km^2. Since a large population exists, human activity is also an important control factor in the systems analysis. Table 4.7 shows human nutrient requirements and manure production (Yi 1984).

3. Environmental Data Sets

(1) Nutrients and Sediment Losses

Water quality protection of the canal has caused great concern by local and central governments since the 1980's because it is related to water supply to Xiamen City -- a special economic zone and the most important city in Southeast China. Many research projects on canal water pollution control have been initiated. Sponsored by CEPA, XEPI has investigated and simulated agricultural nonpoint source pollutant losses in the basin area (Sun et al. 1987 & 1988; Wu et al. 1989; Li & Xu 1988). Soil losses were estimated from an improved Universal Soil Loss Equation (Wischmeier & Smith 1978; Yang 1987), and runoff from the U.S. Soil Conservation Service's runoff equation (Mockus 1972; Wu 1985). Table 4.8 displays the resulting soil losses and runoff from different croplands.

XEMS monitored concentrations of dissolved nitrogen and phosphorus in runoff for individual soil-crop combinations in dry and wet seasons (twice per season) in 1988.

Table 4.7 Human nutrient requirements and manure production

Average Amount of Manure Produced B_0 (kg/one)	Energy Requirement from Onfarm Crops E_0 (10^3 kcal/one)	Energy from External Systems $\otimes(e_0)$ (10^3 kcal/one)	Digestible Protein Requirement from onfarm crops D_0 (kg/one)	Digestible Protein Requirement from External Systems $\otimes(d_0)$ (kg/one)
61.0	876.0	[340.0, 385.0]	24.6	[8.8, 10.1]

Table 4.8 Soil losses and runoff from different croplands

Crop	Rice	Wheat	Vegetables	Sweet Potato
Annual Soil Losses * $\otimes(L_{ij})$ (kg/km^2)	[305, 385]	[550, 650]	[565, 645]	[540, 620]
Runoff in Dry Season * $\otimes(R_{1ij})$ (mm)	[23, 27]	[45, 55]	[44, 53]	[50, 56]
Runoff in Wet Season * $\otimes(R_{2ij})$ (mm)	[71, 81]	[100, 120]	[105, 130]	[95, 120]

* the ranges of calculated values.

Table 4.9 shows the average nitrogen and phosphorus concentrations in runoff for different croplands in different seasons (Huang et al. 1988).

According to data from Xiamen Agricultural Science Institute, the average nitrogen volatilization and denitrification rate of manure in Xiamen Area is about 50%, and that of nitrogen fertilizer is about 15%. Average nitrogen content of manure is 7.5 kg/tonne (Liu et al. 1989).

(2) Water Quality and Pollutant Losses

Concentrations of NO_3^--N, NO_2^--N, and NH_3-N in the canal are mainly determined by nitrogen losses from the basin area. Table 4.10 shows concentrations of NO_3^--N, NO_2^--N, and NH_3-N at the canal's outlet and the values of total nitrogen losses $\otimes(a)$, soil loss $\otimes(b)$, and dissolved and solid-phase nitrogen losses ($\otimes(f_1)$ and $\otimes(c_1)$) in 1988 and 1989. The data indicate that when the nitrogen losses in 1988 were less than those in 1989, NO_3^--N, NO_2^--N, and NH_3-N concentrations in 1988 were also lower correspondingly (Chen et al. 1990).

Table 4.11 shows Total Phosphorus concentrations at the canal's outlet and the values of soil loss $\otimes(b)$, and dissolved and solid-phase phosphorus losses ($\otimes(f_2)$ and $\otimes(c_2)$) from the basin area in 1988 and 1989. The results also indicate the relation between canal water quality and pollutant losses (Chen et al. 1990).

According to data from XEMS, concentrations of NO_2^--N, NH_3-N, and Total Phosphorus at the canal's outlet could not meet the SDWS during 1984-1989. The fact suggests that it is very urgent to cut down pollutant losses from the basin area (Huang et al. 1988; Sun et al. 1990).

Table 4.9 Nitrogen and phosphorus concentrations in runoff from different croplands

Crop	Rice	Wheat	Vegetables	Sweet Potato
Nitrogen Concentration in Dry Season * N_{1j} (mg/l)	1.5	1.6	2.0	1.6
Nitrogen Concentration in Wet Season * N_{2j} (mg/l)	2.8	2.8	3.3	2.6
Phosphorus Concentration in Dry Season * P_{1j} (mg/l)	0.22	0.29	0.28	0.33
Phosphorus Concentration in Wet Season * P_{2j} (mg/l)	0.25	0.28	0.28	0.35

* mean monitoring values from XEMS.

Table 4.10 NO_3^--N, NO_2^--N, and NH_3-N concentrations at canal's outlet and nitrogen losses from canal basin in 1988 and 1989

Year	1988	1989
NO_3^--N Concentration (mg/l)	0.96	0.99
NO_2^--N Concentration (mg/l)	0.038	0.069
NH_3-N Concentration (mg/l)	0.48	0.53
Total Nitrogen Losses (10^6 kg/km^2)	34.89	36.67
Soil Loss (10^3 kg/km^2)	152	159
Dissolved Nitrogen Loss (10^3 kg/km^2)	91.87	92.30
Solid-Phase Nitrogen Loss (10^3 kg/km^2)	30.01	30.15

Table 4.11 Total Phosphorus concentrations at canal's outlet and phosphorus losses from canal basin in 1988 and 1989

Year	1988	1989
Total Phosphorus Concentration (mg/l)	0.032	0.038
Soil Loss (10^3 kg/km^2)	152	159
Dissolved Phosphorus loss (10^3 kg/km^2)	9.95	10.03
Solid-Phase Phosphorus loss (10^3 kg/km^2)	5.86	5.90

In order to reduce pollutant losses, it is essential to know the quantitative relation between canal water quality and sources of pollutant discharges. Therefore, a simulation study of water quality in the canal, sponsored by XEPB, was conducted in 1987 (Wu et al. 1989; Wu 1988; Zhuang 1988). Based on synchronous investigation of water quality and pollutant losses, simulation models were constructed (Zhuang 1988). Thus, when pollutant losses are known, water quality can be predicted by the models. Table 4.12 shows simulation results of NO_2^--N and NH_3-N concentrations at the canal's outlet under different amounts of total nitrogen losses, soil loss, and dissolved and solid-phase nitrogen losses. The results indicate that only when the amounts of total nitrogen losses, soil loss, and dissolved and solid-phase nitrogen losses are less than 32.50×10^6, 138×10^3, 91.0×10^3, and 28.7×10^3 kg/km^2, respectively, can the NO_2^--N and NH_3-N concentrations meet the SDWS. Table 4.13 is Total Phosphorus concentration at the canal's outlet under different amounts of soil loss, and dissolved and solid-phase phosphorus losses. The results indicate that only when the amounts of soil loss, and dissolved and solid-phase phosphorus losses are less than 138×10^3, 9.90×10^3, and 5.77×10^3 kg/km^2, respectively, can the Total Phosphorus concentration meet the SDWS.

(3) Constraints on Nonpoint Source Pollutant Losses

Tables 4.14 and 4.15 are the Standards for Drinking Water Sources (SDWS) and the Quality Grading Standards of Drinking Water Source (QGS) issued by Xiamen Environmental Protection Bureau (XEPB 1988a & 1988b). The lowest requirement of water quality at the canal's outlet is the SDWS. Therefore, the lowest requirements of total nitrogen losses ($\overline{\otimes}(a)$), soil loss ($\overline{\otimes}(b)$), dissolved nitrogen and phosphorus losses ($\overline{\otimes}(f_1)$ and $\overline{\otimes}(f_2)$) and solid-phase phosphorus and nitrogen losses($\overline{\otimes}(c_1)$ and $\overline{\otimes}(c_2)$) should be the amounts of pollutant losses corresponding to the outlet's water quality meeting the

Table 4.12 Simulation results of yearly average NO_2^--N, and NH_3-N concentrations at the canal's outlet under different amounts of annual nitrogen losses

Total Nitrogen Losses (10^6 kg/km^2)	Soil Loss (10^3 kg/km^2)	Dissolved Nitrogen Loss (10^3 kg/km^2)	Solid-Phase Nitrogen Loss (10^3 kg/km^2)	NO_2^--N Concentration (mg/l)	NH_3-N Concentration (mg/l)
32.75	142	93.0	28.85	0.026	0.220
32.50	138	91.0	28.70	0.019	0.201
32.20	133	89.5	28.50	0.015	0.176
31.95	129	88.0	28.35	0.013	0.130
31.65	124	86.5	28.20	0.009	0.095
31.40	119	85.0	28.00	0.005	0.058

Table 4.13 Simulation results of yearly average Total Phosphorus concentrations at canal's outlet under different amounts of annual phosphorus losses

Soil Loss (10^3 kg/km^2)	Dissolved Phosphorus loss (10^3 kg/km^2)	Solid-Phase Phosphorus Loss (10^3 kg/km^2)	Total Phosphorus Concentration (mg/l)
142	5.87	10.15	0.0281
138	5.77	9.90	0.0200
133	5.66	9.65	0.0160
129	5.56	9.40	0.0091
124	5.45	9.10	0.0048
119	5.35	8.85	0.0021

Table 4.14 Standards for Drinking Water Sources

Pollutant	Standard (mg/l)	Pollutant	Standard (mg/l)
NO_3^--N	10	BOD	3.0
NO_2^--N	0.02	Cu	0.01
NH_3-N	0.2	Pb	0.05
Total Phosphorus	0.02	Zn	0.5
DO	6.0	Cd	0.005
COD	4.0	As	0.04

Table 4.15 Quality Grading Standards of Drinking Water Source (QGS)

Pollutant	Grade 1 (SDWS) (mg/l)	Grade 2 (mg/l)
NO_3^--N	10	5
NO_2^--N	0.02	0.01
NH_3-N	0.2	0.1
Total Phosphorus	0.02	0.005
DO	6.0	Saturation Rate ≥ 90%
COD	4.0	2
BOD	3.0	1
Cu	0.01	0.005
Pb	0.05	0.01
Zn	0.5	0.5
Cd	0.005	0.001
As	0.04	0.01

SDWS (Tables 4.10 to 4.13 show their relations). Table 4.16 shows these lowest requirements, which are the upper limits of the grey constraints on pollutant losses.

The higher objective of the outlet water quality is Grade 2 in the QGS. A description of the Grade 2 is a water quality level of river source without the effects of human activities (XEPB 1988). Therefore, $\underline{\otimes}(a)$, $\underline{\otimes}(b)$, $\underline{\otimes}(f_1)$, $\underline{\otimes}(f_2)$, $\underline{\otimes}(c_1)$ and $\underline{\otimes}(c_2)$ should be the amounts of pollutant losses corresponding to this grade of water quality at the canal's outlet (Tables 4.20 and 4.21). Table 4.17 shows these lower limits of grey constraints.

4. Water Supply and Demand

The canal has a flow of 12.5 m^3/sec, and can transport about 3.9×10^8 m^3 of water per year (Liu et al. 1989).

Water quantity demanded by Xiamen City is about 8.4 m^3/sec for industrial (5.4 m^3/sec), domestic (3.0 m^3/sec), and recreational (0.001 m^3/sec) uses. The remaining 4.1 m^3/sec is for agricultural irrigation in the basin area. Table 4.18 shows the quantities of irrigation water required by different soil-crop combinations.

There are three irrigation ditches (subcanals) delivering water over areas farther from the canal (Subarea 1, 4 and 5). Their flows are shown in Table 4.19 (GXSA 1990).

Table 4.16 Upper limits of grey constraints on pollutant losses

Maximum Allowable Total Nitrogen Losses ⊗(a) (10^6 kg/km^2)	Maximum Allowable Soil Loss ⊗(b) (10^3 kg/km^2)	Maximum Allowable Solid-Phase Nitrogen ⊗(c_1) (10^3 kg/km^2)	Maximum Allowable Solid-Phase Phosphorus ⊗(c_2) (10^3 kg/km^2)	Maximum Allowable Dissolved Nitrogen ⊗(f_1) (10^3 kg/km^2)	Maximum Allowable Dissolved Phosphorus ⊗(f_2) (10^3 kg/km^2)
32.50	138.00	28.70	5.77	91.00	9.90

Table 4.17 Lower limits of grey constraints on pollutant losses

Maximum Allowable Total Nitrogen Losses ⊗(a) (10^6 kg/km^2)	Maximum Allowable Soil Loss ⊗(b) (10^3 kg/km^2)	Maximum Allowable Solid-Phase Nitrogen ⊗(c_1) (10^3 kg/km^2)	Maximum Allowable Solid-Phase Phosphorus ⊗(c_2) (10^3 kg/km^2)	Maximum Allowable Dissolved Nitrogen ⊗(f_1) (10^3 kg/km^2)	Maximum Allowable Dissolved Phosphorus ⊗(f_2) (10^3 kg/km^2)
31.65	124.00	28.20	5.45	86.50	9.10

Table 4.18 Irrigation water required by different croplands in 1989

Crop	Rice	Wheat	Vegetables	Sweet Potato	Total
Irrigation Water Required per Cropping Area per Year $\otimes(Q_{ijt})$ (10^6 m^3/km^2)	[1.0, 1.4]	[0.90, 0.99]	[0.74, 0.86]	[0.85, 1.02]	[3.49, 4.27]
Irrigation Water Required per Cropping Area per Second (m^3/km^2 sec)	[0.048, 0.067]	[0.043, 0.047]	[0.035, 0.041]	[0.040, 0.049]	[0.166, 0.204]
Cropping Area (km^2)	41.11	21.78	11.69	21.19	95.77
Irrigation Water Required (m^3/sec)	[1.97, 2.75]	[0.94, 1.02]	[0.41, 0.48]	[0.85, 1.04]	[4.17, 5.29]

Table 4.19 Flows of three irrigation ditches for Subarea 1, 4 and 5

Ditch	Ditch 1 (for Subarea 1)	Ditch 2 (for Subarea 4)	Ditch 3 (for Subarea 5)
Flow (m^3/sec)	[0.70, 0.77]	[0.78, 0.87]	[0.62, 0.72]

5. Costs and Returns

Table 4.20 shows the average prices and cropping costs of rice, wheat, vegetables and sweet potato in 1989 (XSB 1990, Liu et al. 1989). The net returns of livestock husbandry are shown in Table 4.21. Manure disposal and nitrogen fertilizer costs are ¥[9.25, 11.85]/tonne and ¥[2.58, 3.22]/kg, respectively (Liu et al. 1989).

The costs of water for each cropland in a subarea may include the costs to obtain and transport water to the basin area $\otimes(U)$, deliver the water to different subareas $\otimes(V_t)$, and allocate the water to croplands within each subarea $\otimes(X_{ijt})$. Table 4.22 shows these costs (GXSA 1990).

Table 4.20 Average prices and cropping costs of four crops in 1989

Crop	Rice	Wheat	Vegetables	Sweet Potato
Average Prices $\otimes(\delta_j)$ (¥/kg)	[0.36, 0.44]	[0.405, 0.495]	[0.45, 0.55]	[0.25, 0.31]
Average Cropping Costs $\otimes(G_{ij})$ (¥/km^2)	[315, 385]	[342, 418]	[360, 440]	[225, 275]

Table 4.21 Average net returns of livestock husbandry in 1989

Livestock	Ox	Sheep	Pig	Domestic Fowls
Average Net Return $\otimes(\sigma_k)$ (¥/one)	[1168.41, 1483.60]	[98.57, 106.03]	[410.50, 479.50]	[8.33, 9.87]

Table 4.22 Costs of water for each soil-crop-subarea combination

Costs	Costs to Obtain and Transport Water to the Basin Area $\otimes(U)$ (10^{-3} ¥/m^3)	Costs to Deliver Water to Different Subareas $\otimes(V_t)$ (10^{-3} ¥/m^3)	Costs to Allocate Water to Croplands $\otimes(W_t)$ (10^{-3} ¥/m^3)
Subarea 1	[3.5, 4.1]	[4.0, 4.7]	[1.8, 2.4]
Subarea 2	[3.5, 4.1]	[4.2, 4.8]	[1.7, 2.3]
Subarea 3	[3.5, 4.1]	0	[1.4, 1.8]
Subarea 4	[3.5, 4.1]	0	[1.5, 2.0]
Subarea 5	[3.5, 4.1]	[4.2, 4.8]	[1.7, 2.3]

CHAPTER 5
RESULTS AND DISCUSSIONS

1. Model Calculation

The grey linear programming (GLP) model contains thirty-two decision variables corresponding to cropping areas of four soil-crop combinations, amounts of manure and nitrogen fertilizer applications on these combinations, and the numbers of livestocks in five subareas, as well as over fifty constraints corresponding to various water quantity and quality restrictions. The model's objective is the maximization of net income.

The solutions of the GLP model were worked out by a FORTRAN program with simplex algorithm on the M.T.S. computer system in Simon Fraser University.

Two databases were constructed for the coefficients in the GLP model corresponding to the upper and lower limits (Equations 34 & 35) of the model objective, respectively (Appendix 2). They were compiled from data presented in Chapter 4.

2. Results

Table 5.1 shows the solutions of the GLP model (Equation 20), where $\otimes(A)$ is the solution of objective value (net income of the study area), and $\otimes(S_{ijk})$ (cropping area), $\otimes(F_{ij})$ (amount of manure applied), $\otimes(H_{ij})$ (amount of nitrogen fertilizer applied) and

Table 5.1 Solutions of grey linear programming model

	Decision	Variable		Grey Solution	Scheme for Upper Limit of Objective Function	Scheme for Lower Limit of Objective Function
Symbol	Soil Type	Crop Type	Subarea			
Cropping Area (km^2)						
$\otimes(S_{211})$	wet soil	rice	1	[0, 4.11]	4.11	0
$\otimes(S_{121})$	dry soil	wheat	1	[0, 0.000066]	0	0.000066
$\otimes(S_{131})$	dry soil	vegetables	1	12.12	12.12	12.12
$\otimes(S_{141})$	dry soil	sweet potato	1	0	0	0
$\otimes(S_{212})$	wet soil	rice	2	[0, 4.34]	4.34	0
$\otimes(S_{122})$	dry soil	wheat	2	0	0	0
$\otimes(S_{132})$	dry soil	vegetables	2	[13.31, 13.57]	13.31	13.57
$\otimes(S_{142})$	dry soil	sweet potato	2	0	0	0
$\otimes(S_{213})$	wet soil	rice	3	[5.11, 12.87]	12.87	5.11
$\otimes(S_{123})$	dry soil	wheat	3	[0, 10.97]	10.97	0
$\otimes(S_{133})$	dry soil	vegetables	3	[0, 10.97]	0	10.97
$\otimes(S_{143})$	dry soil	sweet potato	3	0	0	0
$\otimes(S_{214})$	wet soil	rice	4	[0, 15.71]	15.71	0
$\otimes(S_{124})$	dry soil	wheat	4	0	0	0
$\otimes(S_{134})$	dry soil	vegetables	4	9.93	9.93	9.93
$\otimes(S_{144})$	dry soil	sweet potato	4	[0, 0.000018]	0.000018	0
$\otimes(S_{215})$	wet soil	rice	5	[0, 4.16]	4.16	0
$\otimes(S_{125})$	dry soil	wheat	5	0	0	0
$\otimes(S_{135})$	dry soil	vegetables	5	10.57	10.57	10.57
$\otimes(S_{145})$	dry soil	sweet potato	5	0	0	0

Table 5.1(continued) Solutions of grey linear programming model

Decision Variable				Grey Solution	Scheme for Upper Limit of Objective Function	Scheme for Lower Limit of Objective Function
Symbol	Soil Type	Crop Type	Livestock			
Amount of Manure Application (10^6 tonne)						
$\otimes(F_{21})$	wet soil	rice		[0.0025, 2.05]	2.05	0.0025
$\otimes(F_{12})$	dry soil	wheat		[0.0000016, 1.10]	1.10	0.0000016
$\otimes(F_{13})$	dry soil	vegetables		[0.014, 2.96]	0.014	2.96
$\otimes(F_{14})$	dry soil	sweet potato		[0, 0.00000071]	0.00000071	0
Amount of Nitrogen Fertilizer Application (kg)						
$\otimes(H_{21})$	wet soil	rice		0	0	0
$\otimes(H_{12})$	dry soil	wheat		0	0	0
$\otimes(H_{13})$	dry soil	vegetables		0	0	0
$\otimes(H_{14})$	dry soil	sweet potato		[0, 17.97]	17.97	0
Size of Livestock Husbandry (10^3)						
$\otimes(T_1)$			ox	[1.39, 4.16]	4.16	1.39
$\otimes(T_2)$			sheep	[0, 8.00]	0	8.00
$\otimes(T_3)$			pig	[0, 2.56]	0	2.56
$\otimes(T_4)$			domestic fowls	[125.00, 140.00]	140.00	125.00
Net Income (10^6 ¥)						
$\otimes(A)$				[8.13, 27.64]	27.64	8.13

$\otimes(T_l)$ (size of livestock husbandry) are the solutions of decision variables, i = 1, 2; j = 1, 2, 3, 4; k = 1, 2, 3, 4, 5; and l = 1, 2, 3, 4. Among them, $\otimes(S_{211})$, $\otimes(S_{121})$, $\otimes(S_{212})$, $\otimes(S_{132})$, $\otimes(S_{213})$, $\otimes(S_{123})$, $\otimes(S_{133})$, $\otimes(S_{214})$, $\otimes(S_{144})$, $\otimes(S_{215})$, $\otimes(F_{21})$, $\otimes(F_{12})$, $\otimes(F_{13})$, $\otimes(F_{14})$, $\otimes(H_{14})$, $\otimes(T_1)$, $\otimes(T_2)$, $\otimes(T_3)$ and $\otimes(T_4)$ are grey numbers, and $\otimes(S_{131})$, $\otimes(S_{141})$, $\otimes(S_{122})$, $\otimes(S_{142})$, $\otimes(S_{143})$, $\otimes(S_{124})$, $\otimes(S_{134})$, $\otimes(S_{125})$, $\otimes(S_{135})$, $\otimes(S_{145})$, $\otimes(H_{21})$, $\otimes(H_{12})$ and $\otimes(H_{13})$ are white ones. The results suggest that the grey messages in input data (grey coefficients in the objective function and constraints of the GLP model) can only have grey responses from the solutions of $\otimes(S_{211})$, $\otimes(S_{121})$, $\otimes(S_{212})$, $\otimes(S_{132})$, $\otimes(S_{213})$, $\otimes(S_{123})$, $\otimes(S_{133})$, $\otimes(S_{214})$, $\otimes(S_{144})$, $\otimes(S_{215})$, $\otimes(F_{21})$, $\otimes(F_{12})$, $\otimes(F_{13})$, $\otimes(F_{14})$, $\otimes(H_{14})$, $\otimes(T_1)$, $\otimes(T_2)$, $\otimes(T_3)$ and $\otimes(T_4)$.

The solutions with white numbers ($\otimes(S_{131})$, $\otimes(S_{141})$, $\otimes(S_{122})$, $\otimes(S_{142})$, $\otimes(S_{143})$, $\otimes(S_{124})$, $\otimes(S_{134})$, $\otimes(S_{125})$, $\otimes(S_{135})$, $\otimes(S_{145})$, $\otimes(H_{21})$, $\otimes(H_{12})$ and $\otimes(H_{13})$) demonstrate that these decision variables are not affected by the existence of grey numbers (grey intervals) in the model constraints. Most of them are equal to zero, which means that they cannot meet even the lowest requirements of the constraints and are not feasible options.

(1) Cropping Area

On the results of cropping areas, the solutions indicate that fourteen soil-crop-subarea combinations, including $\otimes(S_{211})$, $\otimes(S_{121})$, $\otimes(S_{131})$, $\otimes(S_{212})$, $\otimes(S_{132})$, $\otimes(S_{213})$, $\otimes(S_{123})$, $\otimes(S_{133})$, $\otimes(S_{214})$, $\otimes(S_{134})$, $\otimes(S_{144})$, $\otimes(S_{135})$, $\otimes(S_{215})$, are programmed for farming (the solutions are non-zero), and seven combinations, including $\otimes(S_{141})$, $\otimes(S_{122})$, $\otimes(S_{142})$, $\otimes(S_{143})$, $\otimes(S_{124})$, $\otimes(S_{125})$, $\otimes(S_{145})$, should be left idle (the solutions equal to zero).

In subarea 1, three kinds of crops (rice, wheat and vegetables) are programmed for farming. For rice, the solution (cropping area) is [0, 4.11] km². The solution for vegetables is 12.12 km², which means that 12.12 km² of cropping area for vegetables on dry soil is definite. The value of 12.12 km² is the total area of dry soil in subarea 1. The solution indicates that vegetables are very feasible for the area judged by environmental-economic requirements. Therefore, the constraints for both upper and lower limits of objective function can be satisfied under this option. The cropping area of wheat is programmed to be [0, 0.000066] km², and no sweet potato is programmed. Therefore, wheat and sweet potato are not feasible for farming in this subarea.

In Subarea 2, rice and vegetables are programmed for cropping. The cropping area of rice is [0, 4.34] km², which means that its maximum farming area is 4.34 km², and the minimum is 0 km². All dry soils are programmed to be planted to vegetables (cropping area [13.31, 13.57] km². No wheat or sweet potato is programmed

In Subarea 3, rice, wheat and vegetables are chosen. The cropping area of rice is programmed to be [5.11, 12.87] km². Either wheat or vegetables can be planted to dry soils (both have cropping area of [0, 10.97] km²).

In Subarea 4, rice, vegetables and sweet potato are programmed for farming, and their cropping areas are [0, 15.71] km², 9.93 km² and [0, 0.000018] km², respectively.

Only two kinds of crop (rice and vegetables) are programmed to be planted in Subarea 5. The cropping area for rice is [0, 4.16] km², and for vegetables is 10.57 km².

The above results indicate that rice and vegetables are much more feasible for farming than wheat and sweet potato in the whole study area. Sweet potato is nearly not to be planted in the area (its programmed cropping area is [0, 0.000018] km²).

The scheme for upper limit of objective function in Table 5.1 represents an optimal decision scheme with the highest possible of net income and the most of pollutant losses, and the scheme for lower limit of objective function represents a decision scheme with the lowest net income and the least pollutant losses. There is no option with both the highest net income and the least pollutant losses. Therefore, higher $\otimes(S_{211})$, $\otimes(S_{131})$, $\otimes(S_{212})$, $\otimes(S_{213})$, $\otimes(S_{123})$, $\otimes(S_{214})$, $\otimes(S_{134})$, $\otimes(S_{144})$ and $\otimes(S_{215})$, and lower $\otimes(S_{121})$, $\otimes(S_{132})$ and $\otimes(S_{133})$ within the grey solutions should be programmed in order to achieve higher income; and lower $\otimes(S_{211})$, $\otimes(S_{131})$, $\otimes(S_{212})$, $\otimes(S_{213})$, $\otimes(S_{123})$, $\otimes(S_{214})$, $\otimes(S_{134})$, $\otimes(S_{144})$ and $\otimes(S_{215})$, and higher $\otimes(S_{121})$, $\otimes(S_{132})$ and $\otimes(S_{133})$ within the grey solutions should be programmed for better canal water quality. All these grey variables can be adjusted within their grey intervals in the final decision scheme.

Under the scheme for the lower limit of objective function, three kinds of crop (excluding sweet potato) are programmed for farming, and the total cropping area is 62.27 km^2, which is 63.31% of the tillable land area in the basin area. Under the scheme for upper limit of objective function, all four kinds of crop are chosen, and the total cropping area is 98.09 km^2, which is 99.74% of the tillable land area in the study area.

(2) Manure and Nitrogen Fertilizer Applications

Manure and nitrogen fertilizer applications are the major pollutant sources of the canal. The amount of manure applied to rice land is programmed to be $[2.45 \times 10^3, 2.05 \times 10^6]$ tonnes, which means that the maximum amount of manure applied to rice land is 2.05×10^6 tonnes, and the minimum is 2.45×10^3 tonnes. The amount of manure applied to wheat land is programmed to be $[1.63, 1.10 \times 10^6]$ tonnes, that to vegetable lands $[13.6 \times 10^3, 2.96 \times 10^6]$ tonnes, and that to sweet potato land $[0, 0.71]$ tonnes.

On nitrogen fertilizer application, only $[0, 17.97]$ kg are programmed to be applied to sweet potato land as a supplement to manure. The result means that the maximum amount of nitrogen fertilizer application is 17.97 kg, and the minimum is 0 kg when sweet potato is not programmed for farming under the scheme for lower limit of objective function.

The study results indicate that rice and vegetable lands receive most of the manure, which corresponds to the programmed cropping areas (rice and vegetables have the largest areas, and sweet potato the least).

Higher $\otimes(F_{21})$, $\otimes(F_{12})$, $\otimes(F_{13})$, $\otimes(F_{14})$ and $\otimes(H_{14})$ within the grey solutions can be programmed for higher income; and lower $\otimes(F_{21})$, $\otimes(F_{12})$, $\otimes(F_{13})$, $\otimes(F_{14})$ and $\otimes(H_{14})$ should be chosen for better canal water quality. All these grey variables can be adjusted within their grey intervals in the final decision scheme.

Therefore, much more manure and fertilizer should be applied under the upper limit of the objective function than under the lower one, which also corresponds with the cropping area differences between the two limits. Thus, both higher income from more cropping area and lower canal water quality caused by more manure and nitrogen fertilizer applications can be derived under the scheme for the upper limit of objective function. Similarly, lower income but higher canal water quality can be derived under the scheme for the lower limit.

(3) Livestock Husbandry

The results of livestock husbandry indicate that four kinds of livestock are all programmed to be fed. The number of ox is programmed to be $[1.39 \times 10^6, 4.16 \times 10^6]$. The number of domestic fowls is $[125 \times 10^3, 139 \times 10^3]$. The numbers of sheep and pig are programmed to be $[0, 8.00 \times 10^3]$ and $[0, 2.56 \times 10^3]$, respectively.

Domestic fowls are programmed to have the largest size, followed by ox, pig and sheep. However, in terms of net income, ox husbandry contributes the most, followed by domestic fowls, and sheep the least. Incomes of domestic fowl husbandry are from both fowls and eggs.

Higher $\otimes(T_1)$ and $\otimes(T_4)$ and lower $\otimes(T_2)$ and $\otimes(T_3)$ within the grey solutions can be programmed for higher income; and lower $\otimes(T_1)$ and $\otimes(T_4)$ and higher $\otimes(T_2)$ and $\otimes(T_3)$ should be chosen for better canal water quality. These grey variables can be adjusted within their grey intervals in the final decision scheme.

On the difference between the schemes for the upper limit of objective function and that for the lower limit, ox, sheep, pig and domestic fowls are all programmed to be fed under the lower limit, and only ox and domestic fowls are chosen under the higher one. However, the numbers of ox and domestic fowls under the upper limit are much more than those under the lower limit. Thus, both more income and more manure production, which leads to lower canal water quality, can be derived from the scheme for the upper limit, and both less income and less manure production can be derived from the scheme for the lower limit.

(4) Summary

Two schemes for the upper and lower limits of objective function represent two different decision alternatives regarding environmental-economic tradeoffs. When the canal water quality has precedence, the scheme for lower limit of objective function has to be adopted. Under this alternative, the total cropping area is 62.27 km^2, and only three kinds of crop (sweet potato is excluded) are planted; the total amount of manure application is

2.96×10^6 tonnes which are applied to the three croplands; no nitrogen fertilizer is used; and 1390 oxen, 8000 sheep, 2560 pigs and 125000 domestic fowls are fed.

Generally, the values of $\otimes(S_{121})$, $\otimes(S_{132})$, $\otimes(S_{133})$, $\otimes(T_2)$ and $\otimes(T_3)$ should be as high as possible and those of $\otimes(S_{211})$, $\otimes(S_{131})$, $\otimes(S_{212})$, $\otimes(S_{213})$, $\otimes(S_{123})$, $\otimes(S_{214})$, $\otimes(S_{134})$, $\otimes(S_{144})$, $\otimes(S_{215})$, $\otimes(F_{21})$, $\otimes(F_{12})$, $\otimes(F_{13})$, $\otimes(F_{14})$, $\otimes(H_{14})$, $\otimes(T_1)$ and $\otimes(T_4)$ be as low as possible within the grey solutions. Under this decision scheme, the best possible water quality of the canal can be realized, but agricultural income will decrease.

When agricultural income has precedence, the scheme for upper limit of objective function can be adopted. Under this alternative, the total cropping area can be 98.09 km^2, and all four kinds of crop are planted; the total amount of manure application can be 3.16×10^6 tonnes; 17.97 kg of nitrogen fertilizer can be applied; and 4160 oxen and 140000 domestic fowls can be fed.

Generally, the values of $\otimes(S_{211})$, $\otimes(S_{131})$, $\otimes(S_{212})$, $\otimes(S_{213})$, $\otimes(S_{123})$, $\otimes(S_{214})$, $\otimes(S_{134})$, $\otimes(S_{144})$, $\otimes(S_{215})$, $\otimes(F_{21})$, $\otimes(F_{12})$, $\otimes(F_{13})$, $\otimes(F_{14})$, $\otimes(H_{14})$, $\otimes(T_1)$ and $\otimes(T_4)$ should be as high as possible, and those of $\otimes(S_{121})$, $\otimes(S_{132})$, $\otimes(S_{133})$, $\otimes(T_2)$ and $\otimes(T_3)$ be as low as possible within the grey solutions. Under this decision scheme, the highest agricultural income can be achieved, but water quality of the canal becomes poorer and the reliability of meeting water quality objectives becomes lower.

In summary, programming for lower limit of objective function should guarantee that water quality standards be met, but as programming aims toward the upper limit, the probability of achieving water quality objectives decreases (i.e. the risk of substandard water increases). In other words, programming for the lower limit represents a conservative strategy and would be appropriate for 100% certainty of attaining water quality standards.

3. Discussions

(1) From Whole Xiamen Area Point of View

A. Water Quality

Water quality at the canal's outlet will mostly meet the Standards for Drinking Water Sources (SDWS) (XEPB 1988) under the resulting decision schemes. However, it should be emphasized that the scheme for upper limit of objective function is a critical solution corresponding to the standard values of the SDWS, and it may not ensure water quality objectives would be met. Therefore, as programming aims toward the upper limit, the probability of substandard water quality may increase.

The canal water is ultimately imported to Xiamen Waterworks, and, through certain treatment processes, the waterworks will supply tap water to Xiamen City for multiple uses. The inlet water requirements of the waterworks were set to be the SDWS. Therefore, under the resulting decision schemes, these requirements will mostly be met, and satisfactory water quality will be ensured for multiple uses, especially domestic drinking use.

This improvement of canal water quality is based on the decrease of agricultural net income in the canal basin. The study results in Table 5.1 indicate that the higher the requirements of canal water quality, the lower the income in the canal basin. Therefore, in order to improve water supply quality for Xiamen City, the canal basin has to pay costs of reducing agricultural income.

In fact, according to the Function Division of Xiamen Special Economic Zone (Xiamen Government 1984), the main function of Xiamen Suburban Area (XSA) is to assist the development of Xiamen City by supplying agricultural products. In 1989, the gross output value of Xiamen City (¥ 7.80 billions) was over 34 times that of XSA (¥ 229.28 millions), and population in the city (712000) was over 5 times that in XSA (129000). Therefore, the reason why the canal water quality protection has the precedence can be revealed by the comparison of water quality protection for ¥ 7.80 billions of output value and 712000 of population in Xiamen City with agricultural development for only ¥229.28 millions of output value (2.94% of that in Xiamen City) in XSA where the canal basin is included.

B. Water Quantity

According to Water Management Regulation of Beixi Canal (GXSA 1987), water demand of Xiamen City (8.4 m^3/sec) must be ensured without preconditions. This is based on two considerations: first, the canal was designed primarily to supply drinking water to Xiamen City when it was built in the 1970's; and second, the output value per m^3 of water consumption in Xiamen City (¥ 29.44/m^3) was over 70 times of that in the study area (¥ 0.41/m^3) in 1989, which indicates that it is more efficient to supply sufficient water for Xiamen City than for the study area.

Therefore, the water quantity problem for the study area is how to allocate optimally the remaining water (4.1 m^3/sec), which is insufficient for the area, to various soil-crop-subarea combinations. The study results indicate that some soils should be left idle because of water quantity and quality restrictions (Table 5.1). It is recommended that fruit trees consuming less water and manure/fertilizer be planted on the idle soils.

C. Incomes

In 1989, the gross output value of Xiamen City was over 97.1% of that of whole Xiamen Area and over 200 times of that of the study area. From an economic point of view, the development of Xiamen City has precedence over the other parts of Xiamen Area. Therefore, water supply to Xiamen City with good quality and sufficient quantity should be ensured. Thus, the first economic objective of the study area is to supply water with good quality and sufficient quantity to Xiamen City by the canal, and the second is then the maximization of agricultural income of the area itself under the water quantity and quality constraints from Xiamen City.

Comparing the study results in Table 5.1 with environmental and economic situations of the study area in 1989, we can find that water quality at the canal's outlet would be improved from a poor level (concentrations of many pollutants cannot meet the SDWS) in 1989 to a better one (all pollutant concentrations meet the SDWS) under the programmed results, and water demands of Xiamen City would also be ensured. However, agricultural income under the programmed results will become less than that in 1989 (from 35.07 million to [8.13, 27.64] million). The results indicate that in order to supply water to Xiamen City with good quality and sufficient quantity, the canal basin has to pay costs of reducing agricultural income.

(2) From the Basin Area Point of View

A. Farming Areas

The study results indicate that [0.26, 35.04] km^2 of farmland should be left idle because of water quantity/quality restrictions. Of these, [0, 4.11] km^2 should be left idle in subarea 1, [0.26, 4.34] km^2 in subarea 2, [0, 7.76] km^2 in subarea 3, [0, 15.71] km^2 in subarea 4, and [0, 4.16] km^2 in subarea 5.

The most seriously affected crop is sweet potato. In subareas 1, 2, 3 and 5, no sweet potato is programmed to be planted. Only [0, 0.000018] km^2 can be planted in Subarea 4, which is [0, 0.000085]% of its cropping area in 1989.

Thus, in order to satisfy Xiamen City's water requirements, the study area has to pay costs of reducing cropping areas. The costs are worthwhile because the farming output value in the area is only 0.24% of the gross output value in Xiamen City (1989), and it is not allowed by the local government to pay the costs of affecting Xiamen City's industrial, domestic and recreational water uses for increasing the very small farming output value (Xiamen Government 1984).

B. Manure and Nitrogen Fertilizer Applications

The study results (Table 5.1) indicate that both manure and nitrogen fertilizer applications should be restricted. In fact, pollutant losses from farmlands are strongly related to manure and nitrogen fertilizer applications. Therefore, cutting down manure/fertilizer application is a key measure of reducing pollutant losses, which can cause changes in livestock numbers, cropping areas, and agricultural income, etc. For the alternative of manure or nitrogen fertilizer, the former is much preferred. In fact, from the results of canal water quality simulation, only limited amounts of nutrient (mainly from manure or fertilizer) can be applied in the basin area because of the canal water quality constraints. Therefore, how optimally to apply nutrients to croplands, i.e., how to make efficient use of the limited pollutant discharge allowances, becomes a problem.

Manure is cheaper to buy and apply, and is related to livestock husbandry which can also contribute to agricultural income when consuming the limited allowances, while fertilizer is more expensive and consumes the limited allowances without any compensation in income. The study results reflect the fact. Almost no nitrogen fertilizer is programmed to be applied in the optimal solutions (only one soil-crop-subarea combination (sweet potato in Subarea 4) is to use [0, 17.97] kg of nitrogen fertilizer). Manure is preferred, and all manure generated in the basin area is programmed to be applied to farmlands.

C. Livestock Husbandry

Livestock husbandry is related to both income and crop nutrient requirements.

The programming results indicate that more ox and domestic fowls, and less sheep and pig should be fed. In terms of market demands, a great quantity of ox, fowls and eggs is demanded by Xiamen City. Especially, fowls (chicken and duck) are favored by Xiamenese, and their demands frequently exceeded supplies from XSA and were complemented by other parts of the country in recent years.

Over 10 new pig farms have been built in Xiamen Suburban Area since 1980 when Xiamen City became a special economic zone, in order to correspond to the quick development of the city. Presently, pork supplies exceed demands because the population development of Xiamen City does not amount to the predicted scale. Therefore, pig husbandry is not encouraged in other parts of XSA. Mutton is not favored by Xiamenese, and sheep husbandry is not encouraged, too. Therefore, the decision scheme of livestock husbandry corresponds with present market demands and is applicable from both the study area and whole Xiamen Area points of view.

(3) Advantages of the GLP Model Compared with Previous Systems Analysis Methods

In the previous systems analysis methods, input coefficients and parameters in the objective function and constraints are expressed as white numbers (certain numbers), and the derived solutions (decision variables) are white numbers, too. Therefore, neither the inputs (coefficients and parameters) nor the outputs (solutions) can reflect the uncertainties in the real world.

In the GLP model, uncertain messages of the coefficients and parameters are expressed as grey numbers and incorporated into the model, and the derived solutions contain grey numbers which can reflect the uncertainties of the decision schemes. Therefore, for water resource managers, the GLP model provides a better management tool. Its advantages are as follows.

(a) In the interpretation of solutions, the GLP model provides grey outputs (grey solutions) which can reflect uncertainties of decision making, and are direct and convenient for the managers to interpret and apply to practical problems. However, previous systems analysis methods can only give white solutions (certain numbers) which are difficult to be interpreted in complicated systems where problems of uncertainty exist, because it may not be suitable to use certain numbers to represent uncertain problems (uncertainties of decision making) in the real world.

(b) In the GLP model, the grey solutions provide possible ranges of the model objective and relevant decision variables by grey numbers. Therefore, water resource managers can adjust the decision scheme and make tradeoffs between the objectives and relevant decision variables according to the practical situations. For example, in this study, when a conservative strategy, which emphasizes the insurance of the canal water quality, is adopted, the decision scheme for the lower limit of objective value would be appropriate; and when a radical strategy, which emphasizes the development of agricultural production, is adopted, the scheme for the upper limit might be used. However, the risk of substandard water becomes high under the upper limit scheme because the amounts of agricultural pollutant losses will arrive at the critical values corresponding to relevant quality standards (SDWS). Therefore, the managers can adjust the decision variables between the two extreme strategies.

In comparison, the previous methods can provide only one set of solutions of model objective and decision variables, and are not flexible for making adjustments when the results are applied. When the values of model objective or decision variables need to be adjusted, it will be very difficult, or even impossible, for the methods to provide further scientific bases.

(c) Solutions of the GLP model, which contain grey messages, can be interpreted as infinite potential decision schemes (whitening solutions). Therefore, much more options from the GLP model than those from the previous methods are provided for the decision makers. This is especially significant when details of a decision scheme are discussed.

(4) Limitation of the GLP Model

In this study, a GLP model was constructed and applied because relations between decision variables in the model constraints and objective function can be treated by linear expressions. For example, on the constraint of manure application(Equation 4 in Chapter 3), relations between amounts of manure spread on croplands and sizes of livestock husbandry:

$$\sum_{i=1}^{m} \sum_{j=1}^{n} F_{ij} - \left(\sum_{k=1}^{l} \otimes(B_k)\, T_k + B_0\, T_0\right)^{m} = 0$$

can be nonlinear if $m \neq 1$. However, m is very closed to 1: $m \rightarrow 1$, because direct relation between the two variables exist: manure spread on soil-crop component is from livestock and human components. Therefore, linearizing the constraint by the following expression is reasonable:

$$\sum_{i=1}^{m} \sum_{j=1}^{n} F_{ij} - \left(\sum_{k=1}^{l} \otimes(B_k)\, T_k + B_0\, T_0\right) = 0 .$$

Similarly, on the constraint of crop nitrogen requirements (Equation 6 in Chapter 3), relations between amounts of manure spread, amounts of nitrogen fertilizer spread, and cropping areas are linear, because the crop nitrogen requirements are satisfied by manure and fertilizer applications; on the constraints of livestock and human nutrient requirements (Equation 7 and 8 in Chapter 3), relations between cropping areas and sizes of livestock husbandry are linear, because the nutrient requirements by livestocks are principally supplied by onfarm crops; on the constraints of pollutant losses (Equation 9 to 15 in Chapter 3), linear relations exist between cropping areas, amounts of manure spread, and amounts of nitrogen fertilizer spread, because the crop nutrient requirements are supplied by manure and fertilizer applications, and the applied nutrients, not taken by the crops, can leave croplands as pollutant losses; and the constraints of water quantity requirements (Equation 18 to 20 in Chapter 3) describe simple linear relations between cropping areas in different subareas where quantities of irrigation water required and water costs are different.

However, relations between decision variables in some complicated systems can be obviously nonlinear. Therefore, development of grey nonlinear programming (GNP) model would be valuable.

Until now, there has still been no report of the study in grey nonlinear programming (GNP) method. In fact, in complicated systems where many constraints and decision variables exist, even a traditional nonlinear programming (TNP) model is very difficult to be solved (a large amount of human-computer dialog is required), and sometimes only better solutions rather than optimal solutions can be derived. Therefore, whenever possible, most of systems analyzers would rather use linear programming model which is much easier to be solved although errors may exist due to the linearization of the nonlinear relations between variables. For example, given a nonlinear constraint:

$$aX_1 + bX_2^{9/10} \leq c,$$

if we know: $5 \leq X_2 \leq 10$, we can linearize the constraint to:

$$aX_1 + 0.82bX_2^{9/10} \leq c,$$

or express it as a grey linear constraint:

$$aX_1 + [0.79, 0.85]bX_2^{9/10} \leq c.$$

However, when relations between decision variables cannot be linearized in very complicated grey systems, a GLP model has to be applied. Therefore, development of GLP method, especially its solving approach, is very important for broadening the applicable range of grey systems theory.

CHAPTER 6

SENSITIVITY ANALYSES

1. Impacts of Pollutant Loss Constraints on Agricultural Income

The effects of pollutant loss reductions on farm income are determined by solving the GLP model for various values of pollutant loss constraints.

Tables 6.1 to 6.7 (see Appendix VI) show seven sets of solutions with different pollutant loss constraints. Table 6.1 shows the solutions of income-maximizing plans with no restrictions on pollutant losses (Table 6.1). The solutions indicate both the maximum income and pollutant losses that could be obtained from the agricultural production. If these pollutant losses are acceptable, no changes in management practices are necessary, and the net income would be ¥8.09×10^9.

Table 6.2 shows the impact of reductions of allowable total nitrogen losses $\otimes(a)$ from 35×10^6 kg/km^2 to 30×10^6, 25×10^6, or 20×10^6 kg/km^2. These results are obtained by setting $\otimes(a)$ equal to 35×10^6, 30×10^6, 25×10^6, or 20×10^6 kg/km^2, and leaving other pollutant losses unconstrained. The primary effects are to reduce the amounts of manure and nitrogen fertilizer application in order to meet the lower nitrogen losses and, since less manure and/or fertilizer are allowed to be produced and applied, smaller cropping area and livestock sizes will apply. Therefore, as the allowable total nitrogen losses are decreased from 35×10^6 kg/km^2 to 20×10^6 kg/km^2, the net income of the area will decrease from ¥10.59×10^6 to ¥6.05×10^6.

The third set of solution is based on alternative limits on soil loss (⊗(b) = 140 × 10^3, 120 × 10^3, 100 × 10^3, and 80 × 10^3 kg/km^2) (Table 6.3). The results are comparable to those produced by nitrogen restrictions except that more rice soil is planted because it is less erosive. As the allowable soil loss decreases from 140 × 10^3 kg/km^2 to 80 × 10^3 kg/km^2, the net income of the area would decrease from ¥9.94 × 10^6 to ¥6.47 × 10^6.

Tables 6.4 to 6.7 are solutions for restrictions on dissolved nitrogen and phosphorus losses (⊗(f_1) and ⊗(f_2)), and solid-phase nitrogen and phosphorus losses(⊗(c_1) and ⊗(c_2)). The solutions under dissolved nitrogen and phosphorus loss constraints are similar to the solutions obtained with total nitrogen constrained. As the allowable dissolved nitrogen loss decreases from 90 × 10^3 kg/km^2 to 60 × 10^3 kg/km^2, the net income of the area would decrease from ¥9.29 × 10^6 to ¥6.72 × 10^6, and as the allowable dissolved phosphorus loss decreases from 12 × 10^3 kg/km^2 to 6 × 10^3 kg/km^2, the net income of the area would decrease from ¥11.68 × 10^6 to ¥6.59 × 10^6. Solid-phase nitrogen and phosphorus restrictions produce solutions similar to the results for soil loss constraints. As the allowable Solid-phase nitrogen loss decreases from 30 × 10^3 kg/km^2 to 15 × 10^3 kg/km^2, the net income of the area would decrease from ¥9.64 × 10^6 to ¥5.94 × 10^6, and as the allowable Solid-phase phosphorus loss reduces from 6 × 10^3 kg/km^2 to 3 × 10^3 kg/km^2, the net income of the area would decrease from ¥9.55 × 10^6 to ¥6.15 × 10^6.

2. Costs of Reducing Pollutant Losses

The impacts of pollutant loss constraints on agricultural income can be presented as in Figures 6.1 to 6.6 (see Appendix VI) to show the costs of reducing nonpoint source pollutant losses from the basin area. Costs are measured as losses in farm income.

For example, for total nitrogen losses (Figure 6.1), if the losses are reduced from 35 × 10^6 kg/km^2 to 20 × 10^6 kg/km^2 (reduce 42.86%), this costs ¥4.54 × 10^6 in lost income.

Those lines represent environmental/economic trade-offs. Trade-offs must occur when objectives are incompatible. Thus we cannot reduce pollutant losses without also increasing costs (reducing income). The slope of the curve in Figure 6.1 is approximately 105.67 × 10^3, indicating that we can "trade off" income for reductions in total nitrogen losses at the rate of ¥105.67 × 10^3 for each 1% improvement (reduction) in losses. The slope for Figure 6.2 is approximately 81.18 × 10^3, indicating that the rate of "trade off" is ¥81.18 × 10^3 for each 1% improvement (reduction) in losses. The slopes for Figure 6.3 to 6.6 are approximately 77.41 × 10^3, 101.98 × 10^3, 73.78 × 10^3, and 67.79 × 10^3, respectively, indicating that they have similar "trade off" rates.

3. Impacts of Water Quantity Constraints on Agricultural Income

The effects of water supply (from the canal) on agricultural income are determined by solving the GLP model for different values of water quantity constraints (Equation 16).

Table 6.8 (see Appendix VI) shows the impact of reductions of water supply from 50 × 10^6 m^3/yr to 40 × 10^6, 30 × 10^6, or 20 × 10^6 m^3/yr. The primary effects are to reduce cropping area in order to meet the lower water supply. Since the cropping area is smaller, less fertilizer would be applied, and fewer livestocks would be fed due to less nutrient supply. Therefore, as water supply decreases from 50×10^6 m^3/yr to 20×10^6 m^3/yr, the cropping area and livestock number would decrease correspondingly, and the net income of the study area would decrease from ¥11.14×10^6 to ¥6.38×10^6.

4. Effects of Grey Inputs on Grey Outputs

(1) Definition of Grey Degree (Gd)

The grey degree of a grey number is its grey interval divided by its whitening mean value. Given a grey number $\otimes(x) = [\underline{\otimes}(x), \overline{\otimes}(x)]$, and its whitening mean value M(x), we can calculate its grey degree $Gd[\otimes(x)]$:

$$Gd[\otimes(x)] = \{[\overline{\otimes}(x) - \underline{\otimes}(x)]/M(x)\} \times 100\%$$

(2) Grey Inputs and Grey Outputs

Grey inputs are the input data of grey coefficients in the objective function and constraints of the GLP model, and grey outputs are the output solutions of the model. Table 6.9 and Figure 6.7 shows the relations between the grey degrees of grey inputs (grey coefficients) and those of grey outputs (net income) in the GLP model. The results indicate that the grey degrees of grey outputs increase non-linearly with the increases of the grey degrees of grey inputs. The results demonstrate that the grey solutions (grey outputs) are sensitive to the effects of grey coefficients (grey inputs).

Table 6.9 Effects of grey inputs on grey outputs

Increases in Grey Degrees of Grey Inputs (%)	0	10	15	20
Grey Degrees of Grey Outputs $G_d[\otimes(A)]$ (%)	109.09	129.56	147.29	198.94
Increases in Grey Degrees of Grey Outputs (%)	0	18.76	35.00	82.35

Figure 6.7 Effects of grey inputs on grey outputs

CHAPTER 7
CONCLUSIONS

1. Summary

(1) A grey systems analysis of water quantity allocation and quality protection has been applied in a canal basin in Xiamen, China. The trade-offs between meeting water quantity and quality objectives has been evaluated, and the concepts of grey systems theory has been introduced into water resource management as a means for accounting for uncertainty. A grey linear programming (GLP) model was developed, and a new approach for solving the GLP model was advanced.

(2) The results indicate that the quantity of water allocated varies with the demands for domestic, agricultural, industrial and recreational uses, the capacity of canal flow, the size of each subarea in the basin area, and the costs of delivering water to each subarea, and the canal water quality varies with the availability of water supply, the nonpoint source pollutant discharge, the type of fertilizer and manure spread used by farmer, the type of soil, the kind of crops grown, and the type of livestock raised. Water quantity and quality are interrelated and the efficient management of one generally depends on the other. Therefore, a systems analysis of the constraints and uncertainties affecting water quantity and quality management is an efficient way to deal with the water problems.

(3) In terms of technology, this study suggests that grey systems analysis is a useful means for decision making of water quantity and quality management under uncertainty, and the proposed new solving approach for GLP model can efficiently reflect

the effects of grey messages. Reliabilities of the method, its solving approach, and its application have been demonstrated through sensitivity tests of the impacts of pollutant loss constraints on agricultural income, the costs of reducing pollutant losses, the impacts of water quantity constraints on agricultural income, and the effects of grey inputs on grey outputs.

(4) In the case study of Xiamen, China, the results indicate that the derived decision schemes are feasible for the study area. When the canal water quality has precedence, the scheme for lower limit of objective function has to be adopted. Under this alternative, less cropping area, manure application and livestock numbers, and no fertilizer application are programmed. When agricultural income has precedence, the scheme for upper limit of objective function can be adopted. Under this alternative, more cropping area, manure application and livestock numbers, and some fertilizer application are programmed. Therefore, decision makers can adjust the grey decision variables (including cropping area, manure and fertilizer applications and livestock numbers) within their grey intervals according to the applicability analysis of the detailed situations.

2. Contributions of this study

This study has contributed to five aspects of water resource and environmental management:

(1) A new methodology has been first introduced to water resource management. Grey systems theory has been successfully applied in military, agricultural, and economic

decision making. However, there had been no previous application in water resource planning and decision making. This study is a new attempt.

(2) A new solving approach of GLP model has been advanced. It improved the previous creditability methods, and allows grey messages in the GLP model be communicated into optimization processes and solutions. The reliability of the new approach has been demonstrated through the sensitivity test of the effects of grey inputs on grey outputs.

(3) A new application field -- water quantity and quality management in a water delivery canal connected to a drainage basin -- has been studied. Previous studies of water quantity and quality management were related to river or lake basins, and none was about a canal with strict water quality requirements.

(4) A new case -- water quantity and quality management in China -- has been studied. None of the previous studies of water resource planning in China combined the quantity and quality problems in an optimization framework.

(5) For the study area (Xiamen Area), this study will be valuable for the formation of local policies, standards, and regulations of water resources management and protection; the planning of regional economic development; the decision of comprehensive schemes of regional environmental pollution control; the adjustment of the interrelationship between urban and rural areas; and the insurance of good water supply (in both quantity and quality) for Xiamen City.

3. Limitation and Extension of This Study

(1) In this study, a GLP model was constructed and a new solving approach advanced. However, relations between decision variables under some situations can be nonlinear. Therefore, development of grey nonlinear programming (GNP) methods and relevant solving approaches would be very valuable for broadening the applicable range of grey systems theory.

(2) In the GLP model, grey messages are expressed as grey numbers with upper and lower limits. However, when a phenomenon is very fuzzy (i.e., it has a very high grey degree), the solutions will also have high grey degrees. The integration of fuzzy sets theory into the grey systems theory may provide a framework for more efficient solutions.

(3) The constructed GLP model can only deal with average annual conditions, and does not account for interannual variations, nor for lag effects. One lag example is the application of fertilizer which can affect the soil structure, crop yields and pollutant losses in following years.

(4) In this study, fixed prices for the crops (yearly average prices) and water supply are used, which is only applicable for China where the prices are determined by the government. In a free-market economy, the prices will vary with supply (i.e. cropping areas). Therefore, further studies of the effects of the price variations would be significant.

(5) In the case study, the agricultural system is considered as a system with human, livestock, and soil-crop components, and some relations are expressed as linear equations relating to water quality and quantity management. In reality, an agricultural system is a multilevel, multicomponent and multivariable system where intricate relations exist between

subsystems. Therefore, further considerations of the complexity in the grey programming model and its solubility would be helpful for making a more feasible decision.

(6) Owing to the complex nature of water resources problems, the data base required for this study is extensive. Although most data sources are relatively accurate (certain numbers, or grey numbers with low grey degree), others are less so (grey numbers with high grey degree). Therefore, increasing the accuracy of the data sets, i.e., decreasing the grey degrees of the input grey data, would increase the confidence of the results generated. That is, the grey degrees of the output results (solutions) would be decreased.

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APPENDIX I

COMPUTER PROGRAM OF GREY LINEAR PROGRAMMING MODEL

```
C     PROGRAM OF GLP MODEL
      DIMENSION A(900,900),X(9000),NR(9000)
      READ (5,100) M, N, TYPE
  100 FORMAT(1X,2I3,E15.6)
      E=0.0001
      M1=M+2
      M2=M-1
      M3=M+1
      M4=M-4
      M5=M-3
      N1=N+1
      N2=N+M+1
      N3=N+M
      N4=N+2
      DO 105 J=1,N2
      DO 105 I=1,N4
  105 A(I,J)=0.0
      DO 110 I=1,M
  110 X(I)=0.0
      DO 118 I=2,N1
      READ (5,115) (A(I,J), J=1,M4)
  115 FORMAT (1X,4E15.6)
      READ (5,116) (A(I,J), J=M5,M1)
  116 FORMAT (1X,6E15.6)
  118 CONTINUE
      READ (5,117) (A(1,I), I=1,M)
  117 FORMAT (1X,4E15.6)
      DO 120 I=2,N1
      DO 120 J=1,M1
  120 A(I,J)=SIGN(1.0, A(I,M1))*A(I,J)
      DO 125 I=1,M
  125 A(1,I)=-TYPE*A(1,I)
      IF (N.EQ.1) GOTO 135
      DO 130 I=2,N1
      A(I,N2)=A(I,M1)
      A(I,M1)=0.0
      IF (I.EQ.2) GOTO 130
      M4=I+M2
      A(I,M4)=A(I,M3)
      A(I,M3)=0.0
  130 CONTINUE
  135 L=1
      DO 145 I=2,N1
      M5=I+M2
      NR(I)=M5
      IF (A(I,M5).EQ.1.0) GOTO 145
      NR(I)=N2
      DO 140 J=1,N3
  140 A(N4,J)=A(N4,J)-A(I,J)
      L=N+2
  145 CONTINUE
  150 L2=1
```

```
      DO 160 I=2,N3
      IF (A(L,I)-A(L,L2).GT.E) GOTO 160
      IF (A(L,I)-A(L,L2).LT.-E) GOTO 155
      IF (L.EQ.1) GOTO 160
      IF (A(1,I)-A(1,L2).GE.-E) GOTO 160
155   L2=I
160   CONTINUE
      IF (A(L,L2).LT.-E) GOTO 180
      IF (L.EQ.1) GOTO 230
      DO 165 I=1,N3
      IF (A(L,I).GT.E) GOTO 170
165   CONTINUE
      L=1
      GOTO 150
170   DO 175 I=2,N1
      IF (NR(I).LE.N3) GOTO 175
      IF (A(I,N2).GT.E) GOTO 210
175   CONTINUE
      GOTO 230
180   L1=1
      DO 190 I=2,N1
      IF (A(I,L2).LE.E) GOTO 190
      Y=A(I,N2)/A(I,L2)
      IF (L1.EQ.1) GOTO 185
      IF (Y.GE.(A(L1,N2)/A(L1,L2))) GOTO 190
185   L1=I
190   CONTINUE
      IF (L1.EQ.1) GOTO 220
      NR(L1)=L2
      Y=A(L1,L2)
      DO 195 I=1,N2
195   A(L1,I)=A(L1,I)/Y
      DO 205 I=1,N4
      IF (I.EQ.L1) GOTO 205
      Y=A(I,L2)
      DO 200 J=1,N2
200   A(I,J)=A(I,J)-Y*A(L1,J)
205   CONTINUE
      GOTO 150
210   WRITE (6,215)
215   FORMAT (1H0,'INFEASIBLE')
      GOTO 250
220   WRITE (6,225)
225   FORMAT (1H0,'UNBOUNDED')
      GOTO 250
230   DO 235 I=2,N1
      IF (NR(I).GT.M) GOTO 235
      J=NR(I)
      X(J)=A(I,N2)
235   CONTINUE
      Y=TYPE*A(1,N2)
```

```
      WRITE (6,240) Y
240   FORMAT (1H0,20HOBJECTIVE FUNCTION=, E15.6)
      WRITE (6,245) (I,X(I),I=1,M)
245   FORMAT (13X,2HX(, I3,3H)=, E15.6)
250   STOP
      END
```

APPENDIX II

INPUT DATABASES FOR CALCULATIONS

APPENDIX II INPUT DATABASES FOR CALCULATIONS

1. Input Database for Lower Limit of Objective Function

```
32,55,1.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
1.,1.,1.,1.
0.,0.,0.,0.
-117.,-22.5,-82.81,-3.42,0.,1976400.
-1800.,0.,0.,0.
-1800.,0.,0.,0.
-1800.,0.,0.,0.
-1800.,0.,0.,0.
-1800.,0.,0.,0.
3.75,0.,0.,0.
0.85,0.,0.,0.
0.,0.,0.,0.,-1.,0.
0.,-1110.,0.,0.
0.,-1110.,0.,0.
0.,-1110.,0.,0.
0.,-1110.,0.,0.
0.,-1110.,0.,0.
0.,3.75,0.,0.
0.,0.85,0.,0.
0.,0.,0.,0.,-1.,0.
0.,0.,-1100.,0.
0.,0.,-1100.,0.
0.,0.,-1100.,0.
0.,0.,-1100.,0.
0.,0.,-1100.,0.
0.,0.,3.75,0.
0.,0.,0.85,0.
0.,0.,0.,0.,-1.,0.
0.,0.,0.,-1000.
0.,0.,0.,-1000.
0.,0.,0.,-1000.
0.,0.,0.,-1000.
0.,0.,0.,-1000.
0.,0.,0.,3.75
0.,0.,0.,0.85
0.,0.,0.,0.,-1.,0.
332000000.,103000000.,302000000.,162000000.
332000000.,103000000.,302000000.,162000000.
332000000.,103000000.,302000000.,162000000.
```

```
332000000.,103000000.,302000000.,162000000.
332000000.,103000000.,302000000.,162000000.
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0.,0.,0.,0.
-1740000.,-536000.,-880000.,-80000.,-1.,491000.
42560.,30295.,9002.,28520.
42560.,30295.,9002.,28520.
42560.,30295.,9002.,28520.
42560.,30295.,9002.,28520.
42560.,30295.,9002.,28520.
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0.,0.,0.,0.
-81.8,-14.66,-16.6,-3.67,-1.,14.5
105975.,52777.,664928.,61845.
105975.,52777.,664928.,61845.
113395.,58077.,669486.,67940.
113115.,57877.,669314.,67710.
105975.,52777.,664928.,61845.
-14.85,-14.85,-14.85,-14.85
-3.52,-3.52,-3.52,-3.52
1168.41,98.57,410.5,14.33,-1.,0.001
-1800.,-1110.,-1100.,-1000.
-1800.,-1110.,-1100.,-1000.
-1800.,-1110.,-1100.,-1000.
-1800.,-1110.,-1100.,-1000.
-1800.,-1110.,-1100.,-1000.
7.5,7.5,7.5,7.5
1.,1.,1.,1.
0.,0.,0.,0.,1.,31650000.
385.,650.,645.,620.
385.,650.,645.,620.
385.,650.,645.,620.
385.,650.,645.,620.
385.,650.,645.,620.
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1.,1.,1.,1.
1.,1.,1.,1.
1.,1.,1.,1.
1.,1.,1.,1.
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0.,0.,0.,0.
0.,0.,0.,0.,1.,98.35
1.,0.,0.,0.
1.,0.,0.,0.
1.,0.,0.,0.
1.,0.,0.,0.
1.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.,1.,41.19
```

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0.,0.,0.,0.,1.,57.16
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90.3,125.,123.,116.
90.3,125.,123.,116.
90.3,125.,123.,116.
90.3,125.,123.,116.
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19.6,18.3,19.,18.
19.6,18.3,19.,18.
19.6,18.3,19.,18.
19.6,18.3,19.,18.
19.6,18.3,19.,18.
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0.,0.,0.,0.
0.,0.,0.,0.,1.,5450.
259.8,401.,489.9,386.4
259.8,401.,489.9,386.4
259.8,401.,489.9,386.4
259.8,401.,489.9,386.4
259.8,401.,489.9,386.4
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0.,0.,0.,0.
0.,0.,0.,0.,1.,86500.
26.19,49.55,51.24,60.48
26.19,49.55,51.24,60.48
26.19,49.55,51.24,60.48
26.19,49.55,51.24,60.48
26.19,49.55,51.24,60.48
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0.,0.,0.,0.
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1400000.,990000.,860000.,1020000.
1400000.,990000.,860000.,1020000.
1400000.,990000.,860000.,1020000.
1400000.,990000.,860000.,1020000.
1400000.,990000.,860000.,1020000.
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1400000.,990000.,860000.,1020000.
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0.,0.,0.,0.
0.,0.,0.,0.
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1400000.,990000.,860000.,1020000.
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0.,0.,0.,0.,1.,4.11
0.,1.,1.,1.
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0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.,1.,12.12
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1.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.,1.,4.34
0.,0.,0.,0.
0.,1.,1.,1.
0.,0.,0.,0.
0.,0.,0.,0.
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0.,0.,0.,0.
0.,0.,0.,0.,1.,13.57
0.,0.,0.,0.
0.,0.,0.,0.
```

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0.,1.,1.,1.
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0.,0.,0.,0.,1.,10.57
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0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
```

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0.,0.,0.,0.
0.,0.,0.,0.
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0.,0.,1.,1.
0.,0.,0.,0.
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0.,0.,0.,1.
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0.,0.,0.,1.
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0.,0.,0.,1.
0.,0.,0.,0.
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0.,0.,0.,0.
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0.,0.,0.,0.
0.,0.,0.,0.
1.,0.,0.,0.,-1.,0.
0.,0.,0.,1.
1.,0.,0.,0.
0.,1.,0.,0.
0.,0.,0.,1.
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0.,0.,0.,0.
0.,0.,0.,0.
1.,0.,0.,0.,-1.,0.
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1.,0.,0.,0.
1.,0.,0.,0.
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0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.,-1.,0.
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0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.,-1.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
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0.,1.,0.,0.
0.,0.,1.,0.
1.,0.,0.,0.,-1.,0.
0.,0.,0.,1.
```

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3.,0.,0.,0.
1.,0.,0.,0.
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0.,0.,0.,0.
1.,0.,0.,0.,-1.,0.
-100000.,0.,0.,0.
-100000.,0.,0.,0.
-100000.,0.,0.,0.
-100000.,0.,0.,0.
-100000.,0.,0.,0.
1.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.,1.,0.
0.,-100000.,0.,0.
0.,-100000.,0.,0.
0.,-100000.,0.,0.
0.,-100000.,0.,0.
0.,-100000.,0.,0.
0.,1.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.,1.,0.
0.,0.,-100000.,0.
0.,0.,-100000.,0.
0.,0.,-100000.,0.
0.,0.,-100000.,0.
0.,0.,-100000.,0.
0.,0.,1.,0.
0.,0.,0.,0.
0.,0.,0.,0.,1.,0.
0.,0.,0.,-100000.
0.,0.,0.,-100000.
0.,0.,0.,-100000.
0.,0.,0.,-100000.
0.,0.,0.,-100000.
0.,0.,0.,1.
0.,0.,0.,0.
0.,0.,0.,0.,1.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
1.,0.,0.,0.,1.,6000.
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0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
```

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0.,0.,0.,0.
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0.,0.,0.,0.
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0.,0.,1.,0.,1.,20000.
0.,0.,0.,0.
0.,0.,0.,0.
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0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,1.,1.,125000.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
1.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.,1.,0.
105975.,52777.,664928.,61845.
105975.,52777.,664928.,61845.
113395.,58077.,669486.,67940.
113115.,57877.,669314.,67710.
105975.,52777.,664928.,61845.
-11.85,-11.85,-11.85,-11.85
-3.22,-3.22,-3.22,-3.22
1168.41,98.57,410.5,8.33
```

APPENDIX II INPUT DATABASES FOR CALCULATIONS

2. Input Database for Upper Limit of Objective Function

```
32,53,1.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
1.,1.,1.,1.
0.,0.,0.,0.
-143.,-27.5,-101.2,-4.18,0.,1976400.
-1800.,0.,0.,0.
-1800.,0.,0.,0.
-1800.,0.,0.,0.
-1800.,0.,0.,0.
-1800.,0.,0.,0.
3.75,0.,0.,0.
0.85,0.,0.,0.
0.,0.,0.,0.,-1.,0.
0.,-1110.,0.,0.
0.,-1110.,0.,0.
0.,-1110.,0.,0.
0.,-1110.,0.,0.
0.,-1110.,0.,0.
0.,3.75,0.,0.
0.,0.85,0.,0.
0.,0.,0.,0.,-1.,0.
0.,0.,-1100.,0.
0.,0.,-1100.,0.
0.,0.,-1100.,0.
0.,0.,-1100.,0.
0.,0.,-1100.,0.
0.,0.,3.75,0.
0.,0.,0.85,0.
0.,0.,0.,0.,-1.,0.
0.,0.,0.,-1000.
0.,0.,0.,-1000.
0.,0.,0.,-1000.
0.,0.,0.,-1000.
0.,0.,0.,-1000.
0.,0.,0.,3.75
0.,0.,0.,0.85
0.,0.,0.,0.,-1.,0.
308000000.,89000000.,249000000.,144000000.
308000000.,89000000.,249000000.,144000000.
308000000.,89000000.,249000000.,144000000.
```

```
308000000.,89000000.,249000000.,144000000.
308000000.,89000000.,249000000.,144000000.
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0.,0.,0.,0.
-2390000.,-561000.,-1190000.,-106500.,-1.,536000.
39175.,26230.,7415.,24840.
39175.,26230.,7415.,24840.
39175.,26230.,7415.,24840.
39175.,26230.,7415.,24840.
39175.,26230.,7415.,24840.
0.,0.,0.,0.
0.,0.,0.,0.
-86.2,-17.15,-19.2,-4.99,-1.,15.8
-1800.,-1110.,-1100.,-1000.
-1800.,-1110.,-1100.,-1000.
-1800.,-1110.,-1100.,-1000.
-1800.,-1110.,-1100.,-1000.
-1800.,-1110.,-1100.,-1000.
7.5,7.5,7.5,7.5
1.,1.,1.,1.
0.,0.,0.,0.,1.,32500000.
305.,550.,565.,540.
305.,550.,565.,540.
305.,550.,565.,540.
305.,550.,565.,540.
305.,550.,565.,540.
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0.,0.,0.,0.
0.,0.,0.,0.,1.,138000.
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1.,1.,1.,1.
1.,1.,1.,1.
1.,1.,1.,1.
1.,1.,1.,1.
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0.,0.,0.,0.
0.,0.,0.,0.,1.,98.35
1.,0.,0.,0.
1.,0.,0.,0.
1.,0.,0.,0.
1.,0.,0.,0.
1.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.,1.,41.19
0.,1.,1.,1.
0.,1.,1.,1.
0.,1.,1.,1.
0.,1.,1.,1.
0.,1.,1.,1.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.,1.,57.16
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76.3,110.,113.,108.
76.3,110.,113.,108.
76.3,110.,113.,108.
76.3,110.,113.,108.
76.3,110.,113.,108.
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0.,0.,0.,0.
0.,0.,0.,0.,1.,28700.
17.1,16.5,17.,16.2
17.1,16.5,17.,16.2
17.1,16.5,17.,16.2
17.1,16.5,17.,16.2
17.1,16.5,17.,16.2
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0.,0.,0.,0.
0.,0.,0.,0.,1.,5770.
233.3,352.,434.5,327.
233.3,352.,434.5,327.
233.3,352.,434.5,327.
233.3,352.,434.5,327.
233.3,352.,434.5,327.
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0.,0.,0.,0.
0.,0.,0.,0.,1.,91000.
22.81,41.05,41.72,49.75
22.81,41.05,41.72,49.75
22.81,41.05,41.72,49.75
22.81,41.05,41.72,49.75
22.81,41.05,41.72,49.75
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0.,0.,0.,0.
0.,0.,0.,0.,1.,9900.
1000000.,900000.,740000.,850000.
1000000.,900000.,740000.,850000.
1000000.,900000.,740000.,850000.
1000000.,900000.,740000.,850000.
1000000.,900000.,740000.,850000.
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0.,0.,0.,0.
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1000000.,900000.,740000.,850000.
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0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.,1.,16101000.1
0.,0.,0.,0.
1000000.,900000.,740000.,850000.
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0.,0.,0.,0.
0.,0.,0.,0.
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1000000.,900000.,740000.,850000.
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0.,0.,0.,0.
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0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.,1.,4.11
200.,0.,0.,0.
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0.,0.,0.,0.
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0.,0.,0.,0.
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0.,0.,0.,0.
0.,0.,0.,0.,1.,820.
0.,1.,1.,1.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
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0.,0.,0.,0.,1.,12.12
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1.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.,1.,4.34
0.,0.,0.,0.
0.,1.,1.,1.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.,1.,13.57
0.,0.,0.,0.
0.,0.,0.,0.
```

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0.,0.,0.,0.
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0.,0.,0.,0.
0.,0.,0.,0.,1.,12.87
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0.,0.,0.,0.
0.,1.,1.,1.
0.,0.,0.,0.
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0.,0.,0.,0.
0.,0.,0.,0.
0.,0.,0.,0.,1.,10.97
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0.,0.,0.,0.
0.,0.,0.,0.
1.,0.,0.,0.
0.,0.,0.,0.
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0.,0.,0.,0.
0.,0.,0.,0.,1.,15.71
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0.,1.,1.,1.
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0.,0.,0.,0.
0.,1.,1.,1.
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0.,0.,0.,0.
0.,0.,0.,0.,1.,10.57
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0.,0.,0.,0.
0.,0.,0.,0.
0.,1.,1.,1.
0.,0.,0.,0.
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0.,0.,0.,0.
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0.,0.,1.,1.
0.,0.,0.,0.
0.,0.,0.,0.
1.,0.,0.,1.
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149565.,80793.,938684.,94705.
154065.,84843.,942014.,98530.
153965.,84753.,941940.,98439.
149565.,80793.,938684.,94705.
-9.25,-9.25,-9.25,-9.25
-2.58,-2.58,-2.58,-2.58
1483.6,106.03,479.5,9.87
```

APPENDIX III

COMPLETE NAMES OF VARIABLES USED

APPENDIX III COMPLETE NAMES OF VARIABLES USED

A = agricultural Incomes (¥);

$\otimes(a)$ = the maximum allowable total nitrogen losses (kg/km^2);

$\otimes(b)$ = the maximum allowable soil loss (kg/km^2);

$\otimes(B_k)$ = the amount of manure discharged by livestock k (t/one);

B_0 = the amount of manure discharged by human (t/one);

$\otimes(c_1)$ = the maximum allowable solid-phase nitrogen loss (kg/km^2);

$\otimes(c_2)$ = the maximum allowable solid-phase phosphorus loss (kg/km^2);

C_{ij} = the yield of crop j on soil i (kg/km^2);

CC = the canal capacity (m^3);

$\otimes(d_k)$ = the digestible protein absorbed by livestock k from other systems (kg/one);

$\otimes(d_0)$ = the digestible protein absorbed by man from other systems (kg/one);

D_k = the digestible protein requirement of livestock k to be satisfied from onfarm crops (kg/one);

D_0 = the digestible protein requirement of man to be satisfied from onfarm crops (kg/one);

$\otimes(e_k)$ = the net energy absorbed by livestock k from external systems (kcal/kg);

$\otimes(e_0)$ = the net energy absorbed by man from external systems (kcal/kg);

E_k = the energy requirements of livestock k to be satisfied from onfarm crops (kcal/one);

E_0 = the energy requirements of man to be satisfied from onfarm crops (kcal/one);

F_{ij} = the amount of manure spread on soil i planted to crop j *(t);*

$\otimes(f_1)$ = the maximum allowable dissolved nitrogen loss by runoff (kg/km^2);

$\otimes(f_2)$ = the maximum allowable dissolved phosphorus loss by runoff (kg/km^2);

$\otimes(G_{ij})$ = the farming cost on S_{ij} *(¥/km^2);*

$\otimes(G_f)$ = the cost of manure disposal (¥/t);

G_h = the cost of nitrogen fertilizer (¥/kg);

h_{i1} = nitrogen contents of soil i (%);

h_{i2} = phosphorus contents of soil i (%);

H_{ij} = the fertilizer nitrogen applied to S_{ij} (kg);

i = *type of soil;*

j = *type of crop;*

K_i = the tillable area of soil i (km²);

k = *type of livestock;*

l = the number of livestock kinds in the study area;

L_{ij} = the soil loss from S_{ij} (kg/km²);

m = the number of soil types in the study area;

$MS_{ij} = 1$ if manure can be spread on S_{ij}, and $MS_{ij} = 0$ otherwise;

n = the number of crop types in the study area;

N_{1j} = dissolved nitrogen concentrations in wet season runoff from land planted to crop j (mg/l);

N_{2j} = dissolved nitrogen concentrations in dry season runoff from land planted to crop j (mg/l);

P_{1j} = dissolved phosphorus concentrations in wet season runoff from land planted to crop j (mg/l);

P_{2j} = dissolved phosphorus concentrations in dry season runoff from land planted to crop j (mg/l);

p_1 = the percentages of the applied nitrogen lost to the atmosphere because of ammonia volatilization (%);

p_2 = the percentages of the applied nitrogen lost to the atmosphere because of ammonia denitrification (%);

APPENDIX III COMPLETE NAMES OF VARIABLES USED - Continued

$\otimes(q_k)$ = the average consumptions from external systems by livestock k (¥/one);

Q_{ij} = the nitrogen requirement of crop j on soil i (kg/km^2);

q_t = the channel capacities within subarea t (m^3/sec);

QW_0 = the total quantity of water required in the study area (m^3);

QW_1 = the total quantity of water required by Xiamen City (m^3);

$\otimes(QW_{ijt})$ = the quantity of irrigation water required per km^2 of crop j on soil i in subarea t (m^3/km^2);

r = nitrogen content of manure (kg/t);

R_{1ij} = wet season runoff from S_{ij} (mm);

R_{2ij} = dry season runoff from S_{ij} (mm);

S_{ij} = the area of soil i planted to crop j (km^2);

S_{ijt} = the area of soil i planted to crop j in subarea t (km^2);

$SC_{ij} = 1$ if the soil/crop combination (i, j) is permitted, and $SC_{ij} = 0$ otherwise;

t = names of subareas;

T_k = the numbers of livestock k in the study area;

T_0 = the number of man in the study area;

T_{max} = the maximum possible sizes of livestocks;

$\otimes(U)$ = the costs to obtain and transport water to the basin area associated with the canal capacity (¥/m^3);

$\otimes(v_t)$ = the costs of delivering the water to Subarea t with ditch capacity q_t;

$\otimes(X_{ijt})$ = variable costs associated with each water allocation QW_{ijt}, including the costs to obtain and allocate water to each S_{ijt};

α_{ij} = the net energy content of C_{ij} (kcal/kg);

β_{ij} = the digestible protein content of C_{ij} (%);

APPENDIX III COMPLETE NAMES OF VARIABLES USED - Continued

$\otimes(\delta_j)$ = the price of crop j (¥/kg);

$\otimes(\sigma_k)$ = the average net return of livestock k (¥/one);

$\otimes(\Omega_{ij})$ = the costs of water for each S_{ij} (¥/m^3).

APPENDIX IV

"CREDITABILITY" METHOD FOR THE SOLUTION OF GREY LINEAR PROGRAMMING MODEL

APPENDIX IV "CREDITABILITY" METHOD FOR THE SOLUTION OF GREY LINEAR PROGRAMMING MODEL

The following is a grey linear programming (GLP) model:

$$
\begin{aligned}
& Max\ f = \otimes(\boldsymbol{c})\ \boldsymbol{x} \\
& subject\ to\ \ \otimes(A)\ \boldsymbol{x} \leq \boldsymbol{b} \\
& \boldsymbol{x} \geq 0, \qquad\qquad\qquad\qquad \text{----------------}\ \ (1)
\end{aligned}
$$

where:

$$\otimes(\boldsymbol{c}) = [\otimes(c_1), \otimes(c_2), \ldots, \otimes(c_n)], \quad \text{----------------}\ \ (2)$$

$$\boldsymbol{x}^T = (x_1, x_2, \ldots, x_n), \quad \text{----------------}\ \ (3)$$

$$\boldsymbol{b}^T = (b_1, b_2, \ldots, b_m), \quad \text{----------------}\ \ (4)$$

$$\otimes(A) = \begin{bmatrix} \otimes(a_{11}) & \otimes(a_{12}) & \ldots & \otimes(a_{1n}) \\ \otimes(a_{21}) & \otimes(a_{22}) & \ldots & \otimes(a_{2n}) \\ \vdots & \vdots & & \vdots \\ \otimes(a_{m1}) & \otimes(a_{m2}) & \ldots & \otimes(a_{mn}) \end{bmatrix} \qquad \text{--------------}\ \ (5)$$

For grey vector $\otimes(\boldsymbol{c})$ and grey matrix $\otimes(A)$, we have:

$$\otimes(c_i) = [\underline{\otimes}(c_i), \overline{\otimes}(c_i)], \qquad \forall\ i \quad \text{---------------}\ \ (6)$$

$$\otimes(a_{ij}) = [\underline{\otimes}(a_{ij}), \overline{\otimes}(a_{ij})], \qquad \forall\ i, j \ \text{----------------} \ (7)$$

$\otimes(\mathbf{c})$ and $\otimes(A)$ can be whitened as:

$$\otimes_m(\mathbf{c}) = [\otimes_m(c_1), \otimes_m(c_2), \ldots, \otimes_m(c_n)], \qquad \text{----------------} \ (8)$$

$$\otimes_m(A) = \begin{bmatrix} \otimes_m(a_{11}) & \otimes_m(a_{12}) & \ldots & \otimes_m(a_{1n}) \\ \otimes_m(a_{21}) & \otimes_m(a_{22}) & \ldots & \otimes_m(a_{2n}) \\ \vdots & \vdots & & \vdots \\ \otimes_m(a_{m1}) & \otimes_m(a_{m2}) & \ldots & \otimes_m(a_{mn}) \end{bmatrix} \qquad \text{--------------} \ (9)$$

or:

$$\otimes_m(\mathbf{c}) = (\otimes_m(c_i)), \quad \forall\ i \qquad \text{----------------} \ (10)$$

$$\otimes_m(A) = (\otimes_m(a_{ij})), \quad \forall\ i, j \qquad \text{----------------} \ (11)$$

where $\otimes_m(c_i)$ *and* $\otimes_m(a_{ij})$ are the whitening values of $\otimes(c_i)$ *and* $\otimes(a_{ij})$, respectively.

Thus, we have:

$\otimes_m(c_i) \in [\underline{\otimes}(c_i), \overline{\otimes}(c_i)]$, where $\underline{\otimes}(c_i)$ is the whitening value of the lower limit of $\otimes(c_i)$, and $\overline{\otimes}(c_i)$ is the upper limit of $\otimes(c_i)$;

$\otimes_m(a_{ij}) \in [\underline{\otimes}(a_{ij}), \overline{\otimes}(a_{ij})]$, where $\underline{\otimes}(a_{ij})$ is the lower limit of $\otimes(a_{ij})$, and $\overline{\otimes}(a_{ij})$ is the upper limit of $\otimes(a_{ij})$.

These relations can be expressed as:

$$\otimes_m(c_i) = \underline{\otimes}(c_i) + \alpha\,[\overline{\otimes}(c_i) - \underline{\otimes}(c_i)], \qquad \forall\ i, j \qquad \text{----------------} \quad (12)$$

$$\otimes_m(a_{ij}) = \underline{\otimes}(a_{ij}) + \alpha\,[\,\overline{\otimes}(a_{ij}) - \underline{\otimes}(a_{ij})], \qquad \forall\ i, j \qquad \text{----------------} \quad (13)$$

where α is a grey coefficient . From Equation (12) and (13), we have:

1) When $0 < \alpha < 1$, *i.e.*, $\alpha \in (0, 1)$, $\otimes_m(c_i)$ *and* $\otimes_m(a_{ij})$ will change between their upper and lower limits, i.e., $\otimes_m(c_i) \in (\underline{\otimes}(c_i), \overline{\otimes}(c_i))$, and $\otimes(a_{ij}) \in (\underline{\otimes}(a_{ij}), \overline{\otimes}(a_{ij}))$;

2) When $\alpha = 0$, $\otimes_m(c_i)$ *and* $\otimes_m(a_{ij})$ will reach their lower limits, i.e., $\otimes_m(c_i) = \underline{\otimes}(c_i)$, and $\otimes(a_{ij}) = \underline{\otimes}(a_{ij})$;

3) When $\alpha = 1$, $\otimes_m(c_i)$ *and* $\otimes_m(a_{ij})$ will reach their upper limits, i.e., $\otimes_m(c_i) = \overline{\otimes}(c_i)$, and $\otimes(a_{ij}) = \overline{\otimes}(a_{ij})$.

For constraints in the GLP model (1), if $\otimes(a_{ij})$ $(i = 1, 2, \ldots, n; j = 1, 2, \ldots, m)$ equals $\overline{\otimes}(a_{ij})$ (upper limit value), $\boldsymbol{x}$ $(\boldsymbol{x}^T = (x_1, x_2, \ldots, x_n))$ will have lower limit solution $\boldsymbol{x}_{min}$; and if $\otimes(a_{ij})$ $(i = 1, 2, \ldots, n; j = 1, 2, \ldots, m)$ equals $\underline{\otimes}(a_{ij})$ (lower limit value), $\boldsymbol{x}$ $(\boldsymbol{x}^T = (x_1, x_2, \ldots, x_n))$ will have upper limit solution $\boldsymbol{x}_{min}$.

Conversely, for the objective function in the GLP model (1), if $\otimes(c_i)$ $(i = 1, 2, \ldots, n)$ equals $\overline{\otimes}(c_i)$ (upper limit value), objective function f will have the maximum weights; and if $\otimes(c_i)$ $(i = 1, 2, \ldots, n)$ equals $\underline{\otimes}(c_i)$ (lower limit value), objective function f will have the minimum weights.

Therefore, when $\alpha = 1$, which means that $\otimes_m(c_i)$ *and* $\otimes_m(a_{ij})$ reach their upper limits, decision variable $\boldsymbol{x}$ will have its lower limit solution $\boldsymbol{x}_{min}$, while objective function has the maximum weights. Therefore, the objective value f is:

$$f_1 = f_\alpha = \overline{\otimes}(\boldsymbol{c})\,\boldsymbol{x}_{min} \qquad \text{----------------} \quad (14)$$

When $\alpha = 0$, which means that $\otimes_m(c_i)$ and $\otimes_m(a_{ij})$ reach their lower limits, decision variable $\boldsymbol{x}$ will have its upper limit solution $\boldsymbol{x}_{max}$, while objective function has the minimum weights. Therefore, the objective value f is:

$$f_0 = f_\alpha = \underline{\otimes}(\mathbf{c})\,\boldsymbol{x}_{max} \qquad \text{----------------} \quad (15)$$

Obviously, we can not compare f_1 with f_0 by saying $f_1 > f_0$ or $f_1 < f_0$ based on the Equation (14) and (15). However, when $\alpha = 0$ for the constraint coefficient $\otimes_m(a_{ij})$ and $\alpha = 1$ for the objective coefficient (weight value) $\otimes_m(c_i)$, the objective value will be the maximum:

$$f_{max} = \overline{\otimes}(\mathbf{c})\,\boldsymbol{x}_{max} \qquad \text{----------------} \quad (16)$$

When $\alpha = 1$ for the constraint coefficient $\otimes_m(a_{ij})$ and $\alpha = 0$ for the constraint coefficient $\otimes_m(c_i)$, the objective value will be the minimum:

$$f_{min} = \underline{\otimes}(\mathbf{c})\,\boldsymbol{x}_{min} \qquad \text{----------------} \quad (17)$$

Thus, we can define a creditability criterion under grey coefficient α:

$$R_\alpha = f_\alpha / f_{max} \qquad \text{----------------} \quad (18)$$

where f_α is the objective value under grey coefficient α:

$$f_\alpha = \otimes_m(\mathbf{c})_\alpha\,\boldsymbol{x}_\alpha \qquad \text{----------------} \quad (19)$$

where $\otimes_m(\boldsymbol{c})_\alpha$ is the whitening weight vector of the objective function under grey coefficient α; $\boldsymbol{x}_\alpha$ is the whitening vector of the decision variables corresponding to the values of $\otimes_m(A)_\alpha$ (coefficient matrix of the constraints) under grey coefficient α.

Obviously:

$$f_{min} \leq f_\alpha \leq f_{max} \qquad \text{----------------} \quad (20)$$

$$R_\alpha \in [0, 1] \qquad \text{----------------} \quad (21)$$

Thus, given a creditability requirement R_α^*, we can judge the feasibility of the model solution:

If $R_\alpha \geq R_\alpha^*$, the requirement is satisfied, and the solving process ends;

If $R_\alpha \leq R_\alpha^*$, the requirement is not satisfied. New α values should be chosen and tested until the creditability requirement is satisfied.

APPENDIX V

MONITORING RESULTS OF THE CANAL WATER QUALITY IN 1989

Table 2.11 Canal water quality in June, 1989 (mg/l)

Monitoring Station	1	2	3	4	5
NO_3^--N	0.391	0.554	0.703	1.112	1.253
NO_2^--N	0.017	0.097	0.157	0.229	0.169
NH_3-N	0.191	1.080	1.730	0.830	1.220
Total Phosphorus	0.008	0.020	0.027	0.040	0.051
SS	244	56	59	51	23
DO	7.27	6.62	6.15	5.49	4.96
COD	5.94	3.96	4.93	5.46	3.74
BOD	1.60	3.60	3.50	4.60	3.10
Cu	0.0192	0.0212	0.0066	0.0062	0.0099
Pb	0.100	0.006	0.012	0.005	0.010
Zn	0.128	0.0640	0.0217	0.0284	0.0673
Cd	0.00036	0	0	0	0.000036
As	0	0	0	0	0

* Station 1 is the source of the canal (i.e. Jiulong River), and Station 5 is the outlet.

Table 2.12 Canal water quality in October, 1989 (mg/l)

Monitoring Station*	1	2	3	4	5
NO_3^--N	0.42	0.52	0.70	1.16	1.04
NO_2^--N	0.010	0.011	0.018	0.023	0.027
NH_3-N	0.099	0.302	0.118	0.177	0.139
Total Phosphorus	0.002	0.014	0.018	0.034	0.038
SS	22	22	50	44	38
DO	6.83	7.24	6.82	6.25	5.86
COD	1.86	3.84	2.41	2.40	2.37
BOD	1.1	1.0	1.4	1.8	1.6
Cu	0.0028	0.0022	0.0168	0.0042	0.0022
Pb	0.0075	0.0081	0.0089	0.0040	0.0047
Zn	0.0103	0.0058	0.0188	0.0057	0
Cd	0	0	0	0	0
As	0	0	0	0	0

* Station 1 is the source of the canal (i.e. Jiulong River), and Station 5 is the outlet.

Table 2.13 Canal water quality in December, 1989 (mg/l)

Monitoring Station*	1	2	3	4	5
NO_3^--N	0.54	0.58	0.74	1.06	0.67
NO_2^--N	0.012	0.010	0.010	0.020	0.012
NH_3-N	0.100	0.111	0.119	0.401	0.220
Total Phosphorus	0.004	0.018	0.030	0.013	0.025
SS	13	29	28	32	32
DO	8.85	8.74	8.72	7.67	8.54
COD	2.33	2.28	2.58	2.26	2.40
BOD	0.82	0.88	1.03	1.10	0.94
Cu	0.00065	0	0.00170	0.002	0.00038
Pb	0.00049	0	0.00058	0	0
Zn	0.0026	0.0050	0	0.0120	0
Cd	0	0	0.00006	0.00012	0.00012
As	0	0	0	0	0

* Station 1 is the source of the canal (i.e. Jiulong River), and Station 5 is the outlet.

Table 2.14 Canal water quality in 1989 (yearly average) (mg/l)

Monitoring Station*	1	2	3	4	5
NO_3^--N	0.45	0.55	0.71	1.11	0.99
NO_2^--N	0.013	0.039	0.062	0.091	0.069
NH_3-N	0.13	0.50	0.66	0.47	0.53
Total Phosphorus	0.005	0.017	0.025	0.029	0.038
SS	93	36	46	42.3	31
DO	7.65	7.53	7.23	6.47	6.45
COD	3.38	3.36	3.31	3.37	2.84
BOD	1.2	1.8	2.0	2.5	1.88
Cu	0.0076	0.0078	0.0084	0.0041	0.0042
Pb	0.036	0.0047	0.0065	0.003	0.0049
Zn	0.047	0.025	0.016	0.015	0.022
Cd	0.00012	0	0.00002	0.00003	0.00005
As	0	0	0	0	0

* Station 1 is the source of the canal (i.e. Jiulong River), and Station 5 is the outlet.

Table 2.15 Canal water quality index in June, 1989*

Monitoring Station**	1	2	3	4	5
NO_3^--N	0.04	0.06	0.07	0.11	0.13
NO_2^--N	0.85	4.85	7.85	11.50	8.45
NH_3-N	0.96	5.40	8.65	4.15	6.10
Total Phosphorus	0.40	1.00	1.35	2.00	2.55
COD	1.49	0.99	1.23	3.14	0.94
BOD	0.53	1.20	1.17	1.53	1.03
Cu	1.92	2.12	0.66	0.62	0.99
Pb	2.00	0.12	0.24	0.10	0.20
Zn	0.26	0.13	0.04	0.06	0.13
Cd	0.07	0	0	0	0
As	0	0	0	0	0

* Water quality index = pollutant concentration/water quality standard;

* Station 1 is the source of the canal (i.e. Jiulong River), and Station 5 is the outlet.

Table 2.16 Canal water quality index in October, 1989*

Monitoring Station**	1	2	3	4	5
NO_3^--N	0.04	0.05	0.07	0.11	0.10
NO_2^--N	0.50	0.55	0.90	1.15	1.35
NH_3-N	0.50	1.51	0.59	0.89	0.70
Total Phosphorus	0.10	0.70	0.90	1.70	1.90
COD	0.47	0.96	0.60	0.60	0.59
BOD	0.37	0.33	0.47	0.60	0.53
Cu	0.28	0.22	1.68	0.42	0.22
Pb	0.15	0.16	0.18	0.08	0.09
Zn	0.02	0.01	0.04	0.01	0
Cd	0	0	0	0	0
As	0	0	0	0	0

* Water quality index = pollutant concentration/water quality standard;
* Station 1 is the source of the canal (i.e. Jiulong River), and Station 5 is the outlet.

Table 2.17 Canal water quality index in December, 1989*

Monitoring Station**	1	2	3	4	5
NO_3^--N	0.05	0.06	0.07	0.11	0.07
NO_2^--N	0.60	0.50	0.50	1.00	0.60
NH_3-N	0.50	0.56	0.60	2.01	1.10
Total Phosphorus	0.20	0.90	1.50	0.65	1.25
COD	0.58	0.57	0.65	0.57	0.60
BOD	0.27	0.29	0.34	0.37	0.31
Cu	0.07	0	0.17	0.20	0.04
Pb	0.01	0	0.01	0	0
Zn	0.01	0.01	0	0.02	0
Cd	0	0	0.01	0.02	0.02
As	0	0	0	0	0

* Water quality index = pollutant concentration/water quality standard;

* Station 1 is the source of the canal (i.e. Jiulong River), and Station 5 is the outlet.

Table 2.18 Canal water quality index in 1989 (yearly average)*

Monitoring Station**	1	2	3	4	5
NO_3^--N	0.05	0.06	0.07	0.11	0.10
NO_2^--N	0.65	1.95	3.10	4.55	3.45
NH_3-N	0.65	2.50	3.30	2.35	2.65
Total Phosphorus	0.25	0.85	1.25	1.45	1.90
COD	0.85	0.84	0.83	0.84	0.71
BOD	0.40	0.60	0.67	0.83	0.63
Cu	0.76	0.78	0.84	0.41	0.42
Pb	0.72	0.09	0.13	0.06	0.10
Zn	0.09	0.05	0.03	0.03	0.04
Cd	0.02	0	0	0.01	0.01
As	0	0	0	0	0

* Water quality index = pollutant concentration/water quality standard;

* Station 1 is the source of the canal (i.e. Jiulong River), and Station 5 is the outlet.

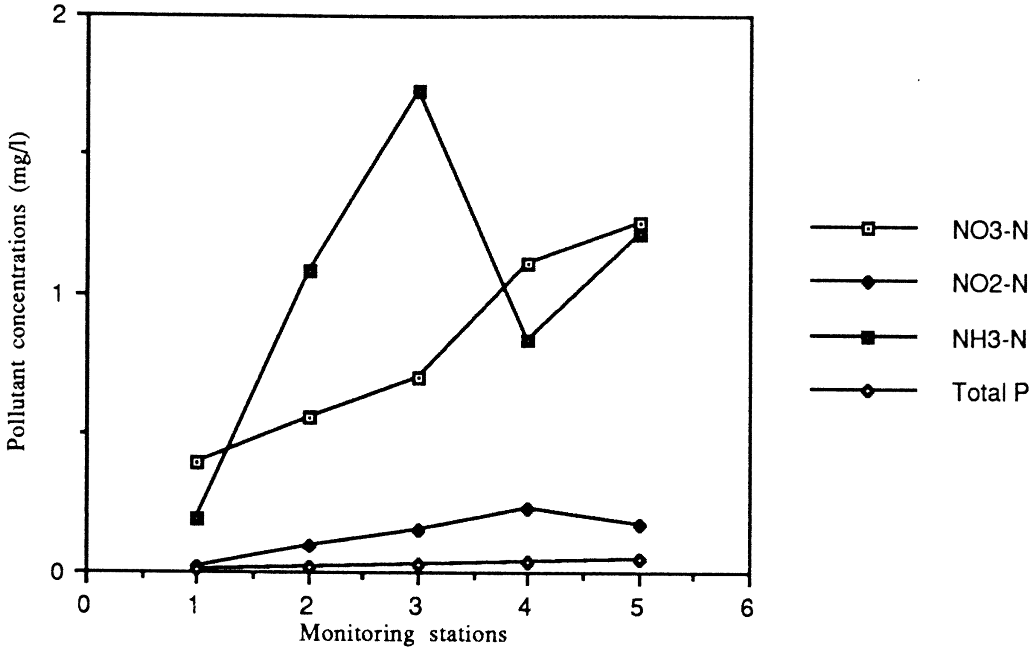

Figure 2.4(a) Canal water quality in June, 1989

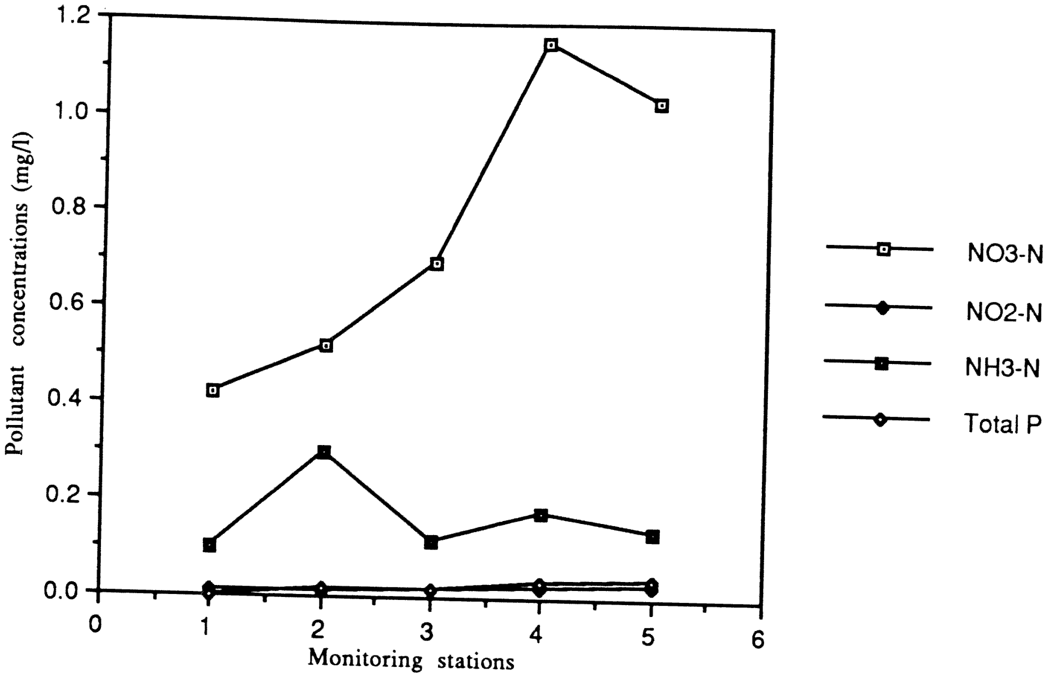

Figure 2.4(b) Canal water quality in October, 1989

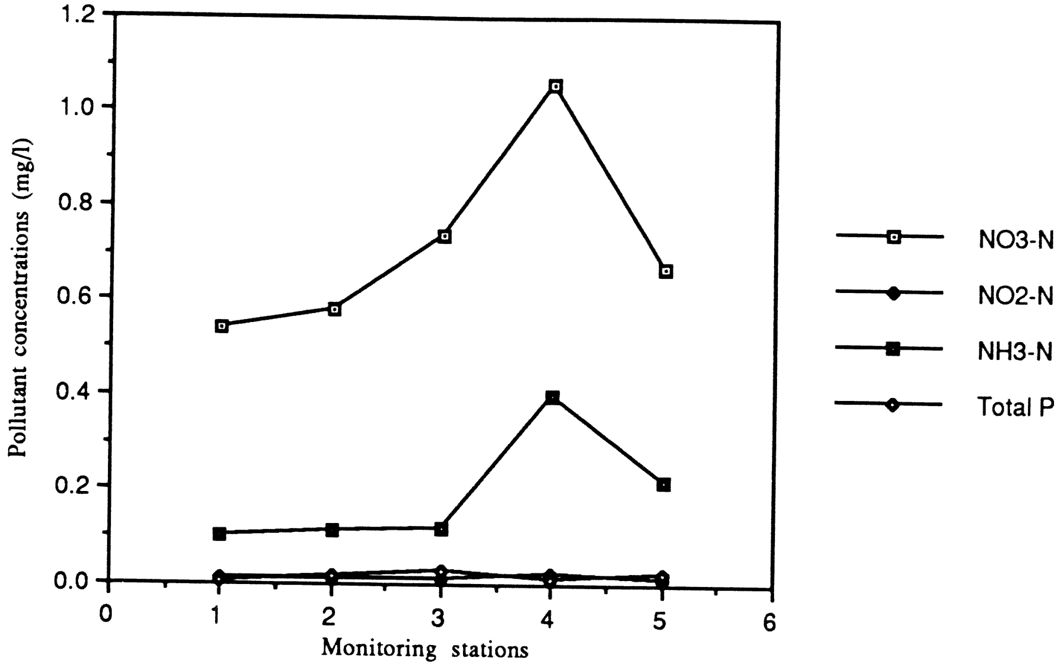

Figure 2.4(c) Canal water quality in December, 1989

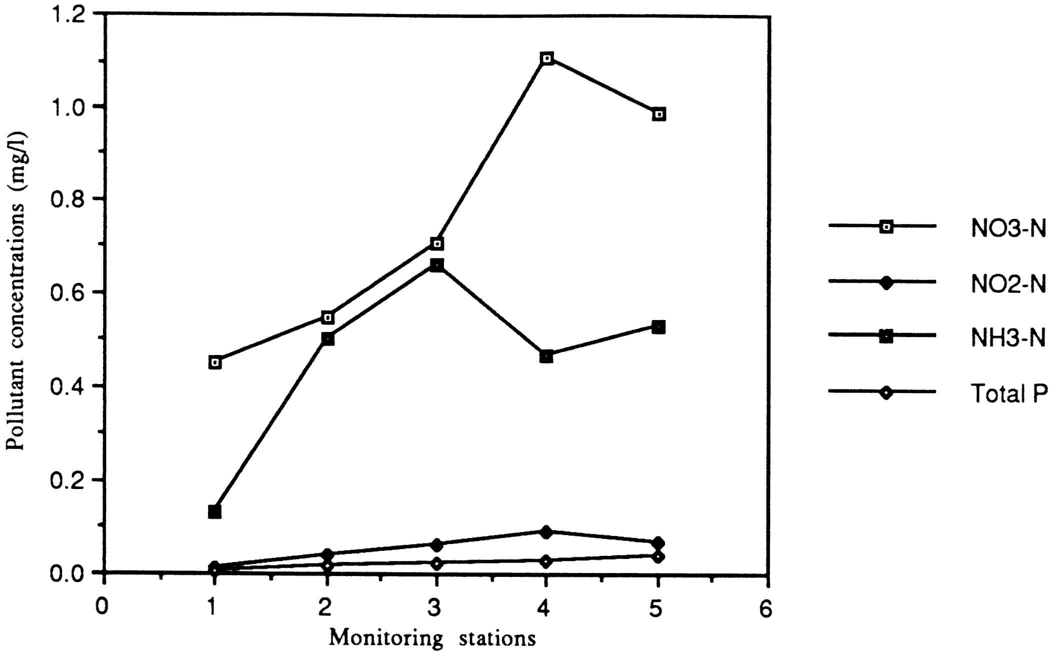

Figure 2.4(d) Canal water quality in 1989 (yearly average)

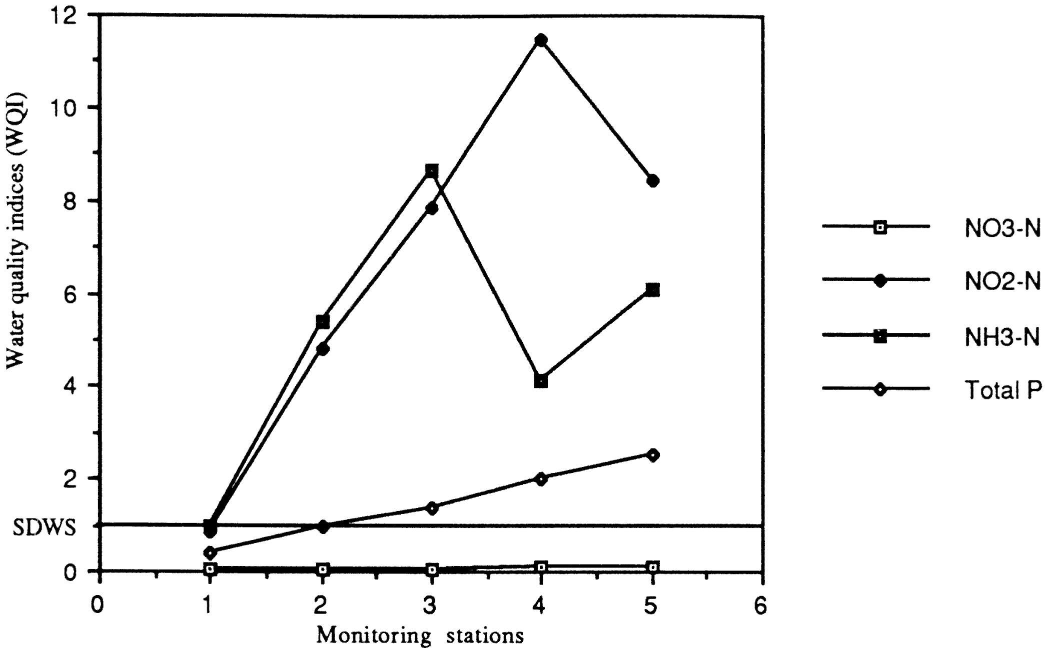

Figure 2.5(a) Canal water quality indices in June, 1989

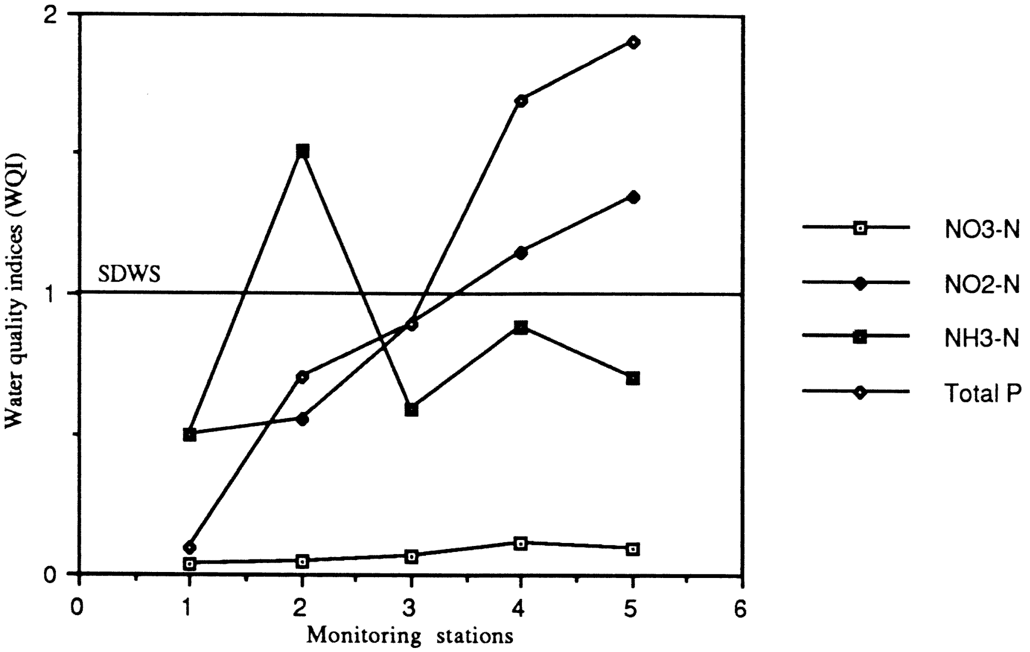

Figure 2.5(b) Canal water quality indices in October, 1989

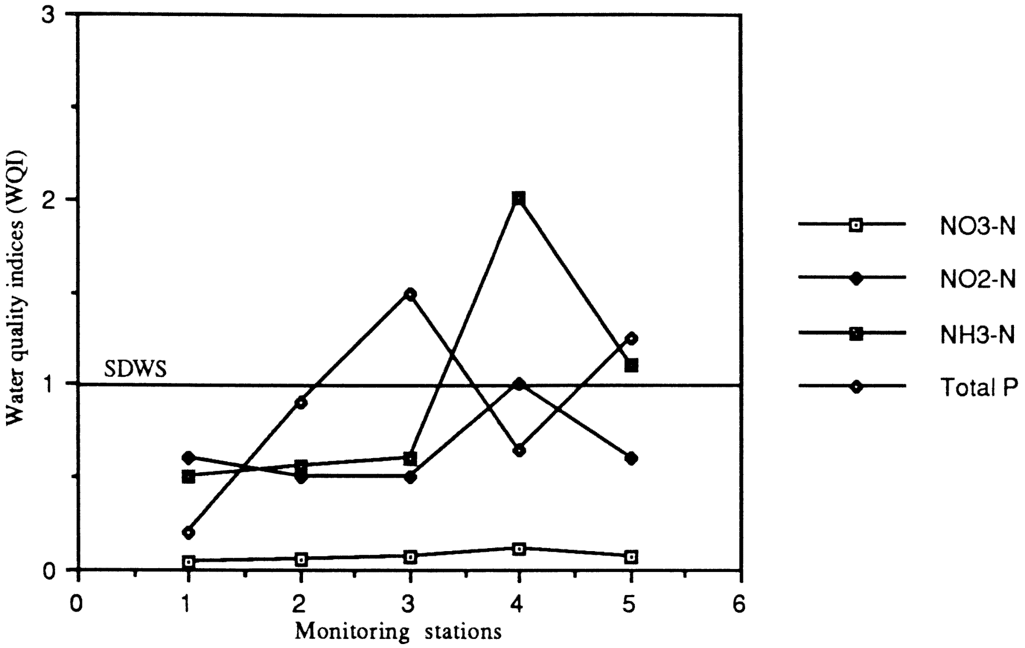

Figure 2.5(c) Canal water quality indices in December, 1989

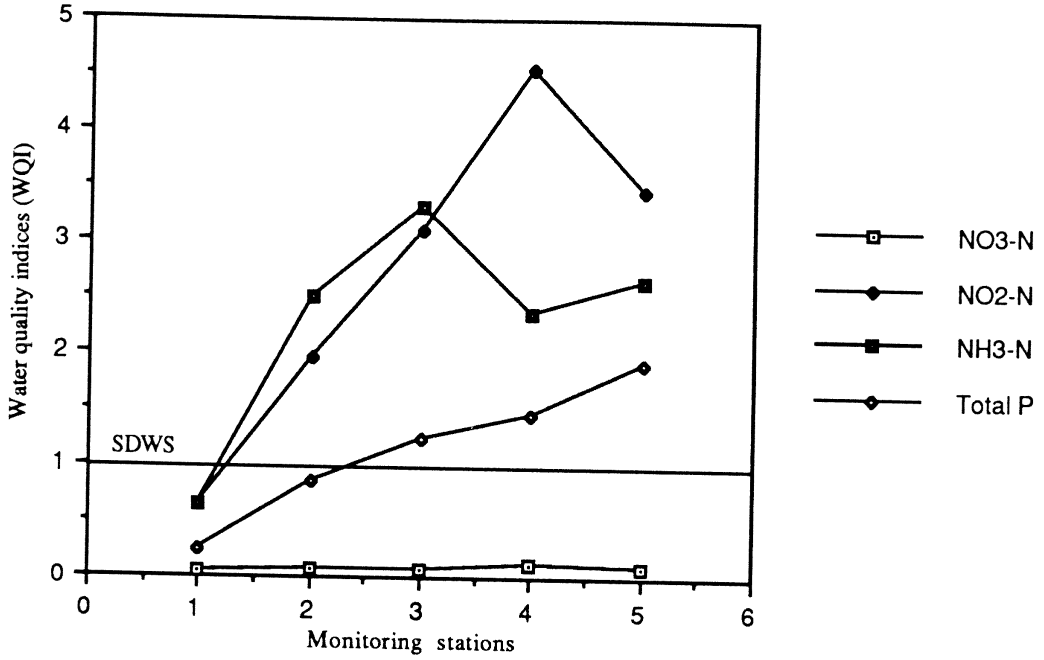

Figure 2.5(d) Canal water quality indices in 1989 (yearly average)

APPENDIX VI

DETAILED RESULTS OF SENSITIVITY ANALYSES

Table 6.1 Solutions with no restrictions on pollutant losses

Decision Variable	Grey Solution	Decision Variable	Grey Solution
Cropping Area (km^2)		Amount of Manure Application (10^6 tonne)	
$\otimes(S_{211})$	4.11		
		$\otimes(F_{21})$	0
$\otimes(S_{121})$	0		
		$\otimes(F_{12})$	0
$\otimes(S_{131})$	12.31		
		$\otimes(F_{13})$	0.017
$\otimes(S_{141})$	0		
		$\otimes(F_{14})$	0
$\otimes(S_{212})$	5.32		
$\otimes(S_{122})$	0	Amount of Nitrogen Fertilizer Application (10^9 kg)	
$\otimes(S_{132})$	11.80		
		$\otimes(H_{21})$	26.95
$\otimes(S_{142})$	0		
		$\otimes(H_{12})$	0
$\otimes(S_{213})$	12.85		
		$\otimes(H_{13})$	0
$\otimes(S_{123})$	0		
		$\otimes(H_{14})$	0
$\otimes(S_{133})$	10.81		
$\otimes(S_{143})$	0	Size of Livestock Husbandry (10^3)	
$\otimes(S_{214})$	15.38		
		$\otimes(T_1)$	0
$\otimes(S_{124})$	0		
		$\otimes(T_2)$	0
$\otimes(S_{134})$	9.92		
		$\otimes(T_3)$	137165
$\otimes(S_{144})$	0		
		$\otimes(T_4)$	0
$\otimes(S_{215})$	0		
$\otimes(S_{125})$	0	Net Income (¥10^6)	
$\otimes(S_{135})$	10.57	$\otimes(A)$	8086.61
$\otimes(S_{145})$	0		

Table 6.2 Solutions with total nitrogen loss constraints

Decision Variable	Total Nitrogen Loss Constraints $\otimes(a)$ (10^6 kg/km^2)			
	20	25	30	35
Net Income (¥10^6)				
$\otimes(A)$	6.05	7.57	9.08	10.59
Amount of Manure Application (tonne)				
$\otimes(F_{21})$	0	0	0	0
$\otimes(F_{12})$	0	0	0	0
$\otimes(F_{13})$	0	0	0	0
$\otimes(F_{14})$	0.0039	0.0039	0.0039	0.0039
Amount of Nitrogen Fertilizer Application (kg)				
$\otimes(H_{21})$	0.023	0.029	0.035	0.041
$\otimes(H_{12})$	0.0085	0.011	0.013	0.015
$\otimes(H_{13})$	20081500	25101900	30122400	35142700
$\otimes(H_{14})$	22584	28229	33875	39520
Size of Livestock Husbandry (10^3)				
$\otimes(T_1)$	15.19	18.99	22.79	26.59
$\otimes(T_2)$	0	0	0	0
$\otimes(T_3)$	0	0	0	0
$\otimes(T_4)$	0	0	0	0

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Table 6.2 (continued) Solutions with total nitrogen loss constraints

Decision Variable	Total Nitrogen Loss Constraints $\otimes(a)$ (10^6 kg/km^2)			
	20	25	30	35
Cropping Area (km^2)				
$\otimes(S_{211})$	0	0	0	0
$\otimes(S_{121})$	0	0	0	0
$\otimes(S_{131})$	0	0	0	0
$\otimes(S_{141})$	0	0	0	0
$\otimes(S_{212})$	0	0	0	0
$\otimes(S_{122})$	0	0	0	0
$\otimes(S_{132})$	0	0	0	0
$\otimes(S_{142})$	0	0	0	0
$\otimes(S_{213})$	0	0	0	0
$\otimes(S_{123})$	0	0	0	0
$\otimes(S_{133})$	77.24	96.55	115.85	135.16
$\otimes(S_{143})$	19.20	23.99	28.79	33.59
$\otimes(S_{214})$	0.0000049	0.0000061	0.0000073	0.0000085
$\otimes(S_{124})$	0	0	0	0
$\otimes(S_{134})$	0	0	0	0
$\otimes(S_{144})$	0	0	0	0
$\otimes(S_{215})$	0	0	0	0
$\otimes(S_{125})$	0	0	0	0
$\otimes(S_{135})$	0	0	0	0
$\otimes(S_{145})$	0	0	0	0

Table 6.3 Solutions with soil loss constraints

Decision Variable	Soil Loss Constraints $\otimes(b)$ $(10^3$ kg/km$^2)$			
	80	100	120	140
Net Income (¥10^6)				
$\otimes(A)$	6.47	7.63	8.78	9.94
Amount of Manure Application (tonne)				
$\otimes(F_{21})$	0	0	0	0
$\otimes(F_{12})$	0	0	0	0
$\otimes(F_{13})$	16766.7	16766.7	16766.7	16766.7
$\otimes(F_{14})$	0	0	0	0
Amount of Nitrogen Fertilizer Application (kg)				
$\otimes(H_{21})$	21399700	25248900	29098000	32947200
$\otimes(H_{12})$	0	0	0	0
$\otimes(H_{13})$	0	0	0	0
$\otimes(H_{14})$	0	0	0	0
Size of Livestock Husbandry (10^3)				
$\otimes(T_1)$	0	0	0	0
$\otimes(T_2)$	0	0	0	0
$\otimes(T_3)$	61.87	81.47	101.07	120.67
$\otimes(T_4)$	0	0	0	0

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Table 6.3 (continued) Solutions with soil loss constraints

Decision Variable	Soil Loss Constraints $\otimes(b)$ (10^3 kg/km^2)			
	80	100	120	140
Cropping Area (km^2)				
$\otimes(S_{211})$	4.11	4.11	4.11	4.11
$\otimes(S_{121})$	0	0	0	0
$\otimes(S_{131})$	12.12	12.12	12.12	12.12
$\otimes(S_{141})$	0	0	0	0
$\otimes(S_{212})$	4.34	4.34	4.34	4.34
$\otimes(S_{122})$	0	0	0	0
$\otimes(S_{132})$	13.57	13.57	13.57	13.57
$\otimes(S_{142})$	0	0	0	0
$\otimes(S_{213})$	12.87	12.87	12.87	12.87
$\otimes(S_{123})$	0	0	0	0
$\otimes(S_{133})$	10.97	10.97	10.97	10.97
$\otimes(S_{143})$	0	0	0	0
$\otimes(S_{214})$	15.71	15.71	15.71	15.71
$\otimes(S_{124})$	0	0	0	0
$\otimes(S_{134})$	9.93	9.93	9.93	9.93
$\otimes(S_{144})$	0	0	0	0
$\otimes(S_{215})$	75.00	126.94	178.89	230.84
$\otimes(S_{125})$	0	0	0	0
$\otimes(S_{135})$	10.57	10.57	10.57	10.57
$\otimes(S_{145})$	0	0	0	0

Table 6.4 Solutions with dissolved nitrogen loss constraints

Decision Variable	Dissolved Nitrogen Loss Constraints $\otimes(f_1)$ (10^3 kg/km^2)			
	60	70	80	90
Net Income (¥10^6)				
$\otimes(A)$	6.72	7.57	8.43	9.29
Amount of Manure Application (tonne)				
$\otimes(F_{21})$	0	0	0	0
$\otimes(F_{12})$	0	0	0	0
$\otimes(F_{13})$	16766.7	16766.7	16766.7	16766.7
$\otimes(F_{14})$	0	0	0	0
Amount of Nitrogen Fertilizer Application (kg)				
$\otimes(H_{21})$	22224600	25076600	27928600	30780700
$\otimes(H_{12})$	0	0	0	0
$\otimes(H_{13})$	0	0	0	0
$\otimes(H_{14})$	0	0	0	0
Size of Livestock Husbandry (10^3)				
$\otimes(T_1)$	0	0	0	0
$\otimes(T_2)$	0	0	0	0
$\otimes(T_3)$	66.07	80.60	95.12	109.64
$\otimes(T_4)$	0	0	0	0

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Table 6.4 (continued) Solutions with dissolved nitrogen loss constraints

Decision Variable	Dissolved Nitrogen Loss Constraints $\otimes(f_1)$ (10^3 kg/km²)			
	60	70	80	90
Cropping Area (km²)				
$\otimes(S_{211})$	4.11	4.11	4.11	4.11
$\otimes(S_{121})$	0	0	0	0
$\otimes(S_{131})$	12.12	12.12	12.12	12.12
$\otimes(S_{141})$	0	0	0	0
$\otimes(S_{212})$	4.34	4.34	4.34	4.34
$\otimes(S_{122})$	0	0	0	0
$\otimes(S_{132})$	13.57	13.57	13.57	13.57
$\otimes(S_{142})$	0	0	0	0
$\otimes(S_{213})$	12.87	12.87	12.87	12.87
$\otimes(S_{123})$	0	0	0	0
$\otimes(S_{133})$	10.97	10.97	10.97	10.97
$\otimes(S_{143})$	0	0	0	0
$\otimes(S_{214})$	15.71	15.71	15.71	15.71
$\otimes(S_{124})$	0	0	0	0
$\otimes(S_{134})$	9.93	9.93	9.93	9.93
$\otimes(S_{144})$	0	0	0	0
$\otimes(S_{215})$	86.13	124.62	163.11	201.60
$\otimes(S_{125})$	0	0	0	0
$\otimes(S_{135})$	10.57	10.57	10.57	10.57
$\otimes(S_{145})$	0	0	0	0

Table 6.5 Solutions with dissolved phosphorus loss constraints

Decision Variable	Dissolved Phosphorus Loss Constraints $\otimes(f_2)$ (10^3 kg/km^2)			
	6	8	10	12
Net Income (¥10^6)				
$\otimes(A)$	6.59	8.29	9.98	11.68
Amount of Manure Application (tonne)				
$\otimes(F_{21})$	0	0	0	0
$\otimes(F_{12})$	0	0	0	0
$\otimes(F_{13})$	16766.7	16766.7	16766.7	16766.7
$\otimes(F_{14})$	0	0	0	0
Amount of Nitrogen Fertilizer Application (kg)				
$\otimes(H_{21})$	21789400	27448300	33107100	38766000
$\otimes(H_{12})$	0	0	0	0
$\otimes(H_{13})$	0	0	0	0
$\otimes(H_{14})$	0	0	0	0
Size of Livestock Husbandry (10^3)				
$\otimes(T_1)$	0	0	0	0
$\otimes(T_2)$	0	0	0	0
$\otimes(T_3)$	63.86	92.67	121.48	150.29
$\otimes(T_4)$	0	0	0	0

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Table 6.5 (continued) Solutions with dissolved phosphorus loss constraints

Decision Variable	Dissolved Phosphorus Loss Constraints $\otimes(f_2)$ (10^3 kg/km^2)			
	6	8	10	12
Cropping Area (km^2)				
$\otimes(S_{211})$	4.11	4.11	4.11	4.11
$\otimes(S_{121})$	0	0	0	0
$\otimes(S_{131})$	12.12	12.12	12.12	12.12
$\otimes(S_{141})$	0	0	0	0
$\otimes(S_{212})$	4.34	4.34	4.34	4.34
$\otimes(S_{122})$	0	0	0	0
$\otimes(S_{132})$	13.57	13.57	13.57	13.57
$\otimes(S_{142})$	0	0	0	0
$\otimes(S_{213})$	12.87	12.87	12.87	12.87
$\otimes(S_{123})$	0	0	0	0
$\otimes(S_{133})$	10.97	10.97	10.97	10.97
$\otimes(S_{143})$	0	0	0	0
$\otimes(S_{214})$	15.71	15.71	15.71	15.71
$\otimes(S_{124})$	0	0	0	0
$\otimes(S_{134})$	9.93	9.93	9.93	9.93
$\otimes(S_{144})$	0	0	0	0
$\otimes(S_{215})$	80.26	156.63	233.00	309.37
$\otimes(S_{125})$	0	0	0	0
$\otimes(S_{135})$	10.57	10.57	10.57	10.57
$\otimes(S_{145})$	0	0	0	0

Table 6.6 Solutions with solid-phase nitrogen loss constraints

Decision Variable	Solid-phase Nitrogen Loss Constraints $\otimes(c_1)$ (10^3 kg/km^2)			
	15	20	25	30
Net Income (¥10^6)				
$\otimes(A)$	5.94	7.17	8.41	9.64
Amount of Manure Application (tonne)				
$\otimes(F_{21})$	0	0	0	0
$\otimes(F_{12})$	0	0	0	0
$\otimes(F_{13})$	16766.8	16766.7	16766.7	16766.7
$\otimes(F_{14})$	0	0	0	0
Amount of Nitrogen Fertilizer Application (kg)				
$\otimes(H_{21})$	19638200	23741000	27843900	31946700
$\otimes(H_{12})$	0	0	0	0
$\otimes(H_{13})$	0	0	0	0
$\otimes(H_{14})$	0	0	0	0
Size of Livestock Husbandry (10^3)				
$\otimes(T_1)$	0	0	0	0
$\otimes(T_2)$	0	0	0	0
$\otimes(T_3)$	52.91	73.80	94.68	115.57
$\otimes(T_4)$	0	0	0	0

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Table 6.6 (continued) Solutions with solid-phase nitrogen loss constraints

Decision Variable	Solid-phase Nitrogen Loss Constraints $\otimes(c_1)$ (10^3 kg/km^2)			
	15	20	25	30
Cropping Area (km^2)				
$\otimes(S_{211})$	4.11	4.11	4.11	4.11
$\otimes(S_{121})$	0	0	0	0
$\otimes(S_{131})$	12.12	12.12	12.12	12.12
$\otimes(S_{141})$	0	0	0	0
$\otimes(S_{212})$	4.34	4.34	4.34	4.34
$\otimes(S_{122})$	0	0	0	0
$\otimes(S_{132})$	13.57	13.57	13.57	13.57
$\otimes(S_{142})$	0	0	0	0
$\otimes(S_{213})$	12.87	12.87	12.87	12.87
$\otimes(S_{123})$	0	0	0	0
$\otimes(S_{133})$	10.97	10.97	10.97	10.97
$\otimes(S_{143})$	0	0	0	0
$\otimes(S_{214})$	15.71	15.71	15.71	15.71
$\otimes(S_{124})$	0	0	0	0
$\otimes(S_{134})$	9.93	9.93	9.93	9.93
$\otimes(S_{144})$	0	0	0	0
$\otimes(S_{215})$	51.22	106.59	161.97	217.34
$\otimes(S_{125})$	0	0	0	0
$\otimes(S_{135})$	10.57	10.57	10.57	10.57
$\otimes(S_{145})$	0	0	0	0

Table 6.7 Solutions with solid-phase phosphorus loss constraints

Decision Variable	Solid-phase Phosphorus Loss Constraints $\otimes(c_2)$ (10^3 kg/km^2)			
	3.0	4.0	5.0	6.0
Net Income (¥10^6)				
$\otimes(A)$	6.15	7.29	8.42	9.55
Amount of Manure Application (tonne)				
$\otimes(F_{21})$	0	0	0	0
$\otimes(F_{12})$	0	0	0	0
$\otimes(F_{13})$	16766.8	16766.7	16766.7	16766.7
$\otimes(F_{14})$	0	0	0	0
Amount of Nitrogen Fertilizer Application (kg)				
$\otimes(H_{21})$	20334600	24115100	27895500	31675900
$\otimes(H_{12})$	0	0	0	0
$\otimes(H_{13})$	0	0	0	0
$\otimes(H_{14})$	0	0	0	0
Size of Livestock Husbandry (10^3)				
$\otimes(T_1)$	0	0	0	0
$\otimes(T_2)$	0	0	0	0
$\otimes(T_3)$	56.45	75.70	94.95	114.19
$\otimes(T_4)$	0	0	0	0

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Table 6.7 (continued) Solutions with solid-phase phosphorus loss constraints

Decision Variable	Solid-phase Phosphorus Loss Constraints $\otimes(c_2)$ (10^3 kg/km^2)			
	3.0	4.0	5.0	6.0
Cropping Area (km^2)				
$\otimes(S_{211})$	4.11	4.11	4.11	4.11
$\otimes(S_{121})$	0	0	0	0
$\otimes(S_{131})$	12.12	12.12	12.12	12.12
$\otimes(S_{141})$	0	0	0	0
$\otimes(S_{212})$	4.34	4.34	4.34	4.34
$\otimes(S_{122})$	0	0	0	0
$\otimes(S_{132})$	13.57	13.57	13.57	13.57
$\otimes(S_{142})$	0	0	0	0
$\otimes(S_{213})$	12.87	12.87	12.87	12.87
$\otimes(S_{123})$	0	0	0	0
$\otimes(S_{133})$	10.97	10.97	10.97	10.97
$\otimes(S_{143})$	0	0	0	0
$\otimes(S_{214})$	15.71	15.71	15.71	15.71
$\otimes(S_{124})$	0	0	0	0
$\otimes(S_{134})$	9.93	9.93	9.93	9.93
$\otimes(S_{144})$	0	0	0	0
$\otimes(S_{215})$	60.62	111.64	162.66	213.68
$\otimes(S_{125})$	0	0	0	0
$\otimes(S_{135})$	10.57	10.57	10.57	10.57
$\otimes(S_{145})$	0	0	0	0

Table 6.8 Solutions with water quantity constraints

Decision Variable	Water Quantity Constraints (10^6 m^3/year)			
	20	30	40	50
Net Income (¥10^6)				
$\otimes(A)$	6.38	7.96	9.55	11.14
Amount of Manure Application (tonne)				
$\otimes(F_{21})$	0	0	0	0
$\otimes(F_{12})$	0	0	0	0
$\otimes(F_{13})$	16766.7	16766.7	16766.7	16766.6
$\otimes(F_{14})$	0	0	0	0
Amount of Nitrogen Fertilizer Application (kg)				
$\otimes(H_{21})$	21082700	26375400	31668100	36960800
$\otimes(H_{12})$	0	0	0	0
$\otimes(H_{13})$	0	0	0	0
$\otimes(H_{14})$	0	0	0	0
Size of Livestock Husbandry (10^3)				
$\otimes(T_1)$	0	0	0	0
$\otimes(T_2)$	0	0	0	0
$\otimes(T_3)$	60.26	87.21	114.15	141.10
$\otimes(T_4)$	0	0	0	0

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Table 6.8 (continued) Solutions with water quantity constraints

Decision Variable	Water Quantity Constraints (10^6 m^3/year)			
	20	30	40	50
Cropping Area (km^2)				
$\otimes(S_{211})$	4.11	4.11	4.11	4.11
$\otimes(S_{121})$	0	0	0	0
$\otimes(S_{131})$	12.12	12.12	12.12	12.12
$\otimes(S_{141})$	0	0	0	0
$\otimes(S_{212})$	4.34	4.34	4.34	4.34
$\otimes(S_{122})$	0	0	0	0
$\otimes(S_{132})$	13.57	13.57	13.57	13.57
$\otimes(S_{142})$	0	0	0	0
$\otimes(S_{213})$	12.87	12.87	12.87	12.87
$\otimes(S_{123})$	0	0	0	0
$\otimes(S_{133})$	10.97	10.97	10.97	10.97
$\otimes(S_{143})$	0	0	0	0
$\otimes(S_{214})$	15.71	15.71	15.71	15.71
$\otimes(S_{124})$	0	0	0	0
$\otimes(S_{134})$	9.93	9.93	9.93	9.93
$\otimes(S_{144})$	0	0	0	0
$\otimes(S_{215})$	70.72	142.15	213.58	285.00
$\otimes(S_{125})$	0	0	0	0
$\otimes(S_{135})$	10.57	10.57	10.57	10.57
$\otimes(S_{145})$	0	0	0	0

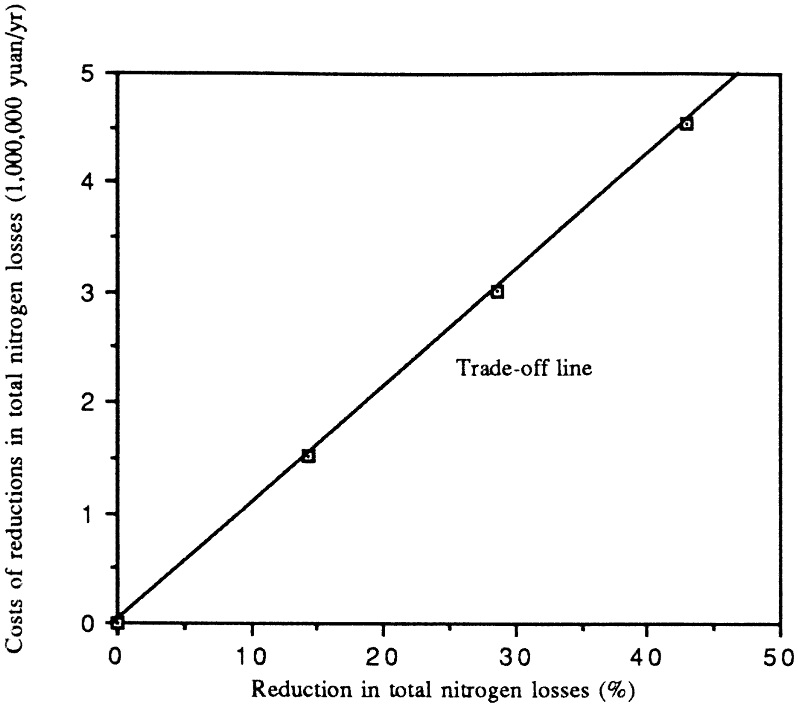

Figure 6.1 Effects of reductions in total nitrogen losses on agricultural income

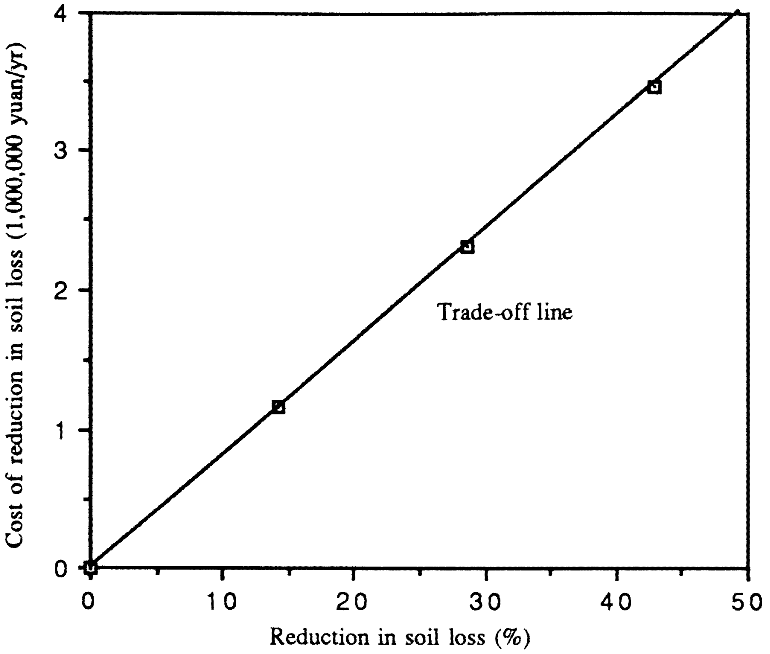

Figure 6.2 Effects of reduction in soil loss on agricultural income

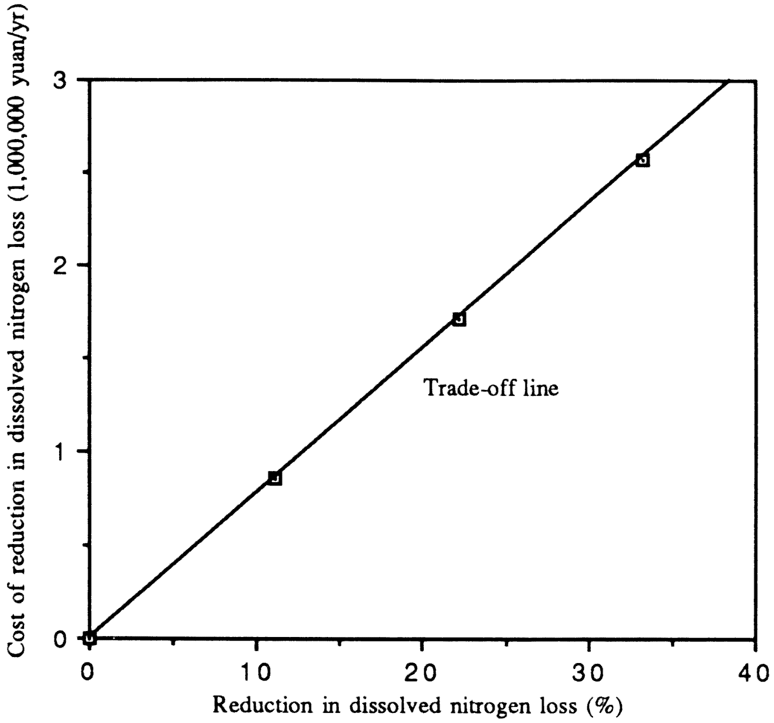

Figure 6.3 Effects of reduction in dissolved nitrogen loss on agricultural income

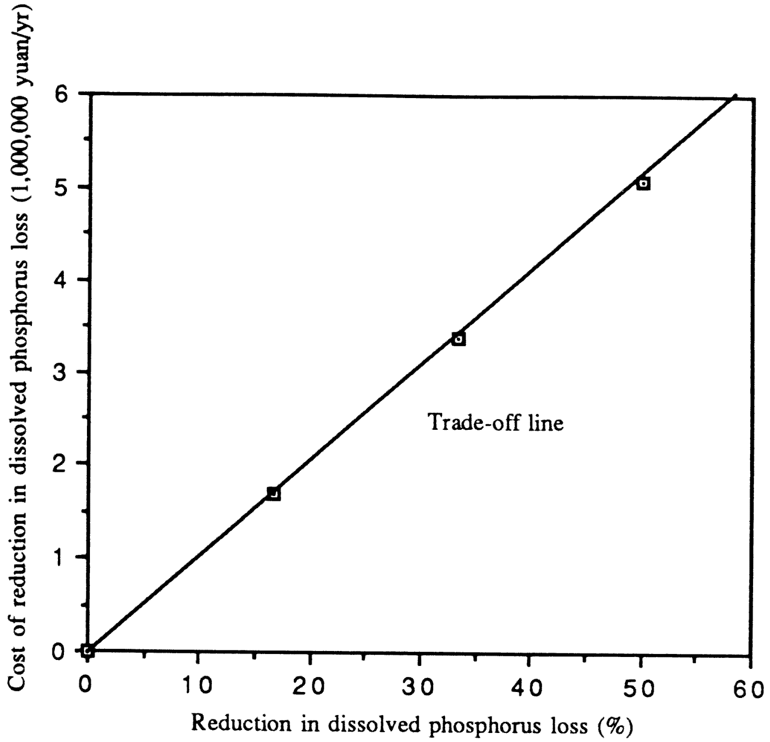

Figure 6.4 Effects of reduction in dissolved phosphorus loss on agricultural income

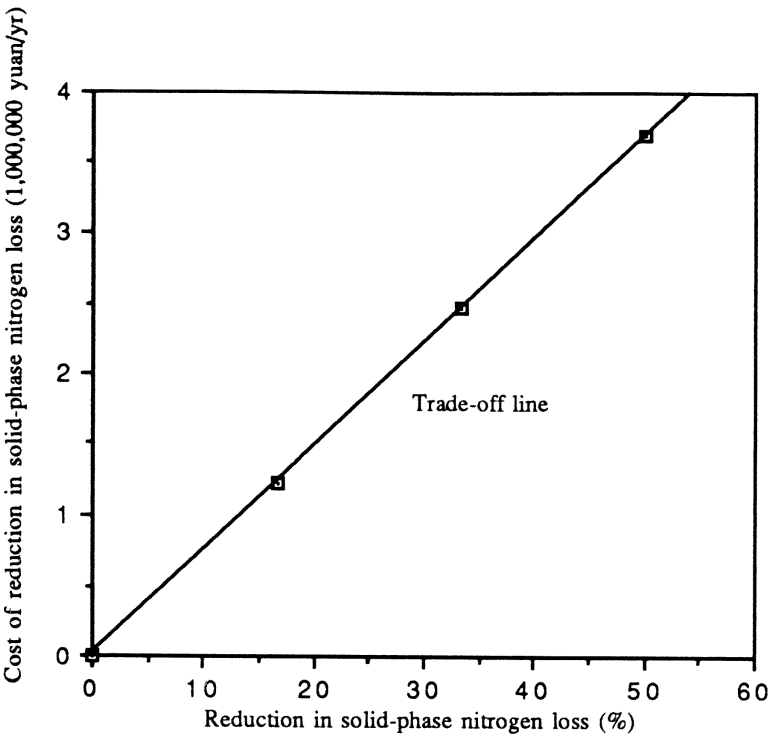

Figure 6.5 Effects of reduction in solid-phase nitrogen loss on agricultural income

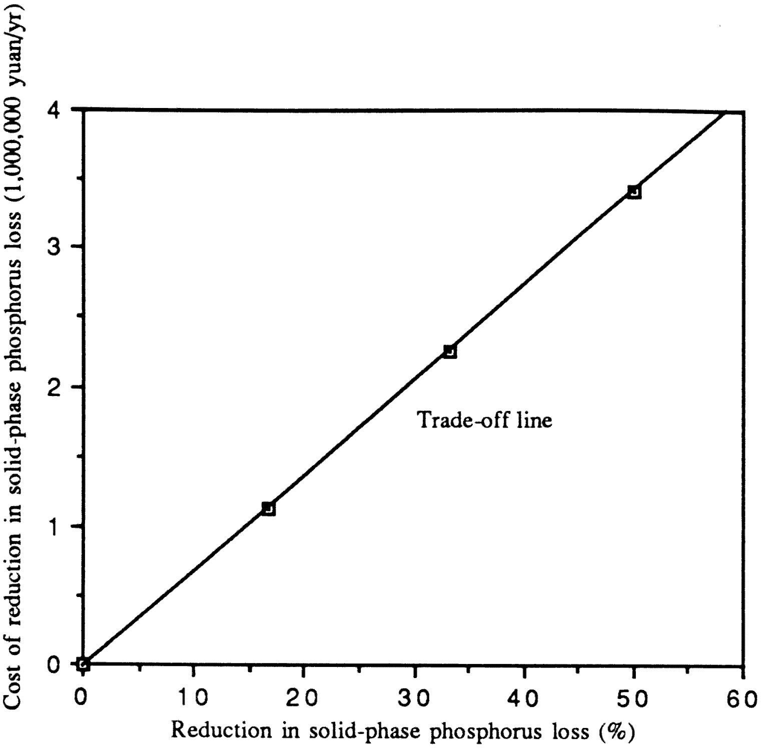

Figure 6.6 Effects of reduction in solid-phase phosphorus loss on agricultural income