PURIFICATION FUNCTION OF WETLANDS:

Spatial Modelling and Pattern Analysis of
Nutrient Reduction in the Liaohe Delta

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LI Xiuzhen

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To those who are helpful.

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Propositions

1. The integration of GIS and process models offers interesting possibilities for enlarging the analysis of our environment. GIS forms a good platform for the storage and management of model input data and the presentation of model results, while the process model provides the analysis capabilities lacking in current GIS.
   (*Bregt A.K. and Bulens J., 1998. Integrating GIS and process models for land resource planning. In: Heineke, H.J., Eckelmann, W., Thomasson, A.J., et al., (eds). Land information systems: developments for planning the sustainable use of land resources. Luxembourg: Office publications of the European communities. 293-304.*)

2. Mander-&-Mauring's generic linear regression model for nutrient reduction in wetlands has been proved to be applicable in the situation of Liaohe Delta.
   (*The thesis*)

3. The effect of landscape pattern on purification function is not always so obvious as we might expect due to the internal compensation of different processes.
   (*The thesis*)

4. Landscape indices should be chosen according to the purpose of the study, and be based on the criteria of simplicity, generality and meaningfulness.
   (*The thesis*)

5. The solution to coastal seawater eutrophication is in the transportation route from the source to the sink.
   (*The thesis*)

6. Economic development can be a driving force for nature conservation.

7. Stones from other hills can carve the jade.
   (*Chinese proverb*)

8. Nothing is "waste" in nature. "Waste" only exists in the eyes of human beings.

9. The impact of human activity is a double-edged sword, with one side towards the nature, and the other towards Man himself.

Propositions related to the dissertation
Purification Function of Wetlands: Spatial Modelling and Pattern Analysis of Nutrient Reduction in the Liaohe Delta
LI Xiuzhen, Wageningen, January 5, 2000.

Abstract

LI Xiuzhen, 2000. **Purification function of wetlands: Spatial modelling and pattern analysis of nutrient reduction in the Liaohe Delta**. ISBN: 90-5808-165-6. Wageningen University, the Netherlands.

The eutrophication of coastal seawater has been a serious problem for the last two decades in Eastern China. The purification function of natural wetlands at big river deltas provides a potential solution to cut down nutrient input into the sea. The purpose of this research is to give a quantified evaluation as to what extent the natural wetlands can be used as a treatment system for nutrient enriched river water. By integrating process-based mathematical models with GIS, a number of valuable results and conclusions have been obtained through this study.

A spatial simulation model has been established based on the field and literature data, to simulate the nutrient reduction and its distribution in the wetland of Liaohe Delta, China. A non-linear regression model is used for the nutrient reduction in the canal system, while Mander-&-Mauring's linear regression model is adopted for the reed fields. According to the simulation result, there is a "mutual compensation" for the nutrient reduction in the reed system and canal system, so that the total reduction rate remains relatively stable in spite of the input concentration change at the pumping station. It is 66% for total nitrogen and 90% for soluble reactive phosphorus. In combination with the canals, the present 80,000 ha of reed can remove about 3,200-4,000 tons of nitrogen and 80 tons of soluble reactive phosphorous during the irrigation period each year. But this is only 1/10 of its total reduction capacity, with water being the limitation factor.

Four spatial combinations of reed, canals and pumping stations are designed to investigate the effect of pattern on nutrient reduction: 1) canal density, 2) reed area size, 3) reed shrinking pattern and 4) pumping station position. The simulation results indicate that each factor brings less than 10% deviation in total nutrient reduction rate, though the absolute reduction quantity can be different. If the reed area is stable, it is better to remain a low canal density, and keep the pumping station near the border of the reed area. Generally speaking, smaller reed area close to the pumping station is more efficient in nutrient reduction than larger, scattered ones. The shrinkage pattern of land transformation for the reed is most recommended in keeping a high reduction rate for the nutrients. The present reed area can accept at least 4 times more water in spring.

The relationship between landscape structure and nutrient reduction is measured with the help of some landscape indices. Not all the landscape pattern indices are closely related to the nutrient reduction of the wetland system. Therefore the ability of pattern indices to characterize the effect of pattern change on function is rather limited. Redundancies also exist among similar indices. Landscape indices should be chosen according to the purpose of the study, based on the criteria of simplicity, generality and ecological meaningfulness.

The research work is a combination of landscape ecology, wetland ecology and GIS technology. The spatial model developed is also applicable for other areas with similar situations. The results will contribute to a sustainable landscape planning in the study area. It is concluded that the natural wetlands have a great potential to be used for reducing nutrient input into the sea.

Key words: Wetland, landscape, nutrient reduction, process model, spatial model, GIS, pattern analysis, input load, reed, canal, pumping station, Liaohe Delta.

Acknowledgement

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Li Xiuzhen
Wageningen, 1999

Contents

1. Introduction

1.1 Research topic

1.1.1 Why is this research?

The contradiction between development and environment protection has been an unavoidable issue in developing countries. This problem is especially serious in areas where economic growth is fast. In Eastern China, the coastal sea water eutrophication has become one of the biggest hazards in the last two decades. Whenever it happens, great damage is caused in fishing, aquaculture, tourism and many related industries. How to reduce the potential risks of algae blooming is one of the key topics among researchers and policy makers.

Theoretically, the problem can be solved by controlling pollutants at the source, reducing them on the route and mitigating the algae blooming at the destination. As source control is difficult because of the large area involved, and destination mitigation unpredictable, nutrient reduction on the transportation route becomes more important. Many landscape ecologists and environmentalists have already noticed this and started to work on it (Paterjohn and Correll, 1984; Phillips, 1989; Pinay, et al., 1993; Vought, et al., 1994; Brunet, et al., 1994). In China this kind of research has just started, and mainly focused on the coastal wetlands to reduce the pollutants (Guo and Zuo, 1997; Li, et al., 1999).

Although constructed wetlands have become more and more popular in the world, it is difficult to be put into practice in China because of the huge population and relative shortage of arable land. What is left for pollution control is the so-called "wasteland", where cultivation is difficult, such as natural wetlands, beaches or deserts. To make full use of the natural coastal wetlands and investigate the possibility of using them as treatment system for nutrient enriched river water, a national key project[1)] was funded in China in 1997. The subject of this thesis is one of the key components in this project. In combination with other research subjects, the results will be used in a sustainable land use planning in the study area.

According to the research work on wetland treatment systems from many countries, and the actual situation in China, the thesis study tries to provide a more quantitative measure to the nutrient reduction function of wetland at the landscape level. With the help of geographical information systems, a spatially explicit simulation model will be established and serve as a linkage between point process studies and global landscape planning practices.

1.1.2 Problem definition

Nitrogen and phosphorous are considered to be two major contributors to the eutrophication problem. In the Liaodong Bay, where our study area is close to, the main restricting nutrient for

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1) NSFC 49631040.

algae blooming is phosphorous, especially soluble reactive phosphorous. The nitrogen is a contributing factor, but not a limitation. Most of the nutrients come from inland soil-water erosion, industrial wastewater and urban sewage in the catchments of large rivers running into the Liaodong Bay. In combination with the measures taken in the upstreams to control the release of pollutants and nutrients, using the natural estuary wetland as a filtering system to the river water provides a pragmatic and less expensive alternative to cut down the total nutrients input into the sea.

The extensive natural wetland distributed in the Liaohe Delta is the second largest reed marsh in the world. The high productivity, irrigation regime and annual harvesting system provide ideal basis for this piece of land to be used as a treatment system for nutrient enriched river water. At present wastewater irrigation is only conducted in a limited area and period. The potential capacity for the wetland system to receive nutrients has never been studied yet. The spatial configuration of reed-covered area, canals and pumping stations are also important management factors if we use it as a treatment system in the future.

Therefore the problems to be solved can be defined as:

- How efficient the wetland in the Liaohe delta functions as a nutrient reduction system? Or, what is the present situation and potential capacity for nutrient reduction?
- What are the effects of different spatial element configurations on the nutrient reduction?
- How to quantitatively measure the relationship between landscape pattern and nutrient reduction?

To answer the above questions, point measured data has to be extrapolated into area. This is a methodological problem. The study will improve the scientific understanding about the purification function of natural wetland systems and enhance the application of scientific knowledge into management strategies.

1.1.3 Objectives of the research

The main objective of this research is to investigate the possibility of using the estuary wetland as a treatment system to cut down nutrient input into the sea. A model will be established to simulate the reduction ability of the natural wetland to some nutrient elements and to analyse the change of this function when landscape pattern changes. The sensitivity of some landscape indices will also be tested corresponding to the scenarios of nutrient reduction function. More specifically:

- To study the purification function of the wetland as a treatment system to reduce some pollutants and nutrients input into the sea.
- To establish a spatial simulation model for the reduction function of the natural wetlands to nitrogen and phosphorous in the Liaohe Delta.
- To investigate the effect of different landscape components and their combination on the nutrient reduction function.
- To evaluate the relationship between landscape pattern and nutrient reduction with the help of some landscape indices.

1.1.4 Materials and methods

The research work is based on field data, remotely sensed data and existing digital and printed maps. Literature is also used as references as well as important data sources.

Statistics for field data is conducted in Excel97®, in order to establish the regression model for the nutrient reduction in the wetlands. TM images are processed and classified in Erdas® (Imagine 8.3), so as to delineate the desired landscape features such as reed-covered area and canals. The model is implemented in the Grid module of Arc/Info®, with the help of AML (Arc Macro Language) programs designed by myself. Arcview® (3.0.b) is used for spatial data presentation. The detailed methods used will be given in each chapter.

1.2 Theoretical background of the research

The thesis deals with the purification function of the wetland landscape in the Liaohe delta, China, and the spatial modelling of this function. The theoretical background of the research work is mainly related to wetland, landscape ecology and geographical information systems (GIS). Most of the research works related to each subject of the thesis will be given at the beginning of each chapter. Here just a global review on different themes is provided.

1.2.1 Wetland

A wetland is defined as land that is saturated with water long enough to promote wetland or aquatic processes as indicated by poorly, hydrophytic vegetation, and various kinds of biological activity which are adapted to a wet environment (Canadian wetland classification system, 1987). The presence of water, unique soil and hydro-vegetation are three main components to distinguish a wetland from its adjacent landscapes. Wetland is the transitional system between deep water and terrestrial uplands, and interacts with both. The depth and duration of flooding, size and location may vary considerably from wetland to wetland (Mitsch and Gosselink, 1993).

The study area is an estuary wetland in Liaohe Delta, China. The word "estuary" refers to a semi-enclosed body of water, such as a river mouth or coastal bay, where the salinity is intermediate between salt and fresh water, and where tidal action is an important physical regulator and energy subsidy (Odum, 1993). At a larger scale, the estuary wetland is an ecotone, or transitory area between land and sea, with the water table fluctuating round the ground surface (Wilen, et al., 1993).

Estuary is often an efficient nutrient trap that is partly physical and partly biological. This property enhances the estuary's capacity to absorb nutrients in wastes provided organic matter has been reduced by secondary treatment (Odum, 1993). In recent years, both natural and constructed wetlands have been used to remove nutrients from non-point agricultural sources (Mitsch, 1992b; SFWMD, 1992; Craft and Richardson, 1993a, b; Mitsch, et al., 1995), livestock operations (Du-Bowey and Reaves, 1994) and treated wastewater (Kadlec, 1985; Richardson and Marshall, 1986). The privileges and limitations of these wetland treatment systems have also been discussed (Craft, 1997; Hopkinson, 1992).

The functionality study of the wetland as a treatment system to nitrogen (N) and phosphorous (P) enriched water from upstream and breeding ponds along the coast will provide an insight into the interaction between landscape structures and functions. People have been discussing about the creation of wetlands to cut down N&P input into the sea (AMBIO, 1994; 1995). It is unreasonable to do so if we do not make good use of the existing natural wetlands to reduce coastal seawater pollution. Actually it is also urgent to make responses to the "red-tide" problem in the Bohai Sea emerged in the recent years.

Ecological modelling for wetlands has been focused on energetic, hydrological or biological processes of the system (Dorge, 1994). Little work has emphasized the spatial aspects of the wetland system. This thesis will deal with the modelling on the spatial distribution of pollutant concentration in the wetland, regarding to its retention function on some nutrient elements.

1.2.2 Landscape ecology

Landscape ecology is an interdisciplinary science that considers the development and dynamics of spatial heterogeneity, spatial and temporal interactions and exchange across heterogeneous landscapes, influences of spatial heterogeneity on biotic and abiotic processes, and management of spatial heterogeneity (Risser, et al., 1984; Naveh and Lieberman, 1984). Generally speaking, it focuses on three characteristics of the landscape (Forman and Godron, 1986):

Structure: the spatial relationships among the distinctive ecosystems or elements present — more specifically, the distribution of energy, materials, and species in relation to the sizes, shapes, numbers, kinds, and configurations of the ecosystems.

Function: the interactions among the spatial elements, that is, the flows of energy, materials, and species among the component ecosystems.

Change: the alteration in the structure and function of the ecological mosaic over time.

Thus, landscape ecology involves the study of landscape patterns, the interactions among patches within a landscape mosaic, and how these patterns and interactions change over time (McGarigal and Marks, 1995). The two leading principles are "system approach and attention for the spatial aspect" (Zonneveld, 1995).

Landscape ecology is concerned with large-scale relationships between spatial pattern and ecological processes (Kareiva and Wennergren, 1995; Turner, 1989; Turner and Gardener, 1991). How to quantify spatial pattern and its effect on processes is also one of the core topics in landscape ecology (Forman and Godron, 1986; Turner, 1987, 1990). A series of indices have been defined to measure landscape pattern differences (Pielou, 1975; O'Neil, et al., 1988; Gustafson and Parker, 1992; McGarigal and Marks, 1995), but the ecological meaning of these indices still need further evaluation and verification.

Landscape functions are closely related to its structure, or distribution pattern of landscape elements (Forman and Godron, 1986; Xiao, 1991; Zonneveld, 1995). Case studies on the purification function of wetlands have been documented on both superficial and linear landscape elements (Mander and Mauring, 1997; Meuleman, 1999; Li, et al., 1999). Yin and Lan (1994, 1995) used to study the nutrient retention function of the reed marsh around Baiyangdian Lake, Northern China, and got very good results. Natural rivers have been proved to be effective in reducing certain kinds of pollutants (Brunet, et al., 1994; Haycock, et al., 1993). But artificial canals also have strong dilution and absorption ability to some pollutants, according to our experiments done in the Liaohe delta. All the above researches provide important basis for our study on the purification function of the wetland landscape in the Liaohe Delta.

1.2.3 Spatial modelling with GIS

The integration of landscape ecology and GIS (geographical information systems) is of fundamental importance to the development of both. The former is theoretical and empirical in nature, while the latter is more a technological development of the last decades. Landscape ecology can serve as the theoretical basis for the applications developed in GIS. On the other hand, GIS can help in perceiving how spatial patterns occur and how they change over time, and provide an insight into the complex interactions between physical, climatic, biological, ecological and human processes. This may result in new theories and expand the understanding of landscape dynamics (Perez-Trejo, 1993; Bregt and Bulens, 1998).

The integration of landscape ecology with GIS has been attempted by landscape ecologists (Baker and Cai, 1992; Haines-Young and Green, 1993; Pizzolotto and Brandmayr, 1996; Rooij, 1994; McGarigal and Marks, 1995). But there is still a long way to go because both landscape ecology and GIS are newly emerged sciences and are developing fast. GIS is not only a convenient "map producer" (Bridgewater, 1993) for landscape ecology study, but also can be used for data analysis. It provides a strong tool to quantify spatial aspects of landscape elements, while the quantification procedure helps GIS for further improvement.

At the beginning of 1990s, the landscape pattern indices had to be calculated indirectly via computer language such as Fortran (Turner, 1990; Gustafson and Parker, 1992). Now most of the indices can be calculated easily within the GIS package (Arc/Info, for example) (McGarigal and Marks, 1995; Li, 1998). It is also possible to do a lot of test analysis over a variety of artificial "landscape patterns" and find suitable parameters to describe the landscape (Gustafson and Parker, 1992; Plotnick et al., 1993; Li and Reynolds, 1993; Shumaker, 1996; Meisel and Turner, 1998; Li, 1998). Later on these parameters can be used to interpret or predict ecological processes at larger scales.

Both landscape ecology and GIS theory emphasize on the hierarchical character of spatial objects (Ollier, 1977; Forman and Godron, 1986; Molenaar, 1994). There is a group of commonly used terms for the descriptive elements of landscapes (Zonneveld, 1995):

Ecotope: The smallest unit that can be considered to be a landscape in the sense of a system.
Microchore: A horizontal arrangement of ecotopes.
Mesochore: A pattern of microchores.
Macrochore: A pattern of mesochores. (The so-called landscape level)
Megachore: Larger landscape at the transition to the geospheric dimension.

Apart from the terms given above, there are also some other land unit names such as "site" (Christian and Stewart, 1953), "ecotope", "landfacet" (Zonneveld, 1979), "biotope (Agger and Brandt, 1984), and so on. They are defined by different users and often synonymous with each other.

According to Zonneveld (1995), a land unit can be defined as "a tract of land that is ecologically relatively homogeneous at the scale level concerned". Therefore the size and attribute of a "land unit" is scale-dependent. Land unit is a feasible mapping tool in GIS and landscape ecology. It provides the possibility of generation and conversion of point data into area data.

The integration of GIS and process models offers interesting possibilities for enlarging the analysis of our environment. GIS forms a good platform for the storage and management of model input data and the presentation of model results, while the process model provides the analysis capabilities lacking in current GIS (Bregt and Bulens, 1998). Spatial modelling offers a valuable link between process studies and spatial models (Burker, et al., 1990).

A lot of research work has also been done in the study area of Liaohe Delta (Huang and Wang, 1982; Xiao, et al., 1996; Zhang, et al., 1997), most of which is focused on the ecological processes (Wang, 1996; Li, et al., 1999) and biological diversity (Hu, 1997). These studies provide valuable knowledge for the spatial modelling on the nutrient reduction in the study area.

1.2.4 Position of the research work

The thesis work will be a result of knowledge combination on the theory of landscape ecology, wetland, and GIS (figure 1.1).

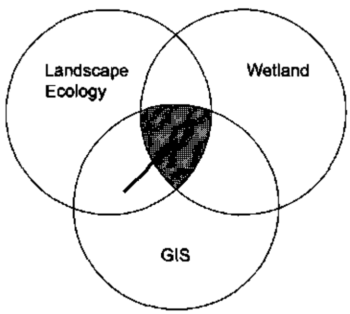

Figure 1.1 Position of the thesis work in its theoretical background.

The knowledge of landscape ecology and wetlands will provide theoretical basis for the designing of experiments and research subjects, while GIS will serve as a powerful tool to realize the research objectives. The elaboration of process models with GIS will provide new knowledge that can not be achieved within any one of the above disciplines. Further more, the results of the research will contribute to the sustainable land use planning for the Liaohe Delta and other areas with similar situations, so as to reduce the risks of coastal seawater eutrophication. In this sense, the practical value of this study is no less than its scientific significance.

1.3 Outline of the thesis

A general description of the thesis structure is shown in figure 1.2. It has seven chapters, from general description of the study area, to model development and application. Following is the main contents of each chapter:

Chapter 2 will give a general description about the natural and managed situation of the study area in Liaohe Delta, China, including the geographical and biological background, as well as the effect of human activities.

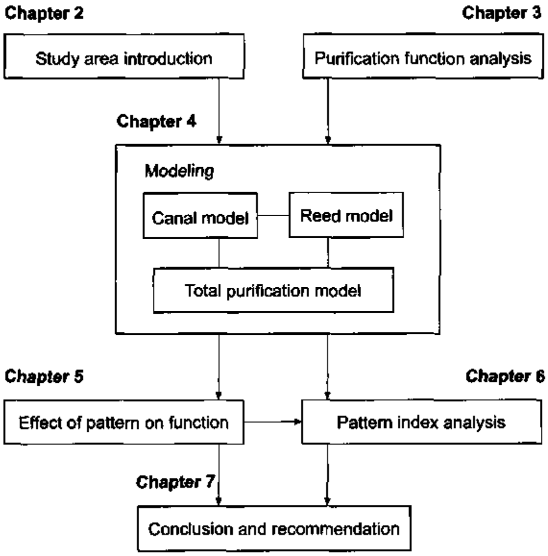

Figure 1.2 Structure of the thesis

Chapter 3 is about the multi-functions of the wetland landscape, mainly focusing on the purification function of the system. Reed and canal systems are inspected for the purification of wastewater from paper factories and oil drilling. The potentiality of using *Suaeda* community as treatment system for breeding water is also discussed.

Chapter 4 is the central part of the thesis. The spatial model for nutrient reduction is established, first based on field data and later on modified with literature data. A logarithmic regression model is used for the canal system while a linear regression model is adopted for the reed system. Applications of the model are made to calculate the total nutrient reduction, temporal dynamic and maximum reduction capacity of the study area.

Chapter 5 studies the effect of landscape pattern on the nutrient reduction function, according to the simulation results of the above model. Different scenarios of landscape components are designed and simulated to test the effect of each factor.

Chapter 6 investigates the relationship between the quantity of nutrient reduction and landscape structure with the help of some pattern indices. Different indices are chosen for different pattern scenarios to compare with the simulated nutrient reduction quantity. The sensitivity and redundancy of these indices are discussed in relation to the nutrient reduction function of the system.

Chapter 7 concludes the research. Some reflections regarding to the research and suggestions on management are also given.

2. The Wetland Landscape in Liaohe Delta, China

2.1 Introduction

The Liaohe delta can be classified as a coastal wetland, according to its geomophological, hydrological and hydrodynamical characters (Brinson, 1993; Yin and Ni, 1998). It is mainly composed of the lower Liaohe fluvial plain, most part of which belongs to the administrative district of Panjin City, Liaoning Province. In this book, the "Liaohe delta" refers to the administrated area of Panjin City, for the convenient of data collection.

The developing history of this area is very short. Originally it is low and swampy, with few human activities. People started to colonize and reclaim this piece of land in the middle of the 17^{th} century. At first only soybean and maize were grown. Later on rice was introduced by the Japanese in the 1930s. Gradually canals, dikes and reservoirs have been constructed. More and more reed marsh has been converted into agricultural fields. Prawn and crab breeding ponds are also created along the coast. Since the discovery of oil in 1970s, a lot of oil wells have been drilled all over the delta, along with industrial development.

Now about 2,000,000 people are living in the 4,000 km^2 area, with oil, rice, seafood and reed as their main products. The contradiction between economic development and environment protection has become a serious problem.

In this chapter, we will give an introduction about the natural conditions and the effects of human activities in the study area, as the background for nutrient reduction research.

2.2 Natural condition

The natural condition of a geographical area includes several aspects, such as geographical position, climate, soil, water, flora and fauna. All these aspects are interrelated with each other and form the basis for ecological functionality of a landscape.

2.2.1 Geographical position

The Liaohe Delta is situated in Liaoning Province, China, to the north of Liaodong Bay (figure 2.1), within the range of 121°35'-122°55'E and 40°40'-41°25'N. The total area is about 4,000 km^2, almost 1/10 the area of the Netherlands. Several large rivers, such as Daliao River, Shuangtai River, Daling River, Xiaoling River and Daqing River, run into the sea with 11.7 billion m^3 of water every year. Counteracted by sea tides, 76 million tons of sedimentation is accumulated here annually, forming a complex delta[1)]. According to Hu Yuanman (1997), the coastline is pushed seaward

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1) Environment Effect Assessment on Oil and Agricultural Exploration in Liaohe Delta, 1992

2,730m from 1989 to 1994 on the western side of the Shuangtai river mouth, and 118m on the eastern side. The main landscape types include open water, beach, reed marsh and paddy fields, etc.

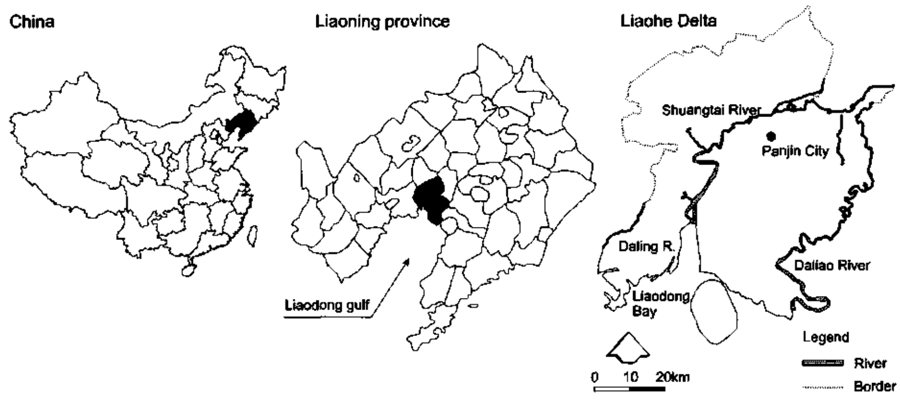

Figure 2.1 The location of the study area

2.2.2 Climate

The climate of the Liaohe Delta is semi-humid temperate monsoon. High precipitation (July) always comes together with high temperature (figure 2.2). The annual average temperature is 8.3 - 8.4°C, with 27.4°C in July and −10.4°C in January. The frost-free period is about 170-200 days, from late March to late October. In recent years, the frost period tends to come later and goes earlier than average years, probably because of the global climate change. During winter, the frozen soil can be 90-100cm thick. Almost no natural bioactivity occurs. Therefore, the Liaohe delta is a seasonally inundated estuary wetland in summer, frozen and dry in winter.

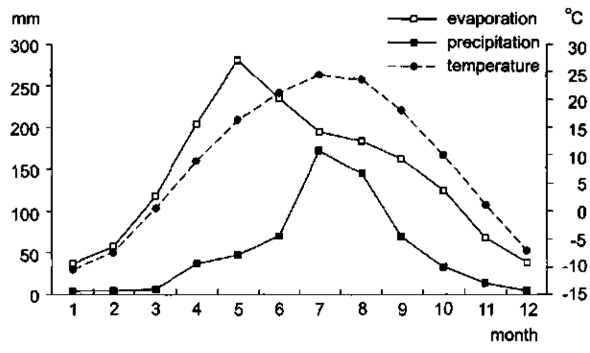

Figure 2.2 Climate of the Liaohe delta, China

The average annual precipitation is 611.6 mm, 70-80% of which falls between July and September, constituting the flooding season, while less than 10% falls between April and June (figure 2.2). The annual evaporation is 1,390-1,705mm, about 2.5 times of the precipitation. The highest evaporation month (281.3mm) is in May, nearly 6 times that of the precipitation. But the driest month is March, in which the evaporation is 17 times higher than the precipitation.

2.2.3 Geology/topography

Geologically the Liaohe delta belongs to the lower Liaohe fault basin, as a part of the Northern China continental plateau. The whole sedimentation layer is 1,000 to 8,000 meters thick due to the strong sink during the Quaternary Period.

The plain is rather flat, with an average slope of 1/20,000 - 25,000. The maximum altitude is less than 7 meters above sea level. Local relief is caused by river and tidal ditch migration, or, dike and breeding ponds construction.

2.2.4 Soil

Generally speaking, the Liaohe delta is a saline wetland. The combination of water and salt concentration in the soil is the decisive factor of the ecosystem. Normally the farther away from the sea, the lower the soil salt content is, and the soil is also better developed. With natural succession and agricultural activities going on, desalinization of the soil continues gradually. The nutrient level of the soil also improves accordingly. The soil often becomes very clayey after several years of reed or rice growth.

The main soil types in the Liaohe delta are coastal solonchak, (saline) bog soil, (saline) meadow soil and paddy soil (Zhu Qinghai, 1993). Coastal solonchak is relatively sandy and less developed along the coast. Saline bog soil and meadow soil are main soil types in the reed marsh and river side. Paddy soil is only distributed in the agricultural area with rice planted for years. Each type of soil can be further divided into sub-types according to the soil salt concentration, water condition, and time of vegetation growth or agricultural use.

2.2.5 Flora

As the physical forces tend to shape the landscape, vegetation and animal communities colonize those sites that have sufficient moisture or nutrients for them to be established. These communities begin to change the site's characteristics and generate a pattern of landscape element units that interact to determine the global erosion, run-off, and sedimentation patterns (Perez-Trejo, 1993). In the temperate wetlands as Liaohe delta, the number of natural plant species is very limited, and is often dominated by non-woody species, due to the extreme water and soil conditions.

According to the field investigation in the Nature Reserve of Liaohe Delta, there are 126 plant species. But only less than ten of them are dominant species, such as reed (*Phragmites communis*), *Suaeda heteroptera,* cattail (*Typha spp.*), *Aeluropus litoralis var. Sinense*, and so on.

Reed is the dominant local grass species in the Liaohe Delta, occupying more than 20% of the whole delta. Before 1929, it is only sparsely distributed here and there. The big flooding in 1929 created a large area of alluvial shoals, upon which the reed expanded quickly. By 1940s, the area of the reed reached its peak. Then it began to shrink at the northern side, and was pushed south by the rivers as well as by the human activities. Now the total reed area is over 90,000 ha, being the largest reed marsh in Asia. It is mainly distributed between the Daling River and Daliao River, as well as the area near the large river mouths (figure 2.3).

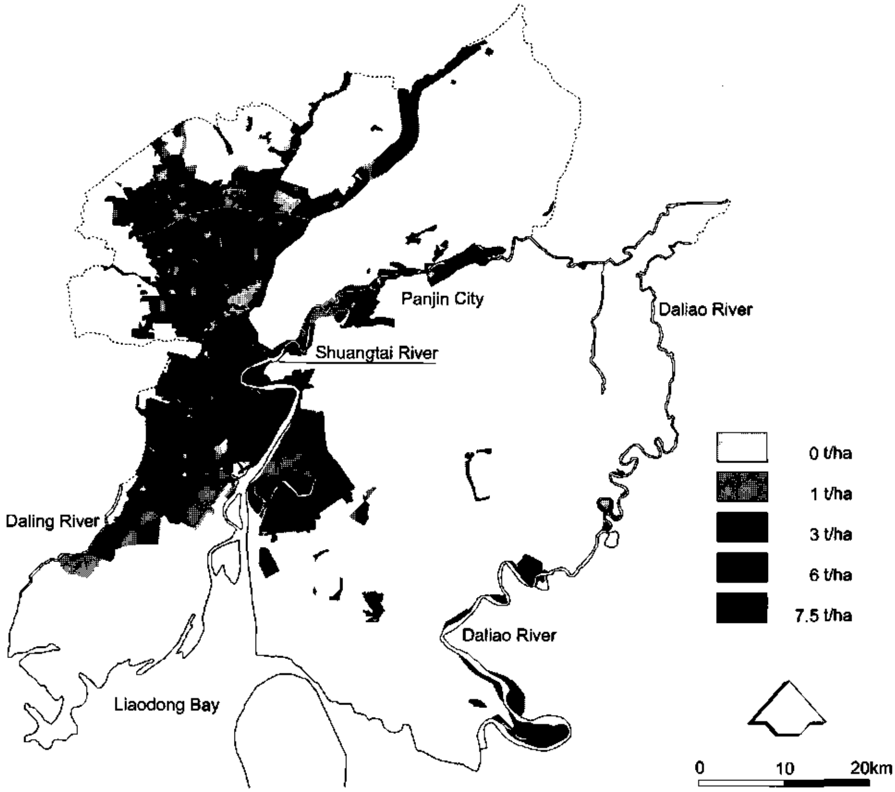

Figure 2.3 The distribution of different productive reed fields in the Liaohe delta.

The reed is not homogeneous if we take a close look into the fields. The height varies from 70 cm to more than 200 cm. The productivity also differs from place to place. According to the reed growth condition, the area can be classified into four categories (figure 2.3):

1) **High productivity fields**: The irrigation and discharge condition is usually very good, with high power pumping stations and well-managed canals. The soil organic matter is usually higher and the salt content is lower. The reed is about 2-3 meters high, at a density of 60-100 stems/m^2. The diameter of above ground stem is about 6-10 mm, and the average productivity is about 7,500 kg/ha. The area of this kind of reed fields has been increasing in the recent decades, thus caused the increase of total productivity in spite of the total reed covered area decrease. It is the "core" area of the reed farms managed by the government.
2) **Middle productivity fields**: The irrigation and discharge condition is moderately good, but often has long period of seasonal water inundation. The root system moves to the upper layer of the soil, and the height of the reed is about 1.5-2.5 meters. The stems are slim and dense, with 110-250 stems/m^2 at the diameter of 3-5 mm. The productivity is about 4,500-7,500 kg/ha. Originally this is the main part of reed farms.
3) **Low productivity fields**: This kind of reed fields are often far away from rivers, or on high land where soil salinity is too high, with poor irrigation conditions. The reed density is about 30-100 stems/m^2, at the diameter of 2-4 mm, and height of 1-2 meters. The productivity is about 2,250-3,750 kg/ha.

4) **Extremely low productivity fields**: This is distributed in the place where reed is newly colonizing, or soil salt concentration is so high that *Suaeda heteroptera* is often mixed with the reed. The average productivity is about 1,000 kg/ha. The local people often improve this kind of fields by planting new reeds.

The different reed productivity area can be delineated from TM images and will be used in the model establishment for nutrient reduction in Chapter 4.

The *Suaeda heteroptera, Aeluropus lithoralis* var. *sinensis* and *Carex scabrifolia* are important pioneer communities on the beach. The height of these communities is much lower than that of the reed, about 40-70 cm, or even lower.

Shrubs are highly salt tolerant species, such as *Tamarix chinensis* and Baici (*Nitraria sibirica* var. *globicarpa*). The latter often forms small shrub mounds in the inter-tidal belt, which is an important habitat for black-billed gulls (*Larus saundersi*).

The forest area in the Liaohe Delta is rather limited, due to the high salt concentration in soil. There is almost no local tree species here. Only "domestic" trees such as poplar (*Populus* spp.), willow (*Salix matsudana*) and elm (*Ulmus pumila*) are planted near residential sites, along main roads, or around the agricultural fields. The total forest cover in the Liaohe Delta is about 7,000 ha, 62% of which is artificial "shelter forest".

Agricultural vegetation is also an important component in the flora of Liaohe delta. Rice field occupies 54.6% of the delta, and is still expanding due to land reclamation in the reed and *Suaeda* occupied area. Maize, soybeans and other dry land crops are planted in the north-western and north-eastern part of the delta, where groundwater level is lower and irrigation water is less available.

2.2.6 Fauna

The species of fauna in the wetlands is always more abundant than that of the flora. Water fowls and other bird species are often dominant among vertebrates.

More than 200 species of fish, 60 species of invertebrates, and 250 species of birds are living in the Liaohe delta. Prawn (*Penaecus chinensis*) and hair-chela crabs (*Eriocheir sinensis*) are two main breeding species in the coastal ponds created by local people. A prawn can reach 24cm long, with fresh meat and abundant nutrition. Therefore it has very high economic value. Now both artificial breeding and sea fishing are conducted. The hair-chela crab is naturally spawned and hatched in the mixed water of sea and river, while grows up in the reed marsh. Now it is artificially hatched, and brought up in the reed or paddy fields (Local chronicles of Panjin City, 1998).

Among the bird species, 40 are residents, 77 are summer migrants, 11 are winter migrants, and 122 are passing-by species. Seven birds are first-class protected, including red-crowned crane (*Grus japonensis*), white crane (*Grus leucogeranus*), *Ciconia nigra, Ciconia boyciana* and golden vulture. Thirty-five species are second class protected birds, such as black billed gull (*Larus saundersi*) and *Cygnus cygnus* and so forth (Hu, 1997).

Mammals are not so abundant as birds in the Liaohe Delta. Now only rats (9 species), hares (*Lepus sinensis*), foxes (*Vulpes corsac*), and yellow weasels (*Mustelina sibirica*) are encountered sometimes. Near the river mouth, Pacific spotty seal (*Phoca largha*) is often encountered in spring.

It is one of the rare species along the North-western Pacific Ocean coast. The cubs are born on the ice and become independent before ice melting.

2.2.7 Hydrological condition

Water is the key factor in the seasonally inundated wetland ecosystem. The water situation in dry season is often a limiting factor for the productivity of flora and fauna living in the wetlands. This is the reason why people build water regulation projects in this kind of area. In the Liaohe Delta, a canal network has been established since 1950s, in both rice and reed covered area.

In the estuary wetland of Liaohe delta, water resources can be classified as seawater, river water, lake/pond water and ground water. Terrestrial surface water and ground water exchange water and salt with the sea seasonally. The water situation in the wetland ecosystem is mainly affected by the following factors:

1) Annual and seasonal rainfall in the catchment of large rivers that enter the sea here. The annual fluctuation of precipitation often causes drought and flooding in the delta. The large estuary wetland can act as a regulator for the local water allocation. A large amount of water is retained in the wetland during flooding season, while in the dry season, the wetland water is supplied by sea tide flow and groundwater.
2) Agricultural use of freshwater upstream. The water situation of the natural wetland in spring is especially dependent on this condition. According to the local policy, water must firstly satisfy the need of agriculture, especially paddy fields. The irrigation for reed is always in the second place. Now a large area of the reed is irrigated with wastewater from paper factories.
3) The soil-water capacity and vegetation growth situation that changes seasonally.

The vegetation and fauna changes with water and temperature seasonally in the Liaohe Delta. In winter, when it is cold and dry, almost nothing alive can be seen above the barren, frozen ground. Spring is still dry, but the ice and frozen soil begin to melt out. Reed and other plants sprout quickly with the softened soil and released moisture. If irrigation or rainwater is available in time, their growth speed can be very fast. Summer is warm and humid, which is the best season for vegetation growth. Large amount of biomass is reserved in the leaves, stems and later on in the seeds. As autumn comes up, the water level above ground decreases gradually, and the stems and leaves begin to dry out, ready for harvest. Reed is the best raw material for paper factories in the Liaohe delta.

2.3 Human management factors

2.3.1 Landuse

The landscape of the Liaohe delta is very much intensively used, especially in the paddy fields. About 2/3 of the land has been turned into agricultural or built up area since 1950s, while new reed field is formed on the newly created beach, either through natural succession or artificial planting. Now the area of paddy fields occupies about 54% of the delta, and reed occupies about 22% (Figure 2.4). Since 1987, an area of 10,000 ha has been reclaimed for agricultural use on the eastern bank of Shuangtai River mouth, close to the Nature Reserve.

In addition, the breeding ponds for prawn, crab and fish (c.a. 1,300ha) on the beach, as well as the residential and water exchange equipments, also changed the original situation of the environment. The habitat for black-billed gull and other waterfowls are greatly endangered.

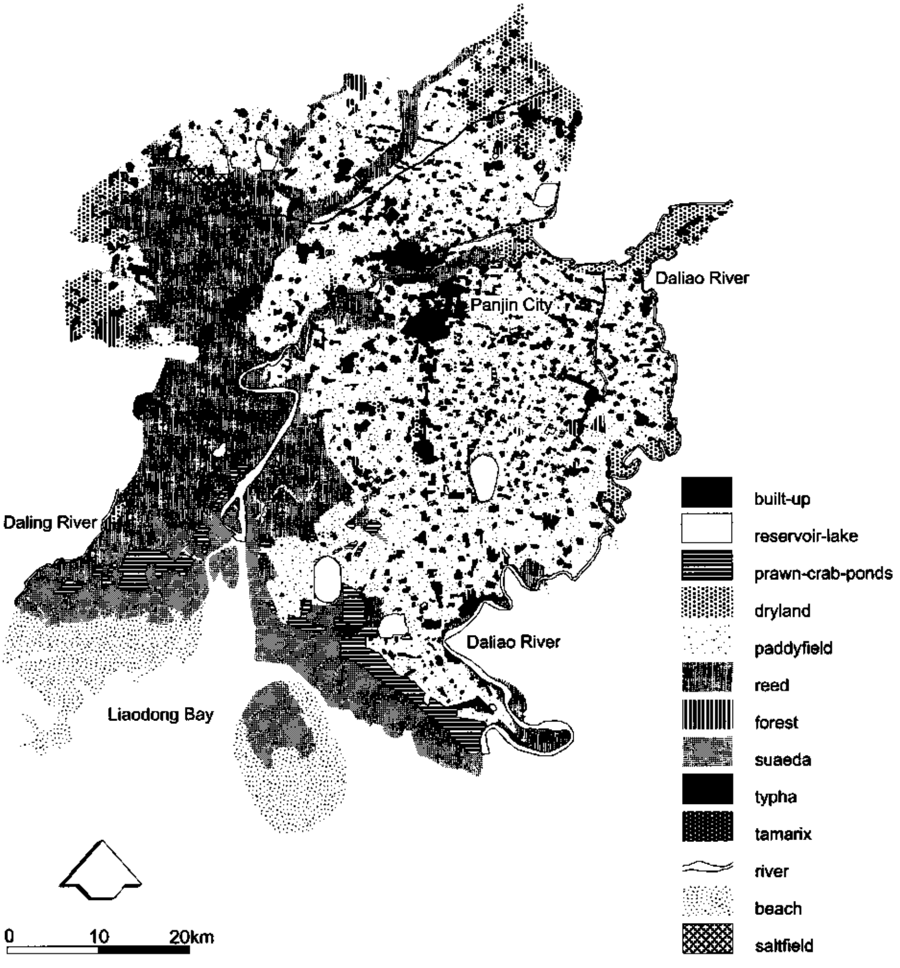

Figure 2.4 Landscape map of the Liaohe Delta, China

The natural reed marsh has been managed regularly by the local people. Now a well organized irrigation and harvesting system has been established. Almost all the reeds are cut in winter and transported to paper factories as raw materials. Normally the harvesting is done from the middle of November to the coming January, which is best for the reed quality, and brings no negative effects to the next year's reed growth. The reed leaves left in the fields are usually collected by local people as fuel or fodder for domestic use.

Reed is sometimes artificially planted in places where it is sparsely distributed, such as on the newly formed beach. Fortunately, the reed can survive easily after planting, either from seeds, underground stems, or green stems. The management is good for the improvement of reed production and wetland protection. But the irrigation, full harvesting and spring fire usually have a negative impact on the inhabitation and reproduction of residential birds.

2.3.2 Water management

In the Liaohe delta, a criss-crossing network of water canals has been constructed since 1950s, mainly for paddy fields and reed fields management (figure 2.5). In spring and early summer, when it is relatively dry, these canals are important for irrigation. The water is usually pumped from nearby rivers. During the flooding season in summer, these canals are usually used for water discharge from saturated reed and paddy fields.

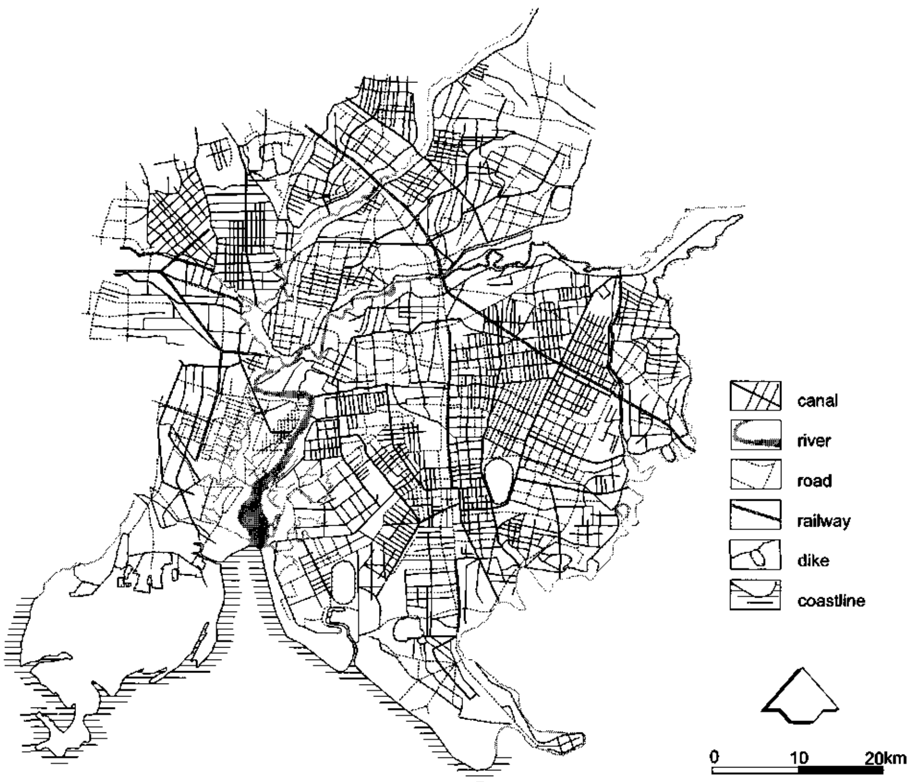

Figure 2.5 Canal network system in the Liaohe delta.

Water regulation in the Liaohe Delta focuses on agricultural use because this area has been designated as a "National Commercial Cereal Production Base". The quantity and quality of water pumped into the reed marsh is very much dependent on the "left-over" of agricultural use, not on the real demanding of plant growth. Fortunately, the reed has a large range of water tolerance, from moderately dry to more than 1 meter of seasonal inundation for one or two months.

Dikes are also a kind of important water project as canals in the Liaohe Delta (figure 2.5). Apart from flood regulating dikes along large rivers, about 130 km of dikes has been built along the coast to protect the agricultural fields against the tide. This has cut off the regular tidal flow into the wetland and changed the water and salt situation there. The flora and fauna inward the dikes have changed as a result, with a quick succession towards desalinization.

2.3.3 Fire management

In the estuary wetland of the Liaohe delta, fire as a management tool is only restricted to the reed fields, not in the *Suaeda* community and agricultural fields. Fire is carefully practised in early spring, so as to remove and mineralize the dry residual of reed stems. The reed is harvested during winter for paper factories. The leftover of the stems is sometimes very high, depending on the thickness of ice. If the dry mass above ground is too thick, it will impede the sprouting in spring. The burned stem layer can also add nutrients into the soil. In addition, fire can warm up the top layer of the soil to stimulate new stem sprouting. The soil is frozen into a hard block during cold winter. If the upper layer is warmed up, new sprouts will come out quickly because it contains large amount of underground reed stems.

Fire management must be conducted carefully because of the oil drilling systems scattered all over the area, as well as the piled up reed stem bundles under transportation. In the area where soil salinity is very high, or the irrigation condition is quite poor, fire can cause heavy salinity in the upper layer of soil, and affect the reed growth.

2.3.4 Pesticides and fertilizer

The reed fields in the Liaohe delta are managed extensively. Thus little pesticides and fertilizer are used. Pesticides are used only when heavy pest problem breaks out, such as in the year of 1966, 1977, and 1978. Helicopters must be hired to spray insecticides in the reed fields. Now fertilizer and herbicides are temporarily used in part of the reed farms, where the reed quality is too low.

In the paddy fields, fertilizer, herbicides and pesticides are normally used, in order to keep the high productivity. In addition, more and more farmers choose to breed crabs in their paddy fields, which need extra foodstuffs input into the fields, and thus cause more nutrient outlet from the paddy fields into the nearby canals, rivers, and finally into the sea with ground or surface water. Some of the reed fields also use the water from paddy fields for irrigation.

2.3.5 Biodiversity protection

Ecotourism, especially sight seeing for birds, is one of the most effective ways to keep biodiversity as well as a relatively high income in the wetlands.

In the Liaohe delta, a special area of about 80,000 ha has been designated for biodiversity protection since 1985. The suitable area for birds did not improve so much compared to the worst period. But it does help to stop some birds from moving away from this delta. The area suitable for red-crowned cranes has increased from the lowest point of 10% to about 30% since the Nature Reserve was established (Hu, 1997) (table 2.1).

Table 2.1 Area percentage suitable for red-crowned crane in the Nature Reserve of the delta.

Year	1977	1986	1994
Suitable area (%)	80	10	27

2.4 The effects of human activities

2.4.1 Water regulation capacity change

In the Liaohe Delta, many dikes and canals have been constructed to redistribute the water spatially and temporarily according to the needs of human beings. Other activities such as land reclamation also changed the water regulation capacity of the wetland.

The natural wetland in the Liaohe Delta has undergone a continuous loss in the recent decades due to the following factors:

1) Agricultural land reclamation.
2) Reservoir and canal construction.
3) Oil field occupation with drilling wells and refinery plants.
4) Residential area expansion.
5) Crab and prawn ponds created on the beach.
6) Construction of dikes, roads and highways.
7) Natural process, such as river and tide erosion along the beach, though more land may be created in other area.

The area of reed marsh has decreased from 1,066 km^2 in 1986 to 918 km^2 in 1994, at a loss of about 15% (Wang, 1995). The shrinking of natural wetland has resulted in the decreased water holding capacity in flooding seasons and water providing ability in dry seasons.

2.4.2 Biodiversity change

There is a wide variety of migrating and breeding birds in the Liaohe Delta, such as red-crowned crane (*Grus japonensis*), black-billed gull (*Larus saundersi*) and white stork (*Ciconia ciconia*). It is also the habitat of other animals and waterfowls. But, as a result of human disturbance, the area of the habitats for wild life has greatly shrunk, and some animals become extinct. In the 1950s, wolf (*Canis lupus*), fox (*Vulpes corsac*) and hare (*Lepus sinensis*) were popular animals in the Liaohe Delta. Now they are seldom encountered. Their habitat is limited in the reed marsh near the sea, with less food resources due to water quality deterioration caused by oil and agricultural exploration (Wang, 1995).

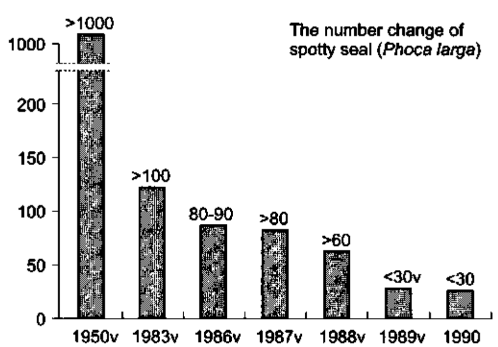

Figure 2.6 Number of *Phoca largha* change due to human activity.

A good example is the Pacific spotty seal (*Phoca larga*). In the 1950s, the number of this animal witnessed near the Shuangtai river mouth was more than 1000. By the 1980s, the number decreased to less than 100 (figure 2.6). But now the number of this animal has increased again since the Nature Reserve was established.

2.4.3 Habitat area change for wildlife

The suitable area for wildlife has shrunk and fragmented in the Liaohe delta. The intensive agricultural exploitation since 1960s and oil exploitation since 1970s have turned 2/3 of the area into agriculture or built-up land, leading to the fragmentation of habitat for wildlife.

The tidal protection dike along the coast has cut the seawater off. Habitat inward the dike has turned into other types of environment. For example, the area where the "plain reservoir" is situated now used to be the habitat for black-billed gulls. After the dike was constructed, and the reservoir was built, the black billed gull has totally moved out from this area (Hu, 1997). Moreover, the oil wells either in use or deserted, together with the roads connecting them, are all distributed in and around the Nature Reserve, where the habitat for many migrating and residential birds is supposed to be protected. Since 1970s, more than 4,000 oil wells have been drilled (figure 3.9), together with the increase of roads, pipelines and vehicles. The effect of oil drilling to bio-diversity change is no less than that of the agricultural exploitation. According to Hu (1997), the roads and working oil wells have led to the habitat fragmentation of many wild animals. Figure 2.7 gives an example of habitat fragmentation for the red-crowned crane. Most part of the suitable area has been disturbed by oil wells and roads.

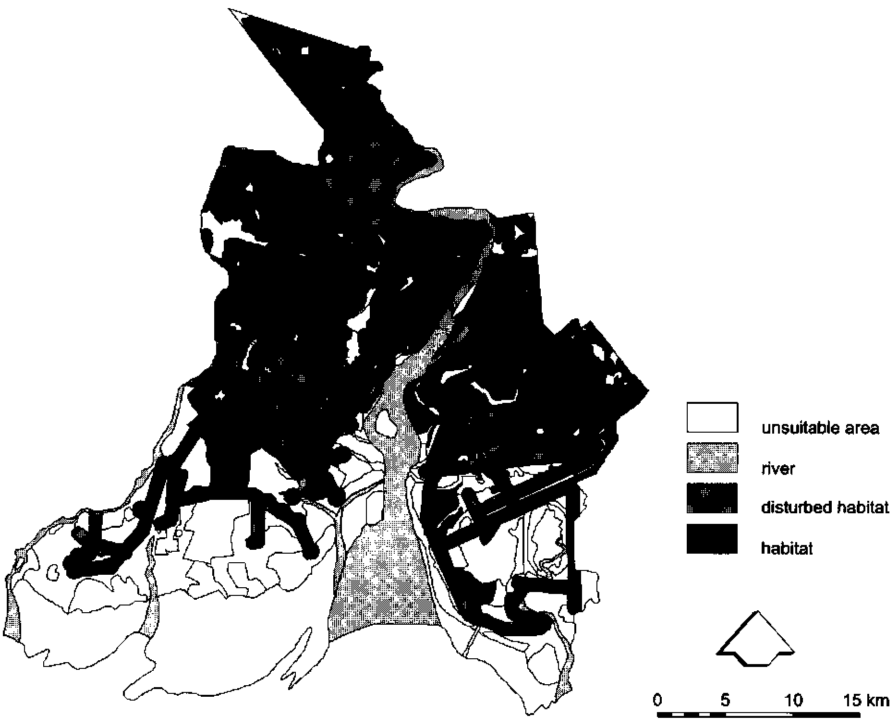

Figure 2.7 The fragmented habitat for red crowned crane (*Grus japonensis*) in the Nature Reserve of the Liaohe Delta.

2.4.4 Bio-production change

On account of the heavy fishing and water pollution, the production of high economic valued species has decreased greatly, even disappeared, such as *Pseudosciaena polyactis, Trichiurus haumela*, prawn (*Penaecus Chinensis*), and *Meretrix meretrix*, while the production of low economic valued species increased, such as jellyfish (*Scyphozoa* spp.) and chub mackerel (*Pneumatophorus japonicus*). Table 2.2 gives an overview on the production change of some aquatic products from 1970s to early 1980s.

Table 2.2 Production change of some aquatic products around 1980 (tons).

Year	*Penaecus Chinensis*	*Meretrix meretrix*	*Scyphozoa* spp.	*Chub mackerel*
1970		27000		
1978	14672		69	888
1979	19736		2262	1633
1980	5341		747	1745
1981	3518		8588	1763
1982	1570	15000	8778	3243
1983		16764		

2.5 Conclusion

The natural conditions of Liaohe Delta provide ideal habitats for many wild species. This area is also of high value because of its oil storage underground, high agricultural productivity, as well as profitable aquaculture. The contradiction between nature conservation and human exploration has become a serious problem. A sustainable landscape planning is needed to compromise the conflict between short term and long term benefits. It is important to be aware of the different functions of the wetland landscape in the Liaohe delta for such a planning. This study will mainly contribute to the investigation of the purification function in the reed and canal systems.

3. Purification Function of the Wetland Landscape in the Liaohe Delta[1)]

3.1 Introduction

Landscape function refers to the interactions among spatial elements, such as the flows of energy, materials, and species among the component ecosystems. The wetland is a multi-functional landscape that should be used wisely (Koudstaal, et al., 1994). One of the most important wetland functions is the purification ability, on account of which, many natural wetlands are utilized and artificial wetlands are created as treatment systems for domestic or industrial wastewater (Pride, et al., 1990; Guo and Zuo, 1997).

A lot of research has been done on the purification function of wetlands on municipal, industrial or agricultural waste waters (Hammer, 1989; Teal, et al., 1982; Whigham, 1982), either focusing on nutrient elements (Mulamoottil, 1989; Richardson and Qian, 1999; Craft and Richardson, 1995) or on pollutants such as mineral oil (De la Cruz, 1982). In 1994 and 1995, AMBIO published two special issues on wetland treatment systems and coastal eutrophication mitigation. But different research projects often focus on different aspects. This is especially the case in the wetland of Liaohe delta, China. Some of the work was done on the appeal of a paper factory (Huang, 1983), a reed farm (Song, 1982; 1984), or the oil company[2)]. Such kind of research often lacks of overall analysis for the purification function of the wetland.

This chapter will first give a brief description of the wetland functions in the Liaohe Delta. The main attention will be focused on the purification function of the reed and canal system to waste water and oil drilling water. The potential purification function of *Suaeda* community for breeding water will also be discussed.

3.2 Wetland functions in the Liaohe Delta

It is important to take the wetland as a whole that can interact positively with the environment. The natural wetland in the Liaohe delta is not only a land treatment system, but also a valuable natural resource. The wetland landscape in the Liaohe delta has several important functions, in relation to the biomass production, local water regime, soil formation, biodiversity, environment protection and coastline stabilization.

[1)] Part of this chapter has been published as: Li, X., Qu, X., Wang, L., Zhang, H. and Xiao, D., 1999. Purification function of the natural wetland in the Liaohe Delta. *Journal of Environmental Sciences*. Special Issue on "International Conference on Landscape Ecology of Asia-Pacific Regions" (Oct. 5-7, 1998, Shenyang, China). 11(2): 236-242.

[2)] Sun Tiehang, Chang Shijun, et al, 1994. Wetland treatment system on oil drilling water, spilled oil, and drilling mud in the Liaohe Oil field. Environment protection section of Liaohe Oil Field, Shenyang Institute of Applied Ecology, Chinese Academy of Sciences, and Institute of Reed Science, Liaoning Province.

3.2.1 Biomass production and output

First of all, the wetland is a highly productive ecosystem. The Liaohe delta has three main wetland vegetation types: the reed, the *Suaeda* and the rice. The production and productivity of these systems are shown in figure 3.1. In 1998, the average bio-productivity of the reed community reached 14 t/ha.yr, and the total production was around 540,000 tons. About 92% of the reed is cut in winter and transported to the nearby paper factories as raw materials every year. The biomass productivity of the *Suaeda* community is about 3.7 t/ha.yr[1]. And the productivity of rice is as high as 6 tons/ha.yr in the recent years.

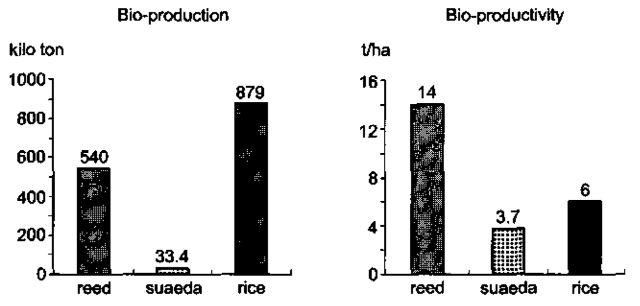

Figure 3.1 Bio-production and productivity of main communities in the Liaohe delta. The reed and *Suaeda* are above ground biomass, while the rice is grain production.

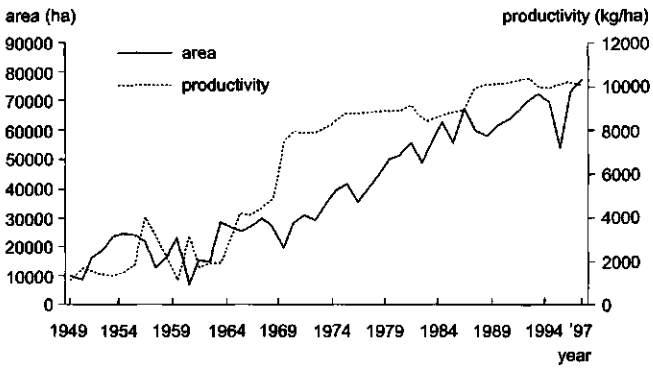

Figure 3.2 Productivity and area change of rice in the Liaohe Delta, from 1949 to 1997 (Local Chronicles of Panjin City, 1998).

About 2/3 of the delta has been reclaimed into paddy field in the last decades. But this did not change its character as a wetland. Partly due to technology and partly due to climatic condition, the productivity and quality of the rice here are very high. Now the Liaohe delta has become one of the most important production bases for commercial cereals in China. Both the total area and productivity have increased almost 10 times from 1949 to 1997 (figure 3.2). The increase in area is mainly due to agricultural reclamation in the reed marsh, while the increase of productivity is due to better technology in fertilizer and genetics. In addition, the new tillage system of "vertical

[1] Environment Effect Assessment of Oil and Agricultural Exploration in the Liaohe Delta, 1992.

planting" has also substantially increased the economic value of the agricultural land by introducing duckweed and crabs into the rice fields.

The high productivity of the main ecosystems in the wetland of Liaohe Delta provides materialistic basis for other functions such as water regulation, soil formation, bio-protection and purification.

3.2.2 Water regulation

The wetland in the Liaohe Delta plays an important role in regulating the spatial and temporal water distribution in the local area, including the delta, the Liaodong Bay and large river mouths. The wetland receives about 11.8 billion m^3 of water and 10.4 billion tons of silts from the four major rivers running into the sea here (figure 3.3). Therefore it has become a large natural reservoir for flooding water before running directly into the sea in summer. According to the Environment Effect Assessment on Agricultural Exploration in the Liaohe Delta (1992), the buffering capacity of the wetland for flooding water can be as large as 2.8 billion m^3. During dry seasons as winter and spring, ground water comes up to supply surface water and discharges in forms of evaporation, evapotranspiration, and surface flow.

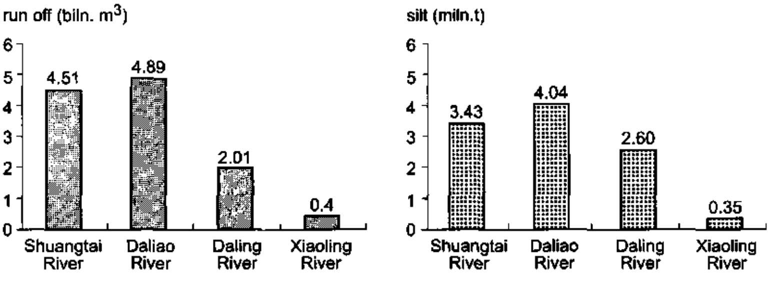

Figure 3.3 Water and silt input into the Liaodong Bay each year by the four main rivers in the Liaohe Delta. (Environmental effect assessment of oil and agricultural exploration in the Liaohe delta, 1992)

All the four large rivers contain high rate of silt because of the heavy water-soil erosion upstream, as a result of deforestation and grassland reclamation. The rich soil is brought down stream and deposits near the river mouths, pushing the coastline southward into the Liaodong Bay (figure 3.6).

3.2.3 Desalinization and soil formation

Suaeda and reed are two main pioneer species in the wetland of Liaohe Delta. They contribute substantially to the soil formation process in the new fluvial plain. According to a research during 1965-1975 (Zhang, 1997), the soil salt concentration decreased apparently after a number years of reed growth (table 3.1 and figure 3.4).

In the first two years, the soil salt concentration in the topsoil layer decreased quickly, while it decreased slowly but steadily in the lower layers. After ten years of reed growth, the soil salt concentration in the whole profile had decreased to the normal level, and there was no big difference any more between the top and lower layers.

Table 3.1 Soil salt concentration (%) after different years of reed growth.

Years of reed growth	Depth (cm)				
	0~20	20~40	40~60	60~80	80~100
0	1.80	1.44	1.60	1.60	1.62
1	0.82	1.24	1.16	1.29	1.34
2	0.12	0.70	0.70	0.96	1.20
5	0.11	0.24	0.41	0.65	0.87
6	0.19	0.27	0.39	0.62	0.97
7	0.39	0.32	0.37	0.54	0.71
8	0.24	0.27	0.31	0.44	0.58
9	0.06	0.10	0.16	0.20	0.21
10	0.11	0.09	0.11	0.13	0.17

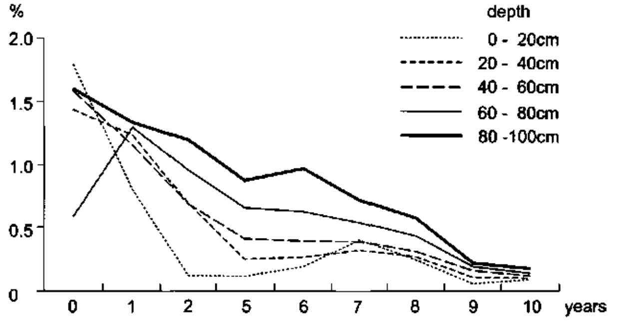

Figure 3.4 Soil salt concentration after different years of reed growth

In addition, the soil volume weight also decreased apparently after more than 10 years of reed growth (table 3.2, figure 3.5), with the improvement of soil fertility. Therefore, the quality of the whole soil profile improved with the colonization of vegetation.

Table 3.2 The effect of reed growth to soil volume weight (g/cm^3). (Zhang, 1997)

Years of Reed growth	Depth (cm)			
	0-15	15-25	25-35	35-55
0	1.44	1.50	1.56	1.58
2	1.34	1.40	1.54	1.51
3	1.34	1.42	1.46	1.48
12	1.05	1.10	1.39	1.40

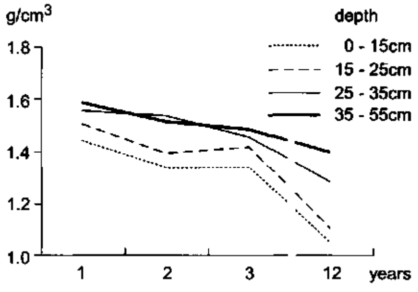

Figure 3.5 Soil volume weight change after different years of reed growth.

Normally the reed fields are reclaimed into paddy fields after some years of reed growth, as a result of improved soil and water condition.

3.2.4 Coastline Stabilization

The vegetation in the estuary wetland can greatly cut down the tidal energy, and decrease its ability to erode the coastline. Silts and sands brought by tides and rivers (figure 3.3) deposit in the shrubs and plant communities along the coastline, forming alluvions. The so-called Baici (*Nitraria sibirica* var. *globicarpa*) mound is a typical alluvial island as an important habitat for black-billed gulls (*Larus saundersi*). The coastline is pushed seaward more than 500 meters per year on the western side of the Shuangtai river mouth, and 20 meters per year on the eastern side (figure 3.6, Hu, 1997).

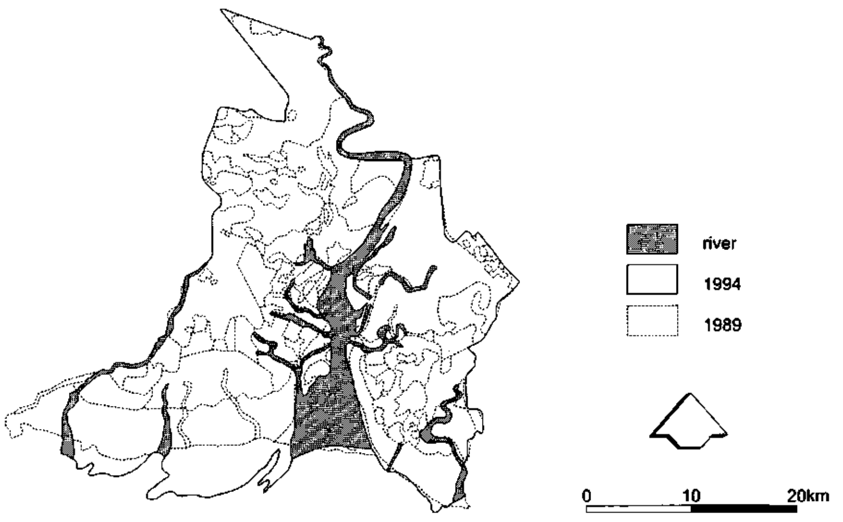

Figure 3.6 Coastline change near the estuary of Shuangtai River from 1989 to 1994

3.2.5 Purification

The rivers bring large amounts of pollutants from the upstream parts of the catchment every year, many of which are nutritious for wetland vegetation species. After those elements or components, such as N (nitrogen), P (phosphorous), COD (chemical oxygen demanding) and BOD (biological oxygen demanding), are retained and decomposed in the wetland, they can nourish the plants and improve the bio-production, while the water quality can be improved simultaneously. This can greatly decrease the risks of coastal water eutrophication. We will mainly focus on the purification function of the wetland system in this chapter.

In addition, the reed marsh can also be used as a land treatment system for oil drilling water (Xiao, et al., 1996), as the Liaohe delta has the third largest oil field in China. The *Suaeda heteroptera* community can be used for treating the exchanged water from prawn and crab breeding ponds on the beach.

3.2.6 Biodiversity protection

The Liaohe Delta is situated right on the migration route of some Eastern Asian Avifauna. The wetland ecosystem provides abundant food resources and shelter sites, and thus becomes an important habitat for many residential wild animals, as well as a stop place for migrating birds. The food resources such as fish, shrimp, crab, clam and seeds are widely distributed from coastal seawater and breeding ponds to inland reed and paddy fields. Habitat types include various reed communities, *Suaeda heteroptera* community, *Aeluropus litoralis* community and *Nitraria sibirica* community. Now a National Nature Reserve of 80,000ha has been established to protect this unique habitat for the wild species.

Among the above wetland functions of the Liaohe Delta, the purification function is much more concerned in this project. The total catchment of the rivers flowing into the Liaodong Bay is about 290,000 km^2, almost 2 times the area of Liaoning Province. The water-soil erosion in the upper and middle stream catchment, in addition to the sewage water from big cities like Shenyang and Anshan, is finally gathered into the small area of Liaodong Bay. With the expansion of the prawn-crab breeding ponds along the coast, more and more nutrient elements like N and P are poured into the Liaodong Bay. If no measure is taken, the consequence of the pollution will be unimaginable. In combination with the erosion and pollution control in the whole catchment, using the natural wetland as the treatment system to "purify" the water before it running directly into the sea is also an important strategy to prevent heavy marine pollution problems in the long run.

3.3 Wastewater irrigation and purification in the wetland of Liaohe Delta

The Liaohe delta has the world second largest reed marsh (the largest one is in the Danube delta), with a total area of about 917 km^2. How to make full use of this special piece of land is very important for the local ecological and economical environment. Wastewater irrigation in the reed field is an essential strategy of nature management in this area.

3.3.1 Reed irrigation

Irrigation is indispensable for the improvement of reed production, according to the experiment done in the 1960s (tables 3.3 and 3.4) (Sun, 1981; Su, 1983). The productivity of irrigated reed fields can be 40-70% higher than that of the non-irrigated fields (table 3.3). This is due to better growth condition evoked by reasonable irrigation (table 3.4).

According to table 3.4, under the irrigated situation, the average height of above ground stem reaches the highest, while the average diameter of above and underground stems as well as the densities have the optimum values. However, excessive water will also lead to the decrease of productivity, like in the situation of flooded field (table 3.4). Moreover, irrigation can remove some weed species, such as *Hordeum jubatum*, from the reed community.

Table 3.3 Reed production in the irrigated and non-irrigated reed fields.

	1966	1967	1968
Non-irrigated reed (t/ha)	2.70	3.46	5.12
Irrigated reed (t/ha)	3.74	5.84	8.27
Increase (%)	38.5	68.8	61.5

Table 3.4 Comparison of reed growth among dry, irrigated and flooded reed fields.

	Dry field	irrigated field	Flooded field
Distribution depth of underground roots (cm)	1~120	0~80	0~60
Aggregation depth of underground stems(cm)	40~80	20~40	15~30
Average diameter of underground stems (cm)	2.1	1.6	1.2
Average height of above ground stems (cm)	180.0	192.2	157.8
Average diameter of above ground stems(cm)	0.64	0.46	0.39
Density of above ground stems (stem/m^2)	21.5	77.5	376.0
Productivity of above ground stems (t/ha)	4.40	9.58	8.03

Under the suitable irrigation conditions, the reed growth speed changes dramatically with time (figure 3.7). It sprouts in the middle of April, at the growth speed of less than 1 cm/day. By the middle of May, the reed begins to grow very quickly, at the speed of 1-4 cm per day, till late July, when it reaches 60-80% of the final height. Then the growth speed slows down to less than 1cm again. By late September, the height growth totally stops.

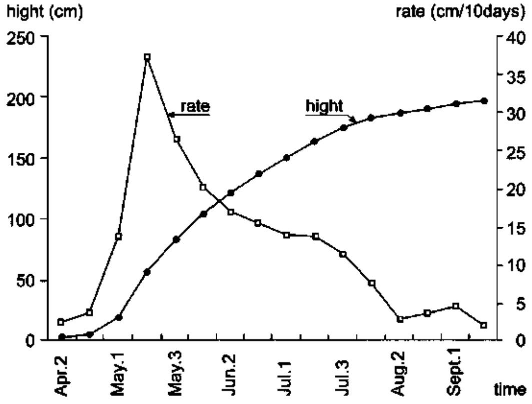

Figure 3.7 Reed growth speed change during growing season. The time axis is 10 days per unit. Apr.2 means the second 10 days of April, and the same in others.

Normally the reed needs 3 times of irrigation during the growth period in spring (Sun, 1981), with temporary discharge or "dry up" in between. In a regular year, the water regime in the reed field is as follows:

March 10th to 30th: Unfrozen water from nearby rivers. The optimum irrigation depth is about 5cm. This kind of water usually has a low salt concentration, but is accumulated with pollutants and nutritious elements from upstream cities during the whole frost season in winter and early spring. The water temperature is usually higher than that of the soil and thus helps in the process of thawing. The fresh water also washes the salt away from the soil so that the new reed can sprout earlier and faster. In the relatively higher sites, water is often irrigated without drainage, while in the lower sites, drainage is needed to cut down the soil salt.

April 20th to May 10th: Water drained from paddy fields and upstream rivers, as well as salty water from the sea. Whether or not to drain after irrigation depends on the quantity of water from upstream. The optimum irrigation depth is about 10cm during this period. The concentration of pollutants and nutrients is much lower than that of March. In this period the reed is about 40-50 cm high, and the growth speed can be 4 cm/day. But in dry-spring year like 1998, this has to be postponed until the middle of May. Otherwise the salty water will kill all the new reeds.

June 1st-15th: Irrigation depends on the precipitation and the quantity of water available from upstream. The reed comes to the blooming period. There is a high demand for water from the reed and the soil, so that a thicker water layer of about 15cm is needed. However, if the groundwater level is too high for a long period, there will be too many underground roots, and the reed stem will be very slim, leading to a low production. Therefore drainage is needed after this period of irrigation, before the raining season comes in July.

July and August: This is the rainy season in the Liaohe Delta as well as in the catchment of large rivers running into the sea here. Normally discharge rather than irrigation is usually needed. In big flooding years such as 1995, the water in the reed fields can be 1.5 meters deep, or even thicker, and the inundation period can last more than one month. If no discharge is conducted, the production of the reed will decrease substantially.

September and October: It is the period in which the reed ripens. Little water is needed for the growth. If there is still some water in the reed field by the end of September, discharge will be needed to lower down the ground water level, as well as the soil salt content. In the mean time, the soil air condition will improve, just suitable for the growth and sprouting of underground stems. It is also good for the above ground stems to get ripe (Local Chronicles of Panjin, 1998).

It is almost impossible to irrigate the reed fields according to the growth needs because of the water shortage for industrial and agricultural use in the Liaohe Delta. One strategy that can be taken is to extend the irrigation period, and accept a wider range of water quality, so as to expand the total irrigation area for the reed.

3.3.2 Waste water irrigation in the reed field

By irrigating the reed with wastewater, both ecological and economical benefits can be obtained in the local area. Wastewater can increase reed productivity better than ordinary water, because it contains more nutrient elements. In the mean time, it can partly solve the water shortage problem in spring and avoid coastal seawater pollution. That is why wastewater irrigation is encouraged in the last decades.

Increase more production than normal water irrigation

According to the field experiment done in the 1980s, the height of reed irrigated with waste water was 45-50 cm higher than that irrigated with normal water (Song, 1984), while the productivity was about 17-26% higher. In the field, the reed irrigated with wastewater has strong stems and dark green leaves, with an optimum stem density (table 3.5). The reason for the production increase is that, wastewater has higher nutrient concentrations than normal water. The deposition of organic matter from the wastewater can improve the soil structure and provide more nutrients for reed growth. Moreover, the wastewater usually has a low salt content, and thus helps in the desalinization process.

Wastewater often has a high level of COD (Chemical Oxygen Demand) (tables 3.6 and 3.11), which decreases the DO (Diluted Oxygen) level in water and impedes plant growth. But reed is rarely affected by this oxygen shortage, since the oxygen for rhizome respiration mainly comes from the photosynthesis of the leaves, and is transported down through a kind of ventilation tissue in the plant body (Song, 1984). During the 3 years' experiment, no growth impedance was observed.

Table 3.5 Comparison between wastewater and normal water irrigated reed growth

Year	Irrigated by	Height (cm)	Diameter (cm)	Number of gnarls	Productivity (t/ha)	Production increase (%)
1981	Waste water	320	0.80	22	10.6	26.3
	Normal water	270	0.70	18	8.6	-
1982	Waste water	310	0.85	21	10.4	16.8
	Normal water	275	0.75	20	8.9	-
1983	Waste water	337	0.75	24	15.0	26.0
	Normal water	297	0.70	22	11.0	-

Relax the water shortage problem in spring.
Spring (March to May) is usually quite dry in the Liaohe Delta (figure 2.2). The evaporation is 17 times higher than the precipitation in March, while the highest evaporation occurs in May (281.5mm). The total spring precipitation in the Liaohe Delta is only 96.5mm, about 15.5% of the annual rainfall. It is far from the actual need of natural vegetation growth, not to say the local industrial and agricultural needs. If the reed fields are irrigated with waste water from upstream factories, no heavy damage will be done to the reed growth, while much better qualified water can be saved for agriculture and industry. In places where reed and agricultural fields are close to each other, water discharged from reed fields might even be used to irrigate the agricultural fields, or vice versa. This should be taken into consideration in the local landscape planning.

Prevent coastal water pollution.
If the wastewater with a high pollutant concentration is discharged directly into the sea, in combination with suitable conditions for some algae species, it may cause great problems in the shallow sea. According to the Report on the Chinese Ocean Environment (1997), published by the Chinese Bureau of Ocean, the general quality of Chinese ocean environment has been decreasing in the recent years. The main pollutants in the seawater are inorganic nitrogen, inorganic phosphorous, and oil. In the Bohai sea, the concentration of nitrogen above the National Standard increased from 16% in 1996, to 68% in 1997. The problem is especially serious near the large river mouths and large cities. For example, in July 1991, the large "red tide" (algae blooming) breaking out in the Liaodong Bay covered thousands of square kilometers' sea surface. Another example was in September 1998, when a large area of 'red tide' broke out along the coast of Bohai Sea. Both caused great damages to the local fishing and shrimp/crab breeding industry.

According to the data released from the local environment monitoring organization, approximately 130,000 tons of COD (Carbon Oxygen Demand) is brought directly into the sea by the major rivers flowing into the Liaodong Bay, together with other nutrient elements such as nitrogen and phosphorous (table 3.6). It is a great waste if we do not make use of these nutrients.

Table 3.6 Runoff, COD and nitrogen release into the Liaodong Bay of the main rivers

River name	Runoff ($\times 10^9$ m^3/yr)	COD (t/yr)	NH_4^+-N (mg/l)	NO_2^--N (mg/l)	NO_3^--N (mg/l)
Shuangtai R.	2.1	21697	0.37~4.23	0.002~0.040	0.11~1.40
Daliao R.	4.0	53903	2.30~104.00	0.000~0.088	0.00~2.38
Daling R.	2.0	49432			
Xiaoling R.	0.4	2245			

Improve soil fertility.
Wastewater usually contains more nutrients than ordinary river water. After several years of irrigation with wastewater, the peat soil in the reed marsh often becomes more fertile. No production decrease has been observed, although large amount of dry material is taken out as raw materials for paper factories from the system every year. So far no accumulation problem has been observed.

3.3.3 Purification of the reed field to waste water from paper factory

During 1997-1998, intensive field experiments in the Liaohe delta were made to investigate the purification function of reed marsh and canal system. The field was irrigated with wastewater from paper factories upstream, 3 times a year in spring. In the reed field, ground water was sampled 3 days after irrigation, at 0, 40, 60 and 80 centimetre depths with the Lysimeter system. Samples were acidified and analyzed with standard methods within 3 days after sampling. The results are given in table 3.7 and figure 3.8.

Table 3.7 Purification of the reed marsh system to waste water from paper factory.

Depth	COD (mg/l)	TN (mg/l)	Organic_N (mg/l)	NH_4^+_N (mg/l)	NO_3^-_N (mg/l)	NO_2^-_N (mg/l)	TP (mg/l)	SRP (mg/l)
0 cm	82.69	3.129	2.676	1.36	0.069	ND	0.150	0.043
40 cm	69.63	1.922	1.212	1.33	0.142	ND	0.082	0.047
60 cm	73.98	1.204	0.861	1.23	0.054	ND	0.067	0.024
80 cm	60.93	1.255	0.811	1.32	0.105	ND	0.080	0.028
Rdc (%)	26.3	59.9	69.7	2.9	-	-	46.7	35.4

1) Concentration values are averaged from 2 years observation. ND = Not Detected.
2) Rdc = reduction rate, calculated as the difference between pollutant concentration in the surface water and 80 cm groundwater divided by the surface concentration value.

It is clear in table 3.7 and figure 3.8 that the concentration value of COD, TN and TP decreases obviously in the profile. The reduction rate for organic nitrogen is especially high (about 70%), because of the strong absorption of the rhizome system. The peat soil is also highly absorptive like a sponge.

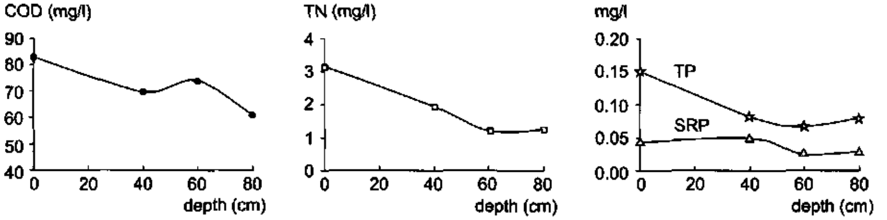

Figure 3.8 Purification of reed marsh system to wastewater from paper factory

The experiment in the reed field is mainly to measure the vertical retention rate of the reed-soil system for polluted water. But the horizontal subsurface flow in the rhizosphere also has a high reduction rate to some nutrients like nitrogen and phosphorous (Yin and Lan, 1995). In combination, the reduction rate of the reed-soil system for nutritious elements is very high. The ground water output from the reed marsh system into the sea will be mostly cleaned up, if all the wastewater flows through the reed field first.

Now the reed field covers an area of about 100,000 ha in the Liaohe Delta, large enough to treat all the wastewater from upstream cities and factories during dry season. How to make full use of this precious land resource is under concern. The next chapter will give an estimation on how much nutrient elements can be retained or removed by the wetland system every year.

3.3.4 Purification function of the reed field to oil drilling water

The Liaohe delta has the third largest oil field in China. Thousands of oil drilling stations is distributed all over the delta (figure 3.9). Due to technological reasons, not all the oil spilled near the oil drilling stations can be recycled. The spilled oil, drilling water and mud often cause pollution problems to the soil, and impede vegetation growth nearby. In early 1990s, a series of experiment had been done in the reed marsh to test it as a kind of treatment system for oil drilling water and spilled oil[1]. The results are given in tables 3.8 to 3.10 and figure 3.10.

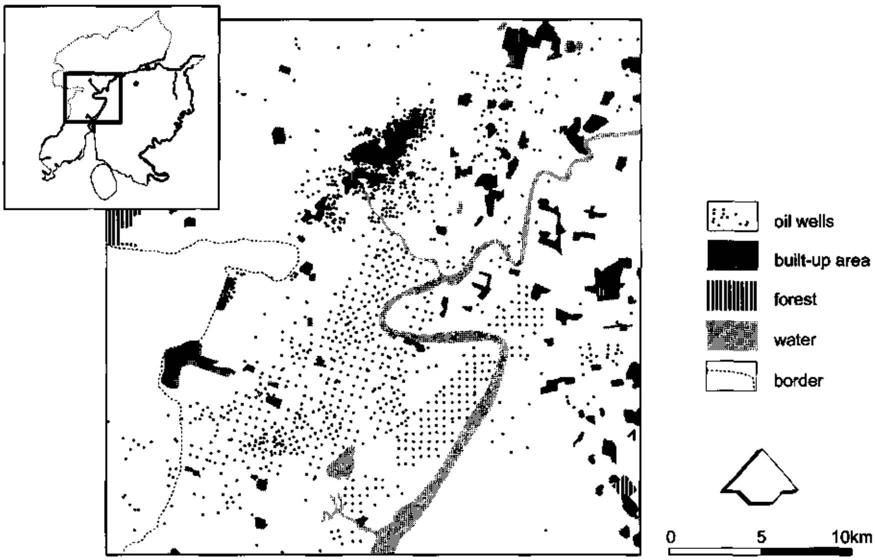

Figure 3.9 Oil wells in the western part of Liaohe Delta

Table 3.8 gives a general description of different treatment systems in terms of water-input methods and loads. Table 3.9 gives the result of different pollutants from different treatment systems. The output from cooling pool is the input for all five treatment systems. Table 3.10 and figure 3.10 present the efficiency of different systems in an annual basis.

[1] Sun Tiehang, Chang Shijun, et al, 1994. Wetland treatment system on oil drilling water, spilled oil, and drilling mud in the Liaohe Oil field. Environment protection section of Liaohe Oil Field, Shenyang Institute of Applied Ecology, Chinese Academy of Sciences, and Institute of Reed Science, Liaoning Province.

Table 3.8 Purification function experiment systems for oil drilling water[1)]

	Treatment code No.	Water flow route	Irrigation Period (d)	Daily water load (m/d)	Yearly water load (m/yr)
Filter	No.1	Vertical and horizontal	3	0.033	2.82
System	No.2	Vertical and horizontal	3	0.020	1.68
	No.3	Vertical and horizontal	3	0.007	0.60
Flooding	No.4	Horizontal flooding	1	0.033	2.78
System	No.5	Horizontal flooding	1	0.067	5.64

1) Vegetation: reed. Annual working days: 150. Method of irrigation: water tubes on the ground surface.

Table 3.9 The effect of different wetland treatment system to oil drilling water

Treatment	Cooling pool		Filter system output			Flooding system output	
	Input	Output	No.1	No.2	No.3	No.4	No.5
COD (mg/l)	459.2	389.3	144.0	77.3	88.2	77.2	113.9
Total purification rate (%)	-	15.2	68.6	83.2	80.8	83.2	75.2
Wetland purification rate (%)	-	-	63.0	80.1	77.3	80.2	70.7
BOD5 (mg/l)	33.5	32.1	5.9	3.1	3.4	3.9	7.3
Total purification rate (%)	-	4.3	82.3	90.7	90.0	88.4	78.3
Wetland purification rate (%)	-	-	81.6	90.3	89.4	87.9	77.3
Oil (mg/l)	27.7	19.9	4.3	2.3	3.9	1.4	1.8
Total purification rate (%)	-	28.1	84.5	91.8	86.1	94.9	93.6
Wetland purification rate (%)	-	-	78.5	88.6	81.0	92.9	91.0
TN (mg/l)	13.7	11.6	3.8	1.7	1.5	1.6	2.3
Total purification rate (%)	-	15.8	72.4	87.9	89.4	88.4	83.6
Wetland purification rate (%)	-	-	67.2	85.7	87.4	86.2	80.6
TP (mg/l)	0.04	0.07	0.14	0.08	0.13	0.18	0.14

1) Total purification rate is the difference between the input concentration value of the cooling pool and the output from the treatment system, divided by the cooling pool input value.
2) Wetland purification rate is the difference between the output concentration value from the cooling pool and the output from the treatment system, divided by the output value from the cooling pool.

Table 3.10 Purification rate (kg/ha.yr) of treatment systems for oil drilling water

	Filter system			Flooding system	
Pollutants	No. 1	No. 2	No. 3	No. 4	No. 5
COD	6917.6	5241.6	1806.6	8676.4	15532.6
BOD5	738.8	487.2	172.2	784.0	1398.7
Oil	439.6	295.8	96.1	512.9	1020.3
TN	219.1	166.5	60.7	277.2	525.6

According to table 3.8-3.10, the flooding system with a yearly water load of 5.64 meters thick has the highest purification ability for oil drilling water (treatment system No.5). More than 15 tons of COD and 1 ton of oil can be removed from 1 hectare of this system each year. None of the system showed an obvious reduction for phosphorous, probably because of the low input load. Figure 3.10 indicates that the leakage system is more efficient than the flooding system in pollutant removal. But the latter is less expensive to construct.

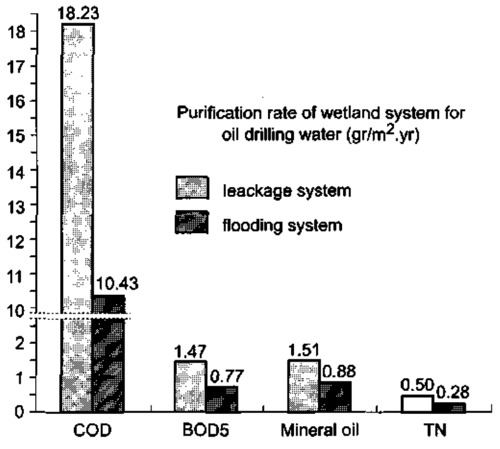

Figure 3.10 Purification function of reed marsh treatment system for oil drilling water

The oil drilling stations are scattered all over the delta, sometimes in the paddy fields and dry land. This experiment provides a possibility for the solution of oil pollution problem with the reed marsh as a treatment system.

Besides the reed marsh, the canal system and *Suaeda* community also have a great potential as a filter system for nutrient enriched river water, according to our field experiment and observation.

3.4 Purification function of the canal system

While investigating the purification function of the reed marsh system, the reduction function of the irrigation canals is also inspected. Experimental results (table 3.11 and figure 3.11) indicate that the natural purification process in the canals is also quite effective. Almost half of the pollutants can be removed from the water as it flows through the 6,000 meters long canal before entering the reed fields, either because of bio-chemical decomposition, sedimentation, or other processes. The reduction rate of nitrate nitrogen (NO_3^-_N) is especially high (about 95%) in the canal system, which is very different from that of the reed system (table 3.7). The reduction rate for phosphorous is also very high.

Table 3.11 Purification function of the canal system

Sample site	Dist. (m)	COD (mg/l)	TN (mg/l)	Organic_N (mg/l)	NH_4^-_N (mg/l)	NO_3^-_N (mg/l)	NO_2^-_N (mg/l)	TP (mg/l)	SRP (mg/l)
Pump. stat.	0	152.32	3.224	2.244	2.79	1.970	0.017	0.17	0.087
Canal1	500	113.15	2.514	1.996	2.53	1.722	0.015	0.10	0.052
Canal2	2000	91.39	2.334	1.715	2.63	0.844	0.008	0.09	0.053
Canal3	6000	88.80	1.741	1.167	1.40	0.100	ND	0.06	0.038
Rdc (%)		41.7	46.0	48.0	49.8	94.9	-	64.7	56.3

1) Concentration values are averaged from 2 years observation. ND = not detected.
2) Rdc = reduction rate, calculated as the difference between pollutant concentration at the pumping station and the canal point 6,000 meters away divided by the concentration value at the pumping station.

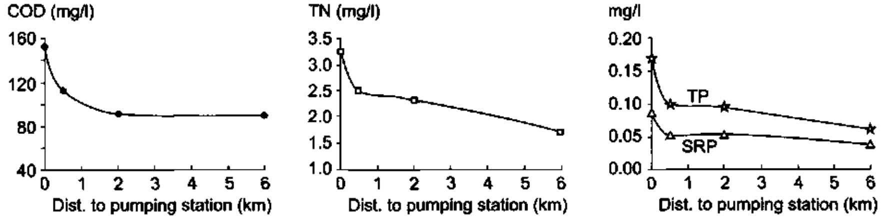

Figure 3.11 Purification function of the canal system to polluted water from paper factories.

The total length of the canal system in the Liaohe delta is more than 2 million kilometers, about half of which is in the reed field. As the management in the reed fields improves, more canals will be built for water irrigation and discharge. There is a great potential to use the canal system here as an additional treatment system for polluted water from paper factories and other waste sewage.

3.5 The purification function of *Suaeda heteroptera* system

3.5.1 The waste water from breeding ponds

The local agriculture and aquaculture in the Liaohe Delta also contribute to the eutrophication problem in the coastal seawater. The effect of exchanged water from prawn-breeding ponds and crab-hatching factories along the beach can not be ignored because of its overwhelming expansion in the last decades.

According to the "Environment Effect Assessment on Oil and Agricultural Exploration in the Liaohe delta" (1992), the breeding ponds affect the coastal seawater mainly because of the large amount of artificial foodstuff, which has a high concentration of N (c.a. 1%), P (ca. 0.75%), as well as BOD. The concentration value of these elements in the exchanged water is still very high after the consuming of prawns and brought away from the system. The nutritious elements are the material basis for the eutrophication procedure of coastal seawater. In case of suitable physical conditions and induced by some bio-chemical factors, red tide will happen inevitably. On the other hand, red tide can also affect the aquaculture industry especially in the densely distributed area of breeding ponds.

The breeding ponds are a seasonal pollutant source, normally from June to September. The main pollutants are COD, NH_4^+-N, PO_4^{3-} and S^{2-} (table 3.12).

Table 3.12 Average pollutant concentrations in the exchanged water of prawn-breeding ponds (mg/l)

	COD	NH_4^+-N	PO_4^{3-}	S^{2-}
June	3.26	0.13	0.013	0.01
July	5.94	0.29	0.018	0.04
August	6.56	0.50	0.030	0.06
September	6.30	0.74	0.021	0.06

According to table 3.12, the main problem of prawn ponds comes in August (COD and PO_4^{3-}) and September (COD and NH_4^+-N). Suppose the average water depth in the ponds is 1 meter (June and

July) and 1.2 meter (August and September), and the water exchange rate is 10% per day, then the total water exchange quantity can be 1,000 and 1,200 m^3/ha per day, respectively.

The total area of prawn ponds in the study area is more than 100 km^2. In places where prawn ponds are densely distributed, the output of COD can reach 2 ton/km.day along the coastline, which can result in heavy problems in the vicinity.

In the last 2~3 years, most of the prawn ponds have stopped breeding, due to the prawn diseases spreading all over the coastal area in Eastern China. At the moment only some prawn and crab hatching factories are working. Though the COD, N, and P concentrations in the exchanged water are still quite high, no heavy problem has been caused because the area and total quantity of wastewater are quite limited.

The pollution problem from breeding ponds is not so serious at present, but it is still important to find solutions to it because it is quite possible that these ponds restart to produce prawns again after the diseases are removed, like Southern China recently.

The problem of pollution from breeding ponds is not easy to solve. The aquaculture is very profitable for the local people. Therefore it is difficult to close them all. A more acceptable solution is to keep the breeding ponds, but cut down the nutrients input into the sea. On the other hand, the breeding ponds also provide abundant food resources for some water birds.

3.5.2 The possibility of using Suaeda heteroptera community as a treatment system

For the convenience of water exchange, the breeding ponds are usually built in the tidal belts, where *Suaeda heteroptera* community is situated as pioneer vegetation. The spatial distribution of these two types of land cover is inlaid with each other. At present the exchanged water from breeding ponds is discharged directly into the sea with low tide. It is reasonable if we make use of the *Suaeda heteroptera* community as a land treatment system for the breeding water, concerning the wide distribution of this species in the area.

If the *Suaeda* occupied beach is used as the treatment system for the water drained from prawn-breeding ponds and crab-hatching factories, in combination with a well-designed distribution pattern, great advantages will be obtained:

- The coastal water quality will be improved, and the chances of eutrophication caused by prawn breeding will decrease.
- The prawn productivity and quality will be improved, due to better seawater exchanged into the breeding pond. The chances for prawn disease spreading will decrease. The entire prawn production will also increase.
- The primary production of *Suaeda heteroptera* community will increase, as a result of improved nutrition condition. More birds and other animals will be accommodated in this habitat. Therefore it is good for biodiversity protection.

The total area of *Suaeda* community is 744 km^2 in the Liaohe Delta. The feasibility to use this area is quite high. But, water projects are needed, especially in the area where prawn ponds are densely distributed. The prawn/crab breeding ponds are distributed randomly along the tidal belt, and have changed the original flat beach into dikes and ponds. Careful planning is needed to avoid further pollution and get a stable production of water products.

3.6 Conclusions and recommendations

The wetland in the Liaohe Delta is a multi-valued landscape that should be highly protected and rationally used. Based on the above analysis and discussions, some general conclusions can be made concerning the wetland functions in the Liaohe Delta:

1. The natural wetland has a high value in biomass production and protection, water regulation, soil formation, coastline stabilization and pollutant purification.
2. Wastewater irrigation in the reed field can solve the water shortage problem in spring, increase reed productivity and prevent coastal seawater pollution. Therefore it should be encouraged as a long-term practice. In addition, the reed marsh can also be used as a treatment system for oil drilling water.
3. The canals can also remove pollutants and nutrient elements substantially. They are important components of the filtering system to reduce terrestrial source pollutants input into the sea.
4. The *Suaeda heteroptera* community has a great potential to be used as a treatment system for exchanged water from breeding ponds.

All the results presented here are point measurements in a restricted number of years. Further study is needed to generalize the data spatially and temporarily so as to get an overall estimation on how much pollutant the wetland can remove. More field investigation and research is also needed in the *Suaeda* covered area as well.

4. Modelling of the Nutrient Reduction in the Wetlands of Liaohe Delta

4.1 Introduction

The problems of nutrient retention in wetland ecosystems have figured prominently in the wide range of topics of landscape ecology (Mander and Mauring, 1994; Verhoeven and Toorn, 1990; Mahlum, 1998; Verhoeven and Meuleman, 1999). This issue is closely related to the techniques for environment management. Therefore it has become more and more important both theoretically and practically.

The modelling for nutrient retention function of wetland systems has been attempted by ecologists (Dorge, 1994; Jorgensen, et al., 1988; Jorgensen, 1994; Mitsch and Reeder, 1991). Some are based on created wetlands for municipal sewage (Pride, et al., 1990; Mander and Mauring, 1997), and some are based on riparian wetlands as a filter for water discharged from fertilized agricultural fields (Vought, et al., 1994; Mander, et al., 1997). Arheimer and Wittgren (1994) suggested a spatial model on a regional scale for the wetland retention of nitrogen in Sweden, to estimate the smallest area needed for cutting down nitrogen input into the sea. Hopkinson, et al. (1988) described a series of wetland and estuarine models at different scale levels, on many aspects from wetland succession, hydrology, to purification. The dynamic spatial simulation models on marsh succession (Costanza et al., 1988; Bakker, 1994) give an insight on spatial modelling methods. Although none of these models predict spatial explicitly the distribution of nutrients or pollutants, they provide strong basis to build a spatial model for the nutrient reduction in the Liaohe delta.

A model is a simplification of the real world, often based on a series of assumptions, or hypotheses. It is useful if it can simulate the landscape processes with mathematical algorithms, in which all the essential factors are taken into consideration, and thus can reveal the mechanisms mostly related and then simulates the possible processes in the system. Mathematical models enable predictions and can be checked against reality by experiment or by survey. But it can also distort the complicated reality and cause large errors, if the simplification procedure is not handled properly (Jeffers, 1978).

A spatial model is the combination of mathematical process model and GIS analysis (Bregt and Bulens, 1998). It has the privileges of both and makes more powerful applications in different fields. Further more, it enables users to make spatial analysis on ecological processes and make predictions on different management results.

The objective of the model is to simulate the nutrient reduction in the estuary wetland of Liaohe Delta, China, and to investigate the possibility to use this area as a treatment system for nutrient enriched river water. We will mainly focus on nitrogen and phosphorous, because they cause eutrophication problems in the coastal seawater. The result will be used by planners and policy-makers to define to what extent the reed marsh should be preserved as a purification system for the Liaohe River, one of the most polluted large rivers in Northern China.

Normally the detail level of a model mainly depends on two factors: 1) the understanding or awareness about the system to be modelled; and 2) the availability of data. Due to lack of detailed insight into the bio-physi-chemical processes in the study area, as well as the limited field data, the nutrient reduction model for the Liaohe delta will be rather empirical.

In fact, an empirical model is more applicable in this study because it is impossible to collect the extensive data needed to build a more precise, predictable model, due to the limited time and funds available. This is also the case in many other wetland projects (Jorgensen, et al., 1988). The model to be built will be based on the following research questions: given the input load of water and nutrient concentrations, the length of canals, the area and main species of wetland vegetation, what would be the estimation for the amount of nitrogen and phosphorus removed by the wetlands?

The preliminary analytical models, spatial simulation models, results and model validation will be presented in the following parts of this chapter.

4.2 Model initiation: data sources and analytical models

The model is based upon the data sources available, to the best knowledge available on the system, as well as some assumptions to simplify the system. Analytical models at different levels will be described in this section.

4.2.1 Data sources

Before the modelling process begins, the data sources must be considered. The following data and information are available for the model to be built:

Field observation and experimental data:

* Nutrient concentration values in the canals at 0, 500, 2000 and 6000 meters distance to the pumping station. Two years of observation, 3 times a year during irrigation period in spring.
* Nutrient concentration values in the surface water and groundwater of reed field at 40, 60 and 80 cm depths. Two years of observation, 3 times a year during irrigation period in spring.
* Other field data collected: nutrient concentration values in plant and soil, primary productivity, and ground stem distribution.

Digital and published maps:

* Raw data of TM image 1987 (Sept.21st)/1988(Nov.10th), and 1998 (May 14th).
* Digital Landscape maps of the study area, delineated from TM image of 1994.
* Digital wetland distribution map delineated from land use map published in 1986.
* Digital maps of irrigation areas, canals, and pumping stations.
* Topographic maps (at scale 1:100,000) of the study area.

Other information:

* Data and knowledge about wetland ecosystems and management factors in the study area.
* National water quality standard for nutrients and pollutant parameters.
* Other information, such as research reports, thesis, and literature.

According to the above list, the spatial data is adequate enough for the model, but field experimental data is relatively limited to make good predictions and extrapolations. Therefore, a spatial model, rather than an ecological function model, will be built, based on some assumptions on processes. Eventually, the nutrient reduction process of the canals and reed fields will be taken as "black boxes", in which, only input and output data is considered.

The spatial model will finally be used to estimate the global reduction for some nutrient elements, based on the current reed and canal distribution pattern. It should also be possible to predict the area of reed needed as treatment system. The model is not supposed to be used in interpreting the ecological processes in the study area, although some conclusions about nutrient reduction can be drawn from the results of the simulation.

4.2.2 Spatial objects in the model system

Many objects and factors are involved into the nutrient reduction process of the reed system, but not all can be incorporated into the model, either because of their importance in the reduction procedure, or because of data limitation. According to the specific situation of Liaohe delta, as well as the objectives of the project, the following objects will be mainly concerned in the model: pumping stations, irrigation areas, canals, reed fields, sample points and their distributions.

Pumping stations

There are many pumping stations in the Liaohe delta, for the purpose of water irrigation during dry seasons and water discharge during wet seasons, both in the paddy fields and reed fields. Most of them are distributed along large rivers or main canals. Eleven big pumping stations are for the reed fields, with different pumping capacities and water sources (figure 4.1, table 4.1).

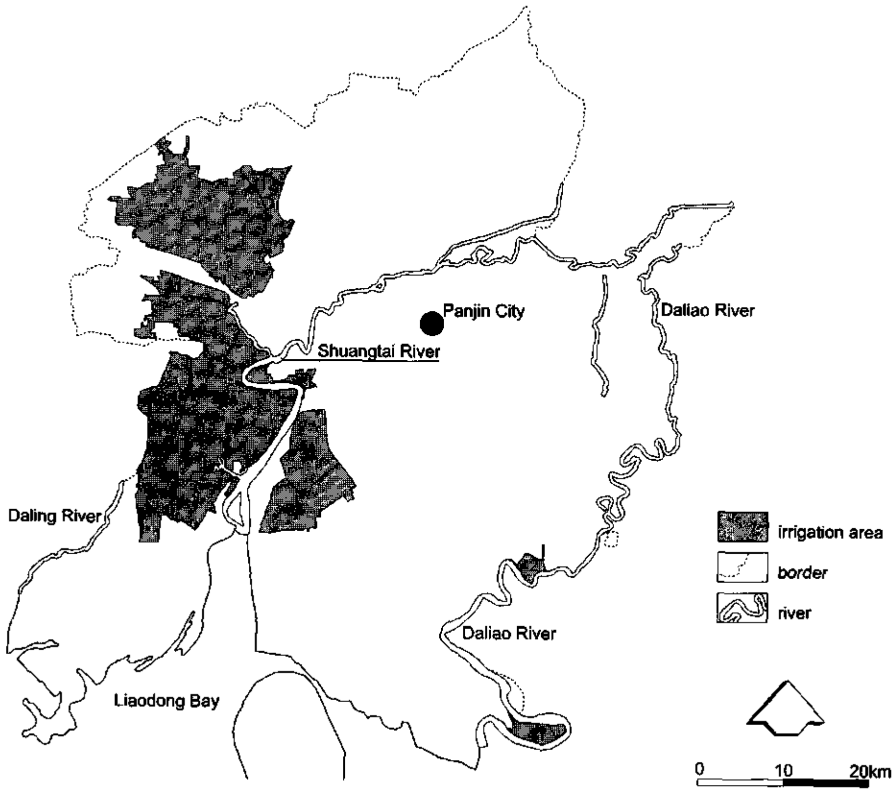

Figure 4.1 The irrigation area distribution in the reed fields of Liaohe delta. Numbers are IDs given to each irrigation area.

Table 4.1 The pumping stations and irrigation areas in the reed field of Liaohe delta

Irri. No.	Name	Pump. ability (m^3/s)	Power capacity (kw)	Area controlled (ha)[1)]	Source water
11	Yangjuanzi_Shengli	21.0	3100	17000	Shuang-Rao R.
12	Yangjuanzi_Xidawan	2.1	165	2800	Shuang-Rao R.
21	Dongguo_Shuguang	10.5	855	1600	Shuang-Rao R.
22	Dongguo_Wanjintan	29.6	2790	19300	Shuang-Rao R.
23	Dongguo_Sanyi	12.5	1360	4600	Daling R.
24	Dongguo_Nanjingzi	20.0	1790	5600	Daling R.
31	Zhaoquanhe_Hongta	6.0	520	1200	Paddy field
32	Zhaoquanhe_ Liuhetang	13.6	1180	4000	Paddy field
33	Zhaoquanhe_Xingsheng	2.1	210	4400	Shuangtai R.
41	Liaobin_Daobazi	4.5	469	1400	Daliao R.
42	Liaobin_Xilaowan	4.9	335	800	Daliao R.

1) The area controlled by each pumping station varies with time because of the reed area change.

Irrigation area
Each pumping station controls a specific area, the size of which varies with the pumping capacity (figure 4.1, table 4.1). In concordance with the pumping stations, 11 irrigation areas are delineated. The boundary of each irrigation area also tends to change with the change of reed-covered area due to natural and artificial conversion. But it is relatively stable within one year.

Canals
Canals are criss-crossing all over the study area (figure 2.5). In practice, there is a hierarchical system of different canals, from main-canal, to 2nd and 3rd level canals, up to 5th level. For the convenience of modelling, the canals are simplified into two levels, and finally nothing but the distance of a canal point to its corresponding pumping station is considered, because canals at different levels do not show an obvious difference in nutrient reduction.

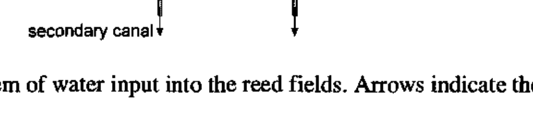

Figure 4.2 The canal system of water input into the reed fields. Arrows indicate the direction of water flow.

Figure 4.2 gives a sketch look of how nutrient enriched water runs from the pumping station, via a series of canals, and finally reaches the reed fields.

The water gates along the canals (figure 4.2) are usually 30-50 meters apart from each other. We choose 30 meters as the cell size for modelling, so that the positions of these water gates are not considered. This will greatly simplify the modelling procedure in the canal system. During nutrient concentration mapping, we just assume that the water in the reed fields comes from the nearest canal point.

Reed fields

Reed fields are the main component of the nutrient reduction system. It is managed via irrigation, discharge and harvest by the local people. All the pumping stations, canals and other facilities are focused on a high production of the reed. The reed is harvested in winter, with stems transported to the paper factory as raw material, and leaves collected away by local farmers as fuel or fodder. This kind of output enables the system to be highly efficient in nutrient removal, with little accumulation.

Figure 4.3 gives a sketch look of how the ground water in the reed fields is sampled. The sample depths are 0, 40, 60, 80cm respectively, which are defined according to the distribution of underground stems (20-60cm), and average water table (80cm) in dry seasons.

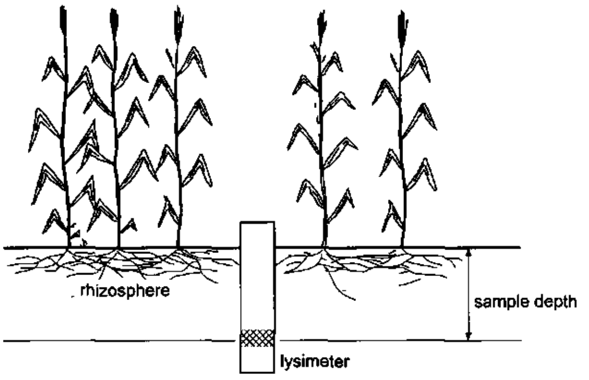

Figure 4.3 Water sampling system in the reed marsh.

Sample points

Sample points are situated along canals and in the reed fields for the purpose of data collection. Water is sampled and analyzed mainly during the irrigation period in spring. The data collected from these sample points will be used to build the process model and validate the spatial model.

There are more objects and factors related to the system, such as rivers, groundwater, precipitation, soil, geomorphology and sea, but these are less closely related to the nutrient reduction procedure and will not be considered at present. Nevertheless, the model will always be open for further improvement in the future, when more data and knowledge are available.

4.2.3 Preliminary analytical models

In order to get a clear insight into the system to be modeled, some analytical models are established. The general model gives an overview of the system. The conceptual model incorporates the main objects and factors into the system and gives a brief description of the main processes. The data model translates the conceptual model into a workable system that can be realized within GIS.

General model

The nutrient reduction system has several input/output possibilities. The major process is presented in figure 4.4.

In figure 4.4, the reed and canals are taken as one system, in which the nutrient reduction process

(1) takes place. Nitrogen and phosphorous are brought into the system with water, 3 times a year in spring, the quantity or input load of which is known. After entering into the system, the nutrients can either go into the air (nitrogen only, via denitrification), into the reed, into the soil, or flow into the sea as reed bed outlet.

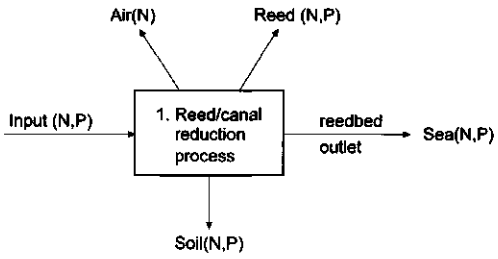

Figure 4.4 General model of the nutrient reduction system. N = Nitrogen; P= Phosphorous. Process number 1 will be decomposed to 1.1 and 1.2 in the conceptual model (figure 4.5).

Most of the nutrients absorbed by reed will finally be taken out of the system because of the stem cutting and leaf collection in winter. The part of nutrients trapped in the soil is gradually denitrified, absorbed by vegetation, or flows into the sea during flooding season, if time is considered. The irrigation system has been established for more than 30 years, and the reed production has kept increasing. Therefore we just assume that no accumulation problem exists, at least for the recent decades. The part of nutrients flowing into the sea is what we are mainly concerned of, because it is an important contribution to the eutrophication problem of coastal seawater.

Conceptual model

The conceptual model of the nutrient reduction system is described in figure 4.5. Since the bio-physi-chemical process will be taken as a "black box", the conceptual model is rather simple.

In figure 4.5, Nutrient enriched water from the nearby river is firstly pumped into the canal system via pumping stations. The quantity of water and nutrients can be taken as the input of the model. Normally the water runs a certain distance through the canals before reaching the reed field (figure 4.2). The running water has a self-purification mechanism in the canals (process 1.1, figure 4.5). We will not go into details of this process. The reduction process in the canal system will be taken as a "black box". Only nutrient concentration is measured after a certain distance. The forcing factors for this sub-model will be input load, distance to the pumping station, types of canal and time.

In the lower part of figure 4.5, the water flows into the reed field from the canals via a series of water gates. The soil-vegetation system has a strong nutrient reduction ability, both on surface and underground, either through absorption, adsorption, uptake, denitrification, or other bio-chemical processes (1.2, in figure 4.5). It is a combination system of both horizontal flooding and vertical infiltration. Here again we simplify the processes by treating the reed system as a "black box", in which, only the nutrient concentration in surface and ground water is measured, at a series of depths. The forcing factors for this model can be the area of the reed, soil types, input load, distance to the water gates, and time.

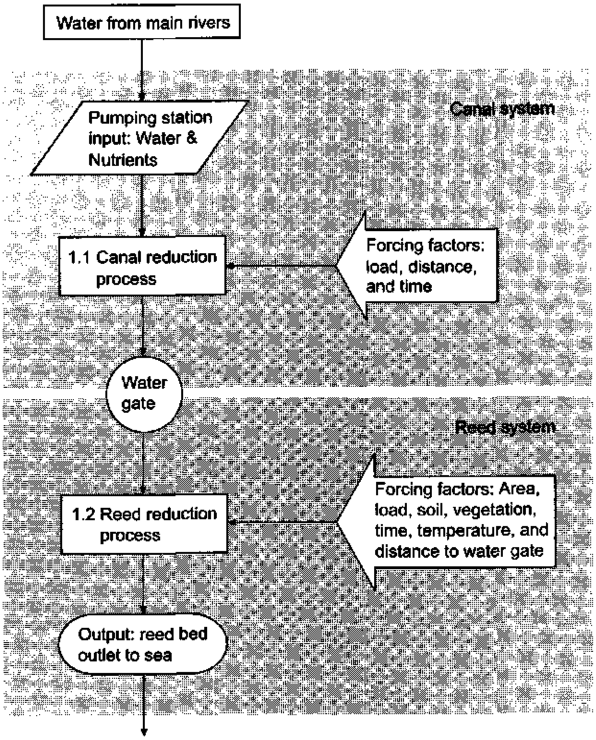

Figure 4.5 The conceptual model of the nutrient reduction system. Processes 1.1 and 1.2 are decomposed from process 1 in the general model (figure 4.4).

Data model

According to the conceptual model of the system, a data flow diagram (figure 4.6) can be established to describe the nutrient reduction model in a systematic way (Turner, et al., 1987).

The canal reduction model: Experimental data from sample points in the canals, as well as the spatial data of pumping station and canal distribution, will be used for modelling the nutrient reduction process in the canal system. The output of this sub-model will be the spatial distribution of nutrient concentration in the canals. It also allows calculating the amount of nutrients removed by the canals.

The reed reduction model: Taking the nutrient distribution in the canals as input, the experimental data from sample points in the reed field, and the spatial data of reed distribution, will be used for modelling the nutrient reduction process in the reed-bed system. The output of this sub-model will be the nutrient distribution in the groundwater of reed fields, according to which, the total amount of nutrient output can be calculated. The total nutrient reduction by the system can be obtained according to the quantity of total input and total output.

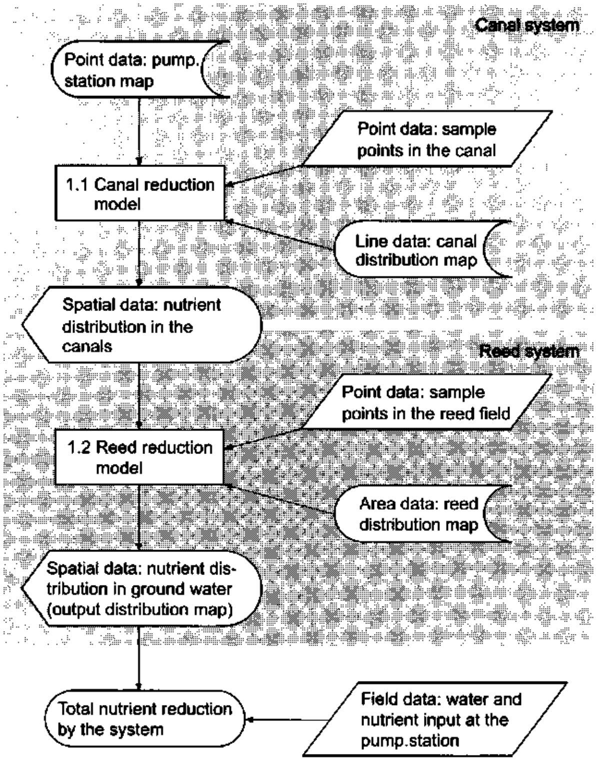

Figure 4.6 Data flow diagram of the nutrient reduction model

4.2.4 General assumptions for the model

It is impossible to model the reality in every detail. Some global assumptions and generalizations have to be made to simplify the modelling process. Here are the main assumptions for the model:

1. The input concentration of nutrients is stable during each irrigation period. There are 3 times of irrigation every year in spring, each lasting 15-20 days (Chapter 2). The dynamics of nutrient concentration will not be taken into consideration within one irrigation period.
2. All the roads (main roads, secondary roads) on the topographic map are converted into secondary canals, because the roads are always accompanied by canals on both sides, and this kind of canals are also used for water irrigation and discharge in growth season. Other linear features, such as railway, dikes, are not used for the model.
3. The nutrient reduction in rivers is not considered. Although some of the river branches extend into the reed fields, the area of reed affected by these small branches is rather limited. Normally large rivers only affect the reed fields via pumping stations, in stead of flowing directly into the reed fields, except in the flooding season, when water floods into the nearby fields. But in the case of flooding, all the nutrients are diluted, and have no serious consequences in the coastal seawater. So, the flooding seasons will not be taken into consideration.
4. The water input into the reed field is considered to be from the closest canal point. Although the real input is from a series of water gates along the canal, the distance between two adjacent

water gates is about the same as the cell size (30m) for modelling. This assumption has greatly simplified the relationship between canal and reed fields, as well as the model itself.

5. The elevation factor is not taken into consideration, because the terrain is rather flat (at a slope of 1/20,000-25,000, Hu, 1997). This will greatly simply the model without considering the direction of water flow caused by local relief.
6. The difference in reed productivity (figure 2.3) reflects the situation of reed fields, such as soil and ground water level, which can affect the nutrient reduction in certain degree. A qualitative factor value is assigned to each production category in terms of their nutrient reduction ability (table 4.2). In addition, the cattail (*Typha spp.*) communities scattered in the reed marsh are also irrigated when the reed is irrigated. This kind of wetland species has high up-taking rate for nitrogen and phosphorous, too (Mander, et al., 1997). In winter it is also cut and moved out of the system as fuel or fodder. Therefore a weight value is assigned to this type of vegetation.

Table 4.2 The weight value assigned to different reed production categories based on expert judgement

	Production (kg/ha)	Weight value
Reed	7500	1.00
	6000	0.95
	3000	0.85
	1000	0.70
Cattail		0.90

Based on the data flow diagram, as well as the primary assumptions described above, two models are established. One is totally based on field data and the other is partly modified with literature data.

4.3 Field data based simulation model

The model is first developed in the irrigation area No.11 (Yangjuanzi Reed Farm, in the northwestern part of the study area, figure 4.1), where our field data is mainly collected, and the irrigation condition is relatively good. Finally the model is extrapolated for the whole irrigated reed area.

At the first stage, a series of percentage based linear simulation models have been tested and validated, in which, the concentration value of nutrients at a canal or reed field point is a certain percent of the concentration value at its source point. We will not go into details describing these models because all of them have proved to be kind of problematic in estimating nutrient distribution in the area farther away from the pumping station. However, the ideas obtained from these models have provided strong basis for a more practical model, which will be introduced step by step.

4.3.1 Non-linear simulation for the canal system

In order to get an estimation of the nutrients removed by canals, the model should be able to predict the nutrient concentration at each point on the canals. The retention rate slows down gradually as water moves farther away from the pumping station, and the nutrient concentration decreases. According to the field data obtained from 1997-1998, a non-linear regression model for the canal system is established for the nutrient concentration based on the logarithm of the distance from a canal point to the pumping station:

$$C_{(x,y)} = -A * \ln(dist.) + B \qquad (A>0, B>0) \qquad (4.1)$$

Where $C_{(x,y)}$ is the nutrient concentration at a certain point in the canal, and "*dist.*" is the distance of this point to the pumping station. "A" and "B" are parameters related to the input concentration of nutrients:

$$A = C_1 * inload + C_2 \qquad (4.2)$$

$$B = C_3 * inload + C_4 \qquad (4.3)$$

Where, C_1, C_2, C_3 and C_4 are constants, and "*inload*" is the input load of nutrient concentration in mg/l. In this study, the values for these four constants are obtained according to the linear regression of field data, and presented in table 4.3.

Table 4.3 The constant values used for non-linear simulation model in the canals

	TN (total nitrogen)	SRP (soluble reactive phosphorus)
C_1	0.0597	0.1230
C_2	0.0987	-0.0006
C_3	1.2717	1.6003
C_4	0.2788	-0.0134

Based on the above regression formulas, a non-linear simulation model is constructed for the area controlled by pumping station 11. Figure 4.7 provides the simulation result for the canal system, given 7.33 mg/l as the input concentration at the pumping station. The simulated concentration distribution in the canal is comparable with that of the field data obtained.

The non-linear simulation model for the canal system is flexible on input load, and independent on the experimental data, once the needed parameters have been obtained.

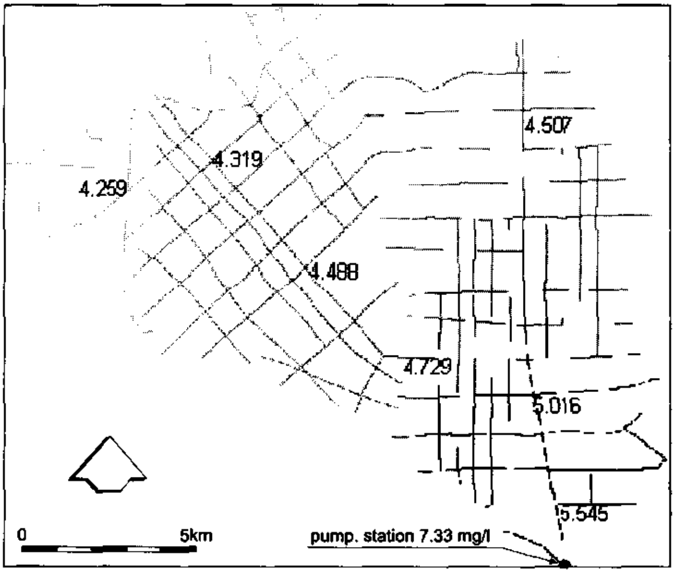

Figure 4.7 Total nitrogen distribution in the canals controlled by pumping station 11, based on non-linear simulation. All values are in mg/l. Darker cells have higher values.

4.3.2 Non-linear and linear simulation for the reed system

When water runs from the canals into the reed fields, the nutrient concentration also follows a non-linear decrease procedure. Using the same algorithms provided in formulas 4.1~4.3, the nutrient distribution values can be obtained for the reed field surface. The simulation results are given in figure 4.8. It is clearly related to the canal distribution pattern. The concentration value in the surface water of reed field decreases quickly after water flows away from the canals.

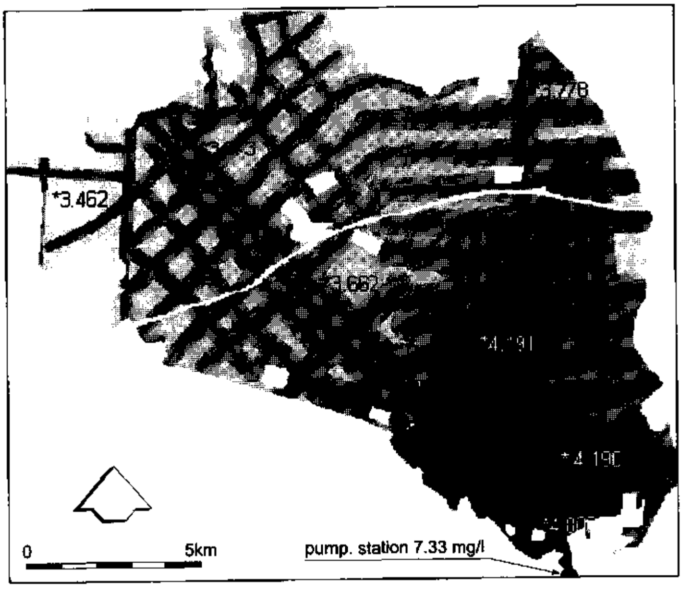

Figure 4.8 Total nitrogen distribution in the surface water of reed fields controlled by pumping station 11. All values are in mg/l. Darker area has higher value.

Using figure 4.8 as input for the vertical reed/soil system, the output nitrogen concentration in 80cm ground water is calculated as 30.4% lower than the surface load, under condition of the highest reed production. Only the average retention rate is used in this simulation model, in combination with reed production weight value (table 4.2). The simulation result for total nitrogen in irrigation area No. 11 is shown in figure 4.9.

The concentration distribution pattern for total nitrogen in the 80cm groundwater reflects the effect of the distance from canal to reed field points, as well as the effect of different bio-productivity (figure 4.9). This will be used to calculate the nutrient output in combination with the quantity of water output.

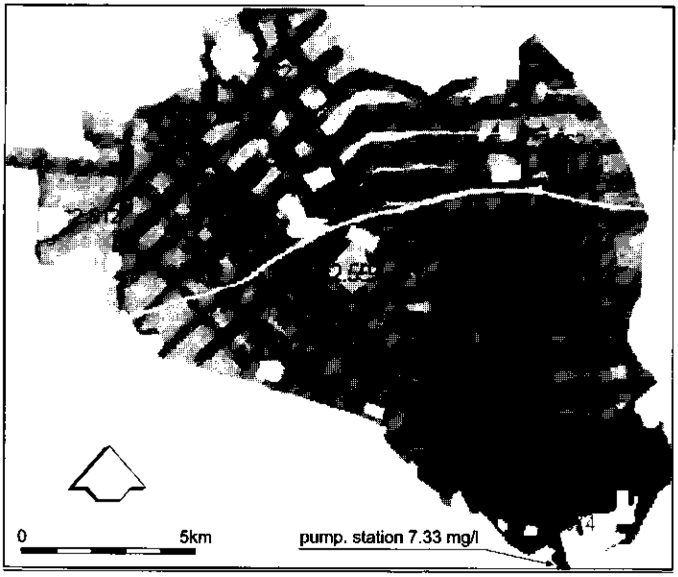

Figure 4.9 Total nitrogen distribution in the groundwater of 80cm in the reed fields controlled by pumping station 11. All values are in mg/l. Darker area has higher value.

4.3.3 The general model for the whole irrigation area

So far the model has been focused on the irrigation area controlled by pumping station No. 11. But the input load and retention rate for different nutrients vary a lot (table 4.4), as a result of time and physical environment change. The input concentration values and retention rates at different irrigation periods and different years show a high variance. It should be avoided to use this kind of average value in the model.

Given the variation character of input load and reduction ability measured in the canals and reed fields, it is important to build a model more flexible in predicting nutrient concentration distributions at different input concentration values, as well as for different nutrients. Based on the simulation models described above, in combination with knowledge about other irrigation areas, as well as some assumptions, it is possible to make such a general model for the Liaohe Delta.

Table 4.4 The variation of input load and reduction rate in the reed-canal systems for nitrogen and phosphorous

Nutrient	Variables	Range	Average
Total nitrogen	Input TN (mg/l)	3.22~12.42	7.33
	Canal_puri_rate TN at 6000m	-10 ~ 55%	23.8%
	Reed_puri_rate TN at 80cm	2.4~72.5%	30.4%
Soluble reactive phosphorous	Input SRP (mg/l)	0.073~0.235	0.137
	Canal_puri_rate SRP at 6000m	13.0~60.0%	40.9%
	Reed_puri_rate SRP at 80cm	17.2~51.7%	34.9%

The steps taken for the general model can be described with a program flow chart in figure 4.10. The key commands or algorithms used are also listed along the description of each step.

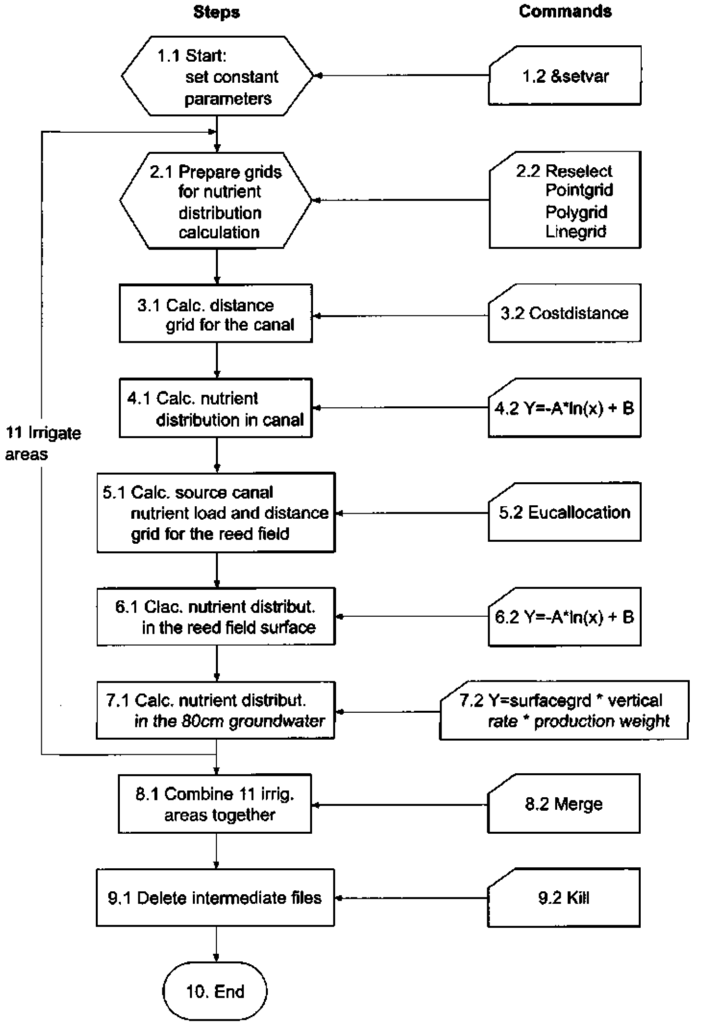

Figure 4.10 Flowchart for the general nutrient reduction model in the Liaohe Delta. The left side shows the logical steps and the right side provides the Arc/Info commands used corresponding to each step.

In figure 4.10, a series of constant parameters has to be set as a start (step1). Then some grids needed for nutrient distribution mapping are prepared (step2). In this step, a specific pumping station, as well as canals and area controlled by this pumping station are selected, and converted into grids. These are done in the ARC module.

The next step is to calculate the distance of each point in the canal to the pumping station (step 3). The command COSTDISTANCE is used in the ARC/GRID module.

Then the nutrient concentration mapping procedure begins (Step 4). According to the formulas 4.1~4.3, the nutrient concentration on each point of the canal can be calculated.

With the command EUCALLOCATION (Step 5), the source cell value (representing nutrient concentration on the closest canal point) of each point in the reed field is calculated, as well as the distance of each point to the closest canal point. The two output grids from this command will be used as input grids in Step 6 to calculate the nutrient distribution in the surface water of reed fields. Special attention must be paid to the condition of command EUCALLOCATION, which accepts integer values only. Data in decimal or floating format has to be exemplified and truncated before this command is executed, and reduce to normal afterwards. This is the limitation of Arc/Info commands.

In Step 6, the same algorithms as Step 4 are used. The difference is that, values for A and B are different from point to point because the nutrient concentration on each canal point is different. While in Step 4, these two values are constant once the input load at the pumping station is defined.

Step 7 calculates the output nutrient distribution in 80cm groundwater in the reed fields. The result is a multiplication of surface distribution grid, the vertical reduction rate, and the reed productivity weight value (table 4.2).

Figure 4.11 The total nitrogen distribution in the groundwater of 80cm in all the irrigated reed fields based on non-linear simulation model. Numbers are the irrigation area ids controlled by each pumping station. Input load is 7.33 mg/l for all pumping stations. Darker area has higher values.

Steps 2~7 are repeated until the nutrient distribution in all 11 irrigation areas are mapped, and stored as separate grids. Finally these grids are spatially merged together (Step 8), and intermediate files have to be deleted (Step 9).

Above are the main points of the model in mapping out the nutrient distribution in the whole area, at a given nutrient load. The program designed here makes it easy to calculate the result for total nitrogen and soluble reactive phosphorous at any given load. One of the simulation results for total nitrogen is given as figure 4.11, where the input load is also set as 7.33 mg/l, the average input load according to the field data. The final output of this model, in combination with the water output, can give an estimation of total nutrient reduction.

Various results as figure 4.11 can be obtained based on different input nutrient concentrations. The purpose of the model is not only to map the spatial distribution of nutrient concentration in the study area, but also to use the simulation results to estimate the potential nutrient reduction for the whole area. To make such an estimation, quantity of water input and output have to be considered as well.

4.3.4 Total reduction estimation based on the non-linear simulation model

The total nutrient reduction model is based on the water and nutrient balance in the whole area. It can be estimated by:

$$R = \Sigma Q_{in} * C_{in} - \Sigma Q_{out} * C_{out} \quad (4.4)$$

Where R is the quantity of nutrients reduced by the system. Q_{in} is the quantity of water input at pumping stations, and C_{in} is the nutrient concentration of the input water. Q_{out} is the quantity of water output from the reed marsh, and C_{out} is the nutrient concentration in the output water. Q_{out} is calculated as:

$$Q_{out} = Q_{pump} + Q_{rain} - Q_{ep} - Q_{canal} - Q_{soil} \quad (4.5)$$

In which, Q_{out} is the quantity of water output, normally as ground water outlet into the sea. Q_{pump} is the quantity of input water at pumping station. Rainfall (Q_{rain}) is also considered as input although it is rather small (161.5 mm, from March to June), compared to the quantity of water irrigation in spring (*ca* 600 mm). Contrary to the amount of rainfall, the evaporation (Q_{ep}) in the same period is much higher (836.1 mm). The amount of water absorbed by canals (Q_{canal}) and reed bed system is difficult to estimate. In the canals, the absorption procedure stops after the bank soil is fully saturated. But in the reed fields, it is more complicated to estimate the water lost (Q_{soil}) because of the evapotranspiration process. The reed transpiration is considered to be included in evaporation because the surface of reed field is always covered with water during the irrigation period. For modelling we assume that the total quantity of water is 0.1% absorbed by the canal system, and 80 mm by soil. The quantity of rainfall, evaporation and soil absorption can be calculated with the value in depth (mm), multiplied by the irrigation area (table 4.5).

Table 4.5 Water balance and total amount of TN (total nitrogen), SRP (soluble reactive phosphorus) input during each time of irrigation, in the irrigation area No.11

Pump. Period	Mar.10-30	Apr.20-May10	June1-15
+Qpump.(m^3)	36288000	36288000	27216000
+Qrain(mm)	5	28	30
-Qevaporation(mm)	80	160	100
-Qcanal (%)	0.1	0.1	0.1
-Qsoil(mm)	80	80	80
TN_input (mg/l)	12.42	7.33	3.22
SRP_input (mg/l)	0.082	0.137	0.235
TN_input (ton)	450.6	266.0	87.7
SRP_input (ton)	3.0	5.0	6.4
Qout estimated (m^3)	8687910	-1448457	514136
Qout/Qpump (%)	23.94	-3.99	1.89

1) Area of reed irrigated: 170 km^2.
2) +Q: quantity of water input into the system; -Q: quantity of water output from the system.
3) Negative value of estimated Qout means no water flows out from the system.

Taking the first time of irrigation in spring (from March 10^{th} to 20^{th}) as an example, the total time of irrigation is about 20 days, and total amount of water pumped is about 36 million m^3. According to the above assumptions and formula 4.5, the total output quantity of water from the reed fields controlled by pumping station No.11 is about 8.7 million m^3. The output water from other two periods is rather limited, even negative, which means all the nutrient input in the water will be trapped and accumulated in the reed fields until the flooding season comes. However, these nutrients would not "stay" constantly in the soil, because of vegetation up-take and bio-chemical procedures. During flooding seasons, the nutrient concentration can be reduced further due to dilution, and horizontal transportation underground.

Several limitations that may reduce the reliability of the above water balance:

- The quantity of evaporation: It is the measured evaporation rate from local weather stations, not evapotranspiration. The value here can be higher than reality. But if we use the value of evapotranspiration, it will be much lower than reality because of the water flooding during irrigation. The value of evaporation is a closer and easier parameter choice for the model.
- The quantity of water infiltrated into the soil of canals: It is also difficult to get an accurate estimation. The 0.1% loss in the canal system is based on expert knowledge.
- The quantity of water absorbed by soil: The soil in the reed field is dominated by salinized bog soil or bog solonchak, both of which are quite clayey. Here it is just assumed that the soil absorbs 80mm of input water, in spite of the original difference of field moisture condition. Similar to the estimation of water loss in the canals, this is also based on expert judgement. Much intensive fieldwork is needed to get a better estimation for this part of water loss, which cannot be carried out in our present project.
- The calculation period: The water output calculated here is only for the period when the pumping station works. But the process of evaporation and vegetation up-take will not stop after the pumping station stops working. The "output" is actually the "left over" of the calculated 20 or 15 days. Only a small fraction of this part of water can really flows into the sea as ground water.

In spite of the above limitations for the calculation of output water quantity, the figures provided in table 4.5 is still meaningful in the sense of awareness about the general water balance in the study area. The output water quantity is also in accordance with the results from the fieldwork in 1998.

Table 4.5 also indicates that the quantity of water is much more a limitation factor for the reed marsh than the nutrient itself. The reed field can accept more water together with the nutrients than what it is doing now.

Based on formula 4.5 and table 4.5, the total amount of water discharged from each irrigation area (*Qout*) during each irrigation period can be calculated. The results are given in table 4.6.

Table 4.6 The water input and calculated output in the irrigation areas of Liaohe Delta (m^3)

Irri.	Mar.10-30 (20 days)		Apr.20-May10 (20 days)		June1-15 (15 days)	
No.	input	output	input	output	input	output
11	36288000	8687909	36288000	-1448457	27216000	514136
12	3628800	-716077	3628800	-2312536	2721600	-1482329
21	18144000	15568083	18144000	14627482	13608000	11119128
22	51148800	20112669	51148800	8718191	38361600	8337772
23	21600000	14416158	21600000	11782301	16200000	9252598
24	34560000	25799136	34560000	22590108	25920000	17449270
31	10368000	8568083	10368000	7909991	7776000	6036402
32	23500800	17245204	23500800	14953401	17625600	11576915
33	6220800	-541722	6220800	-3026297	4665600	-1877422
41	7776000	5649649	7776000	4870560	5832000	3775934
42	8467200	7319226	8467200	6900182	6350400	5241302

1) Negative values of output quantity indicate no water output from the system.
2) Irri. No.: irrigation area identity number used in the model. Please see table 4.1 for more information. Same in table 4.7.

The calculated quantity of water output is sometimes negative (irrigation areas 12 and 33, for example). Such kind of cases means input water is not enough for reed growth and evaporation. Therefore there is no water and nutrient output from them.

The total amount of TN (Total Nitrogen) and SRP (Soluble Reactive Phosphorous) input at each pumping station during each period can be easily obtained by multiplying the concentration value with the quantity of water pumped into the canals, assumed that the input concentration keeps stable during each irrigation period (table 4.7).

Table 4.7 The nutrient input in the irrigation areas of Liaohe Delta (ton)

Irri.	Mar.10-30 (20 days)		Apr.20-May10 (20 days)		June1-15 (15 days)	
No.	TN	SRP	TN	SRP	TN	SRP
11	450.6	3.0	266.0	5.0	87.7	6.4
12	45.1	0.3	26.6	0.5	8.8	0.6
21	225.3	1.5	131.0	2.5	43.9	3.2
22	635.1	4.2	375.0	7.0	123.7	9.0
23	268.2	1.8	158.3	2.9	52.2	3.8
24	429.1	2.8	253.3	4.7	83.6	6.1
31	128.7	0.9	76.0	1.4	25.1	1.8
32	291.8	1.9	172.3	3.2	56.8	4.1
33	77.2	0.5	45.6	0.8	15.0	1.1
41	96.6	0.6	57.0	1.1	18.8	1.4
42	105.1	0.7	62.1	1.2	20.5	1.5

1) TN = Total Nitrogen; SRP = Soluble Reactive Phosphorous

The quantity of output water is assumed to be evenly distributed in the irrigated area. The output of TN and SRP from each point of the reed marsh can be calculated by multiplying the amount of water per unit area with the nutrient concentration value at this point. And the total output is the sum of output from each point of the reed marsh. The simulation results are given in table 4.8. According to the calculation result, the total reduction is about 4,000 tons for TN and 80 tons for SRP in the irrigation period of each year. Or, about 80% of nitrogen and 90% of phosphorous can be removed from the system within the simulated periods. The removal efficiency is higher when the nutrient input concentration is lower (table 4.8).

Table 4.8 The total input and calculated output for TN and SRP in the reed fields

		Input		Reduced		Output
	Period	(mg/l)	(ton)	(ton)	(%)	(ton)
TN	Mar.10th –30th	12.417	2741.0	2154.7	78.6	586.3
	Apr.20th-May 10th	7.330	1627.4	1387.9	85.3	239.4
	June 1st-15th	3.224	542.7	478.8	88.2	63.9
	Total		4911.1	4021.4	81.9	889.6
SRP	Mar.10th –30th	0.082	18.2	16.7	91.8	1.5
	Apr.20th-May 10th	0.137	30.3	27.8	91.7	2.5
	June 1st-15th	0.235	39.1	35.1	89.8	4.0
	Total		87.6	79.6	90.9	8.0

1) TN: total nitrogen; SRP: soluble reactive phosphorous

In table 4.8, the amount of SRP input into the system is lower in early spring, because of the low temperature. Higher input concentration at the pumping station results in a higher absolute reduction quantity, but the relative removal rate in percentage is lower.

4.3.5 Model validation for the field data based simulation model

The data used for model validation must be independent on the data used for model construction (Jeffers, 1980). Due to the limited experimental data sources, all the field data demonstrating the trend of nutrient reduction have been used to establish the regression model. The data left for validation is relatively "poor" and deviates a lot from the non-linear regression model (formula 4.1). Table 4.9 presents the comparison of simulated results and experimental results.

The significant value for sample size N=12 is 0.708, with upper tail area equals to 0.005 (Pearson and Hartley, 1966). Therefore the non-linearly simulated result is significantly related to the experimental data ($R>0.7$, $n=12$) (table 4.9). The value pairs of these two data sets are also quite close with each other. Fieldwork in the future will provide more data to improve and validate the model.

Although a good regression model has been obtained between input concentration at the pumping station and the distance from a canal point to the pumping station, the experimental data in the reed field fails to establish good relationships between input concentration in the surface water and concentration in 80cm groundwater. The vertical reduction rate used in this model is simply an average value in percentages, i.e., 30.4% for total nitrogen and 34.85% for soluble reactive phosphorous, under the highest reed productivity condition. It sounds arbitrary compared to the more accurate estimation in the canals. Moreover, the reed bed is more important than the canal in nutrient removal. Therefore this part of model needs further improvement, in order to get a better estimation for the total reduction in the reed field part. Some related literatures prove to be helpful in improving our model.

Table 4.9 The comparison of experimental result and non-linearly simulated result for total nitrogen (TN) and soluble reactive phosphorous (SRP) in the Liaohe Delta.

		TN		SRP	
	Sample points	Experiment data (mg/l)	Non-linear simulation (mg/l)	Experiment data (mg/l)	Non-linear simulation (mg/l)
Data	50m	5.100	4.834	0.170	0.161
set	500m	4.130	4.255	0.100	0.132
one	2000m	4.590	3.697	0.094	0.104
	6000m	5.019	3.257	0.060	0.082
	0cm	1.530	2.958	0.043	0.069
	80cm	2.289	2.059	0.028	0.045
Data	50m	3.387	3.145	0.082	0.073
set	500m	4.797	2.713	0.066	0.059
two	2000m	3.402	2.297	0.089	0.046
	6000m	1.500	1.968	0.072	0.035
	0cm	3.129	1.703	0.038	0.023
	80cm	1.255	1.185	0.046	0.015

1) Correlation coefficiency $R_{TN} = 0.717$; $R_{SRP} = 0.821$.
2) Data sets one and two are based on two different input concentration scenarios.
3) Sample points are 50, 500, 2000 and 6000 meters away from the pumping station in the canals, while in the reed field it is the surface water and 80 cm groundwater.

4.4 External data based simulation model

4.4.1 Mander and Mauring's regression model

Mander and Mauring (1994) compared more than 40 experimental data sets from Europe and North America, and derived a linear regression model on the relation between the input load and reduction quantity for nitrogen and phosphorous in the wetlands:

Nitrogen:

$$Y = -0.005 + 0.61X \qquad (R^2 = 0.84, n= 41) \qquad (4.6)$$

Phosphorous:

$$Y = -0.013 + 0.85X \qquad (R^2 = 0.98, n= 35) \qquad (4.7)$$

Where Y is retention and X is load, both in g/m^2.d for N and mg/m^2.d for P. No limit for increasing capacity of retention has been found (Mander and Mauring, 1994).

We can not say this statistical result is definitely applicable to our situation in China, but there are some good reasons to use it for the Liaohe Delta case because:

1. The experimental sites used for calculating the regression model are distributed widely in North America and Europe, more than half of which are in the Temperate Zone, the same climate zone as that of the Liaohe Delta.
2. More than half of the wetland sites used for regression are reed (*Phragmites spp.*) or cattail (*Typha spp.*) beds, which are also the main vegetation types in the Liaohe Delta.
3. In the field data based model, average values are used to estimate the vertical reduction in the reed fields. If we take all the experimental data set in the reed field of Liaohe delta into consideration, the reduction rate varies a lot (table 4.4), sometimes higher than Mander-&-Mauring's statistical result, sometimes lower. The standard deviation for this data set is too big to make a good average for use.
4. Using 80cm groundwater as output water from the reed field for the Liaohe Delta is somewhat controversial, because there is also water outflow when groundwater level is above 80cm. In addition, the horizontal reduction capacity was not taken into consideration, but also quite high (Yin, et al., 1994). On the other hand, Mander-&-Mauring's regression model avoided the quantity of water output, which is a big pitfall in the field data based model.
5. The estimation of output nutrients is even more unreliable when the estimated quantity of output water is negative (in the case of irrigation area 12 and 33, table 4.6).

Because of the above reasons, we introduce Mander-&-Mauring's regression model (1994) into our modelling system, for the reed field part. A new estimation on the nutrient reduction will be made for the reed-covered area of Liaohe Delta.

The total reduction is the sum of canal reduction and reed/soil reduction. The amount of nutrients removed by the canals can be easily obtained according to their concentration distribution in the canal system. The nutrient removal in the reed system will be calculated as the sum of reduction at each point of the reed field.

Mander-&-Mauring's regression model includes the surface removal by the wetlands. Therefore the nutrient concentration (mg/l) in the canal is converted into input load ($g/m^2.d$) for the reed fields, according to the water input load. Figure 4.12 gives a schematic overview of this modified model.

In figure 4.12, the steps from 1 to 4 are the same as those of figure 4.10. After the nutrient concentration in the canal is mapped in Step 4, the amount of nutrient output from the canals to the reed fields can be calculated by Step 5. This is simply done by multiplying the nutrient concentration ($mg/l = g/m^3$) and the amount of water output from each 30 meters of canal segment. The result of this step is also a grid, the value of which is the amount of nutrients flowing from each canal point to the reed field during each irrigation period, in grams. The total reduction in the canal system can be calculated as the total input minus output.

The next step (6) is the same as step 5 in figure 4.10, mapping the Euclidean allocation of nutrient concentration from the canals to the reed fields. The result will be used as input grid for the reed bed system to calculate the reduction capacity (Step 7). But first, the values must be converted into $g/m^2.d$ (for total nitrogen) or $mg/m^2.d$ (for soluble reactive phosphorous) according to the water input load and nutrient concentration, so as to consist with Mander-&-Mauring's regression model.

The 11 grids from step 5 and step 7 are merged separately (Step 8) to form the image for the whole reed covered area. The intermediate files are deleted afterwards (Step 9). Finally the total reduction quantity is calculated by summing up the cell values of the whole image (Step 10).

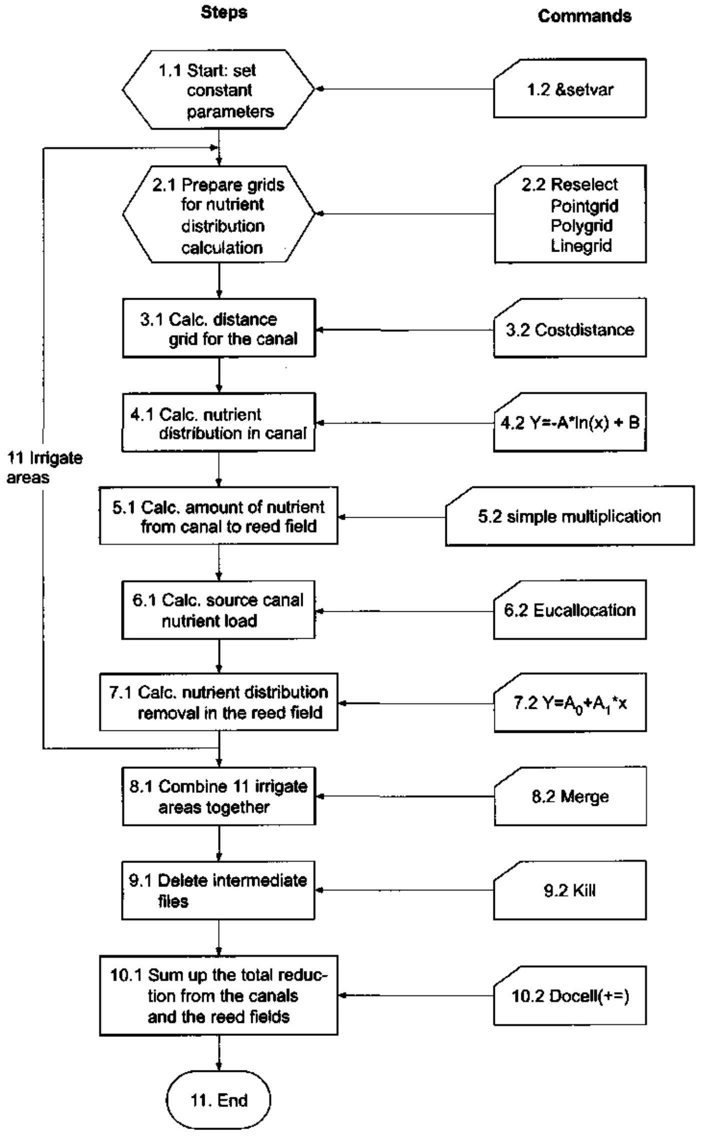

Figure 4.12 The modified program flow chart based on Mander-&-Mauring's regression model. The left side shows the logical steps while the right shows the Arc/Info commands.

The simulation result for the total reduction of nitrogen and phosphorous is shown in table 4.10. The reduction in the canal system and reed system is also provided.

The simulation results for the total reduction quantity of TN (total nitrogen) presented in table 4.10 is lower than that of table 4.8. But the results for SRP (soluble reactive phosphorous) is about the same. In this model, the total reduction rate for nitrogen and phosphorous is about 66% and 90%, respectively, in spite of the input load difference at the pumping station (figure 4.13).

Table 4.10 The total reduction of TN and SRP in the irrigated reed fields, based on Mander-&-Mauring's regression model

	Period	Input (mg/l)	Input (ton)	Canal reduction (ton)	Canal reduction (%)	Reed reduction (ton)	Reed reduction (%)	Total reduction (ton)	Total reduction (%)	Output (ton)
TN	March	12.417	2741.0	824.6	30.1	988.6	36.1	1813.2	66.2	927.8
	April-May	7.330	1627.4	550.0	33.8	532.0	32.7	1082.0	66.5	545.4
	June	3.224	542.7	242.5	44.7	122.6	22.6	365.2	67.3	177.5
	Total		4911.1	1617.1	32.9	1643.2	33.5	3260.3	66.3	1650.8
SRP	March	0.082	18.2	10.7	58.8	5.5	30.2	16.2	89.0	2.0
	April-May	0.137	30.3	16.5	54.5	10.2	33.7	26.7	88.1	3.6
	June	0.235	39.1	20.4	52.2	14.0	35.8	34.4	88.0	4.7
	Total		87.6	47.6	54.3	29.7	33.9	77.3	88.2	10.3

1) March: 10th-30th; April-May: Apr. 20th-May 10th; June: June 1st – 15th.

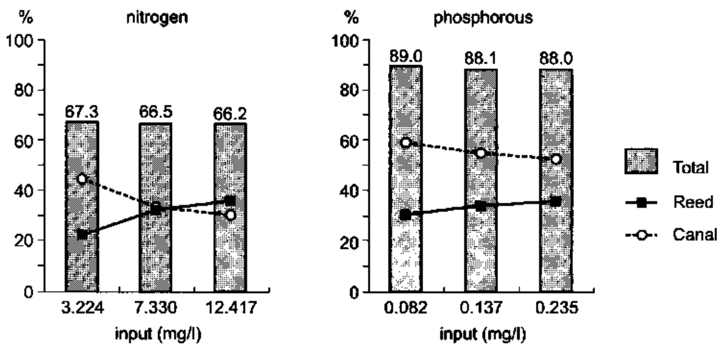

Figure 4.13 The relative nutrient reduction rate of the reed/canal system at different input concentration levels.

The nutrient reduction in the canal system and reed system compensates with each other very nicely, so that the total reduction rate does not change so much with the different input concentration at the pumping station (figure 4.13). When the input load at the pumping station is low, more part of the nutrients is removed by the canals, and vice versa. The total reduction rate decreases a little bit with the increase of input concentration value at the pumping station, though the absolute reduction quantity increases (Table 4.10, figure 4.13).

From table 4.10, we can also see that the output amount of nitrogen into the sea is still quite high. About 1/3 of the nitrogen input becomes output, while one-tenth of phosphorous input flows out. But this conclusion is made only based on the simulation results for the irrigation periods. The retention function still works after the irrigation period. Therefore the output load can be lower than the values presented.

4.4.2 Validation for Mander and Mauring's model.

The main problem associated with validating spatial process models is lack of appropriate spatial data (Heywood, et al., 1998). This is also the case in our model. The field data is measured as concentration values, while Mander-&-Mauring's model is based on load at $g/m^2.d$ or $mg/m^2.d$, which can be extremely low if the experimental data is converted into this unit. To make up this gap, what we can do is to make an indirect comparison between field data and the simulated data, so as to get an approximate idea on whether the model is valid or not.

To validate the new model based on Mander-&-Mauring's regression formula, measured concentration data in the reed field surface water and 80cm groundwater are used as input and output. But before putting into use, the concentration values (in mg/l) have to be converted into load values (in $g/m^2.d$). Unfortunately, the input water load is very low (about 10 mm/day), and the output water load is even lower. In the mean time, the input concentration value of nitrogen and phosphorous is not very high, compared to the constructed wetlands in other places documented (Cooper, 1996; Linden, 1990; Meuleman, 1999). Therefore the input and output load is sometimes too low to be presented here for model validation, especially for phosphorous. Table 4.11 shows the values from field data, and simulated data, and table 4.12 presents the correlation coefficiency between them.

Table 4.11 Comparison between field data and simulated data from different models ($g/m^2.d$)

	T N			S R P		
	Field	Li-model	Mander-model	Field	Li-model	Mander-model
Surface	0,082	0,086	0,094			
Outlet	EL[1)]	EL	0,042			
Surface	0,108	0,086	0,080	EL	EL	EL
Outlet	EL	EL	0,036	EL	EL	EL
Surface	0,023	0,016	0,020	EL	EL	EL
Outlet	EL	EL	0,013	EL	EL	EL
Surface	0,108	0,062	0,068	EL	EL	EL
Outlet	EL	EL	0,032	EL	EL	EL
Surface	0,033	0,017	0,019	0,001	0,001	0,001
Outlet	EL	EL	0,012	EL	EL	EL
Surface	0,016	0,030	0,035	0,001	0,001	0,001
Outlet	EL	EL	0,019	EL	EL	EL

1) EL: Extremely low. Theoretical value exists, but too low to be presented.

Table 4.12 Correlation coefficiency (n=12) between field and simulated data sets[1)]

		Li-model	Mander-model
TN	Field data	0.941	0.836
	Li-model	1.000	0.904
SRP	Field data	0.047	0.047
	Li-model	1.000	-

1) The significant value for R when n= 12 is 0.780 (Upper tail area Q=0.0005)

As far as total nitrogen is concerned, the R (correlation coefficient) value is quite high between field data and the results from my own simulation model (table 4.12). The R-value is also high enough between field data and the results from Mander-&-Mauring's model, though not as high as the former. Most of the value pairs presented in table 4.11 are close with each other. Although no close relationship for phosphorous has been found between the field data and the simulated data, the reason for it is that we do not have enough "high" values to calculate the correlation coefficiency. The values between the total reduction calculated from my model (table 4.8) and Mander-&-

Mauring's model (table 4.10) indicate that the R-value for phosphorous can be higher than that for nitrogen.

Compared to the field data based model, Mander-&-Mauring's model is less accurate, but the correlation coefficiency (R=0.836 for N) between field data and the simulation result is significant enough. Finally this literature based model is chosen for nutrient retention calculation, because it is more generic and does not require so many parameters like water output quantity and reed productivity, which are limitations of my own field data based model.

4.5 Model application

4.5.1 The preliminary nutrient budget for Nitrogen and Phosphorous

Limited by the data collected from the field, it is difficult to make an accurate yearly nutrient budget for the reed-bed system. But we can give an estimation on the empirical balance between the total input into the system in spring, and the total output from the system in winter.

According to the field data measured on the nutrient concentration in dried stems and leaves before harvesting, as well as the production of the reed (table 4.13), the total output from the system can be estimated (table 4.14). About 3,731 tons of nitrogen and 234 tons of phosphorous have been brought out from the system in 1998. Compared to the total input at the pumping station in spring, it seems that we have enough nitrogen, but far less enough phosphorous. However, if we take the reduction in the canal system and the output from reed bed outlet into consideration, the total nitrogen is also not enough for the system output. There must be some other nutrient sources for the system, such as soil, precipitation, summer flooding, and rhizome accumulation.

Table 4.13 Nutrient output with reed harvesting in winter in the Liaohe Delta[1)]

		Concentration (%)	Total Production (ton)	Nutrient Output (ton)
TN	Stem	0.415	5200	2158
	Leave	1.210	1300	1573
SRP	Stem	0.045	5200	234
	Leave	0.121	1300	157

1) Size of the whole reed area: c.a. 80,000 ha. Same in table 4.14.

Table 4.14 Global budget of nutrient elements in the reed system (ton)

	TN	SRP
Total input in spring (ton)	4911.1	87.6
Total output in winter (ton)	3731.0	391.3

It is difficult to make a total budget for the reed system according to the present field data. What we can conclude from tables 4.13 and 4.14 is that the present irrigation with wastewater from paper factories will not cause accumulation problems, as far as nitrogen and phosphorous are concerned.

4.5.2 Ten years' change of the nutrient reduction

Based on the nutrient reduction model, as well as the spatial data of 1988 and 1998, it is possible to estimate the 10 years change of nutrient reduction in the reed-canal system of Liaohe Delta (table 4.15).

The amount of nutrients removed by the system in 1998 is a little bit higher than that of 1988, provided that the input water and nutrient load at the pumping station is the same. This decrease is mainly caused by the change of reed area. But the change in each irrigation area differs from one to another. The reed shrinks in some of the area due to agricultural land conversion, and expands in another due to natural succession or artificial planting. The total length of the canals in each irrigation area also varies accordingly.

Table 4.15 Ten years change of the wetland reduction for nitrogen and phosphorous

	Period	Input		Reduction 1988		Reduction 1998	
		(mg/l)	(ton)	(ton)	(%)	(ton)	(%)
TN	Mar.10-30	12.417	2741.0	1801.4	65.7	1813.2	66.2
	Apr.20-May 10	7.330	1627.4	1069.7	65.7	1082.0	66.5
	June 1-15	3.224	542.7	353.0	65.0	365.2	67.3
	Total		4911.1	3224.1	65.6	3260.3	66.4
SRP	Mar.10-30	0.082	18.2	16.1	88.5	16.2	89.0
	Apr.20-May 10	0.137	30.3	26.6	87.8	28.2	93.1
	June 1-15	0.235	39.1	34.3	87.7	34.4	88.0
	Total		87.6	77.0	87.9	78.8	90.0

The compensation of area gain and loss among different irrigation areas can be the reason of not so much change in the total reduction quantity. But the change in individual irrigation areas can be very different, due to different area size, canal density and the combination pattern of reed and canals. This will be discussed further in the next chapter.

4.5.3 The maximum nutrient reduction capacity of the wetland system

Although no limit is found for the nutrient input load in the reed field, there is a limit for the reed field to accept water at different irrigation periods. According to the research done on reed irrigation in the Liaohe delta (Tian, 1982; Su, 1983), the optimum irrigation depths for the reed are 5, 10, 15 cm/day respectively for each of the 3 irrigation periods. If the highest measured nutrient concentration is used as input for all the 3 irrigation periods, and the water input load is kept at the optimum level, then the maximum nutrient removal capacity for the irrigation water can be calculated. The simulation results are given in table 4.16.

The maximum reduction quantity is about 29.2 kilo tons for total nitrogen and 716 tons for soluble reactive phosphorous, if the present reed area is preserved. This is a conservative estimation because the maximum input concentration used is the highest measured value in the study area, not the real maximum acceptable value. No such kind of maximum input concentration value has been found yet.

Table 4.16 The maximum nutrient removal capacity for the irrigation water in spring

	Period	Input nutrients (mg/l)	Input nutrients (ton)	Input water (cm)	Input water ($10^6 m^3$)	Reduction (ton)
TN	Mar.10-30	12.417	7763.88	5	625.3	5022.9
	Apr.20-May 10	12.417	15527.76	10	1250.5	12786.7
	June 1-15	12.417	17468.73	15	1406.8	11393.3
	Total		40760.37		3282.6	29202.8
SRP	Mar.10-30	0.235	146.94	5	625.3	128.6
	Apr.20-May 10	0.235	293.87	10	1250.5	275.5
	June 1-15	0.235	330.61	15	1406.8	312.2
	Total		771.42		3282.6	716.3

Compared to the potential total reduction capacity showed in table 4.16, the present reed and canal system has only used about 1/10 of its reduction capacity for nitrogen and phosphorous (table 4.10). Much more water and nutrients can be introduced into the reed/canal system without affecting the reed growth. Or, the system can be used at a smaller scale more effectively.

4.6 Discussion and conclusion

Two simulation models have been built for the nutrient reduction of Liaohe Delta. The main difference lies in the method of how to calculate the nutrient reduction in the reed system. My own field data based model is rather problematic when calculating the vertical reduction in the reed beds, though fits better with the measured data. Mander-&-Mauring's model is more general and flexible. Table 4.17 gives a comparison on the advantages and disadvantages of these two models. The literature-based model has more privileges than the totally field-data based model.

Table 4.17 Comparison of advantages and disadvantages of the two models

	Field-data based model	Mander-&-Mauring's model
Accuracy	More accurate compared to field data (+)	Less accurate compared to field data, but significant enough
Generality	More specific for the study area (-)	More general and can be applied to other areas (+)
Water data dependency	Water dependent, which may cause more problems (-)	Not depend on water data (+)
Output value dependency	The reduction is dependent on the calculation result of output from the reed field (-)	The reduction in the reed field is obtained directly (+)
Field data dependency	Totally dependent on field data (-)	Less dependent on field data once the needed parameters are settled (+)
Flexibility on input concentration	Flexible (+)	Flexible (+)

1) + advantages; - disadvantages

Concerning the modelling process as well as the simulation results from the model, some general conclusions can be made:

1. The spatial modelling is a combination of ecological process models and GIS analytical tools.

2. A non-linear simulation model is established for the nutrient reduction in the canals, while Mander-&-Mauring's regression model is adopted for the reed field, in compensation to the experimental data shortage in the study area.
3. The nutrient reduction in the canal system and reed system compensates with each other very nicely, so that the total reduction rate keeps relatively stable when the total input load at the pumping station changes. The reduction rate is 66% and 90% for nitrogen and phosphorous, respectively.
4. About 3,200-4,000 tons of N, and 80 tons of soluble reactive phosphorous can be removed by the present 80,000 ha reed-canal system during the irrigation period.
5. The total nutrient input at the pumping station each year is not enough to compensate the high output by reed harvesting in winter. No accumulation in the reed field is possible at present nutrient input level.
6. There is no big difference in the nutrient reduction between 1988 and 1998, because the total area of reed did not change so much, though local changes can be quite high.
7. The present reed/canal system can accept at least 10 times more nutrients without affecting the reed growth.

Therefore, there is a great potential to use the estuary wetland in the Liaohe Delta as the last barrier for nutrient enriched river water before it runs directly into the sea and causes eutrophication problems. At present this function of the area is not fully used yet. But, before putting into real use, careful planning must be made in combination with the knowledge of some other functions of the wetland, such as bio-production and habitat protection. The effect of each landscape components and their combination should also be studied in order to give better suggestions on a sustainable landscape planning for the delta. This issue will be discussed in Chapter 5.

5. The Effect of Spatial Pattern on Nutrient Reduction of the Wetland System

5.1 Introduction

Landscape pattern analysis has been an old topic of landscape ecology (Forman and Godron, 1986; De La Cruz, 1989; Gardner, et al., 1987; Turner, 1989). Many landscape indices have also been designed to describe the pattern, in order to get an overall idea of how the landscape is structured, and what is the effect of different patterns on large scale ecological processes (Baudry, 1984; O'Neill, et al., 1988; Gustafson and Parker, 1992; Schumaker, 1996; Dawson, 1997). So far this kind of studies have been mainly focused on the habitat analysis, or site selection of wild animals, in the scope of nature conservation (Pizzolotto and Brandmayr, 1996; McGarigal and McComb, 1994; Langevelde, 1999). But few pattern analysis has been done on the purification function yet, though some of the papers did touch this topic (Kesner and Meentemeyer, 1989; Pinay, et al., 1993; Poiani, et al., 1996).

Based on the nutrient reduction model developed in Chapter 4, this chapter will discuss how the reduction rate of the wetland is affected by the spatial pattern of landscape components, more specifically, the distribution of canals, reed fields and pumping stations. The results will contribute to a sustainable landscape planning in the Liaohe Delta.

Three factors are mainly concerned in the nutrient reduction model: 1) nutrient concentration at the pumping station; 2) area of the reed; and 3) distance of a point on the canal to the pumping station. In chapter 3 it is concluded that the input concentration does not have much effect on the total percentage of nutrients removed by the canal and reed system. But how the spatial arrangement of canal, reed area and pumping station affect the nutrient reduction function was not discussed. In general we expect that:

- If the number or total length of canals decreases, the amount of nutrients removed by canals will also decrease. As a result the total reduction rate should decrease.
- If the area of reed decreases, the nutrients removed by both canals and reed should decrease. Therefore the total amount of nutrients removed should decrease.
- Different reed distribution patterns should have different effects on the amount of nutrients that can be removed. But it is difficult to predict which pattern is better in its ability of nutrient removal.
- The positioning of pumping station should also affect nutrient reduction in the canal and reed system.

We will analyze whether these expectations are correct or not with different scenarios of reed, canal and pumping station combinations.

5.2 Methodology

To simplify the analysis procedure, some test maps with different spatial patterns are designed to simulate the nutrient reduction. Taking the irrigation area controlled by pumping station 11 as the case study area, we assume that:

- The input concentration at the pumping station is always 7.33 mg/l and 0.14 mg/l for total nitrogen (TN) and soluble reactive phosphorous (SRP), respectively.
- The pumping period is set as April 20^{th} - May 10^{th}, that is, the second irrigation period in the reed field of Liaohe Delta.
- The daily water and nutrients input load into the system remains stable during one irrigation period.

By changing one variable while keeping the others stable, four series of testing maps are generated: canal density, reed area size, reed area shrinking pattern and pumping station position.

Canal density
If the present area of reed is preserved, but the density of canals is changed into one of the following situation (figure 5.1):

a) No canal at all
b) Quarter of the present canal density (4.40 m/ha)
c) Half of the present density (8.68 m/ha)
d) Present density (17.34 m/ha)
e) Double the present density (34.67 m/ha)

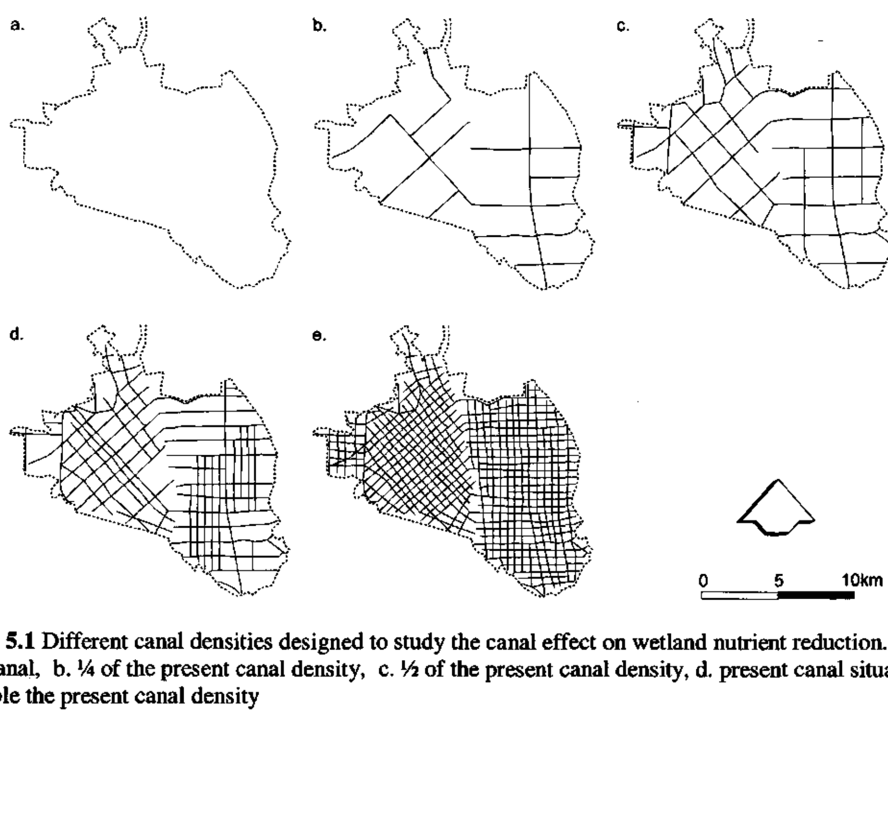

Figure 5.1 Different canal densities designed to study the canal effect on wetland nutrient reduction.
a. no canal, b. ¼ of the present canal density, c. ½ of the present canal density, d. present canal situation, e. double the present canal density

In figure 5.1 b, c and e, the canals are deleted or added until the canal density reaches the desired value. Maybe the distribution pattern of the "designed canals" is somewhat arbitrary, but the simulation results should provide enough information to indicate the overall trend. This is also the case in the following scenarios.

Reed area size

If the canals are kept as present, but the area of reed shrinks into one of the following (figure 5.2):

a) ¼ of the present area (4,250 ha)
b) ½ of the present area (8,500 ha)
c) ¾ of the present area (12,750 ha)
d) The present area (17,000 ha)

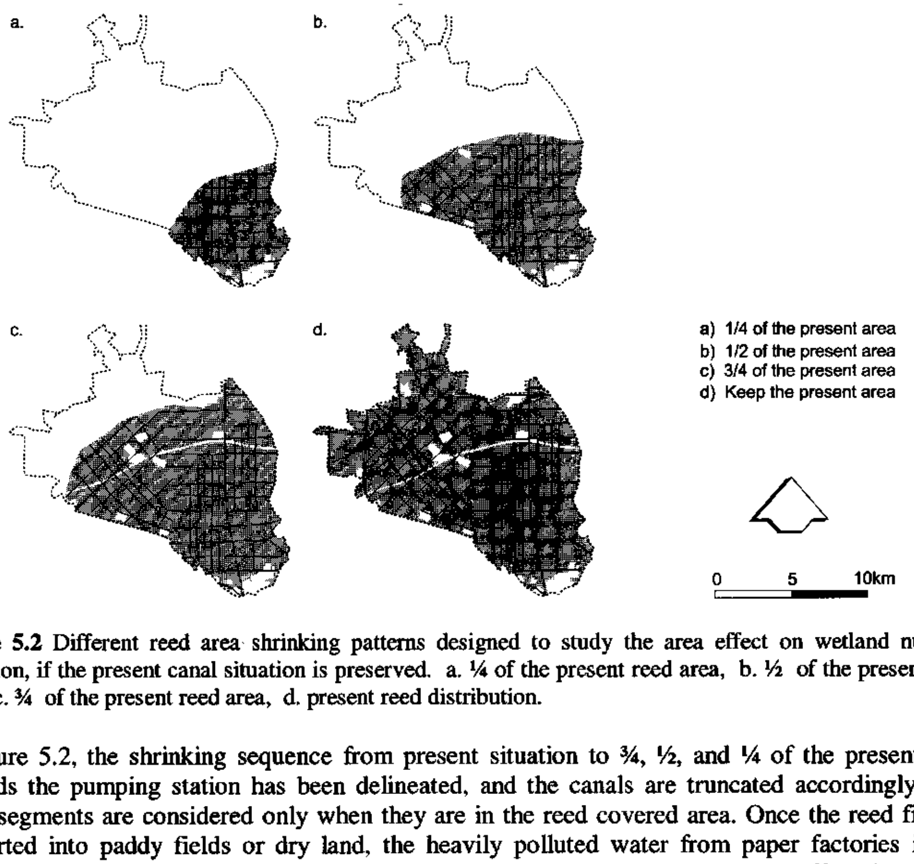

Figure 5.2 Different reed area shrinking patterns designed to study the area effect on wetland nutrient reduction, if the present canal situation is preserved. a. ¼ of the present reed area, b. ½ of the present reed area, c. ¾ of the present reed area, d. present reed distribution.

In figure 5.2, the shrinking sequence from present situation to ¾, ½, and ¼ of the present area towards the pumping station has been delineated, and the canals are truncated accordingly. The canal segments are considered only when they are in the reed covered area. Once the reed field is converted into paddy fields or dry land, the heavily polluted water from paper factories is not allowed to be used any more, because it contains some other pollutants which may affect the quality of crop products.

For the scenario of area shrinking, two alternatives of simulation can be made:

- Keep the total water input load at the pumping station as present, and intensify the water input load per unit area when the total reed area becomes smaller.
- Keep the present water input load per unit area stable, and decrease the total water input load at the pumping station when reed area decreases.

Reed area shrinking pattern

If the area of the reed decreases to half of the present situation, and the canals are kept as present, but the distribution pattern of reed becomes one of the following (figure 5.3):

a) Shrinkage
b) Perforation
c) Fragmentation
d) Bisection

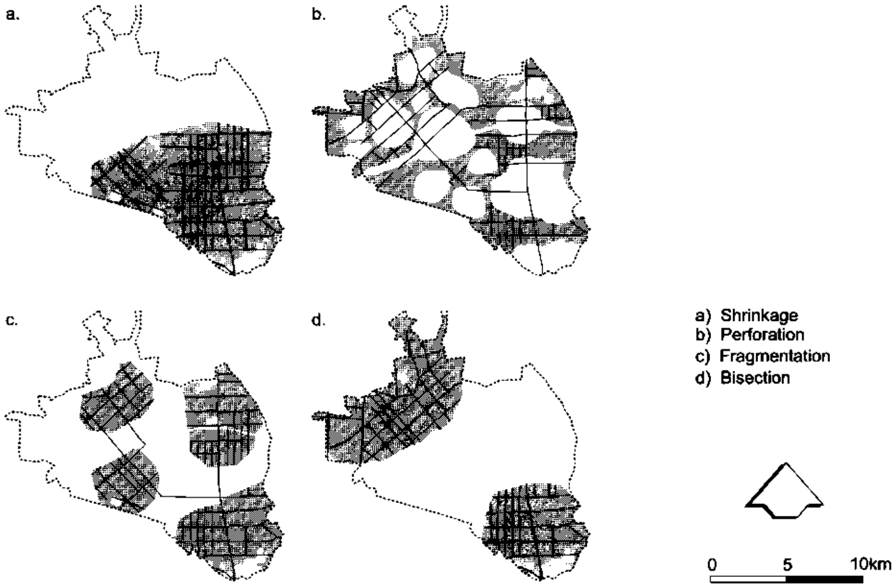

Figure 5.3 Different reed decrease patterns if the area is reduced to half of the present situation.
a. Shrinkage, b. Perforation, c. Fragmentation, d. Bisection

The cases in this scenario is based on Collinge and Forman (1997), who proposed the four land conversion possibilities that vary in their spatial configuration: shrinkage, bisection, fragmentation, and perforation. In the Liaohe Delta, the different patterns of canals and reed are caused by the land conversion from reed marsh to agricultural or other use. The change of the patterns should be based on the logical rule of local land conversion. In reality, "shrinkage" and "fragmentation" are more likely to happen within one irrigation area than "bisection" and "perforation". However, as a theoretical research, the latter two cases will also be taken into consideration.

The four decrease patterns showed in figure 5.3 are delineated according to Collinge and Forman (1997), although the position of different reed and non-reed areas is arbitrarily assigned. As in the reed area shrinking scenario, only those canals that contribute to the irrigation of reed are reserved.

Pumping station position:

Keep the present reed area and canal distribution, and rearrange the position of the pumping station. Water and nutrients input load also remains at present level (Figure 5.4).

The location of pumping stations in figure 5.4 is somewhat arbitrarily chosen. Figure 5.4a represents the present situation with the pumping station sitting on the border of the irrigation area.

Figure 5.4d is similar to 5.4a, with the pumping station sitting on the other end of the irrigation area. The stations are located somewhere inside the irrigation area in figures 5.4b, c and e.

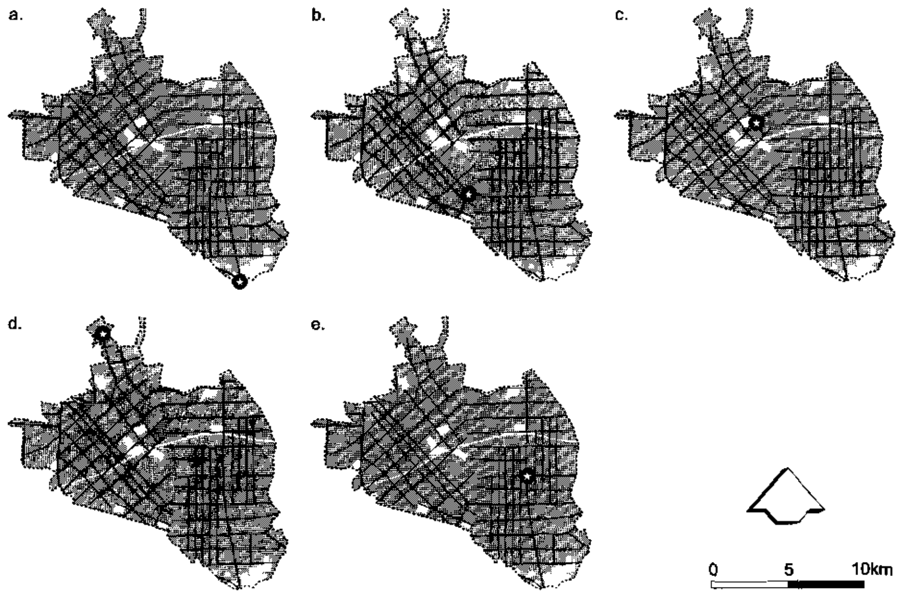

Figure 5.4 Different pumping station positions in relation to the reed and canal distribution, in which, a and d are near the border, and b, c, and e are near the center.

All the test maps in each scenario are prepared in the Arcedit module of Arc/Info. The main part of the model is run in the Grid module of Arc/Info, with AML programs designed in Chapter 4.

5.3 Results

5.3.1 The effect of canal density

Tables 5.1, 5.2 and figure 5.5 provide the different simulation results for different canal densities (figure 5.1) and nutrient elements.

Table 5.1 Total nitrogen (TN) reduction at different canal density

	Canal density	Total input	Canal reduction		Reed reduction		Total reduction	
Case	(m/ha)	(ton)	(ton)	(%)	(ton)	(%)	(ton)	(%)
No canal	0	266.0	0	0.0	138.10	51.9	138.1	51.9
¼ present	4.40	266.0	64.24	24.2	81.05	30.5	145.3	54.6
½ present	8.68	266.0	70.87	26.6	83.30	31.3	154.2	58.0
Present	17.34	266.0	73.08	27.5	83.32	31.3	156.4	58.8
Double	34.67	266.0	75.62	28.4	83.60	31.4	159.2	59.8

1) Input concentration at pumping station: 7.33 mg/l.

2) Correlation coefficiency between canal density and total percent removed: R=0.840 (n=5).

Table 5.2 Soluble reactive phosphorous (SRP) reduction at different canal density

Case	Canal density (m/ha)	Total input (ton)	Canal reduction (ton)	Canal reduction (%)	Reed reduction (ton)	Reed reduction (%)	Total reduction (ton)	Total reduction (%)
No canal	0	4.95	0.0	0.0	3.99	80.6	3.99	80.6
¼ present	4.40	4.95	2.55	51.5	1.52	30.7	4.07	82.2
½ present	8.68	4.95	2.71	54.8	1.55	31.3	4.26	86.1
Present	17.34	4.95	2.72	54.9	1.55	31.4	4.27	86.3
Double	34.67	4.95	2.74	55.4	1.57	31.7	4.31	87.1

1) Input concentration at pumping station: 0.14 mg/l.
2) Correlation coefficiency between canal density and total percent removed: R = 0.811 (n=5).

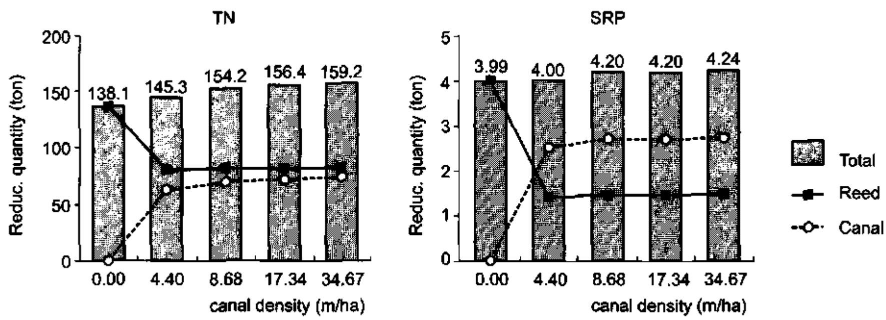

Figure 5.5 The reduction capacity for total nitrogen and phosphorous at different canal density in the reed marsh. Reed area, input water, and N&P input concentration are constant.

From table 5.1, 5.2 and figure 5.5, some general conclusions concerning the canal density scenario can be made:

1. Generally speaking, the increase of canal density does not help much for the total nutrient reduction. Less than 4% more total N or P is reduced by doubling the canal density. Even the highest difference between no canal and double the present canal density is less than 10%. Therefore it is not a good idea to increase the canal density to improve the system efficiency in nutrients reduction.
2. With the increase of canal density, both canal and reed systems show an increase in the nutrient reduction capacity, resulting in the increase of total reduction. The exception is in the situation of no canal, where the reduction by reed is very high. Therefore, in case of canal shortage, the nutrients will be removed by reed system as compensation.
3. With the increase of canal density, the increase extent of nutrient reduction in the canal system is a little bit higher than that of the reed system. This is reasonable because more canals are put into use for water transportation.
4. A higher percentage of phosphorous is removed by the canals than by the reeds, while for nitrogen it is another way around, or about half in half. The whole system is more efficient for P than for N, as discussed also in Chapter 4.
5. If the "no canal" situation is not considered, the amount of N removed by canals has a closer relationship (R=0.860, n=4) with the canal density than P (R=0.678, n=4). On the other hand, the amount of P removed by the reed is more closely related to the canal density (R=0.860, n=4) than N (R= 0.677, n=4).
6. The relationship between total reduction rate and canal density is a little bit higher for N (R= 0.840, n=5) than for P (R=0.811, n=5).

Although the results agree with the expectation that more canal, more reduction, the increase of total reduction quantity seems not so obvious compared to the magnitude of canal density increase.

5.3.2 The effect of different reed area size when total input stable

Tables 5.3, 5.4 and figure 5.6 present the simulation results for the reed area size scenario (figure 5.2) in TN (total nitrogen) and SRP (soluble reactive phosphorous) reduction, provided that the total water input load at the pumping station is kept as present, and the input load per unit area is intensified when the area shrinks.

Table 5.3 Total nitrogen (TN) reduction at different reed area when total water input load at the pumping station is kept at present level.

Case	Reed area (ha)	Total input (ton)	Canal reduction (ton)	Canal reduction (%)	Reed reduction (ton)	Reed reduction (%)	Total reduction (ton)	Total reduction (%)
¼ present	4250	266.0	76.3	28.7	104.4	39.2	180.7	67.9
½ present	8500	266.0	74.4	28.0	96.6	36.3	171.0	64.3
¾ present	12750	266.0	73.2	27.5	89.8	33.8	163.0	61.3
Present	17000	266.0	73.1	27.5	83.3	31.3	156.4	58.8

1) Input concentration at pumping station: 7.33 mg/l.
2) Correlation coefficiency between reed area and total percent removed: R= - 0.997 (n=4).

Table 5.4 Soluble reactive phosphorous (SRP) reduction at different reed area when total input water load at the pumping station is kept at present level.

Case	Reed area (ha)	Total input (ton)	Canal reduction (ton)	Canal reduction (%)	Reed reduction (ton)	Reed reduction (%)	Total reduction (ton)	Total reduction (%)
¼ present	4250	4.95	2.458	49.7	1.955	39.5	4.413	89.2
½ present	8500	4.95	2.575	52.0	1.774	35.8	4.349	87.9
¾ present	12750	4.95	2.650	53.5	1.656	33.5	4.306	87.0
Present	17000	4.95	2.717	54.9	1.553	31.4	4.270	86.3

1) Input concentration at pumping station: 0.14 mg/l.
2) Correlation coefficiency between reed area and total percent removed: R = - 0.990 (n=4).

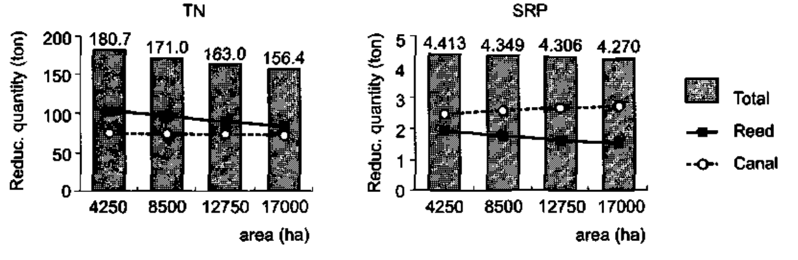

Figure 5.6 The reduction of total nitrogen and phosphorous at different reed areas. Present canals are preserved. Input water, N&P concentration are constant.

From tables 5.3, 5.4 and figure 5.6, some conclusions can be made concerning the effect of different area sizes. If the total water and nutrients input keeps the present level at the pumping station, then:

1. With the decrease of reed area, the total reduction quantity for TN and SRP has both increased, if the area shrinks steadily towards the pumping station. This is contradictory to what we had expected. We will come back to this point later on in the discussion part of the chapter.
2. With the decrease of reed area, the total canal length decreases as well. But the canal reduction quantity for N and P changes differently. For N, it increases, while for P, it decreases.
3. The percentage of P removed by canal is always higher than that by reed. For Nitrogen, it is opposite, as stated before.
4. As for the relationship between the reed area and the amount of nutrients removed by canals, there is a much closer relationship for P (R= 0.991, n=4) than for N (R= -0.938, n=4).
5. Both N and P removed by the reed system are closely related to the area, though negatively (R_N = -0.999, R_P= - 0.991, n=4). That is, the smaller the area, the more N and P are removed by the reed system.
6. The total reduction for N (R= -0.996, n=4) is a little bit more closely related to the reed area than for P (R= - 0.991, n=4).

The simulation results prove to be contrary to our prediction that smaller area will reduce the nutrient removal ability. The reason for this has to be discovered from the way we calculate the reduction for nitrogen and phosphorous. More detailed discussion on this will be provided in the next part of this chapter.

5.3.3 The effect of different reed area size when total input reduce

Tables 5.5, 5.6 and figures 5.7, 5.8 present the simulation results for different reed area sizes (figure 5.2) for nitrogen and phosphorous, provided that the total input of water at the pumping station decreases with the reed area. Therefore the input load per unit area can be kept at the present level. This is more reasonable because the reed field has limited ability to accept the amount of water input into the system, even if there is no limitation for the quantity of nutrient input.

Table 5.5 Total nitrogen (TN) reduction at different reed area, input load per unit area is kept as present.

Case	Reed area (ha)	Total input (ton)	Canal reduction (ton)	Canal reduction (%)	Reed reduction (ton)	Reed reduction (%)	Total reduction (ton)	Total reduction (%)
¼ present	4250	66.5	19.12	28.8	22.93	34.5	42.05	63.2
½ present	8500	133.0	37.25	28.0	44.04	33.1	81.29	61.1
¾ present	12750	199.5	54.96	27.5	64.14	32.2	119.10	59.7
Present	17000	266.0	73.08	27.5	83.32	31.3	156.40	58.8

1) Input concentration at pumping station: 7.33 mg/l.
2) Correlation coefficiency between reed area and total percent removed: R= -0.983 (n=4).

Table 5.6 Soluble reactive phosphorous (SRP) reduction at different reed area, input load per unit area is kept as present.

Case	Reed area (ha)	Total input (ton)	Canal reduction (ton)	Canal reduction (%)	Reed reduction (ton)	Reed reduction (%)	Total reduction (ton)	Total reduction (%)
¼ present	4250	1.24	0.62	50.0	0.48	38.7	1.10	88.7
½ present	8500	2.48	1.29	52.0	0.88	35.3	2.17	87.5
¾ present	12750	3.71	1.98	53.4	1.23	33.2	3.22	86.8
Present	17000	4.95	2.72	54.9	1.55	31.4	4.27	86.3

1) Input concentration at pumping station: 0.14 mg/l.
2) Correlation coefficiency between reed area and total percent removed: R = -0.980 (n=4).

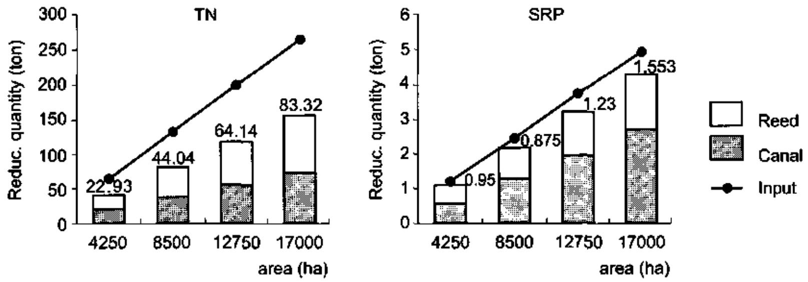

Figure 5.7 The reduction quantity for total nitrogen and phosphorous at different reed area size. Present canals and input load level per unit area are preserved.

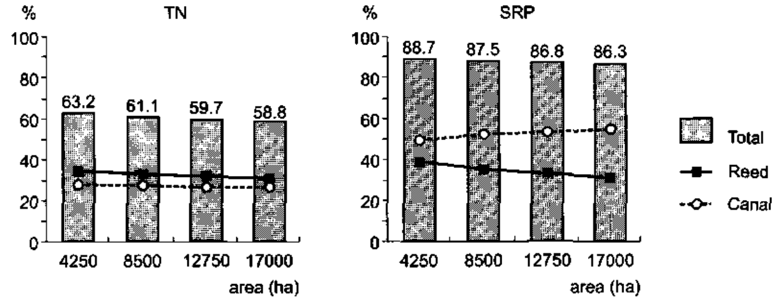

Figure 5.8 The percentage of nutrients removed by the reed-canal system, when total water input at the pumping station decreases with reed area.

According to tables 5.5, 5.6 and figures 5.7, 5.8, if the water and nutrient input load at the pumping station decreases with reed area, so as to keep the present input load per unit area, then:

1. With the shrinking of reed area, the total amount of N and P removed by the system decreases quickly. This can be understood because the total input at the pumping station decreases proportionally with the reed area. It also agrees with the predictions at the beginning of this chapter.
2. Concerning the absolute quantity removed, both the canal and reed systems show a decrease in nutrient reduction, as a result of decreased total input, canal length, and reed area.
3. Concerning the percentage removed, smaller areas are more efficient than larger areas in nutrient removal (figure 5.8). This is concordant with the results obtained when keeping the total input load at the pumping station stable.
4. The percentage of N removed by the canal and reed has both increased with the shrinking of reed area, resulting in an increase of total reduction rate.
5. The percentage of P removed by the canal decreases as the reed area shrinks, while the percentage of P removed by reed increases. After compensating with each other, the total percentage removed increases a little bit with the shrinking of reed area.
6. The total nutrient reduction rate is closely related to the area size of the reed (R_N = -0.983, R_P=-0.980, n=4), negatively. But the total reduction rate difference between the present situation and 1/4 of the present is only about 5% for N and 2.5% for P.

This group of simulation results based on stable input load per unit area agree well with the expectation that the smaller the reed area, the lower the nutrient removal. But there is still a big potential for the reed area to remove more nutrients because the input load per unit area can be higher.

5.3.4 The effect of different reed shrinking patterns

Tables 5.7, 5.8 and figure 5.9 provide the simulation results based on different reed decreasing patterns, namely, shrinkage, perforation, fragmentation and bisection (figure 5.3) (Collinge and Forman, 1997). The sizes of reed covered area are all half of the present situation, and the input load per unit area is also kept at the present situation. It is also possible for us to keep the total input load at the pumping station at present level, but the trend of simulation results should be the same. Therefore, we just provide one calculation scenario for analysis.

Table 5.7 Total nitrogen (TN) reduction at different reed area shrinking patterns

	Reed area	Total input	Canal reduction		Reed reduction		Total reduction	
	(ha)	(ton)	(ton)	(%)	(ton)	(%)	(ton)	(%)
Shrinkage	8500	133.0	37.25	28.0	44.04	33.1	81.29	61.1
Perforation	8500	133.0	36.99	27.8	41.28	31.0	78.27	58.8
Fragmentation	8500	133.0	34.87	26.2	42.76	32.2	77.63	58.4
Bisection	8500	133.0	33.54	25.2	40.94	30.8	74.48	56.0

1) Input concentration at pumping station: 7.33 mg/l.
2) Input load per unit area is kept at present level, and reed area is half of the present situation.

Table 5.8 Soluble reactive phosphorous (SRP) reduction at different reed area shrinking patterns

	Reed area	Total input	Canal reduction		Reed reduction		Total reduction	
	(ha)	(ton)	(ton)	(%)	(ton)	(%)	(ton)	(%)
Shrinkage	8500	2.48	1.29	52.0	0.88	35.3	2.17	87.5
Perforation	8500	2.48	1.38	55.6	0.76	30.6	2.14	86.3
Fragmentation	8500	2.48	1.31	52.8	0.82	33.1	2.13	85.9
Bisection	8500	2.48	1.32	53.2	0.77	31.0	2.09	84.3

1) Input concentration at pumping station: 0.14 mg/l.
2) Input load per unit area is kept at present level, and reed area is half of the present situation.

Figure 5.9 The nutrients reduction for the reed and canal system in different land transformation patterns.

According to tables 5.7, 5.8 and figure 5.9, if the reed area decreases to half of the present area at different patterns, while the water input load per unit area is kept at the present situation, it can be concluded that:

1. In terms of total nutrient reduction, the sequence for different reed distribution pattern is:

shrinkage > perforation > fragmentation > bisection

Therefore, the shrinkage pattern of land transformation is most recommended than other patterns, while bisection is least recommended, if we want to keep a high nutrient reduction rate in the reed field.

2. Comparing the situation of perforation and fragmentation, nutrients removed by the canals in the perforation case are higher than in the fragmentation case. On the other hand, nutrients removed by the reed in the fragmentation case are higher than the perforation case. For the sake of reed growth and harvesting, fragmentation is "better" than perforation pattern. The total reduction of these two cases does not differentiate very much. The spatial allocation of reed and non-reed areas can affect the canal distribution a lot, as well as the simulation results. None of these land transformation patterns is recommended, if we take other factors such as management and bio-conservation into consideration.
3. In the case of shrinkage, the reduction in the reed field is the highest. This is an optimistic result because the irrigation aims to bring more nutrients into the reed field as fertilizers.
4. Concerning the percentage of nutrients removed, the maximum difference between individual patterns is about 5% for nitrogen, and 3% for phosphorous. Therefore the effect of reed area distribution pattern is about the same level as other pattern scenarios.

According to the land reclamation projects in the Liaohe delta, the shrinkage and fragmentation patterns are more likely to happen. The former is more suitable as far as nutrient reduction and management factors are concerned.

5.3.5 The effect of different pumping station position

Tables 5.9, 5.10 and figure 5.10 present the simulation results for different pumping station positions (figure 5.4) and nutrient elements.

Table 5.9 Total nitrogen reduction at different pumping station location cases

	Canal density	Total input	Canal reduction		Reed reduction		Total reduction	
Pumping station	(m/ha)	(ton)	(Ton)	(%)	(ton)	(%)	(ton)	(%)
Present position (a)	17.34	266.0	73.08	27.5	83.32	31.3	156.4	58.8
Position (b)	17.34	266.0	59.23	22.3	89.98	33.8	149.2	56.1
Position (c)	17.34	266.0	60.13	22.6	89.52	33.7	149.7	56.3
Position (d)	17.34	266.0	73.24	27.5	83.76	31.5	157.6	59.2
Position (e)	17.34	266.0	60.85	22.9	89.64	33.7	150.5	56.6

1) Input concentration at pumping station: 7.33 mg/l.

Table 5.10 Soluble reactive phosphorous reduction at different pumping station location cases

	Canal density	Total input	Canal reduction		Reed reduction		Total reduction	
Pumping station	(m/ha)	(ton)	(Ton)	(%)	(ton)	(%)	(ton)	(%)
Present position (a)	17.34	4.95	2.72	54.9	1.55	31.4	4.27	86.3
Position (b)	17.34	4.95	2.30	46.5	1.83	37.0	4.13	83.4
Position (c)	17.34	4.95	2.33	47.1	1.81	36.6	4.14	83.6
Position (d)	17.34	4.95	2.72	54.9	1.57	31.7	4.29	86.7
Position (e)	17.34	4.95	2.36	47.7	1.85	37.4	4.21	85.1

1) Input concentration at pumping station: 0.14 mg/l.

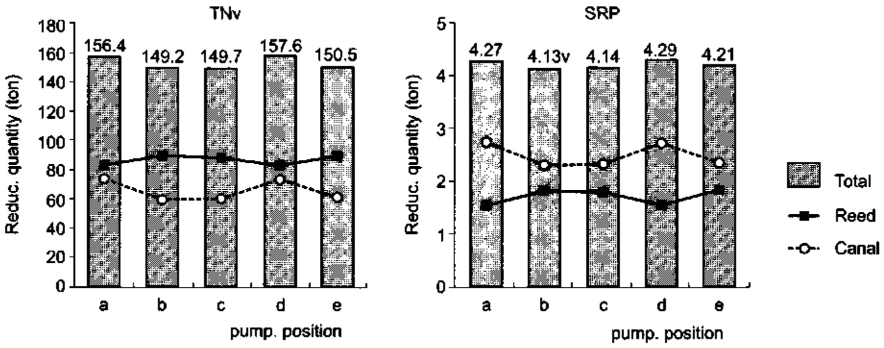

Figure 5.10 The nutrient reduction for the reed and canal system in different pumping station positions.

From tables 5.9, 5.10 and figure 5.10, it can be concluded that:

1. The positioning of pumping station does have a strong effect on the nutrient reduction of both canal and reed systems. But, due to the compensation effect between the reed and canal system, the total reduction does not change so much. Generally speaking, the total reduction rate is higher when the pumping station is far from the spatial center of the system (a, d).
2. When the pumping station is farther away from the spatial center of reed area, the canal reduction for nitrogen and phosphorous is higher (a, d). On the contrary, the reed reduction capacity becomes higher when the pumping station comes closer to the system center (b, c, and e).
3. It remains the same that the reed system removes more N than the canal system in all situations, while the canal system removes more P than the reed system.
4. Concerning the total percentage of nutrients removed, the effect of pumping station position change is not very big. The dynamic range is less than 4% for both nitrogen and phosphorous, about the same level as the effect of changing canal density or reed area distribution pattern.

This series of simulation result has proved the expectation that the position of pumping station has an effect on the nutrient reduction. But the magnitude and trend of the effect obtained from the study is beyond the expectation.

5.4 Discussion

The simulation results for different canal and reed area scenarios seem not so close with what we have predicted at the beginning of this chapter. We do not deny that the test maps generated have too many "artificial factors", and the model has a lot of assumptions in it, too. The reality is far more complicated than the examples presented here. But we still have reasons to trust the trend that the simulation results have demonstrated, because the model has incorporated the most important factors (area, distance, input load, etc.), and regulated the uncertain factors, such as denitrification, sedimentation, plant up-taking, time, temperature and so on, with linear (reed system) and non-linear (canal system) regression models. By checking into the model process, we may find reasons why some of the simulation results are "contradictory" to our prediction. Sometimes the prediction can also be erroneous because it is not based on experiment.

According to the algorithms used to calculate the nutrient reduction in the reed system (Chapter 4):

Nitrogen:

$$Y = -0.005 + 0.61X \qquad (R^2 = 0.84, n = 41)$$

Phosphorous:

$$Y = -0.013 + 0.85X \qquad (R^2 = 0.98, n = 35)$$

where Y is retention and X is load, both in $g/m^2.d$ for N and $mg/m^2.d$ for P. There is no limitation for increasing capacity of retention as load increases (Mander and Mauring, 1994).

The input load here is decided by the daily water load (in m^3), area of reed, and N&P concentration (mg/l) at the source point:

Nutrient Load = daily water load * nutrient concentration / reed area

If the input quantity of water and concentration of N&P at the pumping station are constant, with the decrease of reed area, the quantity of water assigned into each unit of land increases, and the nutrient input load per unit area also increases. The formulas above indicate a positive relationship between load and reduction capacity. The higher the input load (in $g/m^2.d$ or $mg/m^2.d$) is, the more nutrient is removed in each unit area. The total reduction is calculated as the sum of each unit area. If the nutrient reduction rate in each unit area is increased, it is understandable that the total nutrient reduction also increases.

This can also help to answer why the total reduction capacity did not change so much if the present area is kept, but the canal density changes only. In the nutrient reduction model, the canals are taken as a line feature, where width is not taken into consideration. Therefore the increase of canal density does not affect the area of reed. In reality it is also true because the reed grows on the bank and slope of the canals. The area not occupied by reed is rather limited along the canals. Because the nutrient concentration is linearly related to the logarithm of the distance of this point to the pumping station, not the total length of the canals, the effect of canal density on the nutrient concentration of a canal point is very small. As a result, the quantity of water and nutrients assigned into each unit area of reed does not change much, and so is the total reduction quantity, if only the canal density has changed.

But why the amount of N and P removed by canals and reed fields are differently related to the canal density and reed area? This is mainly caused by the different relationship between the input concentration and the distance of a canal point to the pumping station, as well as the different reduction rate of reed field for N and P. In reality there are more complicating factors affecting the system.

If the input water load at the pumping station decreases proportionally with the reed area, the absolute reduction quantity of the canals and reeds also decrease proportionally. In other words, smaller area, smaller reduction. This is more understandable than the simulation results based on constant input load at the pumping station. But in terms of relative reduction, represented as "percentage removed", the value of smaller area is still higher than that of the larger areas. The reason is that, the nutrient concentration value of a canal point has a logarithmic relation with its distance to the pumping station (formula 4.1). The input load into the reed fields from the canal is much higher when the reed is close to the pumping station. Higher daily input load per unit area results in higher nutrient reduction rate. Therefore it is more efficient when the reed area is closer to the pumping station.

The above conclusion also indicates that all other patterns of reed distribution are less efficient than the aggregated pattern in terms of nutrient reduction function. For shrinkage and bisection cases, the canals and reed are more or less aggregated together, therefore the small migration of reed area does not affect too much of the simulation result. But in the cases of fragmentation and perforation, the distribution of reed and non-reed areas may affect the simulation results a lot. The canals scattered farther away from the pumping station have lower nutrient concentration value, and the input load into the reed field is also lower. If the area is the same, but the distribution pattern of fragmented parts differs, the total reduction quantity can be different. Therefore, the simulation results for fragmentation and perforation patterns are less reliable. But the trend in relation to the other two cases is acceptable.

The positioning of pumping station has a stronger effect on the nutrient reduction of canal and reed systems respectively than on the total reduction. This can be understood because when the pumping station is closer to the spatial center of the reed-canal system, the water needs to travel shorter distance to reach the most remote points. Therefore the reduction quantity in the canal system is lower in this case (tables 5.9, 5.10 and figure 5.10). On the other hand, the area of reed with a higher nutrient input load in the vicinity of pumping station is much larger when the pumping station is inside the system than when it is near the border of the system. Thus the reed system can remove more nutrients when the pumping station is closer to its spatial center.

Theoretically, we can improve the nutrient reduction by reducing the reed area, and intensify the input load of nutrients. Although there is no limitation for the input load of nitrogen and phosphorous, the reed field has a limit for the water load. If too much water is pumped into the reed field and lasts too long, especially in spring, the quality of reed will not be good (Chapter 3).

According to the research done on reed irrigation in the Liaohe delta (Tian, 1982; Su, 1983), the optimum irrigation depths for the reed are 5, 10, 15 cm/day respectively for each of the 3 irrigation periods. Taking 5 cm/day as the maximum acceptable water load, the smallest reed area that can be used to purify the quantity of water (1,814,400 m^3/day) pumped by station No. 11 is 3,628.8 ha, about 21.3% of the present situation. The size of the reed area to be reserved for different irrigation area depends on the capacity of each pumping station. The higher the pumping capacity is, the larger the reed area has to be kept.

On the other hand, with the present area of reed reserved, we can remove more nitrogen and phosphorous by irrigating more water into the reed field. Based upon the above conclusion, at least 4 times more of the present nutrients can be removed by increasing the water load in the reed field. Then the water availability becomes a limiting factor because there is not so much water in the nearby rivers in spring.

This result also gives us a good clue to solve the problem caused by prawn-crab breeding ponds along the coastline. Although the nutrient reduction function of *Suaeda* community will be different from that of the reed, we can simply assume that it is lower than that of the reed field. By designating a small piece of land for the treatment of exchanged water from each breeding pond, the total amount of N and P input into the sea will be greatly reduced.

5.5 Conclusion

The analysis on the simulation results according to different canal, reed area and pumping station distributions provides us some general conclusions on the effect of pattern on nutrient reduction function. Table 5.11 summarizes the result of different simulation scenarios.

Although the dynamic range of reduction rate within one scenario is less than 10%, the difference among different scenarios is obvious (table 5.11). The reduction rate is relatively high in the reed area size scenario. Low reduction rate occurs when all the canals are removed from the system. The deviation ranges for the reduction rate of nitrogen is always larger than that for phosphorous.

Table 5.11 Comparison of the simulation results for different pattern scenarios

Scenario	Arrangement of spatial components	Reduction (%)		Effect on nutrient reduction
		TN	SRP	
Canal density	0, ¼, ½, 1, and 2 times of the present canal density	51.9~59.8	80.6~87.1	More canals, more reduction
Reed area size (1)	¼, ½, ¾ and 1 times of the present reed area size	58.8~67.9	86.3~89.2	Smaller area is more efficient
Reed area size (2)	(Same as above)	58.8~63.2	86.3~88.7	(Same as above)
Reed shrinking pattern	Shrinkage, perforation, fragmentation and bisection	56.0~61.1	84.3~87.5	Shrinkage pattern has the highest efficiency
Pumping station position	Near border (2 cases) and near center (3 cases)	56.1~59.2	83.4~86.7	More efficient when it is near the border

1) Reed area size (1): total input water and nutrient at the pumping station is kept as present
2) Reed area size (2): Input water and nutrient load per unit area is kept as present.

Regarding to the nutrient reduction of each pattern scenario, the following conclusions can be made:

1. The effect of canal density on the nutrient reduction of the reed is rather small. Only less than 4% more TN (total nitrogen) or SRP (soluble reactive phosphorous) can be removed by doubling the canal density.
2. The size of reed area has a much stronger effect on nutrient removal in the canals and reed fields respectively. Generally speaking, smaller reed area close to the pumping station is more efficient in nutrient reduction than larger, scattered areas.
3. If we keep the total input load at the pumping station as present, with the decrease of reed area, the input nutrient load per unit area increases, and the total reduction rate also increases. Therefore we can improve the reduction by reducing the reed area and intensifying the water input load.
4. If we decrease the total water input at the pumping station when the reed area is decreased, then the total nutrient reduction will also drop fast, almost proportionally with the decrease of the reed area. But the relative reduction rate is still higher in smaller areas.
5. The sequence for the nutrient reduction of different reed distribution patterns is: Shrinkage > Perforation > Fragmentation > Bisection. The shrinkage pattern of land transformation for the reed is most efficient if we want to keep a high nutrient reduction rate in the mean time.

In general, the main limitation factor for the nutrient reduction in the reed-canal system is water, not nutrients load or the arrangement of the spatial components, though these factors do have effects on it. The present reed area can accept 4 times more water in spring. There are many more direct and indirect factors influencing the nutrient reduction, such as the dynamics of water availability, biodiversity conservation, new management measures and so on. More factors should be taken into account in a sustainable landscape planning.

The conclusions drawn from this study provide valuable basis for the planners regarding to the purification function of the wetland system. Further more, the simulation results on different scenarios can also contribute to the theory of landscape ecology in the analysis of relationship between pattern and function. The next chapter will focus more on this relationship, with the help of some landscape indices.

6. Relationship between Landscape Structure and Nutrient Reduction

6.1 Introduction

The spatial simulation model and scenario analysis in the former chapters provide an interesting background to further study the relationship between landscape pattern and function. It is also a good chance to testify some of the theoretical dogmas in landscape ecology. One of the most important methodologies in landscape ecology is to quantify the structure of land mosaics with some mathematical indices (Turner and Gardner, 1991; Forman, 1995). Some of the indices do help to capture important aspects of landscape pattern in a few numbers (O'Neill, et al., 1988). But there have been not so many cases to clarify the meaning of these indices in interpreting ecological processes (Collinge and Forman, 1998).

At present, a large amount of landscape indices have been defined or proposed by landscape ecologists (Pielou, 1975; Forman and Godron, 1986; O'Neil, et al., 1988; Baker and Cai, 1992; Gustafson and Parker, 1992). Many of the existed landscape indices have been implemented into the software package "FRAGSTATS" (McGarigal and Marks, 1995). But what is more important is the ecological meaning of these indices, or to which extent can the indices reflect the reality. Most of the indices are based on statistical analysis over the spatial attributes of landscape units, namely, area, perimeter and length. According to Giles and Trani (1999), only 6 factors are considered to be important in describing a mapped area, which are: the area, the classes, proportion of dominant class, number of polygons, polygon size variance, and elevation range. Even these six factors are not equivalently important in different research situation.

In the nutrient reduction model for the wetlands of Liaohe Delta, only two types of land cover are considered: reed and non-reed, with reed covered area being the dominant class in calculation. Villages, reed-storage places, highway and open water are considered to be non-reed covered area, while small *Typha* patches are considered to be equivalent to reed-covered area. The delta is very flat as a fluvial plain. Therefore the elevation range is very small and can be ignored within each irrigation area.

With the simulation results from different pattern scenarios designed in Chapter 5, the relationship between some landscape indices and the nutrient reduction function will be investigated for the wetland landscape of Liaohe Delta. The indices are chosen from FRAGSTATS, and other literatures (Forman and Godron, 1986; Forman, 1995), such as network density, connectivity, area, shape and so on (table 6.1), according to the characteristics of different scenarios.

In the study area of Liaohe Delta, the reed is more or less homogeneously distributed, with only differences in productivity caused by different water and salt combination. In the last version of nutrient reduction model for nitrogen and phosphorous (Chapter 4), the reduction ability among different productivity sub-units is not differentiated. Therefore it is a reed-dominated landscape with canals criss-crossing internally (figure 6.1). The canals are also more or less homogeneously distributed in the landscape.

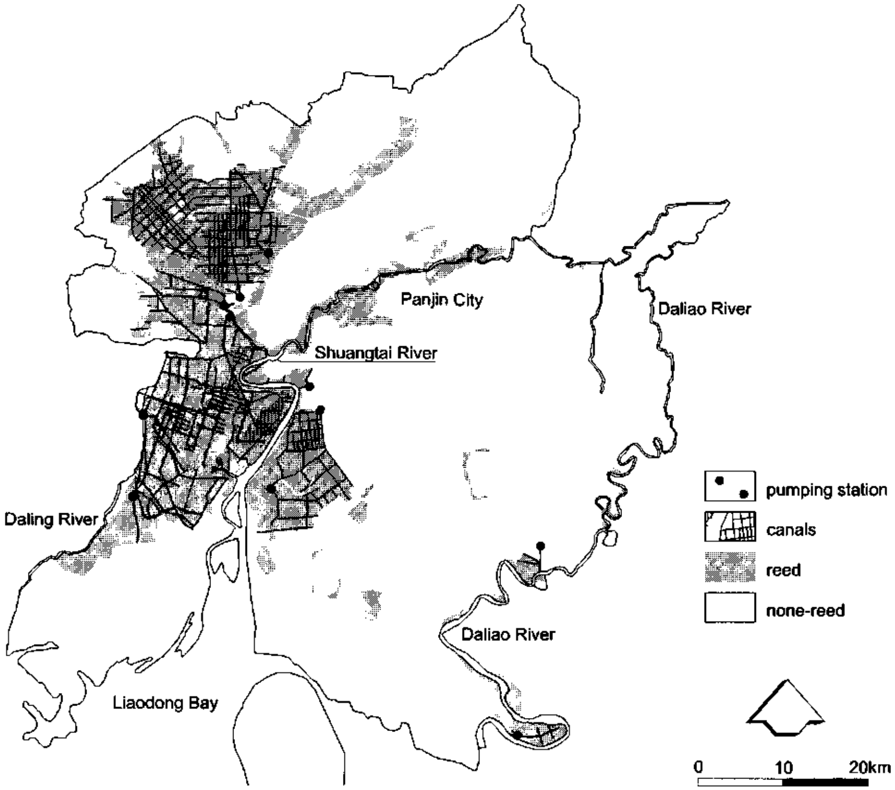

Figure 6.1 The distribution of reed, canal and pumping stations in the Liaohe Delta.

The combination of reed area, canals and pumping stations can affect the nutrient reduction function in the wetland system differently. According to the simulation results in chapter 5, each factor from the combination brings less than 10% change on the total reduction rate.

Apart from the area size, canal length and pumping station position, are there any other factors closely related to the nutrient reduction of the system? For example, the connectivity of the canal network and the different spatial character of the reed field arrangement may also affect the reduction process. These factors were discussed neither in earlier chapters, nor in the literatures available so far.

In this chapter, we will quantify the spatial distribution pattern of the reed-canal system with some landscape indices, and relate them to the simulation results of the nutrient reduction model, to test the sensitivity of these pattern indices to the functioning of the landscape.

It is impossible to test all the landscape indices with our limited data set. Here only a few of them are selected, according to the assumption that they may have close relationship with the nutrient reduction function of the reed-canal system. The ability of these indices in reflecting the nutrient reduction will be tested with the simulated results obtained in chapter 5.

In the nutrient reduction model, the main factors considered are canal, reed-covered area, and pumping stations. Each factor is related to different landscape indices. A brief description of different landscape indices will be given first, and then the calculation result of different factors and indices will be compared.

6.2 Methodology: landscape indices selected for different scenarios

For different pattern scenarios, only the most relevant landscape indices are selected according to expert judgement and some literature. The criteria for the selection are: 1) easy to understand; 2) generally applicable to similar situations; and 3) ecologically meaningful in the specific situation of wetland nutrient reduction. Table 6.1 is a list of the indices chosen for different simulation scenarios designed in Chapter 5. A detailed description of the above indices will be given in the following part of this chapter.

Table 6.1 Landscape indices selected for different pattern scenarios

Factors	Indices selected	Unit	Range
Canal density	Connectivity	-	0~1
	Circuitry	-	0~1
	Line density	m/ha	>0
Reed area size	Area size	ha	>0
	Circuitry	-	0~1
Reed area shrinking pattern	Circuitry	-	0~1
	Area weighted mean shape	-	>1
	Fractal dimension	-	1~1.5
	Contagion	-	0~1
	Mosaic diversity	-	0~1
Pump. station position	Distance source to center	m	>0

For comparison, correlation coefficiency (R) between nutrient reduction and landscape indices is calculated for each scenario. The sample set size for each scenario is 4-5 only. According to Pearson and Hartley (1966, table 13), the lowest R-value for significant correlation between a data pair is 0.900, when $n = 4$; and 0.805 when $n = 5$, with 95% confidence. If correlation coefficiency value is lower than this standard, the landscape index is considered to be not related to the nutrient reduction function.

6.2.1 Indices selected for canal density

Corridors serve as conduits and as filters for much of the movement of animals, plants, materials, and water across the landscape. The index of network connectivity is based on graph theory, and introduced into landscape ecology by Forman and Godron (1986). It includes two independent indices, each representing a different aspect of network connectivity.

1) Gamma (γ) index (Connectivity)

The gamma index of network connectivity refers to the ratio of the number of links in a network to the maximum possible number of links in that network.

$$\gamma = \frac{L}{L\max} = \frac{L}{3(V-2)} \tag{6.1}$$

where L is the number of links, $L\max$ is the maximum possible number of links, and V is the number of nodes in the network.

In landscape ecology, this index may reflect the different possible chances of material and energy flow, or species migration route selection. In the case of water and nutrients flow in the canal network, it will be more efficient for them to be transported to the most remote points if the canals are highly connected.

2) **Alpha (α) index (circuitry)**

The alpha index is a measure of circuitry, the degree to which 'circuits' that connect nodes in a network are present. Circuits are defined as loops that provide alternative routes for flow. It is the ratio of the actual number of circuits in the network to the maximum number of possible circuits in that network.

$$\alpha = \frac{L-V+1}{2V-5} \tag{6.2}$$

Where L and V are the number of links and number of nodes, respectively. (L-V+1) is the actual number of circuits, and (2V-5) is the maximum number of circuits.

Alpha index may reflect the degree of species migration success in ecology, or the possibility of species survival. A connected network with a higher α index usually has a higher species diversity and population size than that with a lower α index.

As for the water and nutrient flow in the wetland system of Liaohe delta, higher circuited canal network may result in shorter water and nutrients transportation distance from the pumping station to a specific point, and finally affect the nutrient reduction efficiency in the canal system and reed system, respectively.

But none of these network indices discussed here has considered the length of the line segments in the network. Therefore, the grain size, or network density is not considered in the connectivity index. Line density is introduced to compensate the description shortage of this aspect.

3) **Line density**

Line density is simply defined as the total length of the lines in the network, divided by the total area of interest.

$$LineDensity = \frac{Total\_Line\_Length}{Total\_Area} \tag{6.3}$$

The lengths of lines between nodes in a network also strongly affect the flows of material, energy and species. The index of line density indicates the relative connectivity of the landscape. It may have both positive and negative ecological effects. High line density can result in higher transportation efficiency when the network is a conduit, and lower efficiency when it is a barrier, such as in the migrating speed of some animal species (Forman and Godron, 1986). The density of canals for water and nutrient transportation is positively related to the nutrient reduction process, according to the simulation results in Chapter 5.

6.2.2 Indices selected for reed area size

1) **Area size**

It is simply the size of area concerned. It affects many aspects of functionality in the landscape. The nutrient reduction function of the wetland in Liaohe Delta is closely related to the size of reed area available for use, as discussed in Chapter 5. The nutrient reduction efficiency becomes higher when the area becomes smaller, though the absolute reduction quantity may decrease.

2) **Circuitry**

The description for this index is the same as in 6.2.1.

6.2.3 Indices selected for reed area shrinking pattern

1) **Circuitry**

The description for this index is the same as in 6.2.1.

2) **Area weighted mean shape index** (AWMS)

It is based on the Corrected Perimeter/Area or shape index (Baker and Cai, 1992):

$$CPA = \frac{0.282 * Perimeter}{\sqrt{Area}} \tag{6.4}$$

This index corrects for the size problem of the index perimeter/area. It is the ratio between the real patch perimeter and the circle perimeter, which has the same area as that patch. The index varies from a value of 1.0 for a circle to infinity for an infinitely long and narrow shape. It is 1.1 for a square.

The Area Weighted Mean Shape index is an overall landscape index which takes the shape index value of all patches into consideration, and makes an average calculation according to their area weight.

3) **Fractal dimension**

Fractal dimension is based on statistics. It indicates the complexity of periphery shapes of the landscape elements (Mandelbrot, 1983; Milne, 1991).

$$D = 2 * k \tag{6.5}$$

Where D is fractal dimension, and k is the regression slope of area and perimeter:

$$\log_2(l/4) = k * \log_2(s) + c$$

in which l is the perimeter of each polygon, s is the area of the same polygon, and c is the intercept of the equation.

The potential range of fractal dimension derived from area and perimeter regression is 1.0 to about 1.5 (O'Neill et al., 1988). The upper value of 1.5 corresponds to shapes drawn by random Brownian movement with zero auto correlation. The low values of fractal dimension relate to agricultural landscapes where simple rectangular shapes dominate.

The fractal geometry of landscapes helps us in awaring of scale and its effects on ecological processes (Milne, 1991). It has been used in the scale detection of home range for wild animals (Swihart, et al., 1988; Loehle, 1990; Stanley, 1986).

4) Texture index: **Contagion**

Contagion quantifies the degree of clumping, or the diversity of local adjacency. According to Li and Reynolds (1993), the newly updated formula for contagion is:

$$C = 1 + \frac{\sum_{i=1}^{m}\sum_{j=1}^{m} P_{ij} * \ln(P_{ij})}{2 * \ln(m)} \tag{6.6}$$

Here the term 2*ln(m) is the maximum of $[-\sum_{i=1}^{m}\sum_{j=1}^{m} P_{ij} * \ln(P_{ij})]$. The range for contagion index is 0~1. Low values indicate highly dissected landscapes, while high values indicate highly compacted landscapes (O'Neill, et al., 1988).

The calculation of contagion index needs the input of a so-called 'grey-level co-occurrence matrix' (GLCM), which is an m×m matrix, and m is the number of landscape types or classes in the sample area. The GLCM contains entries P_{ij}, which are the possibilities of type i being adjacent to type j. P_{ij} is an area weighted probability value. According to Li and Reynolds (1993), P_{ij} is defined by the conditional probability of type i being adjacent to type j, multiplied by the area factor that type i occupied in the total area. That is:

$$Pij = \frac{N_{ij}}{N_i} \cdot \frac{A_i}{A} \tag{6.7}$$

where N_{ij} is the number of times type i being adjacent to type j, N_i is the total number of adjacencies between pixels of patch type i and all patch types (including type i itself). A_i is the total number of pixels or area occupied by type i, and A is the total number of pixels or area of the whole raster map. It can be deduced that:

$$\sum_{i=1}^{m}\sum_{j=1}^{m} P_{ij} = 1 \tag{6.8}$$

There are more other indices describing landscape texture, such as Angular second moment, Inverse difference moment, Entropy, Contrast, and so forth (Baker and Cai, 1992). Among these indices, Contagion is the best accepted and interpreted. Therefore we choose contagion index to test its sensitivity to nutrient reduction simulation results.

5) **Mosaic diversity**

The measurement of mosaic's spatial diversity is a little bit different from other texture indices. It was given by Pielou (1975) as following:

$$Mosaic = -\sum_{i=1}^{m}\sum_{i=1}^{m} P_i * p_{ij} * \ln(p_{ij}) \tag{6.9}$$

Similar to P_{ij} described before, here $P_i = \frac{A_i}{A}$, and $p_{ij} = \frac{N_{ij}}{N_i}$, where A_i, A, N_{ij} and N_i has the same meaning as in formula 6.7.

The contagion and mosaic diversity indices are based on raster data, and thus dependent on cell size. For comparison among different data sets, the same cell size must be specified.

6.2.4 Index selected for pumping station position

1) **Distance from source point to spatial center**

This is an index defined by the author, to testify if there is any close relationship between the quantity of nutrient removal and the distance from source point (pumping station) to the spatial center of concerned area. As described in Chapter 5, the simulation results for the same reed-canal system can be different if the position of pumping station changes.

Most of the indices are calculated in the GIS package of Arc/Info, or Excel. Some of the AML program files are adopted from Li (1998).

6.3 Results

6.3.1 Canal density scenario

The indices chosen for the scenario of different canal density (figure 5.1) are connectivity, circuitry and line density (i.e. canal density, in this case). The calculated value of the indices as well as their relationship to the simulation results of total reduction for nitrogen and phosphorous are given in tables 6.2 (a,b) and 6.3 (a,b).

Table 6.2a The calculated results of total nitrogen reduction and network indices in the canal density scenario

Cases of canal	Total reduc. (ton)	Percent removed (%)	Line density (m/ha)	Connec-tivity (γ)	Circuitry (α)
No canal	138.1	51.9	0.00	-	-
¼ present	145.3	54.6	4.40	0.3492	0
½ present	154.2	58.0	8.68	0.4143	0.1151
Present	156.4	58.8	17.34	0.4938	0.2389
Double	159.2	59.8	34.67	0.5762	0.3639

Table 6.2b Correlation coefficiency between nitrogen reduction and network indices in the canal density scenario

R	Total reduction	Percent removed	Line density (n=4)	Connectivity (n=4)	Circuitry (n=4)
Total reduction	1	0.99996	0.8449	0.9245	0.9367
Percent removed		1	0.8404	0.9187	0.9314
Line density			1	0.9711	0.9634
Connectivity				1	0.9994
Circuitry					1

Table 6.3a The calculated result for soluble reactive phosphorous reduction and some network indices in the canal density scenario

Cases of canal	Total reduc. (ton)	Percent removed (%)	Line density (m/ha)	Connectivity (γ)	Circuitry (α)
No canal	3.99	80.6	0	-	-
¼ present	4.00	80.8	4.40	0.3492	0
½ present	4.20	84.8	8.68	0.4143	0.1151
Present	4.20	84.9	17.34	0.4938	0.2389
Double	4.24	85.7	34.67	0.5762	0.3639

Table 6.3b Correlation coefficiency between phosphorous reduction and network indices in the canal density scenario

R	Total reduc.	Percent removed	Line density (n=4)	Connectivity (n=4)	Circuitry (n=4)
Total reduction	1	0.9999	0.8071	0.8358	0.8534
Percent removed		1	0.8114	0.8403	0.8576
Canal density			1	0.9711	0.9634
Connectivity				1	0.9994
Circuitry					1

From tables 6.2 (a,b) and 6.3 (a,b), some general conclusions can be drawn regarding to the nutrient reduction function and the network indices:

1. The three network indices are more sensitive to the reduction of total nitrogen than soluble reactive phosphorous. Connectivity and circuitry have showed significant correlation ($R>0.90$, $n=4$, table 6.2b) to the reduction of nitrogen, but not phosphorous ($R<0.9$, $n=4$, table 6.3b).
2. The reduction of nutrients is more closely related to the canal connectivity than to the line density. Neither nitrogen nor phosphorous has showed significant correlation with line density. In Chapter 5 it is concluded that the canal contributes 2-5% to the total nutrient reduction rate by doubling the density of canals. But this positive correlation has proved very weak.
3. Circuitry (α index) is a better index than connectivity (γ) in reflecting the nutrient reduction of the reed-canal system. But the difference is not so big. Therefore, redundancy exists between these two network indices. According to our data set, the correlation coefficiency between these two network indices is 0.9994, which is extremely high. To make the comparison of indices among different scenarios more explicit, only circuitry will be used as network connectivity index in the later scenarios.
4. The correlation coefficiency of the indices with relative reduction rate (percent removed) is a little bit higher than with absolute reduction value. But the difference is also not very big. For the percent of nutrients removed is based on the absolute reduction quantity, the correlation coefficiency between them almost equals to 1 (tables 6.2b and 6.3b). To make the comparison more general among different indices in different scenarios, only relative removal value (reduction rate in %) will be used in later discussions.
5. The line density is also highly related to connectivity indices in this case. But it only variates in this scenario. In other scenarios, such as reed area size, shrinking patterns and pumping station positions, the density of the canals does not change so much among different cases. Therefore line density will not be used in later scenarios.

When more canals appear in the reed field, the network becomes more connected, while the area is cut into smaller pieces. Water and nutrient input at a certain point of reed field becomes easier. Therefore the system becomes more efficient in nutrient removal. In the mean time, longer canals increase the absolute reduction quantity as well (tables 5.1 and 5.2).

6.3.2 Reed area size scenario

There are two alternatives in the reed area size scenario (figure 5.2) to simulate the nutrient reduction quantity. One is to keep the water and nutrient input at the pumping station at the present level. Therefore when the area of reed shrinks, the water and nutrient load per unit area increases. The other alternative is to decrease the water input load proportionally at the pumping station, in order to keep water and nutrient input load per unit area at present level. The simulation results of these two alternatives are totally different in terms of absolute reduction quantity (tables 5.3 to 5.6), but the relative reduction rates have similar trend. That is, the smaller the area is, the more effective it is in nutrient reduction.

Only two indices are selected for this scenario: area size of the reed, and circuitry of the canals. Tables 6.4 (a,b) and 6.5 (a,b) provide the calculation results of nutrient reduction rate and the indices, as well as the relationship between reduction and indices.

Table 6.4a The result of total nitrogen reduction and area, circuitry indices in the reed area size scenario

Cases of area	Total reduc. rate% (1)	Total reduc. Rate% (2)	Area size (ha)	Circuitry (α)
¼ present	67.9	63.2	4250	0.1986
½ present	64.3	61.1	8500	0.2191
¾ present	61.3	59.7	12750	0.2401
Present	58.8	58.8	17000	0.2389

1) Total input load at the pumping station is kept at present level.
2) Total input load at the pumping station decrease proportionally with area shrinking.

Table 6.4b The correlation coefficiency between nitrogen reduction and area, circuitry indices in the reed area size scenario

	Total reduc. (1)	Total reduc. (2)	Area	Circuitry
Total reduc. (1)	1	0.9949	-0.9967	-0.9576
Total reduc. (2)		1	-0.9834	-0.9757
Area			1	0.9356
Circuitry				1

Table 6.5a The result of soluble reactive phosphorous reduction and area, circuitry indices

Cases of area	Reduction rate% (1)	Reduction rate% (2)	Area (ha)	Circuitry (α)
¼ present	89.2	88.7	4250	0.1986
½ present	87.9	87.5	8500	0.2191
¾ present	87.0	86.8	12750	0.2401
Present	86.3	86.3	17000	0.2389

1) Total input load at the pumping station is kept at present level.
2) Total input load at the pumping station decrease proportionally with area shrinking.

Table 6.5b The correlation coefficiency between phosphorous reduction and area, circuitry indices

	Reduc. (1)	Reduc. (2)	Area	Circuitry
Reduc. (1)	1	0.9983	-0.9902	-0.9673
Reduc. (2)		1	-0.9803	-0.9735
Area			1	0.9356
Circuitry				1

Tables 6.4 (a,b) and 6.5 (a,b) indicate that the total reduction rate for nitrogen and phosphorous is very closely related to the area of reed fields in both alternatives, especially in the first alternative (|R|> 0.99). The circuitry index for the canal network is also highly related to the reduction rate, but more sensitive when the input water and nutrient load per unit area is kept at the present level (alternative 2).

In addition, the nutrient reduction rate is negatively related to the area and circuitry indices in this scenario. In the canal density scenario, the relationship between nutrient reduction and circuitry index is positive. The reason for this can be explained that, the area size has a much stronger effect on nutrient reduction, while the connectivity of canal system is also highly affected by area size (R=0.9356, n=4). In other words, larger area has more canals and therefore a higher circuitry value. The effect of circuitry on nutrient reduction rate is over-ruled by the effect of area size in this situation.

Another interesting conclusion can be drawn from tables 6.4b and 6.5b is that the relative nutrient reduction for the two alternatives of input load is highly correlated, though the absolute reduction is totally different (tables 5.3-5.6).

6.3.3 Reed area shrinking pattern scenario

The landscape indices selected for the reed area shrinking pattern scenario (figure 5.3) include circuitry of canal network, area-weighted mean patch shape (AWM-shape) of the reeds, fractal dimension, contagion and mosaic diversity of the whole mapped area. As discussed in Li (1998), grid-based pattern indices like contagion and mosaic diversity are very much dependent on the resolution or cell size of the landcover grid. Here the cell size is chosen as 30m×30m, the same resolution as that of the model simulation grid. Calculation results for nutrient reduction rates, pattern indices and correlation coefficiency values between each pair of values are shown in tables 6.6 (a,b) and 6.7 (a,b).

Table 6.6a The results of total nitrogen reduction rate and some pattern indices in the reed area shrinking pattern scenario

Pattern	Total TN reduc. (%)	Circui-try	AWM-shape[1)]	Fractal dimension	Contagion	Mosaic diversity
Shrinkage	61.1	0.2191	2.4792	0.158	0.8547	0.0268
Perforation	58.8	0.0803	2.8382	0.524	0.4369	0.0876
Fragmentation	58.4	0.1150	1.7649	0.358	0.8609	0.0246
Bisection	56.0	0.1606	1.9895	0.551	0.8692	0.0226

1) AWM = Area Weighted Mean

Table 6.6b The relationship between nitrogen reduction and pattern indices for the reed area shrinking pattern scenario

R	Total TN reduc.	Circui-try	AWM-shape	Fractal dimension	Contagion	Mosaic diversity
Total reduc.	1	0.3657	0.4845	-0.8497	-0.0995	0.1256
Circuitry		1	-0.1206	0.6849	0.6946	0.6810
AWM-shape			1	-0.0051	-0.7970	0.8088
Fractal				1	-0.4397	0.4157
Contagion					1	-0.9996
Mosaic						1

Table 6.7a The results of soluble reactive phosphorous reduction rate and pattern indices

Pattern	Total SRP (%)	Circui-try	AWM-shape	Fractal dimension	Contagion	Mosaic diversity
Shrinkage	87.5	0.2191	2.4792	0.158	0.8547	0.0268
Perforation	86.3	0.0803	2.8382	0.524	0.4369	0.0876
Fragmentation	85.9	0.1145	1.7649	0.358	0.8609	0.0246
Bisection	84.3	0.1606	1.9895	0.551	0.8692	0.0226

Table 6.7b The relationship between phosphorous reduction and pattern indices

R	Total SRP reduc.	Circui-try	AWM-shape	Fractal dimension	Contagion	Mosaic diversity
Total reduc.	1	0.2865	0.5281	-0.8050	-0.1788	0.2045

1) The correlation coefficiency values between different pattern indices are the same as in table 6.6b, omitted.

It is disappointing to find that none of the pattern indices chosen for this scenario has a remarkable relationship to the reduction rate of both nitrogen and phosphorous. Only fractal dimension demonstrates a relatively higher and negative correlation with the reduction rate ($|R| > 0.8$). Due to the small sample size ($n = 4$) for statistics, this kind of weak relationship is not reliable either.

Unlike in the scenarios of canal density and reed area size, the network circuitry index has no relationship with the nutrient reduction rate at all in the reed area shrinking pattern scenario. This further indicates that the relationship between the index of network connectivity and landscape functionality is unstable, and prone to change with different situations concerned.

It is not surprising to find that the relationship between contagion and mosaic diversity is extremely high (table 6.6b), because they are representing the same aspect of the landscape structure, using similar algorithms (formulas 6.6 and 6.9). Great redundancy must exist between these two indices. This is also the reason why we did not choose more other similar indices such as entropy, contrast etc. (Baker and Cai, 1992).

In conclusion, as far as nutrient reduction is concerned, these landscape pattern indices are not so informative in indicating landscape functionality. Probably they are more useful in describing landscape structure itself (Li and Reynolds, 1993; O'Neill et al., 1988), or in indicating other procedures such as bio-diversity change. Further study is needed concerning the explanation of landscape indices in the application domain.

6.3.4 Pumping station position scenario

The distance from source point to spatial center refers to the distance from the pumping station to the spatial center of the irrigated reed field. The distance value of each pumping station position case (figure 5.4), as well as the nutrient reduction values, are shown in tables 6.8a and 6.8b.

Table 6.8a The results of nutrient reduction and distance from the pumping station to the spatial center of the reed field

Cases of pump. station	TN%	SRP%	Dist. source to centre (m)
Present position (a)	58.8	86.3	9574
Position (b)	56.1	83.4	2095
Position (c)	56.3	83.6	2979
Position (d)	59.2	86.7	10274
Position (e)	56.6	85.1	4100

Table 6.8b The relationship between nutrient reduction and distance index

R	Nitrogen reduc.	Phosphorous reduc.	Dist. source to centre
Nitrogen reduc.	1	0.9437	0.9974
Phosphorous reduc.		1	0.9598
Dist. source to centre			1

Generally speaking, the reduction of nitrogen and phosphorous are both closely related to the distance index ($R > 0.95$), especially for nitrogen. It is worth noticing that, the reduction of nitrogen and phosphorous is also closely related ($R = 0.94$). In the former scenarios the correlation coefficiency between the reduction of these two nutrient elements was not presented. But, they are also highly correlated with each other ($R=0.9137$, $n=22$). This is because of the similar calculation algorithms for the reduction of these two nutrient types.

If we look details into the reductions of phosphorous in the canal and reed fields separately (tables 6.9a,b), the distance index is also very sensitive to them, especially to the reduction of canal system. There is a negative relationship between the reduction in the reed system and the distance of pumping station to the reed field center, which is also the case for total nitrogen. This can be understood because the distance between a canal point and the pumping station is an important factor in calculating the nutrient reduction in the canal system. While the reduction in the reed field is not so much related to the distance factor.

Table 6.9a The results of SRP (soluble reactive phosphorous) reduction in the canal/reed system and distance from the source to spatial center

	Canal (%)	Reed (%)	Total (%)	Dist. source to center (m)
Present position (a)	54.9	31.4	86.3	9574
Position (b)	46.5	37.0	83.4	2095
Position (c)	47.1	36.6	83.6	2979
Position (d)	54.9	31.7	86.7	10274
Position (e)	47.7	37.4	85.1	4100

Table 6.9b The relationship between phosphorous reduction rate and distance factor

	Canal	Reed	Total	Dist. source to centre
Canal	1	-0.9854	0.9303	0,9940
Reed		1	-0.8544	-0,9636
Total			1	0,9598
Dist. source to centre				1

From table 6.9b we can also notice that the reduction rates in the canal and reed systems are highly correlated, though negative. They are also significantly related to the total reduction rate as well (|R|>0.85).

6.4 Discussion

It is easy to define and calculate large amount of landscape indices with modern GIS packages (Baker and Cai, 1992; McGarigal and Marks, 1995), but not so easy to find the ecological meaning of these indices. One of the objectives of this paper is to find the ecological explanation of some pattern indices, in relation to landscape functionality. The above results do indicate some kind of correlation between index values and nutrient reduction rates in the reed-canal system of Liaohe delta, but still several more points need to be clarified.

The simulation results used for testing the indices may not be good enough because the model and the scenario patterns are based on a lot of assumptions (Chapters 4 and 5). The correlation co-efficiency values derived from the simulated data sets can be higher than from real values. In other words, if the simulated results have no close relationship with some landscape indices, chances are that the field data has no close relationship with them either.

The sample set might be too small (n= 4-5) to make good statistics on correlation coefficiency. Each scenario has only four or five cases to compare the effect of some landscape patterns on nutrient reduction function. It is enough to derive a general trend according to this small data set, but may not be enough to make good correlation for statistics. Therefore, the R (correlation coefficiency) values can be over- or under-estimated because of the small data set.

A significant correlation should also be interpreted with caution. The correlation may not be caused by the direct influence of one variable on the other, but by the influence of unknown factors on both variables (Elliott, 1993). The high correlation coefficiency between nutrient reduction and circuitry in the case of canal density and reed area size, for example, is questionable, because both cases are quite high but one is positive, and the other is negative.

Many landscape indices defined by former ecologists may not have real meaning, or just meaningful in certain aspect of the landscape and its functions. For example, the character of landscape structure described by some indices, such as contagion and mosaic diversity, may affect the behavior of some species migration, but not the bio-physi-chemical process of nutrient element movement.

Many landscape indices have redundancy with each other as well, such as network connectivity (γ) and circuitry (α), and some landscape texture indices, such as contagion and mosaic diversity. We should choose carefully among a large group of indices in order to be concise in describing the structure and function of a landscape.

Different purpose of study, such as species, material, or energy flow, may need different indices. The index of "distance from source to spatial center" has never been documented before. But it is quite closely related to the nutrient reduction rate in the pumping station scenario, while other indices may not demonstrate such a close relationship in this case. Therefore, it is the purpose of study that decides the method of description.

It is better to stick on a small number of ecologically expressive landscape indices according to the objective of the study. The six parameters (area, class, proportion of dominant class, number of polygons, polygon size variance, and elevation range) suggested by Giles and Trani (1999) are fundamental in describing a mapped area, but may not be enough in complicated situations like functionality study. The combination of these factors is also important in characterizing the landscape.

6.5 Conclusion

According to the results and discussion above, several conclusions can be made regarding to the relationship between nutrient reduction function and landscape pattern indices:

1. In the scenario of canal density, the nutrient reduction is more closely related to the connectivity and circuitry of the canal system than the density of canals.
2. The negative relationship between nutrient reduction and area size is so strong that the effect from other pattern factors (such as connectivity of canals) is overruled by this factor.
3. Most of the landscape pattern indices are not informative in describing the nutrient retention change caused by landscape pattern change. Only fractal dimension index demonstrates a weak negative correlation with the nutrient reduction rate.
4. The distance from pumping station to the spatial center of reed field is strongly related to the nutrient reduction rate.
5. Redundancy exists among different landscape indices, such as connectivity and circuitry indices for network, and contagion and mosaic indices for texture.
6. Different indices should be chosen according to the purpose of the study, based on the criteria of simplicity, generality and ecological meaningfulness.

Although limitations of small data sets exist in this study, the conclusions derived above are still informative to many of the cases in landscape ecology. Instead of defining new complicated landscape indices, we should concentrate more on existed simpler ones and make good explanation for them. More importantly, they should be put into application, such as landscape designing. Otherwise landscape indices will become a huge pile of mathematical game without any meaning.

7. Conclusions, Reflections and Recommendations

7.1 General conclusions

The general objective of the thesis is to investigate the possibility of using the estuary wetland as a treatment system to cut down nutrient input into the sea. For this purpose, a spatial simulation model has been established to estimate the nutrient reduction in the estuary wetland of Liaohe delta, China. According to the research work presented in the former chapters, some general conclusions can be made:

The wetland system in the Liaohe Delta is a multi-functional landscape that should be rationally used for environment protection. It has a high reduction rate for non-point source pollutants, such as COD (carbon oxygen demanding), nitrogen, phosphorous, and mineral oil. Both canal and reed systems can contribute substantially in the reduction process. The *Suaeda* community also has a potential in nutrient removal and can be used to treat exchanged water from breeding ponds. Therefore the natural estuary wetland has a great potential to be used as the last barrier for the nutrient enriched rivers before the water running directly into the sea and causing eutrophication problems.

A spatial simulation model has been established to simulate the nutrient reduction in the wetland system of Liaohe Delta. Two different simulation models have been established during the thesis work. One is totally based on field data, which is more complicated and hydrological data dependent. The other is partly based on Mander-&-Mauring's regression model, which demands less data. The simulation results from the two models are comparable. Although the field data based model is slightly better for the Liaohe Delta, Mander-&-Mauring's model was preferred because of its generality and simplicity. Finally, the field data based non-linear regression model for the canal system is used, and Mander-&-Mauring's linear regression model for the reed system is adopted. By integrating these two models with GIS, a spatial simulation model is established.

The total nutrient reduction rate of the wetland system is relatively stable regardless of the deviation of the input load. Given the present size of reed field (c.a. 80,000 ha) and density of canals, about 3,200-4,000 tons of TN (total nitrogen) and 80 tons of SRP (soluble reactive phosphorous) can be removed, which is only 1/10 of the total reduction capacity, with water being the limitation factor. The input concentration in this range has little effect on the relative nutrient reduction ability because of the compensation between canal system and reed system in their nutrient reduction ability. For total nitrogen, the total reduction rate is about 66%, for soluble reactive phosphorous, it is about 90%.

The reed, canal, pumping station and their spatial combination have different effects on the nutrient reduction ability. Each factor brings less than 10% deviation in the total nutrient reduction rate, though the absolute reduction quantity can be tremendously different due to different total input load at the pumping station. Generally speaking, smaller reed areas are more efficient in nutrient reduction than larger, scattered ones. The reduction rate sequence for different reed distribution patterns is: Shrinkage > Perforation > Fragmentation > Bisection. The shrinkage pattern of land transformation is most recommended in order to keep a high reduction capacity for the nutrients in the reed fields. Digging more canals will not contribute much to remove more nutrients. The relative location of the pumping station is better kept far away from the centre of reed area. The limitating factor for the nutrient reduction ability of the Liaohe delta is water, not nutrient load. The present reed area can accept at least 4 times more water in spring.

Not all landscape indices are ecologically meaningful in reality, and redundancy exists among different indices. According to the indices chosen for testing, only a few of them, such as "circuitry" and "distance from source point to spatial centre", have close relationship with nutrient reduction in the wetland landscape. One index may have different sensitivity in different situations. For example, the circuitry index for network connectivity has the highest positive correlation with nutrient reduction in the canal density scenario, but the correlation is negative in the area size scenario. In the reed area shrinking pattern scenario, no correlation exists between reduction and circuitry at all. Actually in this scenario none of the landscape indices selected demonstrates a clear correlation with the nutrient reduction rate, except that fractal dimension showed a weak one ($R > 0.8$, $n = 4$). The distance between source point and spatial centre is highly related to the reduction rate in the pumping station scenario.

7.2 Some Reflections about the Research

The conclusions above provide scientific basis for the application of natural wetland treatment system along the coast as the last barrier to nutrient enriched water from agricultural and industrial discharges, so as to reduce the risks of coastal seawater eutrophication. A few reflections about the results and conclusions from the research work will help to clarify some of the points that are not specified in earlier chapters.

The purification function of the wetland system. The wetland is a multi-functional landscape (Chapter 3) which should be rationally used and protected. At present it is only considered to be a potential land resource for agricultural use, or profitable for its high biomass production. Its purification function, bio-protection function and other functions are not fully recognized and utilized yet. The purification function of the estuary wetland provides a good chance to compromise the contradiction between nature conservation and the impact of human activity. The wetland system should be treated as an entity in terms of its structure and function.

The spatial model of the nutrient reduction system. The spatial simulation model (Chapter 4) is relatively simple and empirical compared to the process-oriented models (Dorge, 1994; Jorgensen, et al., 1988; Jorgensen, 1994; Mitsch and Reeder, 1991). The nutrient reduction procedure in the canal system and reed field is taken as a "black box", in which, only input and output is concerned. The bio-chemical processes are not simulated in detail. Because of this simplicity, the application of this model in similar areas is of great potential. The accumulation problem in the model is not concerned in the model because of the annual harvesting of reed in the Liaohe Delta. But it should be considered when applying this model to other wetlands where harvesting is not conducted.

Nutrient reduction quantity of the wetland system. Unlike many other studies on this subject (Nichols, 1983; Mander and Mauring, 1994; Mander, et al., 1997), the estimation of nutrient reduction in this research is based on a spatial simulation model, which means, no such reduction rate like *X* kg/ha.yr is applicable, because every point (cell) of the wetland has a different reduction rate. The total reduction is the sum of all simulated cells. Although we can say that the 80,000 ha wetland system can remove 4,000 tons of nitrogen or 80 tons of phosphorous during the irrigation period, it is not suitable to say that the annual reduction rate is 50, or 1 ton/ha.yr, because the data source for this average is largely various even in the same period of irrigation. Besides, the nutrient reduction in the canal system is also an important contribution, especially for phosphorous (>50%). It is obviously not suitable to average the nutrient reduction in the canal with that of the reed. That is why "total percentage removed" or "total reduction quantity" was chosen to describe the nutrient reduction situation of the system.

Contribution to land use planning and landscape ecology. The scenario study (Chapters 5 and 6) on different combinations of spatial components in the wetland landscape is an application of the spatial simulation model. It provides theoretical basis for a sustainable land use planning in the Liaohe Delta. It also contributes to the theory of landscape ecology in search of relationship between pattern and function, as well as in the using of landscape indices to represent landscape structure and interpret ecological processes. The different cases in each scenario are designed according to the theory of landscape ecology as well as the real land transformation trend in the Liaohe Delta. The simulation results from these scenarios can enhance the application of landscape ecology in land use planning.

Contribution to the application of GIS. The spatial simulation model established in Chapter 4 is a combination of process models with GIS. It has strengthened the ability of both making predictions with process models and making spatial analysis with GIS. The point data based process models is often weak when dealing with spatial problems, such as smallest area needed, or the shortest route selection. On the other hand, GIS is less powerful in interpreting ecological or other processes. This study is a good example of GIS application in environmental sciences.

Comparison with other sites. According to the statistics made by Meuleman (1999) from more than 100 sites on wetland treatment systems in the world, the annual loading rate for nitrogen is 30~60,000 kg/ha.yr, and for phosphorous it is 0.8~10,000 kg/ha.yr. Compared to most of these sites, especially the constructed wetlands, the current input load in the Liaohe delta is very low (about 57.3 kg/ha.yr for nitrogen and 1.0 kg/ha.yr for phosphorous). The present input load in our study area is still very far from its potential loading capacity.

7.3 Recommendations and prospects

Recommendations for local policy makers of Liaohe delta

The thesis work is mainly focused on the nutrient reduction of the wetland system. Some recommendations can be made for the local policy makers, regarding to the functionality of the wetland:

Keep the canal density as small as possible. The density of canal does not affect the quantity of total nutrient reduction so much, while it can affect the connectivity of the reed field and may cause problems for some wild animals. The canal system is a multifunctional landscape component that not only acts as conduit for water irrigation and discharge, but also can be barrier for the movement of some animal species. It is advisable to create fewer canals when establishing new reed farms on the fluvial beach.

Keep a smaller area for the purification of heavily polluted water. Smaller area is more efficient on pollutant removal within the maximum input load. Most part of reed area should be irrigated with water from less polluted river or outlet from paddy fields, for the sake of bio-protection. However, water availability in spring can be the setback for this suggestion. If heavily polluted water must be applied in a large area, a feasible alternative is to dilute the pollutants with less polluted river water and seawater. But the salt concentration must be kept under the maximum tolerant limit for reed growth.

Keep the reed area as aggregated as possible when reducing the area of reed. Due to agricultural exploration and other human activities, the area of the reed in Liaohe Delta has been shrinking steadily during the last decades. If the conversion from reed to other land use types is unavoidable, it is recommended that the reed area be kept as aggregated as possible, not only because this kind of shrinking pattern can remain a higher nutrient retention rate, but also because it is important for bio-protection (Opdam, et al., 1993).

Multi-factors should be taken into consideration when making an optimistic land use planning. Nutirent reduction is only one aspect of the wetland functions, other aspects, such as bio-diversity conservation, regional pollution control, agricultural and industrial benefits, as well as aesthetic value of the landscape are also very important. Further study is needed to investigate other factors related to the sustainable development of the Liaohe Delta.

Recommendations for landscape ecology research

The study on the relationship between structure and function has been and will still be an important subject of research in landscape ecology. Although the effect of pattern on process is usually obvious, how to quantitatively measure this effect is not so well documented yet. The quanitification procedure of methodologies still has a long way to go. The different pattern scenario study in this thesis is a theoretical exploration for such a measure.

The large amount of landscape pattern indices proposed so far need to be clarified and concentrated. The selection of landscape indices should be based on the rule of generality, simplicity and ecological meaningfulness. GIS can serve as a powerful tool in searching for eclogical expressive indicators.

Prospects of the natural wetland as a treatment system

The research result does not only provide sound basis for the use of natural wetland as a treatment system for nutirent enriched river water in the Liaohe Delta, it is also important for similar situations. If all the natural wetlands along the coast are rationally used or carefully designed for nutrient reduction, the risks of seawater eutrophication will be substantially reduced. Great benefits will also be gained from the wetland itself.

Compared to the lost caused by algae blooming and the cost of building water treatment plants, the cost of regulating and maintaining natural wetland is much less expensive and more beneficial. It is highly recommended that we make good use of natural wetlands along the coasts in Eastern China to cutdown nutrient input into the sea.

Summary

The eutrophication problem of coastal seawater has been a serious hazard in the last two decades in Eastern China. This problem is mainly caused by the nutrients like nitrogen and phosphorous from inland non-point sources. The purification function of natural wetlands at big river deltas provides a potential solution to cut down nutrient input into the sea. The objective of this research is to develop a model to simulate the ability of nutrient reduction in the wetland system so as to evaluate to what extent the natural wetland can be used as a treatment system for nutrient enriched river water.

The study area (Chapter 2) is in the Liaohe Delta, China, where the world second largest reed marsh is located. As many other wetlands, it is the paradise for wild species, especially birds. But, this piece of land has been under great pressure due to the fast development in agriculture, aquaculture and oil industry. The area of natural wetlands has been shrinking because of the conversion into other land use types. The reed marsh itself has also become semi-natural with irrigation in spring and harvest in winter. However, the extensive management in the reed system provides a good chance to compromise the conflict between human activity and nature conservation. If the natural wetlands along the coast are used for nutrient reduction, advantages will be gained for both the wetlands and the nearby sea environment.

The natural wetland is a multi-functional landscape in biomass production and protection, water regulation, soil formation, coastline stabilisation and pollutant purification (Chapter 3). The reed and canal system has a high reduction rate for many pollutants such as COD, nitrogen and phosphorous. Besides, the reed marsh can also be used as a treatment system for oil drilling water. Therefore, wastewater irrigation in the reed field should be encouraged to solve the water shortage problem in spring, increase reed productivity and prevent coastal pollution. In addition, the *Suaeda heteroptera* community has a great potential to be used as a treatment system for exchanged water from breeding ponds.

Two different models have been established to simulate the nutrient reduction and its distribution in the reed-canal system of Liaohe Delta (Chapter 4). One is totally based on field data, which is more complicated and hydrological data dependent. The other is partly based on Mander-&-Mauring's regression model, which demands less data. The simulation results from the two models are comparable. Although the field data based model is slightly better for the Liaohe Delta, Mander-&-Mauring's model was preferred because of its generality and simplicity. Finally, the field data based non-linear regression model for the canal system was used, and Mander-&-Mauring's linear regression model for the reed system was adopted. The algorithms used are:

Canal system:

$$C_{(x,y)} = -A^* \ln(dist.) + B \qquad (A>0, B>0)$$

Where $C_{(x,y)}$ is the nutrient concentration value (in mg/l) of a canal point at a certain distance (*dist.)* to the pumping station. A and B are linealy related to the nutrient input concentration (*inload* in mg/l) at the pumping station:

$$A = C_1 * inload + C_2$$
$$B = C_3 * inload + C_4$$

The values from C_1 to C_4 are obtained for nitrogen and phosphorous according to the field experimental data.

Reed system:

$$Y = A*X+B$$

Where Y is the retention, and X is the input load, both in g/m^2.day for nitrogen and mg/m^2.day for phosphorous. Constants A and B are obtained according to the literature data from more than 40 study sites all over the world (Mander and Mauring, 1994).

According to the simulation result, there is a "mutual compensation" for the nutrient reduction in the reed system and canal system, so that the total reduction rate remains relatively stable in spite of the input concentration change at the pumping station. It is 66% for total nitrogen and 90% for soluble reactive phosphorus. In combination with the canals, the present 80,000 ha of reed can remove about 3,200-4,000 tons of nitrogen and 80 tons of soluble reactive phosphorous during the irrigation period each year. But this is only 1/10 of its total reduction capacity, with water being the limiting factor.

To study the effect of landscape pattern on nutrient reduction (Chapter 5), four spatial combinations of reed, canals and pumping stations are designed.

1) Canal density: no canal, ¼ present, ½ present, present and double present canal density.
2) Reed area size: ¼ present, ½ present, ¾ present and present reed area.
3) Reed shrinking pattern: shrinkage, perforation, fragmentation and bisection.
4) Pumping station position: 2 cases on the reed area border and 3 cases some where inside the reed area.

By changing one factor while keeping the others stable, the nutrient reduction corresponding to each case was calculated with the model developed in Chapter 4. The simulation results indicate that each factor brings less than 10% deviation in total nutrient reduction rate, though the absolute reduction quantity can be different. If the reed area is stable, it is better to remain a low canal density, and keep the pumping station near the border of the reed area. Generally speaking, smaller reed area is more efficient in nutrient reduction than larger, scattered ones. The reduction rate sequence for different reed distribution patterns is: Shrinkage > Perforation > Fragmentation > Bisection. The shrinkage pattern of land transformation for the reed is most recommended in keeping a high reduction rate for the nutrients. The present reed area can accept at least 4 times more water in spring.

The relationship between landscape structure and nutrient reduction (Chapter 6) is measured with the help of some landscape indices. A couple of indices are selected and calculated corresponding to each scenario of spatial patterns designed in Chapter 5. The correlation coefficiency between the value of indices and nutrient reduction rates is calculated for each scenario. The results indicate that not all the landscape indices are closely related to the nutrient reduction of the wetland system. Therefore the ability of landscape indices to characterise the effect of pattern change on nutrient reduction is rather limited. Redundancies also exist among similar indices. Landscape indices should be chosen according to the purpose of the study, based on the criteria of simplicity, generality and ecological meaningfulness.

The research work is a combination of landscape ecology, wetland ecology and GIS technology. The spatial model developed is also applicable for other areas with similar situations. The results will contribute to a sustainable landscape planning in the study area. The final conclusion is that the natural wetlands have a great potential to be used for reducing nutrient input into the sea.

Samenvatting

Eutrofiering van kustwateren is sinds enkele tientallen jaren een ernstig probleem in het oosten van China. Dit probleem wordt voornamelijk veroorzaakt door de nutriënten met stikstof- en fosforverbindingen vanuit diffuse bronnen op het vaste land. De zuiveringsfunctie van natuurlijke wetlands gelegen in de grote rivierdelta's kunnen een oplossing bieden om de nutriëntenvracht naar zee terug te dringen. De doelstelling van dit onderzoek is om een model te ontwikkelen dat in staat de reductie van nutriënten in het wetland te simuleren. Daarmee biedt het een middel voor de evaluatie van de mate waarin natuurlijke wetlands gebruikt kunnen worden als systeem voor de behandeling van met nutriënten rivierwater.

Het studiegebied is gelegen in de Liaohe Delta in het noordoosten van China in het op een na grootste rietmoeras ter wereld (hoofdstuk 2). Zoals vele andere wetlands is het een paradijs voor wilde diersoorten met name voor vogels. Maar dit gebied staat onder grote drukdoor de snelle ontwikkeling van landbouw, aquacultuur en olieindustrie. Het oppervlak natuurlijk wetland is de afgelopen periode afgenomen door omzetting in andere vormen van landgebruik. Het rietmoeras zelf is een halfnatuurlijk systeem geworden met irrigatie in het voorjaar en oogst in de winter. Echter, het extensieve beheer van het rietsysteem biedt een goede mogelijkheid om een compromis te vinden tussen menselijk gebruik en natuurbescherming. Als de wetlands langs de kust gebruikt worden voor nutriëntreductie kunnen zowel de wetlands zelf als het zeemilieu in de omgeving er voordeel van hebben.

Een natuurlijk wetland is een multifunctioneel landschap met functies voor de productie van biomassa, water regulatie, bodemontwikkeling, stabilisatie van de kustlijn en het zuiveren van vervuilende stoffen (hoofdstuk 3). Het rietsysteem en ook het kanaalsysteem kunnen veel vervuilende stoffen binden en omzetten zoals stikstof en fosfor en daarmee het COD gunstig beïnvloeden. Ook kan het rietsysteem functioneren als een reinigingssysteem voor afvalwater van olieboringen. Daarom zou de irrigatie met afvalwater in de rietvelden bevorderd moeten worden om het probleem van watertekort in het voorjaar op te lossen. Bovendien, de *Sueda heteroptera* gemeenschap heeft grote mogelijkheden om gebruikt te worden als zuiveringsysteem voor het uitgeslagen water van de kweekvijvers.

Er zijn twee verschillende modellen ontwikkeld om de nutriëntenreductie en de verdeling ervan in het riet-kanaalsysteem van de Liaohe delta te simuleren (hoofdstuk 4). De een is volledig ontwikkeld op basis van veldgegevens, is tamelijk gecompliceerd en sterk afhankelijk van beschikbaarheid van hydrologische gegevens. Het andere model is gedeeltelijk gebaseerd op het regressiemodel van Mander & Mauring en vereist minder gegevens. De simulatieresultaten van beide modellen zijn vergelijkbaar. Hoewel het model gebaseerd op veldgegevens wat beter presteert voor de Liaohe delta is de voorkeur gegeven aan het model van Mander & Mauring wegens de algemene toepasbaarheid en de eenvoud ervan. Uiteindelijk is het niet-lineaire model gebaseerd op veldgegvens gebruikt voor het kanaalsysteem en het lineaire regressiemode van Mander & Mauring voor het rietsysteem gebruikt. De algoritmes zijn als volgt:

Kanaalsysteem:

$$C_{(x,y)} = -A^* \ln (dist.) + B \qquad (A>0, B>0)$$

Waarbij $C_{(x,y)}$ de waarde is van de nutriëntenconcentratie is (in mg/l) van een punt in het kanaal op een bepaalde afstand (*dist.*) van het pompstation. A and B hebben een lineaire relatie met de concentratie van de nutriënteninput (*inload* in mg/l) bij het pompstation:

$$A = C_1 * inload + C_2$$

$$B = C_3 * inload + C_4$$

De waarden voor C_1, C_2, C_3 and C_4 zijn voor stikstof en fosfor verkregen op basis van gegevens uit veldexperimenten.

Rietsysteem:

$$Y = A^*X+B$$

Waarbij Y de retentie is en X de vracht aan input beide uitgedrukt in g/m^2.dag voor stikstof en in mg/m^2.day voor fosfor. A en B zijn verkregen op basis van literatuur data uit meer dan veertig studiegebieden over heel de wereld (Mander en Mauring, 1994).

Volgens het resultaat van de simulatie vindt wederzijdse compensatie plaats ten aanzien van nutriëntenreductie het rietsysteem en het kanaalsysteem, zodat de totale reductie relatief stabiel blijft ondanks veranderingen in inputconcentratie ter plaatse van het pompstation. De reductie is 66% voor nitraat en 90% voor oplosbaar reactief fosfor. In combinatie met de kanalen kan de huidige 80.000 ha riet ongeveer 3200-4000 ton stikstof en 80 ton oplosbaar reactief fosfor verwijderen tijdens de jaarlijkse irrigatieperiode. Dit is echter slechts 1/10 van de totale reductiecapaciteit, waarin water de beperkende factor is.

Om het effect van patronen in een landschap op de reductie van nutriënten te bestuderen zijn er vier ruimtelijke combinaties van riet, kanalen en pompstations ontworpen (hoofdstuk 5).

5) Dichtheid kanalen: geen kanalen, ¼ van de huidige dichtheid, ½ van de huidige dichtheid en twee keer de huidige dichtheid aan kanalen.
6) Riet oppervlakte: ¼ de huidige situatie, ½ de huidige situatie, ¾ de huidige situatie en de huidige situatie.
7) Riet afname patroon: krimp, perforatie, fragmentatie en bisectie.
8) Positie pompstation: twee situaties aan de rand van het rietsysteem en drie situaties in het rietsysteem.

Door telkens een factor te veranderen en de andere factoren onveranderd te houden is met het model dat in hoofdstuk 4 is ontwikkeld, voor iedere situatie het effect op de nutriëntenreductie berekend. De simulatieresultaten laten zien dat iedere factor minder dan 10% verandering veroorzaakt in de nutriëntenreductie ratio, alhoewel de absolute verandering in reductie aanzienlijk kan zijn. Zoland het rietoppervlak stabiel is blijkt het beter te zijn de dichtheid aan kanalen beperkt te houden en de pompstations aan de rand van de rietvelden te plaatsen. In het algemeen is een kleinere rietoppervlakte meer efficiënt dan grotere verspreide systemen. De volgorde in efficiëntie van patronen van nutriëntenreductie is krimp > perforatie > fragmentatie > bisectie. Het patroon van een krimpend oppervlak door transformatie landgebruikfuncties is het meest aanbevolen voor het instandhouden van een hoge reductie ratio voor nutriënten. Het huidige oppervlakte aan riet kan minstens vier keer zoveel water verwerken in het voorjaar.

De relatie tussen landschapstructuur en nutriëntenreductie is gemeten met behulp van een aantal landschapsindices. Een aantal indices zijn geselecteerd en berekend met behulp voor alle scenario's die zijn ontworpen in hoofdstuk 5. De correlatiecoëfficiënt tussen de waarden van de indices en de nutriëntenreductie is berekend voor ieder scenario. De resultaten geven aan dat niet alle landschapindices nauw gerelateerd zijn aan nutriëntenreductie in wetland systemen. De mogelijkheid om met landschapsindices de effecten van patroonveranderingen op nutriëntenreductie te karakteriseren is dan ook vrij beperkt. Er blijkt ook redundantie te bestaan tussen vergelijkbare indices. Landschapindices moeten dan ook vooral gekozen worden gericht op het doel van de studie, en gebaseerd op de criteria eenvoud, algemenen toepasbaarheid en ecologische betekenis.

Het onderzoek dat hier is uitgevoerd is een combinatie van landschapsecologie, wetland ecologie en GIS-technologie. Het ruimtelijke model dat is ontwikkeld is ook toepasbaar in andere gebieden met vergelijkbare situaties. Het resultaat zal bijdragen aan een duurzame landschapsplanning in het studiegebied. De uiteindelijke conclusie is, dat natuurlijke wetlands een groot potentieel hebben om gebruikt te worden om voor de vermindering van de toevoer van nutriënten naar de zee.

Summary in Chinese

湿地净化功能：辽河三角洲氮磷去除效应空间模型与格局分析

(小　结)

近海富营养化问题是近年困扰中国东部沿海的环境灾害之一，主要是由于陆源营养物质氮磷含量过高所致。位于大型河口的自然湿地为削减氮磷入海通量，解决这一问题提供了出路。本项研究的目的即是通过建立空间模型来模拟湿地系统对氮磷的去除效应，以推测自然湿地在多大程度上可以利用来净化携带大量营养物质的河水。

研究区位于拥有世界第二大苇田的辽河三角洲(第一章)。与其它湿地一样，这里是大量野生生物，尤其鸟类活动的理想场所。但由于农业、水产养殖业及石油工业的迅速发展，研究区承受的压力越来越大，该区的自然湿地不断为其它用地类型所占，面积逐年减少。芦苇沼泽本身也由于春季灌溉和冬季收割变成了半自然湿地。然而，这种粗放的人工管理正好为解决人类活动与自然保护之间的矛盾提供了契机。假如沿海湿地用以削减氮磷入海通量，湿地和近海环境保护都将取得良好效果。

沿海自然湿地是一个多功能系统(第二章)，它在保护生物多样性、协调水资源分配、加速土壤形成、稳定海岸线及治理水污染等方面都具有重要意义。辽河三角洲的芦苇-灌渠系统对诸如 COD、氮、磷等的污染物质具有很强的去除能力，同时，芦苇湿地还可用作落地原油、采油污水的处理系统。因此，应该鼓励污水灌溉，以解决该区春季淡水不足的矛盾，并可提高芦苇产量，防止近海水体富营养化。此外，碱蓬群落也可用作沿海虾蟹养殖交换废水的处理场所。

为模拟辽河三角洲湿地的净化功能及氮磷的分布状况，本书第三章建立了两种模型。一是完全基于野外实验数据，并需要在水文数据上做相应假设，比较复杂，但精度稍高。另一模型部分基于 Mander 和 Mauring 的回归模型，比较简单，普适性强，与前一模型的模拟结果也相近。最终模型中，灌渠部分是以实验数据为基础的非线性回归模型，苇田部分是以 Mander 和 Mauring 的文献数据为基础的线性回归模型。所用公式包括：

灌渠：

$$C_{(x,y)} = A * \ln(dist.) + B$$

$C_{(x,y)}$ 为灌渠上距泵站一定距离(*dist.*)处某点的氮磷浓度(mg/l)。A，B 的值与输入点上的氮磷浓度呈线性相关：

$$A = C_1 * inload + C_2$$

$$A = C_3 * inload + C_4$$

C_1-C_4 的值从实验数据中回归获得。

苇田：

$$Y = A*X+B$$

Y 为去除率，X 为输入负荷，二者单位皆为 g/m^2.day (氮) 或 mg/m^2.day (磷)。A 和 B 的值来自对世界上 40 多处研究结果的回归分析 (Mander and Mauring, 1994)。

研究结果表明，芦苇系统与灌渠系统之间存在一个氮磷去除的"互补效应"，因而无论泵站输入点的浓度如何变化，总去除率变化不大。该湿地系统对总氮的去除率约为 66%，对活性磷的去除率约为 90%。辽河三角洲现有芦苇与灌渠系统的综合去除能力对氮约为 3200-4000 吨/年，对磷约为 80 吨/年。如果以苇田初春可接纳水量为限制因子，这仅相当于其去除潜力的 1/10

为研究景观结构对氮磷去除效应的影响，第五章设计了四个苇田、灌渠、泵站的组合系列，即：

1) 灌渠密度：无灌渠，1/4 当前密度，1/2 当前密度，当前密度和 2 倍当前密度。
2) 苇田面积：1/4 当前面积，1/2 当前面积，3/4 当前面积和当前面积。
3) 面积减小格局：缩减型，穿孔型，破碎型和两分型。
4) 泵站位置：两例位于苇田边缘，三例位于苇田内部。

通过改变单因子，而保持其它因子不变，运用第四章建立的模型计算了各系列组合中氮磷的去除量。运算结果表明，每项因子对总去除率的影响效果不到 10%，但绝对去除量的差别有所不同。如果苇田面积稳定，最好保持一个较低的灌渠密度，并尽量使泵站位置靠近苇田边缘。一般来说，小面积紧凑型的苇田比大面积、散布型的苇田去除效率更高。不同苇田分布格局对氮磷去除效率的排列次序为：缩减型>穿孔型>破碎型>两分型。缩减型的土地转化格局最有利于保持较高的氮磷去除效果。目前苇田在春季尚可接纳四倍于当前的污水量。

第六章运用景观参数，定量研究了景观结构与氮磷去除效果之间的关系。针对第五章设计的每一个系列，选择了若干不同的景观参数，与氮磷去除率之间进行相关对比。研究结果表明，多数景观参数与湿地的氮磷去除效率关系不大，因而景观参数在表现结构对功能的影响上效果有限，而且相似参数之间存在冗余。实际工作中，应根据研究目的之需要，本着简单性、一般性和生态意义性强的原则来适当选取景观参数。

本项研究是景观生态学、湿地生态学与地理信息系统技术的组合。所建立的空间模型也适用于具有相似条件的其它地区。研究结果为辽河三角洲地区可持续性景观生态规划提供了理论依据，也为滨海自然湿地削减氮磷入海通量提供了应用前景。

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Appendix

Definition of some frequently used terms and concepts in the thesis

(From multi-literature sources)

Black box: A system about whose structure nothing is known beyond what can be deduced from its behavior. Statistical relationships between inputs to the system and outputs from it can be deduced by manipulating the inputs.

Canal: The artificial water routes for water irrigation and discharge.

Connectivity: The degree to which a certain type of landscape feature is connected.

Data model: A conceptual description of geographical data.

Eutrophication: The process of nutrient enrichment (usually by nitrates and phosphates) in aquatic ecosystems. The productivity of the system ceases to be limited by the availability of nutrients. The rapid increase in nutrient levels often stimulates algae blooms.

Field data: Lab experimental data from field samples (water, soil and plants), as well as data directly measured in the field.

FRAGSTATS: The package for calculating landscape indices in Arc/Info, originally designed by McGarigal and Marks, and updated by their followers.

Function: the flow of mineral nutrients, water, energy, or species.

GIS (Geographical information system): a system for capturing, storing, checking, integrating, manipulating, analyzing and displaying data which are spatially referenced to the earth. This is normally considered to involve a spatially referenced computer database and appropriated applications software. A GIS contains the following major components: a data input subsystem, a data storage and retrieval subsystem, a data manipulation and analysis subsystem and a data reporting subsystem.

Image processing: Techniques and procedures dealing with the acquisition, analysis and output of digital images.

Input concentration: The concentration value of pollutants/nutrients in the water at the source point (e.g., pumping station), normally in mg/l.

Input load: The total quantity of pollutants/nutrients input into a unit area during a specific period of time, usually in $g/m^2.d$ or kg/ha.yr

Irrigation area: The area controlled by a pumping station, the border of which is defined by reed distribution, as well as some artificial elements, such as roads and canals.

Liaohe Delta: It is a compound delta located in North Eastern China. Several large rivers run into the Liaodong Bay with Liaohe River being the largest one.

Landscape: A heterogeneous land area composed of a cluster of interacting ecosystems that is repeated in similar form throughout.

Landscape ecology: A study of the structure, function, and change in a heterogeneous land area composed of interacting ecosystems.

Landscape function: The flows of energy, materials, and species among the component ecosystems.

Landscape indices: Mathematical parameters designed or adopted by landscape ecologists to describe the spatial characteristics and other aspects of the landscape.

Landscape structure: The distribution of energy, materials, and species in relation to the sizes, shapes, numbers, kinds, and configurations of landscape elements or ecosystems.

Linear simulation: A simulation model using simple linear regression formulas.

Mander-&-Mauring's regression model: A kind of linear regression model for nitrogen and phosphorous reduction in the wetlands, developed by Mander and Mauring (1994).

Model: A simplified verbal, graphic, or mathematical description used to help understand a complex object or process.

Non-linear simulation: Modelling with non-linear mathematical formulas, such as logarithmic function, exponential function and other irregular functions.

Nutrient elements: Elements that can nourish the growth of organisms, such as nitrogen, phosphorous, potassium, and other elements.

Spatial model: A model that includes two to three dimensional data sets and processes, usually implemented in a GIS package.

Patch: a non linear surface area differing in appearance from its surroundings.

Pattern: The distribution of energy, materials, and species in relation to the sizes, shapes, numbers, kinds, and configurations of landscape elements or ecosystems.

Purification function: The ability of a system to remove pollutants via physical, chemical, biological processes.

Outlet: The outflow of water from a filtering system, usually with different components from inlet.

Raster: Attribute data expressed as an array of cells or pixels, with spatial position implicit in the ordering of the cells or pixels.

Reduction quantity: The actual amount of material reduced by the system.

Reduction capacity: The maximum amount of material that can be reduced by the system.

Reed-canal system: The combined system of reed marsh and canal network in the Liaohe Delta.

Reed fields/reed bed: The extensively managed natural reed marsh in the Liaohe Delta.

Rhizome: The underground stems and roots of reed.

Rhizosphere: The underground stems and roots of reed and their surroundings, such as soil and water.

Scenario: A series of designed experiment for testing or practicing.

Soluble Reactive Phosphorus: The element phosphorous in the status that can be easily absorbed by organisms.

Total Nitrogen: The total amount of nitrogen element available in water or soil. Usually the sum of NH_4^+, NO_3^-, NO_2^- and Organic-N is used.

Treatment system: The pollutant reduction or storage system for environment protection.

Wetlands: A piece of land that is saturated with water long enough to promote wetland or aquatic processes as indicated by poorly, hydrophytic vegetation, and various kinds of biological activity which are adapted to a wet environment.

Curriculum Vitae

LI Xiuzhen was born on March 8th, 1970 in Shandong Province, China. She graduated from the Department of Geography in Shandong Normal University in 1991. The same year she continued her MSc study on Environmental Science in Zhongshan University. Her research work was focused on bio-chemical cycling of mineral elements in an orange orchard.

After graduation in 1994, she started working as a researcher at the Institute of Applied Ecology, Chinese Academy of Sciences, in Shenyang, China. She was involved in several projects on landscape ecology, wetlands and environmental sciences.

She began her PhD program in 1995 as an "on-the-job" student. As an employee she was responsible for "the purification function of the wetland system" in the National Key Project NSFC 49631040, from which this thesis was resulted. During her work she was sent to the Netherlands for a training course on GIS and Remote Sensing, where she obtained a second MSc degree from ITC, Enschede and Wagening Agricultural University in early 1998. The subject of the thesis was "Assessment of landscape Change using GIS".

With the Sandwich Ph.D fellowship granted to her, she came back to Wageningen University and continued working on the project after one year's fieldwork and research in China. This thesis is the result of her 4 and a half years' work and study.

She had 5 papers in international journals and 7 papers in Chinese journals published during the thesis study. Three more papers based on this research work are in review. She was one of the key orgnizers of the "International Conference on Landscape Ecology of Asia-Pacific Regions" (Oct. 5-7, 1998, Shenyang, China).