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Water environmental planning considering the influence of non-linear characteristics

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Abstract: In practical water environmental planning, the influence of the non-linear characteristics on the benefit of environmental investment was seldom taken into consideration. This paper demonstrates that there exist a lot of non-linear behaviors in water environment by emphatically analyzing the influence of the non-linear characteristics of the economic scale, the meandering river and the model on water environmental planning, which will make a certain impact on the water environmental planning that sometimes cannot be neglected. This paper also preliminarily explores how to integrate the non-linear characteristics into water environmental planning. The results showed that compared with traditional methods, water environmental planning considering non-linear characteristics has its prevalence and it is necessary to develop the relevant planning theories and methods.

Keywords: water environment; non-linear characteristics; planning

Introduction

Emphases on the environmental protection and the increasing environmental investment call for the detailed analysis of the current practices in environmental planning to improve relevant concepts and methods for the decision strategies. Investment for environmental protection is large but also limited. In Europe, 264 USD is spent for environmental protection per inhabitant per year. The investment can be expected to reach about 380 USD by the year of 2000(Lahore, 1994), 40% to 50% of which is spent mainly on the water resource protection(Falkenmark, 1987). The situation is the same in China, where investment per inhabitant is small but the total is large, which reached 91.070 billion RMB Yuan in the year of 1996 and 1997. Worldwidely, the total investment for water environmental protection amounts to about 100 billion USD(Zang, 1999).

To increase the efficiency, the investment should be spent in the way of maximizing environmental improvement and protection. For this purpose, some characteristics of the environment system itself should be incorporated into the decision strategies. However, non-linear characteristics and uncertainty factors in the system lead to various differences between environmental planning and practices. In past few years, in order to get more accurate and effective planning results than those with traditional methods, the theories of stochastic, fuzzy set and grey system have been integrated into water environmental planning(Liu, 1996), which has got better results. Actually, non-linear characteristics of the environmental system do influence environmental planning to some extent(Ye, 1994). Although most environmental scientists and relevant decision makers have realized the above mentions clearly(Perrings, 1992; Qi, 1993), they often ignore such influence in practice. That is because those non-linear characteristics seem trivial, but unexpectedly and greatly influence the final results of the water environmental planning. Traditional methods do not achieve efficient environmental improvement for the available money, which wastes large investment as well as natural resources(Qi, 1993). Consequently, it is not only a theoretical development to investigate the non-linear characteristics in water environmental system and apply them to environmental planning, but also helpful to have comparatively full consideration for environmental decision strategies in planning methods, investment strategies, etc., which will turn out to be more reliable and effective.

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By mainly demonstrating the influence of the non-linear characteristics of the economic scale, the meandering river and the model on water environmental planning, this paper analyzes the influence of those characteristics on water environmental planning and finds it necessary and significant to develop the theories and methods considering the influence of the non-linear elements. In addition, this paper preliminarily explores how to integrate non-linear characteristics into water environmental planning.

1 Several environmental planning cases neglecting the influence of non-linear characteristics

1.1 Non-linear characteristics of economic scale

1.1.1 Cases of sewage treatment

Sewage treatment is a traditional control method of water pollution. Some relevant standards of effluent quality in sewage treatment plants are often used to control the treatment degree. For sewage treatment, the non-linear relationship between sewage treatment benefit and investment is easily established(Fig.1). For example, the reduction of the final 5 mg/L of the biologically decomposable organic compounds in sewage is about 35 times more expensive than the reduction of the first 5 mg/L(Statzner, 1993). In the water pollution control system, the cost of the planning objective consists of the cost of sewage treatment in entire system and sewage transportation. Cost function used in common is(Cheng, 1991):

$$C = K_1 Q^{K_2} + K_3 Q^{K_2} \eta^{K_4}. \tag{1}$$

Where C is the cost of the sewage treatment; Q is the sewage treatment scale; η is the sewage treatment efficiency; K_1, K_2, K_3 and K_4 are the parameters of the cost function, respectively.

In this function, $K_2 < 1$ and $K_4 > 1$ suggest that with a equal efficiency, the treatment for an unit volume of sewage will decrease with the increase of the sewage treatment scale. While the scale is fixed, the cost will increase with the increase of the efficiency of the sewage treatment. The relationships between the three factors can be expressed in Fig.2, which shows the non-linear characteristics exist in the cost function.

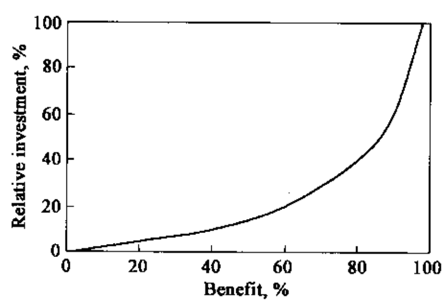

Fig. 1 The relationship between sewage treatment benefit and investment

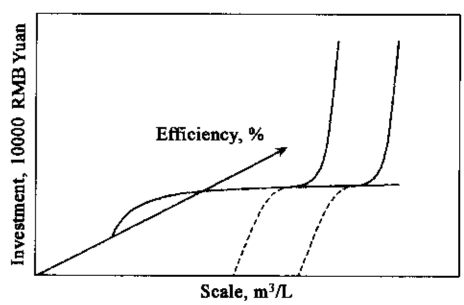

Fig. 2 The relationship between scale and efficiency investment for sewage treatment plants

Considering the sewage treatment scale's economic effect, it is prefered to set up centralized sewage treatment plants. However, the centralized discharge of the sewage is unfavorable to the reasonable utilization of the water self-purification ability. Consequently, the improvement of environmental quality will not be achieved efficiently with the infinite increase of scale of sewage treatment plants. In order to find the most economic scale, the non-linear relationships among scale, economy and environment must be reasonably considered.

In addition, some scholars demonstrate that, in sewage treatment plants, the cost of the terminal treatment is about 3 times of that of the secondary treatment and 7 times of that of the primary treatment, and the cost of the secondary treatment is 1.3 times of that of the primary treatment. The non-linearity between the cost and various sewage treatment classes is shown in Fig.3(Wang, 1990).

Based on Fig.1 to Fig.3, it can be easily concluded that with the same investment, treating untreated sewage or improving the treatment degree of the poor quality sewage primarily will obviously achieve much more environmental improvement than treating the high quality sewage. Actually, traditional water environmental planning often relies on the standards established by environmental protection agencies, such as discharge standards and maximum permissible concentrations. If the above standards are met, large amount of capital will be invested into another new sewage treatment facilities in order to meet higher treatment standards or achieve better environmental improvement. But such decision strategies ignoring non-linear behaviors cannot use the investment effectively. For example, the French Water Resource Administrations increased stepwise investment into sewage treatment in the past decade and with the results that streams of poor water quality switched to an intermediate quality while streams of intermediate quality were hardly improved over that period. Therefore, the French Water Resource Administrations input more investment into streams of poor water quality. The same experiences also happened in China and the former Federal Republic of Germany(Statzner, 1993).

1.1.2 Construction of riparian green belt

In the developed countries, riparian green belt has been widely applied to control non-point water pollution, while in China and some other developing countries, riparian green belt has just come into use. The standard width of the riparian green belt is recommended to be 10 to 20 m. Riparian forest planted along the streams can reduce non-point river pollution, stabilize the river channel and suppress luxuriant aquatic macrophyte growth. Based on the relationship between the cost of the riparian forest and the required land area in China and some European countries, the non-linearity between ecological improvement and the cost of the riparian forest is shown in Fig.4.

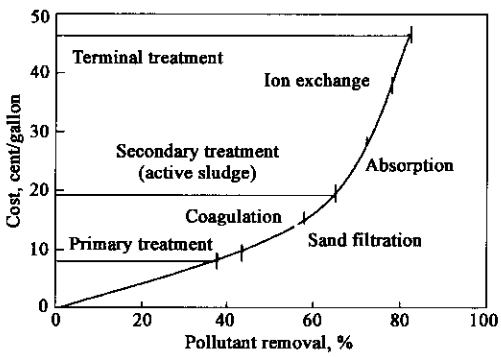

Fig.3 The relationship between the cost and various sewage treatment classes

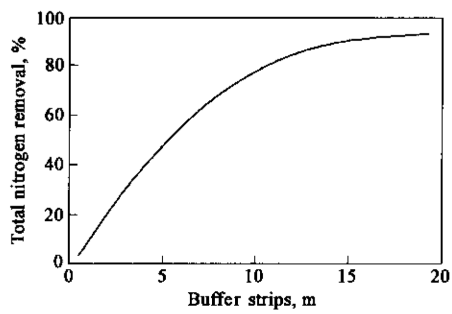

Fig.4 The relationship between ecological improvement and investment

1.1.3 River regulating project

As river regulating project is concerned, it is necessary to keep the river discharge at a certain level so as to offer suitable habitats for aquatic organisms and meet the requirements of shipping, drinking water, etc. A certain ratio of annually average discharge is often used to determine the regulated discharge. This paper uses the relationship between a hydropower station discharge and physical habitat suitability for brown trout reproduction in French to demonstrate the non-linear relationship between the river regulation and the environmental quality improvement. Increasing hydropower station discharge will improve physical habitat suitability for brown trout reproduction and the relationship between discharge and cost is non-linear(Fig. 5), including some complicated non-linear relationships between influent water volume of turbine and electricity production, and between the uneven distributions in the time needed for the electricity quantity and electrovalence. Additionally, it is also a non-linear relationship between the hydropower station discharge and the improvement of physical habitat suitability for the brown trout reproduction(Fig.6). Consequently, the relationship between relative cost for the hydropower station and the improvement of the favorable physical habitat for brown trout is also non-linear.

Thus, the above three cases all illustrate the non-linearity of the cost for achievable environmental improvement. And all three cases have one point in common: it is a moderate investment that can achieve better environmental improvement, not the more, the better.

1.2 The non-linear problems in linear hypothesis

As environmental system has the characteristics of openness, unstable equilibrium and dissipative structure, non-linearity exited among the relationships among the subsystems. Generally, non-linear interactions have the properties of randomness, cooperative effects and interference effects. Therefore, we can conclude that the non-linearity is prevalent in the complex environment systems. But in practice, much non-linearity was approximately presumed as linear problems in order to simplify the treatment. Although sometimes the approximate presumptions are convenient and reasonable, in many cases, they are not satisfactory, possibly result in the false optimal solutions, which makes great negative impact on the water environmental planning

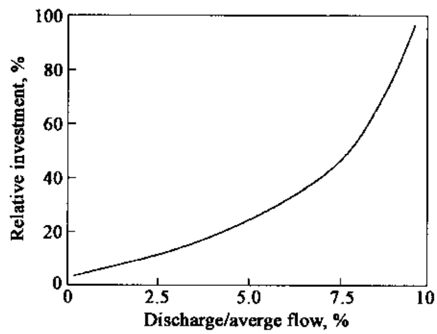

Fig.5 The relationship between the discharge and investment

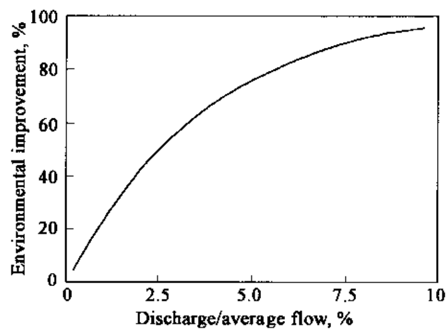

Fig.6 The relationship between the discharge and physical habitat suitability for brown trout reproduction

1.2.1 The problems of the meandering river

Generally, if the linear hypothesis is applied to the two-dimensional water quality simulation in the meandering river, the calculation process will be greatly simplified. However, due to the non-linear characteristics existing in the meandering river, the extensions of errors and the reliability of such linear hypothesis are often neglected in practice.

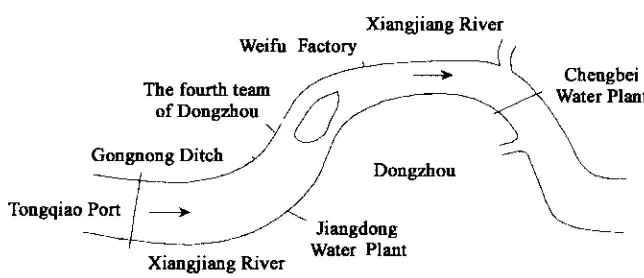

Fig.7 Map of Hengyang City zone in Xiangjiang River

In 1994, the environmental impact on the shipping project of Xiangjiang River (ranging from Hengyang City to Zhuzhou City in Hunan Province) was assessed by the Department of Environmental Science and Engineering of Hunan University using the finite element method of the two-dimensional water quality simulation. During the process, the river reach(about 13 km from the sewage discharge outlet of Tongqiao ort to the downstream of water catchment of Chengbei Water Plant) is divided into 2921 finite elements(Zeng, 2001). The details are shown in Fig.7.

According to Fig.7, there is an isle(Dongzhou) in the river which makes the situation complicated. In order to simplify the problem, we take the regions about 50 km from Tongqiao Port to Dongzhoutou as the research subject(Fig.8), where the meandering phenomenon of the river(non-linear characteristics) are relatively obvious and river width is approximately unchanged. Here, the non-linear characteristic analysis concentrate and only the BOD_5 concentrations are analyzed.

In fact, there are no regulations for the partition of the vertical and horizontal grid spacing for the calculation. Fig.9 demonstrates that with the number of segments increased and the horizontal distance shortened, the partition of the grid will be more approximate to the actual situation and the non-linear characteristics resulting from the meandering river will be fully considered. In reverse, the reliability will decrease and the non-linear characteristics of the meandering river will be less considered. Accordingly, there exist direct relations among the partition of the horizontal grid spacing, water quality simulation and the consideration of the non-linear characteristics of the meandering river.

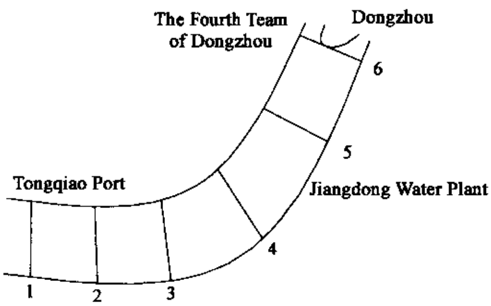

Fig.8 Map of the river reach

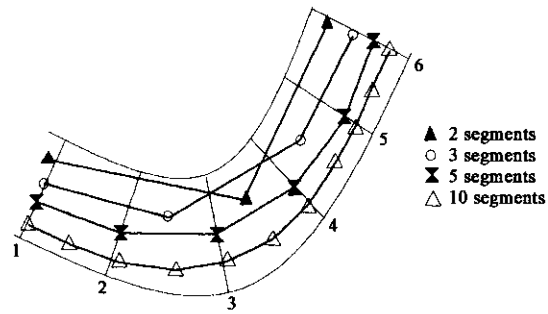

Fig.9 Map of different segments of meandering river

Based on the results of 50 m horizontal grid spacing, this paper analyzes the influence of different horizontal grid spacing on the simulation results using finite element method (Zeng, 2001), and the coefficients of correlation can be found and compared in Fig.10.

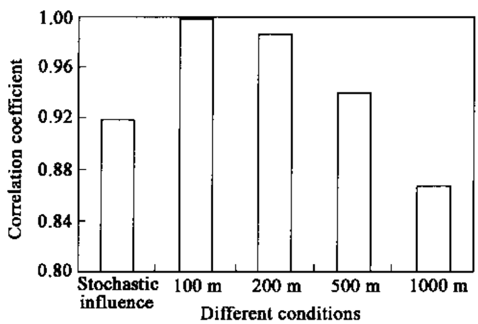

Fig.10 Comparisons of coefficient of correlation

Fig. 10 illustrates that with the increase of the horizontal grid spacing, the non-linear characteristics in the meandering river is less considered, which turns out to be less reliable.

Fig.10 also demonstrates the degree of the stochastic influence on the water quality simulation, which is given by simulating the water quality system under stochastic interference. It is easy to find from Fig. 10 that the nonlinear and the stochastic characteristics have the same quantity class influence on the water quality system. Many researches have done on the latter, while less attention is paid to the former, which requires us to attach the same importance to the research of the stochastic influence and the non-linear influence.

1.2.2 Non-linear problems of model

1.2.2.1 Non-linear problems of the cost function

In water environment planning, all the optimal planning of sewage outlet, factory group and integrated sewage treatment relate to the cost function, such as the formula(Lahore, 1994) that describes the non-linearity in the wastewater treatment. Generally, the non-linear function is always linearized in practice, but such linearization results in some errors due to non-linear characteristics of the function itself and these errors for some situations possibly cannot be neglected. For example, during cost function linearization, there are no certain regulations for interval partition method and plenty of subjective factors are involved. In this paper, with the cost function of one sewage outlet divided into five segments, Table 1 shows the optimal planning results (Qin, 2000) of different segment intervals. Obviously, some resulted errors associated with total cost are unreasonable, so non-linear characteristics of the objective function should be taken into consideration when the linear approach is applied to solutions in water environment planning to achieve more reliable results.

Table 1 Statistical results of 5 segments

Segment intervals	Total costs	Relative errors, %
0-0.1-0.2-0.3-0.4-1	1251.7	22.81
0-0.1-0.2-0.6-0.8-1	1462.3	9.83
0-0.2-0.4-0.5-0.7-1	1567.1	3.37
0-0.2-0.3-0.6-0.8-1	1589.8	1.96
0-0.2-0.3-0.5-0.7-1	1619.4	0.14
0-0.2-0.4-0.6-0.8-1	1621.4	0.014
0-0.2-0.4-0.75-0.9-1	1589.3	2.00
0-0.3-0.5-0.6-0.8-1	1472.0	9.23
0-0.3-0.4-0.5-0.61	1926.4	18.79
0-0.4-0.5-0.7-0.8-1	2109.9	30.00
0-0.5-0.6-0.7-0.81	1021.7	37.00

1.2.2.2 Non-linear problems in water quality model

Dilution, diffusion, decomposition or precipitation of pollutants result from the physical, chemical and biological interactions in water body.

Therefore, the change of water quality has the characteristics of complex certainty and uncertainty and now lots of mathematical models have been established(Fu, 1985), including widely used BOD-DO model. In fact, most of these models are one-class kinetic equations. Plenty of important factors are neglected in initial hypothesis and the models are often simplified as linear matrix equations to get satisfied solutions in practice(such as the application of BOD-DO coupling model in the water quality planning(Dobbins, 1964)). Additionally, the BOD-DO constraining inequality is also non-linear. But such linearization is not always proper due to enormous non-linear characteristics in water environmental system, which even results in false optimal solutions in water quality planning. For example, in traditional linear BOD-DO model, with the low dissolved oxygen concentration, the oxygen consumption velocity is assumed to be independent of it, which sometimes results in negative concentrations(Fu, 1985).

2 Environmental planning considering non-linear characteristics

In fact, non-linear phenomena are ubiquitous in water environment, and the above mentions are only some cases of neglecting non-linear characteristics in water environmental planning. Since the available investment is always finite, the investment with moderate consideration of non-linear characteristics will achieve relatively more environmental improvement or more scientific results. Therefore, it is necessary to analyze the influence of non-linear behaviors on environmental system and accordingly develop the relative planning theories and methods.

2.1 Methods considering non-linear characteristics of economic scale

Relevant investment in traditional stream (water environment) planning is determined mainly by threshold values or limiting values. Since the investment is never sufficient to finance all measures in a particular catchment, managers often attach much importance to the threshold values and limiting values relevant to legislations or rules, particularly in municipal sewage or industrial wastewater treatment. After the standards of sewage treatment or industrial wastewater have been met, the managers will begin to consider to invest in the next measure, which relies also on the threshold values or limiting values relevant to legislations or rules. Consequently, traditional stream (water environment) planning invests in a particular measure before switching to the next one.

This sequential strategy of traditional decision-making is certainly not the most efficient for environmental systems with non-linear characteristics. To support this view, we assume that the sequential strategy follows the three in-order measures as mentioned in sections 1.1.1—1.1.3: (1) sewage treatment plants, riparian green belt and increasing discharge of hydropower station; (2) cost of the performance of each of the measures is equal and is spent stepwise as 5% of the total cost for each measure; (3) spending 100% of the total cost for each measure leads to 100% environmental improvement according to the patterns in Fig. 1, Fig.4 and Fig.6; and (4) environmental improvement achieved by each measure is equal. Under these assumptions, the environmental improvement achieved by the sequential strategy is distinctly slower than that obtained by a strategy of alternating investments into the measure which achieves the greater environmental improvement in the next measure(Fig.11).

In Fig.11, *STP* is the sewage treatment plant efficiency, *RF* is the land area needed for planting a buffer forest belt, *Q* is the increasing discharge of hydropower station to create additional physical habitat suitable for the brown trout reproduction. The lower curve (1) in Fig.11 demonstrates that the measures are performed one after another applying a sequential strategy *STP-RF-Q*, and next measure would not be performed until the former has finished. The upper curve (2) in Fig.11 indicates that the measures are performed alternatively, and the next circulation does not begin until the 5% of the total cost for all the three measures is exhausted. From Fig.11, it can be seen clearly that the strategy in curve (2) is much more efficient than the strategy in curve (1) in achieving environmental improvement.

It is maybe difficult to alternatively spend the 5% of the total cost for each measure in practical environmental planning. However, Fig. 11 shows that investment efficiency will be greatly increased in decision strategies considering relevant non-linear characteristics.

2.2 Planning methods considering non-linear characteristics in the meandering river

Water quality planning is one of the most important means in water environmental protection. Only reasonable methods can provide measures available in practical environmental protection. Generally, correct water quality simulation, which is an important part of the water quality planning, can provide a reliable foundation for the final water quality planning.

Water quality simulation described in the section 1.2.1 is to determine the influence of Xiangjiang (from Hengyang City to Zhuzhou City) Dayuandu Shipping Project on environment. Take BOD_5 concentration as the research example. According to Grade-Ⅱ of the Chinese National Surface Water Quality Standards(GB3838-88, $BOD_5 \leqslant 3$ mg/L), regions where BOD_5 concentrations exceed the standards are two flowing belts about 1.6 km in the downstream of Tongqiao Port, and its maximum concentrations is 5.5733 mg/L with grid spacing of 100 m. Accordingly, with grid spacing of 50 m and flowing belts of about 1.8 km, the maximum concentrations is 5.7622 mg/L. With grid spacing of 1000 m and flowing belts of about 1.0 km, the maximum concentrations is 4.0477 mg/L and the errors of the result are huge. Therefore, having or not having the consideration of the non-linear characteristics of meandering river will greatly influence the planning results.

Table 2 Grid spacing and average errors of water quality simulation

Grid spacing, m	Average errors of water quality simulation, %	Grid spacing, m	Average errors of water quality simulation, %
25	0	500	12.83
50	4.33	1000	15.84
100	7.15	1500	18.10
200	9.50	2000	19.81
250	10.20	2500	21.13

Obviously, the more consideration of non-linear characteristics in the meandering river, the more grids are needed in the partition of the river, which increases the difficulty in the data collecting and the calculation complexity. The process with the linearization hypothesis of the cost function, not considering the non-linear influence of the meandering river, will result in planning solutions with great deviation and even get false results. It is necessary to determine a relationship between the grid spacing and the errors of the final water quality simulation according to the analysis of the relationship between width of the two-dimensional river and the grid spacing, which will help people for the water quality planning to determine the grid spacing properly with the permissible error, or reversely work out the simulation errors based on the surveying data. Doing this will not only get more accurate solutions in water quality planning, but also determine the reliability of the final planning.

To determine such a relationship, this paper works out the average errors of the water quality simulation at different grid spacing using finite element method(all based on 25 m grid spacing). Table 2 shows the results.

To be convenient, this paper deals with the data using multiple regression analysis and a curve is obtained(Fig.12) showing the relationship between the ratio(x/B) of the grid spacing (x) to the average width(B) of the river and the average errors(%) of the final result of water quality simulation, which can be used as a reference for water environment engineers on the meandering river planning.

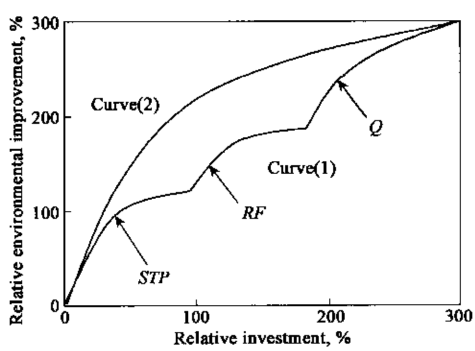

Fig.11 The comparisons of the improvement for various management strategies

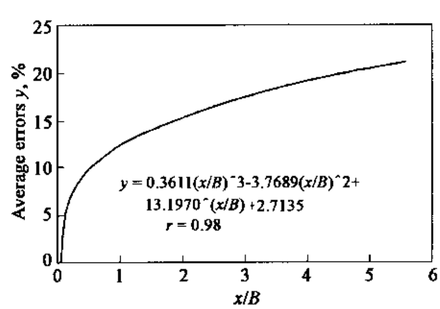

Fig.12 Relationship between average errors of water quality stimulation and x/B

3 Conclusions

Non-linear phenomena are ubiquitous in water environment. However, traditional methods ignore the influence of non-linear behaviors on environmental planning. That is because those non-linear characteristics seem trivial. The non-linear characteristics sometimes have a strong influence on the final results of the water environmental planning. Therefore, traditional environmental planning does not achieve efficient environmental improvement for the available investment, and wastes investment as well as natural resources(Qi, 1993).

This paper states the necessity and significance of the non-linear characteristics in the water environmental planning based on the analysis of the non-linear problems of linearization and economic scale. Although some cases are simple and some conclusions are drawn from ideal hypothesis, they have clearly expressed the catholicity of non-linear characteristics in water environment and the significance of integrating non-linear characteristics into water quality planning. Great deal of work are needed to study and develop water environmental planning theories and methods related to non-linear characteristics.

The application study of the non-linear behaviors in environmental planning is at the initial stage at home and abroad. Due to the enormous non-linear behaviors in water environment, it can be predicted that non-linear theory will be widely applied to water environment to reflect complex phenomena more accurately and veritably.

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