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Assessment of Point and Nonpoint Sources Pollution in Songhua River Basin, Northeast China by Using Revised Water Quality Model

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Abstract: Individual participation of pollutants in the pollution load should be estimated even if roughly for the appropriate environmental management of a river basin. It is difficult to identify the sources and to quantify the load, especially in modeling nonpoint source. In this study a revised model was established by integrating point and nonpoint sources into one-dimensional Streeter-Phelps (S-P) model on the basis of real-time hydrologic data and surface water quality monitoring data in the Jilin Reach of the Songhua River Basin. Chemical oxygen demand (COD) and ammonia nitrogen (NH_3-N) loads were estimated. Results showed that COD loads of point source and nonpoint source were 134 958 t/yr and 86 209 t/yr, accounting for 61.02% and 38.98% of total loads, respectively. NH_3-N loads of point source and nonpoint source were 16 739 t/yr and 14 272 t/yr, accounting for 53.98% and 46.02%, respectively. Point source pollution was stronger than nonpoint source pollution in the study area at present. The water quality of upstream was better than that of downstream of the rivers and cities. It is indispensable to treat industrial wastewater and municipal sewage out of point sources, to adopt the best management practices to control diffuse pollutants from agricultural land and urban surface runoff in improving water quality of the Songhua River Basin. The revised S-P model can be successfully used to identify pollution source and quantify point source and nonpoint source loads by calibrating and validating.
Keywords: ammonia nitrogen; chemical oxygen demand; nonpoint source pollution; point source pollution; revised water quality model; Songhua River Basin

1 Introduction

Human activities influence the surface water quality in a most direct way (Belic and Belic, 1996; Withers and Lord, 2002; Enger and Smith, 2006). Since the 1970s, water quality degradation has been considered a hotspot in the world because water is the essence of life and it has no known substitute (Abu-Zeid, 1998; Luo *et al*., 2006). The combined effects of point source (PS) and nonpoint source (NPS) pollution on water environment make it difficult to completely improve water quality. In many rivers the water quality has been improved due to the reduction in point source discharges in developed countries, whereas aquatic ecosystems remain impaired, due to complex pollution problems caused by nonpoint source pollution (European Environment Agency, 1999; USEPA, 2006).

Identification and quantification of pollutants are the first step in finding out the way to protect the river basin appropriately. Point source pollution is easier to control, and substantial reductions in the discharge of pollutants into water bodies have been realized over the past few decades (Taebi and Droste, 2004). Contrary to point source pollution, nonpoint source pollution is an aggregate of small contaminant inputs released from many sources spatially distributed through a watershed. There is an increasing dependence on computerized models. Consequently, a large number of nonpoint source models have been developed. However, extensive data sets preparation and results analysis for the models are probably the most common problems encountered by model users (Leon *et al*., 2000; 2001). Especially in China, one of major constraints confronting scientific evaluation in a river basin is lack of longer time series

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monitoring data, and sufficient monitoring and gauging stations. Moreover, models were developed for a specific purpose to accomplish a specific job, and application of the introduced models from abroad could result in erroneous answers due to outside specific conditions (Knisel, 1982). Indigenous methods developed or revised according to Chinese specific conditions were almost experimental or empirical models, including mean concentration method (Li, 2000), hydrological method (Chen *et al.*, 2003), correlation method of water quality and quantity (Hong and Li, 2000) and the simplified method using surveyed data and hydrological information of outlet section in a river basin (Yang *et al.*, 2009). However, the methods considering self-purification capacity of river remain underexplored in literatures.

The Songhua River is the key surface water resource for more than 62×10^6 people in Northeast China. Unremitting efforts have been made to improve river water quality, and treatment facilities for waste water from point source have been constructed in the past years. However, these sewage and industrial effluent treatment facilities are not yet fully implemented and operated in the Songhua River Basin. Therefore, point source might be a significant pollution source to the river, and nonpoint source will be an important cause of surface water quality degradation in the Songhua River (Yang *et al.*, 2009). Chemical oxygen demand (COD) has been a major environmental indicator, and ammonia nitrogen (NH_3-N) pollution has shown continually a upward trend in the Songhua River. Non-persistent pollutants, COD and NH_3-N, can be degraded by physical, chemical, and biological actions in surface water body, according to steady one-dimension Streeter-Phelps (S-P) water quality model. The main objectives of this study are to illustrate a revised S-P method, to identify, quantify, and evaluate the pollution sources and loads in the Jilin Reach of the Songhua River Basin.

2 Materials and Methodology

2.1 Study area

The Jilin Reach of the Songhua River, the south birthplace of the river, was chosen as the study area. The population of the watershed was 13.82×10^6 in 2005. The study area has a drainage area of 78 182 km^2, with approximate coordinates of 41°44′–45°24′N, 124°36′–128°50′E (Fig. 1), and has a marked temperate continental-monsoon climate. Average annual precipitation is 400–900 mm, with 80% precipitation occurring between June and September. Multiyear average temperature falls gradually from upstream mountain area to downstream plain area, and the extreme temperature in a year ranges from –36℃ to 39℃. Black soil with relatively high organic matter content of 45–70 g/kg in the surface horizon comprises the dominant soil types.

The Jilin Reach of the Songhua River consists of the main stream (MS) and five tributaries (TRs). Totally 20 sections were selected on MS and three key tributaries of the Huifa River (TR1), the Yinma River (TR2) and the Yitong River (TR3) (Fig. 1).

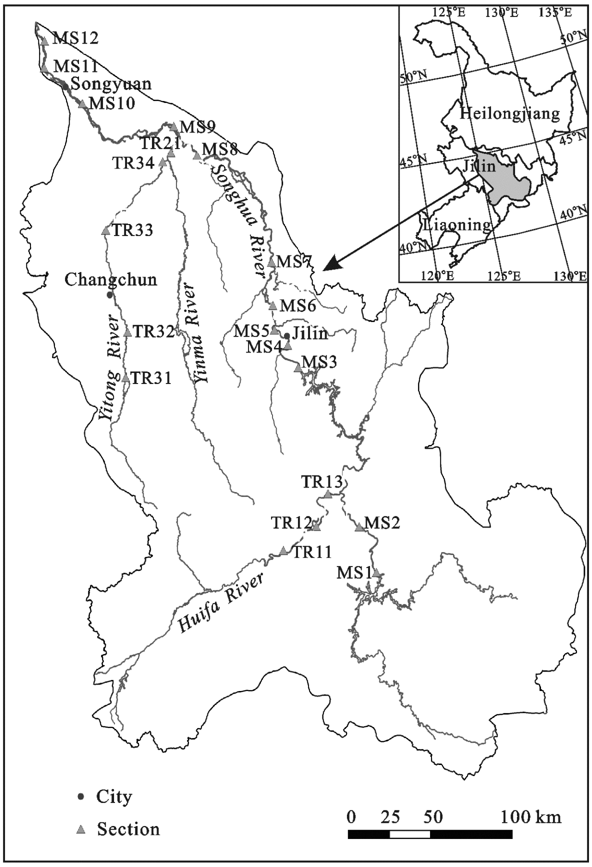

Fig.1 Location of study area and monitoring sections

2.2 Methodology

2.2.1 Revised water quality model

Nonpoint source pollution, coming from many diffuse sources across the landscape, is difficult to specifically identify or abate in contrast to point source pollution. Water quality models are widely used to estimate point source pollution load. In this research a method was revised by considering point and nonpoint sources in steady one-dimension Streeter-Phelps (S-P) water quality model.

The S-P equation can be expressed as:

$$C = C_0 \exp[-K \frac{x}{86400u}] \quad (1)$$

where C is the concentration of a pollutant (mg/L), C_0 is the initialized concentration of the pollutant (mg/L), K is the comprehensive decay coefficient (1/d), x is the distance between initialized and calculated sections (m), and u is the flow velocity (m/s).

The sources of pollutants consist of three components, point source, nonpoint source and river baseline. Therefore, the concentration can be expressed as:

$$C_i = \frac{C_{i-1} \exp(-Kx/86400u) Q_{ri} + C_{pi} Q_{pi} + C_{ni} Q_{ni}}{Q_{ri} + Q_{pi} + Q_{ni}} \quad (2)$$

where C_i is the concentration of a pollutant in section i (mg/L); C_{pi} and C_{ni} are the concentrations of point source and nonpoint source entered in section i (mg/L), respectively; Q_{ri}, Q_{pi} and Q_{ni} are the flow volume of river baseline, point source and nonpoint source in section i (m^3/s), respectively.

Through the transformation, nonpoint source pollution load of the ith section is expressed as:

$$C_{ni} Q_{ni} = C_{ri} (Q_{ni} + Q_{ri} + Q_{pi}) - C_{r(i-1)} \cdot \exp (-Kx/86400u) Q_{ri} - C_{pi} Q_{pi} \quad (3)$$

And the total nonpoint source pollution load (W) is expressed as:

$$W = \sum_{i=1}^{j} (Q_{ni} C_{ni}) \quad (4)$$

It is noticeable that the first section is assumed well mixed and following ones are assumed that the pollutant firstly decayed and then mixed. For each source, the source flow rate multiplied by pollutant concentration was the average annual load in units of ton or kilogram per year. All procedures were performed by iterated interpolation method on the computer.

2.2.2 Basic assumption and input data

The basic S-P equation of the one-dimensional steady state model is developed on the basis of the assumption, that is, the major transport mechanisms, advection and dispersion, are significant only along the main direction of flow. The model allows waste water discharging consecutively. Nonpoint source pollution is driven by rain fall runoff in summer and it is nearly not produced in winter. It is assumed that nonpoint source pollutants enter the river at the monitoring sections installed.

Each generated pollutant load in point sources derived from domestic and industrial activities were estimated in consideration of population and production scales, respectively. Pollution loads and concentrations of point source were the same in the wet (June, July, August, and September), mean (March, April, May, and October), and dry periods (January, February, November, and December)①. The sum of point source loads in 20 sections was equal to COD and NH_3-N emission in the Jilin Province Environmental Quality Reports. Other input data including flow of each section, distance between control sections and velocity were measured and supplied by the watershed hydrological stations. The baseline values of the discharges and concentrations were obtained from local environment protection agency and Jilin Province Environmental Quality Reports (1996–2005). Comprehensive decaying coefficient (K) was obtained by the two-point method, which was authorized by Ministry of Environmental Protection of the People′s Republic of China.

2.2.3 Model calibration and validation

To better estimate the input parameters, the data series of 2005 were used to calibrate this relatively simple and computer-efficient mathematical model. The calibration procedure was performed on both COD and NH_3-N to minimize the effects of error accumulation in pollution loads. Relevant parameters for model calibration included K and the input pollutants concentrations.

The calibration was done by trial-and-error method, with each input parameter being adjusted until the simulation results were reasonably close to the observed values. The statistical measures used to compare observed and simulated data included root mean square error (RMSE) analysis and comparisons between the observed and simulated results. The simulated concentrations and loads were in close agreement with the observed values. The R^2 value (0.9939) indicated that simulation results by the model was satisfactory. It was concluded that the revised water quality model could be used to predict the nonpoint source loads.

3 Results

3.1 Results of monitoring indictors

Chemical oxygen demand is one of the major pollution

① Jilin Province Environmental Quality Report, 2005 control indictors in China, and there is a growing trend to NH_3-N in the Jilin Reach of the Songhua River. Concentrations of COD and NH_3-N are shown in Table 1. Results revealed that the average annual value for both the parameters were higher at urban river sections compared to other ones. The water quality assessment results ranked in descending order were as follows: wet, mean, and dry periods.

Table 1 Average concentrations of COD and NH_3-N along the rivers during 1996–2005 (mg/L)

Section	Period	COD	NH_3-N	Section	Period	COD	NH_3-N
MS1	Wet	4.50	0.14	MS8	Wet	4.78	0.63
	Dry	6.34	0.10		Dry	6.77	0.70
	Mean	6.10	0.18		Mean	6.02	0.40
MS2	Wet	4.69	0.13	TR31	Wet	4.80	0.50
	Dry	6.52	0.12		Dry	4.63	1.00
	Mean	6.53	0.21		Mean	4.65	0.50
TR11	Wet	4.92	0.54	TR32	Wet	6.74	0.40
	Dry	9.01	4.37		Dry	9.22	0.72
	Mean	5.86	0.28		Mean	5.97	0.74
TR12	Wet	4.69	0.77	TR33	Wet	48.17	11.02
	Dry	8.71	4.68		Dry	47.92	17.09
	Mean	6.15	0.24		Mean	49.08	14.15
TR13	Wet	5.81	0.26	TR34	Wet	18.38	9.68
	Dry	10.5	4.23		Dry	42.07	20.4
	Mean	5.80	0.18		Mean	21.81	10.93
MS3	Wet	3.73	0.21	TR21	Wet	11.65	3.31
	Dry	4.82	0.18		Dry	18.23	14.46
	Mean	4.86	0.24		Mean	13.07	6.44
MS4	Wet	5.60	0.26	MS9	Wet	6.06	1.07
	Dry	5.11	0.22		Dry	5.56	3.09
	Mean	5.21	0.32		Mean	6.04	0.65
MS5	Wet	7.03	0.90	MS10	Wet	5.58	0.64
	Dry	6.75	0.97		Dry	4.94	0.76
	Mean	6.50	0.85		Mean	5.21	0.70
MS6	Wet	6.76	0.95	MS11	Wet	6.04	0.95
	Dry	6.95	0.89		Dry	5.25	1.11
	Mean	6.09	0.88		Mean	5.61	0.97
MS7	Wet	6.15	0.72	MS12	Wet	5.63	0.77
	Dry	6.34	0.80		Dry	5.07	0.90
	Mean	5.76	0.78		Mean	5.63	0.88

Note: The sections are arranged in order of spatial distribution.

Among all monitoring sections, 75% of surface water monitoring sections and 90% of urban river sections were subject to pollution at different degrees. Moreover, the water quality of the main stream was better than that of the three tributaries. Water quality of downstream was worse than that of upstream in all tributaries.

3.2 Pollution loads of point and nonpoint sources

Applying the revised water quality model, the loads of COD and NH_3-N entering the Jilin Reach of the Songhua River, and the percentages of point source and nonpoint source loads to the total loads are shown in Table 2 and Table 3. Total nonpoint source loads of both COD and NH_3-N were less than point source loads in the study basin. The COD loads of point source were greater than those of nonpoint source, and the NH_3-N loads of point source were nearly equal to those of nonpoint source in the main stream. The point source loads of COD and NH_3-N in TR1 were greater than nonpoint source loads, respectively. However, there were some difference between the main stream and tributaries. Both COD and NH_3-N loads of nonpoint source were greater than those of point source loads in TR2. COD loads of nonpoint source in TR3 were greater than those of point source, whereas NH_3-N loads were not.

Table 2 Loads of COD and NH_3-N entering study area

Source	COD (t/yr)	Percentage (%)	NH_3-N (t/yr)	Percentage (%)
Nonpoint	86209	38.98	14272	46.02
Point	134959	61.02	16739	53.98
Total	221168	100.00	31011	100.00

Table 3 Pollution loads estimated in study rivers

River	COD (t/yr)		NH_3-N (t/yr)	
	NPS	PS	NPS	PS
MS	55029	109516	6366	6431
TR1	6229	7291	23	659
TR2	822	494	4329	1668
TR3	24129	17658	3555	7980

Note: NPS is nonpoint source; PS is point source.

COD and NH_3-N loads at each monitoring section are presented in Fig. 2 and Fig. 3, respectively. Nonpoint source loads were higher than point source loads at 45% monitoring sections. The pollution loads of downstream were greater than those of upstream, and the loads at cities reaches were higher than those at other reaches.

4 Discussion

4.1 Distribution of pollution loads in main stream

Pollutant loads differ with the river basin area and the flow regime (Ichiki *et al*., 1996; Drolc *et al*., 2007). In this study, flow and concentration of pollutants changed

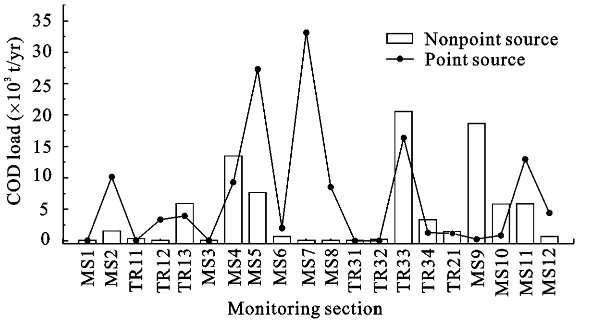

Fig.2 COD load at different monitoring sections

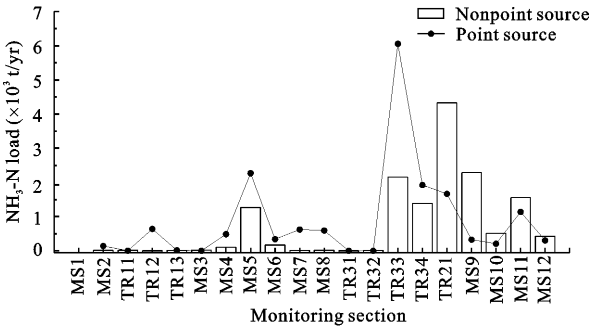

Fig.3 NH_3-N load at different monitoring sections

greatly along the river. The total COD loads varied from 10 t/yr at MS3 to 34 970 t/yr at MS5. COD loads of nonpoint source ranged from 5 t/yr at MS3 to 18 624 t/yr at MS9, and COD loads of point source from 5 t/yr at MS3 to 33 115 t/yr at MS7. MS3 section is close to the mouth of the Songhua Lake with a high vegetation cover. While both MS5 and MS7 are the sections in Jilin City, receiving most of urban sewage and industrial effluent. Jilin City is a second-largest city of Jilin Province and is the heavy and chemical industries base. The urban river sections were worst affected by industrial COD from the chemical plants with insufficient wastewater treatment facilities. The industrial and sewage COD discharge reached 28 625 t/yr and 38 989 t/yr, accounting for 18% and 16% of the total emission in Jilin Province, respectively.

The maximum NH_3-N loads of point source occurred at MS5 which was affected by industrial and sewage effluent in Jilin City. NH_3-N discharge in Jilin City was the most volume and accounted for 34% of the total loads in Jilin Province. Whereas the maximum nonpoint source NH_3-N loads occurred at MS9 section whose upstream is the main area of livestock and poultry breeding industry and has the largest cattle farming and trading market. MS9 is established near to the location of the Yinma River inflowing into the Songhua River. It indicated that the Yinma River played an important role in degrading water quality of the main stream. COD and NH_3-N loads of MS10, MS11 and MS12 sections accounted for 19% and 32% of the total main stream loads, respectively.

Figure 2 and Fig. 3 showed that two peaks occurred in the river of Jilin City and Songyuan City. And the pollution loads of downstream were significantly greater than those of upstream. It indicated that urban sewage and industrial effluent significantly impacted river water quality. Agricultural and industrial productions are concentrated in Changchun City, Jilin City and Songyuan City, which are located in the middle and downstream of the river basin. The up-to-standard discharge rate of industrial effluent was 81% in 2005, failing to meet the anticipated target (85%) for 2005. Urban sewage treatment rate in the three cities were 32%, 17% and 0, respectively. Annual mean waste water discharge in the three cities reached 437×10^6 t/yr, of which COD and NH_3-N loads were 134 958 t/yr and 16 739 t/yr, respectively.

COD and NH_3-N loads of point source were 1.6 times and 1.2 times greater than the loads of nonpoint source, respectively. Point source is still the main pollution source in the Jilin Reach of the Songhua River. Typical pollution sources are urban sewage and industrial effluent, most of which directly discharge into surface waters. Agricultural low economic profitability has caused proliferation of pig and cattle farming as an alternative economic activity in the rural and urban skirt areas, provoking a notorious problem of manure management. Large scale livestock and poultry breeding industry, agricultural activities and urban surface runoff may be responsible for the higher percentage of nonpoint source NH_3-N. The results were in accordance with the findings of other researchers (Yue *et al*., 2007; Qian *et al*., 2007). With the reduction in point source discharges, introduction and operation of treatment facilities, and processing improvement efforts, it is inevitable that nonpoint source pollution loads will exceed point source pollution loads, and become an important environment issue in the study area (Yang *et al*., 2009).

4.2 Distribution of pollution loads in tributaries

The spatial distribution of pollution loads in the tributaries was in accordance with that in main stream. The water quality of downstream and the urban river sections were worse than those of upstream and the remaining sections. The maximum loads of both COD and NH_3-N were shown at TR33 section on the Yitong River. TR33 section was established on the downstream of Changchun City, which is the capital of Jilin Province. The waste water effluent in Changchun City accounted for 28% of the total emission in Jilin Province. In fact, the Yitong River has become a natural drainage channel of Changchun City due to lower urban sewage treatment rate (32%). When the impaired Yitong River flows to the Yinma River, the water quality of the Yinma River suffers dramatically. It indicated the reason why the total NH_3-N loads at TR21 was the greatest among all sections. The TR21 section on the Yinma River was impacted by the seriously polluted Yitong River. Point and nonpoint sources loads of the key pollution factor NH_3-N were 4 329 t/y and 1 668 t/y in the Yinma River basin, respectively.

COD loads of point source and nonpoint source in the Yitong River accounted for 69 % and 77% of the three tributaries loads, respectively, and NH_3-N loads of point source and nonpoint source accounted for 77% and 44% of the total loads, respectively. This showed that the Yitong River contributed significantly to the Jilin Reach of the Songhua River. The Yitong River was polluted seriously due to point source and nonpoint source, probably related to 1) the maximum leaching from the basin caused by rainfall, 2) the low dilution capacity and less active biological, chemical, physical purification capacity of water body, and 3) a large number of livestock breeding farms without wastewater treatment facilities near the river.

4.3 Management options for water quality improvement

Regarding to the quantification of point and nonpoint source loads entering to the main stream and three tributaries, point source, especially point source COD is the key pollution source in the study area. It is necessary to enhance the treatment of industrial effluent, to strictly carry out the discharge standard for water pollutants and the total amount control system, and to incorporate NH_3-N in the total amount control system.

Together with the impact of some industrial effluents, agricultural activities and urban sewage caused a clear impact on water quality of the Songhua River. The proportion of nonpoint source pollution to the total loads is generally rising, and will become the major source of the pollution loads to the river. Agricultural nonpoint source pollution, such as erosion of cropland and the unreasonable application of agrochemicals to cropland, should be controlled and diminished firstly by land use planning and best management practices. Maintaining the natural geomorphologic features, especially the meandering pattern of the river, is also compulsory for the good ecological condition of the river, and it is a key factor in preserving the self cleansing capacity of the river (Torrecilla *et al*., 2005).

5 Conclusions

Water pollution showed significant spatial variations in the Jilin Reach of the Songhua River Basin, and urban river sections were important to improve water quality. The revised water quality model, depending on the hydrometeorological characteristics and monitoring data series of the study area, was an effective method to estimate pollution loads.

Point sources were still the main COD and NH_3-N generators in the Jilin Reach of the Songhua River Basin. Nonpoint sources were the main causes of COD pollution within the Yinma River and the Yitong River, and NH_3-N pollution within the Huifa River and the Yitong River. Both point source and nonpoint source pollution severely impacted the water quality in the Jilin Reach of Songhua River Basin. With the considerable progress in reducing pollutant loads from point source discharges, most of pollutants of water quality impairments will result from nonpoint and other nontraditional sources.

Improvement of urban and industrial wastewater treatment facilities should be quickly undergone. Agricultural nonpoint source could be diminished by carrying out best management practices as well as soil and water conservation.

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