Environ Model Assess (2008) 13:155–167
DOI 10.1007/s10666-006-9079-x

Nonpoint Source Pollution Assessment of Wujiang River Watershed in Guizhou Province, SW China

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Received: 19 April 2006 / Accepted: 22 November 2006 / Published online: 15 March 2007

Abstract The amount of pollution from nonpoint sources flowing in the streams of the Wujiang River watershed in Guizhou Province, SW China, is estimated by a geographic information system (GIS)-based method using rainfall, surface runoff and land use data. A grid of cells of 100 m in size is laid over the landscape. For each cell, mean annual surface runoff is estimated from rainfall and percent land use, and expected pollutant concentration is estimated from land use. The product of surface runoff and concentration gives expected pollutant loading from that cell. These loadings are accumulated going downstream to give the expected annual pollutant loadings in streams and rivers. By dividing these accumulated loadings by the similarly accumulated mean annual surface runoff, the expected pollutant concentration from nonpoint sources is determined for each location in a stream or river. Observed pollutant concentrations in the watershed are averaged at each sample point and compared to the expected concentrations at the same locations determined from the grid cell model. In general, annual nonpoint source nutrient loadings in the Wujiang River watershed are seen to be predominantly from the agricultural and meadow areas. The total annual loadings through the outlet of the watershed are 40,309 and 2,607 tons for total nitrogen (TN) and total phosphorus (TP), respectively.

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Keywords GIS · Nonpoint source pollution · Watershed · Grid model · Loading · Total nitrogen · Total phosphorus

1 Introduction

Nonpoint source pollution (NSP) is an important environmental and water quality management issue. It occurs when rainfall, snowmelt, or irrigation water run over land or through the ground, pick up pollutants, and deposit them into rivers, lakes and coastal waters or introduce them into ground water [2]. Since the late 1960s, point sources of water pollution have been generally reduced due to their relative ease of identification and control. However, water quality problems remain. As further point source control becomes less cost-effective, attention is now being directed towards the contribution of nonpoint sources to water quality impairment [17]. It is becoming increasingly evident that the established water quality goals cannot be attained without controlling NSP. Therefore, identification of the sources and estimation of the loadings of NSP are crucial to environmental management and planning.

Since the early 1970s, a large number of watershed models have been developed, which provide a useful tool for analysis of watershed processes and their interactions, and for development and assessment of watershed management scenarios [8]. Basically, there are two general approaches to diffuse pollution modeling. The more widely used are lumped-parameter models, while models that are more complex are based on the distributed-parameter concept. Lumped parameter models are simple in nature and rely on very general data, but less reliable due to overlooking physical processes and spatial variation. The distributed-parameter models have become very prevalent in the literature in recent years [1, 4, 5, 12], but in application they need extraordinarily large number of parameters and require a considerable amount of work to be calibrated for large watersheds.

In this study, a simplified method of NPS assessment is developed using a geographic information system (GIS), which is based on spatial variation but with few parameters. The model results are used to estimate the mean annual surface runoff, pollutant concentration and pollutant loading for each cell in a grid laid over the landscape of the watershed. In addition, average expected pollutant concentrations generated from NPS are determined.

The Wujiang River watershed, selected for this study, is located in karst areas of Guizhou Province, southwest China, an impoverished mountainous region, where studies about NSP have just begun and very limited field data are available. Thus, the integrated model developed in this study demonstrates an alternative for many areas without sufficient monitoring data. This model can be used by researchers and planners to estimate the loadings from watersheds in environmental management, although the model probably yields, in some cases, a less accurate estimation of loadings of nonpoint sources than some of the distributed-parameter models.

2 Study Area

Wujiang River is the largest river in Guizhou Province, with a total length of 874 km and an approximate watershed area of 66,849 km^2 (Fig. 1). Rising in the Wumeng Ranges on the Yunnan–Guizhou plateau, Wujiang River is the largest tributary of the Yangtze River in the upper reaches and winds through four provinces (Yunnan, Guizhou, Chongqing and Hubei). It has a mean water discharge of 1,690 m^3/s. The highest river discharge observed during summer amounts to 21,000 m^3/s. The climate type of the watershed is typically subtropical monsoon climate. Mean annual precipitation in the watershed, averaged over several years, ranges from 850 to 1,600 mm, and the precipitation decreases from south to north and from east to west. Precipitation during summer averages from 450 to 850 mm, accounting for about 50% of annual precipitation. Altitudes

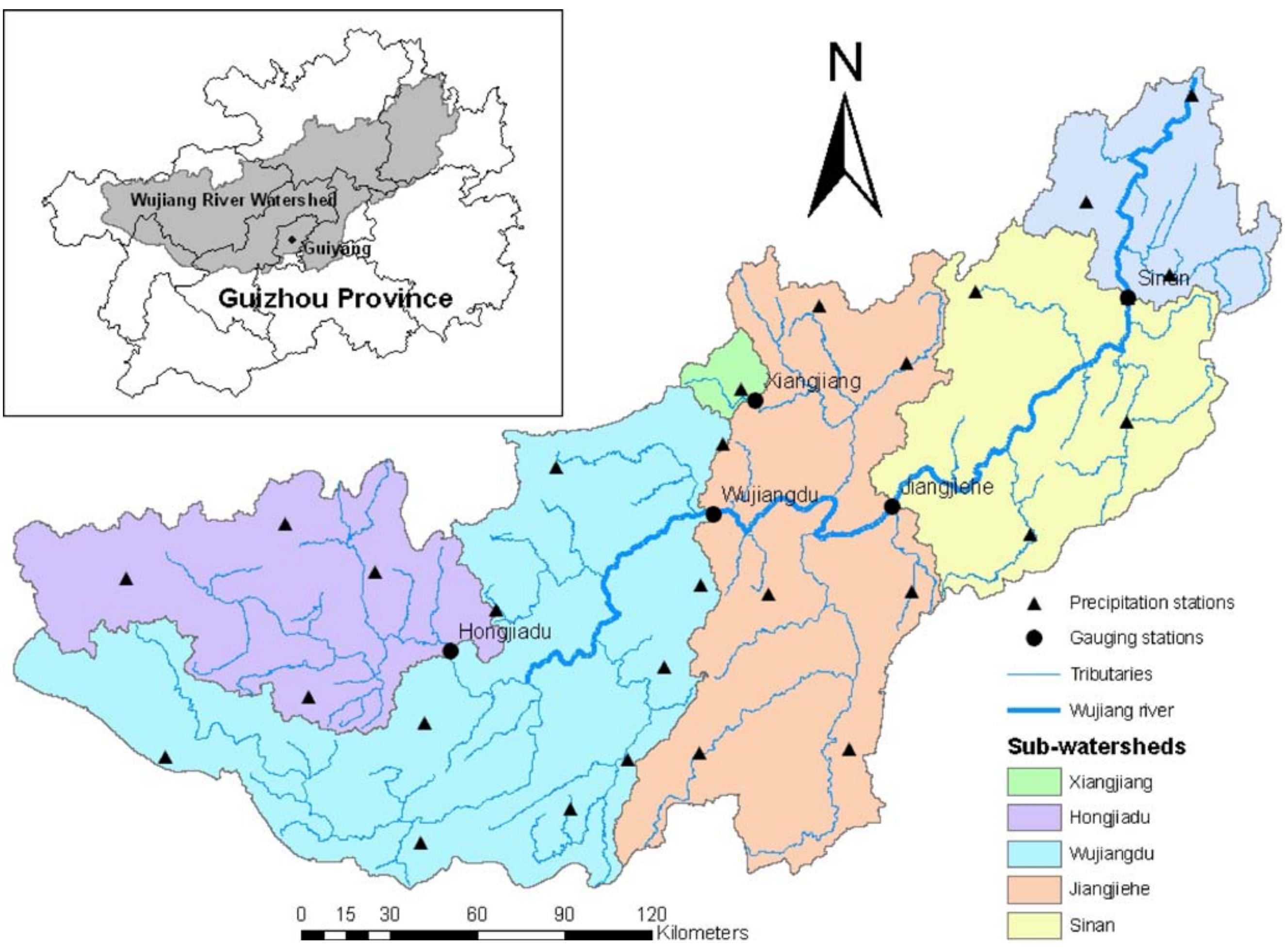

Fig. 1 Location of Wujiang River watershed with different sub-watersheds, gauging stations and precipitation stations

of the watershed are about 1,500 m in its upper reach and about 500 m in its lower reach. Vegetation covers are variable, generally with high vegetation covers in its lower reaches, but the upper reaches pose soil and water loss related environmental problems [7].

3 Methods and Materials

3.1 Data Collection

3.1.1 Data Sources and GIS Projections

This study uses raster and vector data sets that are publicly available from a variety of sources. In general terms, three sources of information, digital elevation model (DEM), digital stream network and watershed boundary, are required to build a grid model of surface drainage. The 1:25,000-scale DEM data is obtained from the National Geomatics Center of China (NGCC) and is reprojected from geographic coordinates to Albers Equal-Area Conic, in which central meridian is 105°E, two standard parallels are 25°N and 47°N, respectively, and the spheroid is Krasovsky-1940, with 100×100 m grid cell size. All other geographic data are projected to the same coordinate system of DEM data. The digital stream network and watershed boundary were created through digitization of a combination of 1:50,000- and 1:10,000-scale Hydrologic Unit Maps of Guizhou Province.

In addition, precipitation data and land use data are required to calculate the surface runoff on each grid cell. Rainfall data typically provide a prime input to any NSP model. The precipitation data obtained from Guizhou Provincial Institute of Geology and Mineral Resources is a mean annual precipitation isoline map for Guizhou province from 1956 to 2000. The isoline map is converted into Triangulated Irregular Network (TIN) data and then converted into grid data with 100×100 m grid cell size (Fig. 2). The 1:10,000-scale land use data file, a GIS polygon coverage, was bought from Beijing CASW Data Technology Co., Ltd., and was created through interpretation of Landsat TM images acquired in 2000. The land use file employs the Chinese State Forestry Land Use Classification System, which identifies two-digit subcategories within the categories of agricultural, forest, meadow, water, urban/industrial/residential, and barren land uses. The polygon coverage is then converted into grid data with same grid cell of DEM data (Fig. 3).

Geographic locations (in degrees, minutes and seconds) of the five gauging stations (Xiangjiang, Hongjiadu, Wujiangdu, Jiangjiehe and Sinan) that have long-term hydrological data are available from Guizhou Provincial Hydrology and Water Resources Bureau (Fig. 1).

3.1.2 Hydrological Data Analysis

Monthly and annual average streamflows of all five gauging stations cited above are available from Guizhou Provincial Hydrology and Water Resources Bureau for the period 1956–2000.

Streamflow is composed of two main elements: baseflow, which has its origin in groundwater, and surface runoff, which is the accumulation of rainfall that drains to

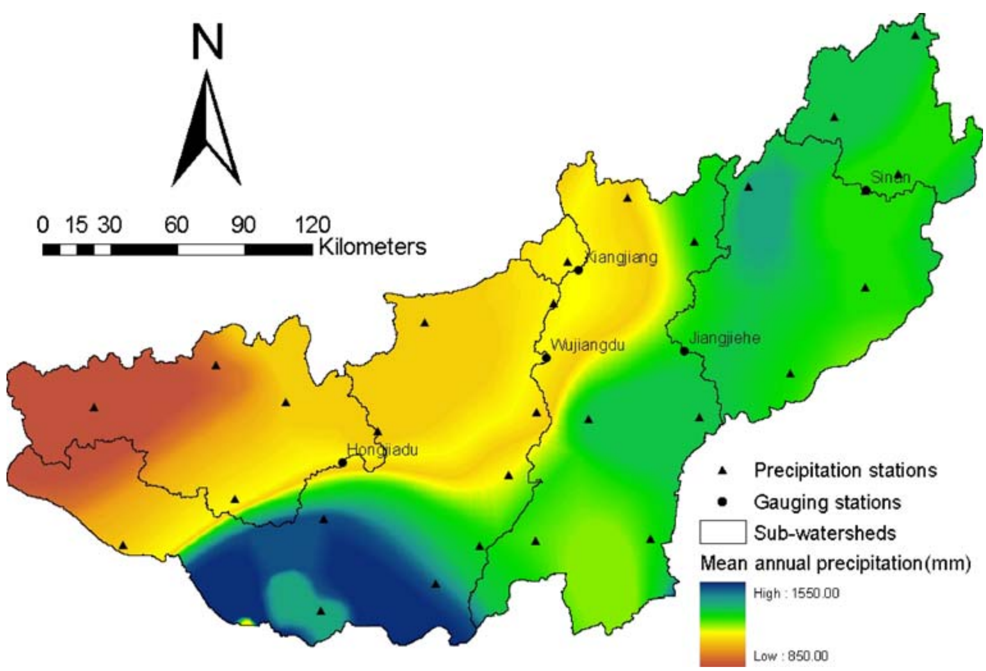

Fig. 2 Average annual precipitation in the Wujiang River watershed

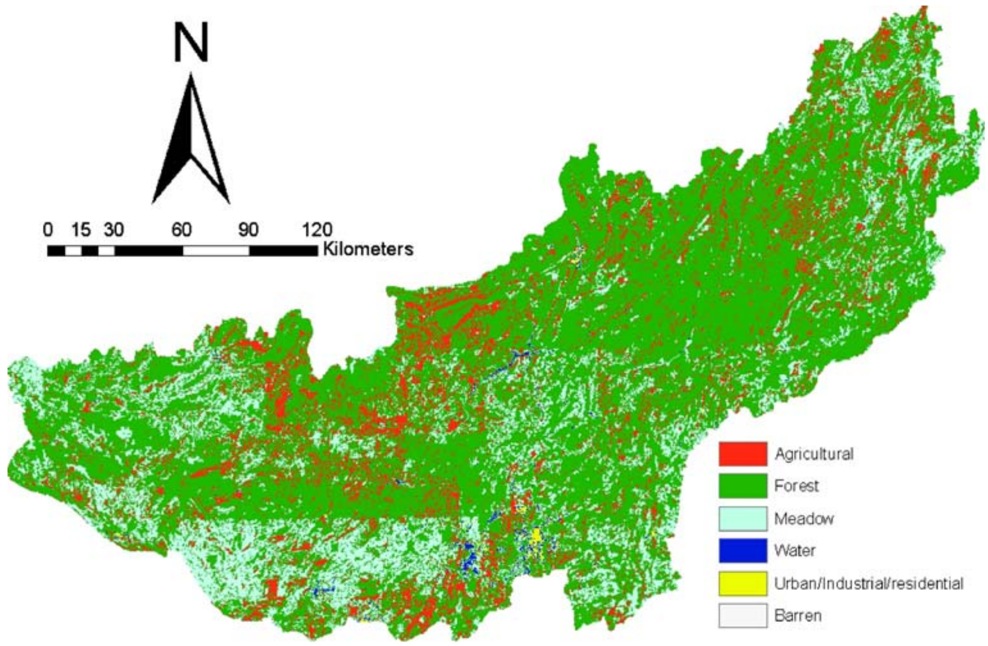

Fig. 3 Land uses in the Wujiang River watershed

the stream. Nonpoint source pollutants are carried over land and into the stream networks of a region by surface runoff. Because karstification is most developed and groundwater is plentiful in the watershed, the contribution of baseflow to the streamflow cannot be ignored. To calculate surface runoff, baseflow should be partitioned off from the streamflow.

Based on the rainfall data of 39 meteorological stations in the 30-year period from 1971 to 2000, daily area rainfalls were computed and then the frequencies of intensive daily area rainfall were analyzed (Table 1). The following observations were noted: (1) no area rainfall with intensity exceeding 20 mm occurred in January, February and December, and one occurred in March; (2) there were three area rainfalls with intensity ranging between 5 and 69.9 mm in 30 years, and all occurred in June or July; (3) area rainfalls with intensity exceeding 20 mm occurred from May to September with a frequency of 90.6%. Therefore, the streamflow in winter (January, February and December) can be used to represent the baseflow. Then surface runoff can be calculated by subtracting baseflow from streamflow. The depth of surface runoff for each sub-watershed is obtainedfound by dividing the volume by the area of the sub-watershed. The annual streamflow, baseflow, surface runoff and annual depth of surface runoff for each sub-watershed are calculated and shown in Table 2, based on the monthly and annual average streamflows of the five gauging stations.

3.1.3 Water Quality Measurement Data

Water quality data measured in the region for a 15-year period spanning 1986–2000 was obtained from Guizhou Provincial Hydrology and Water Resources Bureau. Surface water quality monitoring data available for the Wujiang River watershed included nine monitoring stations measur-

Table 1 Distribution of frequencies of intensive daily area rainfall in Wujiang River watershed from 1971 to 2000[a]

Intensity (mm)	Month									Sum
	3	4	5	6	7	8	9	10	11	
20–29.9	1	7	37	63	27	32	30	15	3	215
30–49.9	0	0	10	35	25	12	6	2	1	91
50–69.9	0	0	0	1	2	0	0	0	0	3
≥70	0	0	0	0	0	0	0	0	0	0
Sum	1	7	47	99	54	44	36	17	4	309
Frequency (%)	0.3	2.3	15.2	32.0	17.5	14.2	11.7	5.5	1.0	–

[a] Data acquired from the Internet (http://www.climate.hb.cn).

Table 2 Annual depth of surface flow of sub-watersheds

Sub-watershed	Annual streamflow (m^3)	Annual baseflow (m^3)	Annual surface runoff (m^3)	Annual depth of surface runoff (mm)
Xiangjiang	2.73350×10^{8}	1.01202×10^{8}	1.72148×10^{8}	310.7
Hongjiadu	4.48329×10^{9}	1.62157×10^{9}	2.86172×10^{9}	302.8
Wujiangdu	1.49639×10^{10}	5.92917×10^{9}	9.03474×10^{9}	325.2
Jiangjiehe	2.20375×10^{10}	8.33291×10^{9}	1.37046×10^{10}	324.0
Sinan	2.76042×10^{10}	1.04990×10^{10}	1.71053×10^{10}	333.6

ing various combinations of 46 water quality parameters. The parameters typically fall into three classes: (1) conventional parameters, such as pH, dissolved oxygen, and temperature, (2) nutrients (e.g., nitrogen and phosphorus), and (3) toxics (e.g., metals and pesticides). These data are used to validate the model by comparing them with modeled values.

3.1.4 Expected Mean Concentrations

The measure of pollutant level during a runoff event is the expected mean concentration (EMC), measured in mg/l, and defined as the ratio of the mass of pollutant in the event divided by the volume of runoff [15, 16]. EMCs are frequently used to characterize nonpoint source pollutants' loadings and can be multiplied by the runoff volume to estimate the mass discharge [3, 6, 11]. EMC has a statistical distribution, and varies in value from event to event [10]. It is believed that EMC is directly related to land use in the watershed. EMC values for total nitrogen (TN) and total phosphorus (TP) were used during this study and are included in Table 3. Values in the table are typical concentrations of constituents found in runoff water from each particular land use. The values are compiled from many field monitoring data of Guizhou Provincial Environmental Protection Bureau and Guizhou Provincial Hydrology and Water Resources Bureau.

3.2 Model Description

The model developed in this study has five components: (1) grid model of the watershed, (2) mean annual surface runoff computed from rainfall, (3) linking EMC of pollutants to land use, (4) calculation of annual pollutant loadings throughout the watershed, and (5) estimation of downstream pollutant concentrations. The detailed description of each component is provided below.

3.2.1 Grid Model of the Watershed

Grid DEMs are readily available and simple to use and hence have seen widespread applications to the analysis of hydrologic problems [13]. A grid of 100-m cells is laid over the landscape based on 1:25,000-scale DEM data. Although many algorithms have been proposed, the algorithm of eight flow directions (D8) is still the most popular approach to model the watershed drainage structure [18]. This method, introduced by O'Callaghan and Mark [14], specifies flow directions following each pixel to one of its eight neighbors, either adjacent or diagonally, in the direction with the steepest downward slope, resulting from a flow direction for each grid cell. By tracing these cell-to-cell drainage connections downstream, the drainage path from every cell to the watershed outlet is determined, thus generating a flow connectivity network through the whole

Table 3 Relationship between land use and expected mean concentrations

Land use	TN (mg/l)		TP (mg/l)	
	Range	Average	Range	Average
Paddy land	0.84–6.24	2.79	0.040–0.267	0.12
Dry land	1.06–12.24	5.04	0.051–0.710	0.30
Forest	0.05–0.58	0.54	0.036–0.050	0.04
Meadow	1.84–1.90	1.87	0.110–0.360	0.17
Beach land	5.20–5.39	5.30	0.320–0.510	0.40
Urban/Industrial	3.38–10.65	7.01	0.210–0.855	0.56
Rural residential	2.24–8.62	6.02	0.108–0.315	0.20
Barren	1.26–4.47	2.32	0.072–0.249	0.11

watershed. From any cell, the number of cells upstream can be counted which is called the flow accumulation grid. Streams are identified as lines of cells whose upstream drainage area exceeds a threshold value; watersheds are identified as the set of cells whose drainage passes through a particular outlet cell on a stream.

To ensure that the mapped streams are correctly reproduced in the drainage paths derived from the digital elevation data, the mapped streams were imposed onto the DEM by a DEM reconditioning method called AGREE developed by Center for Research in Water Resources (CRWR) at the University of Texas at Austin [9]. The AGREE reconditioning process lowers the grid cells corresponding to the mapped streams by an amount designated by the user, while the cells within a buffer distance of the rivers are altered to have a smooth transition from the unmodified land surface to the lowered river cells. This device ensures that the grid streams and the mapped streams are completely consistent at the expense of some distortions in the watershed boundaries where the mapped streams and the digital elevation data are not in complete harmony with each other. Production of an improved digital elevation model for the watershed from digital orthophotoquads would help to overcome the problem regarding inconsistency.

3.2.2 Mean Annual Surface Runoff Computed from Rainfall

For this study, the surface runoff is assumed to be a function of precipitation and land use. The multiple regression tool is used to determine the relationship between surface flow, precipitation and percent land use. Data of the five gauging stations in the watershed (Xiangjiang, Hongjiadu, Wujiangdu, Jiangjiehe and Sinan) were used. For each gauging station, the sub-watershed drainage area was delineated from the grid model, as shown in Fig. 1. The derived drainage areas are then compared with the corresponding surveyed drainage areas done by Guizhou Provincial Hydrology and Water Resources Bureau, as shown in Table 4. The percent errors in Table 4 indicate that the digitally delineated drainage areas match the measured areas fairly accurately.

The mean annual precipitation for each gauging station was determined by spatially averaging the precipitation over the cells in its drainage area. The mean annual depth of precipitation (mm/year) for each sub-watershed is found by dividing the accumulated precipitation by the derived drainage area. The mean annual depth of surface flow (mm/year) for each sub-watershed is shown in Table 2. The land use coverages of each sub-watershed are acquired by clipping the land use file with the sub-watershed boundaries, and then the areas of each land use category in the clipped land use coverages are summarized by a statistical tool of GIS software [15]. The areas of each land use category are divided by the total area and multiplied by 100% to find the percent land use in the sub-watershed. The mean annual depth of surface flow and precipitation, percent land use for each sub-watershed is shown in Table 5.

Using the data in Table 5 as input values, the multiple regression tool is utilized with surface runoff depth for the y input and the precipitation depth and percent land use are used as the x inputs. For each land use category, an equation is calculated. The mean annual runoff can be found for each grid cell by applying equations to the precipitation grid shown in Fig. 2 according to the land use of the cell, to produce a grid of surface runoff, Q, in mm/year.

3.2.3 Linking Expected Mean Concentration of Pollutants to Land Use

For this study, it is assumed that EMC is directly related to land use in the watershed. To associate pollutant EMCs with land use, the land use coverage shown in Fig. 3 is used along with the EMC data from Table 3. The EMC data is attached to the land-use polygon attribute table through use of the Join Data command in GIS, by using the land use category identifier as the linking item between both tables. Then the concentration grids of pollutants are created by converting land use polygon to grid with same grid cell of DEM data using EMCs as the cell values.

3.2.4 Calculation of Annual Pollutant Loadings throughout the Watershed

The pollutant mass contribution that each cell makes to downstream pollutant loading is calculated by taking the

Table 4 Comparison of the derived drainage areas and measured drainage areas for each of the sub-watershed

Sub-watershed	Derived drainage area (km^2)	Measured drainage area (km^2)[2]	% Error
Xiangjiang	535	554	3.43%
Hongjiadu	8,678	9,450	8.17%
Wujiangdu	26,165	27,780	5.82%
Jiangjiehe	40,100	42,299	5.20%
Sinan	49,458	51,270	3.53%

[2] data obtained from Guizhou Provincial Hydrology and Water Resources Bureau

Table 5 Input values used in the multiple regression tool

Sub-watershed	Surface flow (mm/year)	Precipitation (mm/year)	% Agric	% Forest	% Meadow
Xiangjiang	310.7368	1089.69	22%	70%	4%
Hongjiadu	302.8278	979.13	36%	42%	21%
Wujiangdu	325.2245	1112.41	36%	39%	23%
Jiangjiehe	323.9940	1130.05	33%	46%	20%
Sinan	333.6310	1148.73	31%	49%	18%

product of the EMC and surface runoff associated with the cell, or

$$\text{Load(mass/time)} = \text{EMC(mass/volume)} * \text{(volume/time)} \quad (1)$$

For load computations in this study, equation (1) becomes:

$$L = K * Q * \text{EMC} * A \quad (2)$$

where Q is surface runoff (mm/year), EMC is expressed in mg/l, A is the area of one grid cell (10,000 m^2), and K is a constant to make the units consistent, i.e. $K=10^{-6}$ kg m l/mg mm m^3, so that L is expressed in kg/yr.

A value of L is computed for each cell in the landscape to represent its local contribution to contaminant loading. The accumulated loading going downstream is determined by summing the loadings arising from all upstream cells.

An important assumption made in this computation is that the downstream transport process is conservative, that is, the pollutant concentration is not modified by instream water quality processes. A second important assumption is that the EMC from a runoff event is applied here to the mean annual surface runoff, which is the sum of all surface runoff events.

3.2.5 Downstream Pollutant Concentrations Compared to Observations

The pollutant concentration sampled at a particular location on a stream is the result of a mixture of all the flows and pollutant loadings that drain from upstream of that location. This mixing process can be approximated for the grid model by taking the accumulated loadings computed in Section 3.2.4, and dividing them by similarly accumulated mean annual flows derived from the surface runoff found in Section 3.2.2. In other words, for each cell on a stream, if one obtains the total mean annual pollutant loading, L_a, and the mean annual surface runoff, Q_a, from the upstream drainage area, the modeled concentration, C_a, at that location is:

$$C_a = \frac{L_a}{Q_a} \quad (3)$$

Pollutant concentrations have been sampled in the watershed at various locations over times. A simplifying assumption is made that the expected concentration observed at a sampling site is simply the average of the measurements performed there. In other words, at each sampling point, if C_i is the ith measured concentration, i=1, 2, ..., n, then the average observed concentration, C_o, is:

$$C_o = \frac{1}{n}\sum_{i=1}^{n} C_i \quad (4)$$

This is equivalent to assuming that the observed pollutant concentrations, C_i, are statistically stationary through time, from year to year, and also within a year, so that seasonal effects are neglected.

The difference between predicted NPS concentration levels and observed concentration levels at a specific location indicates a single point loading at that location.

4 Results and Discussion

4.1 Mean Annual Surface Runoff

The Microsoft Excel 2003 Regression Tool was used to determine the appropriate equation to represent the relationship between precipitation and surface runoff for each type of land use. The input values for the regression tool is shown in Table 5. The equation takes the following form:

$$lnQ = a + b * P + c * ln(\%A) \quad (5)$$

where Q is surface runoff depth (mm/year); a, b and c are coefficients calculated the using regression tool; P is precipitation depth (mm/year); and %A is percent land use.

For agricultural land use, the coefficients derived from the output of regression analysis (Table 6) are plugged into equation (5):

$$lnQ = 5.220454 + 0.000571 * P + 0.067157 * ln(\%A) \quad (6)$$

Table 6 Summary output for the agricultural land use, precipitation, and runoff analysis

Regresssion statistics	
Multiple *R*	0.97664578
R^2	0.953836989
Adjusted R^2	0.907673977
Standard Error	0.011788657

Anova	*df*	SS	MS	*F*	Significance *F*
Regression	2	0.005742998	0.002871499	20.6623649	0.046163011
Residual	2	0.000277945	0.000138972		
Total	4	0.006020943			

	Coefficients	Standard error	*t* statistics	*P value*	Lower 95%	Upper 95%	Lower 95%	Upper 95%
Intercept	5.220453618	0.097743923	53.40949526	0.00035038	4.799895458	5.64101178	4.79989546	5.641011777
X Variable 1	0.000570901	$9.00327\text{x}10^{-5}$	6.341042483	0.02397923	0.000183522	0.00095828	0.00018352	0.00095828
X Variable 2	0.067156884	0.029489931	2.277281813	0.15048159	−0.059728049	0.19404182	−0.059728	0.194041818

The equation is solved for surface runoff, Q. If percent agriculture is assumed to be 100%, the last term in the equation, which represents percent agriculture, equals one and can then be dropped from the equation. Equation (6) results:

$$Q = 185.0181 * \exp(0.000571 * P) \tag{7}$$

Again, the coefficients derived from the output of regression analysis are plugged into equation (5), and are solved for surface runoff, Q, for forest and meadowland uses, respectively.

$$\text{For forest land use}: Q = 165.4729 * \exp(0.000562 * P) \tag{8}$$

$$\text{For meadow land use}: Q = 184.2624 * \exp(0.000536 * P) \tag{9}$$

For water areas, the precipitation is completely converted to streamflow:

$$Q = P \tag{10}$$

Due to the low percentage of urban/industrial/residential and barren land use (0.61% and 0.02%, respectively) in the study area, there are no gauged watersheds in the study area that represent these two land uses. An empirical equation is used to predict the surface runoff because of the percentage of impervious surface is nearly the same in these two land uses:

$$Q = 0.5 * P \tag{11}$$

Figure 4 shows the precipitation versus expected surface runoff curves for agricultural, forest and meadow land uses. By applying equations (7)–(11) to the precipitation grid according to land use, respectively, a grid of surface runoff is produced as shown in Fig. 5. The accumulated surface runoff going downstream is determined by summing the surface runoff arising from all upstream cells, so the accumulated surface runoff in each gauging station can be found. Results of the comparison of accumulated surface runoff and annual surface runoff in the five gauging stations is shown in Table 7. The relatively low percent errors from Table 7 indicate reliable predict of surface runoff based on the above equations.

4.2 Annual Nonpoint Source Pollutant Loadings

A cell-based loading grid is established from equation (2) for TN and TP. Then these loadings are accumulated going downstream to obtain the expected annual pollutant loadings in streams and rivers. The accumulated annual loadings in the watershed are determined by performing a weighted flow accumulation, using the cell-based loading grids as the weight grid and the watershed flow direction grid. By querying the various outlet cells of the sub-watersheds and outlet of the watershed, annual cumulative loads from each sub-watershed and the entire watershed can be established.

Figure 6 shows the annual cumulative loadings of TN in the Wujiang River watershed, displaying aerial distributed values of loading greater than thresholds of 100, 500, 2,000, 10,000 and 30,000 tons/year. Specific loading values at five sub-watershed outlet points and outlet point of the watershed are identified in the figure. The total annual

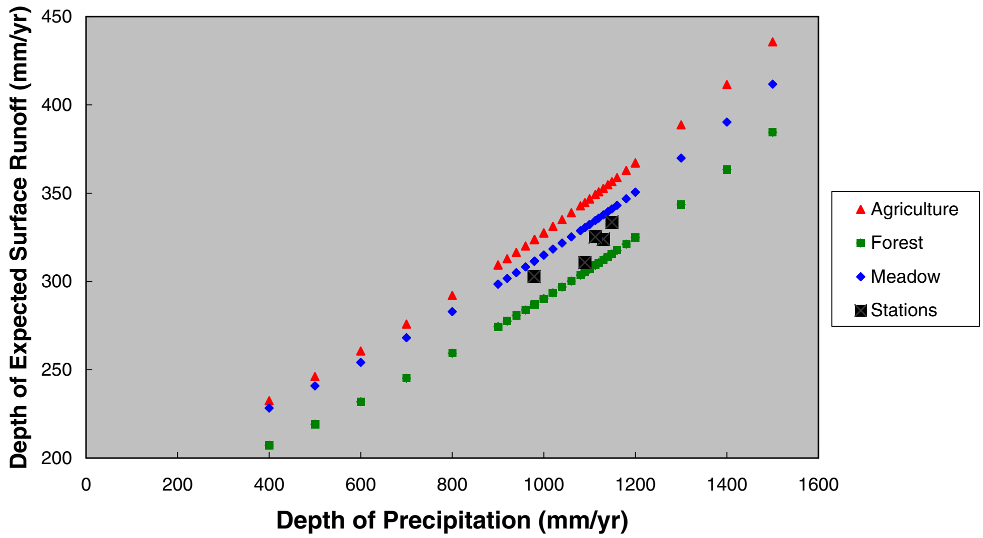

Fig. 4 Depth of precipitation versus depth expected surface runoff for agricultural, forest and meadow land uses

loading of TN through the outlet of the Wujiang River watershed is 40,309 tons.

The average annual cumulative loadings of TP are shown in Fig. 7. In contrast to the loadings of TN, the cumulative loadings of TP in the watershed is generally 1 order-of-magnitude less than that of TN. This is because EMC values for TP are less than those for TN. The total annual loading of TP through the outlet of the Wujiang River watershed is 2,607 tons.

Although the highest nonpoint source derived concentrations of nutrient are expected from urban/industrial/residential and barren land uses, the contributions of total nitrogen from these land uses can be negligible because of the small areas of these land uses, which is less than 2% of the entire watershed area. In general, annual nonpoint source nutrient loadings in the Wujiang River watershed are seen to be predominantly from the agricultural and meadow areas. However, the contributions of nutrient from forest land use cannot be negligible because forests account for 48.35% of the watershed area. Wujiangdu sub-watershed, which accounts for 48.73% of the watershed area, contributes 54.31% and 53.90% for the loadings of TN and TP, respectively, because the areas of agricultural and meadow land uses in the upper and middle Wujiang River watershed are greater than those in the lower watershed.

4.3 Comparison of the Modeled Concentrations and Observations in Stream

Before modeled concentrations can be calculated, grid of annual cumulative surface runoff needs to be established. Annual cumulative surface runoff is created by performing

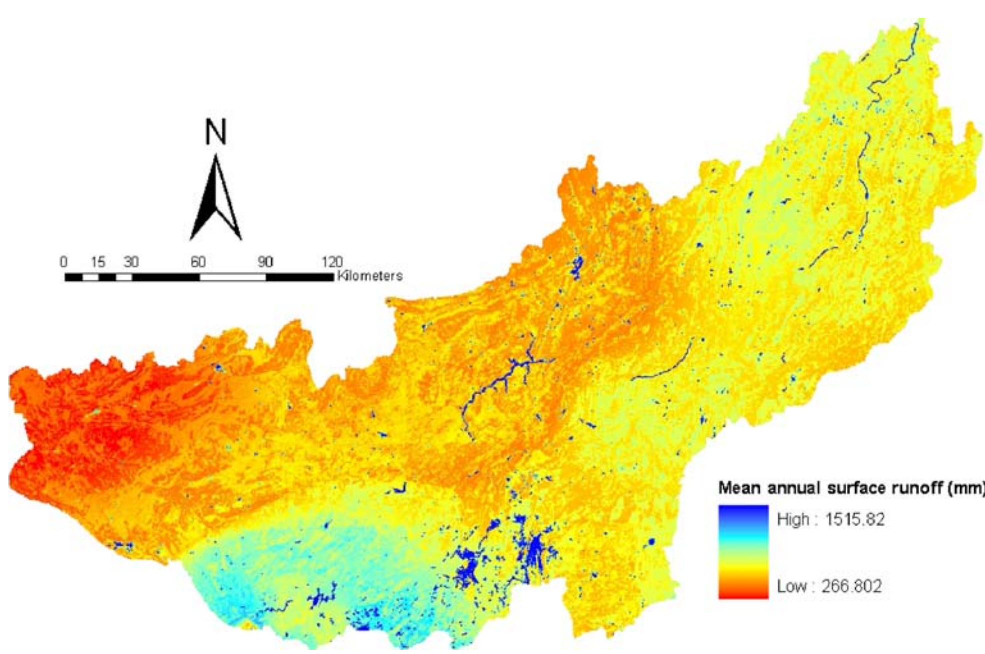

Fig. 5 Estimated surface runoff in the Wujiang River watershed

Table 7 Comparison of accumulated surface runoff (modeled) and annual surface runoff (actual monitored) for each of the gauging station

Gauging station	Accumulated surface runoff (modeled: m^3)	Annual surface runoff (actual monitored: m^3)	% Error
Xiangjiang	1.75745×10^8	1.72148×10^8	−2.09%
Hongjiadu	2.6651×10^9	2.86172×10^9	6.87%
Wujiangdu	8.85053×10^9	9.03474×10^9	2.04%
Jiangjiehe	1.3597×10^{10}	1.37046×10^{10}	0.79%
Sinan	1.68514×10^{10}	1.71053×10^{10}	1.48%

a weighted flow accumulation, using the surface runoff grid as the weight grid. Once the annual cumulative surface runoff grid is created, grids of predicted concentration for TN and TP can be created as per equation (3). These predicted concentrations represent the levels of pollution that are attributed to nonpoint source runoff only.

Figure 8 compares the observed and modeled concentrations of TN. In this map, the cells along the streams have concentration, C_a, computed by equation (3), and are color-coded according to concentration levels. The same color coding scheme is used to shade the circles at each sampling location where the color shown indicates the observed concentration, C_o (equation 4). It is apparent that TN concentrations predicted for the stream networks indicate a heavier contribution of nitrogen from the upper and middle Wujiang River watershed. By comparing the shading of the modeled streams with the sampled circles, the observed concentrations at two locations (Xiangjiang and Guiyang) significantly exceed predicted levels. The average measured concentration at Xiangjiang just downstream from the city of Zunyi is seen to reach 5.77 mg/l, whereas predicted concentration in the same location is 1.98 mg/l. The average measured concentration at Guiyang just downstream from the city of Guiyang is seen to reach 9.37 mg/l, whereas predicted concentration in the same location is 2.94 mg/l. These discrepancies would tend to indicate a significant point source in the area contributing to TN loadings. The observed concentrations at other locations are actually lower than the predicted values. This trend indicates that either (a) the EMC assigned to the specific land use is too high or (b) there is some loss of nitrogen that occurs along the stream network, possibly as the result of sedimentation or decay.

Figure 9 shows a similarly constructed map comparing observed and modeled concentrations of TP. In this case, observed levels are substantially higher than the expected values at Xiangjiang, Guiyang and Sinan, which again indicates a significant point source in those urban areas contributing to TP loadings. Similar to the concentrations of TN, the observed TP concentrations at other locations are lower than the predicted values. Thus, the cause of this phenomenon can also be same as that for TN as described above.

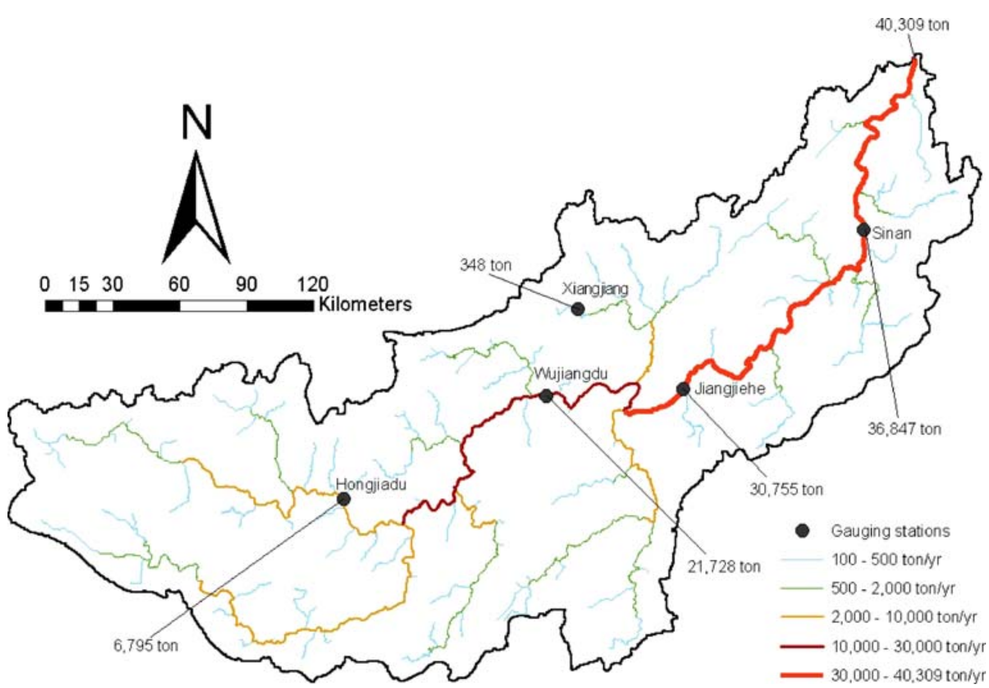

Fig. 6 Average annual total nitrogen loadings in the Wujiang River watershed

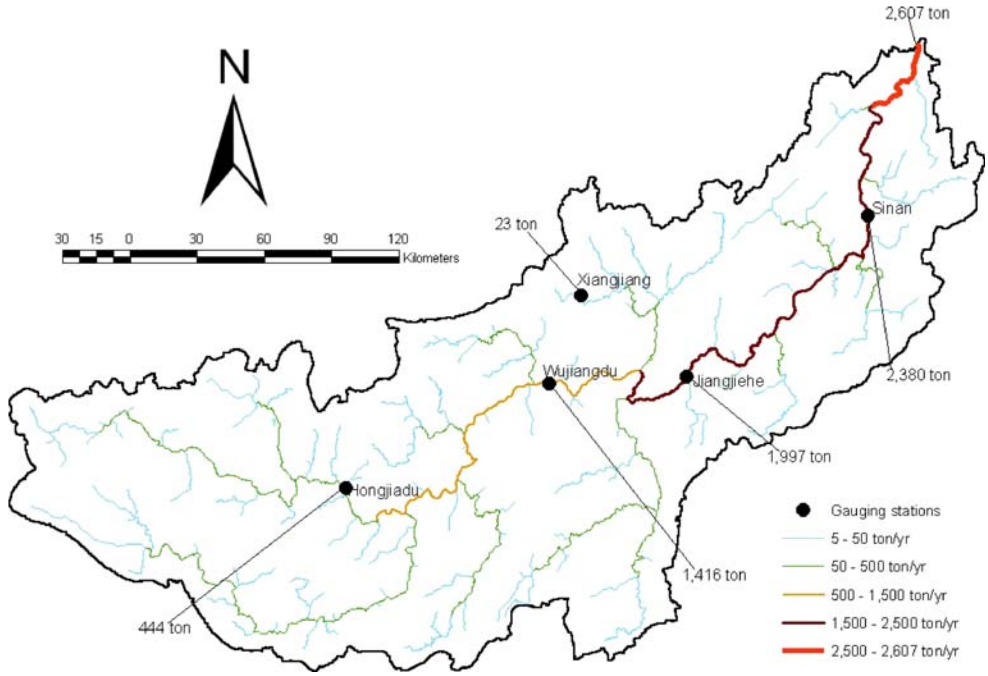

Fig. 7 Average annual total phosphorus loadings in the Wujiang River watershed

5 Summary and Conclusions

In this study, we developed a simplified methodology of NSP assessment using rainfall, surface runoff and land use data based on GIS. The method uses a fine grid of cells of 100 m in size laid over the landscape, accounting for the pollutant loading and runoff derived from each cell. By tracing the flow of water from cell to cell, the movement of pollution over the landscape and through a stream network is simulated. This method allows for the calculation of average annual nonpoint source pollutant loadings to a regional hydrologic system. In addition, estimates of average expected pollutant concentrations resulting from nonpoint sources are determined. In this study, surface runoff is assumed to be a function of precipitation and land use. The multiple regression tool was used to determine the relationship between surface flow, precipitation and percent land use.

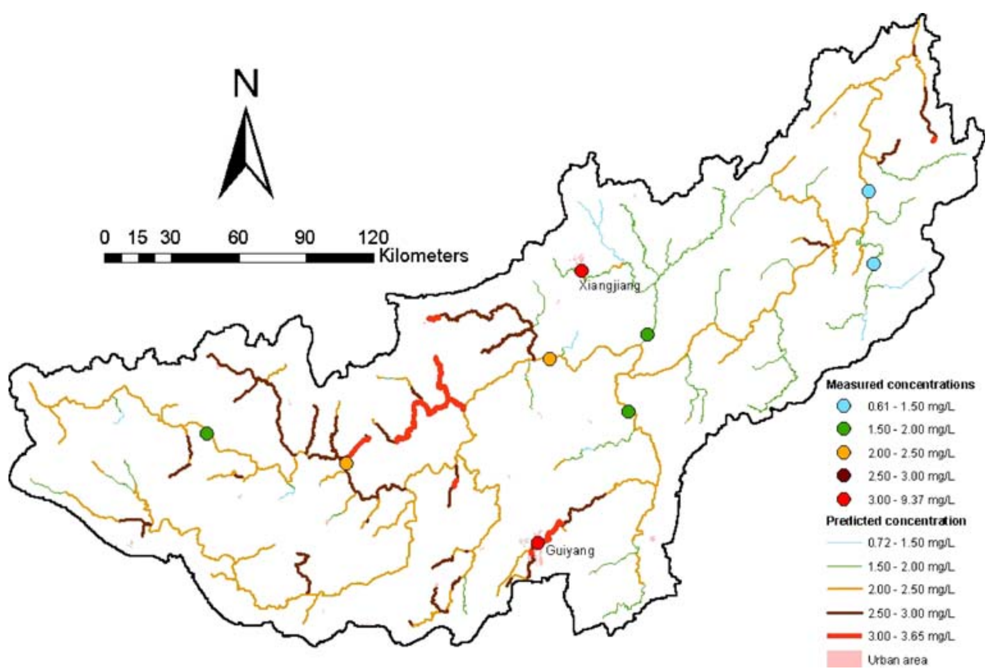

Fig. 8 Comparison of estimated and average observed total nitrogen concentrations in the Wujiang River watershed

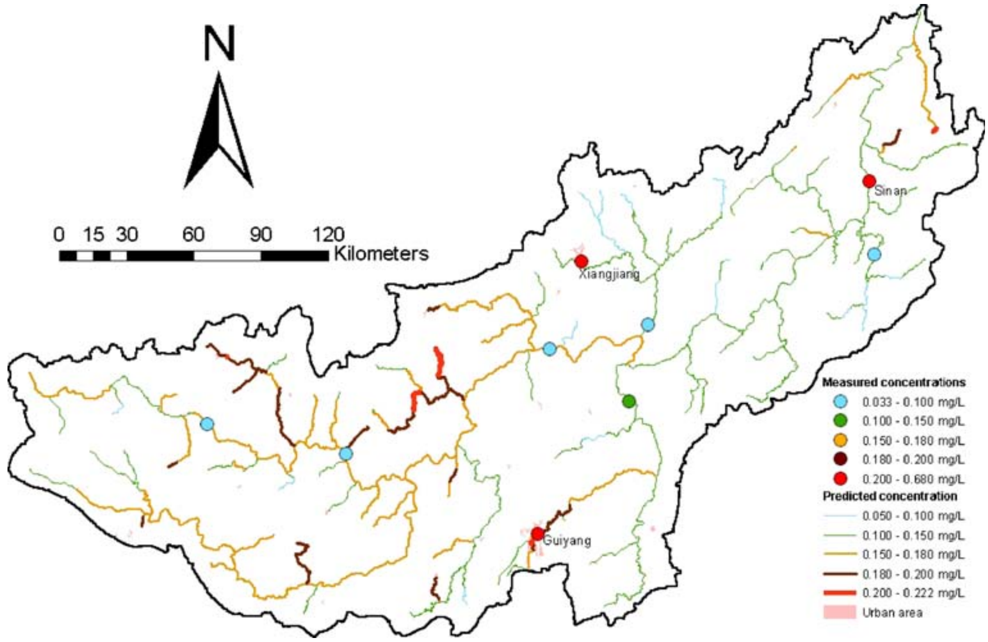

Fig. 9 Comparison of estimated and average observed total phosphorus concentrations in the Wujiang River watershed

The NSP assessment method developed in this study has been shown to present a viable technique of characterizing the nonpoint source contributions to pollution within a watershed or geographic region. The result of this research shows that the association of typical pollutant concentrations with land uses in a watershed can provide a reasonably accurate characterization of NSP in the watershed. Advantages of the method are presented as follows:

(1) Can be used to provide relatively accurate estimates of pollutant loadings and concentrations throughout the stream network of a hydrologic unit.
(2) Can be used to identify areas within a watershed that may contribute more significantly to NPS by spatial analysis of pollutant levels, and to identify the location of significant point source contributors by comparing observed stream concentrations with predicted concentrations.
(3) Easy to adapt to other study areas, such as a large watershed with an area exceeding 10,000 km^2, and the modeled results can be validated. Most of the data used in this method are publicly available in a digital format and are easily obtainable.

Acknowledgements We are very grateful to Dr. K. Tu of Hydro-GeoLogic Inc. for his helpful comments and criticisms on the preliminary version of the manuscript. We also wish to thank Dr. F. S. Wang for providing hydrological data and water quality measurement data. The work was supported by the Foundation of the Chinese Academy of Sciences for Key and Innovation Projects through Grants KZCX3-SW-140 and KZCX1-SW-12 and the Ministry of Science and Technology of China through National Program on Key Basic Research Project (Grant No. 2006CB403200).

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