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Nitrogen transported to three Gorges Dam from agro-ecosystems during 1980–2000

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Abstract To evaluate the effect of human activities on the amount of nitrogen (N) transported to the Three Gorges Dam (TGD), we have developed and applied a model to estimate the riverine N transport from watersheds draining into the upper Changjiang River basin. By using this model and a database of agricultural statistics, we study the temporal and spatial changes in N inputs to watersheds and surface waters. The total amount of N transported to the surface drainage waters from the agro-ecosystem in 2000 showed a 2.9-fold increase over that in 1980. Considering a constant (37%) loss rate from the river, the annual amount of N transported to the TGD from the agro-ecosystem of the Changjiang river upper basin was about 0.35×10^6, 0.47×10^6, 0.59×10^6, 0.64×10^6 and 1.01×10^6 t in 1980, 1985, 1990, 1995, and 2000, respectively. Further, the transported amount of new anthropogenic reactive N approximately quadrupled in 2000, while the amount of riverine N due to rural human waste varied slightly. Of the total N transported to surface drainage waters in 10 watersheds in 2000, the Jialingjiang watershed accounted for 35%; the TGD region, 15%; and the Toujiang, Wujiang and Minjiang watersheds, 11% each. In 1980, the N sources were concentrated in the rural areas surrounding Chendu City and Chongqing City; however, these sources considerably expanded in the 1990s. The increased use of synthetic fertilizers and the decrease in the fertilizer N-use efficiency are implicated as major causal factors of increased riverine N transport; the calculated amount of N transported to the main tributaries agrees well with previously reported data.

Keywords Agricultural field · New anthropogenic reactive N inputs · Riverine N transport · Three Gorges Dam · Upper basin of Changjiang

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Introduction

The well-known Three Gorges Project (TGP) on the Changjiang River was initiated in 1994; two cofferdams of the Three Gorges Dam (TGD) were closed in 1997, and the construction of the dam will be completed by 2009. The TGD has a

2-km stretch of concrete and creates a 600-km-long reservoir behind it. Investigations of the Changjiang River have revealed that the concentrations of nitrates have increased (Edmond et al. 1985) and that eutrophication has become increasingly severe over the past 30 years (Shen et al. 1992). After impoundment, the flow velocity will be reduced, and the reoxygenation and diffusion capacities will also be decreased; this might further increase the local water pollution and enhance eutrophication (Zhang et al. 1999; Liu et al. 2003b). Furthermore, the TGD will have far-reaching effects on environmental and human health issues not only in the reservoir region but also in the drainage basin and the adjacent East China Sea region (Zhang et al. 1999). An understanding of the nitrogen conditions in the agricultural fields of the upper basin of the Changjiang River is of considerable importance because it is the main source of nitrogen transported to the TGD.

Nitrogen (N) is a key indicator of the human impact on the environment, which SCOPE (the Scientific Committee on Problems of the Environment) has identified as a major emerging environmental issue in the 21st century (Munn et al. 1999). Human activities have greatly altered the N cycle, accelerating the rate of N fixation in landscapes and the delivery of N to surface drainage waters (Galloway et al. 1995, 1996, 2004; Høyås et al. 1997; Zhang et al. 1999; Howarth et al. 1996, 2002; Galloway 2000; Galloway and Cowling 2002; Van Breemen et al. 2002; Boyer et al. 2002; Zheng et al. 2002; Yan et al. 2003; Shindo et al. 2003). In China, due to the rapid population growth and fast development of industry and agriculture, the total amount of anthropogenic reactive N input to watersheds reached 3.12×10^7 t in 1995 (Xing and Zhu 2002); this input includes contributions from the application of synthetic fertilizers N, NO_x emission from the combustion of fossil fuels, symbiotic/non-symbiotic N fixation and N imported with food/feed. The river nitrate concentrations and flux increased approximately tenfold between 1968 and 1997 at the Datong Hydrological Station, which is located on the lower reaches of the Changjiang River (Yan et al. 2003); this increase causes a number of human health and environmental problems, such as coastal eutrophication and a potentially increased frequency and severity of harmful algal blooms (Shen et al. 1992; Jin et al. 1990; Jin 1995; Zhang et al. 1999; Townsend et al. 2003).

Several studies have addressed different aspects of this issue for the Changjiang River basin. Zhang et al. (1999) and Liu et al. (2003b) analysed the nutrient conditions in the main stream of the Changjiang River and its largest tributaries based on field expedition data on N and phosphorus (P). Yan et al. (2003) analysed the relationship between N input and the river nitrate concentration at the outlet of the Changjiang River for the period 1968–1997. Shen et al. (2003) determined the various sources of N and studied their transport to the mouth of the Changjiang River catchment based on field investigations, rain sampling and historical and literature data. By using statistical data from different provinces, Xing and Zhu (2002) estimated the N input and output in 1995 for the Changjiang River basin as a whole. However, all these studies were based on statistical data from different provinces or field investigations that were performed prior to 1997, and few of them involved the aspects of the agricultural N budget and its spatial pattern in the upper basin of the Changjiang River, particularly in the TGP region. The N budgets, the major sources of N and the manner in which N reaches the upper basin remain unclear. To answer these issues, we quantified all the new anthropogenic reactive N inputs, riverine N load, and the fertilizer N-use efficiency in the upper basin of the Changjiang River by using a county-level agricultural statistical database for five-year intervals from 1980 to 2000. The unit ‘t’ throughout this paper refers to metric tons of N.

Data and methods

Study area

The upper basin of the Changjiang River corresponds to the catchment region extending more than 4,500 km between the river source and Yichang City in Hubei Province (i.e. 72% of the river’s total length), and it covers an area of approximately 948,107 km^2, comprising 55% of the total area of the Changjiang River catchment. The main stream of the Changjiang River is called the Toutou River for 375 km, the Tongtianhe River for the following 810 km and the Jinshajiang River for a further distance of 2,279 km. There are five main tributaries in the upper region of the river. The Yalongjiang River, which is 1,571 km long with a catchment area of 128,000 km^2, joins the Jinshajiang River before it meets the Changjiang River. The Minjiang River (735 km long with a catchment area of 133,000 km^2), the Tuojiang River (629 km long with a catchment area of 27,860 km^2) and the Wujiang River (1,037 km long with a catchment area of 87,920 km^2) flow into the Changjiang River in the Sichuan basin. To estimate the riverine N export from the agricultural fields surrounding the region, we divide the entire region into 10 segments according to Hayashi et al. (2004) (Fig. 1); this division corresponds to the catchment area of the headwaters, four segments of the main stream and the five major tributaries. The principal land cover types in the entire upper region of the Changjiang basin are forests (19%), bushes and shrubs (15%), grassland (35%), cropland (25%) and waste-land (3%). Grasslands cover most of the regions surrounding the headwater and upper regions of the Jinshajiang and Yalongjiang rivers. Forests, bushes, shrubs and grasslands cover major portions of the Jinshajiang, Yalongjiang, upper Minjiang and upper Wujiang regions. Agricultural fields are well developed in the Sichuan basin and the surrounding areas as a result of deforestation. Other basic data on the ten watersheds are listed in Table 1; these include the drainage area, cultivated land area and population density.

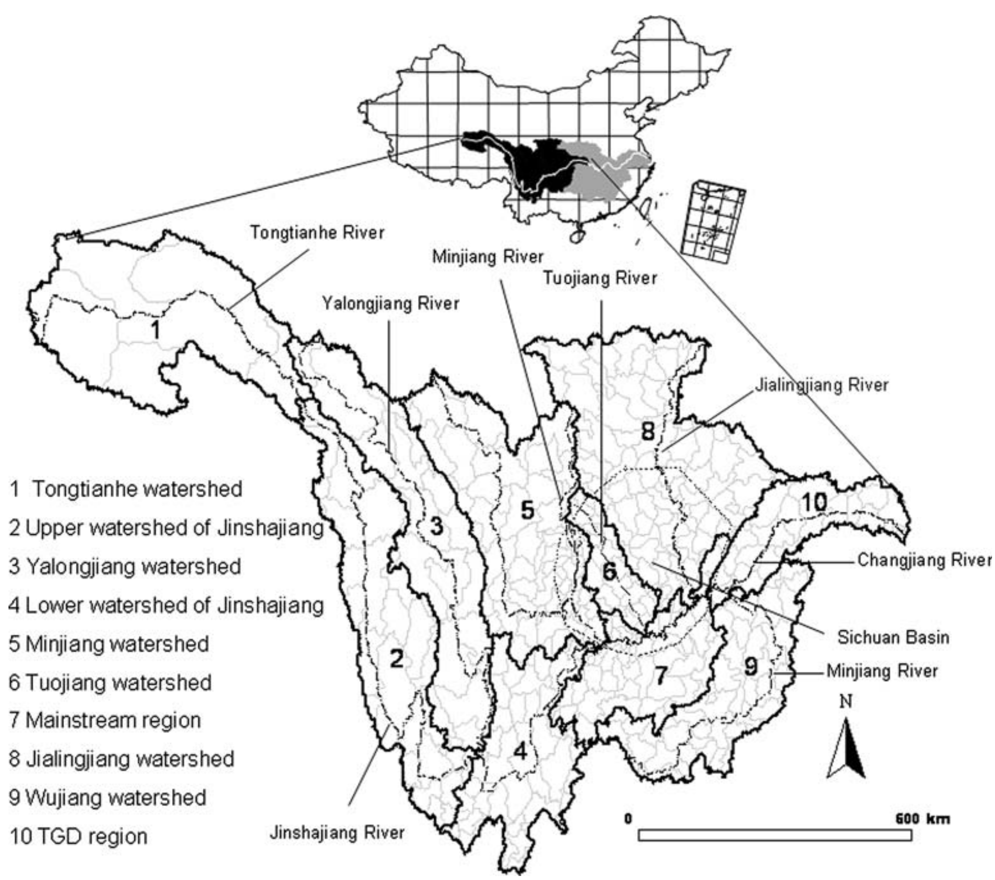

Fig. 1 The upper Changjiang River basin

Table 1 Basic data for each watershed (2000)

	Area (km^2)	Cultivated land (ha)	Population density (person/km^2)
Tongtianhe	111,096	9,458	2
Jinshajiang, upper	117,391	315,770	28
Yalongjiang	117,389	119,920	9
Jinshajiang, lower	79,814	865,568	141
Minjiang	134,017	852,525	72
Tuojiang	25,029	1,055,344	469
Mainstream	67,358	1,097,592	205
Jialingjiang	160,747	3,131,531	242
Wujiang	82,466	1,656,200	254
TGD region	50,375	1,360,566	323

Basic data

Geographic information system (GIS) technologies allow us to manage a variety of data by using a common spatial framework. The use of the ArcGIS software to manage large databases enables the mathematical and spatial analysis of the sources and sinks of agricultural N that are reported in different spatial scales such as counties, stream units and point sampling data.

The main data used in this study and their sources are listed in Table 2. A digital land-use map on a grid base of 1 km^2 that represents land use at the end of the 20th century was cited by Liu et al. (2003a). A total of 350 county units, which comprise the upper reaches of the Changjiang River, are used to aggregate various inputs, N outputs from harvested crops and riverine N transport.

Methods

The new anthropogenic reactive N inputs, including atmospheric wet/dry NO_y deposition, synthetic fertilizer N use, N fixation in cultivated croplands and the net import (or export) of N in food and feed to a region, are frequently cited as the major causes of increased N loading in rivers and estuaries (Boyer et al. 2002; Yan et al. 2003; Galloway et al. 2004). Cole et al. (1993) stated that watersheds with moderate to high human population density are likely to be dominated by sewage rather than other inputs. Most of the watersheds in the upper basin of the Changjiang River have a high population density (Table 1); in the rural areas of China, a large part of the collected human sewage is discharged untreated directly into rivers (World Health Organization 2002). Human waste has a great influence on the N load of rivers. Therefore, in calculating the

Table 2 Basic data used in this study

	Item	Unit	Source
Agricultural data	Cereals (rice, wheat, maize, other cereals), legumes (pulses, soya beans, peanuts), starchy roots, oil crops, cotton, sugarcane, vegetables, fruits	t	China Rural Statistics Yearbook 1981, 1986, 1991, 1996 and 2001
	Green manure	ha	
	Cultivated land, paddy field, upland, sown area	ha	
	Synthetic fertilizer N	t	
Population	Rural population	person	China Rural Statistics Yearbook 1981, 1986 and 1996; Population census 1982, 1990 and 2000
Meteorological data	Annual precipitation	mm	Chinese Meteorological Information Center, National Meteorology Bureau, China

riverine N transport ($N_{riverine_trans}$) from the agro-ecosystem of the upper basin of the Changjiang River according to Howarth et al. (1996), the non-point sources of the new inputs of anthropogenic reactive N ($N_{nonpoint}$) and point sources of human waste (N_{point}) were estimated separately according to the following equation:

$$N_{riverine\_trans} = N_{nonpoint} + N_{point} \quad (1)$$

where

$$N_{nonpoint} = N_{new\_inputs} \times r_{an} \quad (2)$$

$$N_{point} = N_{human} \times P_{rural} \times 0.85 \times r_{hu} \quad (3)$$

N_{new_inputs} refers to new anthropogenic N inputs in each county (t year^{-1}); r_{an}, the rate of transfer of anthropogenic N inputs from agricultural soils to surface drainage waters; N_{human}, the per capita N load from human wastes in wastewaters (t year^{-1} per person); P_{rural}, the rural population; 0.85, the ratio of adult rural population to total population; and r_{hu}, the proportion of human waste discharged directly into rivers to the total amount of human waste.

Following the N mass balance model put forth by Howarth et al. (1996), we quantified the new anthropogenic reactive N inputs (N_{new_inputs}) to the agricultural land in the upper basin of the Changjiang River. The word 'new' refers to reactive N that is either newly fixed in or transported to a region. Budget terms include inputs of atmospheric wet NO_3^- deposition, application of synthetic fertilizer N and biological N fixation (BNF) by leguminous crops and non-symbiotic crops.

In calculating the atmospheric wet NO_3^- deposition, we obtained the annual precipitation data for the period 1980–2000 for 60 meteorological stations located in the upper basin of the Changjiang River from the Chinese Meteorological Information Center. To estimate the annual precipitation of every county unit, we kriged point values to create an isotropic map on a 1-km grid, overlaid county boundaries and finally aggregated the annual precipitation at the county scale by using the ArcGIS software. Owing to the lack of spatial distribution data pertaining to N concentrations in the precipitation, the mean concentration of NO_3^- was replaced with 0.32 mg/l by integrating the monitored results of different studies (Shen et al. 2003; Xing and Zhu 2002; Wang 1994). Because the Tongtianhe and Jinshajiang River catchments were less polluted, the N concentration in the precipitation in these two watersheds was estimated to have a lower value of 0.10 mg/l of NO_3^- according to Shen et al. (2003).

With regard to N fixation by leguminous crops such as soya beans, pulses, peanuts and green manure crops, the N fixation rates were studied by Smil (1999), who summarized the ranges of the published N fixation rates and provided mean values for different kinds of legumes. These mean values were 80, 60, 80 and 150 kg N ha^{-1} year^{-1} for soya beans, pulses, peanuts and green manure, respectively. In addition, the planting of rice and other non-legume crops supplies an additional source of N fixation. We adopted the values of 30 and 15 kg N ha^{-1} year^{-1} (Zhu et al. 1997; Yan et al. 1999) as the N fixation rates of rice and other non-symbiotic crops, respectively.

A strongly positive linear relationship between new anthropogenic reactive N inputs and riverine N transport has been clarified over multiple scales by many studies (Howarth et al. 1996; Boyer et al. 2002; McIsaac et al. 2002; Alexander et al. 2002). The default value of the rate of transfer r_{an} was adopted to be 30% by the International Panel on Climate Change (1996). We used this value along with the value of anthropogenic N inputs calculated by us to estimate the riverine N transport by agricultural non-point sources.

Xing and Yan (1999) suggested that 60% of rural waste was discharged directly into rivers in China while the remaining 40% was used as fertilizers. We therefore assumed that the proportion of human waste discharged directly into rivers (r_{hu}) was 60%. The rate of contribution of human waste to riverine N load (N_{human}) was assumed to be 3.3×10^{-3} t year^{-1} per person according to Meybeck et al. (1989).

In addition, fertilizer N-use efficiency, defined as the amount of N in crop yield (excluding straw) per unit of applied synthetic fertilizer N, is also considered to determine the fate of the synthetic fertilizer applied. The N content in harvested crops is the sum of the N content in the 10 major crops (rice, wheat, maize, legumes, starchy roots, other cereals, oil crops, cotton, sugarcane, vegetables and fruits) listed in Table 2, and the N content in each crop is obtained from the International Panel on Climate Change (IPCC 1996) report.

Results and discussion

Anthropogenic reactive N inputs

The anthropogenic reactive N inputs for the entire study area are shown in Table 3. According to our estimates, the annual inputs of anthropogenic reactive N reached 4.65×10^6 t in 2000, which was more than double that in 1990 and more than quadruple that in 1980. The anthropogenic reactive N inputs dramatically increased at the end of the 1990s. The amount of N from synthetic fertilizers, which comprised over 90% of the total anthropogenic N in 2000, was the biggest contributor to the basin, and it increased rapidly. The total amount of fertilizer N approximately quintupled in the period 1980–2000. N fixation by leguminous crops and non-symbiotic crops was the second major source of N inputs. The amount of N fixation varied slightly during the period 1980–1995 and increased 1.4-fold from 1995 to 2000. This increase was attributed to the increase in legume cultivation. Although the cultivation area of green manure decreased to almost zero in the 1990s, due to the rapidly increasing use of synthetic fertilizers (Yan et al. 2003), the production of legume crops such as soya beans and peanuts increased rapidly in the 1990s. The amount of N input to agricultural fields by atmospheric wet deposition was small when compared to that by fertilizers (only 0–2% of the total anthropogenic N) because our study area mainly comprised agricultural fields; big cities and large industrial areas were limited to Chongqing City and Chendu City.

Atmospheric dry deposition and imported food/feed containing N are also normally considered to be sources of N input (Boyer et al. 2002; Howarth et al. 1996). Lovett and Lindberg (1993) reported that the total (wet + dry) N deposition in eastern North America is approximately twice that from the measured wet deposition; this is a common, if highly imprecise, method used to estimate the amount of N from dry deposition. N from the atmospheric wet deposition as estimated above was considerably low when compared to that in fertilizer inputs, which means that the total N deposition in our study area is likely to be limited. Further, we collected data pertaining to the net import (or export) of the main crops to each county in 1990 and found that the net export amount of the entire area was only 0.5% of the total amount of cereal production. In other words, atmospheric dry deposition and the N imported with food/feed were not the main sources of N in our study area. Moreover, the total amount of anthropogenic reactive N inputs would not change greatly even if the N input through the atmospheric dry deposition and the N imported with food/feed in our study area were included. The amount of atmospheric wet deposition, biological N fixation and synthetic fertilizers in each county in 1980, 1990 and 2000 is provided in the Appendix 1.

N transport to surface drainage waters

The spatial distribution of new anthropogenic reactive N transported to surface drainage waters from 1980 to 2000 is shown in Fig. 2. The distribution of N from rural waste is shown in

Table 3 Estimated anthropogenic N inputs in the upper basin of the Changjiang River

Anthropogenic N inputs	1980		1985		1990		1995		2000	
	t	%	t	%	t	%	t	%	t	%
Atmospheric wet deposition	25,401	2	22,393	1	24,673	1	24,239	1	29,772	0
BNF	257,652	23	283,445	17	280,142	13	278,558	11	395,946	9
Synthetic fertilizer	866,800	75	1,337,090	82	1,941,008	86	2,292,627	88	4,223,791	91
Total	1,149,853	100	1,642,928	100	2,245,823	100	2,595,424	100	4,649,509	100

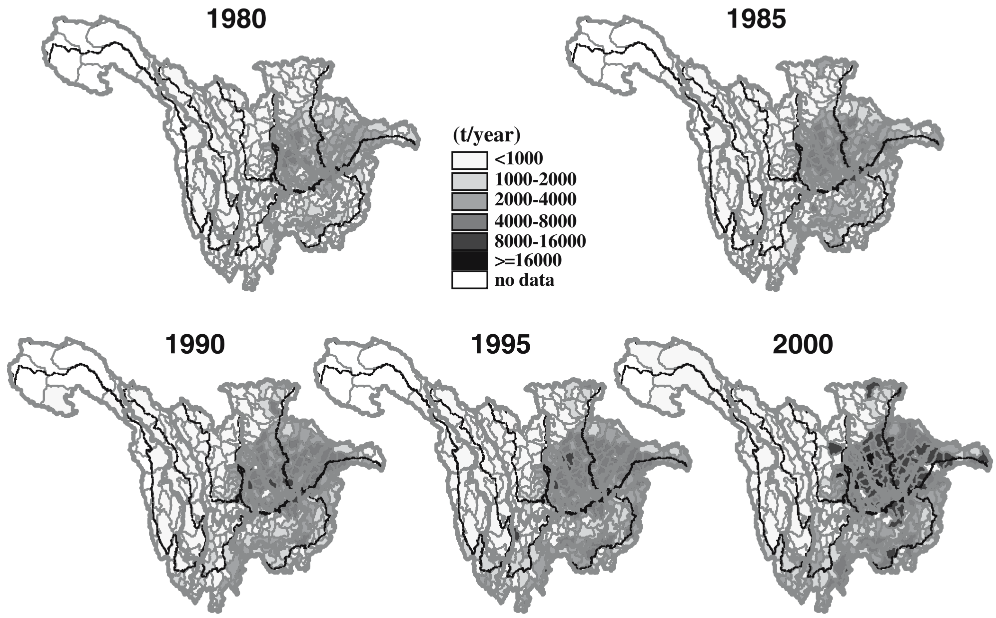

Fig. 2 New anthropogenic N inputs transported to water bodies

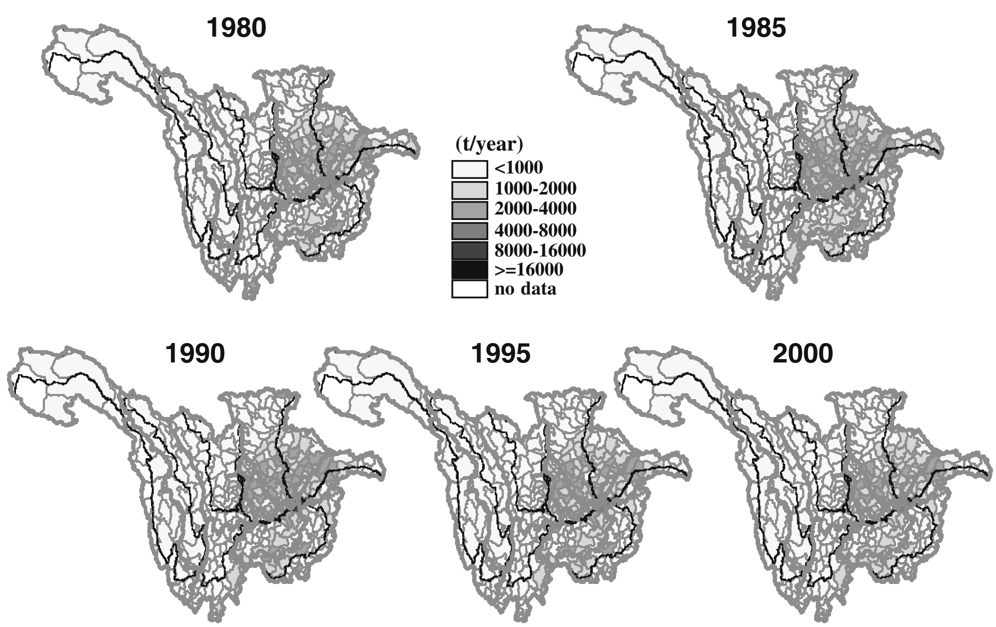

Fig. 3 N transported to water bodies through rural human waste

Fig. 3, and the total model-predicted riverine N transport is shown in Fig. 4. By overlaying the obtained distributions of N with the sub-catchment map, riverine N transport to the 10 sub-catchments was calculated, and the results are shown in Table 4.

Based on the results of our analysis, human impacts on the N transported to rivers in the upper basin of the Changjiang River from 1980 to 2000 can be summarized as follows:

(1) The total amount of N transported to rivers reached 1.61×10^6 t in 2000, a 2.9-fold

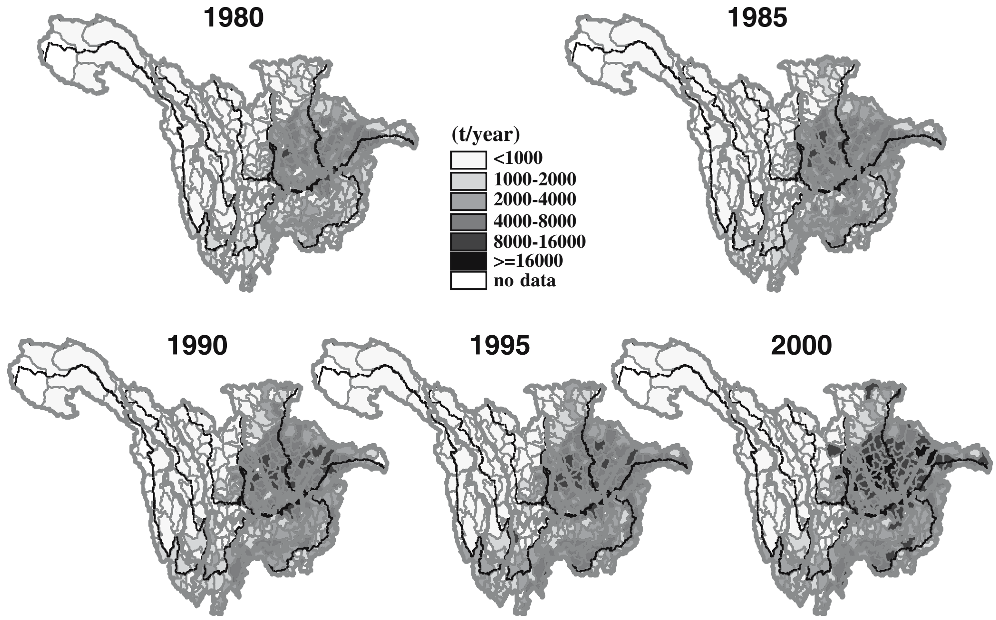

Fig. 4 N transported to water bodies

Table 4 N transported to water bodies

	1980		1985		1990		1995		2000	
	1*	2**	1*	2**	1*	2**	1*	2**	1*	2**
Tongtianhe	518	216	415	253	459	247	490	395	42	465
Jinshajiang, upper	5,752	4,313	7,687	5,499	10,392	5,864	15,639	5,793	14,265	5,613
Yalongjiang	2,184	1,626	2,166	1,746	2,697	1,896	3,060	1,735	2,410	1,862
Jinshajiang, lower	23,644	14,374	36,756	21,475	48,225	22,718	74,586	19,851	87,873	18,914
Minjiang	35,610	18,074	40,081	19,734	61,121	22,112	57,548	18,159	154,793	16,168
Tuojiang	41,321	18,943	60,429	26,015	72,206	25,911	75,138	24,324	162,414	19,740
Mainstream	33,382	25,089	46,515	28,093	61,669	29,069	65,446	27,039	114,484	23,287
Jialingjiang	110,613	67,584	170,644	76,519	232,427	80,564	234,273	71,593	499,621	65,462
Wujiang	41,973	35,843	64,484	39,001	85,480	42,376	122,322	38,781	144,144	35,272
TGD region	49,958	29,349	63,701	36,028	99,071	36,695	130,123	32,297	214,806	27,379
Total	344,955	215,411	492,878	254,363	673,747	267,452	778,625	239,967	1,394,852	214,162
Total	560,366		747,241		941,199		1,018,592		1,609,014	

*Anthropogenic reactive N transported to water bodies

**N transported to water bodies through rural human waste

increase over the export levels in 1980 (Table 4).

(2) Non-point sources of N dominated the riverine N fluxes in all watersheds. Of the total amount of the transported riverine N, the proportion derived from anthropogenic reactive N increased and constituted 62%, 66%, 72%, 76% and 87% of the total N in 1980, 1985, 1990, 1995 and 2000, respectively. The amount of anthropogenic N transported to rivers reached 1.39×10^6 t in 2000, which was about four times that in 1980 (Table 4).

(3) The amount of N transported to rivers through rural human waste varied slightly; it increased in the 1980s, while it decreased in the 1990s (Fig. 3; Table 4). This decrease might be attributed to the rapid urbanization and the large-scale national migration in the 1990s, when a large percentage of the

population migrated from rural areas to cities (Liu et al. 2005). However, this represents a decrease of only the rural population rather than the total population. Based on the urban population in the population census of 1982, 1990 and 2000, let us assume the proportion of human waste discharged directly into rivers to the total amount of human waste (r_{hu}) to be 100% in cities and the ratio of the urban adult population to the total population and the contribution rate of human waste to riverine N load to be similar to those of the rural areas (0.85 and 3.3 kg N year^{-1} per person, respectively). Then, according to equation (3), the amount of N transported to rivers through urban human waste was estimated to be 3.45×10^4 t in 1982, 4.66×10^4 t in 1990 and 12.7×10^4 t in 2000; this amount increased continuously during the period 1980–2000.

(4) The Jialingjiang watershed accounted for 35% of the total N transported to surface drainage waters in the upper basin of the Changjiang River in 2000. On the other hand, the Three Gorges region accounted for 15% of the total N, and the Tuojiang, Wujiang and Minjiang watersheds accounted for 11% each. The proportion of the total N transported to surface drainage waters by the lower Jinshajiang watershed and the region along the main stream of the Changjiang River was less than 10%. The amount contributed by the Tongtianhe, Yalongjiang, and upper Jinshajiang watersheds was fairly small (Table 4).

(5) The counties that exported large amounts of riverine N (≥ 8,000 t year^{-1}) were mainly concentrated in the rural areas around Chendu City and Chongqing City in 1980; however, the area expanded considerably to include the entire Sichuan basin and even the surrounding mountainous and hilly terrains of the lower Jinshajiang and Wujiang watersheds. The size of the area and the degree to which it was impacted by human activity increased noticeably from 1980 to 2000 (Figs. 2, 4).

Furthermore, to determine the agro-ecosystem from which the riverine N load originated, we calculated the riverine N yield (t ha^{-1} year^{-1}) of each county and then overlaid it with a 1-km-grid-based map of the cultivated land to obtain the spatial distribution of each component of the N budgets. The map of the cultivated land was derived from the digital land-use map mentioned above. Figure 5 shows the N yield of the riverine N transport; this yield is different from that seen

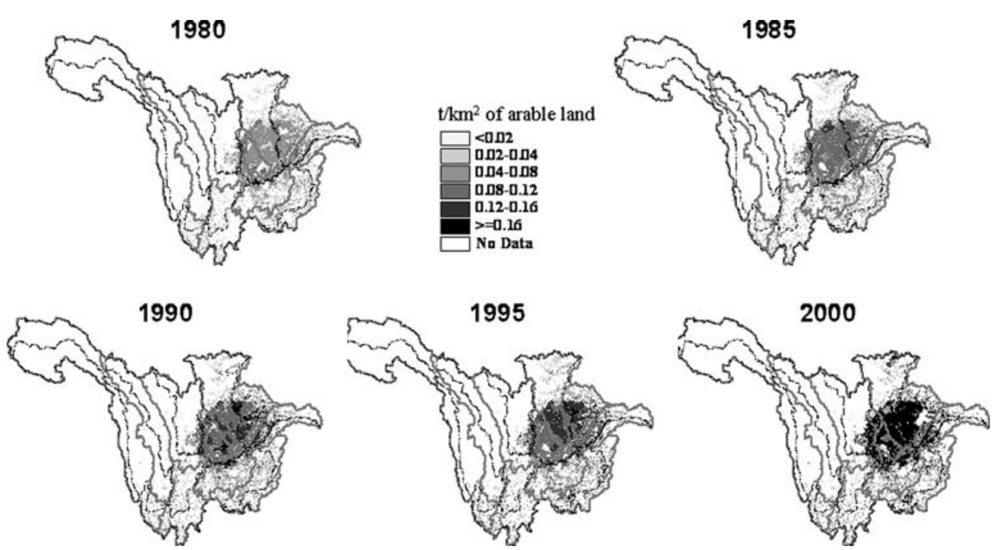

Fig. 5 N transported to water bodies plotted on a 1-km-grid of the cultivated land

in Figs. 2–4, which show the total amount for each county. As shown in Fig. 5, the amount of riverine N transport as well as the number of regions involved in high riverine N transport (≥ 16 t km^{-1}) dramatically increased from 1980 to 2000. In particular, in the late 1990s, the regions responsible for high riverine N transport included all the agricultural fields in the Sichuan basin and its surrounding areas.

It is noteworthy that such a grid-based map shows a pattern of riverine N distribution that is plausible and suggests that the N transported to surface drainage waters is derived mainly from limited areas of cultivated land. Furthermore, such maps also provide a database for the simulation and validation of grid-based ecosystem models.

Fertilizer N-use efficiency

In order to meet the human requirements of food, an increasing amount of synthetic fertilizers was applied to agricultural fields to increase crop yields. The fertilizer N that was not removed with the harvested crop biomass was lost from the cropping system; this loss resulted from soil denitrification, surface runoff, leaching, and volatilization. The fertilizer N-use efficiency and N losses in agricultural fields are closely related: with an increase in the fertilizer N-use efficiency, the rate of loss of N from the agro-ecosystem decreases and vice versa. Fertilizers are the largest source of N in our study area and thus the fertilizer N-use efficiency is a key factor when evaluating the efficiency of fertilizer application and the impact of an agro-ecosystem on the environment. The broadest measure of fertilizer N-use efficiency is the ratio of the amount of N in the crop yield to the amount of applied fertilizer N, also called the partial factor productivity (PFP_N) of applied N; this measure was used in our study. The index PFP_N integrates the N-use efficiency of both indigenous N supply and applied fertilizer N accurately. An increase/decrease in the PFP_N suggests an associated increase/decrease in the fertilizer N-use efficiency only when the indigenous N supply from the net mineralization of soil organic matter, atmospheric N inputs, and biological N fixation are assumed to remain relatively constant. Table 5 gives an overview of the condition of the cultivated land, crop production, and fertilizer N-use efficiency from 1980 to 2000. Figure 6 shows the relationship between N fertilizer application and the N in the crop harvests of 1980, 1990 and 2000. Table 5 and Fig. 6 demonstrate that agriculture in the upper Changjiang watersheds intensified substantially between 1980 and 2000, as indicated by the increased N fertilizer inputs, crop yields, and sown area of rotation. The annual synthetic fertilizer application in the mid 1990s was around 50 kg N ha^{-1} of arable land for the world, and it ranged between 10 and 100 kg N ha^{-1} for the continents (Smil 1999). Compared with the world average, the fertilizer application rate was already high in the mid 1990s, and it dramatically increased to 210 kg N ha^{-1} (sown area) in 2000, an almost twofold increase when compared to the rate in 1995. Furthermore, according to Smil (1999), a total of 80 Tg N $year^{-1}$ (Tg = 10^{12} g) of N fertilizers was produced worldwide, and 50 Tg N $year^{-1}$ was removed with the harvested crops (excluding forages), which means that the average world fertilizer N-use efficiency was approximately 63%. Bock (1984) also reported that, in general, approximately less than 50% of the fertilizer N applied to fields was removed with crop harvests. However, in continuous irrigated rice systems in Asia, the fertilizer N-use efficiency was reported to be 31% (Dobermann et al. 2002;

Table 5 Cultivated land area, sown area, crop yield and fertilizer N use during the period 1980–2000

	1980	1985	1990	1995	2000	Change
Cultivated land area (10^6 ha)	10.69	10.24	10.15	9.38	9.38	– 12%
Sown area (10^6 ha)	17.29	17.90	19.20	19.73	20.10	16%
Crop yield (kg/ha of sown area)	50	75	101	116	210	319%
Fertilizer N (kg/ha of sown area)	35	41	43	48	64	86%
Fertilizer N use efficiency	0.691	0.551	0.423	0.415	0.305	– 56%

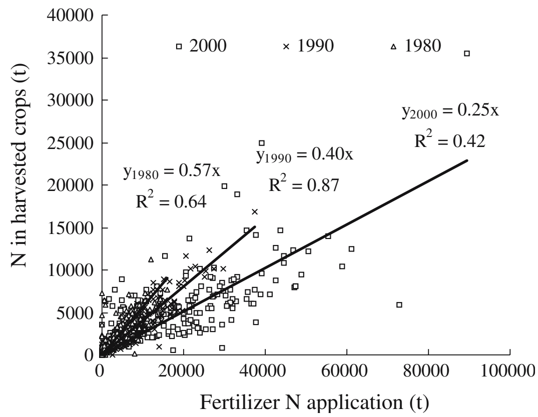

Fig. 6 Relationship between fertilizer N application and N in the harvested crops

Olk et al. 1999). Compared with the average fertilizer N-use efficiency in the rice systems in the world and Asia, the efficiency in the upper basin of the Changjiang River decreased from a high level to a low level in the past three decades. A large amount of excess N from agricultural fields was apparently transported to surface drainage waters by run-off or leaching, which might exert a negative impact on the downstream water quality. Given the potential for environmental degradation resulting from the over-enrichment of surface waters with N, this issue deserves more attention.

The spatial distribution of the fertilizer N-use efficiency in the upper basin of the Changjiang River from 1980 to 2000 is shown in Fig. 7, and the statistical values of the crop-harvested N and N fertilizer application in each watershed are listed in Table 6. Figure 7 and Table 6 show that in mountainous and hilly regions, such as the Yalongjiang watershed, the northern part of the upper Jinshajiang watershed and the Minjiang watershed, the crop yield is relatively low; however, the fertilizer N-use efficiency is high. This is mainly because inorganic N fertilizer inputs are low, and substantial crop yields are sustained by the use of manure fertilizers. However, the fertilizer N-use efficiency in the Sichuan basin and its surrounding areas, such as the central and south Jialingjiang watershed, the TGD region, the Tuojiang watershed and the central region of the Minjiang watershed, decreased dramatically from 1980 to 2000. Most of these agricultural fields have been cultivated since historical times in China and have a long history of intensive land-use activities and frequent overapplication of fertilizers. On the other hand, the fertilizer N-use efficiency in the counties neighbouring the Wujiang watershed increased in the 1990s from

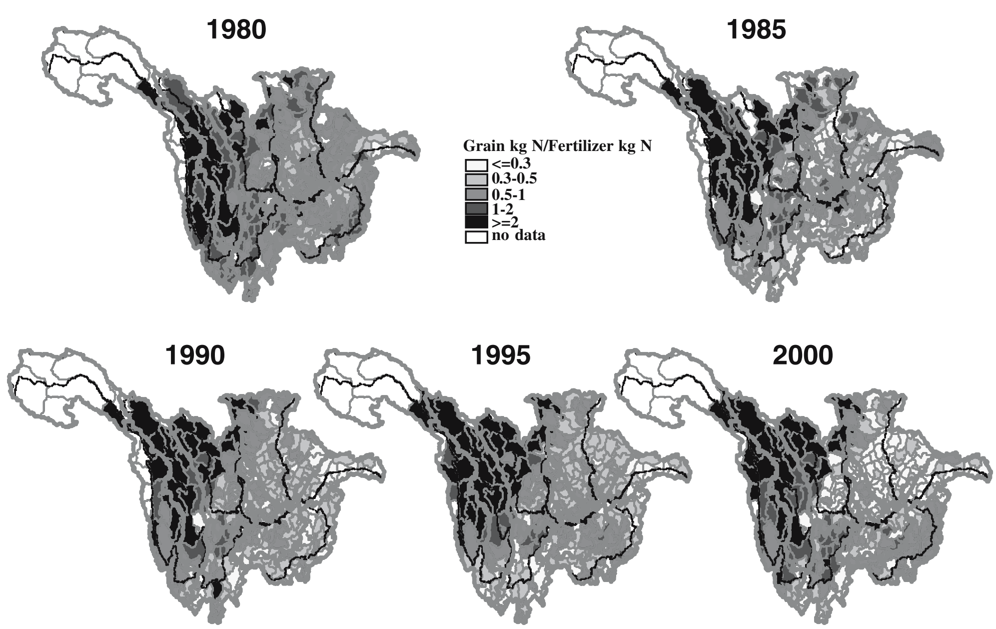

Fig. 7 Fertilizer N use efficiency

Table 6 Crop yield and fertilizer N use in each watershed

	1980			1990			2000		
	1*	2**	3***	1*	2**	3***	1*	2**	3***
Tongtianhe	20	0	51	18	2	10	23	1	17
Jinshajiang, upper	59	85	0.70	91	218	0.42	109	124	0.88
Yalongjiang	32	17	1.86	38	30	1.26	45	47	0.95
Jinshajiang, lower	73	106	0.69	101	201	0.50	125	320	0.39
Minjiang	41	32	1.30	57	86	0.67	132	552	0.24
Tuojiang	49	91	0.54	76	219	0.35	148	456	0.32
Mainstream	73	117	0.63	111	239	0.47	118	308	0.38
Jialingjiang	57	77	0.74	78	169	0.46	115	500	0.23
Wujiang	41	58	0.70	54	150	0.36	131	256	0.51
TGD area	51	63	0.82	64	155	0.41	123	404	0.30

*N in harvested crops/cultivated land, unit: kg N ha^{-1} $year^{-1}$

**Fertilizer N applied/cultivated land, unit: kg N ha^{-1} $year^{-1}$

***Fertilizer N use efficiency, unit: grain kg N (Fertilizer kg N)$^{-1}$

0.36 in 1990 to 0.51 in 2000; we also found that animal farming and the production of soy beans in this region increased rapidly in the 1990s.

The comparison of Figs. 7 and 5 reveals that the regions responsible for high riverine N transport mostly correspond with the low fertilizer N-use efficiency regions. Furthermore, the correlation coefficient between the riverine N transport and fertilizer N-use efficiency of the 350 counties is approximately 0.5 ($P < 0.01$), which suggests that a large amount of excess N that could not be recovered by crops was transported to surface drainage waters.

Comparison of the obtained estimates with previously reported measurements

In order to validate the results of this study, we compared our estimates with the values reported in previous studies. Because the latest available information was for 1997, the estimates of 1995 were used for the comparison. We compared the calculated riverine N load (expressed as kg N $year^{-1}$ km^{-2}) in the Jinshajiang River and its five main tributaries (i.e. Yalongjiang, Minjiang, Tuojiang, Wujiang and Jialingjiang) with the measurements (N concentration × average annual water discharge/total area, expressed as kg N $year^{-1}$ km^{-2}) reported by Liu et al. (2003b). We found that the calculated riverine N transport to the river sources and its main tributaries agreed well with the measurements ($R^2 = 0.87$), as shown in Fig. 8.

The non-point sources of the new inputs of anthropogenic reactive N and the point sources of human waste that are discussed in Sect.“Methods” as sources of N in surface waters are considered to be the causes of increased N loading in rivers. In addition to these, the non-point sources of natural ecosystems, such as forests, grasslands and aquatic ecosystems, the manure N obtained from human and animal wastes that was applied in agricultural fields and the point-source of industrial waste from cities are also thought to be some of the causes. Based on the data regarding the forest and grassland areas that are discussed in Sect. “Study area”, if we assume that the values of N fixation rate are 16 and 2.7 kg N ha^{-1} $year^{-1}$

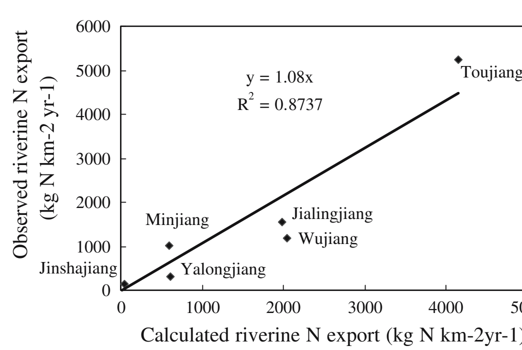

Fig. 8 Agreement between the calculated and observed riverine N export

for forest and grassland ecosystems (Cleveland et al. 1999), and that the rate of transfer to surface drainage waters is 25% (Boyer et al. 2002), the amount of N transported to rivers from natural ecosystems is estimated to be 9.45×10^4 t year^{-1}; of this amount, 7.21×10^4 t year^{-1} is contributed by the forest ecosystem and 2.24×10^4 t year^{-1} by the grassland ecosystem. Quantifying the amount of manure N that is internally cycled within the basin and attributed to the riverine N load is more difficult. According to Smil (1999), if 15% (10–20%) of the applied manure N is added as loss through leaching, the amount of manure N would approach 6.63×10^4 t in 1995; of this amount, 4.23×10^4 t would be due to hogs and 2.40×10^4 t due to the rural population. Shen et al. (2003) reported the total residential sewage waste and total industrial waste from cities that were discharged in the upper catchment to be 5.2 and 7.5×10^4t year^{-1}, respectively, based on both the monitoring data (N concentrations) and statistical data from different provinces (waste water discharge). If we integrate our estimates of the amount of N transported to the surface drainage waters from new anthropogenic inputs (i.e. 7.79×10^5 t in 1995) and by the rural population (i.e. 2.40×10^5 t in 1995), it can be positively stated that the total N input from the upper basin to the Changjiang River is approximately 1.31×10^6 t in 1995. This implies that approximately 83% of the total N input in the upper Changjiang basin originates from agricultural fields, a similar proportion to that estimated by others (Edmond et al. 1985; Shindo et al. 2003). Moreover, it is reported that the annual discharge of the upper Changjiang River is approximately 450×10^9 m^3 (Shen et al. 2003) and that the total N concentration is 130 μM in the TGD (Zhang et al. 1999); thus, we can calculate the total annual N input in the region extending from the upper basin of the Changjiang to the TGP to be approximately 8.19×10^5 t year^{-1}. Comparing this value with the total calculated N input (1.31×10^6 t in 1995), we can state that approximately 37% of the N is lost in rivers before arriving at the TGD. This loss might be attributed to denitrification or storage in the sediments of rivers and reservoirs as well as to storage in groundwater during in-river processes. According to Howarth et al. (1996), the percentage of N loss in rivers is estimated to be 0–45% by a number of studies, and our estimate is within this range.

Conclusion

In this study, we developed and applied a model (a modification of Howarth's 1996 NANI model) to estimate the riverine N transport from watersheds draining into the upper Changjiang River basin. Further, based on China's county-level agricultural statistical databases from 1980 to 2000, we used this model to draw insights regarding the temporal and spatial changes in N inputs to watersheds and surface waters due to agricultural activities and human wastes.

Our results suggested that human activities have significantly altered N cycling in the agro-ecosystems in the upper basin of the Changjiang River. Anthropogenic reactive N, particularly from synthetic fertilizer application, has greatly increased. The total amount of N transported to surface drainage waters reached 1.61×10^6 t in 2000, a 2.9-fold increase over the 1980 export levels. Assuming a constant in-river N loss rate of 37%, the annual total amount of N transported to the TGD from the agro-ecosystem of the upper basin of the Changjiang River was approximately 0.35×10^6, 0.47×10^6, 0.59×10^6, 0.64×10^6 and 1.01×10^6 t in 1980, 1985, 1990, 1995 and 2000, respectively. Meanwhile, the area impacted by human activities expanded during the period 1980–2000. N sources were mainly concentrated in the rural areas surrounding Chendu City and Chongqing City in 1980; however, in the 1990s, the sources expanded to include the entire Sichuan basin and even the surrounding mountainous and hilly regions of the lower Jinshajiang and Wujiang watersheds. The riverine N transport from agricultural fields comprised approximately 83% of the total N input in the upper basin of the Changjiang River. The increase in the use of synthetic fertilizers is considered to be the major driving factor resulting in the large amount of riverine N transport.

Our estimate still has many uncertainties. For example, the different rates of N retention within different watersheds were not considered in this study; this might influence the spatial distribution of riverine N transport and the total amount of N transported to the TGD. Furthermore, rotational cropping can be practised all the year round with double or even triple cropping in major agricultural fields in the upper basin of the Changjiang River, and approximately 40% of its agricultural land comprises rice plantations. In such areas, using a value of 30% as the rate of transfer r_{an} for the calculation of riverine N transport might lead to an overestimation. Nevertheless, since a large region of the upper basin of the Changjiang River is mountainous with large gradients, water loss and soil erosion are severe. In such a case, using a value of 30% as r_{an} might lead to an underestimation. It is obvious that a variety of factors might influence the rate of leaching from agricultural fields into surface waters, such as runoff, fertilizer types, soil types and textures and the type of land use; therefore, r_{an} should depend on the specific conditions of each unit. Further studies are required to focus on the dynamic linkages of the N budget to other determining factors mentioned above by integrating all these factors into ecosystem models.

Acknowledgements We acknowledge the support of the Asia Pacific Environmental Innovation Strategy (APEIS) Project from the Japanese Ministry of Environment.

Appendix 1

Ename	Depo80	BNF80	FerN80	PS80	Depo90	BNF90	FerN90	PS90	Depo00	BNF00	FerN00	PS00
Zhushanxian	192	1115	2416	729	141	1127	5678	791	194	1624	8888	617
Zhuxixian	106	896	1836	572	70	905	2516	606	94	1213	7213	493
Yichangshi	9	60	287	559	103	1159	11166	956	29	297	2543	22
Yichangxian	142	1272	2743	945		0			124	1803	29299	767
Yuananxian	46	453	1493	331	37	458	2932	368	53	447	7073	275
Xingshanxian	52	457	1292	289	38	366	2379	319	49	357	3235	252
Zhiguixian	97	631	2447	659	75	671	6726	712	106	1440	13518	578
Changyangtujiazuzizhi	128	711	2359	667	102	874	5868	720	141	1124	16223	593
Yidushi	82	131			57	549	8804	641	81	508	20397	409
Dangyangshi	153	2092	4051	722	128	1740	13880	786	187	2462	37360	537
Zhijiangshi	147	1717	5612	772	127	1665	17221	899	175	1945	32056	578
Baokangxian	91	639	2498	454	75	701	3455	491	99	655	5206	389
Enshishi	225	1088	3560	1090	161	1324	9861	1203	218	1566	23091	986
Lichuanshi	254	1531	2848	1125	178	1630	7693	1297	242	1651	20018	1132
Jianshixian	130	695	3332	750	95	857	8795	839	132	877	23877	774
Badongxian	149	805	1751	730	108	900	5163	807	145	982	10394	700
Xuanenxian	104	625	1341	482	76	791	2986	537	101	1179	4166	509
Xianfengxian	102	646	1363	498	76	769	3596	566	106	811	7252	529
Laifengxian	87	470	1163	389	62	549	5140	455	83	728	9062	436
Shennongjialinqu	23	153	5	109					27	164	417	88
Chongqingshi	587	3924	11884	3593	473	4644	37346	7869	953	8856	89480	3514
Wanzhouqu	250	2066	6673	2422	178	1933	19817	2617				1809
Changshouxian	153	1351	6282	1364	125	1346	14968	1448	164	1572	33130	1027
Zhuanjiangxian	173	1528	6737	1439	147	1624	14065	1555	189	1775	27203	1251
Tongnanxian	142	1419	4763	1290	142	1756	13134	1449	166	1642	29393	1267
Tongliangxian	147	1426	5690	1240	132	1400	11014	1328	161	1577	23281	1163
Dazhuxian	121	1333	4882	128	120	1412	11393	1452	144	1729	20654	1247
Rongchangxian	106	1202	3691	313	111	1411	8706	1304	131	1614	18518	887
Bishanxian	104	949	3668	908	89	955	7926	983	112	1049	17821	830
Liangpingxian	171	1604	6062	1304	119	1434	12658	1402	183	1655	29753	1237
Chengkouxian	82	490	816	357	60	490	1346	388	79	494	2290	342
Fengduxian	188	1356	5758	1108	134	1403	12835	1241	188	1462	27016	1115
Dianjiangxian	153	1231	11528	1272	116	1164	14563	1379	141	1300	35614	1217

Appendix 1 continued

Ename	Depo80	BNF80	FerN80	PS80	Depo90	BNF90	FerN90	PS90	Depo00	BNF00	FerN00	PS00
Wulongxian	119	708	2020	1005	88	685	5839	635	116	729	8138	567
Zhongxian	191	1499	9206	1499	133	1630	14626	1616	194	1748	31855	1362
Kaixian	276	2000	9347	2147	195	1914	18701	2352	264	2063	44453	2062
Yunyangxian	230	1508	7582	1826	161	1425	12500	1986	226	1604	37651	1799
Fengjiexian	195	1271	8728	1414	136	1189	12937	1550	202	1377	28907	1275
Wushanxian	138	91	4658		100	776	6582	927	147	636	3345	859
Wuxixian	138	841	2743	761	99	762	4447	830	141	938	5846	753
Qianjiangqu	141	911	2221	851	93	912	5061	735	129	1066	8703	597
Shizhutujiazuzizhixia	115	814	3972	773	78	977	7650	762	112	1049	15124	732
Xiushantujiazumiaozuz	148	1032	1849	992	107	1018	6670	893	146	990	8003	764
Qiuyangtujiazumiaozuz	206	1420	3303	962	146	1670	8515	1129	205	1566	10832	923
Pengshuimiaozutujiazu	193	1093	2522	816	144	1211	5621	947	197	973	8771	922
Jiangjinshi	223	2309	7156	2290	195	2412	18715	2423	245	2825	35421	1419
Hechuanshi	245	2347	10504	2344	221	2251	25398	2507	268	2570	43589	1613
Yongchuanshi	153	1687	5953	1531	144	1790	13770	1679	174	2001	24049	1047
Nanchuanxian	138	1193	5356	1169	111	1238	8590	1064	142	1449	22853	761
Chengdushi	134	131			411	3061	26408	3570	210	1558	26476	634
Jintangxian	177	1753	8525	1653					159	3924	32870	1071
Suangliuxian	157	1648	11782	1282	196	1679	14242	1429	203	1889	36654	1209
Wenjaingxian	47	526	3324	399	60	497	4824	446	63	473	12475	351
Bixian	80	1062	5171	651	102	927	7185	709	104	836	20366	409
Xinduxian	84	990	6277	805	107	958	10477	896	110	800	21253	688
Dayixian	89	900	6128	739	107	943	7222	797	113	889	20911	631
Pujiangxian	63	642	3370	380	73	633	4270	413	78	581	11074	290
Xinjinxian	51	550	2903	425	63	545	4750	459	66	724	11331	371
Dujiangyanshi	83	135			101	1018	9390	914	105	914	21069	605
Pengzhoushi	118	1356	7019	1148	148	1343	9902	1242	150	1461	22025	883
Qionglaishi	127	175			148	1361	8249	1041	156	1455	72724	660
Chongzhoushi	116	1409	6506	960	142	1345	9505	1047	144	1303	22149	847
Zigongshi	62	156			70	859	8197	1351	309	1469	15130	758
Rongxian	154	1820	7967	1354	177	2382	11307	1461	197	5720	27471	1254
Fushunxian	139	1955	6924	1731	152	2059	12518	1909	176	3293	27528	1646
Panzhihuashi	8	35			7	234	3446	947	11	3097	6853	216
Miyixian	8	309	1028	288	10	302	3004	303	12	370	4795	302
Yanbianxian	19	207	778	204	29	281	1175	280	34	267	2912	291
Luzhoushi	11	110	518	491	16	194	1438	665	252	1825	978	984
Luxian	197	2544	9043	2279	187	2525	15108	2366	230	1960	30301	1188
Hejiangxian	112	1492	3285	1304	102	1511	8223	1372	127	1812	17239	978
Xuyongxian	122	1349	2519	1213	105	1267	4017	1018	121	1315	7027	890
Gulinxian	136	1293	2616	1108	108	1163	3085	1138	134	1143	6257	1034
Deyangshi	103	1793	7730	1131	150	1777	11244	1295	74	4004	26190	747
Zhongjiangxian	176	2021	12913	218	234	2073	21783	2295	206	5722	50539	1969
Guanghanshi	80	994	5641	813	107	1017	8863	898	106	1475	21440	598
Shefangxian	62	924	4457	629	80	994	10934	690	69	973	22553	453
Mianzhushi	79	1345	5003	786	107	1284	8856	840	103	1183	21476	584
Mianyangshi	106	1540	8276	1345	161	1672	14177	1507	415	3238	35308	640
Shantaixian	196	2268	14221	2248	260	2476	22919	2390	253	7235	55394	1960
Yantingxian	100	868	5240	1001	114	1021	10215	1015	117	1798	26914	799
Anxian	81	1200	4586	758	115	1125	6692	793	104	1216	13744	649
Zhitongxian	77	940	5482	605	100	1040	10126	634	97	2316	23284	502
Beichuanxian	37	1270	625	252	47	462	1483	261	45	382	2953	244
Pingwuxian	59	664	871	286	72	740	1767	303	67	694	1942	258
Jiangyoushi	94	1423	11071	1268	128	1338	13953	1374	119	1389	30862	813
Guanyuanshi	121	1485	3259	1303	130	1347	9931	1446	115	1737	19860	872

Appendix 1 continued

Ename	Depo80	BNF80	FerN80	PS80	Depo90	BNF90	FerN90	PS90	Depo00	BNF00	FerN00	PS00
Wangchangxian	52	428	1000	668	51	521	3514	716	56	490	9805	591
Qingchuanxian	54	585	541	334	65	606	1496	352	63	694	2838	365
Jiangexian	124	1241	2947	968	149	1558	9958	1040	152	1862	28328	958
Changxixian	100	1287	5145	1198	110	1259	11433	1285	113	2165	32135	1132
Suiningshi	188	1809	6566	1903	199	1885	18790	2164	224	5287	46784	2212
Fengxixian	169	1447	1000	1832	187	1751	20306	2058	209	2813	48785	914
Shehongxian	115	923	5829	1531	131	1041	10678	1627	137	1755	21235	1224
Neijiangshi	127	106	953	452	12	128	2063	544	129	2596	42464	1171
Weiyuanxian	92	1012	7947	1096	104	1198	10585	1220	167	736	2467	911
Zizhongxian	175	2099	9962	1891	194	2427	12609	2129	218	8345	29905	1903
Longchangxian	75	954	3948	1091	81	1039	7719	1231	92	1757	16783	1016
Leshanshi	154	1672	5186	1664	368	3649	29850	3444	176	2590	16995	1112
Jianweixian	86	978	3148	863	104	1139	6462	939	112	1546	14354	721
Jingyanxian	92	834	4636	652	109	854	8688	693	118	838	19922	552
Jiajiangxian	57	788	1887	537	69	586	4703	569	75	3712	11236	487
Muchuanxian	51	477	1327	381	54	490	1265	411	55	478	3221	325
Mabianyizuzizhixian	43	350		248	51	378	907	274	58	557	1250	264
Ermeishanshi	66	651	1214	614	78	673	3062	665	82	553	7073	495
Nanchongshi	209	2190	7519	2541	215	2822	16505	2842	242	4705	44544	1936
Nanbuxian	162	1767	9331	1957	178	1771	15504	2098	188	6821	32426	1632
Yingshanxian	122	1161	4223	1294	114	1441	16542	1440	136	1898	31447	1227
Penganxian	97	1003	2929	981	95	1193	9355	1087	111	2310	23143	856
Yilongxian	123	1074	24	140	124	1563	9623	1574	141	1545	21958	1409
Xichongxian	93	829	5915	1015	98	991	9823	1095	108	1183	23878	835
Langzhongshi	103	1073	5933	1374	118	1216	16785	1434	121	1476	25938	992
Yibinshi	5	61	353	395	65	942	3957	1146	69	1077	7612	642
Yibinxian	159	2521	4700	1732	154	2164	8542	1557	74	9362	15329	1337
Nanxixian	70	924	2843	807	53	696	3735	642	60	1332	9295	436
Jianganxian	65	851	2381	720	67	898	5227	809	80	899	10597	648
Changningxian	56	701	1078	574	63	831	4680	666	74	928	6826	522
Gaoxian	69	959	2050	768	72	984	3758	788	81	3032	7420	681
Gongxian	49	609	1772	542	47	671	5882	628	51	983	7483	485
Junlianxian	49	548	1209	494	53	614	2336	569	62	796	2947	523
Xingwenxian	27	283	445	228	59	682	2370	672	66	618	3603	563
Pingshanxian	12	367	896	361	14	382	1438	397	16	436	2608	365
Guanganshi	159	1497	7032	1762	143	1601	16881	1849	152	1626	41257	1496
Yuechixian	140	1558	5881	1619	138	1772	17689	1777	167	2213	38862	1572
Wushengxian	95	1116	4626	1146	95	1083	12246	1267	112	3688	26914	1134
Linshuixian	163	1355	4694	1287	130	1514	11294	1424	170	1532	30637	1269
Huayingshi	36	58			32	330	2305	568	40	283	5874	315
Dachuanshi	20	135	415	300	15	134	1233	498	30	270	3248	205
Wanyuanxian	110	713	2450	658	81	855	8914	855	96	785	23634	748
Daxian	268	1974	7100	2023	193	2059	19963	2064	20	2251	39179	1693
Xuanhanxian	236	1678	7289	1664	162	1598	18240	1827	207	1804	47082	1561
Kaijiangxian	98	751	3080	791	67	739	8666	855	92	1389	21799	697
Dazhuxian	214	1659	6127	1551	163	1657	17764	1683	162	1083	20654	1401
Quxian	219	1701	7715	1962	178	1920	17579	2153	71	1937	37786	1937
Yaanshi	52	447	1863	445	57	455	3257	496	62	435	6581	315
Mingshanxian	57	514	2815	386	66	551	3299	420	70	470	6947	365
Yongjingxian	34	279	1253	202	38	295	2281	216	94	337	1146	186
Hanyuanxian	70	583	2098	494	80	567	4805	548	88	619	12154	498
Shimianxian	17	171	709	181	19	178	1236	191	21	184	2904	164
Tianquanxian	32	278	1334	215	41	337	2254	230	41	314	5028	188
Lushanxian	26	199	1157	165	29	239	2030	188	147	3089	21400	176
Baoxingxian	15	101	500	81	16	92	789	86	17	92	1680	74

Appendix 1 continued

Ename	Depo80	BNF80	FerN80	PS80	Depo90	BNF90	FerN90	PS90	Depo00	BNF00	FerN00	PS00
Wenchuanxian	19	157	529	139	21	155	750	162	23	111	863	142
Lixian	8	66	284	70	8	57	234	71	183	2008	47481	61
Maoxian	18	184	521	128	22	175	618	153	22	127	733	152
Shongpanxian	20	169	306	100	23	160	142	109	24	141	158	100
Jiuzhaigouxian	11	113	440	80	12	103	368	86	12	72	400	74
Jinchuanxian	13	130	178	115	13	112	289	113	14	85	345	96
Xiaojinxian	22	162	224	112	25	148	171	122	27	132	167	114
Heishuixian	14	115	50	96	16	106	85	95	17	71	55	84
Maerkangxian	10	90	220	100	10	78	104	98	12	62	110	55
Rangtangxian	6	50	33	46	5	43	20	50	6	38	15	49
Abaxian	17	150	98	71	18	150	41	84	20	132	51	92
Ruoergaixian	8	79	36	85	9	82	16	97	10	66	25	100
Hongyuanxian	4	31	16	44	1	8	19	50	1	16	23	51
Kangdingxian	21	169	147	142	24	168	194	163	27	145	250	116
Ludingxian	17	174	281	106	20	155	616	116	22	266	749	109
Danbaxian	11	110	49	94	12	109	132	96	13	97	115	82
Jiulongxian	8	68	178	63	9	69	618	73	11	64	575	78
Yajiangxian	6	52	30	57	7	51	37	61	8	46	65	61
Daofuxian	11	98	79	68	12	90	139	73	13	86	103	54
Luohuoxian	10	113	130	55	11	103	48	62	12	89	59	55
Ganzhixian	16	147	11	84	21	209	59	91	25	182	65	81
Xinlongxian	6	55	39	61	7	54	30	67	7	51	32	63
Degexian	9	87	23	84	10	87	18	101	12	84	38	103
Baiyuxian	2	72	12	56	2	68	18	66	3	63	17	65
Shiquxian	4	46	62	89	4	44	21	100	4	46	29	101
Shedaxian	1	13	15	50	1	12	1	55	1	11	4	62
Litangxian	8	72	32	67	8	63	23	74	9	59	27	73
Batangxian	2	69	94	72	2	66	150	80	3	50	126	64
Xiangchengxian	1	35	92	37	1	37	207	40	1	32	156	40
Daochengxian	2	48	8	37	2	49	31	43	2	47	44	43
Derongxian	1	21	14	23	1	20	40	25	1	33	77	36
Xichangshi	20	120	491	238	25	786	5130	790	25	740	8066	622
Mulicangzuzizhixian	25	215	130	167	29	214	194	190	34	198	265	189
Yanyuanxian	81	827	354	394	96	825	1020	465	109	736	1241	476
Dechangxian	9	370	576	236	11	357	3160	279	13	395	3875	273
Huilixian	23	714	1855	609	28	720	3747	664	32	862	6430	673
Huidongxian	15	549	1415	488	19	625	2802	558	21	603	4799	552
Ningnanxian	8	329	945	227	10	312	2258	256	12	618	3182	237
Pugexian	9	281	445	188	11	361	653	214	12	282	773	207
Butuoxian	10	292	361	194	12	503	546	219	13	304	636	215
Jinyangxian	9	276	227	179	10	348	598	210	12	297	703	215
Zhaojuexian	17	572	387	312	20	669	728	339	22	475	748	329
Xidexian	10	278	329	179	12	381	668	200	14	229	792	216
Mianningxian	15	540	977	402	17	523	2095	466	18	495	3437	444
Yuexixian	40	387	493	303	46	389	1578	353	51	325	1982	370
Ganluoxian	35	324	595	221	40	343	539	255	44	252	896	235
Meiguxian	12	379	68	218	14	509	567	254	16	336	706	283
Leiboxian	12	363	589	303	13	409	1074	360	14	459	1145	326
Bazhongshi	173	1551	7310	1745	155	1760	12472	1904	172	1675	24413	1622
Tongjiangxian	130	1134	2843	993	101	1186	7555	1102	122	1129	13784	1040
Nanjiangxian	91	895	1879	870	81	834	9641	945	91	842	13817	908
Pingchangxian	153	1216	3805	1202	125	1337	7554	1341	154	1427	18765	1281
Meishanxian	153	1568	6503	1110	188	1720	10310	1269	164	2233	26593	937
Renshouxian	262	2446	11905	2285	312	2478	27570	2479	264	3047	61268	2101
Pengshanxian	55	610	4607	462	68	629	5877	499	57	991	16354	371

Appendix 1 continued

Ename	Depo80	BNF80	FerN80	PS80	Depo90	BNF90	FerN90	PS90	Depo00	BNF00	FerN00	PS00
Hongyaxian	61	580	1835	511	71	599	4240	547	59	594	10198	440
Danlingxian	27	251	593	198	31	275	1187	220	33	276	1442	238
Qingshenxian	35	417	1379	306	41	437	2957	331	31	899	7487	294
Ziyangshi	191	2314	12923	1530	223	2320	14997	1736	472	12824	33018	1238
Jianyangshi	275	2493	15980	2152	335	2356	20518	2337	310	4155	39105	1921
Anyuexian	222	2522	10699	2189	238	2646	25132	2533	225	4546	58807	2186
Lezhixian	140	1248	8682	1363	163	1303	16008	1452	148	2668	31964	1247
Guiyangshi	77	789	14		63	875	6527	2578	83	935	7984	808
Kaiyangxian	70	625	978	544	61	648	2311	631	79	660	17364	508
Xifengxian	46	381	697	335	38	379	1229	370	51	395	2303	299
Xiuwenxian	47	454	503	413	41	466	1564	447	52	479	2998	348
Qingzhenshi	52	471	1054	607	45	483	3088	728	57	840	5410	466
Liupanshuishi	40	619	806	775	9	128	1019	545	237	1398	1582	174
Liuzhitequ					56	666	4280	905	69	746	6115	678
Shuichengxian	85	897	143	1289	79	979	4649	1057	95	1038	6232	1133
Zhunyishi	15	144	399	550	6	131		215	32	303	2884	230
Zhunyixian	227	2252	3398	1883	174	2194	14923	2011	15	2393	21341	1737
Tongzhixian	112	941	1529	858	91	1086	4253	884	122	1180	5324	766
Suiyangxian	78	735	1687	643	64	605	6375	707	85	840	7171	640
Zhenganxian	90	816	2222	771	76	936	6295	840	99	1006	8720	767
Daozhenkelaozhumiaozh	76	577	2815	449	60	646	6749	475	81	616	7923	411
Wuchuankelaozhumiaozh	98	788	1771	521	76	932	4555	565	100	911	4487	572
Fenggangxian	81	708	1072	514	70	753	3134	546	87	746	5024	544
Meitanxian	90	825	2778	603	76	834	4757	621	96	796	7566	601
Yuqingxian	56	535	801	381	53	566	2358	394	62	521	4227	346
Xishuixian	115	1017	2059	843	100	1054	5200	916	140	3718	31547	896
Chishuishi	40	490	757	424	37	513	1431	387	45	565	2103	293
Renhuaixian	76	692	1416	724	62	731	3973	780	81	740	5174	684
Jiangkouxian	40	401	563	289	35	427	1529	324	42	322	2078	278
Shiqianxian	62	602	613	487	58	636	6014	542	68	513	4242	497
Sinanxian	90	953	1397	800	79	1034	4795	897	97	755	7100	820
Yinjiangtujiazumiaozu	59	627	938	527	52	580	5129	600	64	468	5611	486
Dejiangxian	73	687	812	555	62	738	2729	650	79	602	4187	580
Yanhetujiazuzizhixian	90	758	951	659	73	813	3224	787	97	607	4713	708
Shongtaomiaozuzizhixi	91	873	165	785	77	981	4018	915	98	785	5354	812
Bijieshi	140	1505	5872	1496	141	1781	8345	1785	167	2378	13359	1439
Dafangxian	125	1374	4583	1155	121	1509	5850	1398	144	2074	10676	1300
Qianxixian	126	1079	6705	1024	110	1243	4670	1192	55	1014	29353	1019
Jinshaxian	103	888	3988	779	80	998	3468	899	104	1216	8720	720
Zhijinxian	111	1069	1888	1155	109	1281	4879	1343	86	5033	13363	1217
Nayongxian	76	839	1907	919	77	1150	4682	1084	93	1354	8926	1022
Weininglizuhuizumiaoz	143	1655	3101	1247	153	2139	7154	1490	190	1754	10909	1626
Hezhangxian	77	804	2095	740	85	1120	3218	880	105	1083	5114	964
Anshunshi	77	815	3781	653	75	881	7118	1131	92	872	15098	685
Pingbaxian	48	513	857	438	44	628	2937	507	55	509	5739	400
Pudingxian	46	474	886	503	45	507	3789	581	56	512	5863	527
Huangpingxian	50	479	506	450	48	499	2409	514	57	456	3472	421
Shibingxian	24	235	262	191	23	254	781	221	27	248	1369	185
Zhenyuanxian	38	385	751	325	38	432	1166	378	377	1928	5693	297
Chengongxian		439	887	268		422	1152	309		412	1476	280
Fuquanshi	50	461	1283	366	44	464	2434	431	53	460	4220	299
Guidingxian	38	336	1421	370	36	389	2154	421	44	396	3289	319
Wenganxian	77	680	1820	548	69	677	4517	648	86	746	6707	547
Changshunxian	38	344	1656	309	35	393	2414	354	43	411	4724	314
Longlixian	33	324	844	267	29	349	1403	296	37	357	2627	254

Appendix 1 continued

Ename	Depo80	BNF80	FerN80	PS80	Depo90	BNF90	FerN90	PS90	Depo00	BNF00	FerN00	PS00
Kunmingshi	28	1360	4934	2417	18	625	4086	1307	22	675	10250	358
Dongchuanqu	6				10	356	2280	479	9	276	3312	315
Chenggongxian	5	210	650	213	5	198	4526	232	6	164	17556	236
Fuminxian	4	188	1438	200	5	198	1108	213	6	189	2290	201
Songmingxian	14	597	1828	457	17	591	3764	512	18	473	7552	475
Luquanyizumiaozuzizhi	15	538	1366	639	20	568	651	710	22	572	3738	680
Xundianhuizuyizuzizhi	22	856	2054		29	872	5984	729	28	695	14069	731
Anningshi	4	425	726	377	5	411	2008	404	6	359	5558	189
Qujingshi	12	590	3679		40	1547	10118	1400	40	535	23485	1122
Malongxian	9	393	1009		16	435	1981	298	16	333	4651	258
Huizhexian	24	1088	2536		33	1286	7474	1360	35	1019	18497	1299
Xuanweishi	37	1995	6319		54	2049	14684	1991	59	1439	37073	1809
Yuxishi		400	3005	456		360	4414	543		277	8686	371
Chengjiangxian	5	202	998	201	7	197	1869	224	7	171	3849	181
Yimenxian	7	280	1142	26	9	286	2115	273	10	259	4217	196
Zhaotongshi	65	637	7901	145	74	965	8327	1052	88	1127	10030	904
Ludingshi	12	540	1232	393	14	540	2617	512	17	697	4294	552
Qiaojiaxian	19	760	1350	679	24	756	3419	787	27	1063	4681	757
Yanjinxian	53	543	754	463	60	590	1941	535	69	1024	2744	514
Daguanxian	38	358	303	312	44	383	1034	382	51	498	1552	373
Yongshanxian	68	671	1139	538	76	713	2215	617	97	808	2272	588
Suijiangxian	10	277	696	229	9	243	2756	227	10	316	2915	180
Zhenxiongxian	137	1640	3437	1382	141	1754	9501	1729	170	1693	15112	1613
Yiliangxian	71	846	862	599	79	913	2516	737	95	871	4688	752
Weixinxian	47	631	2990	424	49	778	3182	510	59	684	5228	514
Shuifuxian	1	50	136	59	4	123	456	138	4	227	653	118
Chuxiongshi	15	637	1834	608	17	607	4034	682	21	566	6622	484
Shuangboxian	6	277	381	231	7	306	1665	250	8	441	2085	234
Moudingxian	7	376	694	305	8	337	2596	327	10	341	4777	296
Nanhuaxian	9	323	1094	329	10	324	1890	361	12	290	3524	348
Yaoanxian	8	355	714	295	9	332	1839	316	10	306	3441	286
Dayaoxian	10	412	849	435	6	222	1224	165	14	370	3679	422
Yongrenxian	5	209	508	153	12	400	2221	459	7	254	2410	151
Yuanmouxian	8	408	1109	282	9	395	4441	312	10	1119	9554	280
Wudingxian	10	412	988	363	12	423	2398	407	13	431	4511	391
Lufengxian	14	636	2196	605	16	614	4656	646	19	609	9199	518
Dalishi	11	864	388	11	12	386	2292	733	14	335	3689	448
Xangyunxian	15	600	1878	616	18	566	3295	670	21	513	4882	622
Binchuanxian	17	666	1361	451	19	620	3366	503	24	1762	5459	459
Eryuanxian	16	542	596	438	19	536	2204	504	23	499	1717	452
Jianchuanxian	9				11	319	528	258	12	307	1058	251
Heqingxian	12	529	820	370	14	449	2229	414	17	419	2528	380
Lijiangnaxizuzizhixia	27	938	1466	486	31	865	2441	538	35	751	4230	467
Yongshengxian	19	691	955	532	21	655	2668	596	26	952	4510	547
Huapingxian	7	224	950	212	9	266	2752	236	10	298	6631	217
Ninglangyizuzizhixian	22	605	490	273	23	609	912	338	26	497	1196	355
Lanpingbazupumizuzizh	17	475	121	240	20	482	541	291	24	524	344	282
Zhongdianxian	9	299	213	175	10	283	1030	206	12	266	1312	180
Deqinxian	3	96	33	88	3	95	116	95	4	89	142	92
Naxishulishuzuzizhixi	11	374	251	195	13	451	634	229	15	405	783	228
Jiangdaxian									3	71	25	113
Gongjuexian									2	50	20	73
Chayaxian									2	47	56	85
Manggangxian									3	79	174	114
Yanjingxian									0	0	0	0

Appendix 1 continued

Ename	Depo80	BNF80	FerN80	PS80	Depo90	BNF90	FerN90	PS90	Depo00	BNF00	FerN00	PS00
Tuobaxian									0	0	0	0
Shengdaxian									0	0	0	0
Nierongxian									0	0	0	47
Anduoxian									0	0	0	55
Baqingxian									0	4	0	60
Baojixian	257	1577	7525	1041	246	1382	11854	1128	240	1129	31695	1011
Fengxian	34	312	431	189	28	267	1072	185	192	3708	42494	137
Nanzhengxian	89	1049	4003	839	80	952	10166	878	92	1095	25331	655
Chengguxian		1098	3846	747		1049	10682	822		1191	27071	542
Xixiangxian	93	880	1838	643	78	819	7028	686	93	789	17125	437
Mianxian	12	1038	2992	567	76	863	7806	684	85	906	18748	513
Ningqiangxian	71	792	1531	526	71	823	3888	550	77	812	9328	457
Lueyangxian	45	492	646	315	46	620	1558	328	48	627	3325	248
Zhenbaxian	103	644	529	448	80	580	1982	476	98	439	4267	381
Liubaxian	9	130	323	75	8	145	531	76	8	95	1182	63
Zhiyangxian	149	819	823	534	103	790	2375	570	122	525	4782	414
Zhenpingxian	26	153	247	93	18	148	338	96	25	128	605	72
Tianshuishi	170	121			226	2053	7604	1743	209	1797	10809	1295
Ganguxian		1014	131	693		1084	2362	836		1021	5772	791
Wushanxian	87	718	839	530	120	686	1597	615	112	636	3345	606
Minxian	61	637	103	590	79	628	829	647	77	706	1061	682
Wuduxian	78	939	1334	712	88	882	4306	796	88	1016	5571	774
Dangchangxian	45	473	88	399	55	455	629	449	54	825	950	424
Chengxian	45	612	977	340	55	681	2757	378	54	1123	4137	360
Kangxian	41	573	587	311	48	543	14093	327	48	459	2249	307
Wenxian	40	495	493	350	48	493	1658	374	47	457	1954	358
Xiheixian	63	737	682	477		25			72	573	3245	595
Lixian	103	1204	669	657	130	1087	3015	764	116	2008	47481	788
Liangdangxian	16	181	628	79	17	225	649	80	17	345	1262	71
Huixian	49	721	2333	306	59	881	2861	331	58	1415	4519	319
Hezuoshi												52
Zhouquxian	17	177		168	20	174	69	184	20	146	121	215
Diebuxian	9	89		73	10	82	7	59	10	73	10	86
Luquxian	5	53	4	37	5	41		37	5	39	7	50
Banmaxian	2	21		23	2	18	4	26	2	25	5	37
Darixian				28		0		31	0	0	0	41
Jiuzhixian				23		0		24	0	0	0	33
Maduoxian				14		0		11	0	0	0	18
Yushuxian	2	72	3	73	2	74	16	84	2	64	7	87
Zaduoxian				40	0	7		47	0	7	0	65
Chengduoxian	1	46		52	1	56		58	2	49	6	68
Zhiduoxian				24		0		28	0	0	0	41
Qumalaixian				27		0		29	0	0	0	41

Blank fields indicate that data were not available.

Unit: metric tons of N

Ename: County name

Depo80: Atmospheric wet deposition N in 1980; BNF80: Biological N fixation in 1980; FerN80: Amount of fertilizer N in 1980; PS80: Point source N in 1980

Depo90: Atmospheric wet deposition N in 1990; BNF90: Biological N fixation in 1990; FerN90: Amount of fertilizer N in 1990; PS90: Point source N in 1990

Depo00: Atmospheric wet deposition N in 2000; BNF00: Biological N fixation in 2000; FerN00: Amount of fertilizer N in 2000; PS00: Point source N in 2000

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