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Integrated modeling and assessment of water resources and water environment in the Yellow River Basin

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Abstract

An integrated model is established to simulate both hydrological processes and accompanied pollutant transfer processes in the Yellow River Basin. The model couples distributed hydrological model WEP-L (Water and Energy transfer Processes in Large river basins) and a newly developed water quality module which includes simulation functions of soil erosion and sediment transport, and non-point and point sources transfer to rivers. To overcome the defects of traditional water quality assessment, two aspects of improvement are conducted. One is the improvement of the traditional characteristic channel length approach, i.e., the product of multiplying channel length by lateral section area is selected as a new assessment criterion to reflect the different contributions of small channels and big ones, thus making the assessment results more objective. The other is the suggestion of integrated assessment approach for both water at channel lateral sections and water generated in sub-basins. The assessment results in the Yellow River Basin illustrate: (1) the improved characteristic channel length approach shows rivers of water quality worse than Class III account for 75% whilst the traditional approach give a result of 45%, implying that the actual status of water quality is worse than the traditional understanding; (2) the quality of water generated in sub-basins is much better than the quality of water at channel lateral sections. The assessment results describe the status of water resources quantity and quality from different points of view and thus provide valuable information for the water resources development and management in the basin.

Keywords: Distributed hydrological model; WEP-L; Water quality modeling; Integrated assessment of water quantity and quality; Yellow River

1. Introduction

There exist problems of both water shortage and water quality deterioration in the Yellow River Basin, which has become an important constraint of the social-economic development in the basin. Integrated water resources and water environment management is needed to adopt in the basin, whereas integrated assessment of water quantity and water quality is a fundamental work.

There are many water quality models developed in the past 20 years like Qual2e (Brown and Barnwell, 1987), MIKE11 (DHI, 2001), GIS-based model (Kojiri and Ikebuchi, 1998) and SHETRAN (Ewen et al., 2000) etc., which provide a good basis for the integrated assessment of water quantity and water quality. However, these models have been developed for particular purposes and no model can provide all of the functionality required; e.g., some models like Qual2e and MIKE11 consider quite a lot of pollutant items but are only suitable for water quality problem in freshwater river systems. There are still a lot of problems to solve for applying the models to integrated water quantity and quality assessment. In China, since the National Water Resources Assessment in the mid 1980s, the separate assessment mode of water quantity and water quality has been adopted. The importance of integrated assessment of water quantity and water quality has been recognized for many years, and several studies (Xia et al., 2004, 2005a,b, Xia et al., 2006) have been carried out, but the concrete approach has not been established.

The main characteristics of the existing approach include: (1) the separate and lumped assessment mode of water quantity

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and water quality (2) based on the insufficient historic observations at river lateral sections; (3) adopting the characteristic channel length approach to reflect the general water quality status of a whole basin. Thus, the existing approach is a statistics-based and object-based lumped assessment model, not able to describe the temporal and spatial variations of water quality, and difficult for the scenario analysis of planning e.g. the adjustment of industrial structures and cropping pattern.

In this study, on the basis of distributed hydrological model WEP-L and a newly developed water quality module, an integrated model of water quantity and water quality is established, an integrated assessment approach of water quantity and water quality is suggested, and the suggested model and approach are applied to the Yellow River Basin.

2. Model and approach

2.1. Model framework

The integrated model of water quantity and water quality proposed in this study includes three components, i.e., distributed hydrological model, soil erosion and sediment transport model, and pollutant transfer model.

2.1.1. Distributed hydrological model

The distributed hydrological model WEP-L was developed in a national key basic research project of China (Jia et al., 2005a,b, 2006; Jia and Wang, 2006). The WEP-L model is based on the WEP model (Jia and Tamai, 1998; Jia et al., 2001a,b), but it adopts the contour belts as the calculation units to fit for large river basins like the Yellow River, and to conquer the implausible calculation caused by small grids and anamorphic simulation caused by over-rough grids. Grid-based spatial information like terrain, water system, vegetation, soil, and land use data is provided for the calculative units. On the basis of 1 km-DEM (Digital Elevation Model) and the digitized rivers in plains, 8485 sub-basins are plotted out by the GIS method in the Yellow River Basin. Then 1–10 contour belts are carved in every sub-basin, and 38,720 contour belts are subdivided in the basin. The model has been validated and applied to dynamic assessment of water resources in the basin. For details one is referred to Jia et al. (2005a,b, 2006) and Jia and Wang (2006). The main characteristics of WEP-L model are as follows:

(a) It integrates the merits of distributed hydrological model and SVATS (Soil-Vegetation-Atmosphere Transfer Schemes) model, couples the simulation of water cycle and energy processes, and calculates evapotranspiration from each land use separately.
(b) It adopts ‘‘contour belts within sub-basin’’ as calculation units, and considers diversity of land cover within the units by means of ‘‘mosaic’’ method, to avoid distortions of water balancing and runoff routing resulting from ‘‘coarse grids of large area’’ and to rationally describe spatial variation of hydrological variables.
(c) It performs simulations by adopting ‘‘various time intervals’’ for different hydrological processes (e.g. 1 h for infiltration and runoff yield processes of intensive rainfall, 6 h for runoff routing process on slopes and in river course, and 1 day for groundwater flow) to ensure rational description of dynamic mechanism and efficient calculation.
(d) It incarnates the theory of variable source area (VSA) in the calculation of runoff yield, which can simulate saturation excess, infiltration excess and spring flow out, and dynamically simulate surface water, groundwater and soil water.
(e) It has mutual feedback with a water allocation model to realize close coupling of natural hydrological cycle with artificial water system.
(f) It can calculate at a high speed (e.g. 11 min for 1 year simulation of the Yellow River Basin), and has functions of both flood simulation and long-term continuous simulation.

2.1.2. Soil erosion and sediment transport model

Soil and sediment can absorb and carry many pollutants like nitrogen and metals, thus simulation of soil erosion and sediment transport is quite important for water quality modeling. Taking 1 month as time interval and the above 8485 sub-basins as study object, this study adopts the following USDA (US Department of Agriculture) USLE (Universal Soil Loss Equation) equation (Fernandez et al., 2003; Ruan et al., 2003; Li and Li, 2004; Huang et al., 2004; Xu et al., 2006) to calculate soil loss from each of 29 types of land covers:

$$M_s = KR_pL_sCB \quad (1)$$

where M_s = soil loss (ton/ha/month); K = soil erodibility factor; R_p = rainfall and runoff factor; L_s = length-gradient factor; B = support practice factor; C = crop/vegetation factor.

2.1.3. Pollutant transfer model

The pollutant transfer model simulates processes of point and non-point sources into rivers, and pollutant advection and transfer in river channels. It takes one month as time interval, and the above 8485 sub-basins and correspondent river links as study objects.

(a) Point source load into river links: Point source load into river links equals the point source load multiplied by a coefficient of load into river links. The point source load is estimated using the quota method, whilst industrial point source load is decided by GDP and life point source load is decided by rural population and urban population. The transfer coefficient into river links is estimated from typical investigations in various districts (Yang and Kusuda, 2005).

(b) Non-point source load into river links: Non-point source load into river links is decomposed into dissolved type and solid type. The dissolved type is formed by rainfall-runoff process and computed as:

$$L_D = 0.1C_DRT_DA \quad (2)$$

where L_D = dissolved non-point load into river link in a sub-basin (kg/month); C_D = concentration of dissolved non-point load (mg/L); R = surface runoff generated in the sub-basin (cm/month); A = the sub-basin area (ha); T_D = transfer coefficient into river link of dissolved non-point load.

The solid type is computed based the above USLE equation:

$$L_S = 0.001 C_S M_S T_S A \quad (3)$$

where L_S = solid non-point load into river link in a sub-basin (kg/month); C_S = concentration of solid non-point load (mg/kg); T_S = transfer coefficient into river link of solid non-point load.

(c) Water quality in river links: Water quantity and pollutant balance in every river link in a sub-basin can be conceptualized as Fig. 1.

Water balance equation in the river link is as follows:

$$V_1 - V_{01} = \left(Q_0 + R + W_p\right) - (Q_1 + Q_u + W_t) \quad (4)$$

Pollutant balance equation in the river link is as follows:

$$V_1C_1 - V_{01}C_{01} = \left(Q_0C_0 + RC_R + W_pC_p - W_tC_t\right) - [Q_1C_1 + Q_uC_u + k(V_1C_1 + V_{01}C_{01})\Delta t/2] \quad (5)$$

where $\Delta t = 1$ month; k = pollutant decay factor; Q_0 = inflow from upstream; C_0 = pollutant concentration of inflow; Q_1 = outflow to downstream; C_{01}, C_1 = pollutant concentrations of outflow at the month's beginning and at the month's end; V_{01}, V_1 = water storages at the month's beginning and at the month's end; R = local runoff into river link; C_R = pollutant concentration of local runoff into river link ($C_R = (L_D + L_s)/R$); W_p = non-point source inflow; C_p = pollutant concentration of non-point source inflow; W_t = diversion to outside sub-basin from local river link; C_t = pollutant concentration of diversion water; Q_u = local water withdrawal; C_u = pollutant concentration of local water withdrawal; and the others are the same as explained above. If assuming pollutants in the river link are well-mixed, then $C_u = C_t = C_1$.

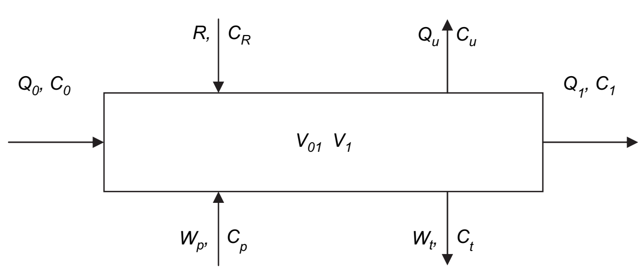

Fig. 1. Water quantity and pollutant balances in river link of a sub-basin. Q_0 = inflow from upstream; C_0 = pollutant concentration of inflow; Q_1 = outflow to downstream; C_1 = pollutant concentration of outflow; R = local runoff into river link; C_R = pollutant concentration of local runoff into river link ($C_R = (L_D + L_s)/R$); W_p = non-point source inflow; C_p = pollutant concentration of non-point source inflow; W_t = diversion to outside sub-basin from local river link; C_t = pollutant concentration of diversion water; Q_u = local water withdrawal; C_0 = pollutant concentration of local water withdrawal; V_{01}, V_1 = water storages at the month beginning and at the month end.

In summary, the computation procedure of the newly developed water quality module of WEP-L model is illustrated in Fig. 2.

2.2. Assessment approach

2.2.1. Improved characteristic channel length approach

The traditional characteristic channel length approach does not distinguish small rivers and big ones in the assessment of general water quality of a river channel system. An improved characteristic channel length approach is suggested by introducing a contributor factor of every river link W_i:

$$W_i = L_i \times A_i \quad (6)$$

where L_i = length of river link i; A_i = average area of river lateral section. W_i reflects the water volume in the river link.

2.2.2. Quality assessment of "water at river sections" and "water in sub-basins"

The water movement makes the quality of water resources in upstream change in downstream. Therefore, it will be difficult to thoroughly reflect the quality status, if just one criterion is adopted, i.e., the criterion of the quality of "water flowing through river sections" (called as "water at river sections" for simplicity). It is suggested to assess water quality from two aspects, i.e., quality of "water at river sections" and quality of "water in sub-basins". The quality of water in a sub-basin denotes the quality status of the water generated in a sub-basin and well-mixed in the local river link, or the quality status of source water.

The quality assessment of water at river sections in a river basin is performed by selecting main control sections in a main river and key tributaries, based on the monitoring data of water quality in gauge stations of control sections to validate the water quality model, and assessing the monthly/seasonal water quality of these control sections.

The quality assessment of water at sub-basins in a river basin is performed by dividing a river basin into small sub-basins (8485 sub-basins in the Yellow River Basin), modeling the runoff generation, soil loss and point/non-point source loads, validating the modeling results basing the monitoring data in gage stations of small rivers, and assessing the monthly/seasonal water quality in the sub-basins. The water quantity and pollutant amount in larger sub-basins or in the whole basin can be obtained by just summing up the results in small sub-basins.

3. Application

The model described above and the approach has been applied to the Yellow River Basin (795,000 km^2) for an

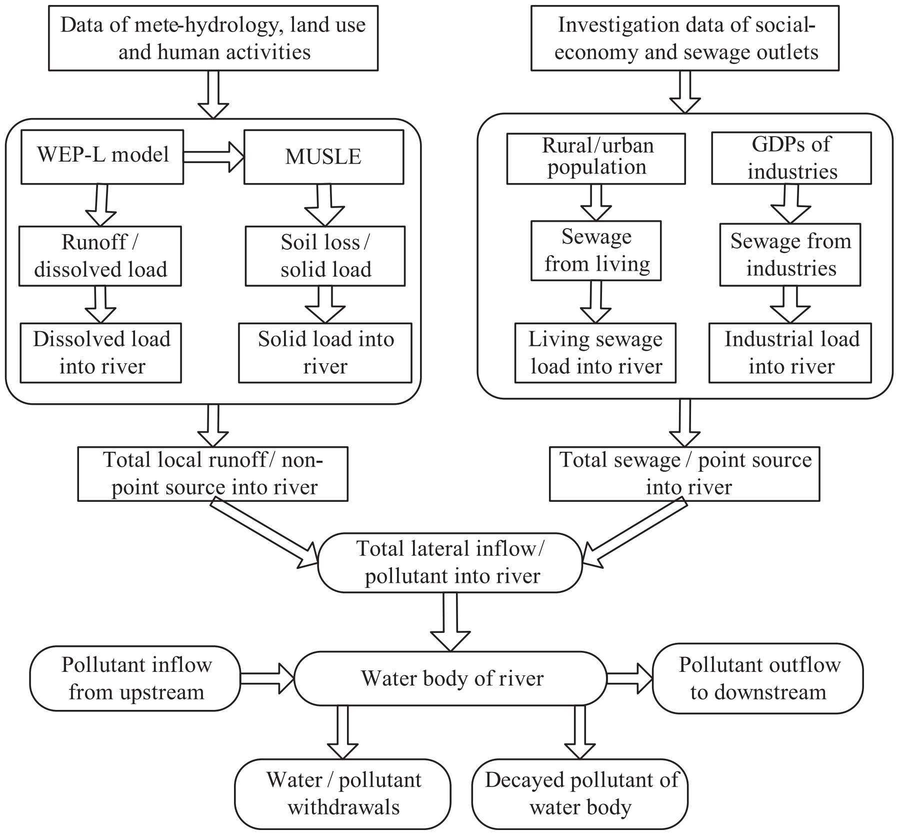

Fig. 2. Computation procedure of water quality module of WEP-L.

integrated assessment of water quantity and quality in 2000. A basic map of the Yellow River Basin is shown in Fig. 3 in which WRA2 and WRA3 denote the 2nd level national water resources assessment sub-basin and the 3rd one in China, respectively. The details of data preparation, parameter estimation, WEP-L model validation and water resources assessment are referred to in the related references mentioned above.

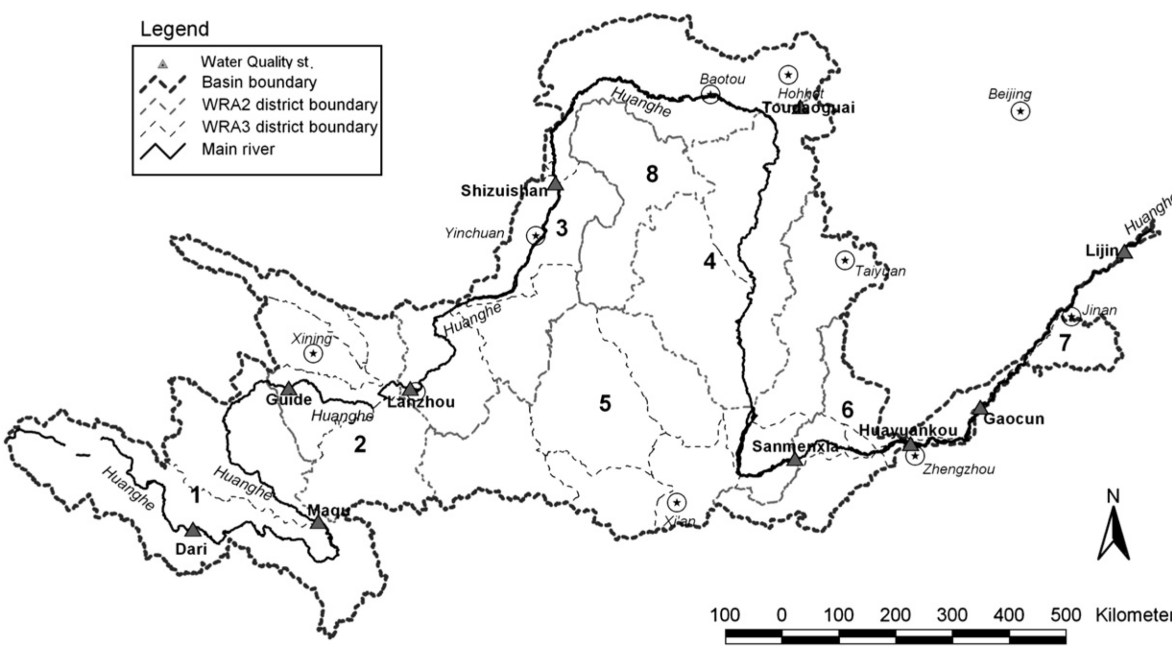

Fig. 3. Map of the Yellow River Basin. Big numbers are codes of 8 WRA2 districts and small ones are codes of 29 WRA3 districts. WRA2 and WRA3 denote the 2nd level national water resources assessment sub-basin and the 3rd one, respectively.

3.1. Pollutant source investigation and water quality status

The pollutant source investigation is based on the results of Comprehensive Water Resources Planning of China carried out from 2002 to 2006. It includes point source investigation and non-point source investigation. For point source investigation, 1029 sewerage outlets into rivers were investigated, and sewerage volume, COD load and NH_4-N load into rivers from these outlets in 2000 were 3.415 billion m^3, 1.396 million tons and 0.151 million tons, respectively which account for 87% of total sewerage, 80% of total COD load and 82% of total NH_4-N load into rivers in 2000 in the Yellow River Basin. The remaining percentages of the COD and NH_4-N loads are from non-point source. However, the investigation shows that 59% of TN and 80% of TP came from non-point source.

3.2. Model validation

The river flow simulations of WEP-L model are validated in 23 gauge stations in the Yellow River (Jia and Wang, 2006; Jia et al., 2006), a validation example at two stations is shown in Fig. 4. The validation of water quality simulation is carried out in this study. Fig. 5 shows an example of comparison of simulated and observed annual averaged concentrations of COD and NH_4-N at main control sections in the Yellow River.

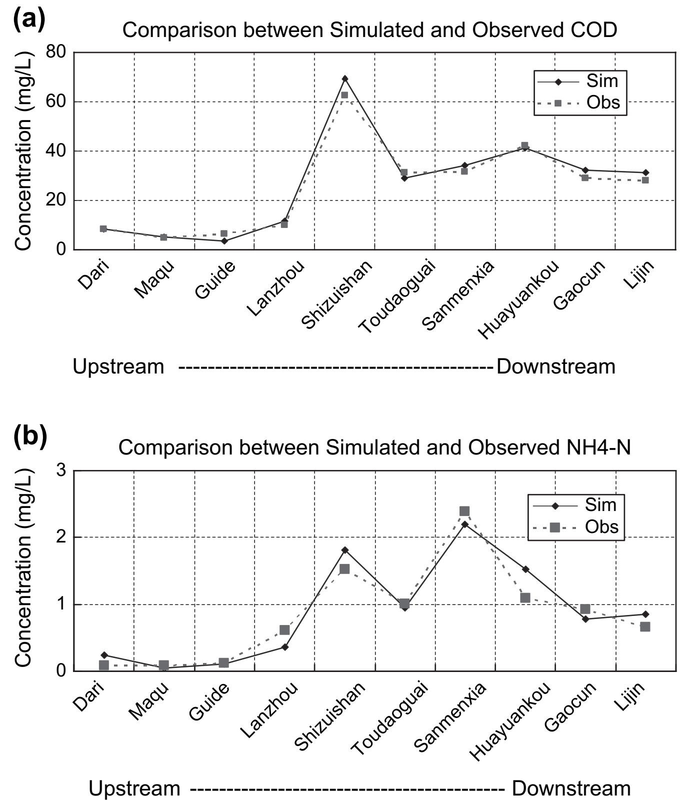

Fig. 5. Comparisons of simulated and observed annual averaged concentrations of COD and NH_4-N at main control sections in the Yellow River.

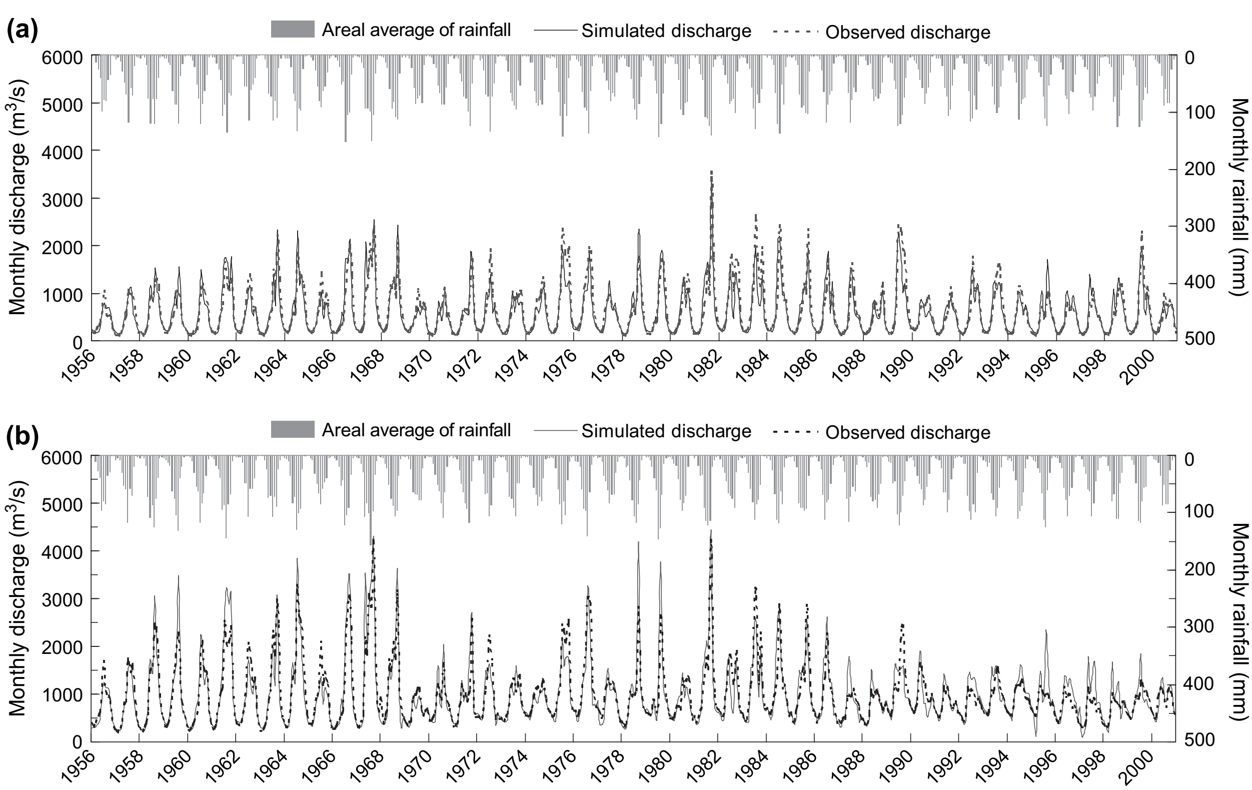

Fig. 4. Validation of simulated monthly discharges at (a) Tangnaihai station, and (b) Lanzhou station of the main river.

Table 1
Assessment result of the Yellow River water quality in 2000 by improved and traditional characteristic channel length approaches

Water quality class	Ratio of assessed channel length to total channel length (%)		
	Traditional characteristic channel length approach	Improved characteristic channel length approach	Difference
I	3.89	1.76	−2.13
II	41.86	19.63	−22.23
III	9.01	3.64	−5.38
IV	12.86	23.02	10.16
V	8.11	14.30	6.19
Worse than V	24.26	37.64	13.38
Sum	100	100	0

3.3. Integrated assessment results in the Yellow River Basin

3.3.1. Assessment result by improved characteristic channel length approach

Table 1 shows the water quality assessment result of the Yellow River in 2000 by improved characteristic channel length approach and the comparison with that by the traditional characteristic channel length approach. The total assessed channel length is 13,670.9 km, among which the main channel length is 5463.6 km and the tributary length is 8207.3 km.

From the result, it can be seen that the improved characteristic channel length approach shows that rivers of water quality worse than Class III account for 75% whilst the traditional characteristic channel length approach gives a result of 45%, implying that the actual status of water quality is worse than the traditional understanding. The water quality class is according to the Surface Water Quality Standard GB3838-2000 of China, which includes 6 classes and main pollutant items are PH, DO, COD, BOD5 and NH_3-N.

3.3.2. Integrated assessment result of ''water at river sections''

The assessment result at 9 control sections (see Fig. 3) in the Yellow River main channel in 2000 is shown in Table 2.

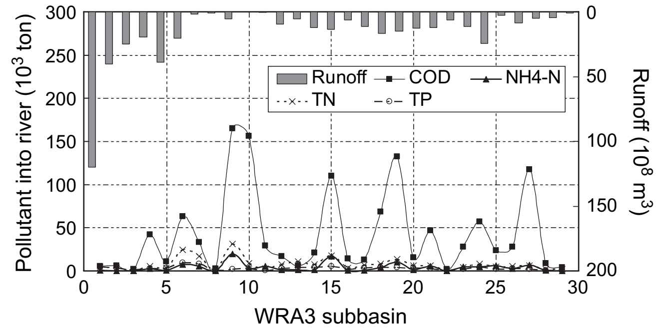

Fig. 6. Runoff and main pollutants into rivers in the WRA3 sub-basins of the Yellow River Basin in 2000.

From the result, it can be seen that the water quality upstream Lanzhou was Class II and III, the water quality downstream Lanzhou was mainly Class IV, V and worse than V. Although the quality of ''water in sub-basins'' is quite good (see the next section), the water quality in the main river downstream Lanzhou got worse because of the pollution in the area of middle and down streams caused by concentrated population and industries.

3.3.3. Integrated assessment result of ''water in sub-basins''

Applying the GIS technique and the model (the computation procedure as shown in Fig. 2), runoff and main pollutants into rivers were obtained in the WRA3 districts (see Fig. 3) of the Yellow River Basin in 2000 by summing up the results of the 8485 small sub-basins. As shown in Fig. 6, it can be seen that the main pollutants into rivers in the districts are closely related to the runoffs but have obvious spatial variations. It can also be seen that the headwater area (1–5 districts) contributes large amount of water but little pollutants, whilst the districts of 9 and 10 (between Lanzhou and Toudaoguai) contribute little water but large amount of pollutants.

Summing up the result of the WRA3 districts, the result of the WRA2 districts is shown in Table 3. It can be seen that according to the assessment result of ''water in sub-basins'', the water with the quality of Class II or better

Table 2
Integrated assessment result of water quantity and quality at main control sections in the Yellow River main channel in 2000 (unit: 100 million m^3)

Section name	Subtotal water quantity	Water quantity correspondent to each water quality class					
		Class I	Class II	Class III	Class IV	Class V	Worse than Class V
Tangnaihai	135.08	0	135.08	0	0	0	0
Guide	155.18	0	155.18	0	0	0	0
Landzhou	226.80	0	54.67	172.13	0	0	0
Toudaoguai	122.28	0	0	0	55.07	13.27	53.94
Longmen	137.15	0	0	14.07	26.37	58.15	38.55
Sanmenxia	142.37	0	0	0	22.72	53.02	66.64
Huayuankou	144.30	0	0	0	0	78.27	66.04
Gaocun	119.60	0	0	0	71.46	48.14	0
Lijin	42.42	0	0	0	26.75	15.68	0

Table 3
Integrated assessment result of water quantity and quality in the WRA2 districts of the Yellow River main channel in 2000 (unit: 100 million m^3)

WRA2 name	Subtotal water quantity	Water quantity correspondent to each water quality class					
		Class I	Class II	Class III	Class IV	Class V	Worse than Class V
Upstream to Longyangxia	159.88	0	159.88	0	0	0	0
Longyangxia–Landzhou	103.24	4	78.51	5.83	10.1	1.83	2.97
Landzhou–Hekouzhen	8.56	0	2.89	1.24	0.05	0.56	3.82
Hekouzhen–Longmen	27.43	0	3.29	5.51	12.32	6.32	0
Longmen–Sanmenxia	87.67	0	7.41	14.82	22.87	8.57	33.99
Sanmenxia–Huayuankou	44.7	2.71	17.97	2.52	1.87	5.22	14.41
Downstream Huayuankou	18.08	0	0	0.06	1.91	0.27	15.84
Sum	450.48	6.74	270.23	30.17	49.24	22.85	71.25
Percentage	100	1.50	59.99	6.70	10.93	5.07	15.82

than Class II is over 60% of total water resources in the Yellow Basin in 2000. The water quality got worse in the middle and downstream sections because of the pollution in the area (see the above section). Therefore, the two assessment criteria can reflect the water quality status and its spatial evolution more thoroughly than when only one criterion is adopted.

4. Conclusions

The integrated water resources and water environment management requests that the integrated assessment of water quantity and quality be carried out, but the existing assessment approaches cannot describe the temporal and spatial changes of water quality, while it is difficult to perform scenario analysis in water resources planning and management.

This study established the integrated model of water resources and water environment by coupling a physically based distributed model, a semi-distributed soil erosion model and a pollutant transfer model, and proposed the integrated assessment approach which is composed of the improved characteristic channel length approach, quality assessment of water at sections and quality assessment of water in sub-basins.

The application results of the newly suggested model and approach in the Yellow River Basin shows that the actual status of water quality is worse than the traditional understanding, and the quality of water in sub-basins is better than that at channel lateral sections. The results provide valuable information for the water resources development and management in the basin.

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