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Development of the WEP-L distributed hydrological model and dynamic assessment of water resources in the Yellow River basin

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Summary Dynamic assessment of water resources becomes desirable to reflect water resources variations in the basins under strong human impacts. A physically based distributed hydrological model, WEP-L, which couples simulations of natural hydrological processes and water use processes, is developed for the purpose. Concepts of special water resources (i.e., surface water resources and groundwater resources) and general water resources (i.e., the special water resources plus the precipitation directly utilized by ecosystem) are proposed, and an approach for dynamic assessment of water resources is suggested. Basin subdivision, classification of land covers, and deduction of water use spatial/temporal distributions in the Yellow River basin are carried out with the aid of remote sensing (RS) data and geographic information system (GIS) techniques. The basin is subdivided into 8485 sub-watersheds and 38,720 contour bands, and the WEP-L model is verified by comparing simulated and observed discharges at main gage stations. Lastly, continuous simulations of 45 years (1956–2000) in variable time steps (from 1 h to 1 day) are performed for various land cover and water use conditions, and water resources assessment results under present condition of land cover and water use are compared with those under historical condition of land cover and water use. The study results reveal that: (1) the surface water resources reduced, but the groundwater resources non-overlapped with the surface water resources increased under the impact of human activities in the Yellow River basin; and (2) the special water resources reduced, but the general water resources increased accompanied with increase of the precipitation directly utilized by ecosystem in the basin.

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Introduction

Limitations of the traditional water resources assessment

Strong interferences of human activities are changing hydrological cycle and water resources in many river basins. Dynamic assessment of water resources, i.e., assessing or predicting water resources and its variations in a basin in the past, at present and in the future becomes desirable for sustainable water resources development and management. However, all of water resources assessment practices both in China (e.g., BOH, 1986) and abroad (e.g., Miloradov and Marjanovic, 1998) were carried out based on the traditional ''observation and naturalization'' approach, with which surface water resources is deduced by naturalizing historic series of observed river discharges based on water use data and water balance equations. To know total water resources in a basin, and to eliminate overlapped part (e.g., river base flow from groundwater and leakage from water bodies) of surface water resources and groundwater resources, a terminology of ''non-overlapped groundwater resources'' was suggested by Chinese experts (BOH, 1986) and widely accepted in the society of hydraulic engineering in China. The traditional approach has the following limitations for the dynamic assessment of water resources: (1) it cannot reflect the impacts of land cover changes on actually available water resources at present, (2) it assesses surface water and groundwater separately though they are strongly interactive, (3) it studies the water resources in forms of surface water and groundwater (''blue water'') but excludes the precipitation consumed by vegetation (''green water''), and (4) it is lumped assessment thus difficult to give detailed distributions of water budgets inside an assessed basin.

The key reason for the limitations described above lies in lack of appropriate models to simulate the water movement in a basin under strong interferences of human activities. A lot of statistic models or lumped models, like the precipitation—runoff relation curve approach, runoff coefficient model, etc., cannot solve the above problems because they are not based on physical hydrological processes and difficult to reflect impacts of land covers and water utilization.

Development and applications of distributed hydrological models

Distributed watershed hydrological models (Singh and Woolhiser, 2002) and SVAT (soil—vegetation—atmosphere transfer scheme) models (Sellers et al., 1997) got great developments in the past 20 years, which provides favorable conditions for the dynamic assessment of water resources with the aid of remote sensing (RS)/geographic information system (GIS) techniques. Marsh and Anderson (2002) claim the contributions of hydrological models and digital cartography against a background of changing information need and the likelihood that the long-term stability, which has characterized water resource variability in the past, may not continue in the future. Refsgaard et al. (1996) emphasized the importance of physically based spatially distributed (PBSD) hydrological models in simulating effects of watershed changes due to human interference. However, some key problems are still confronted and need studied when PBSD hydrological models are applied to water resources assessment in large basins, such as description of spatial heterogeneities of hydrological variables and land surface characteristics, efficient simulation of water dynamics, and coupling simulation of natural water cycle system and artificial water cycle system. On the other hand, SVAT models are capable of simulating detailed evaporation and transpiration processes in canopies and land surfaces, which are required for assessment of general water resources including the precipitation directly utilized by ecosystem. However, SVAT models neglect runoff-generation and groundwater flow processes or treat them too coarsely. Therefore, combination of merits of PBSD models and SVAT models are desired for dynamic and general assessment of water resources.

There are mainly three types of distributed hydrological models according to their spatial structures or basic computation units, i.e., grid type, sub-watershed type and landscape (e.g., hill-slope) type. The grid-based models like SHE (Abbott et al., 1986) are usually difficult to be applied to large basins because of heavy computation, and the landscape-based models like IHDM (Calver, 1988) are also the case because of irregular data preparation burdens. The sub-watershed type models like HYDROTEL (Fortin et al., 2001), CELMOD (Karnieli et al., 1994), etc., can be easily applied to large basins but the effects of topography on saturation overland flow are not explicitly described in these models, which are thought to be quite important according to the runoff generation theory of various source areas (Hewlett, 1982). SWAT (Arnold and Allen, 1996) considers the hydrological heterogeneity through HRU (hydrological response unit) subdivision inside sub-watershed, and TOPMODEL (Beven et al., 1995) implicitly consider the effects of topography and soil by introducing the topography-soil index and assuming the subsurface water level parallel to land surface, but neither of the sub-watershed type models explicitly described the effects of topography. KINEROS (Woolhiser et al., 1990) considers the effects of topography through representing a sub-watershed by one channel and two overland planes flowing into the channel, but it cannot reflect the slope variation in an overland plane, which makes the model applications to large basins questionable because the overland plane has a quite big area in the cases. Therefore, to overcome the model structure defects, the newly developed WEP-L model in this study subdivides every sub-watershed into many contour bands and further subdivides every contour band into many land use mosaics.

Development and applications of distributed hydrological model for large basins have been found in the Elbel river basin (Hattermann et al., 2005) with SWIM (Krysanova et al., 1998), the Mekong river basin (Nawarathna et al., 2001) with BTOPMC (Takeuchi et al., 1999), and all of global river basins with WaterGAP2 (Alcamo et al., 2003; Döll et al., 2003), etc. Hattermann et al. (2005) subdivided the German part (80,256 km^2) of the Elbe into 226 sub-basins, and surface runoff is calculated on daily basis using a modification of the SCS curve number technique (Arnold and Allen, 1996), a conceptual rainfall-runoff model. Their study concentrated on model validation and simulation periods were less than 8 years, water use and water resources assessment were not dealt with. Most applications of distributed hydrological models for large basins like the application of BTOPMC in the Mekong river basin (Nawarathna et al., 2001) were aimed to estimate water use information based on the differences in observed actual river discharges and simulated naturalized river flows, water utilization activities (such as water diversion and drainage as well as reservoir operations, etc.) and correspondent impacts on water resources were not directly incorporated into model structures. WaterGAP2 considered the water use problem in the global hydrological modeling, but it adopted a very coarse spatial resolution of 0.5° and the estimated water use was not compared with statistical data for every basin. There was even no discharge gauge station in the Yellow River basin in its calibration, thus it is difficult to apply it to carry out a sound assessment of water resources in the basin. In addition, the effects of topography inside every sub-basin or grid cell on runoff generation as the above mentioned, are not explicitly described in most of distributed hydrological model for large basins.

Considering the state of the art of distributed hydrological models, a distributed hydrological model for large basins, WEP-L, is developed and applied for dynamic assessment of water resources in the Yellow basin in this study. It is characterized by coupling simulations of natural hydrological processes, energy transfer processes and water use processes, adopting a particular spatial structure inside a sub-watershed, and having a capability to conduct a dynamic assessment of water resources in all forms, i.e., surface water, groundwater and the precipitation consumed by vegetation.

WEP-L model and dynamic assessment of water resources

The water and energy transfer processes (WEP) model (Jia et al., 2001) was developed by combing the merits of PBSD models and SVAT models. The model has been successfully applied in several watersheds in Japan, Korean and China with different climate and geographic conditions (Jia and Tamai, 1998a; Jia et al., 2001, 2002, 2004, 2005; Kim et al., 2005; Qiu et al., 2006). The WEP model has the following main characteristics: (1) combined modeling of hydrological processes and energy transfer processes, (2) consideration of the land use heterogeneity inside a computation unit by adopting the mosaic method (Avissar and Pielke, 1989), and (3) incorporation of the runoff generation theory of various source areas (Hewlett, 1982) into the model through a numerical simulation in groundwater/subsurface water flows to directly reflect topography's effects in runoff generation, thus cable of modeling infiltration excess, saturation excess and mixed runoff generation mechanism.

To make the WEP model applicable for water resources assessment in large basins like the Yellow River basin, the following main improvements are performed and the WEP-L model is established consequently: (1) instead of grid cells, contour bands inside small sub-watersheds, which are obtained based a DEM of 1-km resolution and the area of every sub-watershed is less than 100 km^2, are used as computation units, and the Pfafstetter coding rule (Verdin and Verdin, 1999) is adopted to code subdivided river links and sub-watersheds to aid hydrological modeling in the large basin; (2) the soil-vegetation land use group in the WEP model is further divided into three groups of soil-vegetation (grassland, forest, and bare soil land), irrigated farmland, and non-irrigated farmland to consider cultivation and irrigation effects on hydrological processes; (3) a water allocation and regulation model (WARM) is developed and coupled to WEP-L to model water use processes like reservoir regulation, canal diversion and water allocation in a coupling way with natural hydrological processes; (4) spatial and temporal interpolations of social-economy and water use data are carried out; and (5) a snow melt model based on the temperature-index approach is developed to reflect the impacts of snow storage and melting on hydrological and energy processes as well as water resources.

Model structures and modeling approaches for main processes

The vertical structure of WEP-L within a contour band is shown in Fig. 1(a), and the horizontal structure of WEP-L within a sub-watershed is shown in Fig. 1(b). Land use is divided into five groups within a contour band, namely Soil-Vegetation (SV) group, Non-irrigated Farmland (NF) group, Irrigated Farmland (IF) group, Water Body (WB) group and Impervious Area (IA) group. The SV group is further classified into bare soil land, tall vegetation (forest or urban trees) and short vegetation (grassland). The IA group consists of impervious urban cover, urban canopy and rocky mountain. The areal average of water and heat fluxes from all land uses in a contour band produces the averaged fluxes in the contour band. For pervious groups of SV, NF and IF, nine vertical layers, namely an interception layer, a depression layer, three upper soil layers, a transition layer, an unconfined aquifer, an aquitard and a confined aquifer, are included in the model structure.

The simulated hydrological processes include snow melting, evapotranspiration, infiltration, surface runoff, subsurface runoff, groundwater flow, overland flow, river flow, and water use. The simulated energy transfer processes include short-wave radiation, long-wave radiation, latent heat flux, sensible heat flux, and soil heat flux. Adopted modeling approaches for hydrological and energy processes are referred to in Jia et al. (2001) except snow melting and water use processes.

Evapotranspiration consists of interception of vegetation canopies (evaporation from the wet part of leaves), evaporation from water body, soil, urban cover and urban canopy and transpiration from the dry fraction of leaves with the source from the three upper soil layers. The evaporation from the water body or the ponded water in the depression storage is calculated with the Penman equation. The evaporation from the impervious area is taken as the smaller one of current depression storage and the potential evaporation. The computation of interception is referred to the Noilhan and Planton (1989) model that is an interception reservoir method. The evaporation from soil is assumed to come only from the topsoil layer. The Penman equation is adopted to compute potential evaporation from which actual evaporation of soil is computed using a wetness function suggested by Lee and Pielke (1992). The actual transpiration is calculated using the Penman–Monteith

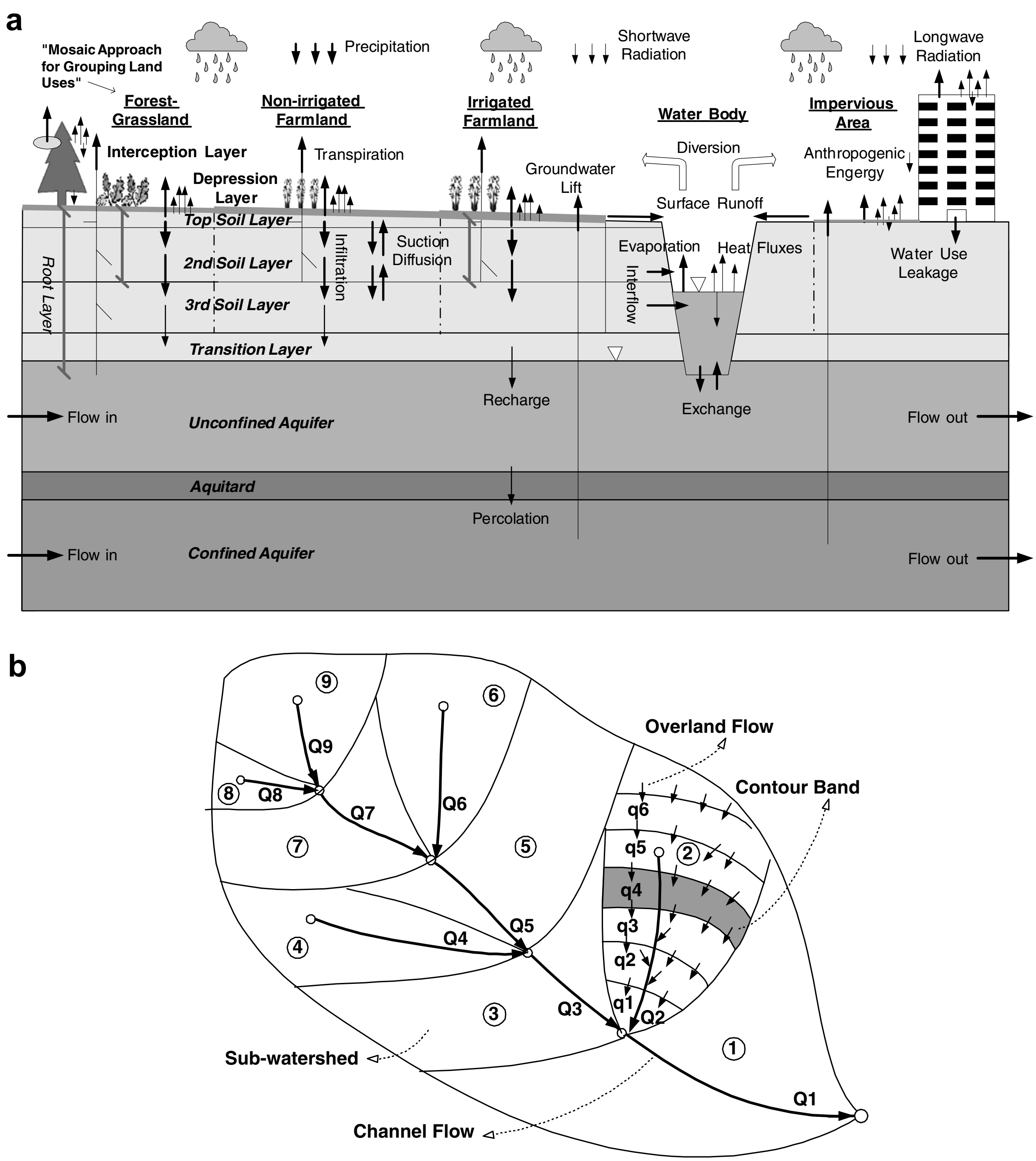

Figure 1 Schematic illustration of WEP-L model structure: (a) vertical structure within a contour band, and (b) horizontal structure within a sub-watershed.

equation (Monteith, 1973) and the canopy resistance (Noilhan and Planton, 1989) which is related to the soil moisture condition. The average evapotranspiration in a contour band is obtained by areally averaging those from each land use.

Infiltration and surface runoff during rains bigger than 10 mm/h are calculated in a time step of 1 h utilizing the generalized Green-Ampt model for infiltration into multi-layered soil profiles suggested by Jia and Tamai (1998b), whereas soil moisture movement in unsaturated soils during other periods is solved using the Richards model. The infiltration excess occurs when the depression storage on land surface surpasses its maximum value. The depression storage is balanced with rainfall as inflow and infiltration, evaporation, and infiltration excess as outflows. The saturation excess during the remaining periods may occur if the groundwater level in the unconfined aquifer rises and the topsoil layer becomes nearly saturated. The saturation excess is deduced by applying the Richards model. Subsurface runoff, or inter flow, is calculated by multiplying land slopes and unsaturated soil hydraulic conductivities in those contour bands inside which there are rivers.

A quasi-three-dimensional simulation of groundwater flow in multi-layered aquifers is performed in a time step of 1 day using the Boussinesq equation. The interactions between surface water and groundwater of the unconfined aquifer are considered through a source term. The source term includes recharge from unsaturated soil layers, groundwater outflow to rivers, leakage of water use system, pumped groundwater, percolation to the lower aquifer and evapotranspiration from groundwater. Groundwater outflow is calculated by applying the Darcy law, and according to the hydraulic conductivity of riverbed material and difference between river water stage and groundwater head in the unconfined aquifer.

Overland flow is routed in a time step of 6 h from the contour band at most upstream to the contour band at most downstream in a sub-watershed using the kinematic wave method in the scheme of one-dimensional sheet flow. River flow routing is conducted in a time step of 6 h for every tributary and a main river using the kinematic wave method or the dynamic wave method in one-dimensional scheme in river links where reservoir storages have impacts on river water levels. The adopted time step of 6 h is to keep the balance between routing accuracy and computation burden and there is no computation stability problem because the implicit scheme is adopted in the numerical simulations.

Snow storage and melting processes are simulated using the temperature-index approach (Maidment, 1992) on the daily basis.

Water use processes are modeled in a coupling way with natural hydrological processes by developing a water allocation and regulation model (WARM). Coupling is interactive in two ways: WEP-L provides WARM inflow and rainfall information, WARM provides WEP-L water use distributions of various water users (industry, living, agriculture, forest, and fishery) and water diversion from river channels, and regulates hydraulic structures like dams and gates. Results of two models are revised through information feedbacks till they are in consistency. The WARM model (Wang and Qin, 2004) requires a network of rivers, canals, water supply structures and water users, and it includes two modules: water use distribution deduction module and dam regulation module. The water use distribution deduction module is also referred to in ''Spatial and temporal interpolations of water use data'' section, and the dam regulation module is based on water balance, water levels for flood control, and water level—storage curve.

Concepts and approaches for dynamic assessment of water resources

The scope of water resources assessed in the traditional approach includes surface water and groundwater, both of which exist in gravity-driven form. However, unsaturated soil moisture in vegetation root zones and intercepted precipitation on vegetation are effective to ecology, and evaporation from depression layer of residential area is also effective to people-living environment because it can wet the dry air and lower the air temperature in hot summer. Thus these parts of evapotranspiration, i.e., the precipitation directly utilized by ecosystem should also be considered into water resources assessment. The traditional water resources can be called as ''special water resources'', and those including the precipitation directly utilized by ecosystem can be called as ''general water resources''.

The general water resources equals sum of the special water resources and the precipitation directly utilized by ecosystem, and it can be calculated as follows:

$$W = (R_s + R_g) + (E_i + E_d + E_t) \tag{1}$$

where the variables are defined as follows: W, general water resources; R_s, surface water resources; R_g, groundwater resources non-overlapped with surface water resources; E_i, interception of vegetation canopies; E_d, evaporation from depression layers of residential and vegetation areas; and E_t, vegetation transpiration, i.e., utilization of soil moisture non-overlapped with surface water and groundwater in vegetated areas. In addition, $R_s + R_g$ is the special water resources, and $E_i + E_d + E_t$ is the precipitation utilized by ecosystem.

The WEP-L model can be adopted to accomplish the general water resources assessment in accordance with Eq. (1). For the case without consideration of water use, R_s in any computation unit can be simply obtained by summing up the surface runoff, the groundwater outflow, and the inter flow output by WEP-L; R_g equals the evapotranspiration from aquifers; and E_i, E_d and E_t can also be easily obtained from the outputs of WEP-L because of the detailed simulation of evapotranspiration in the model. For the case with consideration of water use, R_s are obtained by eliminating the effects of water use on the surface runoff, the groundwater outflow, and the inter flow (precipitation and water use are assumed to have similar roles in generation of the runoffs and the outflow in this study for simplification); R_g equals the evapotranspiration from aquifers plus the net exploitation of groundwater; and E_i, E_d and E_t are obtained by eliminating the effects of water use on the evapotranspiration. In addition, water resources assessment results under different conditions of meteorology and land covers can be obtained by changing input data of meteorology and land covers. Thus the dynamic assessment of water resources can be realized by applying WEP-L.

The study case

Introduction to the Yellow River basin

The Yellow River is the second longest river in China. Map of the Yellow River basin is shown in Fig. 2. The area of the basin is 794,712 km^2. After running through the Tibet Plateau, the Loess Plateau and the North China Plain, the river runs into the Bohai Sea at last. The headstream of the Yellow River is covered by snow and frozen soil for the whole year. The area upstream to Lanzhou city is the main source of the river runoff, and about 54% of the river runoff is from this area. The vast expanse of desert distributes in the area from Lanzhou to Toudaoguai, the dividing line of the upper reaches and middle reaches. Downstream to Toudaoguai, the Yellow River runs through the famous Loess Plateau, where most of the sand of the basin produces because of

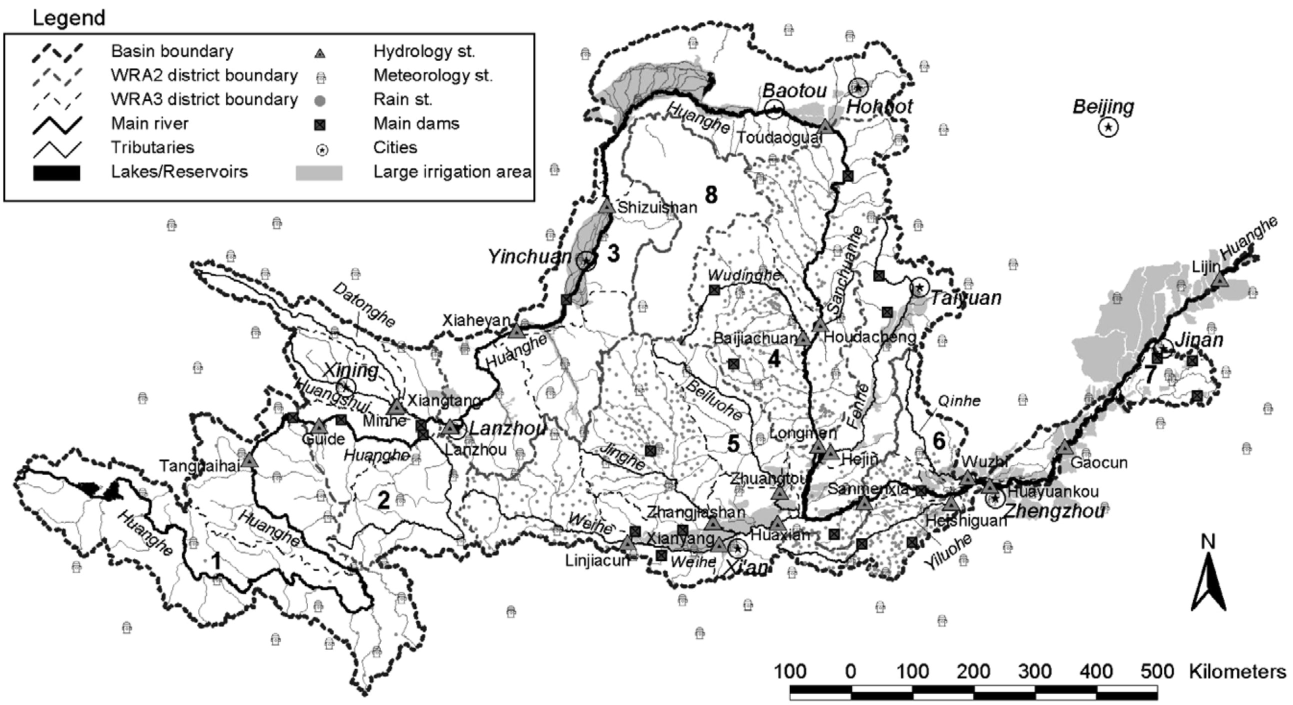

Figure 2 Map of Yellow River basin: numbers (1—8) in the figure are codes of 8 WRA2 districts. WRA2 represents the 2nd level national water resources assessment sub-basin in China, WRA3 means the 3rd level one (a further subdivision of WRA2), and WRA1 means the 1st level one. There are totally 10 WRA1 districts in China, one of which the Yellow River basin is.

the rainstorm frequently occurring in flood season besides the loose soil texture and sparse vegetation. The vegetation in the area from Longmen to Huayuankou is dense because of the abundant rain. The riverbed of most trunk stream is above the ground downstream to Huayuankou, the dividing line of the middle reaches and lower reaches. A small quantity of water flows into the river in this area.

Main problems existed in the Yellow River basin

The Yellow River basin has been playing very important roles in the social-economy development of China. In the past decade, problems of water shortage and environment deterioration became very serious in the basin, e.g., zero-flow or drying-up duration per year in the downstream sections of the main river got longer and longer. The situation is related both to less rainfall in recent years and to strong human activities. According to statistics (''A Preliminary Report on Investigation of Water Resources and Water Utilization in China'', the Ministry of Water Resources of China, 2004), 12 reservoirs (total volume 56.3 billion m^3) at the main river and 170 reservoirs (total volume 10.0 billion m^3) at tributaries were constructed; large amount of soil conservation facilities including 1390 small reservoirs, over 11,200 silt arresters and over 4 million ponds were established in the basin; irrigation area increased to 7.3 million ha in 2000 from 0.8 million ha in 1950s; total water use in the basin increased to 41.9 billion m^3 in 2000 from 12.2 billion m^3 in 1950s and averaged water discharged into sea decreased to 13.2 billion m^3 in 1990s from 48.5 billion m^3 in 1950s. These human activities not only changed hydrological processes but also impacted availability and compositions of water resources, thus dynamic assessment of water resources, i.e., assessing variations of water resources under past, present, and future land cover and water use conditions, is important to sustainable development and management of the water resources in the basin.

There are quite a lot of researches on the variations of water resources and hydrological cycle in the Yellow River basin observed in the literatures. Chang et al. (1998) studied on the rational allocation and optimal regulation of water resources in the basin on the basis of a water resources assessment. Su et al. (1998) concentrated their research on the rational development and utilization of groundwater resources in the basin. In addition, Wang et al. (2004) investigated the effects of human activities on the hydrological cycle in the basin based on observation data and statistic analysis. All of these researches were conducted either using the traditional water resources assessment approach or based on analysis of observation and statistic data, not satisfying the requirement of dynamic water resources assessment to reflect the impacts of strong human activities and climate changes on the availability of water resources in the basin.

Application

Data collection and analysis

Table 1 shows a list of the collected basic data on which the WEP-L input data are based. The data include the following categories: (1) hydro-meteorology; (2) land cover information including land use, vegetation, soil and water

Table 1 List of collected basic data on which the model input based

Category	Item	Content
Meteorological and hydrology	Daily rain/snow	Data of 1045 rain stations, and 212 meteorological stations from 1956 to 2000
	Hourly rain/snow	Data of 904 rain stations from 1956 to 2000
	Wind speed	Daily data of 212 meteorological stations from 1956 to 2000
	Air temperature	Daily data of 212 meteorological stations from 1956 to 2000
	Sunshine hours	Daily data of 212 meteorological stations from 1956 to 2000
	Humidity	Daily data of 212 meteorological stations from 1956 to 2000
	Monthly runoff	Data of 23 hydrologic stations from 1956 to 2000
	Daily runoff	Data of 23 hydrologic stations during partial periods from 1956 to 2000
Remote sensing and land use	Landsat TM and deduced land use	1:100,000 map in 1986, 1996 and 2000
	NOAA-AVHRR	Monthly data between 1982 and 2000
	GMS	Monthly data between 1998 and 2002
Vegetation	Vegetation fractional coverage	Deduced from NOAA-AVHRR from January in 1982 to December in 2000
	Leaf area index	Deduced from NOAA-AVHRR from January in 1982 to December in 2000
	Crop patterns	Data of 3rd level WRA districts of the Yellow River in 1980, 1990 and 2000
Topography, Soil and geohydrology	Topography	USGS GTOPO30 (1 km by 1 km DEM)
	Soil	1:1000,000 and 1:100,000 soil classification maps in China
	geohydrology	Parameters of geohydrology, distribution of lithology and thickness of aquifers
River network, and hydraulic engineering	River network	River network map
	River profiles	133 typical rivers section profiles
	Water conservancy	Basic information of 184 large and medium-sized reservoirs
	Water and soil conservation	Water and soil conservation information in Yearbooks of Water Conservancy Statistics of related counties from 1980 to 2000
Water use	Reservoir operation	Reservoir operation information of 184 reservoirs
	Water use in irrigation areas	Water use data in 119 irrigation area larger than 100 thousand mu
	Water use in administrative areas	Monthly water use data at the county level from 1956 to 2000
	Water diversion	Water diversion processes in representative districts
Social economy	GDP	GDP of 150 overlapped areas of prefectures and the 3rd level WRA districts in 1980, 1985, 1990, 1995, 2000
	Population	Population of 150 overlapped areas of prefectures and the 3rd level WRA districts in 1980, 1985, 1990, 1995, 2000

conservation, crop patterns, etc.; (3) topography, soil and hydrogeology; (4) river networks, river sections and hydraulic structures (dams/reservoirs); and (5) water use and social-economy.

The hydro-meteorological data have two sources: the National Climate Bureau of China (NCBC) and the Yellow River Water Conservancy Commission (YRWCC). NCBC provided the meteorological data of key national meteorological stations (212 stations inside and around the Yellow River basin) with five items of rain/snow, air temperature, sunshine hours, vapor pressure/relative humidity, and wind speed on daily basis. YRWCC provided the daily rain (1045 stations), hourly rain (904 stations) data and river discharge data (23 stations). Both data sets had been strictly reviewed by the correspondent organizations through the analysis of correlativity and consistency, thus having relatively higher accuracies. YRWCC has more stations for rain observation than NCBC but the YRWCC stations are concentrated in the central and downstream areas of the basin, and the data for other meteorological factors can only be provided by the NCBC stations. It has been taken into consideration in the spatial and temporal interpolations of meteorological data to overcome the defect of rain gauge station distribution (see ''Spatial and temporal interpolations of meteorological data'' section). The river discharge data YRWCC provided includes observed and naturalized (reverting the taken water to rivers and reservoirs) monthly data from 1956 to 2000 of 23 stations, and partial daily data of 23 stations.

Land use data of five periods (1960s, 1970s, 1980s, 1990s and 2000) are obtained using the Landsat TM data and the statistic data in the yearbooks of administrative districts, and monthly vegetation information (LAI and area fraction of vegetation) from 1982 to 2000 is obtained using the NOAA-AVHRR data. The land use data include six Level 1 categories and 31 Level 2 categories, and a test of sampling investigation demonstrates that the data have an accuracy of 94%. Soil and water conservation measures include four types: man-made forest, man-made grassland, terraced farmland, and silt arresters. Annual data of the four types of facilities from 1970 to 2000 are obtained from the Annual Water Conservancy Statistics of related counties in the basin, and the check of consistency with the above land use data are carried out for forest and grassland. The irrigation districts data and crop patterns are from Introduction to Irrigation Districts in the Yellow River Basin and Map Collections of the Yellow River Basin, both compiled by YRWCC, and 119 large irrigations districts, each having an area of over 100,000 mu (Chinese area unit, 1 ha = 15 mu), are digitalized. Examples for illustrating historical variation of land use in the Yellow River basin are shown in Fig. 5: (a) main land uses, (b) terraced farmland, (c) farmland formed by silt arresters, and (d) irrigation area.

Topography data are obtained from the global DEM, or called as GTOPO30 data developed by the US Geological Survey's EROS Data Center, which can be downloaded from the website: http://edcdaac.usgs.gov/gtopo30/gtopo30.asp. The data are the grid type of DEM in the WGS84 coordinate system with a resolution of 30″ in the horizontal directions. The data in and around the Yellow River basin are transformed to 1 km by 1 km data using the Albers coordinates projection. The soil data including map of soil types and correspondent characteristic parameters are from National Second Soil Survey Data and Soil Types of China. The soil map has a scale of 1:100,000 and thickness and constitutions of every soil are given by the data of statistical profiles in Soil Types of China. The hydrogeology data of aquifers including hydrogeology unit subdivision, permeability and storage coefficient are from the Distribution Map of Hydrogeology in China and the Second-time Countrywide Comprehensive Water Resources Planning in China (undergoing now).

Surveyed river networks are obtained from the National Geography Database in a scale of 1:250,000, which are combined with the above DEM to carry out the basin subdivisions and codifications (see ''Division and coding of sub-watersheds and contour bands'' section). Surveyed shape data of 133 representative river sections are collected for flow routing, 31 of which are those of the main river. In addition that large amount of silt arresters are considered in the soil and water conservation, data of 184 reservoirs are collected, 21 of which are large scale ones, each having a total volume of over 0.1 billion m^3. The collected data include location data (coordinates) based on Map Collections of the Yellow River Basin compiled by YRWCC; initial operation dates of reservoirs, water level—volume—area curves, characteristic volumes and water levels, sedimentation and storage variation series, and operation rules; water supply purposes and geographic areas. Reservoir data analysis shows that the reservoirs at the main river contribute most of the total water storage volume of the basin. In addition, data of water diversion gates and pump stations related to 119 large irrigations districts are also collected.

Water use and social-economy data of the Yellow River basin are from the Second-time Countrywide Comprehensive Water Resources Planning in China. The statistical units of the data are the national administrative prefecture or municipality. The water use data includes water supply to and water consumption of five sectors (i.e., industrial, farmland irrigation, forest, grassland and fishery water use, urban daily life and rural daily life) with different sources (i.e., surface water, shallow groundwater and deep groundwater), and monthly water diversion processes in some representative districts. The social-economy data include population and GDP of various sectors. Table 2 shows historical variations of gross water use including drainage in the Yellow River basin.

Input data preparation using RS/GIS

Data preparation to run WEP-L includes: (1) stream network generation, basin subdivision and coding; determination of computation units and flow routing sequence; (2) treatment of river section and reservoir data; (3) treatment of land cover information like land uses, soil, hydrogeology, vegetation, reservoirs/dams, lakes, rivers, irrigation systems and soil conservation measures; (4) spatial and temporal interpolations of meteorological data including rainfall; (5) spatial and temporal interpolations of social and economic data like population, GDP, irrigation area and grain production, and

Table 2 Historical variations of gross water use including drainage in Yellow River basin (unit: billion m^3 yr^{-1})

Period	Gross water use			Groundwater among gross water use		
	Total	Industry and life	Irrigation	Subtotal	Industry and life	Irrigation
1956—1959	12.92	1.49	11.43	3.41	0.11	3.30
1960—1969	17.60	2.45	15.15	5.02	0.58	4.44
1970—1979	30.43	3.81	26.62	9.16	1.25	7.90
1980—1989	34.09	5.27	28.81	10.05	1.98	8.07
1990—2000	39.91	8.28	31.64	11.35	2.87	8.47

water use data; and (6) feature tables of sub-watersheds, stream links and computation units (contour bands). RS data (Landsat TM and AVHRR) and GIS (ARCGIS) are utilized to accomplish the data preparation. The main items of data preparation are briefly described as follows.

Division and coding of sub-watersheds and contour bands
By overlapping surveyed watercourses on the DEM (GTOPO30 data), the elevation values of some convex cells in rivers are modified to remove falsely closed depressions of large size. Then a river network consistent with the surveyed river network is extracted from the modified DEM. The river network and the basin are coded according to the Pfafstetter coding rule (Verdin and Verdin, 1999). Subdivisions and codifications of the Yellow River basin at six levels are shown in Fig. 3. The whole drainage basin of the Yellow River is divided into 8485 sub-watersheds, each of which is assigned with a Pfafstetter code. Each sub-watershed in hilly and tableland areas is further divided into 1—10 contour bands, but no further division is performed for sub-watersheds in plain areas because of little topographic effects, i.e., one sub-watershed is taken as one contour

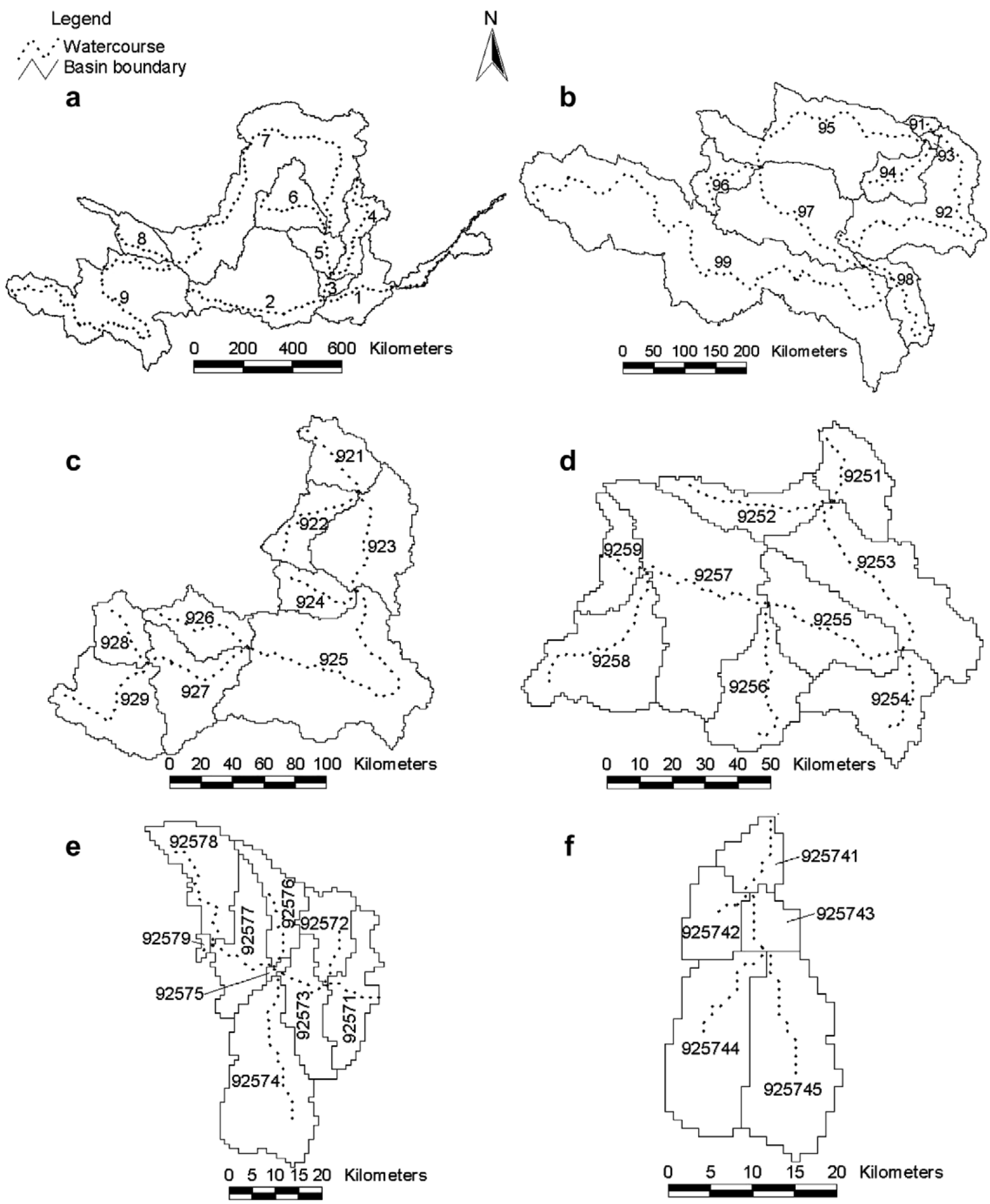

Figure 3 Subdivisions and codification of Yellow River basin: (a) level 1 subdivision of Yellow River basin, (b) level 2 subdivision of sub-basin 9, (c) level 3 subdivision of sub-basin 92, (d) level 4 subdivision of sub-basin 925, (e) level 5 subdivision of sub-basin 9257, and (f) level 6 subdivision of sub-basin 92574.

band. The whole Yellow River basin is divided into 38,720 contour bands. The contour band is selected as the computation unit of WEP-L, which is an area between two different elevation values. The division of contour bands depends on both the difference of maximum elevation and minimum one in a sub-watershed and the area of sub-watershed. The division is performed in a way to ensure each has a similar area and less than 20 km^2. Thus, the bigger a sub-watershed is, the more the divided contour bands are, but the maximum number is 10 in the whole basin. The thickness of Quaternary aquifer and the topographic slope derived from the DEM are combined to determine the dividing lines between plain areas and non-plain areas (i.e., hilly and tableland areas). The subsurface water flow in the saturated soil layers of a sub-watershed in hilly areas is assumed to have no interaction with its neighbor sub-watersheds but the interactions of the groundwater flow in aquifers of plain areas among sub-watershed are considered. An example of computation unit subdivision in the Yiluo River basin, a first level sub-basin of the Yellow River basin is shown in Fig. 4. The details of the basin subdivision and coding are referred to in Luo et al. (2003).

Identification of river section shapes

Approximating the river section as trapezoid shape, the shape data of un-surveyed sections in the main river are deduced by conducting linear interpolations based on the 31 surveyed sections, while regressive formulas are deduced based on the 102 surveyed sections to express the relations between the shape section parameters and the drainage area for tributaries. The whole basin is divided into six districts to get the regressive formulas in the tributaries of different characteristics. The regressive analysis is to find the relations between maximum wet area and control area of the river sections, and linear relations are adopted in three districts while exponential relations in other three districts. The ratios of top width, bottom width and height of trapezoid shape section are assumed to be constant in every district, which are deduced using regressive analysis of surveyed sections. This kind of approximation is believed to be acceptable because the river section parameters are mainly related to flow routing instead of water resources assessment.

Deducing land cover information

Land cover information and model parameters are prepared using ARCGIS, which include soil, hydrogeology, vegetation, land use, and soil conservation. Among these information, land use and vegetation varies with time. The land use data are summarized into every computation unit (contour band) of WEP-L in the mosaic method (Avissar and Pielke, 1989). Fig. 6 shows an example of land use distribution of the Yellow River basin in 2000.

Spatial and temporal interpolations of meteorological data

Precipitation is the most active one among all the meteorological factors. The inhomogeneous spatial and temporal distribution of precipitation has great influence on basin runoff. A spatial interpolation of daily precipitation in large-scale basin is performed in this study. The reference rain gauges are selected for a basic computation unit of the WEP-L model by correlativity. If there are the reference rain gauges significant in correlativity, the reverse distance square (RDS) method is adopted to get the precipitation in the unit; otherwise, the Thiessen polygon method is adopted. The interpolation result is justified by the Yellow River precipitation analysis result of the second-time countrywide comprehensive water resources planning in China undergoing now. Only the spatial interpolation is not enough because rain gauges are sparely distributed in the western part of the basin, downscaling of daily precipitation into hourly precipitation is also carried out. The relation model of precipitation intensity and duration is developed which can generate hourly precipitation from daily data. According to the characteristic of precipitation in different parts of the Yellow River basin, the basin is divided into five districts (see Fig. 7). The parameters of the model are

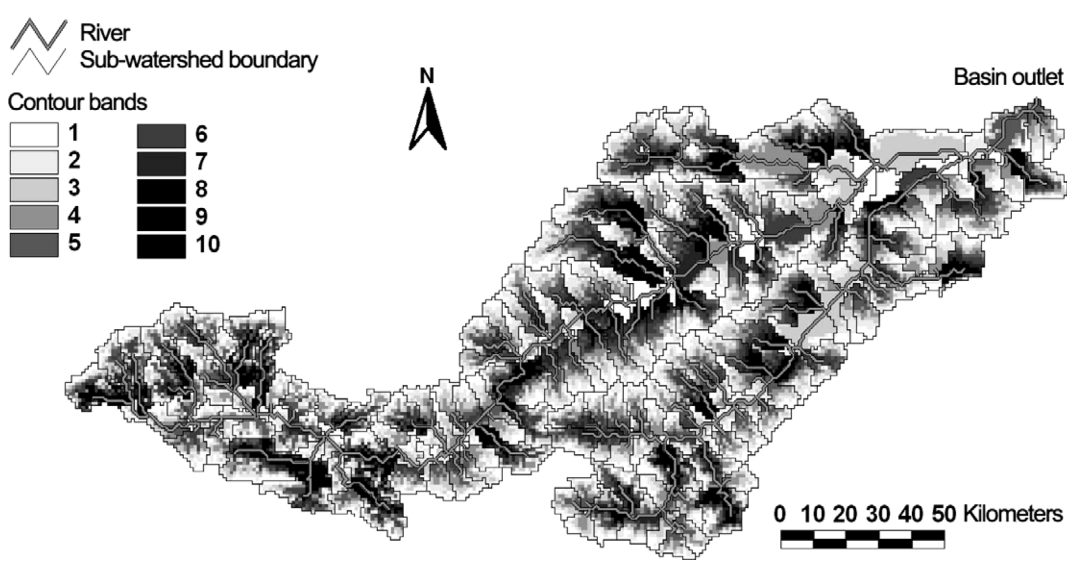

Figure 4 An example of computation unit subdivision in Yiluohe River basin, a first-level sub-basin of Yellow River basin.

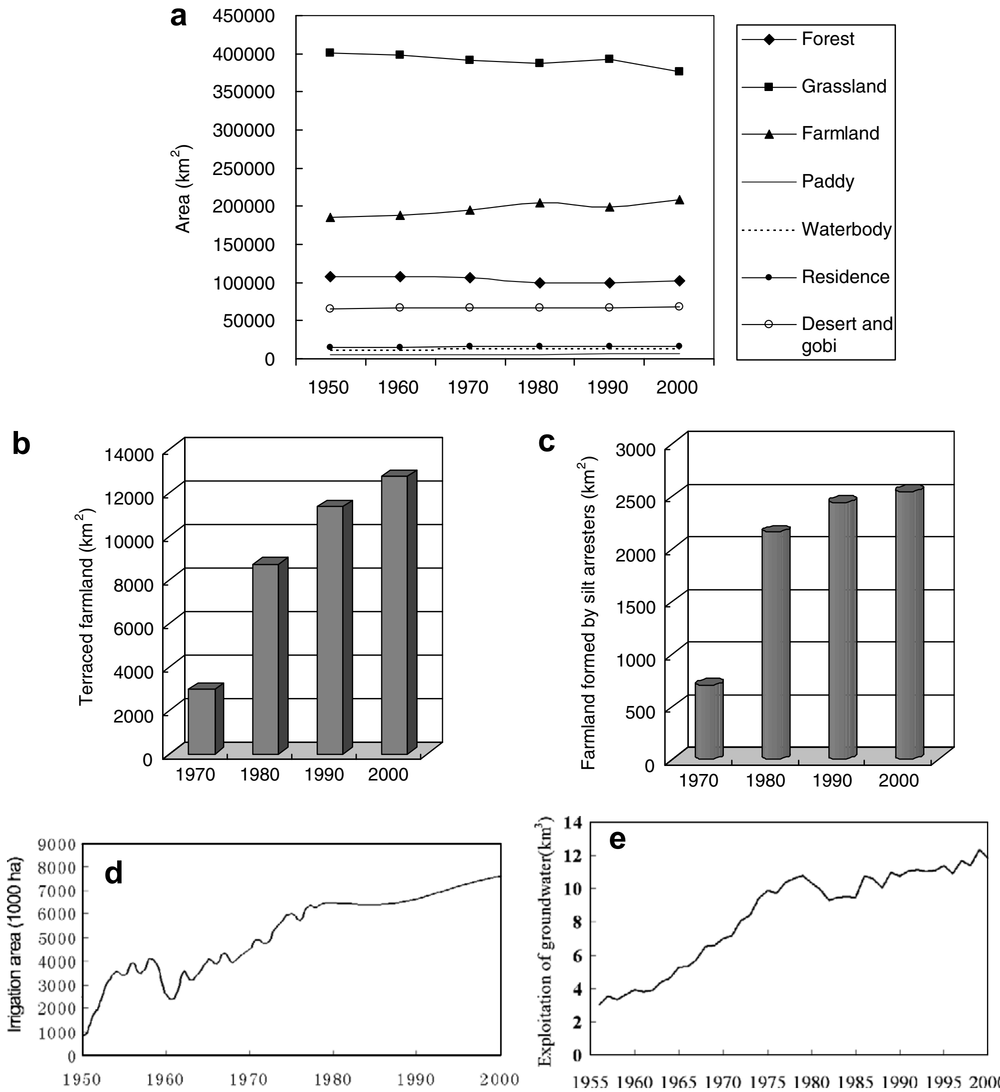

Figure 5 Examples for illustrating historical variation of land covers in Yellow River basin: (a) main land uses, (b) terraced farmland, (c) farmland formed by silt arresters, (d) irrigation area, and (e) exploitation of groundwater.

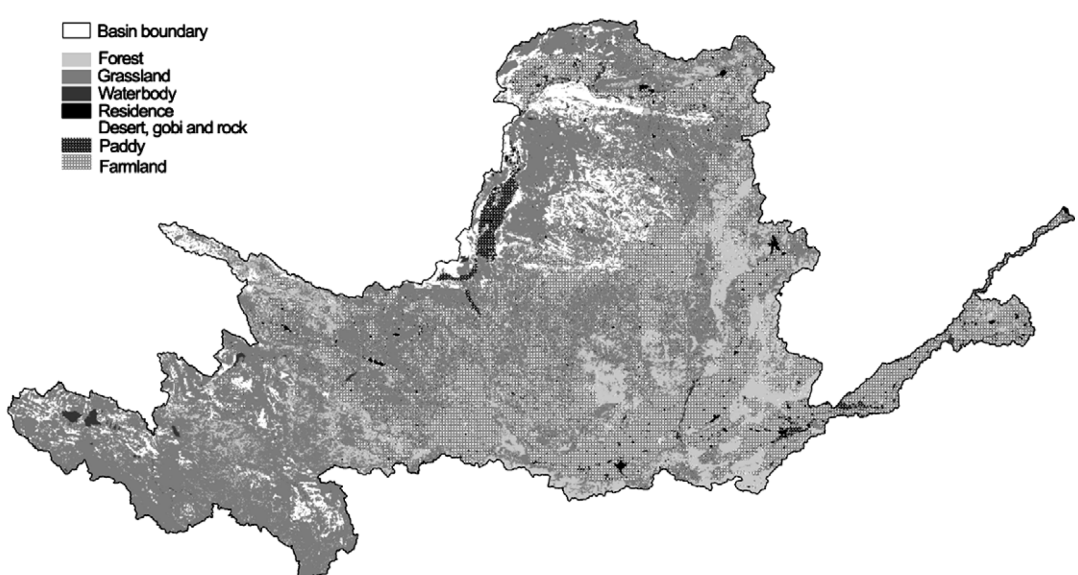

Figure 6 Land use distribution of Yellow River basin in 2000.

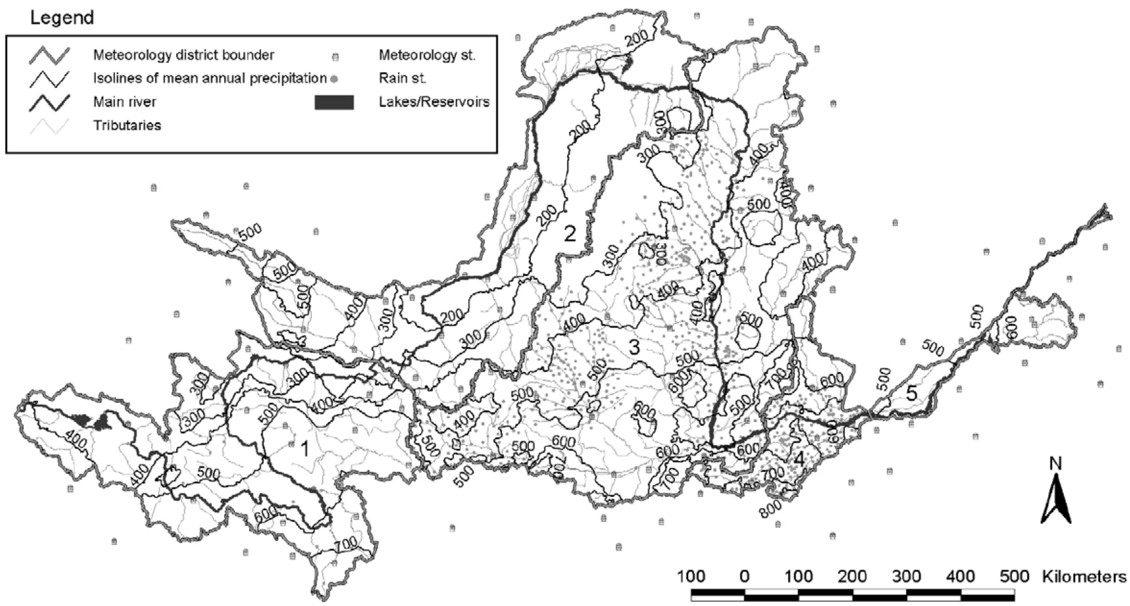

Figure 7 District division for interpolations of meteorological data and obtained isolines of mean annual precipitation in the Yellow River basin. Numbers (1—5) in bigger fonts in the figure are codes of five meteorology districts subdivided for data interpolations.

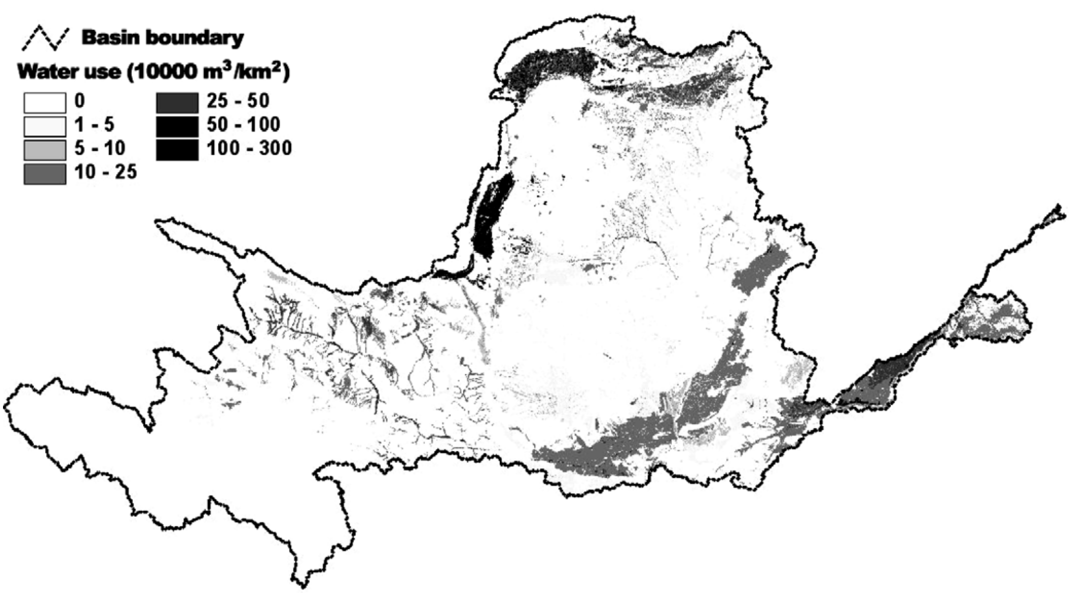

Figure 8 Agricultural water use distribution of Yellow River basin in 2000.

calibrated and the model is validated with measured precipitation data in respective districts. The obtained isolines of mean annual precipitation in the Yellow River basin are also shown in Fig. 7. The details of the interpolations are referred to in Zhou et al. (2006).

In addition, the daily air temperature in the area downstream to Lanzhou is interpolated spatially using the same method as precipitation, whist the Thiessen interpolation method with consideration of altitude effects is used in the daily air temperature interpolation in the area of fluctuant altitude upstream to Lanzhou. The interpolation methods are validated with measured data as well. For the remaining meteorological data, the Thiessen interpolation method is simply adopted because the altitude effects are not obvious.

Spatial and temporal interpolations of water use data

The water use data are in the lumped form (namely statistic data of administrative districts) and long-term form (annual data), thus need spatial and temporal interpolations for utilization in distributed hydrological models. The statistic data of population, industrial GDP, domestic water use, industrial water use, and agricultural water use at the level of prefecture or prefecture-level city are interpolated into 1-km grid cell using GIS techniques based on land use distribution, meteorological data, irrigation district maps, and cropping patterns. The water use modeling approach is referred to in WaterGAP 2 (Alcamo et al., 2003). Some different from WaterGAP 2, the interpolations of lumped agricultural water use into 1-km grid cell and 10 days are accomplished in three procedures: (1) deducing spatial distributions of irrigated crops, irrigated forest, and irrigated grassland; (2) calculating spatial and temporal distributions of theoretical water demand according to evaporation and rainfall data; and (3) modifying the spatial and temporal distributions of theoretical water demand according to river inflows and statistic data of lumped water use in prefectures or prefecture-level cities. The last procedure, which is newly added in this study, guarantees that sum of the deduced

Table 3 List of the WEP-L model parameters

Category	Parameter	Estimation approach or reference	Sensitivity
Land surface and river	Maximum depression storage depth of land surface	Investigation and calibration	High
	Lateral section shapes of river	Interpolation and regressive analysis based on survey data	Low
	Manning roughness	Based on land use; Wang and Li (2002)	Low
	Conductivity of river bed materials	Investigation and calibration	High
Vegetation	Vegetation fractional coverage	Deduced from NOAA RS data	Low
	Leaf area index	Deduced from NOAA RS data	Low
	Root depth	Dickinson et al. (1991), Jia et al. (2001)	Middle
	Aerodynamic resistance	Dickinson et al. (1991), Jia et al. (2001)	Low
	Canopy resistance	Noilhan and Planton (1989), Dickinson et al. (1991)	Low
	Minimum stomata resistance	Noilhan and Planton (1989), Dickinson et al. (1991)	Low
Soil	Thickness of soil layers	Investigation and calibration	High
	Maximum soil moisture content (soil porosity)	Investigation and calibration	High
	Field capacity	Moisture movement experiment in Loess Plateau (Yang and Shao, 2000)	Low
	Residual soil moisture content	Moisture movement experiment in Loess Plateau (Yang and Shao, 2000)	Low
	Saturated hydraulic conductivity	Moisture movement experiment in Loess Plateau (Yang and Shao, 2000)	Middle
	Moisture-suction relationship	Moisture movement experiment in Loess Plateau (Yang and Shao, 2000)	Middle
	Moisture-conductivity relationship	Moisture movement experiment in Loess Plateau (Yang and Shao, 2000)	Middle
	Heat capacity and conductivity of soil	Moisture movement experiment in Loess Plateau (Yang and Shao, 2000)	Low
	Initial soil moisture content	Warming up simulation	Low
Aquifer	Conductivity or permeability	National comprehensive planning of water resources	Middle
	Storage coefficient	National comprehensive planning of water resources	Middle
	thickness	National comprehensive planning of water resources	Middle
	Initial groundwater level	Warming up simulation	Low
Snow	Snow melting coefficient	Maidment (1992) and calibration	Middle
	critical temperature of snow melting	Maidment (1992) and calibration	Middle

Table 4 Maximum depression storage depth and Manning roughness of overland flow

Land use type	F	G	BS	SP	P	IF	SAF	TF	NF	UA	WB
MDSD (mm)	15—35	5—20	5—10	5—10	150—200	100—150	200	100	100	2	0
MROF	0.3	0.1	0.05	0.1	0.2	0.2	0.2	0.2	0.2	0.02	0.01

F, forest; G, grassland; BS, bare soil; SP, sloping plowland; P, paddy; IF, irrigated farmland; SAF, silt arrester farmland; TF, terraced farmland; NF, non-irrigated farmland; UA, urban area; WB, water body; MDSD, maximum depression storage depth; MROF, manning roughness of overland flow.

distributed water use equals the statistical water use in the whole basin and in every administrative district. Fig. 8 shows an example of agricultural water use distribution of the Yellow River basin in 2000.

Model parameter estimation

The parameters of WEP-L and correspondent estimation approaches are listed in Table 3. There are three categories of

Table 5 Averaged vegetation fraction and LAI in the Yellow River basin and the WRA2 districts in 2000

WRA2 district name	Vegetation fraction			Averaged vegetation LAI		
	Maximum	Minimum	Average	Maximum	Minimum	Average
Whole Basin	0.661	0.100	0.339	2.842	0.091	1.148
Upstream Longyangxia	0.830	0.107	0.385	4.044	0.094	1.426
Longyangxia—Lanzhou	0.852	0.122	0.419	4.010	0.111	1.513
Lanzhou—Hekouzhen	0.441	0.057	0.210	1.552	0.048	0.605
Hekouzhen—Longmen	0.548	0.079	0.265	2.083	0.069	0.818
Longmen—Sanmenxia	0.727	0.129	0.412	3.143	0.118	1.424
Sanmenxia—Huayuankou	0.845	0.158	0.491	3.784	0.145	1.738
Downstream of Huayuankou	0.866	0.131	0.458	3.821	0.120	1.525
Neiliuqu	0.325	0.059	0.159	1.032	0.049	0.402

Table 6 Parameters of soil—moisture characteristic in the Yellow River basin

Parameters	Sand	Loam	Clay loam	Clay
Saturated moisture content θ_s	0.4	0.466	0.475	0.479
Field capacity θ_f	0.174	0.278	0.365	0.387
Residual moisture content θ_r	0.077	0.120	0.170	0.250
Saturated hydraulic conductivity k_s (cm/s)	2.5E − 3	7.0E − 4	2.0E − 4	3.0E − 5
Suction at wet front of soils SW (cm)	6.1	8.9	12.5	17.5

Table 7 Verification results of simulated monthly discharges of 45 years at 23 gauge stations

Station number	Station name	Command area (km^2)	River name	Observed average discharge (billion m^3 yr^{-1})	Simulated average discharge (billion m^3 yr^{-1})	Relative error (%)	Nash—Sutcliffe efficiency
1	Tangnaihai	121,972	Huanghe (main river)	20.56	20.31	−1.2	0.82
2	Guide	131,682	Huanghe (main river)	20.72	21.04	1.5	0.82
3	Lanzhou	222,551	Huanghe (main river)	31.31	31.29	−0.1	0.79
4	Xiaheyan	254,142	Huanghe (main river)	30.58	31.66	3.5	0.76
5	Shizunshan	309,146	Huanghe (main river)	27.97	28.68	2.5	0.72
6	Toudaoguai	385,966	Huanghe (main river)	22.14	23.71	7.1	0.51
7	Longmen	497,552	Huanghe (main river)	27.20	28.24	5.7	0.55
8	Sanmenxia	688,421	Huanghe (main river)	35.79	35.3	−1.4	0.62
9	Huayuankou	730,036	Huanghe (main river)	39.06	39.53	1.2	0.69
10	Gaocun	734,989	Huanghe (main river)	36.35	34.93	−3.9	0.70
11	Lijin	751,869	Huanghe (main river)	31.38	32.56	3.8	0.69
12	Minhe	15,342	Huangshuihe	1.61	1.64	1.9	0.62
13	Xiangtang	15,126	Datonghe	2.83	2.63	−7.1	0.64
14	Houdacheng	4102	Sanchuanhe	0.23	0.23	−1.8	0.66
15	Baijiachuan	29,662	Wudinghe	1.19	1.06	−10.9	0.56
16	Hejin	38,728	Fenhe	1.06	1.17	9.8	0.63
17	Linjiacun	30,661	Weihe (upstream)	2.20	2.31	4.7	0.70
18	Zhangjiashan	43,216	Jinghe (into Weihe)	1.74	1.66	−4.6	0.64
19	Zhuangtou	25,154	Beiluohe (into Weihe)	0.86	0.82	−4.7	0.63
20	Xianyang	46,827	Weihe	4.21	4.06	−3.6	0.73
21	Huaxian	106,498	Weihe	7.05	6.58	−6.7	0.69
22	Heishiguan	18,563	Yiluohe	2.66	2.58	−2.9	0.80
23	Wuzhi	12,880	Qinhe	0.81	0.87	7.4	0.60

parameters in the WEP-L model: (1) parameters of land surface and river channel system including maximum depression storage depth of land surface, permeability of riverbed material, impervious ratios of residential area and industrial area, and Manning roughness of overland and river channel; (2) parameters of vegetation including vegetation fraction, maximum interception depth, leaf area index (LAI), aerodynamic resistance, canopy resistance and root distribution parameters; and (3) parameters of soil and aquifer including soil layer thickness, soil porosity, soil saturated hydraulic conductivity, soil suction at infiltration wetting front, soil moisture–suction relation curve, soil moisture–hydraulic conductivity relation curve, thickness and hydraulic conductivities of unconfined and confined aquifers, specific yield of unconfined aquifer, and storage coefficient of confined aquifer. All of parameters are initially estimated according to land cover information, observation data, and remote sensing data, and some parameters are selected for model calibration (referred to in the following section). The following is a brief explanation of estimation of some main parameters.

Parameters of land surface and river channels

Researches on maximum depression storage depth of land surface in the literatures (Black, 1991; David et al., 2001; He et al., 2002) are mainly concerned with forest, pasture, coastal plain and urban impervious area, whist those on farmland and soil conservation area are seldom observed. However, the farmland area is about 215,000 km^2 and the silt arrester area is about 2500 km^2 in the Yellow River basin in 2000, accounting for about 27% of the basin area, thus it needs special considerations. The maximum depression storage depths of various farmland surfaces are first estimated from practical farmland ridges and then calibrated in the model simulation. The adopted maximum depression storage depths are shown in Table 4.

Manning roughness of overland flow is set on the basis of land use type (see Table 4), and the Manning roughness of a

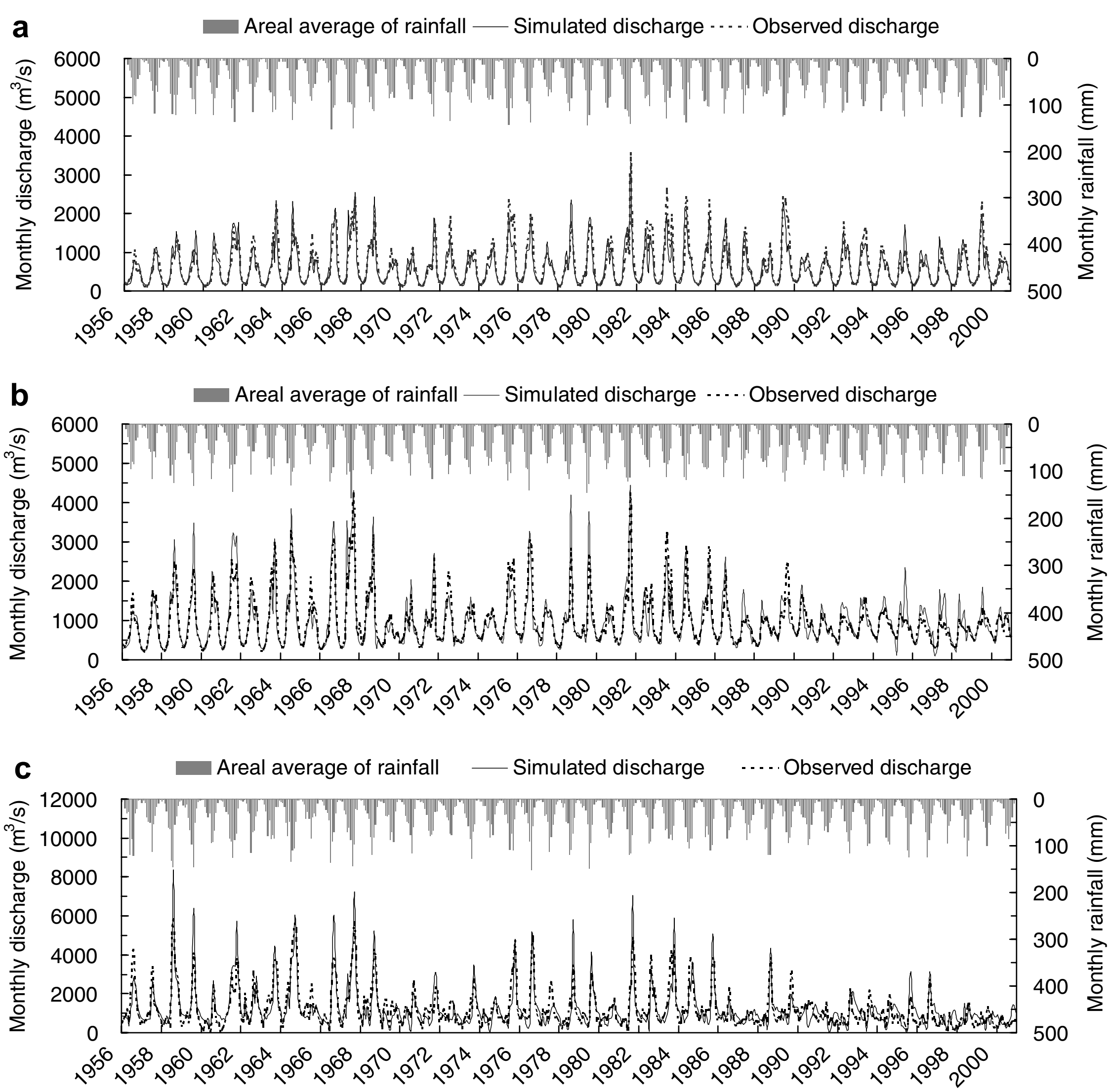

Figure 9 Verification of simulated monthly discharges at: (a) Tangnaihai station, (b) Lanzhou station, and (c) Huayuankou station of the main river.

contour band is taken as the harmonic average of values of different land uses. Manning roughness values of river channel in some representative sections are obtained by the inverse simulation of observed floods, and those for the remaining sections are referred to in Wang and Li (2002).

Vegetation parameters

Vegetation fraction and LAI are estimated from the NOAA-AVHRR remote sensing data with a temporal resolution of 10 days and a spatial resolution of 8 km by 8 km. In this study the data are first interpolated into 1km by 1km data, then NDVI, Vegetation fraction and LAI are deduced from the CH1 and CH2 data of NOAA-AVHRR. Table 5 shows the averaged values in the Yellow River basin and the level-2 WRA districts in 2000 based on the estimation results. The remaining vegetation parameters in Table 3 are referred to in Dickinson et al. (1991) and Jia et al. (2001).

Soil and aquifer parameters

Based on the texture information, i.e., the percentages of sand, loam and clay gains of 11 types of soil in the basin, they are re-classified into four categories: sand, loam, clay loam and clay. The soil experimental results in the Loess Plateau (Yang and Shao, 2000) in the basin are referred to for soil parameter estimation. The main parameters of the above four soils are shown in Table 6. The aquifer parameters, i.e., thickness, hydraulic conductivity and storage coefficient are based on the hydrogeology data of the Second-time Countrywide Comprehensive Water Resources Planning in China, in which the eight big plains are divided into 51 blocks. The hydraulic conductivity of aquifer is calibrated in the model simulation.

Snow parameters

Snow melting coefficient or degree-day index and critical air temperature for snow melting are referred to in Maidment

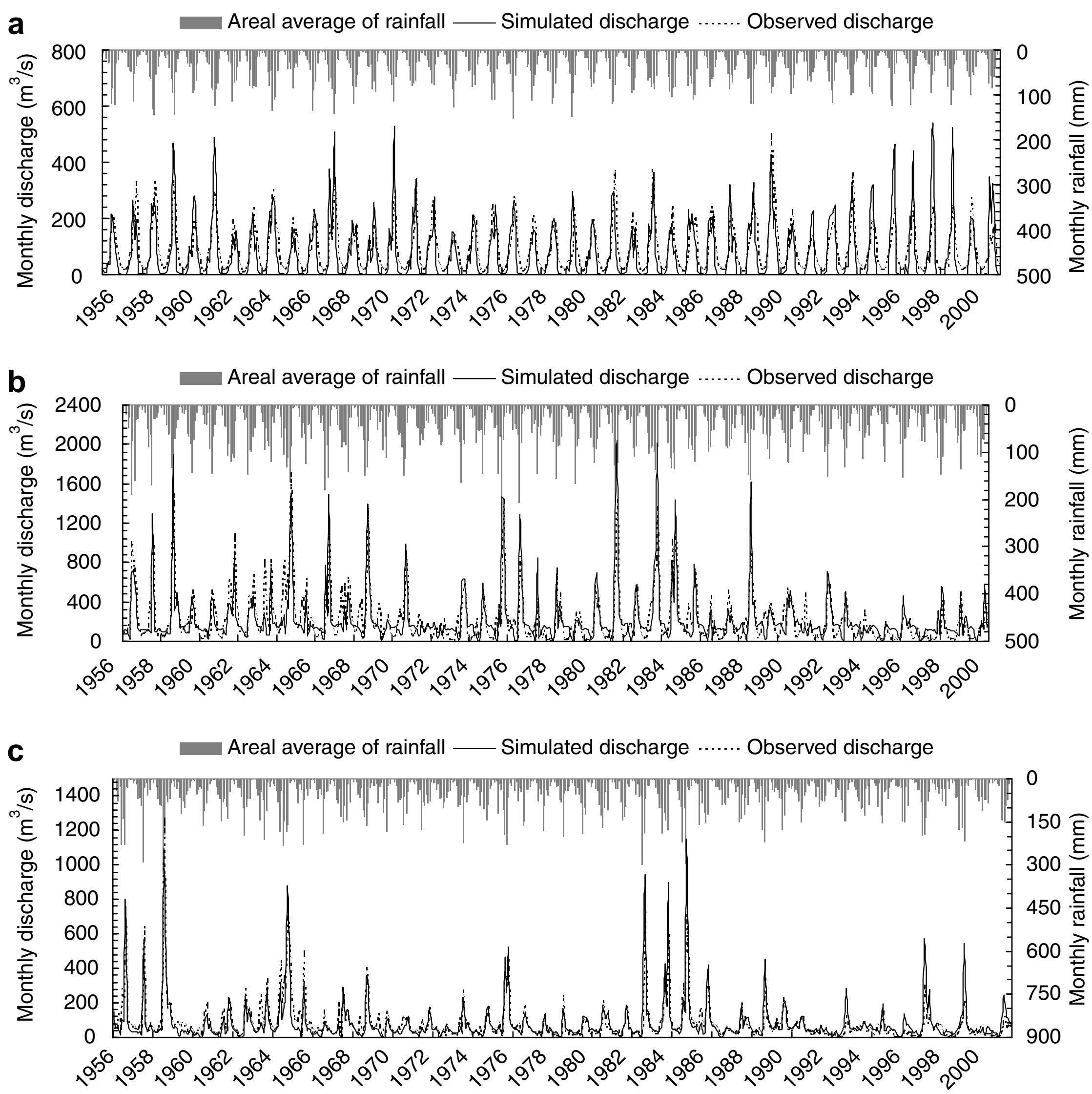

Figure 10 Verification of simulated monthly discharges at: (a) Minhe station of Huangshui river, (b) Huaxian station of Weihe river, and (c) Heishiguan station of Yiluohe river.

(1992) and adjusted after the model calibration. Adopted values in this study are as follows: the snow melting coefficient is 1 mm °C^{-1} d^{-1} for forest, 2 mm °C^{-1} d^{-1} for grassland, 3 mm °C^{-1} d^{-1} for bare soil, 5 mm °C^{-1} d^{-1} for urban area, and 2 mm °C^{-1} d^{-1} for various farmlands; the critical air temperature for snow melting is 0 °C for all land uses.

Model verification

This study carries out continuous simulations of 45 years (1956—2000) in the variable time steps (from 1 h to 1 day), 21 years (1980—2000) of which is selected as calibration period. The variable time steps are adopted because different hydrological processes have different time scales and the variable time steps can save model computation times. For example, the groundwater flow is much slower than surface overland flow and river flow, thus adopting a time step of 1 day is enough for its simulation. Infiltration excess surface runoff during some heavy rains in permeable areas is related to both rain intensity and soil infiltration capability, thus 1 h is adopted for its simulation.

The calibration is performed on a basis of ''try and error''. The calibration parameters include maximum depression storage depth of land surface, soil saturated hydraulic conductivity, hydraulic conductivity of unconfined aquifer, permeability of riverbed material, Manning roughness, snow melting coefficient, and critical air temperature for snow melting. Because only discharge data of 23 stations are

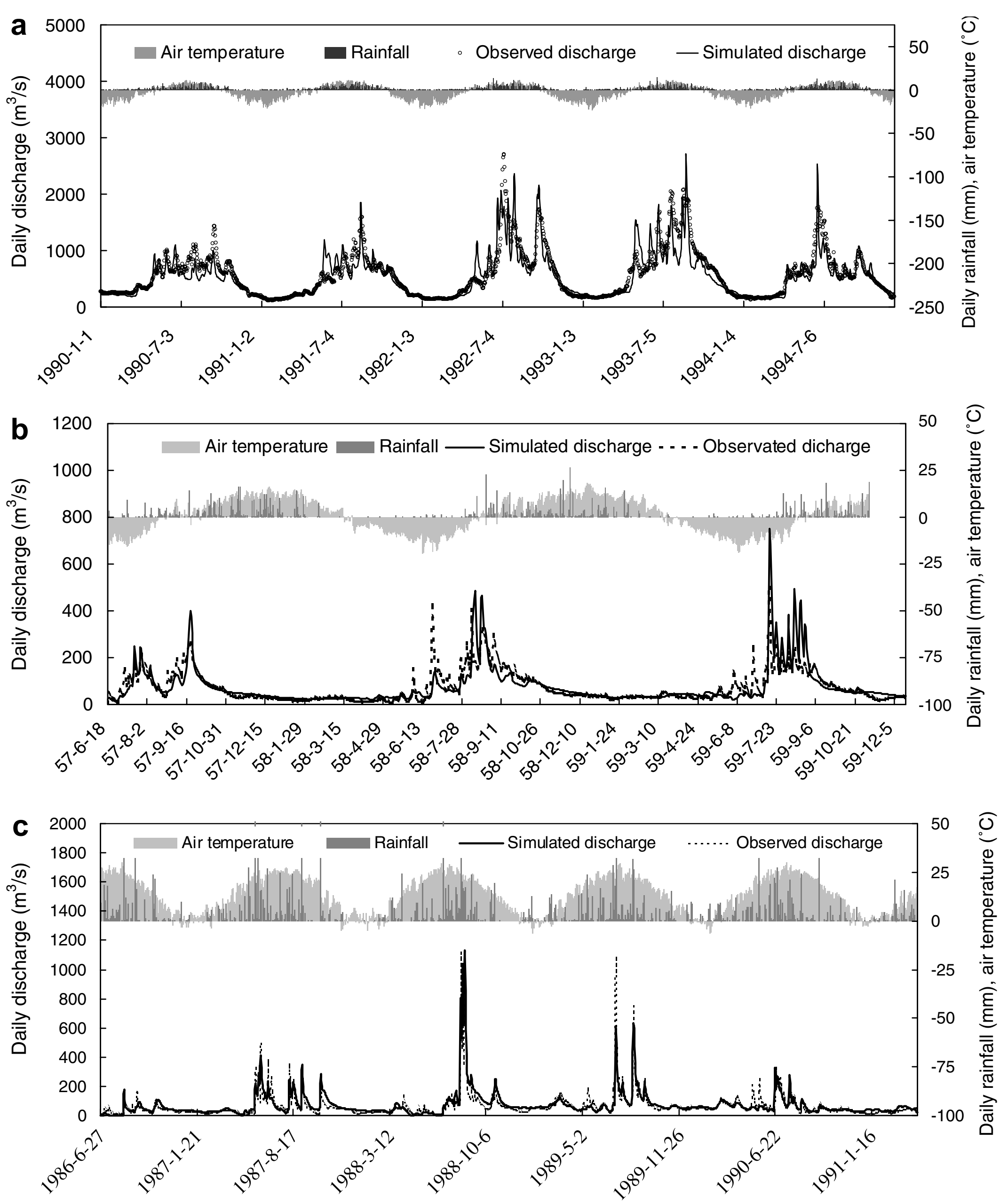

Figure 11 Verification of simulated daily discharges at: (a) Tangnaihai station, (b) Minhe station, and (c) Heishiguan station.

available, the calibration is carried out for the correspondent sub-basins of the 23 stations, and the calibration parameters are calibrated on the basis of the third level WRA districts (sub-basins) shown in Fig. 2, in stead of the 8485 last level sub-watersheds mentioned in ''Division and coding of sub-watersheds and contour bands'' section. The calibration and verification criterions include: (1) minimizing the simulation error of annually averaged river runoff, (2) maximizing the Nash—Sutcliffe efficiency of discharges, and (3) maximizing the correlation coefficient between simulated discharges and observed discharges. Because the main objective of this study is to perform a long-term water resources assessment instead of a short-term river flow forecast, the priority is laid on the first criterion.

After the model calibration, all parameters are kept unchanged, continuous simulations from 1956 to 2000 are performed to verify the model by using the observed monthly and daily discharges at 23 main gage stations in the basin.

Verification results of simulated monthly discharges of 45 years at the 23 gage stations are shown in Table 7. Monthly discharges of 45 years at representative stations in the main river (the Yellow River or called as Huanghe in Chinese) are shown in Fig. 9, those at some stations in some tributaries in Fig. 10 and daily discharges at some stations are shown in Fig. 11. The biggest relative simulation error in the main river occurs at the Toudaoguai station (Table 7), the reason is believed to due to the difficulty in simulating the complex water diversion and drainage processes in the Inner-Mongolia Hetao irrigation district between Shizuishan and Toudaoguai (see Fig. 2), the largest irrigation district in China. The Baijiachuan station in the Wudinghe river gives the biggest relative simulation error in tributaries, which might be due to that part of the Neiliuqu, an inland sub-basin (the 8th WRA2 in Fig. 2) actually drains into the river but the simulation neglects it. Some obvious differences between the simulated and the observed in Figs. 9(c) and 10(b) are also

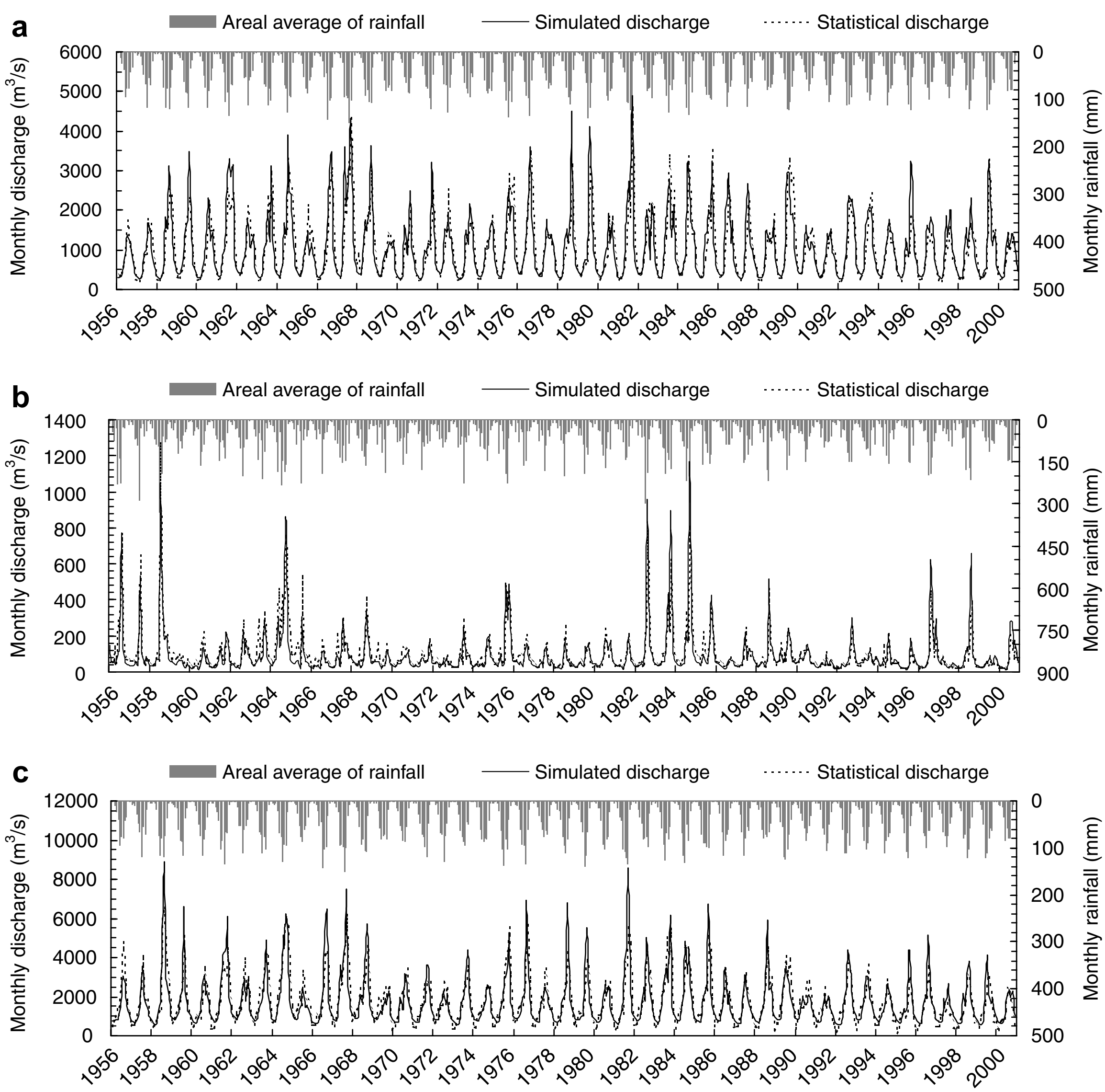

Figure 12 Comparison of simulated monthly discharges without consideration of water use and the statistical ones at: (a) Lanzhou station, (b) Heishiguan station, and (c) Huayuankou station. The statistical discharge in the figure is the naturalized river discharge by reverting statistical water consumption to rivers and reservoirs.

due to the interferences of water diversions and reservoir regulations. In spite of these defects, generally speaking, both the simulation errors of average discharges and the Nash—Sutcliffe efficiencies are quite encouraging, and the simulated discharge hydrographs have good matching with the observed ones.

In addition, the simulated monthly discharges without consideration of water use are also compared with the statistical ones, which are the traditional naturalized river discharges by reverting statistical water consumption to the observed ones. One example is shown in Fig. 12. The simulated annual average discharges from 1956 to 2000 are 33.4 billion $m^3\,yr^{-1}$ at the Lanzhou station and 56.7 billion $m^3\,yr^{-1}$ at the Lijin station, having little differences from the correspondent statistical values, 33.1 billion $m^3\,yr^{-1}$ at the Lanzhou station and 56.5 at the Lijin station. It illustrates that the WEP-L model are surely suitable to simulate natural hydrological processes without consideration of water use.

Sensitivity analysis

Model uncertainty depends on the model structure, the model parameters and input data. The common method of

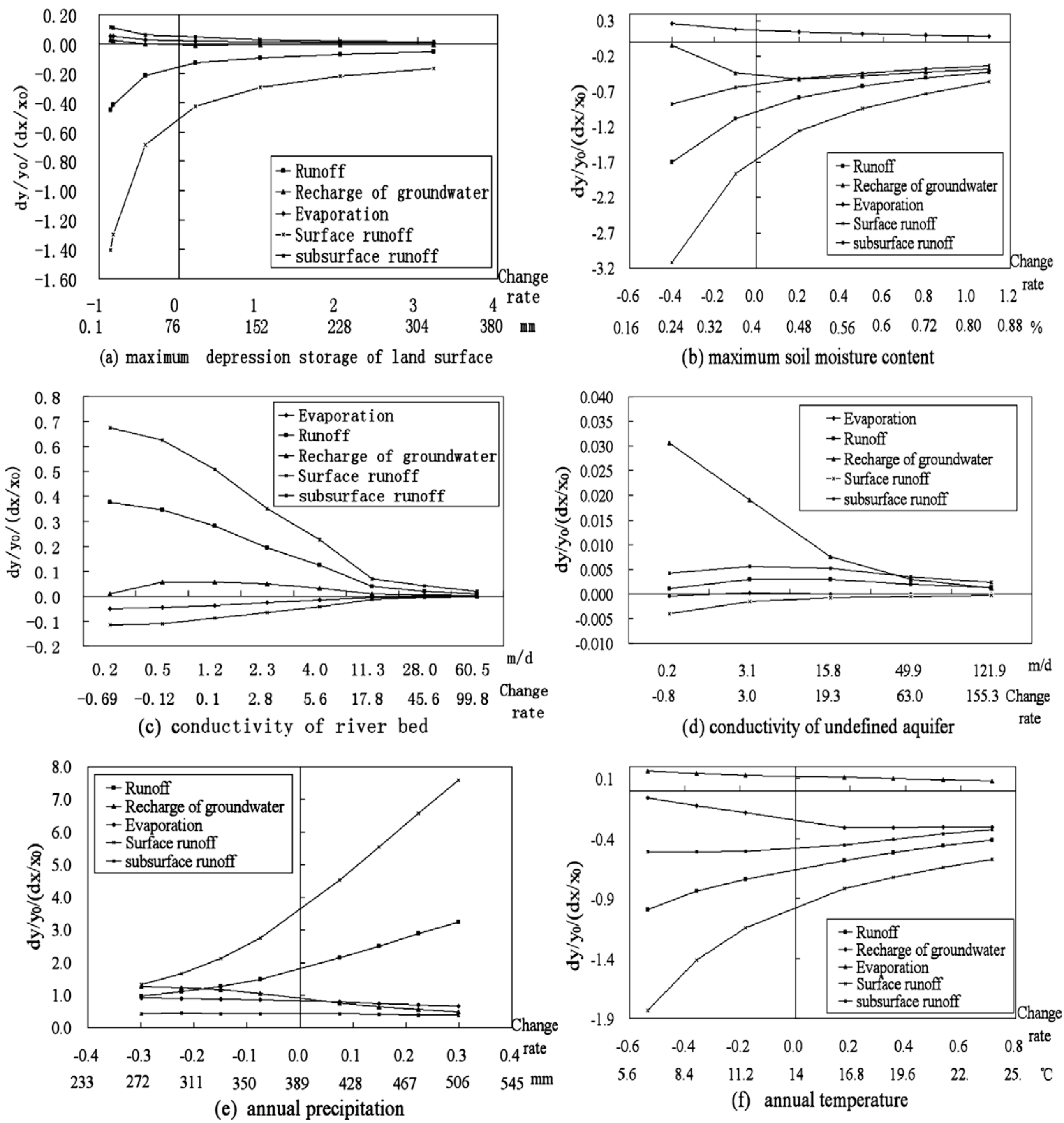

Figure 13 Sensitivity analysis of key parameters and input data on annual water budgets in Weihe river subbasin.

predicting model uncertainty at present is sensitivity analysis. Sensitivity analysis is a valuable tool for setting up, improving, testing, and calibrating hydrological models (Angela and Uhlenbrook, 2005). Saltelli (2000) pointed out that sensitivity analysis can prove the suitability of a model concept and strengthen trust in a model and its prediction.

The simple common method of sensitivity analysis is the disturbance analysis, that is, when the model computes, one of the system parameter has an exiguity of change, while the other parameters are kept unchanged. The ratio of output change rate to the parameter change rate, called as the sensitivity, is expressed as follows:

$$I = \frac{\Delta y/y_0}{\Delta x/x_0} = \frac{(y - y_0)/y_0}{(x - x_0)/x_0} \quad (2)$$

In which, I is the sensitivity, having dimensionless value and a character that the greater the value, the larger the sensitivity, and vice versa; x_0, initial input value of a parameter; x, another input value of the parameter; y and y_0, the corresponding output values of x and x_0, respectively.

This paper analyzes the sensitivities of main parameters and input data of the WEP-L model on the annual averages of model outputs. There are a lot of model outputs, but those of great influence on water resources are runoff, surface runoff, subsurface runoff (groundwater outflow plus interflow from soil layers), recharge of groundwater and evaporation. The sensitivity analysis results of main parameters are shown in the last column of Table 3, which are based on the maximum of the sensitivities of the five outputs to the particular parameter. The terms of ''High'', ''Middle'' and ''Low'' in Table 3 correspond to a given interval of the sensitivity I in Eq. (2), i.e., ''High'' denotes $I \geqslant 0.1$, ''Middle'' means $0.01 < I < 0.1$, and ''Low'' denotes $I \leqslant 0.01$. The high sensitive include maximum depression storage of land surface, maximum soil moisture content (soil porosity), conductivity of river bed materials as well as thickness of soil layers; the middle sensitive include the conductivity and storage coefficient of aquifers, root depth and saturated conductivity of soils, etc.; and the low sensitive include vegetation parameters, manning roughness of river and lateral section shapes of river, etc. In addition, the annual average water budgets are found very sensitive to precipitation and temperature.

The impacts of the sensitive parameters upon the model outputs in the Weihe sub-basin are shown in Fig. 13. It can be seen that the influences of the studied parameters upon the outputs are distinct, and influences of the same parameter on different outputs also have great differences. The precipitation has positive correlativity with runoff, surface runoff, subsurface runoff, recharge of groundwater and evaporation, in which the influence on surface runoff is the biggest whilst that on subsurface runoff is the smallest. The temperature has positive correlativity with evaporation but negative correlativity with others, in which the influence on surface runoff is the biggest while that on evaporation, is the smallest. Although the conductivity of riverbed materials, similar to the conductivity of aquifers, has positive correlativity with runoff and subsurface runoff but negative correlativity with surface runoff and evaporation, the sensitive intensity of the former is much greater than that of the latter. At the same time, the recharge of groundwater has positive correlativity with the both conductivities, but the sensitive intensity depends on the values of the conductivities. The maximum soil moisture content has positive correlativity with evaporation but negative correlativity with others. The maximum depression storage of land surface has positive correlativity with subsurface runoff, recharge of groundwater and evaporation but negative correlativity with surface runoff and total runoff. The sensitivity analysis shows that the behavior of model parameters accords with the physical mechanism of hydrological cycle, and the sensitivities of most model parameters are identified.

Dynamic assessment of water resources in the Yellow River basin

Water resources assessment under present condition

Table 8 shows water resources assessment results under present condition in the Yellow River basin and various second level WRA districts using the WEP-L model and 45 years (1956–2000) meteorological data. The present condition means land cover condition and water use condition in 2000. It can be seen that the special water resources under present condition is 67.64 billion $m^3\ yr^{-1}$, and the general water resources is 208.01 billion $m^3\ yr^{-1}$, which is 3.1 times

Table 8 Assessment of general water resources under condition of present land cover and water use (unit: billion $m^3\ yr^{-1}$)

WRA2 district name	WRA2 district code	Precipitation	Special water resources	Precipitation directly utilized by ecosystem				General water resources
				Farmland	Forest and grassland	Residential area	Total	
Whole Basin		356.30	67.64	89.09	117.33	1.59	208.01	275.66
Upstream Longyangxia	1	63.23	21.21	0.55	22.72	0.01	23.28	44.48
Longyangxia–Lanzhou	2	43.30	11.61	4.85	18.28	0.10	23.23	34.84
Lanzhou–Hekouzhen	3	42.76	5.37	11.96	11.67	0.28	23.91	29.29
Hekouzhen–Longmen	4	48.02	4.92	14.46	14.30	0.06	28.82	33.74
Longmen–Sanmenxia	5	103.89	14.35	38.68	33.01	0.67	72.36	86.71
Sanmenxia–Huayuankou	6	27.47	5.03	8.96	11.85	0.16	20.97	26.00
Downstream of Huayuankou	7	15.78	3.20	8.58	2.08	0.29	10.95	14.15
Neiliuqu	8	11.86	1.95	1.05	3.41	0.01	4.47	6.43

of the special water resources and accounts for 77.4% of the annual average precipitation in the basin.

Dynamic assessment of water resources

Table 9 shows assessment results of the special water resources in the whole basin correspondent to various periods of meteorological data under the condition of historical land cover and water use. It can be seen that under the driving of ''natural-artificial'' dualistic forces, water resources compositions changed obviously: the surface water resources from 1980 to 2000 decreased by 6.9% than that from 1956 to 1979, the non-overlapped groundwater resources increased by 21.4% than that from 1956 to 1979, and the total special water resources from 1980 to 2000 decreased by 3.1% than that from 1956 to 1979.

The impacts of land cover and water use conditions on water resources assessment can be seen from Tables 10 and 11: compared with those values under historical land cover condition: (1) total special water resources under present land cover condition decreased by 2.0 billion $m^3\,yr^{-1}$, among which the surface water resources decreased by 4.1 billion $m^3\,yr^{-1}$, and the non-overlapped groundwater increased by 2.1 billion $m^3\,yr^{-1}$; (2) the precipitation directly utilized by ecosystem increased by

Table 9 Assessed special water resources correspondent to various periods of meteorological data under condition of historical land cover and water use (unit: billion $m^3\,yr^{-1}$)

Meteorological periods	Precipitation	Surface water resources	Groundwater resources		Total special water resources
			Total	Non-overlapped with surface water	
1956–1959	378.88	60.86	37.28	6.94	67.80
1960–1969	374.38	65.02	38.30	8.97	73.99
1970–1979	354.34	56.98	39.65	11.20	68.17
1980–1989	353.75	61.40	39.58	10.99	72.39
1990–2000	335.76	52.49	39.37	12.28	64.77
1956–1979	366.78	60.94	38.69	9.62	70.56
1980–2000	344.43	56.71	39.47	11.68	68.39
1956–2000	356.30	58.94	39.06	10.67	69.62

Table 10 Assessed water resources of WRA districts under condition of historical land cover and water use (unit: billion $m^3\,yr^{-1}$)

WRA2 district name	Surface water	Total groundwater	Non-overlapped groundwater	Special water resources	Precipitation directly utilized by ecosystem
Whole basin	58.94	39.06	10.67	69.62	196.62
Upstream Longyangxia	22.33	6.77	0.18	22.51	20.73
Longyangxia–Lanzhou	12.35	3.77	0.23	12.59	21.89
Lanzhou–Hekouzhen	1.99	5.83	3.37	5.35	23.31
Hekouzhen–Longmen	4.11	3.70	0.53	4.64	27.54
Longmen–Sanmenxia	11.48	11.62	2.93	14.42	69.99
Sanmenxia–Huayuankou	4.23	3.54	0.78	5.01	17.62
Downstream of Huayuankou	2.14	1.98	1.16	3.30	10.84

Table 11 Assessed water resources of WRA districts under condition of present (2000) land cover and water use (unit: billion $m^3\,yr^{-1}$)

Districts	Surface water	Total groundwater	Non-overlapped groundwater	Special water resources	Effective evaporation
Whole basin	54.87	40.42	12.77	67.64	208.01
Upstream Longyangxia	21.01	6.53	0.19	21.21	23.28
Longyangxia–Lanzhou	11.28	3.70	0.34	11.61	23.23
Lanzhou–Hekouzhen	1.85	5.86	3.52	5.37	23.92
Hekouzhen–Longmen	4.23	4.00	0.69	4.92	28.82
Longmen–Sanmenxia	10.45	12.51	3.90	14.35	72.36
Sanmenxia–Huayuankou	3.92	3.51	1.10	5.03	20.98
Downstream of Huayuankou	1.80	2.36	1.40	3.20	10.95

11.4 billion $m^3 yr^{-1}$; and (3) the general water resources increased by 9.4 billion $m^3 yr^{-1}$. The decrease of the surface water resources can be explained by that the soil conservation and farmland construction in the basin strengthened vertical infiltration process and weakened runoff generation, and the increase of the non-overlapped groundwater is because of the increase of net exploitation of groundwater.

Discussions and conclusions

Discussions

The traditional approaches are suitable for assessing the water resources under the condition of historical land covers and water use, but it is difficult to assess the water resources under present condition or predict the change of water resources in the future. Theoretically speaking, simple relationships between river discharge and land cover condition can be deduced from observed and statistical data, but we have not enough hydrological stations to establish the relationships, where the land use should has a abrupt change instead of a gradual one and the impact of groundwater exploitation on discharge can be easily distinguished from that of land use change. The newly suggested water resources assessment approach based on WEP-L can perform the dynamic water resources assessment, namely the assessment of water resources in the past, at present and in the future, because WEP-L adopts the integrated simulation of hydrological processes including the interactions between surface water and groundwater. In addition, WEP-L carry out the assessment in the Yellow River basin on the basis of 8485 small sub-watersheds, thus it can provide results for almost any area in the basin including ungauged ones, which is out of the capability of the traditional approaches.

Any model is inevitably to have prediction uncertainty, thus no exception for the WEP-L model. The verification and sensitivity analysis shows that WEP-L gives relative low simulation errors and is capable of describing the physical mechanism of watershed hydrology even under strong interferences of human activities. It should also be meaningful even if the difference between different scenarios is less than the model simulation errors, because the errors are usually the model systematic errors and at the same order in different scenarios.

It is often puzzled why the groundwater resources non-overlapped with the surface water resources of the basin increased from 8.0 billion m^3 (1956–1979) in the first countrywide water resources planning to 11.0 billion m^3 in 1990s (Chang et al., 1998). This study has answered the question for the first time through analyzing the water resources evolutionary law in the basin, and re-illustrated the increase trend of non-overlapped groundwater resources (Table 9) through the model simulation. This is because the increased groundwater exploitation in the basin has changed the drainage way of groundwater from natural outflow into rivers to evaporation into atmosphere. This kind of change trend not only caused the deterioration of groundwater environment because of groundwater decline, but also endangered the river ecosystem because of decreased river base flow, thus it should be controlled in the water resources development of the basin. This may be one of main findings in this study. Another main finding is that the special water resources reduced, but the general water resources increased accompanied with increase of the precipitation directly utilized by ecosystem in the basin. This gives some hints to the sustainable development strategy in the Yellow River basin threatened by very serious water shortage, ecology and environment problems: efficient utilization of precipitation, instead of mainly relying on irrigation, should be pursued by strengthening the water and soil conservation, and reverting part of over-cultivated farmland (especially the sloping farmland) to forest or pasture.

Broadly speaking, every drip of rainfall plays roles in the global hydrological cycle. However, taking whole precipitation as the scope of water resources assessment goes against distinguishing different contributions of various forms of water resources to human beings and nature, while limiting water resources assessment to the special water resources is unfavorable to objective reflection of active roles of soil and water conservation (e.g., forestation and construction of terraced farmland) in efficient utilization of water resources. The concept of general water resources and the dynamic assessment model are believed to be important to the sustainable and efficient utilization of water resources in water shortage areas, although further studies are desired to improve the suggested approach, e.g., assessing the utilization efficiency and functions of various forms of water resources and coupling simulation of climate models and WEP-L.

Conclusions

In this study, WEP-L, a distributed hydrological model for large basins, was successfully developed, and the dynamic assessment of water resources in the Yellow River basin was conducted using WEP-L and RS/GIS techniques. RS data (GTOPO30, Landsat TM data, and AVHRR data) and GIS were utilized to perform basin subdivision, land cover classification, and spatial and temporal interpolations of water use data in the basin. The basin was subdivided into 8485 sub-watersheds and 38,720 contour bands, and the WEP-L model was verified by comparing simulated and observed discharges at main gage stations. Continuous simulations of 45 years (1956–2000) in variable time steps were performed for various land cover conditions, and water resources assessment results under present land covers were compared with those under historical land covers. The study shows: (1) the surface water resources reduced, but the groundwater resources non-overlapped with the surface water resources increased under human impacts; and (2) the special water resources reduced, but the general water resources increased accompanied with increase of the precipitation directly utilized by ecosystem. Although further studies are desired related to the suggested approach for the dynamic assessment of water resources, especially on the utilization efficiency assessment of various forms of water resources, the achievement of this study is believed to provide a reference for the sustainable development of water resources in the Yellow River basin.

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