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Two-way coupling of unsaturated-saturated flow by integrating the SWAT and MODFLOW models with application in an irrigation district in arid region of West China

Yi LUO[1, 2*], Marios SOPHOCLEOUS[3]

[1] Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China;
[2] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China;
[3] Kansas Geological Survey, University of Kansas, Lawrence, Kansas 66047, USA

Abstract: This paper presents the realization of two-way coupling of the unsaturated-saturated flow interactions of the SWAT2000 and MODFLOW96 models on the basis of the integrated surface/groundwater model SWATMOD99, and its application in Hetao Irrigation District (HID), Inner Mongolia, China. Major revisions and enhancements were made to the SWAT2000 and MODFLOW models for simulating the detailed hydrologic budget and coupled unsaturated and saturated interactions, and irrigation canal hydrology for the HID. The simulation results of seasonal groundwater recharge to and evaporate from the shallow groundwater, and the annual water budget over the district are presented and discussed. The results implied the necessity of two-way coupling of the unsaturated-saturated interactions when groundwater is shallow, and the feasibility of making comprehensive use of the information coming from both the surface water and groundwater models to make a more physically-based assessment of the coupled interactions.

Keywords: SWAT; MODFLOW; SWATMOD; coupled unsaturated-saturated flow; irrigation canals; groundwater recharge; groundwater evaporation

The Hetao Irrigation District (HID) is one of the largest irrigation diversion districts in the Yellow River Basin. It is located in Inner Mongolia, China, and also the upper reaches of the Yellow River. It has a land area of 1.07×10^6 hm^2 with 0.578×10^6 hm^2 irrigated.

The annual precipitation of the HID ranges from 150 mm to 200 mm from its west part to the east part. The HID diverts 5.2×10^9 m^3 of water from the Yellow River to irrigate crops according to the records of 1990–2000.

The depth of the shallow groundwater changes between 0.5 m to 3.5 m in the HID during the year. The variation of the shallow water table is caused mainly by the irrigation diversion and groundwater evaporation. The HID aquifers receive recharge from the Langshan and Wulanshan mountain areas in the north and east of the district and from the Yellow River totaling less than 2×10^8 m^3 annually according to hydrologic records. Shallow groundwater drains to the Wuliangsuhai Lake at the lower reaches of the HID through drainage channels (Fig. 1).

The HID is confronted with reduction of diversion quotas from the Yellow River by state law. The annual diversion of 5.2×10^9 m^3 was decreased by 1.2×10^9 m^3 in a normal year. The management bureau of the district is planning to take water saving measures, such as water saving irrigation practices, lining of the irrigation canals to raise the canal conveyance efficiency, adjusting the crop planting to reduce water use, and

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* Corresponding author: Yi LUO (E-mail: luoyi.cas@hotmail.com)

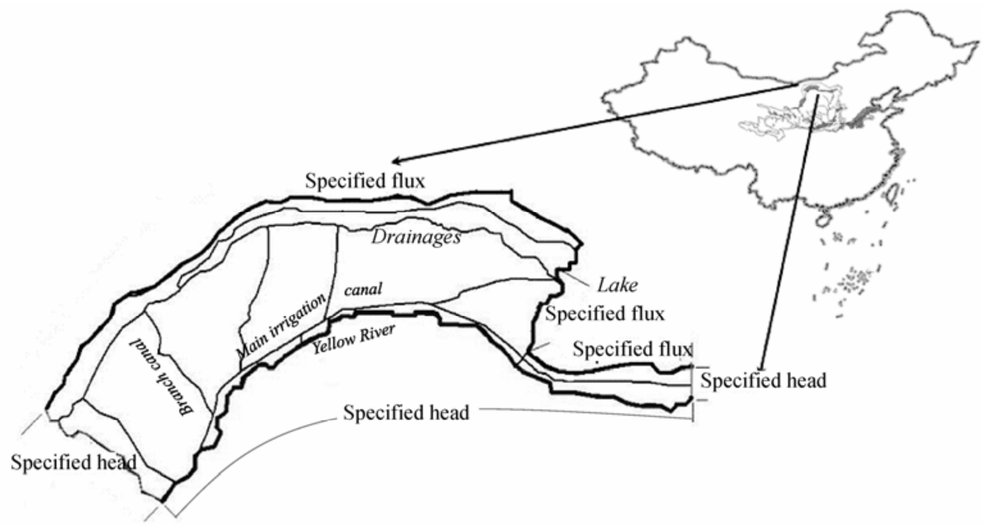

Fig. 1 Hetao Irrigation District and the conceptual groundwater model

pumping groundwater for irrigation to adapt to the reductions in surface-water allocations for irrigation. A number of questions arise, such as: Is the water enough for the irrigation requirements of the district? How much water is needed? How to adjust the crop planting and adapt water-saving practices to meet with the water shortage situation? How will the land use change and water-saving practices affect the hydrological processes in the district? How the surface and ground-water interact? How to implement conjunctive use of surface water and groundwater? To answer such questions, use of a comprehensive, integrated, basin-wide model is needed to investigate the complicated issues in the district. The first step is to quantify the impact of irrigation and major land-use changes on both surface- and ground-water resources. This needs to be done on a basin-wide basis, from the standpoint of anticipating and minimizing potential environmental impacts. To accomplish this task, numerical simulation models must be developed that are comprehensive, basin-wide, and continuous in time, as well as practical and conceptually clear. Given the proliferation and widespread availability of numerical models during the last two decades, and the broad recognition of the need for integrated surface and groundwater resources management, there is still a surprising scarcity of operational, integrated models, applicable to irrigation district problems. Especially two-way coupling of watershed and ground-water models is lacking, which not only accounts for inputs to the groundwater system but also for the impact of the groundwater system on the overlying unsaturated zone and, in particular, the root zone. Such two-way interactions are common in areas of shallow water table caused by frequent irrigation recharge, as is evident in the HID.

SWAT (Neitsch *et al*., 2002) and MOFLOW (Harbaugh and McDonald, 1996) are widely recognized watershed and groundwater simulators, respectively in both scientific and industrial communities. With respect to the very important unsaturated and saturated flow interactions, the SWAT model deals with shallow groundwater evaporation and lumped groundwater dynamics, and the MODFLOW model deals with recharge to and evaporation from the shallow groundwater, both in fairly rough ways. The SWAT model does not actually simulate the groundwater dynamics, whereas the MODFLOW model does not simulate the unsaturated soil water dynamics.

Sophocleous and Perkins (2000) developed the SWATMOD99 model by integrating the SWAT99.2 and MODFLOW96 models to simulate the recharge of irrigation to groundwater in the Lower Republican River Basin in Kansas, USA. This model improves the estimation of recharge in the MODFLOW model. However, the information on soil water, crop root and canopy, crop water status from the SWAT model, and depth to water table from the MODFLOW model were still not completely and/or generally integrated to estimate the shallow groundwater evaporation. Meanwhile, the successive approximation concept they presented in their publications to couple the SWAT and

MODFLOW models in a two-way sense has not yet been realized in application.

To apply the SWATMOD99 model in the irrigation district other than a natural watershed, its capacity in dealing with the irrigation canal hydrology needed to be developed. With primary concerns about crop growth, yield, and their ecological interaction with hydrological systems, the crop growth simulation capacity in SWAT model needs to be enhanced as well.

The objective of this paper is to present how the two-way coupling of the unsaturated and saturated flow was realized by integrating the SWAT2000 and MODFLOW96 models based on the integrated surface/groundwater model SWATMOD99 with an application in the HID.

1 Materials and methods

1.1 Irrigation canals and drainage channels

The HID is a flat alluvial plain of the Yellow River. The average slope of it is approximately 1/6,000 that runs down from the northwest to the southeast. In the eastern part of the HID is Wuliangsuhai Lake, which is the drainage zone of the district. The HID has very dense irrigation and drainage canal systems. Each system consists of 7 levels of sub-canals. Water from the Yellow River flows into the district in the general irrigation canal that is running from the southwest to northeast along the Yellow River (Fig. 1). Diversion water is distributed in the district through a dense irrigation canal network. The drainage ditches collect water from the fields through a system of lower level ditches to the general drainage channel (Fig. 1) that is connected to Wuliangsuhai Lake. The flat topography and the dense canal networks pose a challenge to the subbasin delineation of the SWAT model. Usually, subbasin delineation is automatically done by using a DEM.

Both aquifer hydraulic conductivity and storativity vary widely, based on the limited data that exist for the HID. According to hydrogelogical investigation data, the aquifer can be modeled as a single-layer, unconfined system. Although there are clay layers or lenses in the area, modeling the aquifer as a single unit is justified because the lenses are discontinuous on a regional scale.

The boundary conditions considered are indicated in Fig. 1. These take into account the fact that the ground-water system in the basin is not a closed watershed system. Thus, lateral ground-water inflows to the district at the north boundary (along the Langshan and Wulashan Mountains) are simulated as specified flux boundaries; lateral ground-water outflows at and near the northeastern boundary (Wuliangsuhai), and also at the south (the Yellow River) are simulated as variable specified head (general head) boundaries. Specified head boundaries are simulated in areas where the general direction of ground-water flow (inferred from water-table contour maps) approximately coincides with the basin boundaries.

A conceptual hydrological balance in the HID is described as follows. Surface runoff and subsurface lateral flow become lateral inflow to the drainage channels. Recharge from the soil profile and irrigation canals and channel transmission losses all go to the shallow aquifer. Groundwater baseflow goes to the drainage system. Drainage goes to Wuliangsuhai Lake. Shallow groundwater evaporation moves to the unsaturated soil profile. The stream and aquifer interact via leakage driven by hydraulic gradients across the streambed.

1.2 Numerical simulation model

1.2.1 Modifications to the SWAT2000 model

1.2.1.1 Canal transmission loss module

The SWAT2000 code that was officially released (Neitsch *et al*., 2002) was employed in this study. SWAT2000 was selected because of its ability to simulate crop planting and irrigation management, and hence the coupled interactions among crops and the hydrological processes.

A new canal transmission losses module was added to the SWAT model to simulate canal irrigation. The canal transmission losses module was linked appropriately to other routines within SWAT. Additionally, changes were made as follows to read some of the inputs required using the existing input files and to produce separate output files specific for this study:

(1) To read inputs for canal-related variables, such as canal dimensions for each district, and canal segments with different hydraulic conductivity for seepage estimation.

(2) To allocate the total water diversion of the district to each subbasin and each Hydrologic Response

Unit (HRU) for a recorded total water supply (top-down case).

(3) To calculate the total water demand for the diversion from the river for the situation of the scenarios simulation (bottom-up case).

(4) To write output files at the HRU and subbasin levels showing crop water demand, canal losses, total water demand, irrigation water releases, and canal water transport ratio of different segments. A similar work was reported by Santhi *et al.* (2005).

(A) Transmission loss of irrigation canals

Irrigation canal water balance is depicted in Fig. 2. It is assumed that water storage in the irrigation canal does change with time. Then, the water balance equation for the canal segment is written as:

$$Q_{in} = Q_{out} + E + S\ , \tag{1}$$

where Q_{in} and Q_{out} are the inflow and outflow rate, respectively; E is canal evaporation; S is canal seepage.

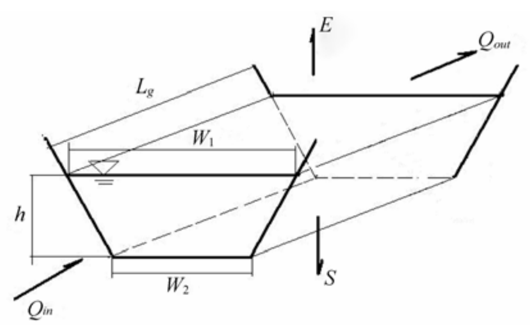

Fig. 2 Depiction of irrigation canal water balance (Q_{in} and Q_{out} are the inflow and outflow rate respectively; E is evaporation; S is seepage; L_g is the length of the segment; W_1 and W_2 are the water surface width and canal bed width, respectively; h is the water depth.

E and S are calculated by the following approaches that calculate surface water evaporation and water seepage used in SWAT model as:

$$E_{canal} = coef_{ev} \times E_0 \times L_g \times W_1 \times fr_{\Delta}\ , \tag{2}$$

$$S = K_{canal} \times TT \times P_{canal} \times L_g\ . \tag{3}$$

Where $coef_{ev}$ is an empirical evaporation coefficient, E_0 is the potential evaporation; L_g is the canal segment length; W_1 is the water width in the canal; fr_{Δ} is the fraction of the time step in which water is flowing in the canal; K_{canal} is the effective hydraulic conductivity of the canal; TT is the flow travel time, and P_{canal} is the wetted perimeter of the canal. Seepage from the general and main canals is assumed to go to the shallow aquifer. Seepage from the branch canal and field canal is assumed to go to either the soil profile or the shallow aquifer.

(B) Diversion irrigation water allocation

There are two cases that need to be considered for the diversion irrigation water. In one case, the diversion water amount of the district or subbasins is known. When only the total amount of diversion water to the district is known, it needs to be allocated first among the subbasins and then among the HRUs. When the diversion water amount for each subbasin is known, it needs to be allocated among the HRUs in the subbasins. This case is a top-down procedure. In another case, scenarios were simulated to investigate how much water was needed for each HRU under different conditions, such as climate change, best management practices of irrigation, fertilization, tillage, planting, etc. In that case, the diversion water requirement can be obtained by adding the HRUs water requirements and transmission losses. This case is a bottom-up procedure. Those two cases were modeled in the Canal Transmission Loss Module.

1.2.1.2 Enhancement of wheat and maize growth simulation

SWAT2000 model uses the general crop model to simulate the annual variation of crop growth. Wheat and maize are usually the main crops in the irrigation districts in the Yellow River Basin. Sole crop growth models are usually robust and may provide more detail information on the growth process. The crop growth modules of the CERES-Wheat and Maize models (Jones *et al.*, 2003) were merged into the SWAT2000 model as alternatives for wheat and maize growth simulation. The purpose of doing this is to enhance the crop growth simulation capacity of SWAT2000 model. The code of the CERES-Wheat and Maize models are from the officially released DSSAT4.0, and it is not intended to be discussed in further details in this paper.

1.2.2 Two-way coupling of unsaturated-saturated flow

1.2.2.1 Brief introduction to the SWATMOD99 Model

Sophocleous *et al.* (1999) developed and implemented a comprehensive computer model that was capable of simulating the surface-water, ground-water, and stream-aquifer interactions on a continuous basis for the Rattlesnake Creek watershed in south-central Kansas. The agriculturally-based watershed model SWAT99.2 and the groundwater model MODFLOW96 with stream-aquifer interaction routines, suitably modified, were linked into a comprehensive basin model as SWATMOD99. Introduction to the structure and applications of SWATMOD99 were presented by Perkins and Sophocleous (2000), and Sophocleous and Perkins (2000). Typically, the SWATMOD99 model has the following unique features.

(1) Soil water-atmosphere simulation model SWAT, average over HRUs model SWBAVG, and stream-aquifer interaction model MODFLOW are executed separately for simulation of a basin's hydrology. Those three separate packages constitute the integrated watershed model SWATMOD99.

(2) Three conceptual models of spatial heterogeneity of increasing complexity were adopted in the case where the aquifer and watershed boundaries do not coincide.

HRU1: Watershed completely underlain by an aquifer; water table below root zone (deep water table); no interaction of water table with overlying sediments.

HRU2: Watershed may be partly underlain by an aquifer; water table below root zone (deep water table); no interaction of water table with overlying sediments.

HRU3: Watershed may be partly underlain by an aquifer; water table is within the root zone (shallow water table), thus interacts with overlying sediments.

The third conceptualization (HRU3) further disaggregates the watershed areas underlain by a non-coinciding aquifer into shallow and deep aquifer components, but with the shallow aquifer interacting with the overlying soil. This latter conceptualization demonstrates a method for coupling separately executed simulations of SWAT and MODFLOW using successive approximation. Shallow ground water is considered to be at a depth that is less than the extinction depth as defined for MODFLOW's evapotranspiration package. MODFLOW approximates evapotranspiration from shallow ground water as a linearly varying function of depth to water, where the maximum rate can be specified by potential evapotranspiration calculated by SWAT.

1.2.2.2 Upgrading the SWATMOD99 model

(1) SWAT99.2 in SWATMOD99 was upgraded into SWAT2000 (or SWAT2K);

(2) Canal Transmission Losses module was developed in SWAT2000 and some other minor modifications made to the SWAT2000 code. This was briefly described earlier in section 1.2.1.1.

(3) SWAT2000, MODFLOW96, and the interface programs in the SWATMOD99 model were merged. Therefore, the coupled model is solely a basin-wide simulator that is capable of simulating watershed hydrological processes, groundwater dynamics, and saturated-unsaturated interactions. A steering subroutine was developed to coordinate the coupling processes of watershed hydrology and groundwater dynamics simulation. Meanwhile, standalone simulation of the watershed hydrology by SWAT2000 or groundwater dynamics by MODFLOW96 remains as options for the users. When coupled SWAT2000 and MODFLOW simulation was selected, the successive approximation method was adopted to realize the two-way interactions between unsaturated and saturated zones. The two-way coupling principles are depicted in Fig. 3.

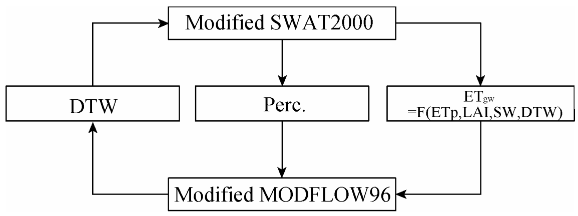

Fig. 3 Two-way coupled saturated and unsaturated, stream-aquifer interactions in the integrated SWAT2000 and MODFLOW96 model (DTW, depth to water table; Perc., percolation from the unsaturated soil profile to groundwater; ET_{gw}, groundwater evaporation; ET_p, potential evapotranspiration; LAI, leaf area index; SW, soil water content over the unsaturated soil profile)

The SWAT2000 model calculates potential evapotranspiration, plant water uptake, and plant root density development, hence the plant water stress on the daily basis. This information, averaged over the groundwater model's time step, is transferred to the MODFLOW model. The MODFLOW model uses this feedback information and the depth to the water table to calculate the shallow groundwater evaporation. The shallow groundwater evaporation is then feedbacked to the SWAT2K model to update the unsaturated soil profile, and the depth of the water table in order to update the HRU types as mentioned previously. The coupled process is realized by adapting the successive approximation concept (Perkins and Sophocleous, 2000; Sophocleous and Perkins, 2000).

$$ET_{gw} = \left[1 + \left(1 - \frac{RD}{RD\max}\right)(WSTRS - 0.3)\right] \left(1 - \frac{DTW}{RD\max}\right) ET_0 \,. \tag{4}$$

Where RD is the root depth; RD_{max} is the extinction depth; DTW is the depth of groundwater; ET_0 is the potential evaporation; $WSTRS$ is the water stress to the plant. Following the theoretical document of SWAT2000 (Nietsch *et al.*, 2002), $WSTRS$ is calculated as

$$WSTRS = 1 - \frac{W_{actup}}{ET} \,. \tag{5}$$

Where ET is the maximum plant transpiration on a given day; W_{actup} is the total plant uptake for the day. The calculation of the maximum plant transpiration and determination of the total plant uptake can be found in the document. RD is the root profile depth of the plant. The determination of it can be found in the document as well.

Equation (4) takes into account all the main factors that affect the shallow groundwater evaporation. Those factors are the atmospheric demand, crop canopy, root profile, soil water profile, and the depth of the water table.

1.3 Application of the upgraded model in the HID

1.3.1 Surface water model set-up

1.3.1.1 Delineation of the sub-basins

The HID was delineated into 11 subbasins according to the distribution of the general and main drainage channels, as shown in Fig. 4 and Table 1. Subbasin 1 lies along the mountains of Langshan. Subbasin 2 is within the Wulanbuhe dessert. Subbasin 3 lies along the Pedo Mountains of Wulashan. Subbasins 1, 2, and 3 have no agricultural development in them. Subbasin 4, 8, 9, 10, and 11 are between the general irrigation canal and general drainage channel. Subbasin 7 is between the general drainage channel and subbasin 1. Subbasins 5 and 6 are between the general irrigation canal and the Yellow River.

Subbasins 1, 2, 4, 7, 8, 9, 10, and 11 drain to the general drainage channel through which the water goes into Wuliangsuhai Lake. Subbasin 3 drains to subbasin 5. Subbasins 5 and 6 drain directly to the Yellow River. Table 1 gives the statistical data of those subbasins. The total land area of HID is 14,917.4 km^2. The area of the lake is 218.7 km^2, which may change with the water amount in it.

Fig. 4 Delineation of subbasins in HID (the numbers in the graphs are the subbasin codes)

Table 1 Characteristic values of the subbasins

Subbasins		Area	Elevation	Slope
Code	Name	(km^2)	(m)	(%)
1	Langshan	1,905.0	910.6	0.014
2	Wulanbuhe	661.6	980.7	0.025
3	Wulashan	460.1	1,007.3	0.014
4	Yigan	2,100.1	974.6	0.070
5	Sanhehu	703.5	998.6	0.014
6	Zonggannan	1,112.6	1,015.3	0.070
7	Wubei	1,187.5	930.5	0.014
8	Yongji	1,938.3	1,015.3	0.070
9	Jiefangzha	1,565.1	950.2	0.070
10	Yichang	2,366.9	930.4	0.070
11	Wulate	899.6	1,015.3	0.070

1.3.1.2 Land cover, soils, underlying aquifers, and HRUs

The HID has diverse land cover types. Mainly, they include the farm fields, urban land, desert and barren land, water bodies, prairie land, and fruit trees. Main crops include spring wheat, summer maize, sunflower, soybean, and sugar beet. Wuliangsuhai Lake is the largest water body in the HID, which is also the drainage zone. Eventually, eleven land cover types were adopted. They were spring wheat, summer maize, sugar beet, sunflower, soybean, millet, apple trees, alfalfa, urban, barren land, and water body. Soil distribution was retrieved from the 1∶00,000,000 soil map. Reclassification of soil types was done with ArcGIS 8.31. Finally, the soil types of sandy loam, silt, and silt clay were adopted, which respectively account for 41%, 38%, and 21% of the HID's soils. Underlying shallow and deep aquifers were adopted. Combinations of land cover, soils, and underlying aquifers make up 33 types of HRU in the district. In each subbasin may be updated by the depth of the shallow groundwater.

1.3.1.3 Diversion and meteorological data

Monthly diversion water amount for each subbasin from 1991–2000 was used in the simulation. The annually averaged diversion water amount of the district over the simulation period was 50.4×10^8 m^3. There are 4 meteorological stations in the HID. Among them, daily data are available for Linhe station and Hangjinhouqi station, and monthly data for Wuyuan station and Wulateqianqi station. The daily data were used to drive the SWAT2000 model.

1.3.1.4 Parameters calibration and evaluation

The hydrological model was calibrated with the data from 1991 to 2000, and validated with data from 1980 to 1990. There are not any river gauge stations in the district. Actually, other data such as the flow that can be used to calibrate and validate the hydrological processes are also very limited. The calibration and validation of the parameters were mostly based on fundamental judging and limited data sources. The calibration and validation of the hydrological model were undertaken by executing the SWAT2000 model as a standalone.

1.4 Groundwater model set-up

The aquifer depth distribution in the flow domain was determined by extrapolating the drilling well data. The flow domain was discretized using a 1.97 km × 1.97 km mesh grid. A single layer numerical model was set up as described in the conceptual model part. The specified flux boundary was assigned according to the historical hydrological record. The specified head flux boundary was assigned according to the water level record of the Wuliangsuhai Lake and the Yellow River water stage record. The aquifer hydraulic conductivity and storativity parameters and variation in the flow domain were first determined according to the hydrogeological survey documents, and then calibrated and validated with the limited groundwater monitoring well data. The calibration and validation were undertaken by executing the MODFLOW model as a standalone.

1.5 The integrated watershed model set-up

The integrated watershed model was set up based on the calibrated and validated hydrological model SWAT2000 and groundwater model MODFLOW96. The subbasins hydrological model and the grid domain of groundwater model were associated by a correspondence map as demonstrated by Perkins and Sophocleous (2000). Basin and subbasin boundaries were adjusted to fit the mesh grids. The integrated model was executed from 1990 to 2000 with the calibrated parameters.

2 Results and discussion

2.1 Canal conveyance efficiency

The conveyance losses include seepage and evaporation. Evaporation accounts for a relatively minor part of the conveyance losses. Seepage is related to the canal dimensions, hydraulic conductivity, and water flowing time in it. No lining is undertaken in the irrigation canals of the HID yet. The canal alluvium is mostly sandy loam, silt, or loamy clay. The conveyance efficiency of the canals varies with levels and locations in the HID. According to the field test and overall evaluation data source, the comprehensive value of the canal conveyance efficiency in the HID is very low, estimated as 0.42 approximately. The dimensions and irrigation operation time of the different levels of the irrigation canals were obtained from the technical reports of the HID management bureau. The hydraulic conductivity of the canals was input according to the alluvium soil types and calibrated with the overall conveyance efficiency reported in other data sources. The simulation results show that, the averaged conveyance efficiency over the year varies among subbasins. Except for subbasins 1, 2 and 3, which have no irrigation canals, the conveyance efficiency ranges from 0.38 to 0.45 in different subbasins. The average over the subbasins is approximately 0.42. The low conveyance efficiency of the canals indicates that the earth alluvium canals play an important role in recharging the shallow groundwater. That is an important way of surface water-aquifer interaction.

2.2 Recharge to the shallow groundwater

Recharge to shallow groundwater in MODFLOW needs to be input. The input recharge rate is taken as proportional to the precipitation and irrigation water applied. In SWATMOD, subroutine modified from SWAT2000 calculates the recharge rate dynamics by the unsaturated soil water movement equations. Recharge is jointly determined by the topography, soil properties, antecedent soil water content profile, rainfall or irrigation events, and crop root uptake. This can be thought of as far more realistic as the simplified approach adopted in the MODFLOW model (Ramireddygari *et al.*, 2000). Being a lumped-parameter model, SWAT calculates a uniform value of recharge in each subbasin. The recharge specified to MODFLOW cells within a subbasin was, therefore, modified to account for such variations as a function of the depth to the water table. This was achieved through a "weight matrix", which determined the relative distribution of recharge within each subbasin. The value at each location in this matrix, which corresponds to a MODFLOW grid cell matrix, indicates the magnitude of recharge within a cell relative to other cells in the same subbasin. With this scheme, the model-estimated total recharge for the subbasin is maintained; only the distribution of recharge within the cells in a subbasin is modified (Sophocleous *et al.*, 1999). Figure 5 depicts the seasonal recharge to the shallow groundwater in the irrigated subbasins. The recharge sources come from seepage from the irrigation canals and percolation from the unsaturated soil profile. Percolation caused by precipitation is quite insignificant in the HID because of the small total annual precipitation and scarcely large-amount precipitation events. The SWAT2000 model assumes that irrigation water fills the soil profile to field capacity from the upper-most layer down to the lowest layer, and percolation occurs when soil water storage in a layer is over field capacity. Those assumptions prevent percolation that may be caused by over irrigation to occur. And, realistically speaking, flood irrigation wets the soil usually to near saturation from the upper layer down to the lower layers. So, it was assumed that the soil layer was irrigated to saturation from the upper layers down. The HID starts crop irrigation usually from the middle of April and ends in August. Late June and early July are the most intensive irrigation time in which crop water use gets to its peak. In late October, 'autumn irrigation' is traditionally adopted to store water in the soil profile for use in the next growth season. As a result, the recharge rate gets two peaks in the year (Fig. 5). Recharge rate differs greatly among subbasins. This is mainly because of the difference of diversion water amount in totality and in unit area among the subbasins. Subbasins 8 and 9 rank the highest in recharge, where irrigation agriculture is the most advanced, and subbasin 4 the lowest, because of the least irrigation near the Wulanbuhe Desert.

2.3 Seasonal water table fluctuations

The groundwater flow vector maps derived from the simulated water table show the horizontal flows in the HID. It was found that the more active horizontal flow occurs in the subbasins Langshan and Wulashan that receive the seasonal recharge from the mountains. Horizontal flow density slows down gradually from the higher west to lower east, and becomes almost stagnant in subbasin 11 (Wulate). The sluggish horizontal groundwater flow implies that the groundwater

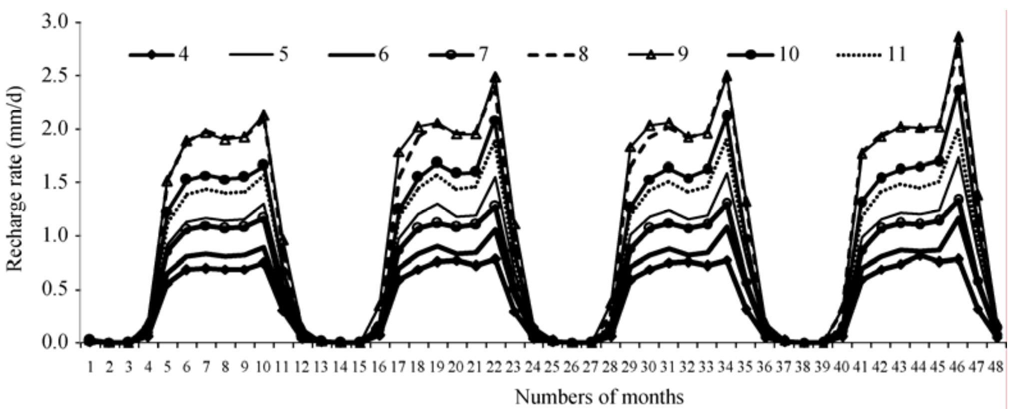

Fig. 5 Recharge from the unsaturated profile to the shallow groundwater in different subbasins (Numbers of 4–11 in the legend are the subbasin codes)

is most active in the vertical direction, i.e., recharge and evaporation. Seasonal variation of depth to water table in subbasins 9 (Jiefangzha) and 1 (Langshan) are depicted as Fig. 6. In subbasin Jiefangzha, water table decreases from the start of the year to late March and early April, then goes up because of the irrigation recharge until late October. Autumn irrigation at September causes another rise of the water table. From October, the water table decreases until late March of the following year. For subbasin Langshan, the water table shows little seasonal fluctuation because no irrigation recharge takes place. Recharge by precipitation is insignificant. In 1991, the initially set groundwater elevation decreased very rapidly to the fairly stable stage (Fig. 6). The depth of the water table in that subbasin reached approximately 3 m, which implied weak saturated-unsaturated interactions. The seasonal patterns of the water table in the non-irrigation subbasins 3 (Wulashan) and 2 (Wulanbuhe) are very similar with that in subbasin 1 (Langshan), and the seasonal patterns in the other irrigated subbasins are very similar with those in subbasin 9 (Jiefangzha). The seasonal fluctuation of the water table both in pattern and amount agreeds with what was reported in the HID as well.

2.4 Groundwater evaporation

Shallow groundwater evaporation was calculated with the approach provided in the MODFLOW96 model, and equation (4) in the upgraded model. Figure 7 depicts the seasonal variation of evaporation. Evaporation calculated with the two different approaches changes in very similar way seasonally. Yet, the upgraded model gave result that was higher than MODFLOW96 did. The difference was caused by the soil water stress. The higher the soil water stress index was, the bigger the difference. Shallow groundwater evaporation is closely related to not only the depth to water table, but also to the soil moisture status, crop water demand, and crop root density profile as well. The dryer the unsaturated profile, the more possible for the groundwater to move up. The comprehensive effect of soil water status, crop water demand, and crop root uptake to draw more water from the shallow groundwater is reflected in the soil water stress index. Equation (4) is thought to be more physically-based than the formulas adopted in SWAT and MODFLOW models. In the SWAT model, groundwater evaporation is taken solely as a proportion of the atmospheric demand. The theoretical document of SWAT2000 suggests that the ratio ranges between 0–0.2. In MODFLOW96, the approach adopted does not take into account the effect of crop and unsaturated soil moisture profile to shallow groundwater evaporation at all. Those models are limited due to lacking the necessary information. This also implies the necessity of integrating the hydrological and groundwater models to treat the unsaturated and saturated flow as a coupled system.

2.5 Water budget of the Hetao Irrigation District

Table 2 gives the main components of the water budget over the Hetao Irrigation District. It could be found that diversion water from the Yellow River is the main input source of water in the district. Precipitation contributes a minor part. Evapotranspiration is the most important output. It could be found also that surface water and groundwater interactions are very strong. Shallow groundwater evaporation is believed to play an important part in supplying the unsaturated soil profile. The annual shallow groundwater in the barren land was approximately 7.5×10^8 m^3, which

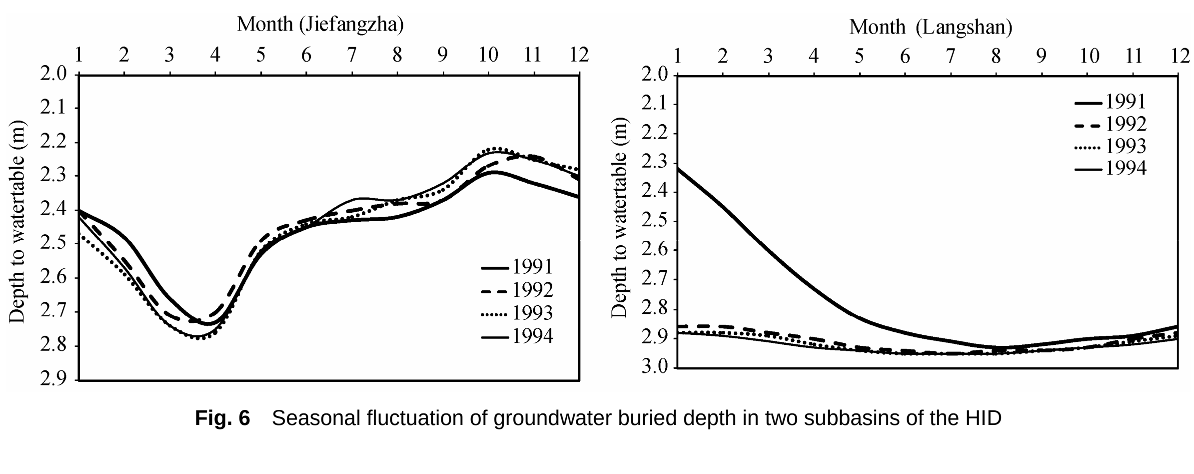

Fig. 6 Seasonal fluctuation of groundwater buried depth in two subbasins of the HID

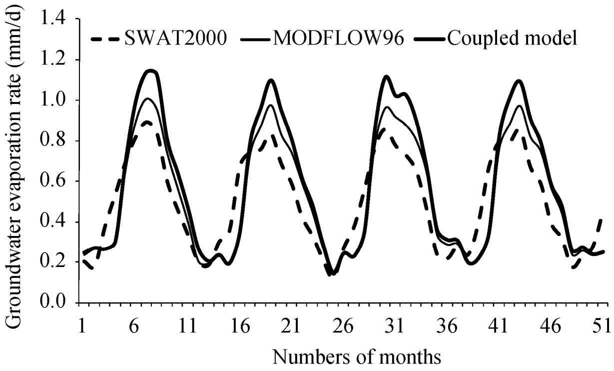

Fig. 7 Comparison of groundwater evaporation among different estimation approaches

Table 2 Components of the water budget of the district

Items	Amount (10^8 m^3)
Diversion from Yellow River	50.4
Precipitation	7.5
Evapotranspiration	44.0
Recharge to shallow groundwater	29.0
Shallow groundwater evaporation	23.0

accounts for 32.6% of the total shallow groundwater evaporation, and 25.8% of the total recharge. This strongly implies the importance of ‘dry drainage’ of bare land in the district and the potential risk of the secondary land salinity. How to maintain a proper water table to reduce the potential risk is an issue of concern.

3 Conclusions

The integrated watershed and ground-water models allow a complete analysis of the land-based hydrologic cycle, thus providing the means for evaluating the impacts of land use, irrigation development, and climate change on both surface and groundwater resources. Such models allow predictions of the impact of management changes on total water supplies. Evaluation of such impacts is at the core of present-day debates on the sustainability of water resources. The seasonal variation of water-table levels and recharge can be more accurately predicted by the soil-moisture accounting system employed in the integrated model than by using only the groundwater model (Sophocleous and Perkins, 2000). For the irrigation districts that have shallow groundwater depth, the two-way coupling the unsaturated-saturated interaction is quite necessary. Meanwhile, making use of information coming from both the watershed and groundwater models to simulate groundwater evaporation is more physically-based and feasible. In the Hetao Irrigation District, this approach was successfully adopted. However, it should be noted that the finer spatial resolution of the water table information in MODFLOW was averaged over the subbasin for use in the SWAT model. This may have negative effects for this approach to calculate evaporation in a more reliable way. Other issues that need to be addressed in coupling the saturated and unsaturated flow are how to change the thickness of the unsaturated soil profile with the changing water table, how to harmonize the temporal steps of the SWAT model and MODFLOW model, and how to account for the effects of water table on canal seepage. Relevant efforts are being made on the basis of the current model code.

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