

## Evaluation of the applicability of the SWAT model in an arid piedmont plain oasis

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### ABSTRACT

Hetao Oasis is located in a typical piedmont alluvial plain bounded by the Langshan Mountain Range in the north, desert in the west, and the Yellow River in the south. Agricultural activities within the oasis significantly impact the hydrological cycle and water quality in downstream locations. The research uses the Soil and Water Assessment Tool (SWAT) for a piedmont plain by defining the watershed boundary as coinciding with the natural mountain ridge, the border between the oasis and the desert, and the Yellow River. The model simulates water discharge with coefficient of determination and a Nash–Sutcliffe model efficiency of 0.78 and 0.62 during model calibration, and 0.75 and 0.69 during model validation, suggesting that delineation of the watershed as carried out in this research is suitable for piedmont plain topography. From the results, the mountains contribute 28.4% to the water discharge at the outlet of the watershed, and water-use efficiency of irrigated water is about 40%, which is consistent with field-based measurements. Methodologies used in delineating watershed boundaries and parameterizing SWAT provide a solid foundation for water balance studies in other regions of the world with similar topography.

**Key words** | discharge simulation, irrigation scheduling, piedmont of Langshan Mountain, SWAT, watershed delineation, water-use efficiency

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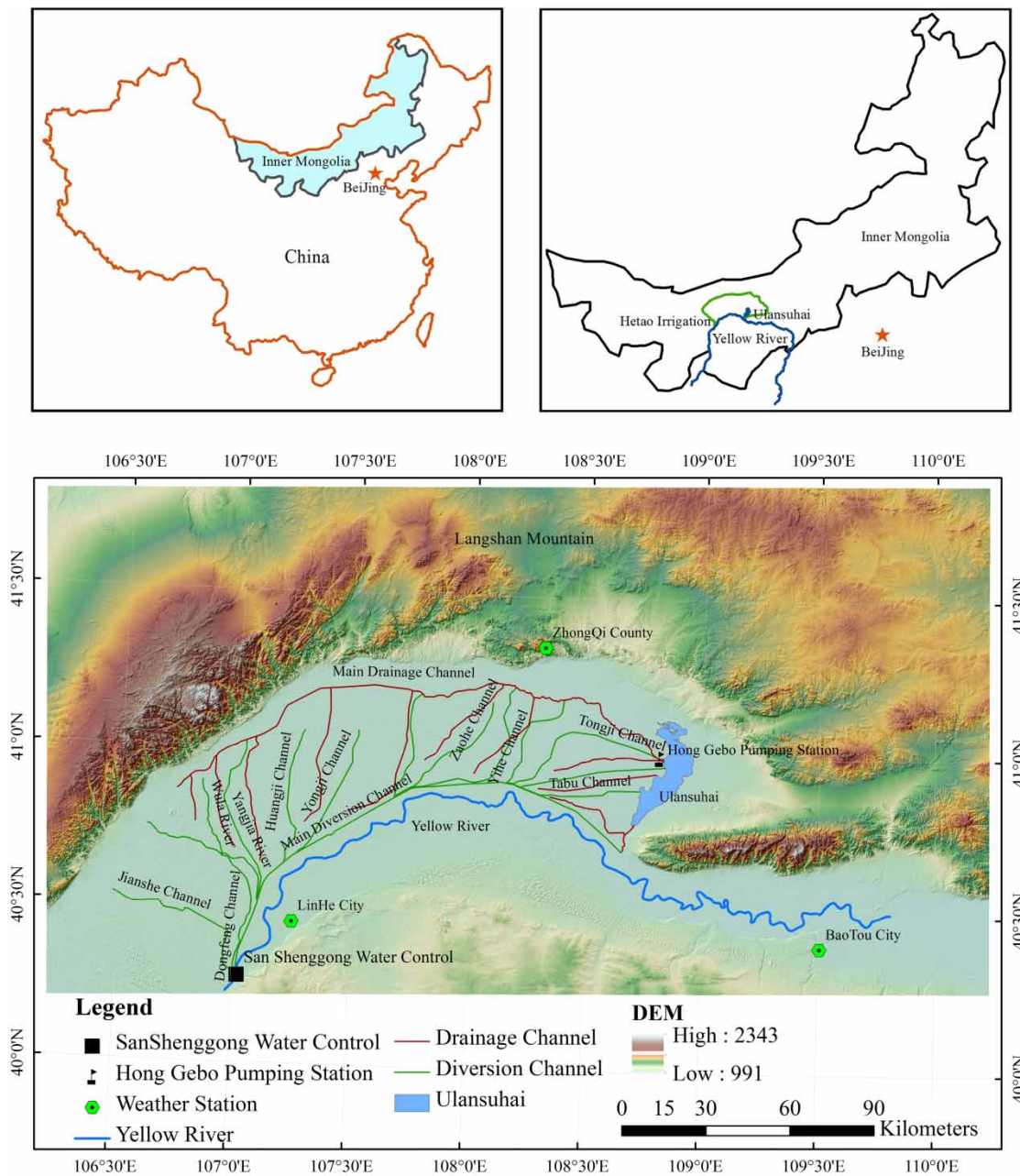
### INTRODUCTION

Hetao Oasis, located in the arid climate region of Inner Mongolia, China (40°12' to 41°20' north latitudes and 106°10' to 109°30' east longitude), is an important grain-producing area of China (Yang *et al.* 2012). At present, approximately 600,000 tons of fertilizers are used annually in the support of agriculture in the oasis. The nutrient and organic pollutants frequently drained from the oasis to Ulansuhai Lake, which is one of the eight largest lakes in China (Figure 1). These pollutants have caused significant environmental impact on aquatic ecosystems of the lake and the Yellow River (Zhu *et al.* 2014). As a consequence, the lake is undergoing severe eutrophication (Sun *et al.* 2013).

Hydrology is the main driving force for pollutant transport. Most previously reported work focused on the water balance and field measurements in the plain due to the complex hydrological processes in the whole

basin. Hao *et al.* (2008) examined the water cycle of the plain in Hetao Oasis. Their assessment, however, failed to recognize the importance of discharge from the watershed portion of the Langshan Mountains. Comparable work by Zhang & Luo (2009) also ignored the importance of discharge from the mountains. As the method did not account for seasonal discharge from the oasis, results from the research could not be used to describe the seasonal export dynamics of streamwater pollutants from the oasis (Liu *et al.* 2014).

The Soil and Water Assessment Tool (SWAT) model is the most widely used semi-distributed hydrological model, which has been successfully applied to simulate seasonal water and pollutant exports from watersheds in mountainous, plain, and coastal areas of the United States (USA) and other countries around the world, across a range of spatial scales (Arnold & Allen 1996;



**Figure 1** | Study area; shown are the Water Control Project at Sanshenggong, Ulansuhai Lake, Honggebo Hydrometric Station at the outlet, and three climate stations.

Arnold *et al.* 1999; Eckhardt & Arnold 2001). Watershed delineation is fundamental to accurately simulating water and water-pollution dynamics with SWAT (Getirana *et al.* 2009). SWAT has been successfully applied to mountains, plains, and coastal areas. However, it has yet to be applied to the piedmont alluvial plains adjacent to Langshan Mountain, owing to their complex topography and uncertainty associated with drainage characteristics in flat terrain.

The objectives of this research are to: (i) delineate watershed boundaries of the greater Hetao area by analyzing water-cycle processes associated with a piedmont plain arrangement; (ii) evaluate the applicability of SWAT in an arid to semi-arid climate and irregular topography; (iii) estimate the contribution of water from the watershed portion of the Langshan Mountains to the oasis and from the oasis to Ulansuhai Lake; and (iv) estimate water-use efficiency of irrigation systems within the study area.

## MATERIALS AND METHODS

### Study site

The greater Hetao area is in a typical continental arid and semi-arid region with mean annual precipitation of 188 mm, of which 80% occurs in June–August. The annual potential evaporation is about 1,999–2,346 mm. The mean annual temperature in the region is about 6–8 °C. Soil freezes from late November to early May, and the frostline is about 100–200 cm deep (Zhang *et al.* 2014). Soil parent material of the area is alluvium deposited by the Yellow River. The average soil thickness is greater than 120 cm. Due to high groundwater recharge from irrigation leakage, the mean water table depth fluctuates from 1.5 m in March to about 0.6 m in October (Zhu *et al.* 2014).

The Hetao Oasis covers a total land area of 11,195.4 km<sup>2</sup>, in which irrigation is applied to about 5,740 km<sup>2</sup> of the area. Farmland occupies about 5,246.7 km<sup>2</sup> and grassland and forests, about 493.3 km<sup>2</sup> of the area. Main agricultural crops grown are wheat, corn, and sunflower, covering 17%, 19%, and 29% of the total farmed area, respectively. Water from the Yellow River is diverted to the oasis by the Sanshengong Water Control Project in Dengkou County. The annual extraction volume for irrigation is about 4.5 to 5.5 × 10<sup>9</sup> m<sup>3</sup>. The irrigation system consists of a 180 km trunk diversion and 13 branch canals; wastewater from the oasis drains through a 220 km trunk drainage and 10 branch channels to Ulansuhai Lake (Figure 1).

### Data collection

The 90 × 90 m resolution digital elevation model (DEM) was downloaded from the US Geological Survey website ([www.usgs.gov](http://www.usgs.gov), last accessed September 2012). Landuse and soil distribution data were obtained from the Scientific Data Center of the Cold and Arid Regions website (<http://westdc.westgis.ac.cn>, last accessed September 2012). The irrigation and drainage system is vectorized from a 1:250,000 irrigation and drainage map. The monthly irrigation and drainage data from 2003–2012 were obtained from the Hetao Irrigation Bureau of Bayannaoer League. Daily meteorological data from 1992–2012 were acquired from Linhe City, Wulatezhong County, and Baotou City meteorological stations (Figure 1) through the China Meteorological Data Sharing Service System (<http://data.cma.gov.cn>, last accessed September 2012).

### Watershed delineation

#### Analysis of water cycling processes in the Hetao Oasis

Watershed delineation is fundamental to accurately simulating water dynamics with SWAT. Water cycling in the Hetao Oasis is dominated by several important processes, including: (i) the formation of orographic precipitation in the Langshan Mountains, which flows downslope as surface and shallow subsurface water to supply the drainage channels; (ii) water diversion to the oasis is controlled by the Sanshengong Water Control authority; (iii) excess irrigation water from the oasis flows to the main drainage channel; (iv) water from the main drainage channel flows to Ulansuhai Lake, which eventually enters into the Yellow River; and (v) as irrigation has been taking place in the oasis for decades, the groundwater in the desert and oasis are at roughly the same level. Thus, groundwater exchange between the desert and oasis is minor.

#### DEM preprocessing

As topography in the plain area is quite flat, the drainage channels and the boundary of sub-basins in this area cannot be directly determined with SWAT, without an initial pre-processing of the DEM. For instance, elevations along the main and branch irrigation channels need to be artificially increased, whereas elevations along drainage channels need to be decreased to simplify the search and delineation of streams within SWAT (Duke *et al.* 2003).

#### Determination of the length of streams and drainage channels

In SWAT, the drainage channels are extracted from the upstream accumulation area with a specific threshold value, which should vary with topography, vegetation, and regional climate. The threshold value could feasibly be determined by either the ‘trial and error’ or ‘stream network density’ method (Zhou *et al.* 2012). In this research, we opted to use the ‘stream network density’ method, based on a ratio between the total river network length and watershed area. A stream network density of 0.09 km/km<sup>2</sup> is commonly used for arid regions. This corresponds to a threshold value of 120 km<sup>2</sup>.

#### Delineation of watershed and sub-basins

Based on these processes, we use the convergent point between the Yellow River and Ulansuhai Lake as an outlet to delineate the Hetao Oasis watershed boundaries. The Langshan

Mountain Ridge, and the border between the desert and oasis, and the Yellow River, in the south, in forming the boundaries of the Hetao Oasis watershed. The watershed and drainage network can now be implemented in SWAT (Figure 2).

### Derivation of irrigation schedule

SWAT requires that actual irrigation volumes to each crop type be specified. Owing to the complex crop-planting provisions in the oasis, it is difficult to gather the irrigation data which can fully capture actual practices in the field over the long term. In practice, the timing of application and the amount of irrigation water needed depend on the amount of precipitation available during the growing season and specific water needs of different crops. In this work, each irrigation volume is acquired by (i) referring to field-based estimates of irrigation volumes reported in Ren (2013) and (ii) treating irrigation volumes as a parameter during model calibration.

### Sensitivity analysis, model calibration and validation

Sensitivity analysis is very important for model users to make proper adjustments for sensitive parameters

during model calibration. The Latin hypercube one-factor-at-a-time method, which was incorporated into the SWAT model, was adopted for sensitivity analysis in this study. This method combines the advantages of global and local sensitivity analysis methods and can efficiently give the rank orders of parameters (Sun & Ren 2013). The hydrometric station at Honggebo, which monitors about 80% of farmland drainage in the oasis, is chosen to represent the drainage outlet (Figure 2). The monthly average runoff data acquired from the hydrometric station at Honggebo from 2006 to 2009 are used in model calibration and data from 2010 to 2012, in model validation.

### Model performance evaluation

The coefficient of determination ( $R^2$ ) and Nash–Sutcliffe coefficient (Ens; Nash & Sutcliffe 1970) are used to evaluate the performance of SWAT for current conditions. In cases, where  $R^2$  is greater than 0.5 and Ens is greater than 0.6, performance of the model is viewed as acceptable (Moriasi *et al.* 2007). Performance statistics,  $R^2$  and Ens,

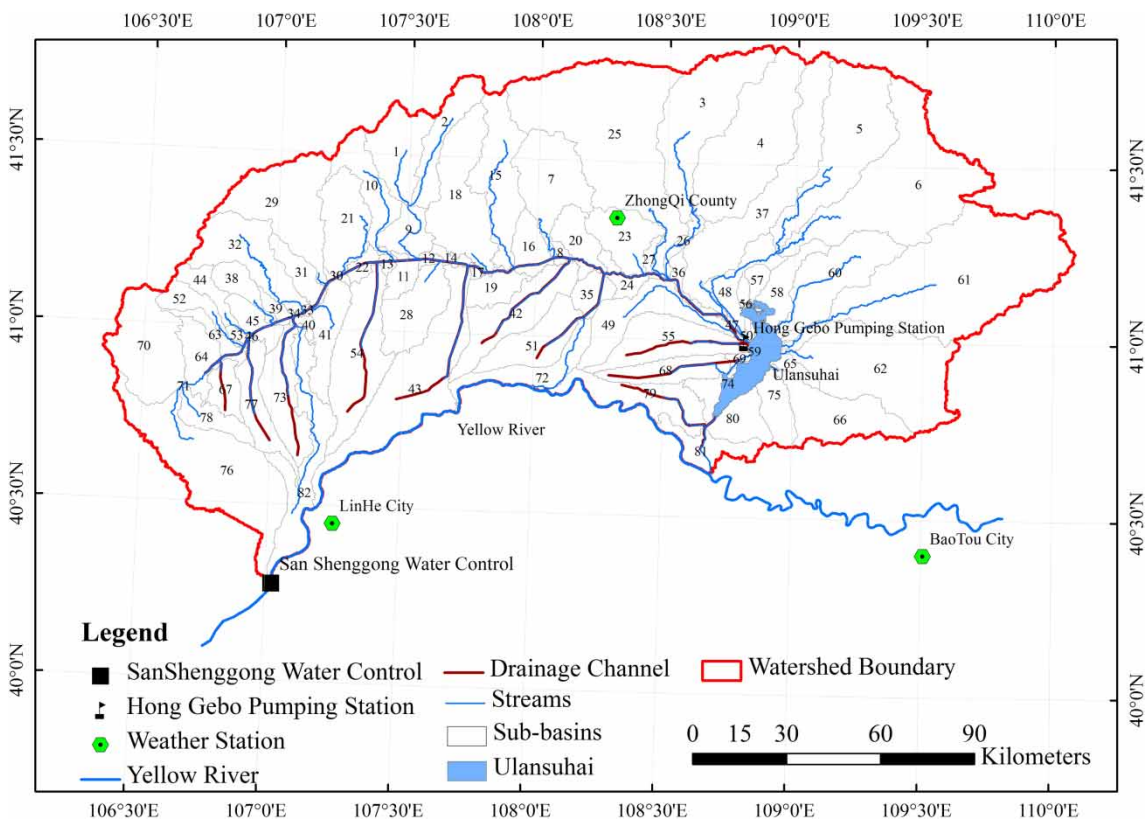


Figure 2 | Watershed and sub-basin delineation.



are computed according to

$$R^2 = \left\{ \frac{\sum_{i=1}^n (Q_0 - \bar{Q}_0)(Q_s - \bar{Q}_s)}{\left[ \sum_{i=1}^n (Q_0 - \bar{Q}_0)^2 \right]^{0.5} \left[ \sum_{i=1}^n (Q_s - \bar{Q}_s)^2 \right]^{0.5}} \right\} \quad (1)$$

and

$$\text{Ens} = 1 - \frac{\sum_{i=1}^n (Q_0 - Q_s)^2}{\sum_{i=1}^n (Q_0 - \bar{Q}_0)^2} \quad (2)$$

where  $Q_0$  and  $Q_s$  are the observed and simulated values,  $\bar{Q}_0$  and  $\bar{Q}_s$  are the averages of observed and simulated values, and  $n$  is the number of data points.

### Irrigation efficiency definition

Water-use efficiency is the ratio between the net water volume used by cropland and the total water inflow from the water control project during a single irrigation period. It is an important indicator to assess the quality of irrigation canals and field-management practices.

The efficiency of field irrigation was estimated based on field measurements of canals and field-use coefficients (Brouwer *et al.* 1989). The scheme irrigation efficiency,  $IE$ , is

$$IE = \text{conveyance efficiency} \times \text{field application efficiency} \quad (3)$$

In this work, the water-use efficiency was calculated by dividing the modeled total net irrigation amount by the diverted amount by the water control project (Kruse 1978). The definition of irrigation efficiency,  $IE$ , is

$$IE = \frac{\text{volume delivered to the crop root zone}}{\text{volume diverted from the supply}} \quad (4)$$

## RESULTS AND DISCUSSION

### Sensitivity analysis

Sensitivity and values for the different calibration parameters are indicated in Table 1. Significant parameters, in order from most to the least sensitive, are Gwqmn, Rchrg\_dp, Esco, Sol\_z, Gw\_revap, Gw\_delay, Revapmn, Alpha\_bf, and Cn2. The Cn2 is the least sensitive parameter. Other parameters are mainly associated with soil water or groundwater processes. Sensitivity of these parameters suggests that groundwater processes are critical to the cycling of water in the Hetao watershed. All parameters, except Gwqmn, have values consistent with values determined for either mountainous or plain areas.

### Model calibration and validation

Figure 3(a) shows an example of the modeled results during one set of calibration and validation periods.

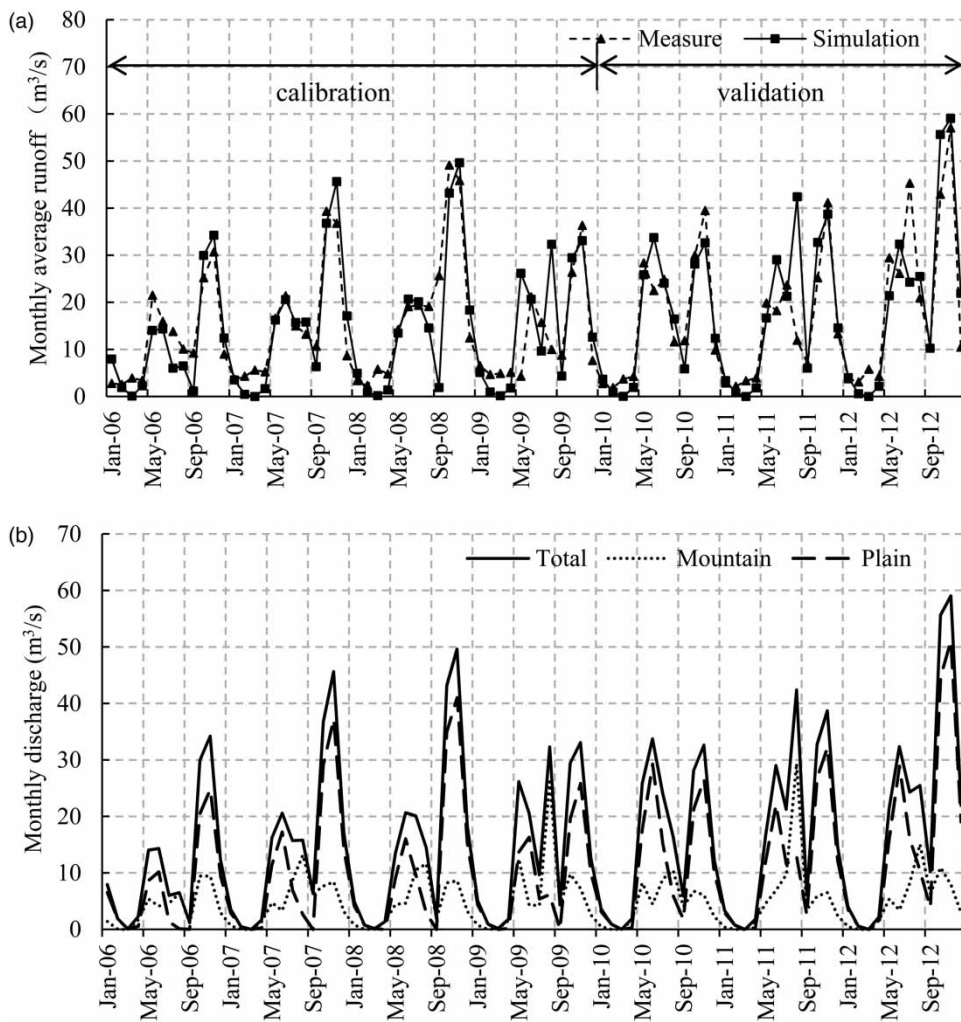
**Table 1** | Rang specifies the range of parameters and for the sensitivity analysis

Sensitivity ranking	Parameter	Description (units)	Calibrated value	Range
1	v_Gwqmn.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	560 <sup>a</sup> 90 <sup>b</sup>	300–600 5–100
2	v_Rchrg_dp.gw	Deep aquifer percolation fraction	0.05	0.01–0.50
3	v_Esco.bsn	Soil evaporation compensation factor	0.95	0.81–0.95
4	v_Sol_z.sol	Depth of soil layers in the oasis (mm)	1,000 <sup>c</sup> 1,400 <sup>d</sup>	–
5	v_Gw_revap.gw	Ground water ‘revap’ coefficient	0.02	0.02–0.12
6	v_Gw_delay.gw	Ground water delay (days)	21	9–23
7	v_Revapmn.gw	Threshold depth of water in the shallow aquifer for ‘revap’ to occur (mm)	300	0–304
8	v_Alpha_bf.gw	Baseflow alpha factor	0.06	0.01–0.50
9	v_Cn2.mgt	Initial SCS runoff curve number for moisture condition II	35	35–98

<sup>a</sup>‘v\_’ indicates a replacement of the original parameter value.

<sup>a,b</sup>Parameter values for non-irrigated and irrigated land, respectively.

<sup>c,d</sup>Parameter values for the first and second soil layers, respectively, and constant for whole watershed.



**Figure 3** | The results of runoff simulation. (a) Monthly average runoff calibration and validation results. (b) Modeled monthly total discharge, discharge in the plain oasis, and discharge from the mountain portion of the Hetao watershed.

Within the first calibration period (2006–2009), the model captured the field-measured monthly discharge fairly well, producing  $R^2$  and Ens of 0.78 and 0.62, respectively. During model validation, the model captured field measurements reasonably well with  $R^2$  and Ens of 0.75 and 0.69, respectively. Performance statistics suggest that the model is a suitable implement for piedmont plain oasis conditions.

Discrepancy between observed and simulated data during the growing season could have been caused by the fact that: (i) actual irrigation timing and volumes vary from year to year, whereas set times and application volumes in the model are dealt with as a single-time specification; (ii) the oasis, covering a large area, is potentially affected by variable environmental conditions; and (iii) irrigation application times for individual crops vary.

### Discharge from the mountain area

Contribution of discharge water from the mountains is summarized based on sub-basins distributed throughout the mountain portion of the watershed. The mountain portion of the watershed contributes about 28.4% of the discharge water to the outlet during 2006–2012 (Figure 3(b)). The contribution is mainly focused in the high precipitation season of each year (i.e. August–November; Figure 3(b)). This indicates that it is essential to include the mountain area as part of the watershed in assessing the regional water balance.

### The irrigation schedule and the efficiency of irrigation

Table 2 shows the irrigation schedule of the principle crops in the oasis. The reference values are derived from a

**Table 2** | Derived irrigation schedule; unit of irrigation is in millimeters

Irrigation period	Corn		Spring wheat		Sunflower	
	Referred	Applied	Referred	Applied	Referred	Applied
I	145–160	120–145	135–150	130–160	180–200	160–200
II	60–80	60–80	90–130	60–80	90–120	0
III	110–130	110–140	0	0	105–140	140
IV	90–110	110	90–110	230	80–110	0
V	250	180–240	260	180–240	260	180–240

Note: Irrigation period I corresponds to crop development stages (i) tillering, (ii) stem elongation, and (iii) before planting of wheat, corn, and sunflower; period II corresponds to (i) stem elongation, (ii) bell stage, and (iii) bud stage of the three crops; periods III and IV correspond to the stages of (i) heading/flowering, and (ii) grain filling; period V corresponds to irrigation in autumn.

field-plot experiment by Ren (2013). From the Table 2, some of the irrigation volumes and frequencies are different from the reference values. Based on inquiries to local farmers, the applied irrigation frequency and values for each crop are closer to actual operation per year. The irrigation efficiency calculation can indicate the applied values in the Table 2 representing an optimum irrigation schedule.

Irrigation-use coefficients calculated from this work are shown to be fairly close to the values of field-based measurements 0.41, 0.42 and 0.40 in the high-flow, medium-flow and low-flow, respectively; representing deviations of –4.9, –2.4, and –2.5% from the values of field-based measurements (Liu et al. 2013). This study also provides a useful way to assess the efficiency of irrigation projects and agriculture-management practices by local governments.

## CONCLUSION

In this study, SWAT is applied for the first time to a pied-mont plain oasis setting in arid northern China. The model simulates water discharge with coefficient of determination and a Nash–Sutcliffe model efficiency of 0.78 and 0.62 during model calibration (2006–2009), and 0.75 and 0.69 during model validation (2010–2012). The mountainous portion of the Hetao Oasis watershed was shown to contribute 28.4% of the discharge water at the outlet, indicating the need to account for its contribution with assessing the water balance of the area. The water entering the study area from the mountains is not neglected and, on the contrary, might have an important effect. Water-use coefficients of irrigation calculated from this work were 0.39, 0.41 and 0.39 in different hydrological years, respectively. Previously reported values about efficiency of irrigation are in agreement with the estimations made.

Watershed and sub-basin boundaries were delineated in this study based on a new water-course analysis. It can provide a reference to be used in regions of similar climate and topography.

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