Application of SWAT model to Zhangweinan Canal sub-watershed

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Abstract—Hydrological and water quality simulation faces big challenge because of intensive human activities in the Zhangweinan Canal sub-watershed of the Hai River basin. The Soil & Water Assessment Tools (SWAT) modeling system was established depended on various of spatial and attribute data of this watershed, and parameters for hydrological, water quality and evapotranspiration (ET) simulation were calibrated and verified using measured stream flow, water quality and remote-sensing derived ET data, and different scenarios were simulated and analyzed. The results show that point source pollution contributed most of the pollutant loadings of pollutants in Zhangweinan sub-watershed, and non-point source pollution (NPS) contributes small and NPS pollutant losses are predominantly located in mountainous area.

Keywords- Soil and Water Assessment Tool (SWAT); non-point source pollution; scenario analysis; Zhangweinan sub-watershed

I. INTRODUCTION

The Zhangweinan Canal sub-watershed (37,700 km²) is located in the southern part of the Hai River basin in Northern China Plain and is located between 112-118°E longitude and 35-39°N latitude. The watershed terrain is high in western area and low in eastern area, which includes about 68% of the mountainous area and 32% of the plain area. The upstream locates in the Taihang Mountain, where most of the areas have elevation above 1000 m. Land use in the watershed includes 53.4% agricultural land (mainly rotation areas of winter wheat and summer maize, and rain-fed farmland) and 20.3% pasture area. There are many reservoirs and water gates in the upstream areas and downstream areas respectively, and the water consumption for irrigation, industrial and domestic water uses in this watershed are extremely complex, which made the hydrological and water quality simulation more complicated and being challenged.

Depended on large amount of data collection and in-situ investigation, this study applied SWAT model to simulate hydrological process and water quality process considering various water uses, point source pollution and non-point source pollution, and to conduct scenario analyses of pollution control and water quality management.

II. METHOD AND MATERIALS

Soil and Water Assessment Tool (SWAT) is a watershed scale model developed by Dr. Jeff Arnold for the USDA Agricultural Research Service (ARS). It was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time [1, 2].

In order to setup SWAT model system, various spatial data and properties were collected (TABLE I and Figure 1), which included digital elevation model (DEM), land use map, soil map, weather data, rainfall, reservoir properties, agricultural management, water uses and water quality data, and etc.. These data were pre-processed according to SWAT data format and inputted into model.

TABLE I. DATA COLLECTION

Type	Scale/Gauge	Description	Source
DEM	1:250,000	Elevation, channel slopes, lengths, aspect	National Fundamental Geographic Database
Land Use	1:100,000	Land use classifications	Remotely Sensed image and Survey
Soil Map	1:1000,000	Soil types; physical properties, e.g. bulk density, texture, etc.	ISS, CAS ¹
Weather Data	16 gauges	Precipitation, temperature, relative humidity, wind speed	NMIC, CMA ²
Precipitation	113 gauges	Precipitation	NMIC ³ CMA and ZRAB ³
Reservoirs	18	Storage capacity, out flow, water supply	ZRAB
Irrigation	Main irrigation areas	Distribution of irrigation areas, water source, irrigation amount	Field surveys and ZRAB
Management Practices	-	Tillage, fertilization, pesticide, etc.	Field surveys and ZRAB
Water Uses	-	283 water intakes; groundwater pumping	Field surveys and ZRAB
Water Quality	5 sections	Concentration of water quality items such as TN, TP, COD, NH ₃ -N...	ZRAB
Point sources pollution	110 discharge outfalls	Wastewater discharge flow, discharge loadings of COD, NH ₃ -N.	Baseline investigation of 2004

¹: Institute of Soil Science, Chinese Academy of Sciences; ²: National Meteorological Information Centre, China Meteorological Administration (CMA); ³: Zhangweinan River Administration Bureau.

The Zhangweinan sub-watershed of the Hai River basin has a relatively small catchment area in the downstream area because there are dikes along the canal river and no any tributary concentrates into the main reaches (Figure 1). The main catchment area is predominantly located in middle and upper area of the watershed. The main tributary Zhang River and Wei River concentrates near the Nantao hydrological station of the Guantao County, Hebei Province. Because the Zhangweinan Canal sub-watershed covers four provinces, which including the Shanxi Province, the Henbei Province, the Henan Province and the Shandong Province (mainly in downstream canal river catchment area), the human activities inside watershed are extremely complicated and water use data are not known and shared completely among these four provinces, and the water rights conflicts happened sometimes in the past.

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Figure 1. Study area and weather/precipitation gauges

A. Land Use

The main land use classes are irrigated farmland of rotation of winter wheat and summer maize, pasture, rain-fed farmland in highland and mountainous area, and deciduous forest (TABLE II), which are coded as WWHT, PAST, CORN and FRSD in SWAT model respectively. These four classes account for more than 84% area of the watershed, and rotation areas of winter wheat and summer maize are mainly located in the middle and downstream area of the watershed.

TABLE II. LAND USE CLASSIFICATION

Land Use Class	SWAT Code	Area%
Rotation farmland of Winter Wheat and Summer Maize with irrigation	WWHT	40.43
Pasture	PAST	20.29
Rain-fed farmland in highland and mountainous area	CORN	12.81
Deciduous Forest	FRSD	10.50
Range-brush	RNGB	3.73
Range-grasses	RNGE	2.54
Urban with low density	URLD	7.39
Water	WATR	1.14
Other land use classes	-	1.17
Total		100

B. Soil Map

The main soil classes include cinnamon soils, fluvo-aquic soils and cultivated loessial soils, which account for about 78% of total area of the watershed and are coded as HETU, CAOTU and HMTU in SWAT model respectively (TABLE III). These three main soil classes are mainly located in middle-stream (highland and mountain front areas), downstream areas (plain area) and upper stream areas of the Zhang River, respectively.

TABLE III. SOIL CLASSIFICATION

Soil Class	SWAT Code	Area%
Cinnamon soils	HETU	31.08
Fluvo-aquic soils	CAOTU	28.82
Cultivated loessial soils	HMTU	18.10
Calcic litho soils	GZSZTU	4.64
Calcic skeletal soils	GZCGTU	3.93
Acid skeletal soils	SXCGTU	3.45
Other soil classes	-	9.98
Total		100

C. Irrigation Scheme

Most of the irrigation areas in the Zhangweinan Canal sub-watershed are rotation farmlands of winter wheat and summer maize, which include so-called top 5 irrigation areas, i.e., the Hongqiqu, Zhangnan, Yuefengqu, Yuejinqu and Mingyouqu irrigation areas. Water sources for top 5 and some other small irrigation areas are mainly from inside sub-watershed, and for some other irrigation areas in the Wei River catchment are also from the Yellow River. For example, some irrigation areas near the Xinxiang City of Henan Province draw water from main reach of the Yellow River through Gongchanchuyi and ReminShengli Channel.

The general irrigation scheme in the rotation farmlands of winter wheat and summer maize are investigated and generalized in TABLE IV. The investigations show that about 3~5 times of irrigation events are necessary during a rotation period of winter wheat and summer maize depending on precipitation and soil moisture conditions. Therefore, the SWAT settings of irrigation time should consider amount and time of precipitation event.

TABLE IV. INVESTIGATED IRRIGATION SCHEME

Plant	Time (Lunar calendar)	Time (Solar calendar)	Irrigation amount (m3 mu ⁻¹ per time)	Description
Winter Wheat	Second 10 days in Feb.	Second 10 days in Mar.	40~50	While turning green
	Second 10 days of Apr.	Second 10 days in May	40~50	During wheat filling stage
	Grain in ear	~June 6	40~50	~10 days before harvest
	Harvest and plant period	Middle in June	0	Harvest wheat and plant maize
Summer Maize	-	Second 10 days in Jul.	40~50	Irrigate or not depending on soil moisture condition
	-	Second 10 days in Aug	40~50	Irrigate or not depending on soil moisture condition
	~Aug. 15	Beginning of Oct.	0	Harvest maize
Winter Wheat	-	~Oct. 5	0	Plant winter wheat
	Before winter comes	Second 10 days in Oct.	40~50	Irrigate or not depending on soil moisture condition

III. MODEL CALIBRATION AND VALIDATION

SWAT model system is established using all data described in Section II, and model parameters for evapotranspiration (ET), hydrological and water quality simulation were calibrated and verified using remote-sensing derived ET, measured stream flow and water quality data.

A. ET Calibration & Validation

Most SWAT applications focused on calibration and verification of hydrological process and water quality (NPS) process and neglect to discuss ET simulation and calibration [3-12]. To fine tune the crop growth and ET simulation in SWAT model, some researchers tried to calibrate ET simulation using ground-observed and remote sensing derived ET. For example, Arnold et al [13] applied SWAT to simulate ET and calibrated using observed ET from conventional method. Immerzeel and Droogers [14] calibrated and verified ET simulated by SWAT using RS derived ET. Using RS-derived ET to calibrate crop growth and ET parameters is a

relatively new approach in recent SWAT model application, and its key procedure is to determine suitable soil and crop growth parameters according to real growth process of the simulated crops [15].

RS derived ET data with 1km-resolution, which was derived from ASTER/TM and AVHRR/MODIS data by the Institute of Remote Sensing and Application (IRSA) of CAS and using ETWatch model, was applied to calibrate and validate the monthly ET simulated by SWAT model. This RS derived data are verified using ground observed ET data by Expert Panel of GEF Hai River Basin Project and recommended for use in the Project. Please refer to reference [16] for details on ETWatch model and data set evaluation.

Depending on irrigation investigation and researches for rotation crops of winter wheat and summer maize, crop growth and ET parameters are calibrated and validated [17]. Thereinto, ET data of 11 typical sub-basins which covered fully by rotation crops of winter wheat and summer maize (coded as land use class WWHT) were averaged and compared with RS-ET (Figure 2). The coefficient of determination (R^2) and Nash-Sutcliffe coefficient (E_{NS}) reached 0.93 and 0.92 respectively. It is shown that SWAT-simulated ET matches RS-ET well and represents growth cycle of winter wheat and summer maize.

Figure 2. ET calibration and validation for rotation crops of winter wheat and summer maize (WWHT)

B. Hydrograph Calibration & Validation

The hydrological processes are calibrated and validated after ET calibration. Year from 2001 to 2003 was selected as calibration period and 2004 was selected as validation period. Parameters sensitivity analysis showed that the main parameters sensitive to hydrological simulation were CN2 (SCS curve number), SOL_AWC (Available water capacity), ALPHA_BF (Base-flow alpha factor), CANMX (Maximum canopy storage) and etc.. The parameter CANMX is not paid more attention in the previous studies, however, it is very important in semi-arid and arid areas, and its value should be determined based on land use classes. The calibration and validation of hydrological process was shown in Figure 3. The simulated hydrograph could basically match the observed ones, and Nash-Sutcliffe coefficients of hydrological station Guantai, Yuancun, Linqing and Xinji reached 0.61, 0.68, 0.81 and 0.81 during calibration period, and reached 0.47, 0.59, 0.75 and 0.77 during validation period, respectively. The model simulation was not perfect, but it can meet the requirements for relatively comparison in scenario analysis.

Figure 3. Hydrological process calibration and validation at (a) Guantai, (b) Yuancun, (c) Linqing, and (d) Xinji Stations

C. NPS Simulation

Model inputs for water quality simulation mainly include point source discharge data, agricultural fertilizer application data and management practices, which were from baseline investigation of 2004 of the GEF Hai River Basin Project, Chinese Natural Resources-Environment-Economic and Population Database [18], and in-situ investigation in the sub-watershed respectively. Hereinto, the fertilizer applications were detailed to county-level, and agricultural manure from livestock and human beings in villages were converted to net nitrogen and phosphorus components and inputted the model.

The NPS simulation was calibrated and validated at in the year manner (Figure 4). The simulated yearly TN and TP loadings can basically match observed ones well.

Figure 4. TN and TP calibration and validation at the most downstream station Xinji (left: TN, right: TP)

Figure 5. Spatial distribution of (a) rainfall, (b) soil losses, (c) TN and (d) TP

The simulation results showed that NPS pollutant losses were predominantly located in mountainous area, and the NPS losses were small in the plain area because (1) terrain is flat and there are dikes between agricultural fields to keep irrigated water from the fields, and (2) study area is arid and small runoff occurs due to small precipitation (Figure 5).

IV. SCENARIO SIMULATION AND ANALYSES

Different scenarios were designed considering precipitation, irrigation, point source pollutant loadings and fertilizer application (TABLE V). Hereinto, scenario S0 is a base case scenario which represents the present condition of the study area, and simulation results of other scenarios were compared to base case scenario.

The scenario simulation and analyses showed that (1) TN and TP loadings into the sea will decrease 24% and 8% if point sources can meet discharge standards, and decrease 15% and 9% if point source discharged according to water environmental capacity; (2) TN and TP loadings into the sea will decrease 7% and 15% if point sources loadings decrease 15%; (3) TN and TP loadings into the sea will decrease 4% and 2% if fertilizer application amount decrease 10%, and (4) point sources contributed more than 70% of TN, 60% of TP loadings into the Bohai sea, and are predominantly from tributary watershed of the Wei River.

TABLE V. SCENARIO DESIGNS

Scenario #	Precipitation	Water depth for Irrigation	Point source loadings	Fertilizer application
S0	baseline	Baseline	baseline	baseline
S1	baseline	↓ 10%	meet standards	baseline
S2	↓25%	↓ 10%	meet standards	baseline
S3	↑25%	↓ 10%	meet standards	baseline
S4	baseline	↓ 10%	meet standards	↓ 10%
S5	↓ 25%	↓ 10%	meet standards	↓ 10%
S6	↑ 25%	↓ 10%	meet standards	↓ 10%
S7	↓ 25%	↓ 20%	match WEC	↓ 10%
S8	baseline	↓ 20%	meet standards	↓ 20%
S9	↑ 25%	↓ 20%	↓ 15%	↓ 20%
S10	baseline	baseline	0	baseline

Note: baseline - baseline data of 2004; meet standards - point source discharged according to discharge standards; match WEC - point source loadings allocated based on water environmental capacity (WEC); ↓ - decrease (reduce); ↑ - increase

V. CONCLUSIONS

Simulated results did not match observed data perfect due to complexity of water use activities in sub-watershed and data unavailable, however, the established model system can be applied for scenario analyses, and simulated NPS data can be relatively compared among different scenarios.

NPS pollutant losses are predominantly located in mountainous area. Point source pollution is the main issue in Zhangweinan sub-watershed, especially in the Wei River tributary watershed.

The key task to improve water quality in the canal sub-watershed is to assure that all point discharges can meet the discharge standards, and then pollution control focus can be switched to non-point source pollution control.

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