SIMULATION OF DISCHARGE AND POLLUTANT'S CONTENT IN TUUL RIVER BASIN WITH THE HYDROLOGICAL MODEL ArcSWAT

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Abstract: Urban area waste water treatment, unmanaged mining activities, land cover degradation and forest area changes are the key processes that negatively affect the water resources of the Tuul river basin. Due to the climatic and man-made impact conditions, discharge decline and growth of concentration of pollutants are being observed in that basin. For that reason, there is a need to identify runoff, discharge and critical pollutants, its loss and transport potential. The aim of this study was to test the performance of the ArcSWAT model and the feasibility of using this model as a simulator of discharge and nitrogen and phosphorus yields over the Tuul river basin. Spatial data layers of land slope, soil type and land use were combined with GIS to aid in creating HRUs. And daily weather data obtained from CFSR, digital elevation model were also used as model input data. Calibration and validation were conducted using the SWAT-CUP program. The observed discharge and pollutant's concentration data at Tuul-Ulaanbaatar, Tuul-Altanbulag gauging station were used to calibrate and validate the model with SUFI-2 algorithm. Time series plots and statistical measures were used to verify model predictions. The correlation between the simulated and the observed flow is measured by r2 was 0.75 in Tuul-Altanbulag gauging station and r2 was 0.67 at the Tuul-Ulaanbaatar gauging station. Based on the simulated flows value, phosphorus and nitrate concentrations in streamflow have been identified. Nitrate and phosphorus content was positively correlated with range between 0.5-0.7 with gauge stations measurements.

Keywords: ArcSWAT model, Discharge, Hydrologic modeling, Nitrogen and Phosphorus, Tuul river basin

Introduction

The Tuul river basin is located in the central part of Mongolia crossing the economic regions of Ulaanbaatar, Tuw, and Khangai. As for administrative units, it covers the territories of 7 districts of Ulaanbaatar city and 37 soums of 5 aimags includes Arkhangai, Bulgan, Uwurkhangai, Selenge and Tuw aimag (Ministry of environment and green development, 2012). The Tuul river basin occupies only 3.2 percent of Mongolia's territory, but as of 2016, about 47.6 percent of total population lives in there (Ministry of environment and green development, 2012). In that year, Ulaanbaatar value produced was MNT 16274.9 billion and in Tuw aimag was MNT 508.3 billion, which was some 67.9% of Mongolian gross domestic product. Based on these testimonies, that basin is an economically viable and highly productive region in terms of society and economy. Also due to population growth in this area, significance of Tuul river basin will be more expanding in the future. On other hand global warming is taking place in research area. The apparent indication of this is that the temperature increased by 0.043^{0}C by year between 1940 and 2008.

Since 2000, this increase has been even higher and it was 0.14^{0}C by year between 1991 and 2008 (Ministry of environment and green development, 2012).

The thermal resources accumulating during the plant growing period are increasing due to climate warning. Therefore the water that evaporates form the land and water surface is increasing. Some researchers believed that this increase has been influence the water losses of rivers, lakes and reservoirs. Between 1961 and 2008, surface evaporation increased by 153 mm, whereas the summer rainfall decreased by 51 mm. The research works which are oriented to determine water quality index based on field survey, define chemical and physical properties of surface water using laboratory analysis, and simulating surface runoff with TOPLATS, HEC-HMS, HBV, DeFLOW and other hydrologic models are mainly carried out in tributaries of Tuul river basin (Byambakhuu, 2011). The study works to estimate surface runoff and concentration of pollutants in given case, inseparably using simulation methods had rarely done previously.

Method

Description of Swat model

The SWAT model, developed by the Agricultural Research Service (Arnold et al., 1998, Neitsch et al., 2005), is a river basin scale or watershed scale model, which simulates hydrological cycle, cycles of plant growth, transportation of sediment, and agricultural chemical yields in a daily basis time step (Yipung Wu & Ji Chen, 2009).

It was developed to predict the impact of land management practices on water, sediment, agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time (Neitsch et al., 2005). The benefits of this model are watersheds with no monitoring data (such as discharge gauges) can be modeled and the relative impact of alternative input data on water quality can be examined (Benedikt, 2016). Input information for each sub basin is grouped or organized into the following categories: climate, hydrologic response unit, ponds and wetlands, groundwater and the main channel, or reach, draining the sub basin. Hydrologic response units are lumped land areas within sub basin that are comprised for unique land cover, soil and management combinations (Neitsch et al., 2005)

Input data collection and analysis

The model requires sets of spatial datasets including topography, land use, soil and the temporal dataset of the weather (precipitation, minimum and maximum air temperature, relative humidity, wind speed, and solar radiation). The DEM data were required to delineate the watersheds in the ArcSWAT interface. The soil and land cover data were important to define the HRUs. Supervised classification method was used for land use classification from satellite imagery of the June in 2018. General 18 types of land use in the ArcSWAT database are used as input data types to preparing land use data.

The model structure of SWAT requires continuous data for the whole watershed as well as information about depth-related soil properties. Due to the lack of adequate, affordable national soil data in Mongolia, the global soil dataset of FAO/UNESCO and global soil access database of MWSWAT were applied. Soil cover data is used from the International Soil FAO classification database. The FAO soil classification system distinguishes the 106 soil types of the world, and the 6 types of soil are dominant in study area.

Weather datasets are used to simulate the hydrological processes in SWAT. We applied two types of weather data, one for SWAT simulation and another for weather datasets validation process. The two weather datasets sources used were observed weather data from Ulaanbaatar, Terelj meteorological stations in Tuul river basin and weather datasets from the NCEP's CFSR (Climate Forecast System Reanalysis). The conventional weather has daily rainfall and average temperature from 2 climatic stations. It spans the period 2000-2014 with monthly. CFSR weather datasets includes rainfall, maximum and minimum temperature, wind speed, relative humidity, and solar radiation (Chinzorig, 2017) for 10 stations by day period. The CFSR weather is produced using cutting-edge data-assimilation techniques (both conventional meteorological gauge observations and satellite irradiances) as well highly advanced atmospheric, oceanic, and surface-modeling components at 38 km resolution (Saha et al., 2010).

Equations

In SWAT model, surface runoff volume was calculated by using a SCS curve number method initially developed by the Natural resource conservation service (USDA Soil conservation, 1972).

$$Q_{surf} = \frac{(R_{day}-I_a)^2}{(R_{day}-I_a+S)} = \frac{(R_{day}-0.2S)^2}{(R_{day}+0.8S)} \quad (1)$$

I_a is the initial amount of water that includes surface storage, canopy interception, and infiltration before runoff. S is the maximum soil moisture retention after runoff begins. I_a and S are determined with the runoff curve number CN.

CN had a range between 30 and 100 where values increase with runoff potential. CN is determined empirically and based on NRCS soil groupings, surface characteristics such as vegetation cover or impervious surface area, and antecedent soil moisture conditions (Lance Olot Le, 2015).

Potential and actual evapotranspiration were determined by the Penman-Monteith equation (Monteith, 1965).

$$\lambda E_t = \frac{\Delta(H_{net}-G)+\gamma*K_1*(0.622*\lambda*p_{air}/P)*(e_z^0-e_z)/r_a}{\Delta+\gamma*(1+\frac{r_c}{r_a})} \quad (2)$$

r_c, r_a are plant canopy and diffusion resistance, γ is the psychrometric constant, e_z^0, e_z are the saturation and water vapor pressure, p_{air} is the air density, K_1 is dimension coefficient, P is atmospheric pressure, λ is latent heat of vaporization, H_{net} is net radiation, G is the heat flux density to the ground (Jensen et al., 1990).

The SWAT in-stream water quality algorithms incorporate constituent interactions and relationships used in the QUAL2E model (Brown & Barnwell, 1987). The equations were used to determine the concentration of organic phosphorus, nitrogen, nitrate, and nitrite is given below.

$$\Delta orgP_{str} = \left(\alpha_2 * \rho_a - \beta_{p,4} * orgP_{str} - \sigma_5 * orgP_{str}\right) * TT \quad (3)$$

$$\Delta orgN_{str} = \left(\alpha_1 * \rho_a - \beta_{N,3} - \sigma_4 * orgN_{str}\right) * TT \quad (4)$$

$$NO_2 = \left(\beta_{N,1} * NH_{4str} - \beta_{N,2} * NO_{2str}\right) * TT \quad (5)$$

$$NO_3 = \left(\beta_{N,2} * NO_{2str} - (1 - fr_{NH4}) ** \alpha_1 * \mu_a\right) * TT \quad (6)$$

Statistical parameters for evaluation of model

R^2 is used to evaluate how accurately the model tracks the variation of the observed values. The difference between the NSE and the R^2 is that the NSE can interpret model performance by replicating individually observed values while the R^2 cannot (Green and van Griensven, 2008).

$$R^2 = \frac{\left(\sum_{i=1}^{n}(Y_{i,obs}-\overline{Y_{obs}})(Y_{i,sim}-\overline{Y_{sim}})\right)^2}{\sum_{i=1}^{n}(Y_{i,obs}-\overline{Y_{obs}})^2 \sum_{i=1}^{n}(Y_{i,sim}-\overline{Y_{sim}})^2} \quad (7)$$

Calibration of model performance

Model calibration is the adjustment of model parameters, within recommended ranges, to optimize the agreement between observed data and model simulation results (Tolson & Shoemaker, 2007). Furthermore, the SWAT mode, version 2005, has an embedded auto-calibration procedure that is used to obtain an optimal fit of process. This procedure is based on multi-objective calibration and incorporates the Shuffled Complex Evolution Method algorithms (Green & Van Griensven, 2008). SWAT-CUP stands for Calibration and Uncertainty Programs and is an automated model calibration tool for the SWAT model. This tool was developed by the aquatic research institute Eawag located in Switzerland (Abbaspour, 2015). SWAT-CUP is a public domain program and uses a generic interface. Different sensitivity analysis, calibration, validation and uncertainty analysis are possible within SWAT-CUP. Five different uncertainty algorithms (SUFI-2, PSO, MCMC, ParaSol and GLUE) are implemented in SWAT-CUP.

Results

Watershed delineation.

This watershed delineation resulted in the definition of 6 sub basins from above the outlet point. Outlet points had chosen coordination of Tuul-Altanbulag and Tuul-Ulaanbaatar gauging station.

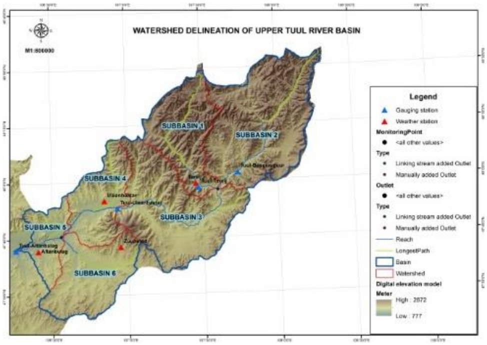


Figure 1. Watershed delineation of study area

Surface average elevation in the study area was 1694 meter, the highest point is 2672 m, and the lowest is 1165 meters. Total area of study is 8678.59 km^2.

HRU analysis result.

Land use reclassification. Figure 2 gives an overview about the spatial distribution of the 5 SWAT land use classes in study area. In the north east part of the catchment, the land use characteristic is clearly dominated by forest (almost 28% of area). As shown in table 1, also 28.3% of the watershed area is covered by range grass land, 16.5% in the urban areas, 16.0% in the agricultural land and 11.3% occupied by water bodies.

Table 1. Land use type by area

Land use type	Area, km^2	Area, %
Residential-URBN	1433.92	16.52
Water-WATR	981.53	11.31
Forest-Mixed-FRST	2414.69	27.82
Range grasses-RNGE	2459.72	28.34
Agricultural land-Generic-AGRL	1388.95	16.00

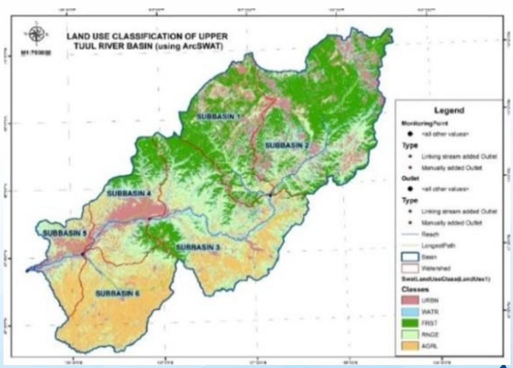


Figure 2. Classification of land use classes in Tuul river basin using SWAT model, percentage distribution of land use

Soil reclassification. The FAO soil classification system distinguishes the 106 soil types of the world, and the 6 types of soil are dominant in study area.

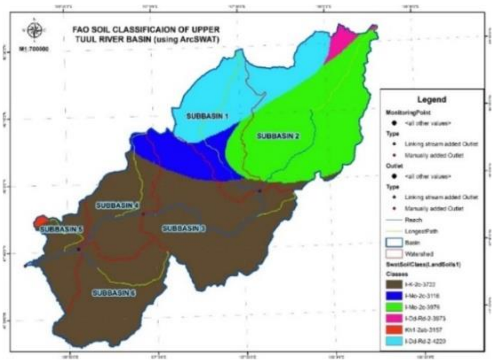


Figure 3. Soil classification of study area

Table 2. Dominant soil type by area

Soil type by FAO classification	Area, km^2	Area, %
I-Dd-Rd-2-3973	104.01	1.20
I-Dd-Rd-2-4220	1294.27	14.91
I-K-2c-3722	4435.05	51.10
I-Mo-2c-3116	642.35	7.40
I-Mo-2c-3976	2202.90	25.38

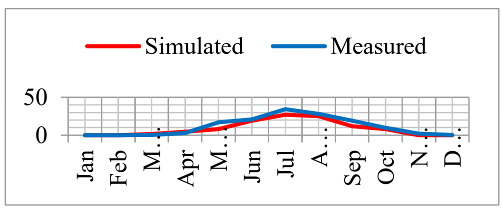
Surface flow estimation, calibration and validation.

The average flows in the Tuul river basin is given with 127.5 mm/year (Ministry of environment and green development, 2012), which shows a good correlation with the simulated flow (169.4-211.2) mm/year. The actual base flow factor is 0.25 (Davaa & Erdenetuya, 2004) at Tuul river basin which correlates well with the simulated base flow of 0.28 in the SWAT model. The reference ratio of streamflow and precipitation is 0.69 (Davaa & Erdenetuya, 2004) which shows good accordance with the simulated ratio of 0.8.

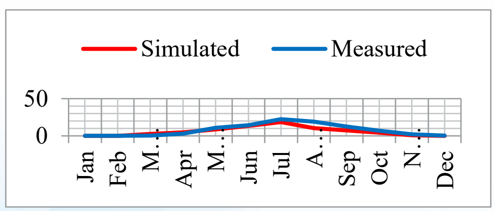
Table 3. Simulated hydrological water balance in SWAT model, with values of evapotranspiration, surface runoff and several hydrological ratios

Constituent	Unit	Simulated by SWAT
Water balance ratios		
Base flow/Total flow	-	0.28
Surface runoff/Total flow	-	0.72
Streamflow/Precipitation	-	0.8

Graph 1. Correlation between measured and simulated values of discharge (Tuul-Ulaanbaatar gauging station)



Graph 2. Correlation between measured and simulated values of discharge (Tuul-Altanbulag gauging station)



Discussion and conclusion

Using the Penman Monteith method for calculating evaporation of each sub basin, and also SCS curve number method is used for estimating surface runoff for each sub basin. In this study, calibration effort focused on improving model predictions of daily streamflow at the main watershed flow gauging station at Tuul-Ulaanbaatar and Tuul-Altanbulag. Daily streamflow observations at these stations for the period from January 1, 2005 to December 31, 2014 are available. And 3 year warm up period was used for minimizing the impacts of uncertain initial conditions in the model simulation. The correlation between the simulated and the measured flow rate is measured by r^2 was 0.75 in Tuul-Altanbulag hydrological station and r^2 was 0.67 at the Tuul-Ulaanbaatar gauging station. Based on the simulated flows value, phosphorus and nitrate concentrations in streamflow have been identified. Nitrate content was positively correlated with range between 0.5-0.7 with gauge station measurements. Phosphorus concentration is 0.16 non-dependents on the Tuul-Altanbulag station, which is related to the need to increase the number of source data and repeat the calibration. It is believed that this model can be used to calculate the surface flow and nitrate rate effectively.

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