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Scenario study of the effect of different land use to a sub-basin in Yeongsan River basin using SWAT model

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ABSTRACT

Land use and cover is one of the important factors that influence water flow within a watershed. Alteration of land use through time affects hydrological processes as well as the water budget in the watershed. In analyzing these processes that occur within basins and watershed, Soil and Water Assessment Tool (SWAT) is considered an indispensable tool. In this study, scenario analysis was done through the SWAT model by simulating stream discharge in a sub-basin in Yeongsan River Basin for the years 1990 (scenario 1) and 2000 (scenario 2). Input data in two scenarios were all the same except for the land use data. Land use data shows a decrease in forest and agricultural land area and increase in urban area from year 1990 to 2000. Developed models were evaluated to have acceptable performance since statistical parameters Nash-Sutcliffe efficiency (NSE) and ratio of mean squared error to the standard deviation of the measured data (RSR) in the validation for both scenarios are within the satisfactory rating limits. Water budget analysis showed an increase in annual average surface runoff and decrease in annual average evapotranspiration and lateral flow which is attributed decrease in forest and agricultural area and increase in urban area.

Keywords: Land use and cover; watershed; SWAT

1. Introduction

Hydrologic cycle is an important process that occurs within watershed allowing material flows in and out of the system. It is composed of certain processes within the watershed such as precipitation, evapotranspiration, runoff and storage in subsurface [1]. One of the most important modifications in water flow within a watershed is land use change (LUC). Water budget is modified according to land use. In a study [2], urbanization in Leipzig, Germany was linked to changes in water cycle in time frame between 1870 and 2007. Although the forest cover has not significantly changed for more than a century, there were significant changes in riparian wetland and grassland which has a considerable impact in the water cycle increasing the direct runoff as much as 182% for the time period. Urbanization activity involves increase in built-up area and subsequently increasing the impervious cover [2]. This has been the most important modification that affects water balance in urban areas. It has decreased lag time between precipitation input and discharge increasing the risk of flooding [3].

Another study [4], effects of LUC was also studied in Olifants Basin in South Africa at shorter time period, 2000–2013. Results also showed that there was an increase in surface runoff generation by about 47% resulting from decrease in rangeland and increase in urban, forest and agricultural lands. In some areas, urbanization is not the main land use change that can be observed.

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In South Korea, Yeongsan River is considered as one of the four major rivers, with an estimated length of 137 km and 3,468 m^2 basin area. Water flows at an annual average runoff of 2.7 billion cubic meters of water and receives an average of 1,318 mm of precipitation annually [5]. Watershed area is predominantly agricultural area of about 1,000 km^2 passing through Jeollanamdo province and Gwangju City [6]. However, through the years, arable area has decreased. In 1985, there was 600.12 million ha of arable land area but this has been reduced to 405.85 million ha in 2009 [7]. To assess effects of LUC in portion of Yeongsan River Basin, a sub-basin in the watershed was set as study area. SWAT model was used to simulate stream flow and determine water budget changes in the sub-basin from 1990 to 2000 using scenario analysis.

2. Materials and methods

2.1. Study area

The sub-watershed under study covers Gwangju City that is found within Yeongsan River Basin. Fig. 1 shows the location of the study area. The study area covers an area of 270 km^2 and is bounded by mountains in the east and agricultural areas in west [8]. The area receives an average annual precipitation of 1,391 mm with peak rainfall occurring in July while lowest amount of rainfall occurs during December with an average 33.5 mm which was based on climate data from 1981–2010 from Korea Meteorological Administration.

2.2. SWAT model simulation

The SWAT model was used for the scenario analysis in portion of Gwangju City located in a sub-watershed within Yeongsan River Basin. SWAT model simulation consists of three major steps which include data collection, simulation, and performance evaluation for each scenario. Different land use data were used in two SWAT model simulation in the years 1990 and 2000 through fix changing method that employs varying land use data while using same data for other factors such as digital elevation map, soil type, meteorological data and flow discharge monitoring data [4]. In this study, scenario analysis of different land use change data sets (1990 and 2000) were assessed in terms of changes in water budget in sub-watershed under study. An ArcSWAT version 2.3.4 software was used for the modeling, with the overall steps shown in Fig. 2.

2.3. Input data

The SWAT model simulation begins with gathering of database for topographical data, land use and soil map, meteorological data and monitoring data. Digital elevation model with a resolution of 30 m was used for the topographical data. For the land use map, land cover data for year 1990 and 2000 with resolution of 30 m were used as inputs. For the soil data, map from National Academy of Agricultural Science of Korea was used. These first three arrays of data were used as input to determine the different hydrologic response units (HRU) within the sub-basin wherein each unit has its distinct characteristics. On the other hand, meteorological data which consists of daily data on rainfall, temperature, solar radiation, relative humidity and wind speed from years 2000–2009 were used. Lastly, the daily monitoring data for stream discharge from 2000–2009 were used. These latter two arrays of data where then used as input data for each HRU where hydrology calculations are carried out. Calculations

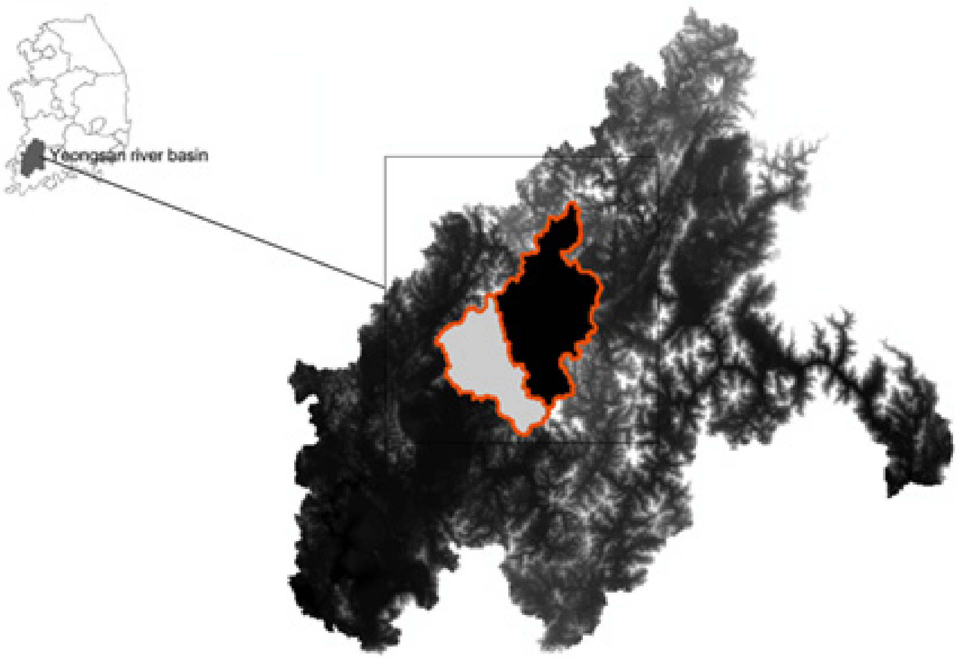

Fig. 1. Lower portion (grey) of sub-basin in Yeongsan River Basin under study.

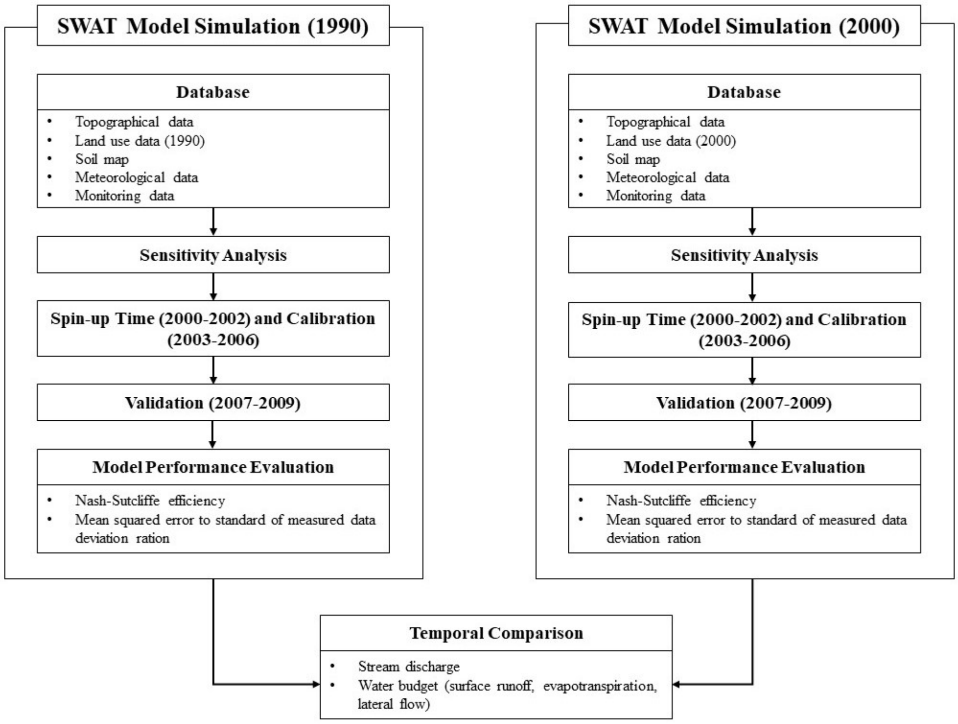

Fig. 2. Overview of scenario analysis using SWAT model in the sub-watershed in Yeongsan River Basin.

involve sensitivity analysis, calibration and validation where output simulations are stream discharge as well as water budget. From the arrays of data, scenario analysis was done using same set of data except for the land use. Table 1 shows description and source of database needed for SWAT modeling. These data were used as input in ArcSWAT software to obtain stream discharge simulation and values for water budget.

Table 1
Database collection

Data	Description	Source
Topographical data	Digital elevation model (DEM)	Ministry of Environment of Korea
Land use	Classification of land use in the area (1990 and 2000)	Ministry of Environment of Korea
Soil data	Soil property map in the area	National Academy of Agricultural Science of Korea
Meteorological data	Daily data on rainfall, temperature, solar radiation, relative humidity and wind speed from 2000–2009	Korea Meteorological Administration
Monitoring data	Stream discharge data (2000-2009)	Ministry of Environment of Korea

2.4. Sensitivity analysis

After the database has been updated, data output has gone through sensitivity analysis to determine which factors (see Table A-1 for list of ArcSWAT parameters) significantly influence the variability in the obtained values [9]. ArcSWAT Interface uses both Latin-Hypercube and One-factor-At-a-Time sampling method to maintain robustness but not sacrificing run time for the all the input data [10]. From the results of sensitivity analysis, 10 significant parameters out of 27 are used as input factors for calibration and validation procedures. This eliminates flow parameters which have insignificant impact in the model and hence decreases model complexity.

2.5. Model calibration and validation

Calibration and validation were then done to compare the actual observed values with simulated values from the model. Calibration process is undertaken to initially compare model output of stream discharge to the observed data through adjustment of parameters determined to be significant based from sensitivity analysis. ArcSWAT interface uses Shuffled Complex Evolution Algorithm in the process and Parasol mode enables setting of optimal calibration. Validation, on the other hand, is the process after significant parameters have been adjusted that determines the performance of the model by comparing the model output and observed data in time frame different from that used in calibration process [11,12]. In this step, optimal values from calibration were used as values for the significant parameters determined from sensitivity analysis. Simulation was done for the sub-basin with time frame from years 2000–2009 and was divided into three periods: spin-up time (2000–2002), calibration period (2003–2006) and validation period (2007–2009).

2.6. Evaluation of model performance

Model performance was evaluated using different statistical parameters namely Nash-Sutcliffe efficiency (NSE) and ratio of mean squared error to the standard deviation of the measured data (RSR). Nash-Sutcliffe efficiency describes the goodness of fit of the data obtained by comparing observed values with predicted values with variances while RSR is used to quantify index of error [13,14]. These two statistical parameters are commonly used for SWAT model evaluation. Table 2 shows the criterion values of each statistical parameters and their corresponding performance rating based on [14].

2.7. Temporal comparison of stream discharge and water budget

After the SWAT model evaluation, results of stream discharge and water budget simulation were then compared. Comparison includes result of most sensitive parameters in sensitivity analysis and values of hydrological parameters (surface runoff, evapotranspiration and lateral flow) based on the results of the SWAT model simulation for the two scenarios.

Table 2
Performance rating of model evaluation criteria for flow discharge

Performance rating	RSR	NSE
Very good	0.00≤RSR≤0.50	0.75≤NSE≤1.00
Good	0.50<RSR≤0.60	0.65<NSE≤0.75
Satisfactory	0.60<RSR≤0.70	0.50<NSE≤0.65
Unsatisfactory	RSR≥0.70	NSE≤0.50

3. Results and discussion

3.1. Sensitivity analysis of stream flow parameters

Sensitivity analysis of 27 flow parameters in that were built-in in ArcSWAT revealed the top 10 parameters, which were determined to significantly influence variability. For both 1990 and 2000 scenario analysis, these parameters were determined to be Alpha_Bf, Blai, Canmx, Ch_K2, Cn2, Esco, Gwqmn, Revapmn, Sol_Awc and Sol_Z. However, their rankings were different for 1990 and 2000. Table 3 shows flow parameter rankings as well as best parameter values obtained from calibration step for years 1990 and 2000 (see Table A-1 for parameter definition). These 10 parameters were then used for subsequent simulation for calibration and validation [13].

One of the notable changes from 1990 to 2000 is the change of ranking of the top two parameters which are Alpha_Bf and Cn2. Alpha_Bf is known as base flow alpha factor which describes response of groundwater flow to changes in recharge, indexed values that determine whether recharge is fast or slow. Fast response to recharge has value range of 0.9–1.0 while 0.1–0.3 for slow response to recharge. On the other hand, Cn2 represents initial runoff curve number. It is affected by certain soil properties such as permeability, land use and initial soil water conditions [11,15]. For 1990, Alpha_Bf was ranked as most sensitive parameter while it is Cn2 for 2000. This implies that response to recharge in 1990 affects stream flow more significantly compared to other parameters than it is in 2000. In the year 2000, it is Cn2 that has greatest influence among flow parameters. With LUC, there was a shift in most sensitive parameter from recharge influence to runoff influence.

3.2. Calibration, validation and model performance evaluation

Ten parameters chosen from sensitivity analysis were then used as input parameters for calibration and validation steps of SWAT model. Fig. 3 shows the plots of observed values and simulated values of the two scenarios that were generated by SWAT model as well as their model performance in terms of NSE and RSR.

From the figures shown, it is only the 1990 calibration that has unsatisfactory rating for all the statistical param-

Table 3
Sensitivity analysis results for flow parameters for 1990 and 2000

Rank	1990			2000		
	Parameter	Sensitivity value	Fitted value	Parameter	Sensitivity value	Fitted value
1	Alpha_Bf	0.18	0.98	Cn2	0.22	25.00
2	Cn2	0.16	25.00	Alpha_Bf	0.16	0.76
3	Gwqmn	0.12	–692.39	Esco	0.13	1.00
4	Esco	0.11	1.00	Gwqmn	0.11	–1000.00
5	Revapmn	0.05	8.06	Revapmn	0.06	32.80
6	Canmx	0.04	10.00	Sol_Z	0.03	–23.29
7	Sol_Z	0.03	–24.66	Blai	0.03	0.69
8	Sol_wAwc	0.02	–24.76	Canmx	0.02	0.04
9	Blai	0.02	0.00	Sol_Awc	0.02	–23.77
10	Ch_K2	0.02	149.92	Ch_K2	0.02	150.00

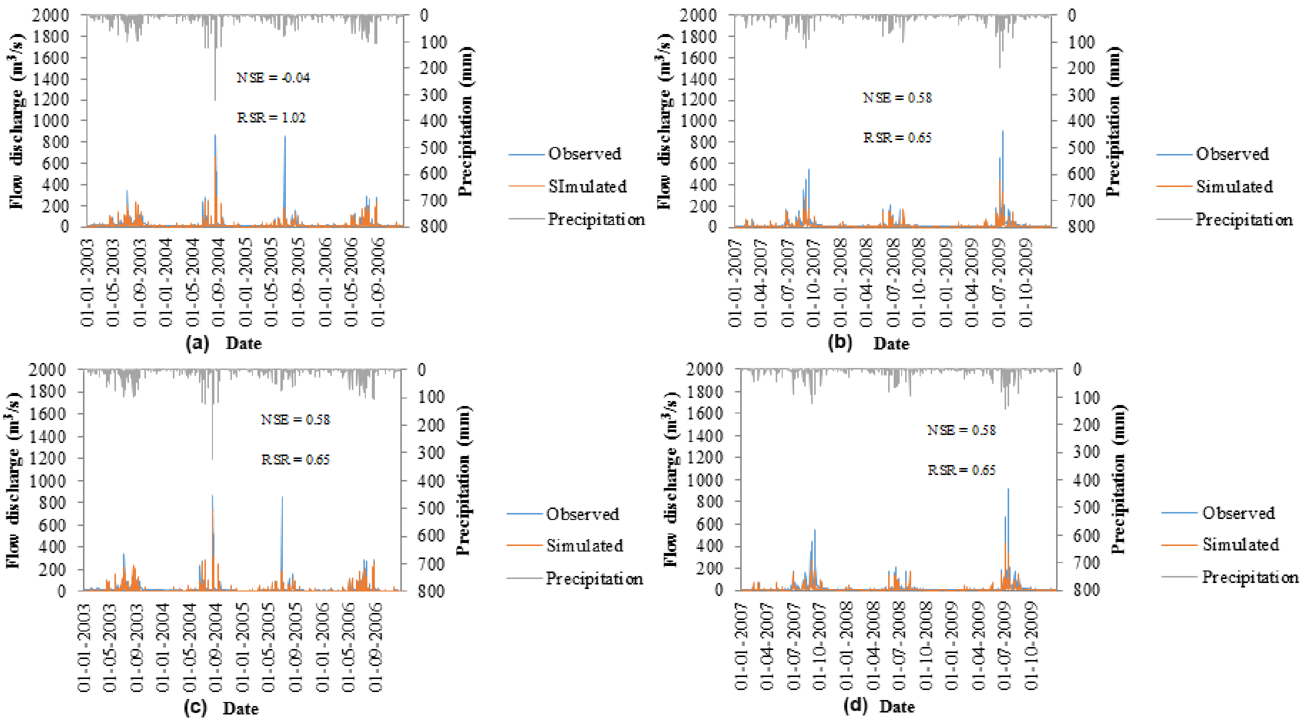

Fig. 3. Observed and simulated daily discharge for the sub-basin: (3a) calibration (1990 land use data); (3b) validation (1990 land use data); (3c) calibration (2000 land use data); and (3d) validation (2000 land use data).

Table 4
LUC and average annual sub-basin values of hydrological parameters in 1990 and 2000

		1990	2000	Difference
Land cover	Forest (% of Area)	35.76%	30.01%	–5.75%
	Agricultural	45.70%	39.14%	–6.56%
	Urban	17.57%	29.25%	+11.68%
Hydrological parameters	Surface runoff (mm)	1095.11	1198.76	+103.65
	Lateral flow (mm)	1.03	0.01	–1.02
	Evapotranspiration (mm)	264.3	233.8	–30.5

eters measured with values –0.04 and 1.02 for NSE and RSR respectively. Negative value of NSE implies that the model is unacceptable and hence, observed values are better predictors compared to the simulated value. RSR was also determined to have an unsatisfactory performance for the same period of calibration. Higher values of RSR imply that there is high root mean square error (RMSE) which is more acceptable if it has lower RMSE. However, after the calibration has done and parameter values were adjusted, NSE and RSR values of 0.58 and 0.65 resulted to satisfactory performance upon validation. For the year 2000, statistical parameters all have an acceptable range. For calibration period, values of statistical parameters are 0.56 and 0.66 for NSE and RSR respectively whereas in validation period, the values are 0.58 and 0.65. These values show that SWAT model developed has acceptable outputs. This is also supported by precipitation data in Fig. 3 wherein peaks in precipitation resulted to increase in discharge observed and measured. However, it was observed that simulated data underestimated high flow discharge which can be attributed to limitation in the empirical methods employed in model development, specifically Soil Conservation Service Curve Number method [16]. Nevertheless, the model predicted peak periods in synch with observed data.

3.3. Water budget and land use

For the study of changes in water budget, three hydrological parameters were calculated and obtained from the SWAT model namely, surface runoff, evapotranspiration, and lateral flow. These parameters were chosen based on previous studies that have been done relating these parameters to different land uses such as agricultural, urban and forest land uses. Table 4 shows the LUC and average annual sub-basin values of these hydrological parameters in different land use data.

Increase in surface runoff from 1990 to 2000 can be attributed to increase in urban area by 11.68%, as shown in Table 4. According to [2], urbanization activity involves increase in built-up area and hence increasing the impervious cover. Subsequently, water moves within the sub-basin as surface runoff. This is also the reason in the abrupt decrease in lateral flow from 1990 to 2000. With lesser area available for water to penetrate through the surface, lateral flow is also reduced. Gyamfi et al. [4] found positive correlation of surface runoff with urban and agricultural areas. This was supported by another study conducted [17] wherein there was a decrease in forest land area and increase in built-up area – the same scenario that occurred from 1990–2000 in this study.

A decrease in evapotranspiration was also simulated from 1990 to 2000. This is a result of decrease in forest and agricultural area from 1990 to 2000. Evapotranspiration is a process that is primarily governed by evaporation from land surface and plant processes. Gyamfi et al. and Kim [4,5] observed increasing evapotranspiration with increase in forest and agricultural area. Moreover, urban areas are negatively correlated to evapotranspiration [5]. Hence, the observed decrease in evapotranspiration is suggested to have resulted from the decrease in forest and agricultural area and increase in urban area.

4. Conclusion

Using long-term meteorological and stream discharge monitoring data as well as land use, topography and soil map of a sub-basin in Yeongsan River Basin, we have tested, calibrated and evaluated the performance of SWAT model in two scenarios (1990 and 2000). Performance evaluations suggest that the SWAT model has satisfactorily simulated stream discharge based on statistical parameters RSR and NSE. The model also quantified the relative changes in hydrological parameters where LUC played an important role in the observed changes in water budget of sub-basin in Yeongsan River. Increase in annual average surface runoff, and decrease in annual average evapotranspiration and lateral flow are found to be attributed to the decrease in forest and agricultural area, and an increase in urban area. It is recommended that these results may be used for the monitoring flood-prone areas in river basins.

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Appendix

Table A1
Definition of flow parameters from sensitivity analysis

Flow parameter	Process	Definition
Alpha_Bf	Groundwater	Baseflow alpha factor (days)
Blai	Crop	Leaf area index for crop
Canmx	Runoff	Maximum canopy index
Ch_K2	Channel	Effective hydraulic conductivity in main channel alluvium (mm/h)
Cn2	Runoff	Initial curve number
Esco	Evaporation	Soil evaporation compensation factor
Gwqmn	Soil	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)
Revapmn	Groundwater	Threshold depth of water in the shallow aquifer for percolation to deep aquifer (mmH_2O)
Sol_Awc	Soil	Available water capacity of the soil layer (mm/mmsoil)
Sol_Z	Soil	Maximum canopy index soil depth