Aceh Int. J. Sci. Technol., 5(3), 116-125
December 2016
doi: 10.13170/aijst.5.3.5762

Aceh International Journal of Science and Technology
ISSN: 2088-9860
Journal homepage: http://jurnal.unsyiah.ac.id/aijst

Modeling hydrologic response to land use and climate change in the Krueng Jreu sub watershed of Aceh Besar

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Received : October 17, 2016
Accepted : December 24, 2016
Online : December 29, 2016

Abstract - Water resources are highly vulnerable due to climate and land use change. This study aims to simulate land use and climate change impacts on water resources of the Krueng Jreu subwatershed using Soil and Water Assessment Tool (SWAT) model. The subwatershed, located in Aceh Province Indonesia, is a primary source of water for a 233.52 km² paddy field area. The results showed that the model performance was considerably good in predicting streamflow. The coefficients of determination varied between 0.58 and 0.72, while the Nash-Sutcliffe coefficients (ENS) ranged between 0.65-0.72 and the percentage bias was in the range of -0.36 to 2.30. The model predicted increases in both runoff and water yield by 1% and 0.1% respectively as the result of increasing 15% settlement area. When all agricultural lands within subwatershed were converted to forest, water yield would increase by 1% during dry periods and runoff contribution would decrease by 5%. Increases in surface flow by 23.6% and water yield by 15.1% were found under the scenario of increasing 10% of daily precipitation. Increasing in evapotranspiration caused by an increase of 1.5^{0}C in daily air temperature would decrease surface flow and water yield by 0.8% and 1.3% respectively. Combination scenarios of changes in daily temperature and precipitation would increase evapotranspiration rate, annual water yield and runoff contribution.

Keyword: Climate change, land use change, hydrologic response, SWAT model, Krueng Jreu Subwatershed.

Introduction

Climate change is an accumulation of the impacts of humans in the long run. Naturally the world's climate has always fluctuated, but human activities have made this process into something that is not natural. Industrial activities such as logging and burning have been releasing carbon into the atmosphere thereby increasing the temperature of the earth as one of the greenhouse effect. The global mean surface air temperature has risen by an estimated 0.4°-0.8°C (Houghton *et al.,* 2001). This condition is exacerbated by rampant deforestation to provide new land for agriculture, housing and industries.

The deforestation rate in Indonesia is relatively high. According to UNDP (2007), Indonesia's forests have reduced from 129 million hectares in 1990 to 82 million hectares in 2000 as result of deforestation, which is about 600,000 ha per year. Meanwhile, Greenomics Indonesia noted that within period of 2002-2004, illegal logging in Aceh Province reached 200,000 Ha (Serambi Indonesia, 2006).

Land use and climate change will eventually return to threaten human life and environments. Studies have shown that water resources are highly vulnerable to these changes (Gosain et al, 2006; Heuvelmans et al, 2005; Bouraoui et al, 2004 dan Legesse et al, 2003). However, these impacts vary from one location to another due to their characteristics such as climate, landscape, soil, and socio economic status. It is important to quantify the impacts of land use and climate change on specific locations rather than to generalize them to better understand the response and provide accurate information for proper mitigation management.

The application of hydrologic model is one way to investigate the impact of land use and climate change because modeling offers an effective approach to reduce cost and time consumption for long term analysis. In general, spatially distributed hydrologic models have been widely used to quantify the impact of changes in watershed. The Soil and Water Assessment Tool (SWAT) model is one of most common hydrologic model used to quantify the watershed response to the land use and climate changes. Generally, applications of SWAT model were driven by the need of government agencies to evaluate the impacts of anthropogenic, climate and other changes on water resources (Gassman *et al.,*, 2007). However, lack of data is a major barrier in application of the SWAT model.

During rehabilitation and reconstruction in Aceh, the Aceh Government and NGO's intensively developed spatial data for the entire Aceh Province, especially to the tsunami affected areas, therefore the spatial data in Aceh is considerably the most complete in Indonesia. Unlike spatial data, hydrologic and climatologic data were not enhanced since the last few decades. Until now, only four stations are active and continuously record climatic data in Aceh Province. The hydrologic data are even worse; only 4 gauging stations are available and active for the entire Aceh Province. These stations have been recording daily streamflow data since 2008. Considering most of watersheds in Aceh are dominated by agriculture and plantation activities, the threat on water resources in the future becomes greater, therefore an evaluation of land use and climate changes impact is essential.

The goals of this study were to develop SWAT model for Aceh's watershed; to evaluate the model performance and to simulate land use and climate change impacts on water resources. Since SWAT is a data intensive model, application of this model is one big challenge due to the data availability issue, particularly in the Aceh Province. Another challenge is to provide information that could benefit local stakeholders to evaluate water resources management program in the study area.

Materials and Methods

SWAT Model

SWAT is a physically based, continuous time model developed by United States Department of Agriculture – Agricultural Research Service (USDA-ARS) to predict the impacts of land management practices on hydrology, sediment and agricultural chemical yields in large and ungauged basins (Arnold *et al.*, 1998). The model initially separated the watershed into sub watersheds which are then further lumped together into homogenous units, called hydrologic response units (HRU), at which all the hydrologic processes are simulated.

Hydrologic processes are generally divided into upland and stream components (Fohrer *et al.,*, 2005; Govender and Everson, 2005). The upland component simulates movement of water, nutrients, sediment and pesticides to the main channel in each subbasin based on a mass balance approach. The stream component simulates the water flow in channels to the watershed outlet using the variable storage coefficient and Muskingum routing methods. The water balance in SWAT is calculated as (Neitsch *et al.,*, 2002):

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \right) \quad (1)$$

Where, t is the daily time step, SW_0 and SW_t are the initial and current soil water content, R_{day} is precipitation on day i, Q_{surf} is surface runoff on day i, E_a is evapotranspiration on day i, W_{seep} is percolation on day i, and Q_{gw} is amount of return flow on day i.

The surface runoff is calculated by using either the Soil Conservation Service (SCS) Curve Number (CN) for daily time step or the Green Ampt infiltration method for sub-daily time step. To estimate the potential evapotranspiration, SWAT provides three methods i.e. Priestley-Taylor, Penman-Monteith and Hargreaves. Continuous downward flow or percolation will occur only if the soil's water holding capacity is exceeded. The water that flows downward below the root zone is considered lost from the watershed until it appears again as return flow (Arnold *et al.,*, 1998).

The model requires climate input including precipitation, minimum and maximum air temperature, relative humidity, wind speed and solar radiation. Those climate variables could be recorded data from weather stations or generated by the model. The model uses the WXGEN weather generator model to generate climatic data or to fill in gaps in measured record (Neitsch *et al.,*, 2002).

Study Area

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Krueng Jreu Sub Watershed (KJSW) was selected in this study to evaluate SWAT performance and to investigate land use and climate change impact on water balance (Figure 1). The subwatershed, which lies between latitudes of 5°12'29.5" to 5°23'57.5" N and longitudes of 95°21'49" to 95°30'45.2" E, is part of Krueng Aceh Watershed that provides fresh water for people in Banda Aceh City (i.e. capital of Aceh Province) and Aceh Besar District. The water resources in KJSW are primarily used for irrigation collected by a near reservoir outlet and delivered through a permanent surface irrigation system for 233.52 km^2 of paddy field area.

According to Forest and Water Area Designation Map issued by Indonesian minister of forestry and plantation in 2000, 86% of KJSW area is designated for protected forest. However based on the 2009 land use map collected from Krueng Aceh Watershed Management Agency (BPDAS Krueng Aceh) the forest area within KJSW is approximately 57%, while the rest of KJSW is dominated by agricultural land (23%) and shrub land (18%).

Two flow gauging stations were found within the study area. The first station, located at Krueng Jreu River, is the outlet of the 166.14 km^2 drainage area (SW1). This station has recorded data for 1992, 1995 and 1996. Another station, situated at the Krueng Meulesong River, having approximately 5.52 km^2 drainage area (SW2), is a new flow station established and operated by Krueng Aceh Watershed Management Agency (BPDAS Krueng Aceh) since 2008.

Input Data

Daily precipitation, minimum and maximum air temperature, relative humidity and wind speed data were collected from local weather station (Indrapuri Weather Station). The daily solar radiation data was derived from air temperature differences using the Hargreaves' radiation formula. Daily dew point data was calculated from temperature and relative humidity. Monthly statistics of user weather station were computed using the available excel macro called wxgen.

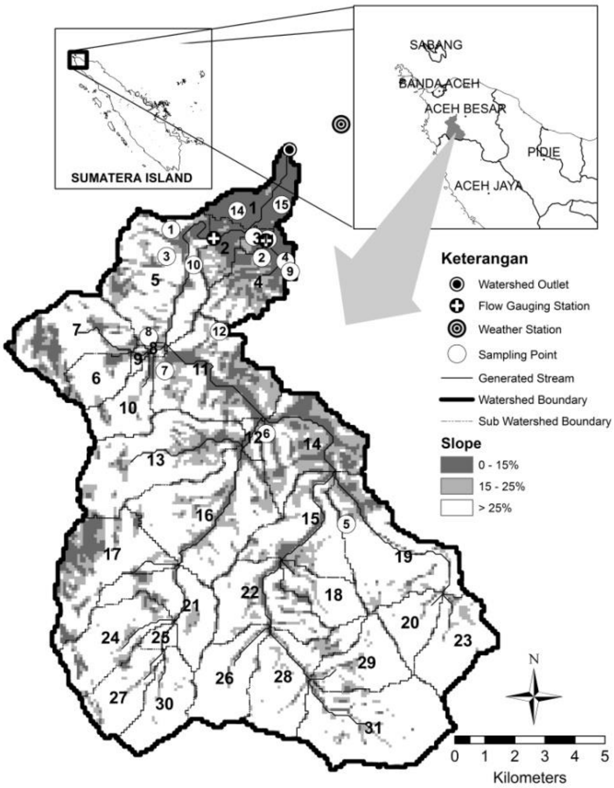

Figure 1. Krueng Jreu Sub Watershed, Aceh Besar District, Province of Aceh.

Soil properties including texture, bulk density, organic carbon, saturated hydraulic conductivity and electric conductivity were measured at 15 locations within KJSW (Figure 1). A 3 arc second of Shuttle Radar Topography Mission (SRTM) digital elevation model, downloaded from CGIAR-CSI GeoPortal (http://srtm.csi.cgiar.org), was used as the elevation input for watershed and stream network delineation as well as slope estimation. A 2009 land use land cover map classified the study area into five classes including settlement, water body, forest, shrub land, grassland and agricultural land which was obtained from BPDAS Krueng Aceh.

Scenarios

In this study, scenarios were simulated using best fit model for 8 years with 2 years warm up period. The scenarios were 1) increasing 15% settlement area (LU1); 2) converting all agricultural land to forest (LU2); 3) increasing 10% daily precipitation (CC1); 4) increasing 1.5 degrees to daily temperature (CC2); and 5) combining scenario 3 and 4. These scenarios were then compared to one simulated under existing conditions for the period of 1993-2000 called as the control scenario. For LU1 scenario, additional settlement areas were selected within agricultural or grassland areas having a slope less than 10%.

Results and Discussion

Model Development

SWAT divided a 17,836.51 Ha total area of KJSW into 31 sub watersheds based on 297 Ha of minimum area for river generation and 2 manually added points for flow gauging stations. Sub watershed areas range from 34.29 Ha up to 1,240.6 Ha. These sub watersheds were then segregated into 161 lumped units called hydrologic response units (HRU) based on soil type, topography and land use. The number of HRU varied from 1 to 13 for each sub watershed. The final sub watershed was occupied primarily by forest (69.42%) shrubland (15.08%), agricultural land (14.26%), grassland (0.73%) and settlement (0.51%).

Model Performance

The model was calibrated both manually and automatically with monthly stream flow recorded at two flow gauging stations. The observed streamflow data from two flow gauging stations within the watershed were used in the calibration process. The first station has 3 years of recorded data (1992, 1995 and 1996) and was used to calibrate streamflow produced by SW1 area while another station with 2 years of data starting from 2008 was used for SW2 area. Due to the flow gauging station locations, there was 3.76% (670.46 Ha) KJSW area which remained uncalibrated. Before calibration, a sensitivity analysis was performed on model parameters to find the 10 most sensitive flow affected parameters. The selected parameters were the parameters that affect the surface water response (Cn2; Sol_Awc; Esco), sub surface water response (Alpha_Bf; Gw_Delay; Gw-Revap; Gwqmn), and watershed response (Ch_K2;Ch_N2; Surlag).

Table 1 presents the sensitivity rank, description, initial and the best value for each parameter based on selected criteria for model performance evaluation.

Table 1. Description, initial and final values of selected parameters based on sensitivity rank

Rank	Model Parameter	Description	Value		
			Initial	Range	Best*
1	Ch_K2	Channel effective hydraulic conductivity	0	0 - 150	112.7/ 150
2	Ch_N2	Manning's value for main channel	0.035	0.023-0.05	0.03/ 0.045
3	Cn2	SCS CN for antecedent moisture condition II	default	+/- 10	+3 /-10
4	Surlag	Surface runoff lag time	4	1-24	7.9
5	Sol_Awc	Available water capacity	default	+/- 0.04	-0.01/- 0.03
6	Esco	Soil evaporation compensation factor	0.95	0 - 1	0.95
7	Alpha_Bf	Baseflow alpha factor	0.048	0 – 0.3	0.01
8	Sol_K	Saturated hydraulic conductivity	default	-/+ 50%	default
9	Gw_Delay	Groundwater delay	31	+/- 10	-2.4
10	Gw_Revap	Groundwater "revap" coefficient	0.02	+/- 0.036	-0.02

*First value for SW1 and second one for SW2, if only single value is presented then it for both areas

Model performances were evaluated by using three commonly used criteria, coefficient of determination (R^2), Nash-Sutcliffe coefficient (E_{NS}) and percent bias (P_{BIAS}). The parameters were adjusted manually such that the E_{NS} value reaches 30% prior to automatic calibration. The final statistical parameter values are tabulated in Table 2. The model performance was considerably good in predicting streamflow recorded at two flow gauging stations. Overall, the calibration using Krueng Meuleusong River station was slightly lower than Krueng Jreu River station.

Table 2. Model performance evaluation using streamflow data recorded at two flow stations

Stations	Drainage Area (km²)	E_{NS}	R^2	P_{BIAS}
Krueng Jreu River (KJR) – SW1	166.14	0.72	0.72	2.30
Krueng Meuleusong River (KMR) – SW2	5.52	0.65	0.58	-0.36

Figure 2 presents the observed and simulated monthly streamflow for both stations. Even though, in general, the model predicted flow variation relatively well, it failed to accurately simulate the flow for both low and high flow months. This fact is clearly shown in Figure 2b which the model tried to simulate flow at SW2 Station. The model had over predicted at the first year monthly flows while it is then under predicted at second year flows.

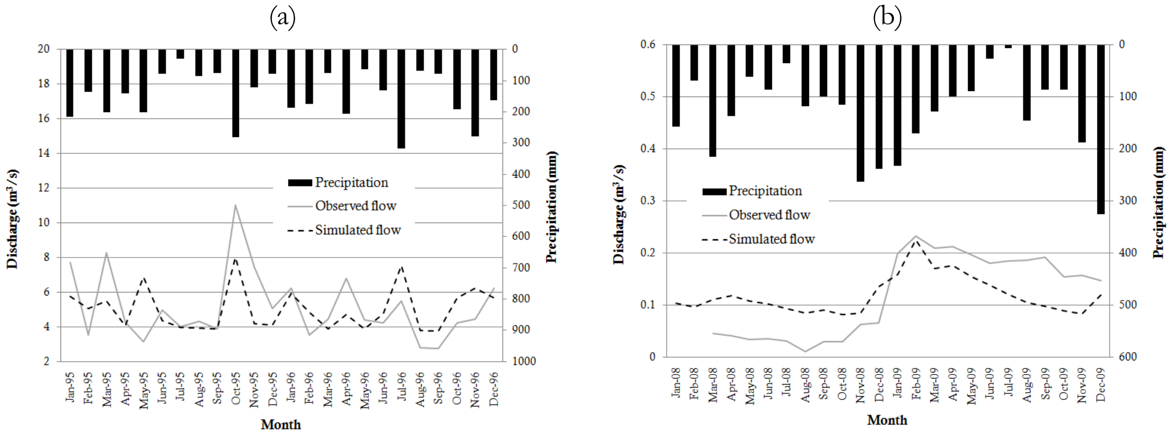

Figure 2. Monthly observed and simulated streamflow for (a) Krueng Jreu River gauging station and (b) Krueng Meuleusong River gauging station.

Both figures show monthly observed precipitation collected at the nearest weather station. The figures reveal a lack of a relationship between the recorded precipitation and the observed streamflow. Inconsistent trends were found during the calibration period. There were some months with higher precipitation but produced less streamflow, for example in May 1995; February, July, and November 1996. Additionally, similar occurrences of precipitation recorded on October 1995 and November 1996 produced a contradictive amount of streamflow. However, since 93 % of area was calibrated with the result of E_{NS} which is greater than 0.7, the model was considerably acceptable in representing the whole hydrological processes of KJSW.

Water Balance Krueng Jreu Sub Watershed

From the simulation results, we can conclude that KJSW has an average annual precipitation of 1632 mm within the period of 1993 to 2000. More precipitation occurred during October to January ranging from 76.7 to 213.8 mm. May to September is the drier period caused by low precipitation and high potential evapotranspiration. November was the wettest month while August was the driest month of the year.

The model predicted that the average annual water yield of KJSW is 945.33 mm with ± 30% contribution coming from runoff. Monthly evapotranspiration ranged from 37.46 to 92.79 mm and the average annual evapotraspiration was 644.7 mm. August and September was the period with least water produced by watershed due to low precipitation and high potential evapotranspiration. Distribution of monthly water balance components, including runoff, water yield and evapotranspiration is illustrated in Figure 3.

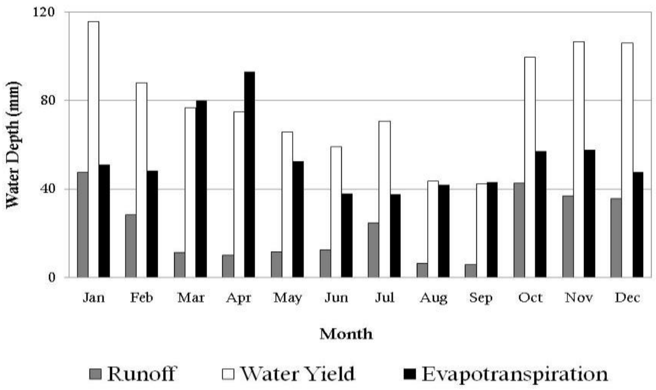

Figure 3. Average monthly runoff, water yield and evapotranspiration of Krueng Jreu sub Watershed for the period of 1993-2000.

Land Use Change Impact

Land use changes were simulated by increasing 15% of the settlement area (LU1) and converting agricultural land into forest area (LU2). Figure 4 shows the percentage of annual deviation for baseflow, runoff, water yield and evapotranspiration for both land use scenarios.

Under LU1 scenario, SWAT predicted increases in runoff (1%) and water yield (0.1%), and decreases in baseflow (0.32%) and evapotranspiration (0.1%). An increase in runoff and a decrease in baseflow were the results of more effective water collecting and conveying system under the presence of settlement area.

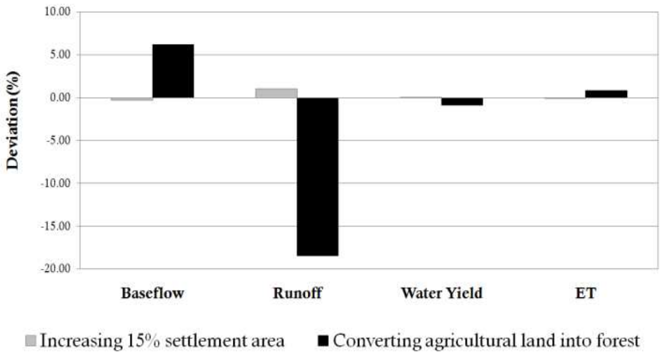

Figure 4. Deviation of annual water balance for land use change scenarios

However, increase in water yield did not occur throughout the year, particularly during the dry period such as May, June, July and August (Figure 5). During those periods more precipitation was used to substitute soil water depletion caused the decrease in monthly water yield by an average 0.05 mm. Although, the decline in water yield is insignificant, LU1 scenario increases monthly runoff contribution to water yield both in the wet (0.4%) and the dry season (0.3%) implying the threat to water quality is getting higher.

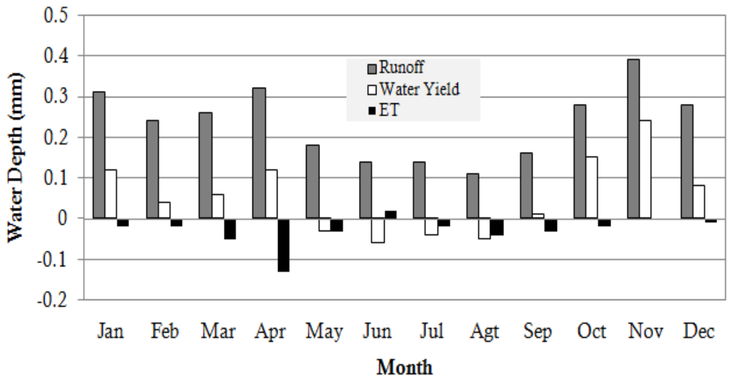

Figure 5. Monthly average water balance deviation under scenario of increasing 15% settlement area.

Contrary to LU1, under LU2 the KJSW landscape returned to its natural condition by converting agricultural land to forest. The forest covered area is an effective soil water storage because water can easily be absorbed by soil. The movement of water through soil pores increases the time of water to reach the drainage system therefore increasing area covered by forest, which in turn will increase base flow. Under LU2 scenario, the model predicted decreases the annual runoff by 18.4%, and annual water yield by 0.9%. Meanwhile annual baseflow and evapotranspiration increases by 6.18% and 0.8% respectively (Figure 6). An increase in baseflow decreased contribution of runoff to water yield by 5%.

From Figure 6 we can see that the monthly runoff had decreased throughout the year meanwhile monthly water yield had increased by 1% during the dry season but had decreased by 1.6% during the wet season. This finding implies that converting 2,500 Ha of agricultural land into forest will increase daily streamflow by 0.03 m^3/s during the dry season with the minimum monthly flow of 3 m^3/s.

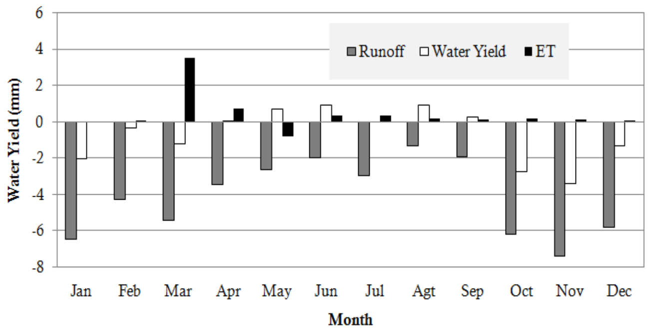

Figure 6. Monthly average water balance deviation under scenario of converting agricultural land into forest

Climate Change Impact

Scenarios under climate change were conducted by increasing 10% in daily precipitation (CC1); increasing 1.5^{0}C in air temperature (CC2) and a combination of CC1 and CC2 (CC3). Water balance components under those scenarios were compared to the control scenario as it shown on Figure 7.

The figure 7 shows that increasing precipitation (scenario CC1), under the same temperature condition, would increase runoff, water yield and evapotranspiration. The SCS Curve Number used in SWAT for daily runoff generation suggested without any changes in soil characteristics, increasing precipitation will produce more runoff. When more water is in the system, the more water will be evaporated through evapotranspiration causing an increase in evapotranspiration by 2.3%. The runoff and overall water yield increased by 23.6% and 15.1%, respectively while a 2% increase in runoff contribution to the water yield occured.

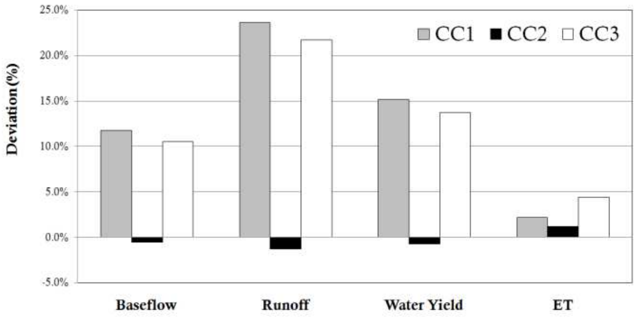

Figure 7. Deviation of annual water balance for climate change scenarios

Surface air temperature is a good estimator on how much solar radiation reaches the earth surface. The more solar radiation the higher the air temperature and the more energy for evaporation is available. SWAT predicted an increase of 1.3% of evapotranspiration as a response to the 1.5° daily temperature increase. Compared to CC1 scenario, in this scenario, the model predicted an increasing 4.2% of potential evapotranspiration but since there was no change in water availability, less water evaporated to the atmosphere. The increase in potential evapotranspiration causes more water in soil storage to be evaporated. The water which entered the system through precipitation was initially used for soil storage; therefore CC2 scenario produced less runoff and baseflow. Under the same precipitation pattern, the model predicted decreases in water yield (0.8%) and runoff (1.3%) when average daily temperature is increased by 1.5°.

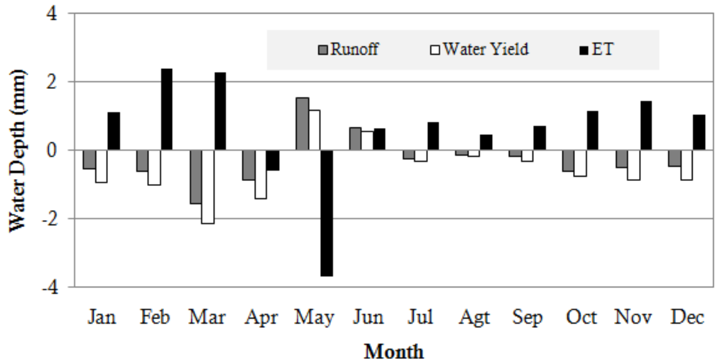

Figure 8. Monthly average water balance deviation under scenario of 1.5^0 increase in air temperature.

Figure 8 displays monthly water balance deviation for the CC2 scenario. From the figure, the decreases in runoff and water yield were found in all months except in May and June. The increases in those months were caused by the decreases in evapotranspiration during April and May. Analysis on baseflow suggested that CC2 scenario would decrease monthly baseflow. However, the decrease in runoff increased the contribution of baseflow to water yield by 0.2%.

The impact of an increase in precipitation and air temperature were simulated under CC3 scenario. Simulation results suggested that the scenario increased all observed water balance components including baseflow (7.5%), runoff (21.7%), water yield (13.7%) and evapotranspiration rate (4.4%). In general the impacts of the CC3 scenario on water balance components were slightly lower but had a similar trend to the impacts of the CC1 scenario.

In general, increasing the precipitation will increase surface and base flow. The percentages of surface flow contributed to the total water yield for climate change scenarios are shown in Table 3. The model predicted contribution of surface runoff to the total water yield increased with the increase in precipitation. The increase of runoff fraction in the water yield suggested that less water had been transferred through soil; therefore producing a drier soil condition that lead to higher potential of agricultural drought. More runoff will have significant impact on water quality and soil erosion as well. Furthermore, in order to have more efficient water utilization, it is important to improve existing or generate a new more effective surface water collecting system.

Table 3. Contribution of runoff to water yield under climate change scenarios

Scenarios	Runoff contribution
No change in climate variables	28.7%
Increase 10% in daily precipitation (Scen 1)	30.8%
Increase 1.5° in daily temperature (Scen 2)	28.5%
Combination scen1 and scen2 (Scen 3)	30.7%

Conclusions

SWAT model was applied to simulate the impact of land use and climate change on water balance in the Krueng Jreu Sub Watershed, Aceh Besar district. The model was good enough to predict streamflow recorded at two stations located on the River Krueng Jreu and Krueng Meuleusong based on analysis on the models performance. The coefficients of determination varied between 0.58 and 0.72, while the Nash-Sutcliffe coefficients (E_{NS}) ranged between 0.65-0.72 and the percentage bias were in the range of -0.36 to 2.30. Under land use change scenarios, the model predicted increases in both runoff and water yield as the impacts of increasing 15% of settlement area. Converting all agricultural land (14.26% of watershed area) into forest increased water yield during the dry month period by approximately 1% and decreased runoff contribution to water yield by 5%. The increases in runoff (23.6%), water yield (15.1%) and evapotranspiration (2.3%) were found under the scenario of 10% increase in precipitation. The model also predicted an 1.2% increase in annual evapotranspiration and the decreases in both runoff (1.3%) and water yield (0.8%) as the response to the 1.5 ° increase in daily air temperature. A combination of increasing 10% in daily precipitation and 1.5^{0}C in daily air temperature caused increases in all observed water balance components.

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