Land use planning for water resource conservation in the Krueng Aceh watershed, Indonesia

Bos A. Muis

Faculty of Agriculture, Teuku Umar University, Meulaboh, Aceh Province, Indonesia. Corresponding author: B. A. Muis, bosariadimuis@utu.ac.id

Abstract. Flooding in the wet season and drought in the dry season has caused it difficult to fulfill the water needs of the people living in the Krueng Aceh Watershed. This indicates that land use is not yet in line with the principles of soil and water conservation. The purpose of this study was to create an alternative land use for water resource conservation in the Krueng Aceh Watershed through a hydrological modeling approach by predicting the surface runoff volume and by using the soil conservation service method. The results of the study demonstrated that the use of land for the development of 37,815.54 ha of mixed dryland agriculture in the Krueng Aceh Watershed could reduce the surface runoff by 211.52 mm or 23.46% of the current land use condition. It could also increase the infiltration capacity by 53.96%, preventing the rainwater falling to the ground from immediately becoming surface runoff, but undergoing an infiltration and percolation process first.
Key Words: DAS Krueng Aceh, hydrological modeling, land use change, soil and water conservation.

Introduction. Watersheds have an important role as a rainwater reservoir, storing and channeling water in quantities, quality, and continuity for the people living downstream (Muis et al 2017). The dynamics of development lead to inevitable changes in land use to pursue economic growth (Cosgrove 2015). Land use shifts from forests to agricultural land will occur (Sandrasekaran 2017). Many watersheds in Indonesia have suffered from damage, including the Krueng Aceh watershed. Rainwater that falls in the Krueng Aceh watershed is not infiltrated much so that it becomes surface runoff, resulting in fluctuating river discharge. One of the efforts that can be made to prevent further damage is through water resource conservation.

Not all water resource conservation techniques are suitable for all watersheds because they each have their own characteristics (Price 2011; Muis 2017) and are influenced by the climate, topography, type of soil, land use, vegetation, and shape of the watershed (Trigunasih et al 2018). The precipitation rate strongly influences the volume of water that will become the basis for planning the water resource conservation technique (Nsubuga 2014). Through a hydrological modelling approach that is appropriate with the Krueng Aceh watershed's biophysical conditions, it is hoped that land use planning in order to use the land according to its functions and the management would be easier (Loucks & van Beek 2017).

The purpose of this study was to formulate an alternative land use planning for water resource conservation in the Krueng Aceh watershed. The three scenario models applied were scenario I based on the land use of the Krueng Aceh watershed used in 2014. Scenario II implemented the land coverage according to the 2012-2032 Aceh Besar Regency Regional Spatial Plan. Scenario III was formulated based on a regression model of the land use changes in the Krueng Aceh watershed. The results of the modeling with the least surface runoff volume was selected as the scenario to be recommended as an effort to overcome the water scarcity issue in the Krueng Aceh watershed.

Material and Method. The present study was conducted from September to December 2017, located in the Krueng Aceh watershed, Aceh Province, Indonesia. The area where the study was conducted covered 197,903.62 hectares. It is geographically situated at $5^o03'41''$-$5^o38'10''$N and $95^o11'41''$-$95^o49'46''$E (Figure 1).

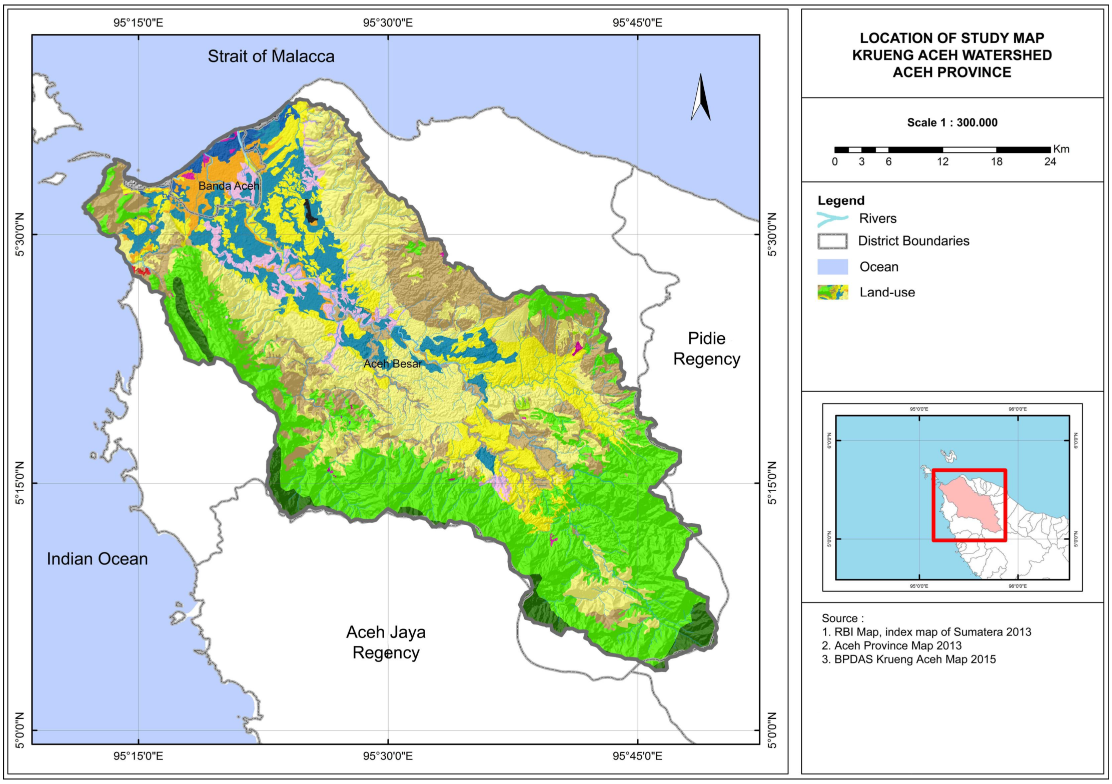

Figure 1. Location map of Krueng Aceh Watershed in Aceh Province, Indonesia.

The materials used were a digital map of the Aceh Province, a topographical map, and a land use map at a scale of 1:100.000, soil type map was at a scale of 1:250.000 and the map Aceh Besar Regency Regional Spatial Plan of 2012-2032. The data required were the daily precipitation rate data for 2014 from the Indrapuri Agency of Meteorology, Climatology, and Geophysics and the 2014 Krueng Aceh River debit data from Station I Center for Sumatran River Areas, Kampung Darang observation station. The data were analyzed using the ArcGIS 10.2 software. The equipment used to measure the infiltration was the double ring infiltrometer in accordance with ASTM D3385 and a global positioning system to determine the coordinates of the soil sample collection and infiltration measurement sites. The current study was conducted using the survey method which began with the data collection phase followed by the data analysis and land use modeling scenario formulation.

Data collection. The initial phase required biophysical data of the land which were collected through analysis of the land coverage, the slope, elevation, and types of soil using the ArcGIS 10.2 software. The analysis resulted in a land use map, a slope map, an elevation map, and a soil type map of the Krueng Aceh watershed. The four maps were then overlaid to produce a land unit use map. The next step involved a ground check to the study location. If it is suitable, the land unit use map was used as a guideline to determine the actual land use condition, the infiltration measurement location points, and to collect soil samples.

The second phase required hydrological data which were collected by directly measuring infiltration in the field. The technique to determine the infiltration measurement points and soil sample collection were based on the land unit use map by dividing it into three, the upstream, middle, and downstream of the Krueng Aceh watershed through a purposive sampling method. The infiltration rate was measured using a double ring infiltrometer. The results of the measurement were analyzed using Horton model (Schwab et al 1981) with the following equation:

$$f = f_c + (f_o - f_c)e^{-Kt}$$

where: f = infiltration capacity (cm/hour);
fc = constant infiltration rate (cm/jam);
fo = initial infiltration rate (cm/jam);
e = the Naperian logarithmic number, 2.71828;
K = constant;
t = time, starting from when it began to rain (hours).

Data analysis. The estimation of the surface runoff volume in the Krueng Aceh watershed was made using the Soil Conservation Service-Curve Number (SCS-CN) method which is a rain runoff correlation model (Arsyad 2010). In order to obtain the CN value, a number of steps were needed:

1. Classification of the hydrologic soil groups (HSG): the classification of the hydrologic soil groups was conducted three ways, based on the soil type map, minimum infiltration rate measurement, and soil texture resulting from laboratory analysis. Table 1 showed that the HSG condition A was predominantly sandy soil, B and C had ratios between sandy clay soil, and D was predominantly loam (NRCS 2009);

Table 1

Hydrologic soil groups (HSG)

HSG	*Minimum infiltration rate (cm hour^{-1})*	*The soil's physical characteristics*
A	0.76-1.14	Low surface runoff potential. Water quickly infiltrates into the soil. Contains < 10% clay and > 90% sand or gravel. The texture is loamy sand, sandy loam, loam, or silty clay.
B	0.36-0.76	Medium surface runoff potential. Contains 10-20% clay and 50-90% sand. Has loam, loamy silt, silt, or sandy clayey loam textures.
C	0.13-0.36	High surface runoff potential. Contains 20-40% clay and < 50% sand. Have loam, silt loam, sandy clay loam, clay loam, and silty clay loam textures.
D	< 0.13	Very high surface runoff potential. Water movement is very slow. Contains > 40% clay, < 50% silt. The dominant textures are clay, clayey loam, silty clay, sandy clay, and silty clayey loam.

Source: NRCS (2009).

2. Antecedent Moisture Condition (AMC): the soil moisture content can influence surface runoff volume and rate. The SCS-CN method differentiates the AMC conditions, namely conditions I, II, and III (Schwab et al 1981). The AMC value was calculated by totaling the precipitation rate data from the previous 5 days then matched with the precipitation rate maximum limit during planting season (Table 2).

Table 2

Antecedent moisture condition (AMC)

AMC condition	*Notes*	*Total precipitation in the previous 5 days (mm)*	
		Dormant season	*Growing season*
I	The soil is in a dry condition but not to the point of wilting; has been planted with satisfactory results.	< 13	< 35
II	Average condition.	13-28	35-53
III	Heavy or light rains and low temperature occurring the previous 5 days; the soil is saturated.	> 28	> 53

Source: Schwab et al (1981).

Based on the AMC value, the CN value in each land map unit based on the land cover data and soil texture in the Krueng Aceh watershed can be determined. The CN values range from 0 to 100, influenced by land use, land management, and AMC conditions. After this, the weighted CN was calculated using the following equation:

$$CN_{Weighted} = \frac{(CN_a x A_1) + (CN_b x A_2) + \cdots + (CN_n x A_n)}{A_{Total}}$$

where: CN_1 = the curve number of the AMC I condition;
CN_2 = the curve number of the AMC II condition;
CN_3 = the curve number of the AMC III condition;
$CN_{a,b,n}$ = the curve number for HSG and certain land uses;
$A_{1,2,n}$ = the area of each $CN_{a,b,n}$;
A_{Total} = the size of the Krueng Aceh watershed.

After obtaining the HSG, AMC and weighted CN data, a prediction of the surface runoff was made based on the SCS-CN method:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}$$ the value of S was estimated using the equation $$S = \frac{25400}{CN} - 254$$

where: Q = amount of surface runoff (mm);
P = precipitation rate (mm);
S = maximum water retention potential (mm);
CN = runoff curve number.

3. Model calibration: The calibration method used was a manual method with modifications in the parameter values by trial and error. The statistical analysis used was the determination coefficient (R^2) and Nash-Sutcliffe efficiency (Nash & Sutcliffe 1970) using the following equation:

$$NS = 1 - \sum_{i=1}^{n} \frac{(Q_{obs} - Q_{sim})^2}{(Q_{obs} - \bar{Q}_{avg})^2}$$

where: Q_{obs} = debit from field measurement (mm);
Q_{sim} = debit from the model result (mm);
$\bar{Q}_{avg}$ = average debit from the measurement result (mm).

The Krueng Aceh watershed land use modeling. The land use planning for water resource conservation in the Krueng Aceh watershed used hydrological modeling by predicting the surface runoff volume from 3 scenario models. The criteria for the best scenario which is to be recommended is the one with the least surface runoff volume, having the least River Regime Coefficient (RRC) and surface runoff coefficient (C) from the existing condition. The land use planning scenarios were set as follows:

- scenario 1: describes the current biophysical conditions of the Krueng Aceh watershed (existing) with the 2014 land use size;
- scenario 2: implementing the land coverage according to Regional regulation number 4 year 2013 pertaining to the 2012-2032 Aceh Besar Regency Regional Spatial Plan;
- scenario 3: implementing the results of the land use change regression model which influences the hydrological response, especially the Krueng Aceh watershed's RRC and surface runoff coefficient.

Results and Discussion

The biophysical characteristics of the Krueng Aceh watershed. The results of the analysis of the land coverage in the Krueng Aceh watershed in 2014 revealed 14 types of land use. It was dominated by secondary dryland forests at 60,193.55 ha (30.42%) followed by savannas/grasslands at 44,600.09 ha (22.54%) and rice fields at 31,476 ha

(15.90%). The smallest land use was mining at 90.91 ha (0.05%). The still spacious secondary dryland forests indicated a still high infiltration potential, a large rainwater absorbance, and the utilization of water for living needs can be fulfilled (Table 3).

Table 3

The land use in the Krueng Aceh Watershed in 2014

No.	*Land use*	*Land use area (ha)*	*Percentage (%)*
1	Airport	151.87	0.08
2	Primary dryland forest	9 999.50	5.05
3	Secondary dryland forest	60 193.55	30.42
4	Planted forest	493.83	0.25
5	Settlement	4 182.87	2.11
6	Mining	90.91	0.05
7	Dryland agriculture	23 524.19	11.89
8	Mixed dryland agriculture	6 015.54	3.04
9	Savanna/Grassland	44 600.09	22.54
10	Rice field	31 476.00	15.90
11	Shrub	14 761.00	7.46
12	Fishpond	1 363.56	0.69
13	Water bodies	797.15	0.40
14	Open land	253.56	0.13
	Krueng Aceh watershed	197 903.62	100.00

Source: GIS analysis results.

There were 9 types of soil in the Krueng Aceh Watershed dominated by latosol which covered 34,373.68 ha (17.37%). The types of soil strongly influence the hydrology of an area and will affect the downstream area (Nepal et al 2014). The soil texture classification showed that the dominant type was clayey loam at 100,177.86 ha (50.62%) and the smallest was loam at 7,472.61 ha (3.78%) of the total Krueng Aceh watershed area.

There were 3 soil hydrological groups in the Krueng Aceh watershed which were dominated by Group C at 59.11%, Group B at 26.79%, and group D at 14.10%. In 2014 the dominant AMC condition was AMC I condition at a total of 88 days, 22 days at AMC II condition, and 15 days at AMC III condition. The soil hydrological group classification and CN value according to the AMC conditions in the Krueng Aceh Watershed are presented in Table 4.

Table 4

The soil hydrological groups and CN value in the Krueng Aceh Watershed in 2014

Land use	*Land use area*		*HSG*	*CN value*		
	(ha)	*(%)*		*AMC I*	*AMC II*	*AMC III*
Airport	151.87	0.08	D	71.93	90	96.27
Primary dryland forest	9 999.50	5.05	C	50.78	70	85.66
Secondary dryland forest	60 193.55	30.42	C	53.84	73	87.55
Planted forest	493.83	0.25	C	53.84	73	87.55
Settlement	4 182.87	2.11	B	68.54	87	94.95
Mining	90.91	0.05	D	65.29	84	93.55
Dryland agriculture	23 524.19	11.89	C	58.99	78	90.45
Mixed dryland agriculture	6 015.54	3.04	C	58.99	78	90.45
Savanna/Grassland	44 600.09	22.54	B	45.69	65	82.26
Rice field	31 476.00	15.90	D	62.12	81	92.05
Shrub	14 761.00	7.46	B	40.62	60	78.54
Fishpond	1 363.56	0.69	C	65.29	84	93.55
Water bodies	797.15	0.40	C	68.54	87	94.95
Open land	253.56	0.13	C	40.62	60	78.54
Krueng Aceh watershed	197 903.62	100.00	-	-	-	-

Source: The soil texture analysis and Arsyad (2010).

Land use in the Krueng Aceh watershed. Prior to using the modeling, calibration of the model was conducted by testing the comparison between the 2014 debit field measurement data and the SCS model prediction data. The initial model testing resulted in a surface runoff of 902.08 mm year^{-1}, and the SCS model prediction resulted in 1113 mm year^{-1} (Table 5). The comparison between the Krueng Aceh River's average daily surface runoff measurement results and the SCS model prediction is close to the real conditions in the field. This was proven by the Nash-Sutcliffe efficiency (NSE) value which was 0.84 and the determination coefficient value (R^2) at 0.78. This means that the data used was good (NSE > 0.75). The calibration result of this model is considered optimum and can represent the actual field condition.

Table 5

The 2014 actual Krueng Aceh River average daily surface runoff and the SCS model results

Month	*Precipitation rate (mm)*	*Surface runoff (mm)*	
		Measurement results	*Model prediction results*
January	124.46	79.37	86.44
February	79.37	46.23	52.67
March	61.27	30.22	57.51
April	133.28	68.08	70.50
May	142.06	74.47	67.40
June	70.68	39.35	27.31
July	43.83	15.34	40.18
August	121.10	62.05	60.61
September	140.54	87.83	82.17
October	331.95	152.44	178.38
November	326.16	103.71	203.14
December	383.24	142.99	186.70
Total	1 957.94	902.08	1 113.00

Source: Data analysis results.

Scenario I model. The scenario I applied the land use planning modeling according to the 2014 Krueng Aceh Watershed land use. The precipitation rate in the Krueng Aceh watershed area was 1,957.94 mm year^{-1}, producing a surface runoff of 902.08 mm, and the results of the SCS model prediction was 1,113 mm. The result of the Nash-Sutcliffe efficiency (NSE) model statistical test was 0.84 with a determination coefficient (R^2) of 0.78. According to Motovilov et al (1999) an NSE with a value > 0.75 indicated good data, and Moriasi et al (2007) stated that if the R^2 > 0.5, the model is better and there is a small chance of error.

Based on the River Regime Coefficient (RRC) of the simulation model result, the maximum debit volume (*Qmax*) in one day during the rainy season was 104.52 m^3 second^{-1}. The minimum debit volume (*Qmin*) in one day during the dry season was 2.75 m^3 second^{-1}. This means that the highest surface runoff was in November at 203.14 mm, and the lowest surface runoff was in June at 27.31 mm. The debit ratio was 37.98.

The changes in land use will affect the surface runoff coefficient (C) as one of the determining indicators of the biophysical condition damage rate in the Krueng Aceh watershed. The results of the ratio between the total surface runoff volume from the model prediction results and the area's precipitation rate indicate that 56.85% of the total precipitation rate cannot infiltrate the soil into groundwater. The soil then becomes saturated, causing the rainwater to flow to the river and channeled to the sea.

Scenario II model. Scenario II implemented the land coverage area according to Regional Regulation number 4 Year 2013 pertaining to the 2012-2032 Aceh Besar Regency Regional Spatial Plan. The regional spatial plan used was an area with the main function as a protected area and an agricultural area. The protected area use covered 47,200.98 ha while the agricultural area was 150,702.64 ha.

The scenario II model simulation resulted in a surface runoff value of 1,091.30 mm. This demonstrated a surface runoff decrease by 1.99% or 21.70 mm from the scenario I model. The debit fluctuation value (*Qmax/Qmin*) decreased from 33.02, obtained from the maximum debit in one day during the rainy season, 99.91 m^3 $second^{-1}$. The lowest debit in one day during the dry season was 3.03 m^3 $second^{-1}$. The hydrological effect of the change of land use in the scenario II model resulted in a surface runoff coefficient (C) of 55.74%. This means that out of the total precipitation rate that fell to the ground surface, only 44.26% infiltrated into the soil.

Scenario III model. In scenario III, the land use planning was formulated based on the regression model analysis results of the land use changes that had a significant effect on the Krueng Aceh watershed hydrological response. Based on the scenario III modeling results, the predicted surface runoff was 901.48 mm. This demonstrated a 211.52 mm (23.46%) decrease in surface runoff compared to the scenario I model.

The ratio debit was 26.77 from the maximum debit volume (*Qmax*) in one day during the rainy season, 88.57 m^3 $second^{-1}$, while the minimum debit volume (*Qmin*) in one day during the dry season was 3.31 m^3 $second^{-1}$, resulting in the highest surface runoff in October at 164.10 mm, and the lowest surface runoff was in June at 33.86 mm. Based on the surface runoff coefficient (C), only 46.04% of the total precipitation rate became direct surface runoff, the remaining 53.96% could infiltrate into the soil and become groundwater and surface water.

Based on the simulation results of the 3 modeling scenarios by predicting the surface runoff volume, the best land use from the hydrological aspect was the scenario III model. The scenario III model could decrease the surface runoff coefficient (C) to 46.04% from 56.85% in the scenario I model. The decrease in the surface runoff and increase in the infiltration capacity were higher at scenario III due to the increased size of land used for mixed dryland agriculture by 37,815.54 ha. This caused the land conditions to be capable of retaining rainwater, preventing it from immediately becoming surface runoff, and giving a chance for rainwater to seep into the soil through the infiltration process. Simulation results demonstrated that the use of land for mixed dryland agriculture is one of the factors that have a significant effect on decreasing the surface runoff.

Conclusions. Change in the land use from vegetation land cover to non-vegetation land cover has influenced the hydrologic system and had an effect on the availability of water resources in the Krueng Aceh watershed. The best land use model for water resource conservation in the Krueng Aceh watershed is by increasing the mixed dryland agricultural land to 84.09%. This could decrease the surface runoff by 211.52 mm or 23.46% and could decrease the debit ratio to 26.77 so the potential water that cannot immediately infiltrate could be reduced to 46.04% of the total precipitation rate which becomes direct surface runoff.

Acknowledgements. Thanks to Dr. Sri Malahayati Yusuf, SP., M.Si for the technical advice on hydrological modeling using the SCS-CN method. The author would like to thank Fachruddin, S.TP., M.Si from the GIS and Remote Sensing Laboratory, Syiah Kuala University who had helped analyze the soil type mapping in the Krueng Aceh watershed.

References

Arsyad S., 2010 Konservasi tanah dan air. Bogor (ID): IPB Press, 466 pp. [in Indonesian]

Cosgrove W. J., Loucks D. P., 2015 Water management: current and future challenges and research directions. Water Resources Research 51:4823-4839.

Loucks D. P., van Beek E., 2017 Water resource systems planning and management: an introduction to methods, models, and applications. Springer Nature, Switzerland, pp. 51-71.

Moriasi D. N., Arnold J. G., Van Liew M. W., Bingner R. L., Harmel R. D., Veith T. L., 2007 Model evaluation guidelines for systematic quantification of accuracy in watershed simulation. Transactions of the ASABE 50(3):885-900.
Motovilov Y. G., Gottschalk L., Engeland K., Rodhe A., 1999 Validation of a distributed hydrological model against spatial observation. Agricultural and Forest Meteorology 98-99:257-277.
Muis B. A., 2017 Model perencanaan penggunaan lahan untuk konservasi sumberdaya air di DAS Krueng Aceh. Doctoral dissertation, Bogor (ID): Institut Pertanian Bogor, pp. 1-95. [in Indonesian]
Muis B. A., Murtilaksono K., Jaya I. N. S., Haridjaja O., 2017 Analysis of water demands for freshwater aquaculture ponds in Krueng Aceh watershed, Aceh Province, Indonesia. AACL Bioflux 10(5):1119-1126.
Nash J. E., Sutcliffe J. V., 1970 River flow forecasting through conceptual models. Part I: A discussion of principles. Journal of Hydrology 10(3):282-290.
Nepal S., Flugel W. A., Shrestha A. B., 2014 Upstream-downstream linkages of hydrological processes in the Himalayan region. Ecological Processes 3(19):1-16.
[NRCS] Natural Resources Conservation Service, 2009 Hydrologic Soil Groups. United States Department of Agriculture, United States, pp. 1-13.
Nsubuga F. N. W., Namutebi E. N., Nsubuga-Ssenfuma M., 2014 Water resources of Uganda: an assessment and review. Journal of Water Resource and Protection 6:1297-1315.
Price K., 2011 Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: a review. Progress in Physical Geography: Earth and Environment 35(4):465-492.
Sandrasekaran M., Thilagam V. K., Khola O. P. S., 2017 Soil and water conservation in India: strategies and research challenges. Journal of Soil and Water Conservation 16(4):312-319.
Schwab G. O., Frevert R. K., Edminster T. W., Barnes K. K., 1981 Soil and water conservation engineering. 3rd edition, John Wiley & Sons, New York, 525 pp.
Trigunasih N. M., Kusmawati T., Lestari N. W. Y., 2018 Erosion prediction analysis and land use planning in Gunggung watershed, Bali, Indonesia. IOP Conf. Series: Earth and Environmental Science 123(2018):012025.

Received: 10 June 2019. Accepted: 23 July 2019. Published online: 02 August 2019.
Author:
Bos Ariadi Muis, Teuku Umar University, Faculty of Agriculture, Department of Agrotechnology, Indonesia, Aceh Province, Aceh Barat District 23615, Jl. Alue Peunyareng, e-mail: bosariadimuis@utu.ac.id

How to cite this article:
Muis B. A., 2019 Land use planning for water resource conservation in the Krueng Aceh watershed, Indonesia. AES Bioflux 11(2):67-74.