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CROSS-DRAINAGE CULVERT DESIGN UNDER GLOBAL CLIMATE AND LAND USE CHANGES

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ABSTRACT

The objective of this research is to assess the effects of climate and land use changes on the amount of runoff that flows through 3 types of hydraulic structures: pipes, R.C. box culvert and bridges using a SWAT model and Rational Method. Hydraulic structures in Roi -Et Province, Thailand were selected as a case study. We also a reviewed the suitability of the hydraulic structures by comparing their cross-sectional areas obtained from the SWAT model and Rational Method with the original drainage structures sizes obtained from the survey data. The results showed that runoff volume estimated from the SWAT model was greater than with the Rational Method, which used the graph of the rainfall intensity-duration-frequency curve (IDF Curve). However, the SWAT model evaluated runoff using the simulation of climate scenarios with the data from the PRECIS model under the emission conditions of B2 and did consider the current land use data. Therefore, the resulting cross-sectional areas of the hydraulic structures evaluated from the SWAT model have more hydraulic cross-sectional areas than the estimated cross-section by Rational Method and cross-sectional area determined from the survey data.

Keywords: box culvert; climate change; land use change; rational method; water crossing.

INTRODUCTION

Water is an essential natural resource for human, animal and plant life, regarded as one of the world's greatest wonders. Nowadays, many problems are related to water resources, including flood and drought problems that can damage both the economy and society. In general, these problems are affecting global climate change [1, 2] and land use changes [3, 4, 5]. This is due to the rapid increase in population and the need for residential areas or even agriculture, industry, transportation, etc. Global climate change affects temperatures in many areas around the world which are tending to increase, and storms are becoming more intense during the rainy season and average rainfall is decreasing [6, 7, 8]. As a result, surface water flow behavior in basins is influenced by changes in volume and runoff and there is increased frequency of floods and droughts.

In north eastern Thailand, especially in the Chi River basin, which serves a large population that is engaged in agriculture that requires water for cultivation; climate change has resulted in the number of hot days increasing per year, the number of days with precipitation has decreased, but the average annual precipitation has increased. Over the past 20 years, farmers in the area have shifted from traditional rice cultivation to planting cassava, sugarcane rubber or eucalyptus [9] for those crops yield higher prices due to demand from marketing or through influence of economic policies.

A culvert is a structure that allows water to flow under a road, railroad, trail, or similar obstruction, from one side to the other side. Typically embedded, so as to be surrounded by soil, a culvert may be made from a pipe, reinforced concrete or other material. In order to minimize the impact of a water crossing the environment, culverts require the proper size, design and installation, to ensure that they do not cause downstream erosion, upstream flooding, alter stream habitat or block the passage of organisms. The engineer must also incorporate personal experience and judgment, to determine which criteria must be considered and how to design the final dimensions of the culvert [10]. A drainage culvert should be designed according to design standards that can safely drain the design peak flow. Culverts in rural areas are designed on the basis of flow calculated using a design rainfall intensity of at least a 50-year return period. The hydraulic dimensioning book of the Department of Highways (DOH), Thailand introduces a method to determine design flow. This method is primarily based on the Rational Formula, one of the simplest and most widely used methods in engineering applications [11, 12]. The rational method relates the runoff-producing potential of a watershed, design rainfall intensity, and the watershed drainage area. However, the calculated flow from the rational method has to be adjusted for different catchments in various geographical locations throughout Thailand by a correction factor for climate change the percentage of lake area and a correction factor for climate change.

This study aims to predict the changing quantity of the runoff within climate change and land use change situations using the simulated climate data from the PRECIS scenario, and the future runoff forecast with the hydrological SWAT model.

The study assesses global impact of climate change and agricultural land use in the Chi Basin. It uses mathematical models including the SWAT model (Soil and Water Assessment Tool) [13, 8, 14] for analysis of runoff from past to future: PRECIS for predicting future climate change in the case of IPCC B2 for create scenario land use maps. The methods and results of the study are expected to be applied in water resource planning, drought prevention management or in other basins with similar physical and hydrological characteristics. Furthermore, the comparison of their cross-sectional areas obtained from the SWAT model and Rational Method with the original drainage structures sizes obtained from the survey data will be perform in this study.

MATERIALS, METHODS AND STUDY AREA

The study area was irrigation is in Roi-Et Province located in the northeast of Thailand in branches of the Chi River basin (Figure-1). Most of the population is engaged in agriculture using rainwater and irrigation systems. The most commonly planted crops are rice, cassava, maize, sugarcane, and plantations (especially rubber trees, which are likely to increase during the next 5-10 years). There were 3 types of hydraulic structures: pipes, R.C. box culvert and bridges considering in this study (see Figures 2 and 3).

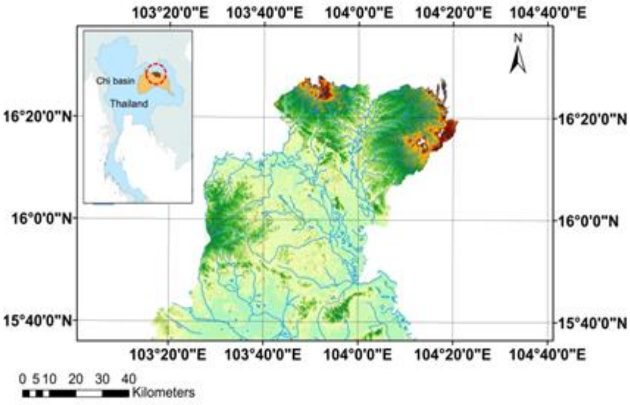


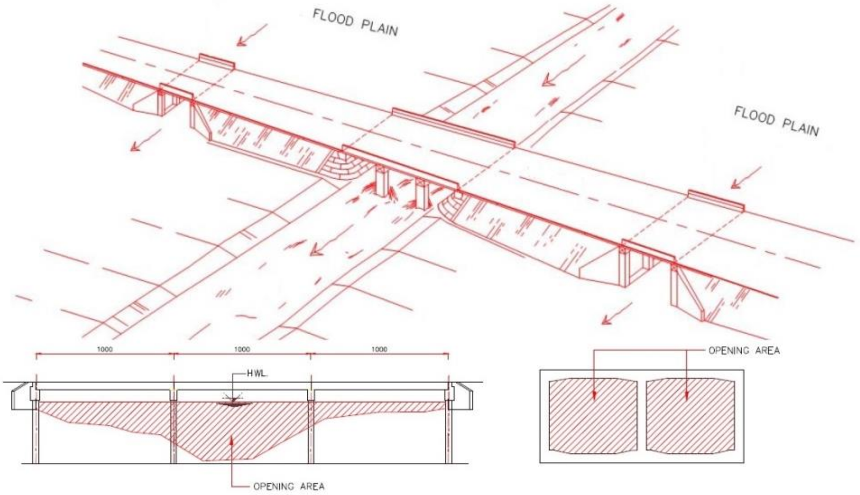
Figure-1. Map of the study area.

(a) Bridge

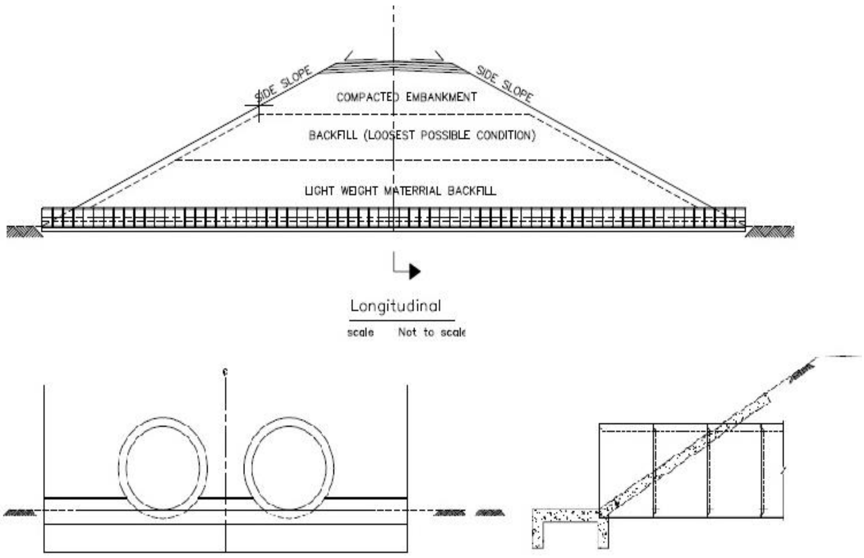
(b) Box culvert

(c) Pipe

Figure-2. The original hydraulic structures.



(a) Bridge and box- culvert structures.



(b) Pipe Structure

Figure-3. Side-Plan of hydraulic structures.

ESTIMATION OF FUTURE LAND USE

SWAT (Soil and Water Assessment Tool) is a semi-distributed hydrological model developed for the measurement of the runoff, sediment, and water quality under climate and land use changes. SWAT can be used to continually measure the daily runoff and land use change on runoff for continuous daily levels, which can be analyzed over a long period into the future. It can also connect and import the spatial data from Geographic Information Systems (GIS) [15, 16] in order to evaluate the runoff. The spatial data and SWAT performance evaluation is presented in Table-1.

Table-1. Spatial data and observed runoff data for SWAT performance evaluation.

Data types	Period	Scale	Source
Spatial data (model input)			
DEM	2018	30x30 m	LDD
River map	2018	1:50,000	
Soil types	2018	1:50,000	
Land use map	2018	30x30 m	
Climate	1997-2018	Daily	TMD
Observed runoff (model performance assessment)			
E.66A	1999-2018	Daily	RID
LDD: Land Develop Department (Thailand) TMD: Thai Meteorological Department (Thailand) RID: Royal Irrigation Department (Thailand) EGAT: Electricity Generating Authority of Thailand			

SITUATION OF CLIMATE CHANGE IN THE FUTURE

PRECIS is a regional climate model, based on the development of the ECHAM4 model, displaying the data as a "grid" with high resolution of 22 x 22 km^2 [17]. The data recorded during 1997-2018 was used as the baseline and data from 2016-2064 was used for the scenarios covering an area bounded by 15° 40´ 00´´N, 103° 20´ 00´´E;15° 40´ 00´´N, 104° 40´ 00´´E; 16° 20´ 00´´N, 103° 20´ 00´´E and 16° 20´ 00´´N, 104° 40´ 00´´E. This data presents the precipitation, maximum and minimum temperatures, solar intensity, relative humidity, and wind speed. The IPCC SRES scenario B2 was used as the model of the sustainable social, economic, and environmental problem solving including the economic development at average level and the environment conservation and social equality at local and regional levels [18].

The PRECIS data was downscaled to reduce possible deviation using the Change Factor (CF) method [19], which is the ratio of the average and the difference between the observed data and PRECIS data during the baseline for precipitation and temperature and can be found using Equation (1) and Equation (2), respectively.

$$PC_{sim,\,fut-rev} = PC_{sim,\,fut}\left[\frac{PC_{obs,base}}{PC_{sim,base}}\right] \tag{1}$$

$$T_{sim,\,fut-rev} = T_{sim,\,fut} - \left[T_{sim,base-}T_{obs,base}\right] \tag{2}$$

Where $PC_{sim,fut-rev}$ is the simulated precipitation from PRECIS (future) with bias correction; $PC_{sim,fut}$ is the original simulated precipitation from PRECIS (future); $PC_{obs,base}$ is an average of monthly observed precipitation (baseline); $PC_{sim,base}$ is an average of monthly precipitation from PRECIS (baseline); $T_{sim,fut,rev}$ is the simulated temperature from PRECIS (future) with bias correction, $T_{sim,fut}$ is the original simulated temperature from PRECIS (future); $T_{sim,base}$ is an average of monthly temperature from PRECIS (baseline); and Tobs, base is an average of monthly observed temperature (baseline). The value generated by CF method was presented in Table-2.

Table-2. The values from CF method for downscaling simulated climate data.

Month	C_{pc}	C_{tx}	C_{tn}
January	0.0301	-1.0479	2.6101
February	0.1416	-0.2241	0.7417
March	0.2062	-0.3543	-0.4276
April	0.5972	1.6965	-0.2293
May	1.1033	1.1978	0.2185
June	0.8283	1.9813	1.7610
July	1.0644	4.8100	2.3661
August	1.5838	4.4786	2.5926
September	3.0005	1.7694	2.9922
October	1.4377	-0.4711	2.3737
November	0.4510	-1.4511	1.4168
December	0.2171	-4.7202	1.2564

MODEL SETUP FOR FUTURE RUNOFF

After the SWAT model with customized hydrological parameters was shown to be satisfactory by comparing the runoff from the stations between the years 2006-2014 (baseline) with the simulation results, which gave an evaluation value of R^2, RE and E_{ns} thereby confirming the SWAT model was effective and can be used to analyze future runoff between the years 2015-2024 (scenario). The analysis simulates the climate using data from the PRECIS and Used SWAT, the runoff simulation flow chart is shown in Figure-4.

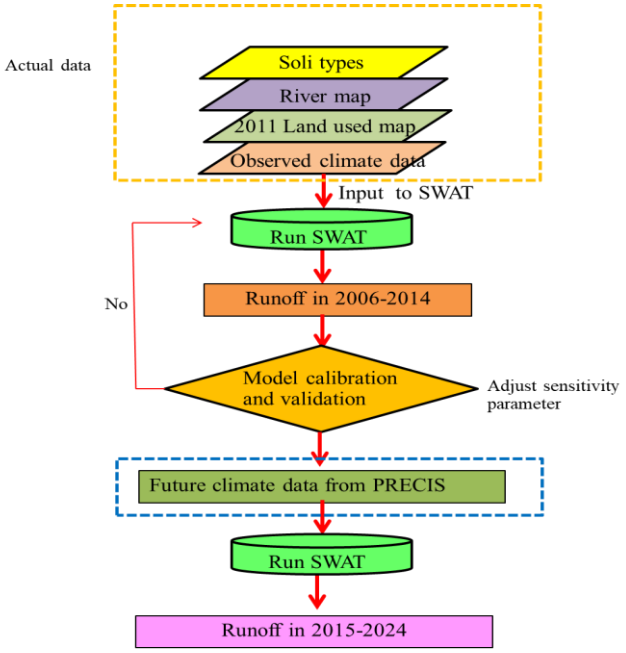


Figure-4. Flow chart of the modeling process.

CALCULATION OF CROSS-SECTIONAL AREAS

The Manning equation was used to calculate the diameter of culvert, as follows:

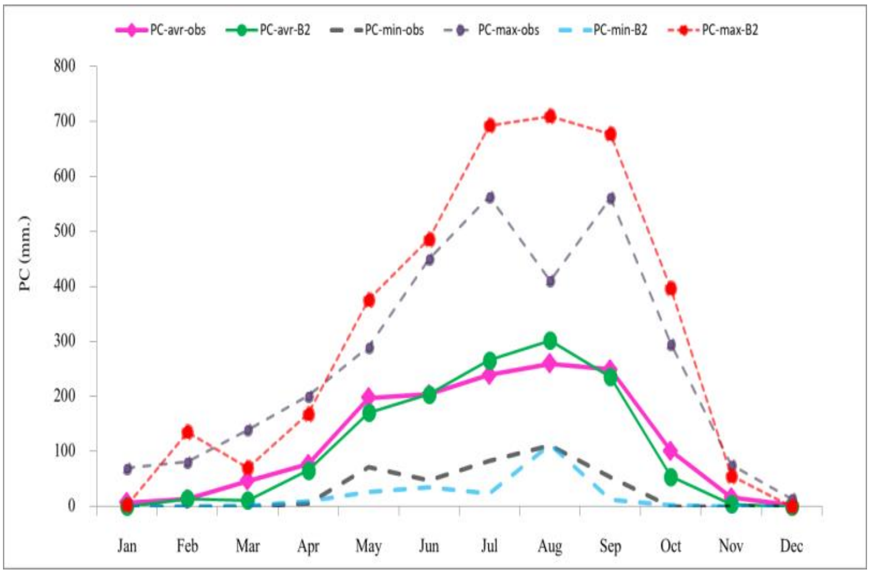
$$D = \left(\frac{Q^{3/4} n^{3/4}}{S^{3/4} \pi^{3/4}}\right), \quad (3)$$

where, D is culvert diameter (m), S is culvert slope (m/m) (a value of 0.015 was selected by default), n is roughness coefficient of the culvert, which was set to 0.021, Q is discharge (m^3/s). Whereas, the cross-sectional areas of bridge were calculated using continuity equation of flow.

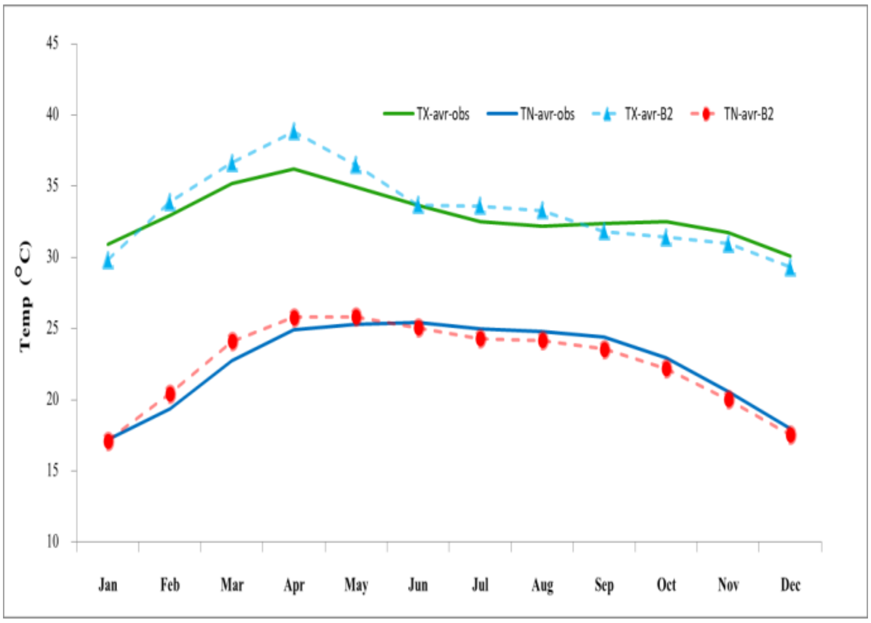
RESULT AND DISCUSSIONS

Climate Change Scenario

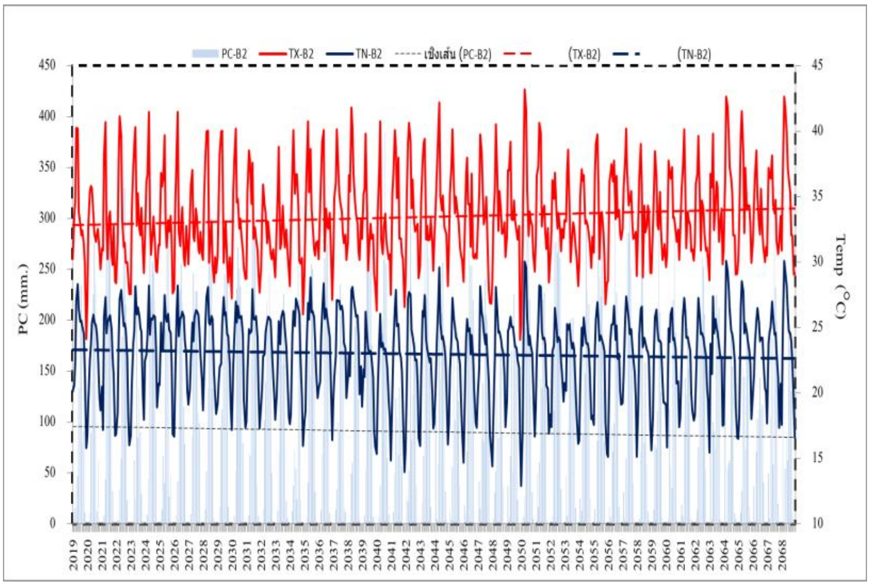
The model calibration was performed using Equation (1) and Equation (2). Namely, the downscaled data were compared with the average monthly data from the Roi-Et meteorology station during the baseline year and indicated the goodness of fit of the precipitation and temperatures as presented in Figure-5. For the average precipitation, the simulated results were less than the observed data, in which the R^2 was 0.62. For the average maximum and minimum temperatures, the R^2 values were 0.56 and 0.68, respectively.



(a) Monthly precipitation



(b) Monthly maximum and minimum temperatures



(c) The highest and lowest temperature and precipitation between 2019-2611 calculated from PRECIS.

Figure-5. Average monthly PRECIS data downscaled and compared with data from study area station (baseline).

SWAT Runoff Performance Evaluation

An evaluation of SWAT accuracy used the data found during 2007-2018 (12 years; 2007-2012 for calibration and 2013-2018 for validation) for E.66A station. Practically, 7 parameter values were selected and used to analyze the flexibility score, as the modified parameter values of the flexibility by adjusting the runoff volume to closely match with the data from the rainfall measuring stations and is presented in Table-3.

Table-3. SWAT sensitivity parameter.

No.	Parameter	Range	E.66A
1	ALPHA_BF	0-1	0.2
2	GWQMN	0-500	498
3	CN2	-20% -20%	20%
4	SOL_AWC	0-1	0.69
5	EPCO	0-1	0.8
6	ESCO	0-1	0.2
7	GW_DELAY	0-500	40

The runoff calculated by SWAT and compared with the data from the two observed stations shows the runoff during the period of model calibration and validation. Also, R^2, RE, and Ens were satisfactory and accurate as the deviation as presented in Table-4 was acceptable; the goodness of fit of the data is depicted in Figure-6.

Table-4. SWAT performance evaluation index.

Range	Assessment index		
	R^2	*RE*	E_{ns}
Calibration (2005-2012)	0.77	27.48	0.74
Validation (2018)	0.81	44.74	0.79

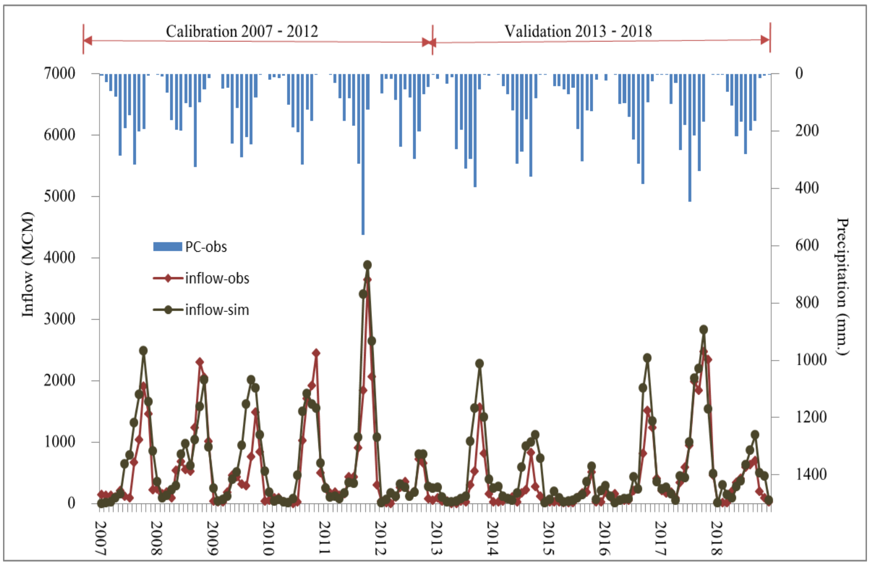


Figure-6. Model calibration and validation result.

Peak Flow Calculation by Using SWAT Model

After creation of the land use maps projected using the CA Markov model based on climate scenarios with the data from the PRECIS model under the emission conditions of B2 and therefore estimate runoff with the SWAT model. The surface flow rates were calculated for 50 years of rainfall intensity and are shown in Figures 7 and 8.

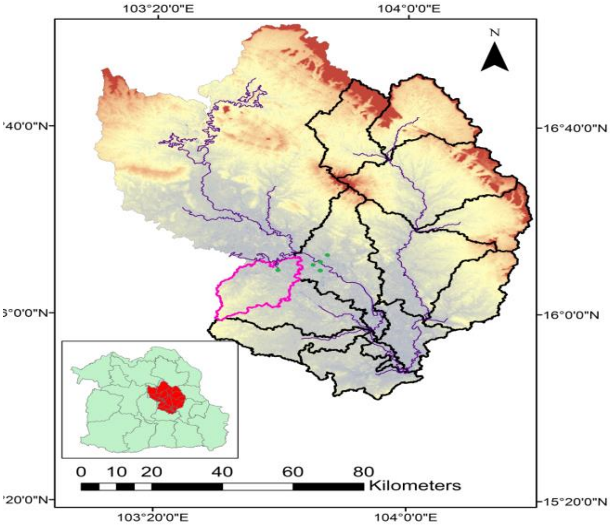


Figure-7. Surface flow rate Q, calculated using SWAT model for 50 years.

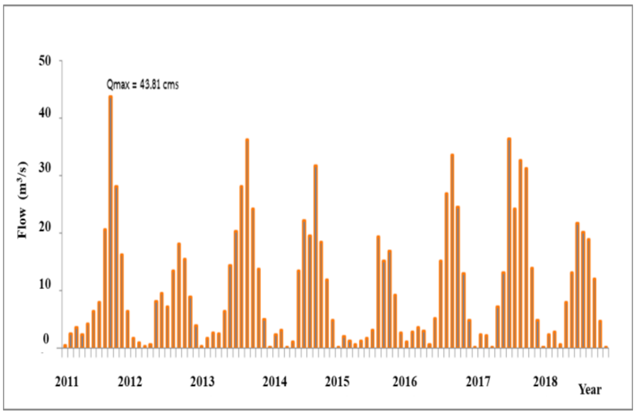


Figure-8. The SWAT model evaluates runoff using the simulation.

Comparison of Flows and Cross-Sectional Areas

Table-5 shows the calculated discharges and cross-sectional areas obtained from the SWAT model, Rational Method and the original sizes of survey data. It indicated that runoff volume estimated from the SWAT model was more than calculated with the Rational Method for all hydraulic structure types. It also presents that cross-sectional areas of the hydraulic structures evaluated from the SWAT model have more hydraulic cross-sectional areas than the estimated cross-section by Rational Method and cross-sectional area determined from the survey data for all hydraulic structure types. Furthermore, in case of pipe, the runoff volume estimated from the SWAT model was higher than pipe design criteria, hence the box culvert was substituely used to design.

Table-5. Calculated and predicted discharges.

Types	**Runoff (m^3/s)**		**Cross-sectional areas**		
	$Q_{Rational}$ (m^3/s)	**Q_{SWAT} (m^3/s)**	**$A_{Rational}$**	**A_{SWAT}**	**$A_{field\ work}$**
Pipe	15.56	40.75	2 - ø 1.20	3-□2.10x2.10	2 - ø 0.80
	10.74	41.23	2 - ø 1.50	3-□2.40x2.40	2 - ø 1.00
	9.808	40.63	3 - ø 1.50	3-□2.40x2.40	3 - ø 1.00
Box- culvert	41.71	43.35	3-□2.70x2.70	3-□2.70x2.70	2-□1.80x1.80
	42.68	44.89	3-□2.70x2.70	3-□2.70x2.70	2-□1.80x1.80
	43.55	45.81	3-□2.70x2.70	3-□2.70x2.70	3-□1.80x1.80
Bridge	18.61	21.14	9.00x20.00	9.00x30.00	9.00x20.00
	48.07	50.89	9.00x40.00	9.00x42.00	9.00x30.00
	284.27	335.32	9.00x40.00	9.00x42.00	9.00x40.00

CONCLUSIONS

This research studied and evaluated runoff using the Rational Method and SWAT model under climate and land use change. It compared the cross-sectional area size of hydraulic structures obtained from the SWAT model and Rational Method with the original drainage structures sizes obtained from the survey data. The results showed that runoff volume estimated from the SWAT model was more than calculated with the Rational Method, which used the graph of the rainfall intensity-duration-frequency curve (IDF Curve). The SWAT model evaluated runoff using the simulation of climate scenarios with the data from the PRECIS model under the emission conditions of B2 and considering the current land use data. Therefore, the resulting the cross-sectional area size of the hydraulic structures evaluated from the SWAT model have more hydraulic cross-sectional area size than the estimated cross-section by the Rational Method and cross-sectional area size from the survey data.

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