International Journal of GEOMATE, March, 2020, Vol.18, Issue 67, pp. 135-141
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2020.67.9218
Special Issue on Science, Engineering and Environment

HISTORICAL HYDROLOGICAL DATA GENERATION FOR UNGAUGED WATERSHED BY WATER BALANCE TOOL

Wachirawit Plinruttanadet[1], *Supasit Konyai[2], Vichai Sriboonlue[3]

[1]Faculty of Engineering, Khon Kaen University, Thailand; [2,3] Khon Kaen University, Thailand

*Corresponding Author, Received: 16 June 2019, Revised: 24 Oct. 2019, Accepted: 01 Jan. 2020

ABSTRACT: Effective water resources planning and management need accurate historical hydrological data for simulation and prediction. Many watersheds in Thailand are ungauged and many have unreliable or incomplete data. This study focuses on using available meteorological data to generate accurate monthly hydrological data, including direct runoff, evapotranspiration, and groundwater recharge for Lam Takhong watershed in Buriram Province, Thailand, as a case study. The Lam Takhong River is a tributary of the Mun River in northeastern Thailand covers an area of 1,560 square kilometers. This study examined nine years of daily meteorological data, including rainfall, temperature, relative humidity, and solar radiation obtained from a meteorological station, Buriram 436401, Royal Meteorological Department, from January 1, 2006 to December 31, 2014. Direct runoff values were evaluated from rainfall data using SCS-CN method. The CN and λ parameters were evaluated from accurate GIS maps of soil and land-use. Evapotranspiration values were determined from recorded climatic data using Morton's CRAE method. Results from the study period indicated that the wettest and driest years were 2008 and 2007, respectively. Groundwater recharge occurred every year except in 2007 with the greatest recharge occurring in 2011. Water balance was demonstrated to be a valuable tool for generating accurate historical hydrological data.

Keywords: Lam Takhong, Water balance tool, SCS-CN, Morton's CRAE

1. INTRODUCTION

Buriram is a fast-growing township located in the southern part of Northeast, Thailand. Lam Takhong (Buriram) is a small river that supports the livelihood of its population. It is one of the main tributaries of the Mun River that flowing to the great Mekong River. The Lam Takhong, apart from the only water supply source for the Buriram township and its satellites, is responsible for surrounding agriculture, ecology, and socio-economic of the area. The river is subjected to flood and drought almost every year and recently increasing in frequency and intensity. There are three medium reservoirs and several small scale ones along the river. Water resource and watershed planning and management are therefore extremely important so that river flood and droughts are to be mitigated and so water pollution.

The hydrological data of the area in the past are crucial for the river and its watershed planning and management studies. Surprisingly, the past hydrological data of the Lam Takhong (Buriram) watershed are very scarce and not reliable even though serious problems are always at hand. The river is a so-called ungauged river [1]. Fortunately, meteorological data from the township's weather station are fairly reasonable, therefore, historical, hydrological, data can be generated.

The foremost driving force of river flow is the rainfall on the watershed. Total rainfall can be divided into vegetation interception, surface detention and retention, direct runoff, interflow, and groundwater flow. The interception, detention, and retention are evaporated back to the atmosphere. The interflow and groundwater flow become base flow. The direct runoff together with base flow constitutes the river flow [2]. The Buriram weather station recorded precipitation and other meteorological data since 2006. The objective of this study was to construct monthly hydrological data namely river flows and groundwater recharges of the Lam Takhong (Buriram) watershed from 2006 to 2014 by utilizing the daily meteorological data. The SCS-CN method was used for rainfall-runoff modeling. Monthly actual evapotranspiration was evaluated by Morton's CRAE method. The water balance tool was used to generate the time series of direct runoffs and groundwater recharges of the watershed. The river flow was finally the results of direct runoff and baseflow.

2. STUDY AREAS AND DATA SETTING

Our study area is the Lam Takhong (Buriram) watershed which is located in the southern part of Northeast Thailand (Fig. 1). It is a sub-basin of the Mun River, one of the main tributaries of the Mekong River. It covers the area of 1560 km2 in between 14°41’ 54” to 15° 17’ 51” latitude and 102° 56’ 15” to 103° 17’ 15” longitude Takhong flows northward with a length of about 95 km. From the two southernmost tributaries Huai Jorkhemak and Huai Raj, they form the Lam Takhong.

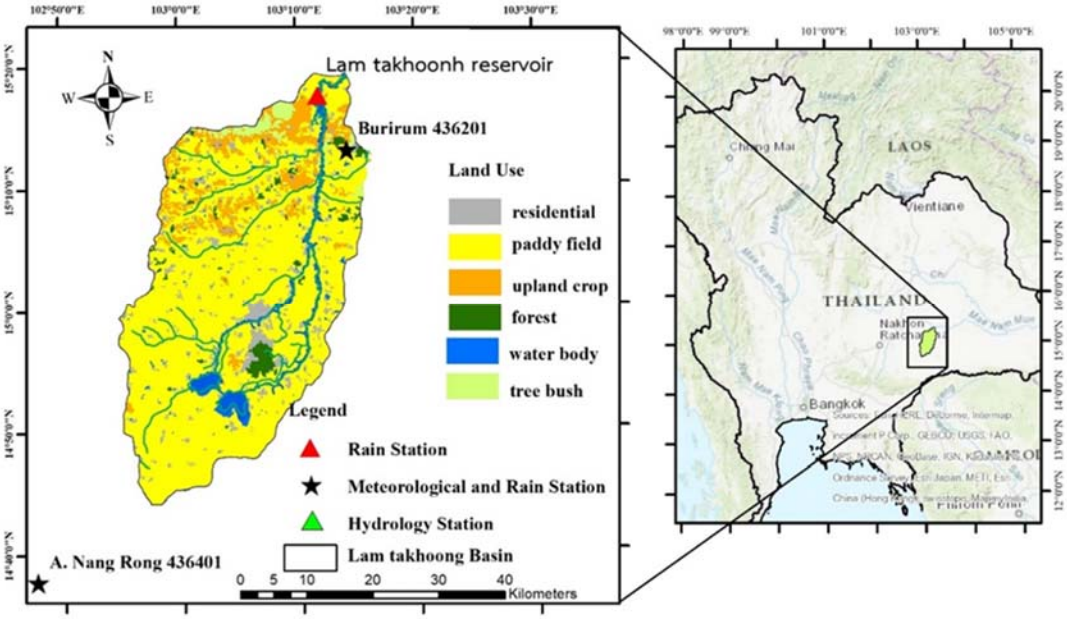

Fig. 1 Study area with drainage networks and other information.

River which drains into the Mun River. The climate of Lam Takhong is the typical Northeast, Thailand, climate demonstrating wet and dry cycle each for half a year. Humidity causes of rainfall come from two sources namely, the southwest monsoon and the tropical cyclone. The mean annual rainfall of the region is 1,420 mm (2006 to 2014) and normally peaks in August. The mean annual of actual evapotranspiration of the same periods as rainfall is about 910 mm and also peaks in August due to large amount of soil water availability (Fig. 2).

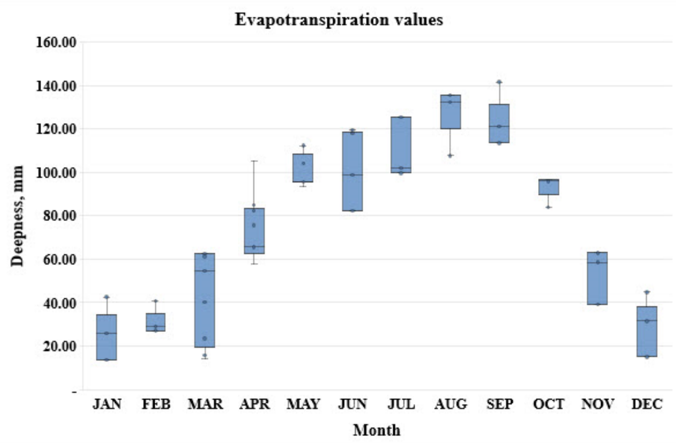

Fig. 2 Actual evapotranspiration of the region.

The landform of the study area is a mild undulating terrain with highest elevation of 180 m (from the annual mean sea level) at the southernmost of the watershed and the lowest at the confluence with the Mun River of about 140 m (amsl.). Its geology is the Khorat Group with the majority of Mahasarkham formation. The formation consists of sandstone, mudstone, and rock salt-producing sandy, clayey, and saline soils. The soils of the whole watershed were studied for hydrological properties and classified into 4 hydrological soil groups as shown in Table 1 and Fig. 3. The main soil groups are C and D which can produce large amount of runoff. This is one of the reasons for frequent flooding of the downstream area.

Table 1 Hydrological soil groups and their hydrological properties.

	Land use	Area km^2	% Area	CN II				CN*%Area	CN II
				Soil A	Soil B	Soil C	Soil D		
2014	residential	109.60	7.02	77	85	90	92	6.18	77.64
	paddy field	1,167.06	74.76	59	70	78	81	57.51	
	upland crop	178.73	11.45	62	71	78	81	8.99	
	forest	31.94	2.05	30	55	70	77	1.12	
	tree bush	35.15	2.25	30	55	70	77	1.37	
	water body	38.56	2.47	100	100	100	100	2.47	
2010	residential	108.39	6.94	77	85	90	92	6.10	77.58
	paddy field	1,206.16	77.27	59	70	78	81	59.43	
	upland crop	160.60	10.29	62	71	78	81	7.95	
	forest	36.78	2.36	30	55	70	77	1.24	
	tree bush	10.42	0.67	30	55	70	77	0.38	
	water body	38.67	2.48	100	100	100	100	2.48	

Table 2 Land-use classification and curve numbers class 2 (CN2).

HSG	Description	Area km^2	Final Infiltration Rate (mm/h)	Field capacity (%)	Wilting point (%)
A	Lowest Runoff Potential. Includes deep sands with very little silt and clay, also deep	128.21	8-12	5.5	2
B	Moderately Low Runoff Potential. Mostly sandy soils less deep than A	201.23	4-8	28.4	12.15
C	Moderately High Runoff Potential. Comprises shallow soils and soils containing considerable clay and colloids,	604.75	1-4	33.95	13.4
D	Highest Runoff Potential. Includes mostly clays.	626.84	0-1	33.5	20.2

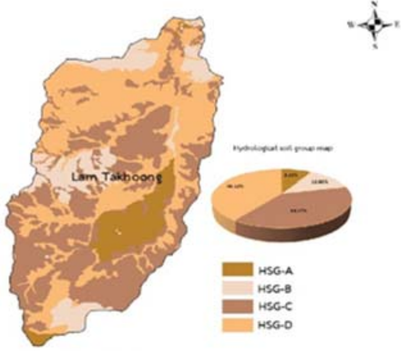

Fig. 3 Hydrological soil groups of the Lam Takhong Watershed.

The land-use of the study area was derived from the two land-use maps (2010 and 2014) of the Department of Land Development of Thailand. The land-use types were classified into 6 types with the majority of paddy fields and upland crops (Fig. 1 and Table 2). The change of 2010 land-use to 2014 one is negligibly small therefore we used 2014 one in our curve number (CN) calculations. The CN value is the function of soil, land-use, and antecedent soil moisture. We normally estimate CN2 first from look-up tables then it is changed to CN1 or CN3 for dry or wet conditions, respectively, using antecedent rainfall see Eqs. (6) and (7).

3. METHODOLOGY

3.1 Water Balance of Lam Takhong Watershed

Water balance can be defined as the inflow rate subtracted by outflow rate equals to time rate of change of the soil water. We are only interested in the critical zone which ranges from the base of effective root zone up to the crown of the plant [3]. Considering the whole watershed, the only input is assumed to be precipitation even though there are some other inflows but they are so negligibly small [4]. There are three outputs namely runoff, evapotranspiration, and groundwater recharge. Water balance equation for the effective root zone can be written as [3]:

$$\frac{Zd\theta}{dt} = P - E - R - D \qquad (1)$$

where Z is thickness of effective root zone, θ is moisture content of the soil, P is precipitation, E is evapotranspiration, R is runoff, and D is deep drainage below the root zone. In the form of finite-difference Eq. 1 is:

$$Z(\theta_t - \theta_{t-1}) = P_t - E_t - R_t - D_t \qquad (2)$$

where subscript t and t-1 are the present time and the past time for one period, respectively. In case of daily time series t and t-1 are today and yesterday. The definition of effective root zone, Z, is loosely defined as the depth of soil with rather constant moisture content plant root can however penetrate much deeper than that [3]. Several studies of variability of soil moisture content in the Northeast of Thailand found that northeastern soil profiles normally keep moisture constant at about 1 m depth [5]-[6]. So we presume Z value at 1 m deep that $Z\theta_t$ and $Z\theta_{t-1}$ are the soil water depths of today and yesterday, respectively. The equation to predict soil water depth for today can be written as:

$$Z\theta_t = Z\theta_{t-1} + P_t - E_t - R_t - D_t \qquad (3)$$

The upper and lower limits of soil moisture content are the field capacity and permanent wilting point conditions, respectively. By deducing from the study of, for example, [5]. we obtained soil water depths of 10 and 150 mm for lower and upper limits.

3.2 Direct Runoff

A direct runoff (R) is a part of the whole precipitation that flow along the soil surface and shallow interflow to constitute the river flow. One of the most popular methods to evaluate direct runoff is the soil conservation service curve number (SCS-CN) method [7]. It is the function of total precipitation (P) and potential retention of soil (S) at the time of runoff occurring which can be written as [8],

$$R = \frac{(P - Ia)^2}{(P - Ia + S)} \quad \text{for } P > Ia \qquad (4a)$$

$$R = 0 \qquad \text{otherwise} \qquad (4b)$$

where I_a is initial abstraction (mm) meaning the volume of precipitation loss before runoff to begin and is a function of potential retention, S, as

$$Ia = \lambda S \qquad (5)$$

where λ is the ratio of initial loss to potential retention which was assigned to 0.2 at the beginning [9]. Several studies found the values of λ in the range of 0 to 0.3 [10]-[11]. Most of the studies in semiarid regions obtained the λ values less than 0.2 at the average of 0.05 [12] however for the area of humid climate the λ values are higher than 0.2 or up to 0.3 [13]. Lam Takhong (Buriram) watershed is in sub-humid climate in which its initial abstraction may be in the middle between humid and semiarid climates. We decided λ to be 0.1 in this watershed.

For simplicity, the value of S is related to a dimensionless parameter called curve number (CN) which depends on land use, soil type, and antecedent soil moisture [7]. The CN values are classified with antecedent soil moisture into three groups. The values of CN1, CN2, and CN3 are for antecedent wet soil, normal, and dry soil respectively. The CN2 value can be determined from the prepared tables e.g. [2] then CN1 and CN3 can be evaluated from CN2 as:

$$CN1 = \frac{4.2CN2}{(10 - 0.058CN2)} \qquad \# \qquad (6)$$

$$CN3 = \frac{23CN2}{(10 + 0.13CN2)} \qquad (7)$$

The antecedent soil moisture in this study was classed using the depth of rainfall of two previous days plus half of today. The potential retention of the watershed, S, can be calculated from CN value as

$$S = \frac{25400}{CN} - 254 \qquad (8)$$

3.3 Evapotranspiration

In majority of water balance models the value of actual evapotranspiration (E_a) is always the unknown or output of the model, but in this study, we estimated E_a directly from climatic data with the model of Morton's complementary relationship areal evapotranspiration (CRAE). [14]. extended the assumption of [15] which stating that the sum of regional actual evapotranspiration (E) and potential evapotranspiration (E_p) rates equals to twice the wet environment evapotranspiration rate (E_w), namely

$$E + E_p = 2E_w \qquad \#\#\#\#\#\#\#\#\#\#(9)$$

Morton (1983) solved this equation using two equations, the energy balance, and vapor transfer equations, respectively,

$$E_p = R_T - [\gamma f_T + 4\varepsilon\sigma(T_P + 273)^3](T_P - T) \qquad (10)$$

$$E_p = f_T(e_P - e_d) \qquad \#\#(11)$$

in which T_P and T are the equilibrium and air temperatures, respectively, in degree C; R_T is the net radiation at critical zone at air temperature; γ is psychrometric constant; σ is the Stefan-Boltzmann constant; ε is the surface emissivity; f_T is the vapor transfer coefficient; e_P and e_d are the saturated vapor pressure at T_P and at dew point temperatures, respectively. Eq. (10) and (11) can be solved for Ep and Tp by iterative technique. The value of E_w can be estimated from [16]:

$$E_w = b_1 + b_2[\frac{\Delta_p}{(\Delta_p+\gamma)}][R_n - 4\varepsilon\sigma {T_P}^3(T_P - T_a)] \qquad (12)$$

where b_1 accounts for large scale advection during season of low net radiation is equal to 14 W/m^2, and b_2 equals to 1.20, Δ_p is the slope of the saturated vapor pressure curve at T_p. Eqs (9) to (11) can be solved for actual evapotranspiration, E, [14].

Since solving simultaneously Eqs (9) to (11) is very complicated however [17] presented a computer programming in R language to solve them. The daily climatic data from 1/1/2006 to 31/1/2014 were used in this calculation. The accurate output results from MortonCRAE model must be in monthly forms.

3.4 Groundwater Recharge

Groundwater is one of the important hydrologic components. It resides in aquifers far below the bottom of effective root zone. Top of the uppermost aquifer is a water table. The drainage water from the root zone feeds the groundwater system through the unsaturated zone down to the water table called groundwater recharge. The drainage from root zone begins when the root zone reaching field capacity which is about 150 mm of soil water of the root zone [18]. Groundwater can be lost from an aquifer by two ways discharging to rivers as baseflow and flowing upward to a root zone as capillary action.

3.5 River Flow

River flow is composed of direct runoff and baseflow. The former comes from precipitation whereas the later from groundwater discharge. The baseflow of the interest region is one of the lowest in the Mekong Basin which is about 53 mm/year [18]. We estimated baseflow from the concept of baseflow index, i_b, which is

$$ib = \frac{R}{Q} \qquad (13)$$

where R and Q are runoff and river flow, respectively. We obtained the value of baseflow index from [19]. Which is about 0.17.

4. RESULTS AND DISCUSSION

The time series of rainfall, runoff, and actual evapotranspiration of the study area from 2006 to 2014 are shown in Fig. 4. It shows the distributions of rainfall, runoff, and ETa for each year. The runoff and ETa are always followed the pattern of rainfall. The daily distribution of rainfall for each month of the years dictates the amounts of runoff and ETa.

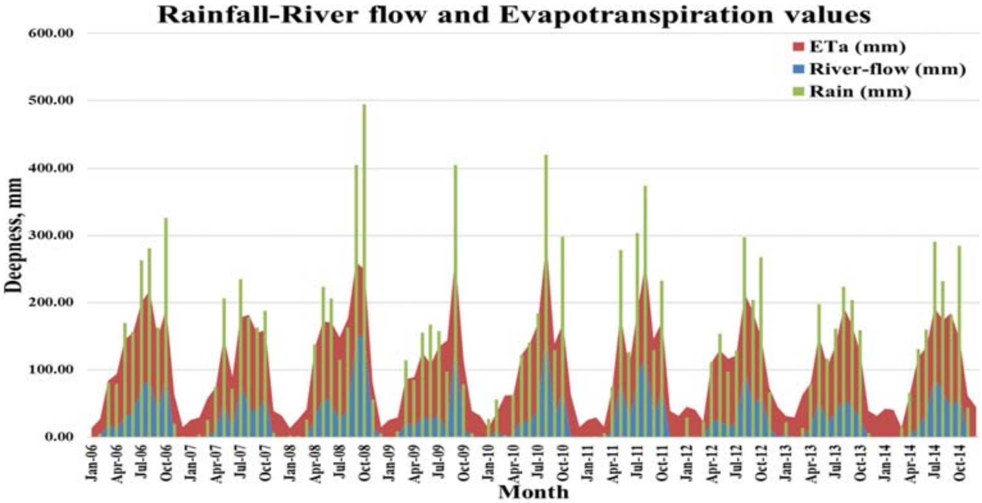

Fig. 4 The time series of rainfall, runoff, and actual evapotranspiration of the study area.

Table 3 Summarized results of water balance.

Year	Rain	Runoff	ETa	GW	Base flow	River flow	ETa/ Rain	Runoff/ Rain	River-flow/Rain
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)			
2006	1,545.03	391.52	964.04	160.90	80.67	472.19	0.62	0.25	0.31
2007	1,152.68	291.90	878.96	0.00	60.06	351.97	0.76	0.25	0.31
2008	1,838.57	524.08	963.29	294.96	89.19	613.27	0.52	0.29	0.33
2009	1,302.67	295.65	882.40	148.58	50.26	345.91	0.68	0.23	0.27
2010	1,445.71	362.14	920.77	125.66	62.99	425.13	0.64	0.25	0.29
2011	1,527.00	425.30	838.90	255.59	72.49	497.79	0.55	0.28	0.33
2012	1,378.98	318.42	934.55	93.69	54.91	373.33	0.68	0.23	0.27
2013	1,183.48	265.18	885.48	44.69	45.43	310.61	0.75	0.22	0.26
2014	1,404.69	316.67	901.27	190.57	54.29	370.96	0.64	0.23	0.26
Mean	1,419.87	354.54	907.74	146.07	63.36	417.91	0.65	0.25	0.29

Table 3 summarizes the results of the water balance during 2006 to 2014 period. The highest annual rainfall was in the years 2008, 2006, and 2011 at 1839, 1545, and 1527 mm, respectively which produced runoff at 524, 392, and 425 mm while ETa at 963, 964, and 838 mm, and river flow at 613, 472, and 498 mm. The second-largest precipitation (2006) produced the least river flow among these three years due to its lower runoff and higher ETa. This shows that higher precipitation does not mean to produce higher river flow.

The lowest annual rainfall were in the years 2007, 2013, and 2009 at 1,153, 1,183, and 1,303 mm respectively which produced surface runoff at 292, 265, and 296 mm, ETa at 879, 885, and 882 mm, and groundwater recharge at 0, 45, and 149 mm. The precipitation of the year 2007, even though, was much less than that of the year 2013 but it produced runoff as high as that of the year 2013, that is why it could not produce groundwater recharge, it was the only year without groundwater recharge.

From Table 3, we can evaluate the runoff coefficient of the study area as 0.25 for surface runoff and even higher for that of river runoff at 0.3 which is quite high for the mean value of Northeast region e.g. for the Chi-Mun Basin the runoff coefficient is 0.1-0.15 [20]. This discrepancy indicates that the runoff from the study watershed is exceptionally very large due to soil and land-use types. The soils of the watershed are mostly clayey and compact sandy soils of Roi-et series which is the paddy soil (Fig. 2). The main land-use of the study area is paddy field which is saturated most of the time during rice growing season (Fig. 1). The saturated and heavy soil creates high rate of runoff [2].

5. CONCLUSIONS

We presented an effective water balance tool for generating hydrological data from the available and accurate meteorological data for an ungauged or poorly gauged watershed. Rainfall data as well as other essential meteorological data were needed for our procedure. The soil water conservation service-curve number (SCS-CN) method was used to transform rainfall data to surface runoff values with the helped of land-use and soil information. The actual evapotranspiration (ETa) was evaluated from meteorological data using Morton's CRAE method. Knowing 3 hydrological components namely rainfall, runoff, and ETa, the water balance of the root zone proceeded. The groundwater recharge and the river flow were evaluated with the help of baseflow index. The generation of hydrological data for a watershed is very useful for the and reservoir management. It is interesting to compare this method to any accurate gauged data in the future.

6. ACKNOWLEDGMENTS

The authors would like to thanks the Graduate School and Applied Engineering for Important Crops of North East Research Group, Khon Kaen University for funding support. We would also like to thanks the Water Engineering Group, Faculty of Engineering, Khon Kaen University for data supporting

7. REFERENCES

[1] Bloschl, G., Sivapalan, M., Wagener, T., Viglione, A., and Savenije, H., Runoff Prediction

in Ungauged Basins,1st ed. Vol.1, Cambridge University Press, 2013, pp189-225

[2] Chow, V.T., Maidment, D.R., and Mays, L.W., Applied Hydrology., 1988, McGraw-Hill.

[3] Scott, R.L. and Biederman, J.A., Critical Zone Water Balance Over 13 Years in a Semiarid Savanna, Water Resources Research, Vol.55, Issue 1, 2019, pp. 574-588.

[4] Cook, P.G., Hutton, T.J., Pidsley, D., Herezeg, A.L., Held, A., O'Grady, A.O., and Eamus, D., Water Balance of a Tropical Woodland Ecosystem, North Australia: A Combination of Micro-Meteorological, Soil Physical and Groundwater Chemical Approaches, Journal of Hydrology, Vol.210, Issue 1-4, 1998, pp. 161-177.

[5] Hamada, H. and Sukchan, S., Relationship Between Soil Water Content of a Surface Sandy Soil and Groundwater Level in a Study Site in Northeast Thailand, Journal of Japanese Society of Soil Physics, Vol. 110, 2008, pp. 79-87

[6] Moroizumi, T., Hamada, H., Sukchan, S. and Masahiro, I., Soil Water Content and Water Balance in Rainfed Fields in Northeast Thailand, Agricultural Water Management, Vol.96, Issue 1, 2009, pp. 160-166

[7] Hawkins, R.H., Ward, T.J., Woodward, D.E., and Van Mullem, J.A., Curve Number Hydrology: State of the Practice, American Society of Civil Engineers, 2009, pp6-20,

[8] Tailor and Shrimali, Rainfall-runoff Estimation of Bojiang Lake Watershed Using SCS-CN Model Coupled with GIS for Watershed Management, Journal of Applied and Advanced Research Vol.4, Issue 1, 2016, pp. 16-24

[9] Rallison, R.E., Origin and Evolution of the SCS Runoff Equation, Proceeding of the Symposium on Watershed Management 80, 1980, ASCE

[10] Bosznay, M., Generalization of SCS Curve Number Method, Journal of Irrigation and Drainage Engineering, Vol.115, Issue 1, 1989, pp. 139-144.

[11] Ponce, V.M. and Hawkins, R.H., Runoff Curve Number: Has it Reached Maturity? , Journal of Hydrologic Engineering, Vol.1, Issue 1, 1996, pp. 11-19.

[12] Shi, Z-H., Chen, L-D., Fang, N-F., Qin, D-F. and Cai, C-F., Research on the SCS-CN Initial Abstraction Ratio using Rainfall-runoff Event Analysis in the Three Gorges Area China, Catena Vol.77, Issue 1, 2009, pp. 1-7.

[13] Satheeshkumar, S., Venkateswaran, S., and Kannan, R., Rainfall-runoff Estimation Using SCS-CN and GIS Approach in the Pappiredipatti Watershed of the Vaniyar Sub basin South India, Modeling Earth Systems and Environment, Vol.3, Issue 24, 2017, pp. 1-8.

[14] Morton, F.I., Operational Estimates of Areal Evapotranspiration and Their Significance to the Science and Practice of Hydrology, Journal of Hydrology, Vol.66, Issue 1-4, 1983, pp. 1-76.

[15] Bouchet, R.J., Evapotranspiration Reelle et Potentielle, Signification Climatique, International Association of Hydrological Sciences, Symposium Publication Number 62,1963, pp. 134-142

[16] Xu, C.-Y. and Singh, V.P., Evaluation of Three Complementary Relationship Evapotranspiration Models by Water Balance Approach to Estimate Actual Regional Evapotranspiration in Different Climatic Regions, Journal of Hydrology, Vol.308, Issue 1-4, 2005, pp. 105-121.

[17] Guo, D., Westra, S. and Peterson, T., Evapotranspiration: Modelling Actual, Potential, and Reference Crop Evapotranspiration, CRAN-Package Evapotranspiration,2019

[18] Lacombe, G., Douangsavanh, S., Vongphachanh, S. and Pavelic, P., Regional Assessment of Groundwater Recharge in the Lower Mekong Basin, Hydrology, Vol.4, Issue 4, 2017, pp. 1-18

[19] Swatpru, K. and Konyai, S. Base flow index evaluation for Yom River, Thailand. The 2nd International Conference on Engineering and Applied Science (ICEAS), 2013, pp.523-532.

[20] Floch, P. and Molle, F., Water Traps:The Elusive Quest for Water Storage in the Chi-Mun Basin, Thailand, University of Natural Resources and Applied Life Sciences,2009.