Development of Synthetic Unit Hydrograph for Watersheds in Lake Tana Sub-Basin, Ethiopia

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Abstract
Unit Hydrograph (UH) is commonly used technique for the characterization and parameterization of watershed hydrology and design of hydraulic structures. UH study was undertaken in four gauged (Megech, Gummaro, Gumara, and Ribb) and two un-gauged (Ambagenen and G/mariam) watersheds of Lake Tana sub-basin, to estimate coefficients and UH parameters for the watersheds. Twenty nine rainfall-runoff events were used and accordingly, twenty nine one hour duration unit hydrographs were developed. Out of the above UHs, twenty five events were used for calibration and the remaining events for validation of Snyder's model. The best single predictor of Ct was found to be Ad, for Cp it was Dd, and for Cb it was Sl. For UH parameters, the best single predictor of Qp was found to be Fr, L for tp, Ad for Tb. Highest R^2 change come about when composite term HKR was added for Ct, Gray for Cp, and S for Cb. For UH parameters Murphy was added for tp and Tb, and Dd for Qp. Statistical and visual comparison between predicted and observed data, revealed that calibrated Snyder's model was suitable for study region under hydro-meteorological similar watersheds and watershed characteristics within the range of model simulation. Therefore, it could be a grant to estimate the required UH parameters for un-gauged watersheds in the region. UH parameter tp (1.60 and 1.31 hr), Qp (18.06 and 13.92 m^3s^{-1}), and Tb (6.87 and 8.86 hr) were estimated for Ambagenen and G/mariam watersheds, respectively. These could be recommended as input parameters during construction of hydraulic structures and hydrological study of the watersheds. However, further studies are

temporal variations in rainfall, there is no sufficient water to produce more than one time per year. Therefore, to overcome shortage of water, construction of earthen dams and hydraulic structures are required at each of the sub basins. In Ethiopia, projects were launched to develop water harvesting structures. Most of them failed due to the utilization of unreliable data during runoff estimation (Daniel, 1997). For determining design discharge for hydraulic structures, a gauged stream flow data and detail information about the rainfall events for that particular watershed is required. However, in many cases rainfall and runoff data are seldom adequate to determine a unit hydrograph of a basin or watershed. This situation is also common in Ethiopia due to lack of gauging stations along most of the rivers and streams. Generally, basic stream flow and rainfall data are not available for planning and designing water management and other hydraulic structures in most watersheds.

Therefore, techniques have been evolved that allow generation of synthetic unit hydrograph. The peak runoff rate and total runoff volume can be obtained from the design storm hydrographs developed synthetically. The best known approach is Tozefs t!Tzoui fujd!VojuI zesphsbqi!n fui pe!)Sbhi vobui !3117 /!Ui fsfgpsf!ui jt!n pef!m was used for developing synthetic unit hydrographs for un-gauged watersheds in Lake Tana sub-basin. The need for a synthetic method to develop unit hydrograph has inspired many studies (Kull and Feldman, 1998). For calibration and validation of this model basin parameters were collected from DEM with ILWIS software and unit hydrograph (UH) parameters were analyzed from flood hydrograph data collected from Ministry of Water Resource. Besides, coefficients and hydrograph parameters can be modeled in terms of basin characteristics and it will be very helpful for future studies and design works for the hydro-meteorological similar watersheds. Based on the above background, the objective of this study was to develop a synthetic unit hydrograph for selected un-gauged watersheds in Lake Tana sub-basin.

Materials and Methods

Description of the Study Area

Lake Tana sub basin has a catchment area of 15,054 km^2. Geographically it extends between 10.95^{0}N to 12.78^{0}N latitude and from 36.89^{0}E to 38.25^{0}E longitude. The topography of the study area was generally flat where 60% of the area had average slope less than 10%. However, terrain slope within the basin ranged from 0% to 128%. Major and dominant soil types identified within the sub basin are Luvisols, Fluvisols, Leptosols, Vertisols, Alisols, and Cambisols. Annual rainfall distribution ranges from 964 mm up to 2000 mm in the sub basin.

The selection of un-gauged watersheds in the study area was made on the basis of their irrigation potential and hydraulic structure construction priority given by the regional government. The main criteria considered for the selection of gauged watersheds were the availability of concurrent rainfall and stream flow data. Besides, hydro-meteorological similarity between the un-gauged and gauged watersheds was also part of the se;ection criteria. Based on the above criteria two un-gauged watersheds (Ambagenen and G/mariam) and four gauged watersheds (Megech, Gummero, Gummara, and Ribb) were selected and their drainage maps are given in Figure 1.

Snyder's Model Input

In Lake Tana sub-basin, only a small number of streams are gauged. There are many watersheds for which no stream flow records are available and unit hydrographs may be required for such watersheds. For these reasons Snyder synthetic unit hydrograph generation method was generally adopted. When coefficients are known for watersheds, it is possible to determine any duration unit hydrograph for those watersheds. To efwfmpq!b!voju!izesphsbqit!cbtfe!po!Tozefs t!nfuipe!cbtjdbmmz!gjwf!joqvu!parameters are required. These are watershed area, length of main stream from outlet to divide, length from centroid of watershed to outlet, and Ct and Cp (model coefficients). Besides the basic five inputs, three regional constants i.e., base time coefficient (Cb), and the time width coefficients of the unit hydrograph at 50% and 75% of the peak discharge, (Cw50) and (Cw75), respectively and a number of watershed characteristics were considered. These model coefficients were determined from four gauged watersheds in the region and transferred to the un-gauged watersheds. Generally, the basic input data used to analyze the regional coefficients of these watersheds were collected in the following ways.

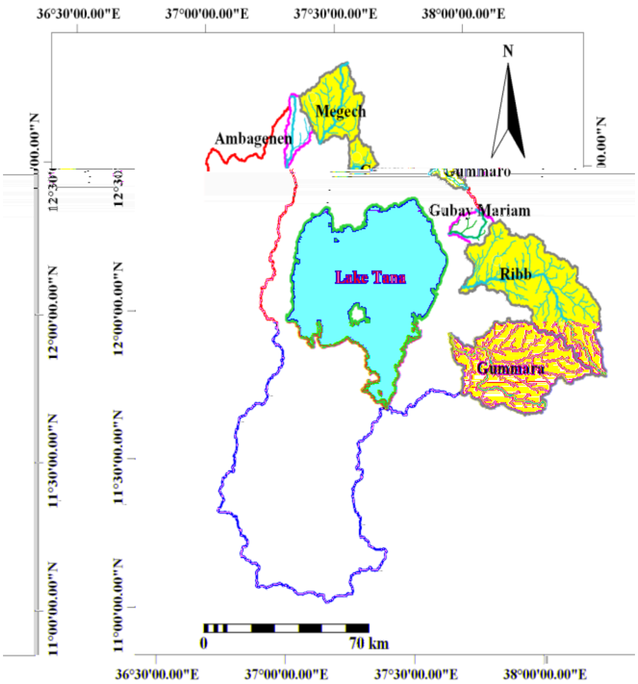

Figure 1. Gauged and un-gauged watersheds used for the study

One of the hydrological data required for this study was the stream flow records taken from automatic continuous water level recorder. The stream flow data for the development of flood hydrographs of the gauged watersheds were collected from Ministry of Water Resources (MoWR) for gauged watersheds. The corresponding rating curve equations were also obtained from the same source. The single peaked water level readings from recording charts were discretized for each gauged river. For this study, twenty nine stream flow data from 1988 through 1995 were used. Out of the twenty nine events only five suitable flood hydrograph events were found at Ribb River, due to frequent siltation problem at the gauging station. For the rest of the watersheds, nine events from Megech River, eight events from Gummaro River, and seven events from Gumara River were generated. Corresponding meteorological data was collected from Ethiopian National Meteorological Service Agency (NMSA). All selected watersheds have rain gauge as per the WMO (1994) recommendation.

The primary elevation data was satellite derived products of the Shuttle Radar Topography Mission digital elevation model data (DEM) with 90 m resolution collected from web site (http:/srtm.csi.cgiar). A multiple step process was enacted in ILWIS

DEM hydro-processing to define watershed characteristics and boundary of the watershed. After the analysis of each step, raster map, segent map, polygon map, and attRibbute table were generated and displayed. The watershed boundary and characteristics were obtained from raster map and attRibbute table generated, respectively. Determining factors which influence the selection of watershed characteristics were requirements to complete the study and extractability with ILWIS DEM hydro-processing. Besides these watershed characteristics, three composite parameters (HKR, Gary, and Murphey) developed by previous researchers (Hickok *et al*., 1959; Gray, 1961; Murphey *et al.*, 1977) were incorporated.

Derivation of Unit Hydrograph from Observed Data

Observed storm hyetographs and their corresponding total runoff hydrographs were studied in detail to derive the required unit hydrograph. Unit hydrographs only model direct runoff hydrographs and they do not account for base flow. The observed hydrographs were separated into base flow and surface flow using straight line base flow separation technique. The total runoff volume for each event was determined by integrating the direct runoff hydrograph. Effective rainfall hyetograph (ERH) was computed by subtracting $\emptyset\Delta t$ from the graph of the observed rainfall, ignoring intervals where ERH is negative. Number of non-zero pulse of rainfall excess (m) was obtained one for all twenty nine events. Thus all unit hydrograph events were one hour duration, since continuous chart was discretized for one hour interval. The ordinates of one-hour unit hydrograph were then computed by dividing the ordinates of direct runoff hydrograph by excess rainfall depth. Therefore nine one-hour UH at Megech, eight one-hour UH at Gummaro, seven one-hour UH at Gummara and five one-hour UH at Ribb were generated. Average unit hydrographs were computed by the arithmetic mean of the peak flows (Q*p*) and times to peak (t*p*) sketching a median line.

Development of Non-Linear Regression Models

A correlation matrix was developed between dependent variables (coefficients and UH parameters) and all single watershed characteristics. Out of all the watershed characteristics, those having high correlation coefficient (r > 0.8) were considered for further analysis. Various forms of least square regression equations were tried to evaluate the relationship between individual coefficients and UH parameters, and one of the watershed characteristics. Then parameters which yielded highest value of coefficient of determination (R^2) were considered for final modeling. In the final stage, coefficients and UH parameters were modeled with all watershed characteristics. These analyses were done using SPSS, statistical analysis software package. The dependent variables obtained in the previous step were listed with descending order of R^2 value. Then non-linear regression models were developed with one of the watershed characteristics having highest R^2 first, then another parameter with next lower value of R^2 was added to find out the improvement in R^2. It was used for selection of the best model for the set of data and also the model giving highest value of R^2 was preferred.

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correlation between main stream length and length from centroid to outlet was very high ($r > 0.99$), the Lca was dropped from further analysis. The correlation matrix is presented in Table 1.

Least square equations of all forms (linear, logarithmic, power, exponential, and polynomial) were developed, taking regional coefficients as dependent variables and individual watershed characteristics as independent variables. It was found that equations developed in the power form had higher coefficients of determination (R^2) as compared to the other forms of equations for the same variables in all cases. So, equations in the power form were used to relate dependent variables with individual watershed characteristics. The best single predictor of C_t was found to be Ad, for C_p it was Dd, and C_b it was Sl. Since these results have not been tested for other regions or basins, they cannot be accepted as general, but still they will provide information about the study region. The best-fit regression equations are listed below.

$C_t = 0.018\ Ad^{0.41}$ $(R^2 = 0.942)$

$C_p = 5 \times 10^{-18}\ Dd^{6.156}$ $(R^2 = 0.923)$

$C_b = 0.139\ Sl^{0.79}$ $(R^2 = 0.955)$

For unit hydrograph parameters, the best single predictor of Q_p was found to be Fr, L for t_p, Ad for T_b. The best-fit regression equations are listed below.

$Q_p = 22.21\ Fr^{1.258}$ $(R^2 = 0.934)$

$t_p = 0.174\ L^{0.666}$ $(R^2 = 0.965)$

$T_b = 1.084\ Ad^{0.336}$ $(R^2 = 0.928)$

Development of non-linear models

The non-linear regression models were developed with one of the watershed characteristics having highest R^2 first, and then another parameter with the next lower value of R^2 was added to find the change in R^2 value. Based on this, it was found that by incorporating Dd, and Sl in the model developed for estimating Ct, the R^2 value increased from 0.942 to 0.995. Similarly the following models were developed for estimating regional coefficient based on highest R hydrograph shape was observed in all watersheds. For all watersheds the calibrated models did not perform well around hydrograph peak. It showed far too little attenuation of peak discharge for Gummaro and Megech watersheds and slight over prediction of peak discharge for Gummara and Ribb watersheds. Besides, slight delayed time to peak than observed hydrograph was observed for Gummara watershed. In hfofsbmdbmjcsbufe! Tozefs t!n pefmt bsf! bddfqubcmf! gps! uif! tuvez! xbufsti fet! cbtfe! po! uif! graphical comparison as per the guidelines of ASCE Task Committee (1993), except slight under estimation and over prediction of basic UH parameters.

Statistical evaluation

As indicated in Table 4.5, low positive values of CRM for t_p, T_b, W50, and W75 show ui bu ui f! dbmjcsbufe! Tozefs t! n pefmt i bt! b! tmjhi u! ufoefodz! pg! voefs! qsfe jdujpo !x i fsfbt! ju has slight tendency of over prediction for estimating Q_p. Tuvefou t! u-test results indicated critical t value is greater than the t-calculated value, which revealed that all predicted UH parameters had no significant difference to the observed UH parameters at P > 0.05.

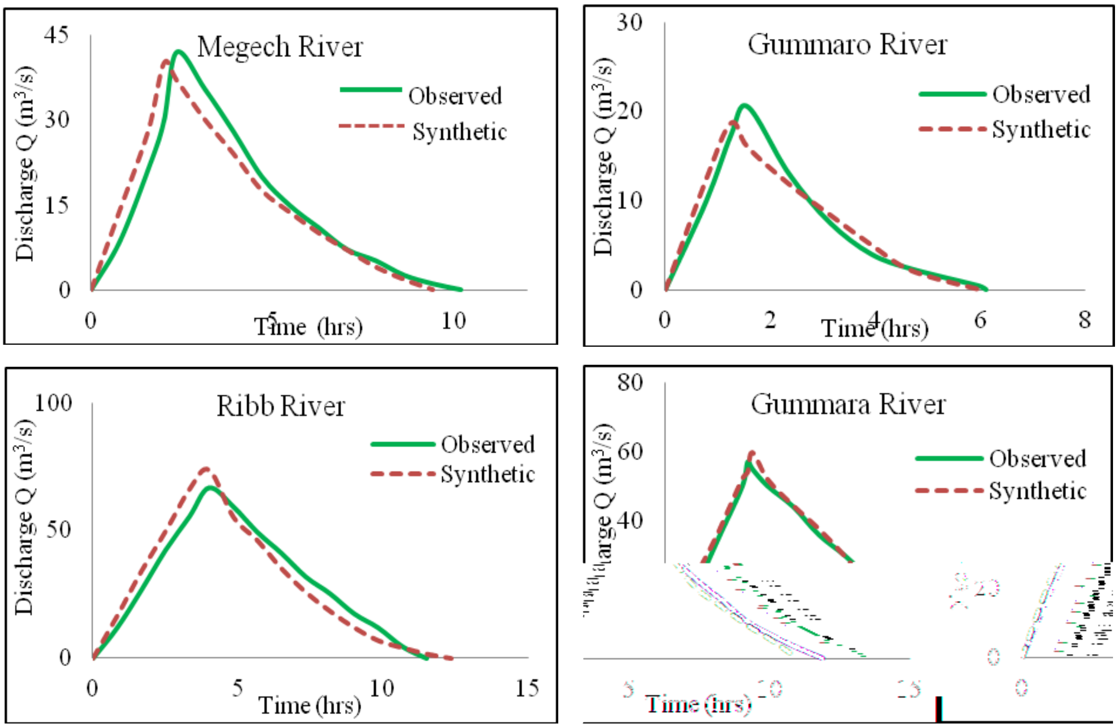

Figure 2. Observed Vs Synthetic unit hydrograph for gauged watersheds

Development of One Hour Duration UH for Un-gauged Watersheds

Tozefs t! tzoui fujd! vojl i zesphsbqi! qbsbn fufst! gps! Bn c bhfofo! boe! H0n bsjbn! vo-gauged watersheds were estimated in accordance to Ramirez (2000) and Arora (2004). As shown in the Figure 3, the estimated peak discharge was to be 18.06m^3/s and 13.92m^3/s their respective time to peak was 1.6hr and 1.31hr for Ambagenen and G/mariam watersheds, respectively. Ambagenen and G/mariam un-gauged watersheds had a time base of 6.87hr and 8.86hr, respectively. Time width of hydrograph at 50% of peak discharge was estimated to be 1.74hr and 1.95hr for Ambagenen and G/mariam watersheds, respectively. Time width of hydrograph at 75% of peak discharge was the estimated time width at 75% of peak discharge to be 0.73hr and 0.95hr for Ambagenen and G/mariam watersheds, respectively.

Table 2. Performance evaluation of developed models using different statistical tests

Name of watersheds	**Unit hydrograph parameters**									
	t_p		**Q_p**		**T_b**		**W50**		**W75**	
	Obs.	**Syn.**	**Obs.**	**Syn.**	**Obs.**	**Syn.**	**Obs.**	**Syn.**	**Obs.**	**Syn.**
Megech	2.35	1.97	42.05	40.19	10.12	9.38	2.86	2.59	1.43	1.22
Gummaro	1.57	1.25	20.48	18.71	6.11	5.90	1.89	1.81	0.79	0.84
Gummara	2.94	3.11	55.64	60.79	11.91	11.21	4.53	4.45	2.27	2.06
Ribb	4.00	3.84	66.27	73.54	11.50	12.71	4.35	4.24	2.12	1.96
CRM	0.064		-0.048		0.011		0.040		0.080	
t-calculated	0.223		-0.141		0.056		0.150		0.294	
Critical table value ($t_{0.99,6}$) of t-distribution = 3.707										

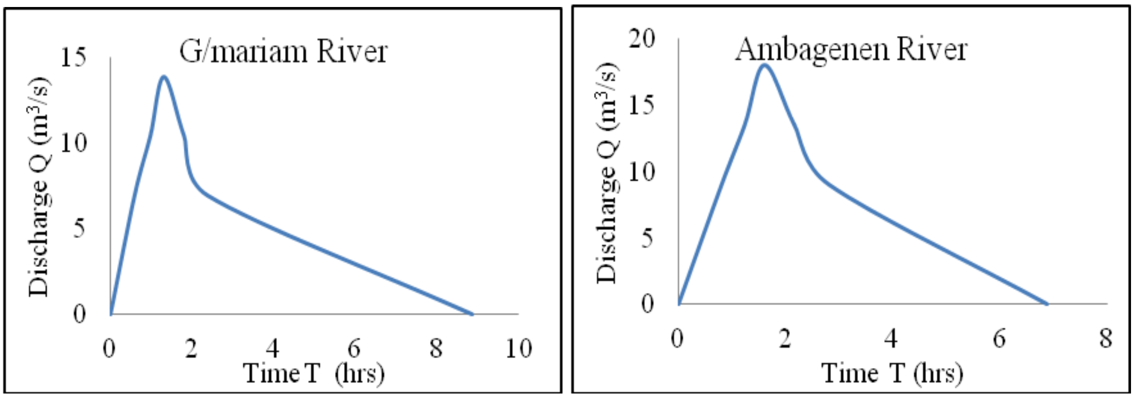

Figure 3. One hour duration synthetic unit hydrograph for un-gauged watershed

Conclusion and Recommendations

This study provided a unique opportunity to estimate unit hydrograph parameters for un-gauged watersheds and the relationship between regional coefficients and unit hydrograph parameters with watershed characteristics in northern and eastern part of Lake Tana sub-basin. The following conclusions had been drawn on the basis of results obtained from the study for the prevailing sub watersheds

1. Wbmvft! pg! uif! dpfggjdjfout! pg! uif! Tozefst synthetic unit hydrograph (SUH) equations estimated in this study were seen to have quite considerable variation from values obtained by other investigators in some other regions.
2. Regional coefficients (C_t, C_p, and C_b) and respective unit hydrograph parameters having high variation among gauged watersheds could be modeled with geomorphologic parameters, which could subsequently be used to generate unit hydrographs for un-gauged basins of similar hydrologic condition.
3. Bothe visual and statistical test revfbmfe! uibu uif! dbmjcsbufe! Tozefst! npefmt! ibwf! well performed, except slight under estimation and over estimation of basic unit hydrograph parameters
4. Synthetic unit hydrograph developed for Ambagenen and G/mariam watersheds based on mean value of time width coefficients, borrowed coefficients and equation would contribute a lot in water resource management and planning works.

In developing such models it is very important to have adequate and reliable sets of hydrological and meteorological data. Unless these data are reasonably sufficient and reliable it is difficult to have better estimate of the required coefficients as they vary quite considerably from region to region. Thus it is recommended that:

- Applying the equations may result in reliable synthetic unit hydrographs, as long as the physical characteristics of the watersheds under consideration are within the range of these characteristics for the gauged watersheds considered in this study. However, for more reliable results the coefficients and equations should be tested on hydro meteorologically similar gauged catchment, which has reliable data set and can be modified accordingly.

- The conclusions from this study are based on four stream flow and three automatic recording rainfall station data. For future studies, large number of station data, specially automatic rainfall recording data should be incorporated to achieve better result.
- In this research empirical equation to estimate regional coefficients and unit hydrograph parameters are modeled with only physical watershed characteristics. However, both rainfall and watershed characteristics should be studied together to improve explanation power of the model.

References

Arora, K. R., 2004. Irrigation, Water Power and Water Resources Engineering. Standard Publishers Distributions, NAI SARAK, Delhi. 79   106p.

ASCE Task Committee on Definition of Criteria for Evaluation of Watershed Models, 1993. Criteria for evaluation of watershed models. *Journal of Irrigation and Drainage Engineering*, 119 (3): 429   442.

Daniel Gamachu, 1997. Aspects of climate and water budget in Ethiopia, A technical monograph. Addis Ababa university press, Addis Ababa.

Gray, D. M., 1961. Synthetic unit hydrographs for small watersheds. *Journal of Hydraulics Division, Proceedings of ASCE* , 87(HY4): 33   54.

Haan, C. T., B. Allred, D. E. Storm, G. J. Sabbagh, and S. Parbhu, 1995. Statistical procedure for evaluating hydrological water quality models. *Transaction of the American Society of Agricultural Engineers*, 38 (3): 725   733.

Hack-ten Broeke, M. D. and J. H. Hegans, 1996. Use of soil physical characteristics from laboratory measurements or standard series of modelling unsaturated water flow. *Agricultural Water Management*, 29 (2): 201   213.

Hickok, R. B., R. V. Keppel, and B. R. Rafferty, 1959. Hydrograph synthesis for small arid land watersheds. *Agricultural Engineering*, 40(10): 608   611.

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Murphey, J. B., D. L. Wallace, and L. J. Lane, 1977. Geomorphic parameters predict hydrograph characteristics in the southwest. *Water Resources Bulletin of the American Water Resource Association*, 13 (1): 25   38.

Raghunath, H. M., 2006. Hydrology principles, Analysis, and Design. New Age International Publishers, New Delhi. 104   106p.

Ramirez, J. A., 2000. Prediction and Modeling of Flood Hydrology and Hydraulics. In : W. Ellen (Ed). Inland Flood Hazards: Human, Riparian and Aquatic Communities, Chapter 11. Cambridge University Press, UK.

Seleshi Bekele, Aster Denekew, Makonnen Loulseged, Willibald Loiskandl, Mekonnen Ayana, and Tena Alamirew, 2007. Water Resources and Irrigation Development in Ethiopia. International Water Management Institute, Colombo, Sri Lanka.

World Meteorological Organization, 1994. The science and forecasting of tropical cyclones. Geneva, Switzerland.

Xevi, E., J. Gilley, and J. Feyen, 1996. Comparative study of two crop yield simulation models. *Agriculture Water Management*, 30: 155   173.

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