RECOGNISING TEMPORAL VARIABILITY OF LUMPED WATERSHED BEHAVIOUR AND EVALUATING AVERAGED PERFORMANCE OF A HYDROLOGIC MODEL

W.M.D Wijesinghe ,
Research Assistant (Department of Civil Engineering, University of Moratuwa)
(email: dulanjanw@gmail.com)
N.T.S. Wijesekera,
Senior Professor (Department of Civil Engineering, University of Moratuwa)
(email: sohan@civil.mrt.ac.lk)

Abstract: Majority of watersheds associated with civil engineering infrastructure projects are ungauged and most commonly used method to determine streamflow in ungauged basins is mathematical modelling with the use of Synthetic Unit Hydrograph (SUH) technique. Mathematical models require watershed characteristics to be spatially and temporally averaged. The SUH is an event based model which estimates direct runoff. Hence model calibration and verification requires event based evaluations with a baseflow separation effort or a method incorporating a baseflow model to combine with the SUH model and generate total runoff. In this study, a rainfall runoff model was developed using SUH and a linear baseflow concept while selecting the watershed of Attanagalu Oya at Karasnagala as the study area. Other than the SUH parameters to be identified, the conceptual model used for this work consisted of 5 model parameters to be optimised. The main objective of this research was to identify the issues during calibration and verification of this five parameter model. Model calibration was carried out for 30 datasets, selecting the Mean Ration of Absolute Error (MRAE) as the objective function. Optimum model parameters for each event were determined and the most probable range of values for each parameter was computed. Using 30 datasets, model verification was carried out by assuming that the average of each range would lead to a representative watershed model. A successful calibration produced a good match of observed and calculated streamflows with a MRAE of 0.34. Parameter optimisation revealed the inability to obtain an average initial moisture level for the entire watershed while catering both wet and dry conditions. The runoff coefficients and rainfall thresholds also indicated the need of further investigations. Event based modelling approach in this work provides an insight to the watershed behaviour and to the appropriateness of model parameters, however in order to identify the spatially and temporally averaged parameters it is necessary to carryout optimisations using a lengthy data series together with an appropriate model.

Keywords: Synthetic unit hydrograph, Parameter selection, Model calibration, Rainfall-runoff modelling, Sri Lanka

---

1. Introduction

Streamflow estimations from ungauged watersheds is a challenge faced by many engineers, hydrologists and watershed managers. The world over, majority of stream reaches which require streamflow information are ungauged (Young, 2006). In Sri Lanka out of 103 major basins only 13 gauging stations are in existence (Hydrological Annual, 2010). Information on streamflow is a central component for water resource and water quality engineering and management. Incorporation of mathematical models either physical, empirical in nature or their combinations is the most commonly used method for streamflow estimations.

Though there are many watershed models which facilitate the estimation of watershed runoff, the most sought models are those which can be used to estimate runoff generation from ungauged watersheds. Sherman (1932) introduced the theory of Unit Hydrograph (UH) for the generation of direct runoff from a catchment, which is still considered as one of the most important contributions to hydrology especially with work on ungauged watersheds. Synthetic Unit Hydrograph (SUH) is the only available UH derivation method for direct runoff estimation from ungauged watersheds.

Mathematical modelling of watersheds require conceptualisation of the reality to suit a particular requirement whether it is flood control, water management or design of water infrastructure. Watersheds and their porous soil mass covered with vegetation demonstrate a wide spatial heterogeneity and a temporal variability. Lumped watershed models attempt to aggregate both spatial and temporal variability in order to capture the requisite watershed behaviour, while spatially distributed modelling try to incorporate a lesser aggregation of spatial variability. In case of calibration, a model would identify a set of parameters that would reproduce the streamflow variations over a significant time period or reproduce a set of selected sections from a hydrograph spanning over a longer duration.

The calibration and verification of direct runoff models require either a baseflow separation from the observations or a baseflow generation model coupled to the direct runoff generation model. Modelling of direct runoff is an event based task and hence a modeller is required to calibrate individual events which take place at various stages in the annual hydrological cycle. In this task the modeller has to consider the temporal variation of watershed parameters such as initial storage, runoff coefficient, baseflow coefficient etc.

The most common method of handling such variations is to conceptualise threshold parameter values in order to represent circumstances such as wet and dry conditions, flat and hilly terrain, change of monsoonal winds etc. In this backdrop the present work carried out the development of a conceptual watershed model with a UH concept coupled to a baseflow generation component in order to estimate streamflows for selected sections of rainfall time series. Selected sections were chosen to represent peakflows that occurred at the gauging point.

2. Objectives

The following tasks were undertaken as the objectives of the present work.

(i) Develop a hydrologic model having a UH concept to represent direct runoff and a linear storage concept to conceptualise the baseflow

(ii) Identify optimum model parameters to predict streamflows from a particular rainfall dataset

(iii) Evaluate parameter behaviour with individual events and make recommendations for model development

3. Methodology

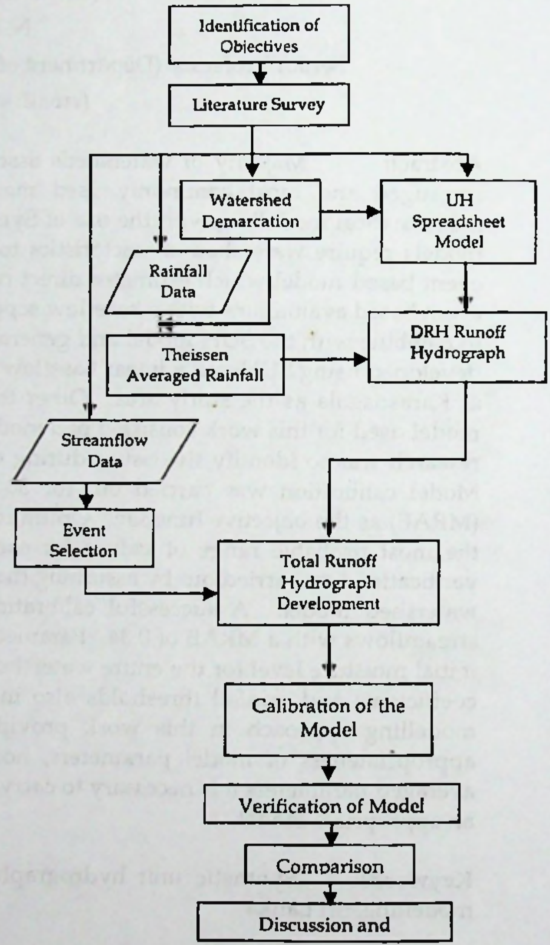

Figure 1: Methodology Flowchart

The methodology used for the present work (Figure 1) included a literature survey, identification and checking of data, model development, model calibration and verification.

There are several methods that are popularly used for unit hydrograph model development. They are the Rational method (Ponrajah, 1984), US Soil Conservation Service (SCS) method (Chow, Maidement and Mays, 1988), and Snyders method (Mays, 2004). Though, there are several publications on the comparison of results generated with the use of these methods, it is still not clear which method could be recommended for a particular watershed or for a particular purpose. In the published literature there are only limited cases pertaining to applications in the Sri Lankan context. Among them there are two on the application of SCS method. Wijesekera (2000) in a comparison of SCS and other UH applications for small urban watersheds have indicated a wide variation of outputs. Batuwitage, Manchanayake and Wickramasuriya (1986) applied Rational Method, Snyder's Method, SCS Methods for peak flow estimation and compared the results with the outputs from the Statistical Methods. Zlatunova, Gergov and Littlewood (2002) developed a UH based flow simulation model for five Bulgarian Rivers, discussing the potential of the UH approach in assisting with regional surveys and water resources management. In this model, a preliminary assessment of the suitability of a UH-based modelling methodology for application to small and medium-sized rivers in south-east Europe has been carried out. Yen and Lee (1997) used the Geomorphic Instantaneous UH Method for two hilly watersheds in the Eastern United States and two flat-slope watersheds in Illinois, where a comparison between the simulated and observed hydrographs for a number of rainstorms has indicated its potential in watershed rainfall-runoff analysis.

Different techniques have been used for modelling the watersheds whose watershed parameters are spatially distributed. Saghafian, Julien and Rajale (2002) used variable isochrone techniques to simulate the runoff hydrographs for a 15.6 ha pilot watershed in West Africa. This work had utilised a raster based runoff simulation of rainfall intensity and infiltration rate to model the watershed.

Several sub watershed approaches have been cited to incorporate spatial heterogeneity. Maidment, (1993) applying a distributed model integrating a cell based system had used isochones for sub watershed division. Perera and Wijesekera, (2010) carried out a study to identify the spatial variability of runoff coefficients of three wet zone watersheds of Sri Lanka featuring a GIS analysis where model calibration and verification has been carried out satisfactorily. This work had been based on the development of a MIKE BASIN model consisting of 18 sub watersheds.

Linear storage concept is widely used to represent watershed baseflow behaviour (U.S. Army, 1980, Wijesekera, 2000). Model calibration and verification techniques for Parameter optimisation use several objective functions (WMO, 1986). Among them the mostly used indicator is the Mean Ratio of Absolute Error (MRAE) (Wijesekera and Gnanapala, 2003, Nandalal and Rathnayake, 2010, Perera, 2011). The MRAE which provides guidance on the degree of matching with respect to two datasets consider the mean deviation of model predictions (Equation 1).

$$MRAE = \frac{1}{n}\sum\frac{|(q_1-q_2|}{q_2} \qquad \text{......} (1)$$

where, q_1 is usually the calculated data while q_2 is the observed data. n is the number of data in each data set.

4. Data

Present work selected the Karasnagala watershed of Attanagalu Oya due to the availability of a lengthy gauged data series. Attanagalu Oya is one of the 103 major rivers of Sri Lanka, located in the Western Province. Watershed at Karasnagala (Figure 2) is located at the upper most section of the river basin. Streamflow measurement of Attanagalu Oya had been carried out from 1970 to 1982 at the Karasnagala gauging station. Since 2005, the gauging station had been moved from Karasnagala to Dunamale which is further downstream of the river. Annual average rainfall and streamflow values for the considered study period are 1433mm and 242 MCM, respectively. Karasnagala Watershed has an area of 52.8 km². Gauged streamflow data of this basin has been checked extensively during previous studies (Prerera, 2010, Wijesekera and Perera, 2012). Prior to modelling, the entire rainfall and streamflow data series was plotted and checked for any visual inconsistencies. The topographic survey sheets of 1:10,000 published by the Survey Department of Sri Lanka were used for the watershed delineation. Length of the longest stream of the watershed is 9.8km and the slope of the watershed along the longest stream is 2.34%. The watershed is at a rural setting with a very small urban area. The main land use classes are paddy, forest, scrub and commercial cultivations like rubber, tea and coconut. Field visits were undertaken to observe the watershed and drainage characteristics.

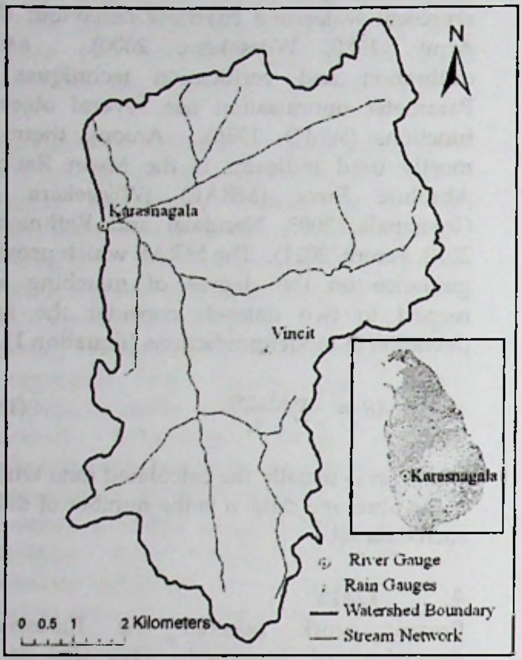

Figure 2: Karasnagala Watershed

5. Modelling

The work described in this paper conceptualised the entire watershed as a single lumped system (Figure 3), where the direct runoff from effective rainfall is combined with linear baseflow storage to generate the Total Runoff (TRO). In this model, the only input is rainfall (R_t) and the outputs are Direct Runoff (DR) and Baseflow (BF).

Since the measured rainfall values are available in daily resolution, computational time resolution was taken as one day. In this particular time interval, the amount of effective rainfall is C_tR_t where, the fraction of rainfall converted to direct runoff is indicated by the runoff coefficient, C_t. The model incorporated two runoff coefficient thresholds to represent the runoff variation during high and low rainfall events. These two runoff coefficients, C_L and C_H were taken as two model parameters to be calibrated. C_L denotes the coefficient for low rainfall values while C_H is the coefficient for high rainfall values. Demarcation of the boundary of runoff coefficients was done with the use of a rainfall threshold value, R_0 which is also a model parameter. Direct runoff computations were based on the Unit Hydrograph model [$U(t)$] using effective rainfall as input. It was assumed that the amount of rainfall which does not contribute to direct runoff, would infiltrate to enhance groundwater storage and later appear as baseflow. Accordingly the infiltration amount is $R_t(1-C_t)$. Since baseflow was taken as directly proportionate to the watershed storage (S_t), the amount of baseflow from the watershed is αS where α is the coefficient of proportionality. The parameter m_i was taken as the model parameter representing the initial moisture content of the system.

SCS UH equations were used for the determination of UH. In the $U(t)$ a standard UH was determined first for a standard rainfall duration of t_r. Time to peak, T_p and the peak discharge, Q_p of the standard UH were computed following Equations (2) to (5) (Maidemnt, 1994).

$$T_c=0.002L^{0.77}S^{-0.395} \quad ..... (2)$$
$$T_p = 0.7T_c \quad .....(3)$$
$$t_r = 0.133T_p \quad ..... (4)$$
$$Q_p = (0.208A)/T_p \quad ..... (5)$$
$$t_p = T_p - t_r/2 \quad ..... (6)$$
$$t_{pR} = t_p+(t_R-t_r) \quad ..... (7)$$
$$T_{pR} = t_{pR}- t_R/2 \quad ..... (8)$$
$$Q_{pR} = 0.375A/2T_{PR} \quad ..... (9)$$

Basin lag of the standard UH, t_p can be calculated by Equation (6). According to Mays (2004), the basin lag of the UH of required duration, t_R is calculated by Equation (7). The required duration was selected as 1 day, since the computational resolution of the model is 1 day. Time to peak, T_{PR} and the Peak discharge, Q_{PR} of the 1 day UH were calculated using equations (8) to (9). In the equations Length of the longest watercourse, L, Watershed slope, S and Watershed Area, A are watershed parameters. The UH was converted to curvilinear UH using the SCS dimensionless parameters (Chow, Maidment and Mays, 1988). The area under the UH was checked for unity. In the case of discrepancy, the noted minor differences were adjusted by distributing the error proportionate to the hydrograph ordinates.

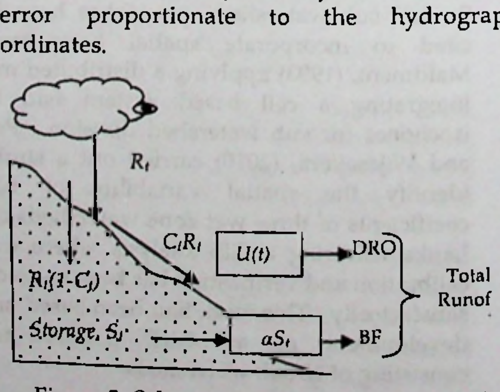

Figure 3: Schematic Diagram of the Model

After examining the observed streamflow and rainfall time series, 60 data sets were separated from the selected date series. Thirty were used for model calibration and the other 30 were used for verification. Optimisation of parameters C_H, C_L, R_0, α and m_I was done using a systematic trial and error methodology by minimising the MRAE.

6. Results

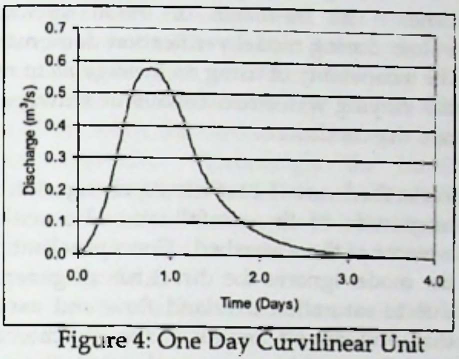

Figure 4: One Day Curvilinear Unit Hydrograph of Karasnagala Watershed

Table 1: Conceptual Model Parameters of Calibration Dataset

Event No.	α	m_I	C_H	C_L	R_0	MRAE
1	0.01	450	0.16	0.43	58	0.3915
2	0.001	11300	0.1	0.23	50	0.1416
3	0.1	75	0.85	0.41	56	0.2543
4	0.05	85	0.01	0.5	20	0.4496
5	0.01	700	0.9	0.52	20	0.5765
6	0.004	1400	0.32	0.0005	74	0.1643
7	0.4	4	0.01	0.88	93	0.8264
8	0.02	600	0.1	0.48	66	0.2620
9	0.02	350	0.17	0.88	92	0.3255
10	0.001	2000	0.2	0.2	80	0.0959
11	0.001	6100	0.12	0.14	69	0.0356
12	0.01	850	0.145	0.8	66	0.3985
13	0.002	3550	0.18	0.009	63	0.1842
14	0.02	205	0.36	0.99	137	0.2549
15	0.1	76	0.14	0.5	67	0.4393
16	0.03	150	0.09	0.17	49	0.1078
17	0.02	310	0.47	0.25	39	0.1025
18	0.01	100	0.7	0.1	177	0.4679
19	0.01	280	0.36	0.3	35	0.2214
20	0.003	1000	0.3	0.3	91	0.1455
21	0.045	100	0.27	0.292	58	0.4718
22	0.001	11300	0.2	0.43	50	0.1974
23	0.08	90	0.75	0.44	56	0.2338
24	0.05	85	0.01	0.6	20	0.4211
25	0.01	700	0.9	0.32	20	0.1987
26	0.02	260	0.31	0.001	74	0.1043
27	0.4	4	0.01	0.78	93	1.1198
28	0.02	600	0.1	0.38	66	0.0443
29	0.02	350	0.17	0.78	92	0.3070
30	0.001	2000	0.2	0.1	80	0.0141
Maximum	0.400	11300	0.900	0.990	177	0.0356
Minimum	0.001	4	0.010	0.001	20	0.8264
Average	0.049	1502	0.287	0.407	[illegible]	[illegible]

The curvilinear one day Unit hydrograph of the Karasnagala watershed is shown in Figure 4.

Time to peak and peak discharge of the Standard Unit Hydrograph Parameters computed for the watershed are 67.15minutes and 9.77m³/s respectively. The same for the one day UH are 1140minutes and 0.58m³/s. Parameters pertaining to α, m_I, C_H, C_L and R_0 for the 30 calibration datasets are shown in the Table 1 and Figure 5. The parameter values were categorised to identify the most frequently occurring ranges and the average values of each most frequent range for α, m_I, C_H, C_L and R_0 are 0.01, 265mm, 0.296, 0.126, 67.67mm respectively.

The MRAE value for each event during calibration showed good matching with an overall average value of 0.3423 for the 30 events. Two calibrated data sets with one showing a good matching and the other showing a relatively poor matching are shown in the Figure 6.

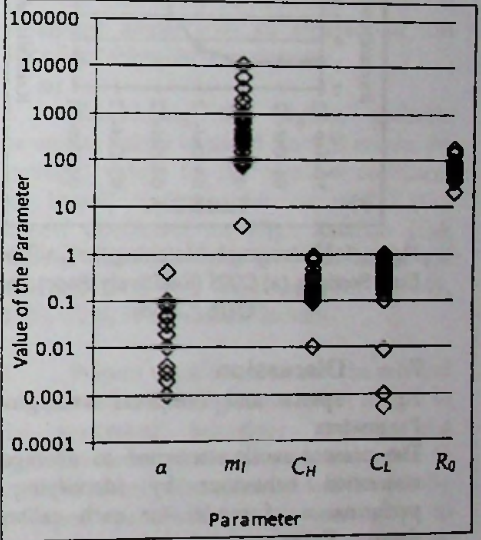

Figure 5: Conceptual Model Parameters of Calibration Dataset

The average set of calibration parameters were used with the verification data set. In general, the matching of hydrographs were not successful and the MRAE values reflected the poor performance. Outputs showed that four verification data sets were very poorly matched by model predictions with average datasets. These four datasets, which had problems with the initial moisture levels, produced excessively high peak runoff values leading to MRAE values of 4.1875, 2.8628, 2.0386 and 3.994. Other than these four events the other 26 verification data sets produced an average MRAE value of 0.4901 which still falls in the category of poor performance.

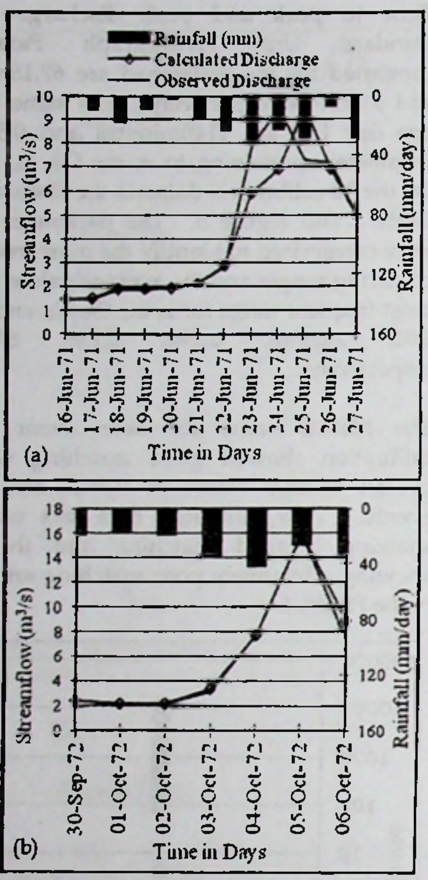

Figure 6: Hydrograph Matching for Calibration Date Sections (a) C008 (Relatively Poor) and (b) C016 (Good)

7. Discussion

7.1 Spatial and Temporal Averaging of Parameters

The present work attempted to average the watershed behaviour by identifying the performance of model for each calibration dataset. Parameter optimisation corresponding to each calibration dataset showed very good matching reflecting the representativeness of the conceptual model which was used to mathematically model the Karasnagala watershed. The matching of each individual event with a low MRAE is a good demonstration of the ease of spatially lumping the hydrological processes for individual events of short duration. The variability observed with each parameter shows the difficulty that would be faced by a modeller when attempting to model the temporal variability of watershed responses. This work identified the parameters of most frequently experienced events in order to obtain a temporally averaged set of spatially averaged parameters. Poor model verification results showed that such averaging does not lead to representative streamflow estimates.

7.2 Parameter Value Variations

During model calibration, the Initial moisture level (m_I), expressed as a per unit area value varied between 4mm and 11,300mm. This wide variation of values noted during calibration is an indication of the inappropriateness of using m_I as a model parameter to be averaged over time. The mismatch of initial streamflow values during model verification demonstrated the incapability of using an average m_I to reflect the varying watershed behaviour between wet and dry conditions.

Watershed runoff coefficients change with the magnitude of the rainfall and also with the wetness of the watershed. Conceptualisation in the model ignores the direct runoff generation due to saturation overland flow and assumes that any runoff increase due to catchment rainfall would occur only by increased baseflow. In the search for a simple watershed model, the saturation overland flow component was not considered in the present work.

The model used in this work made an attempt to simplify the variation of watershed runoff by using a rainfall threshold value as a parameter to reflect two rainfall dependent runoff coefficients which were also optimised as parameters. Two runoff coefficients C_L and C_H varied in the range of 0.01-0.9 and 0.0005-0.99 respectively. Threshold rainfall value R_0 varied between 20.18 to 177.13mm. The ranges of runoff coefficient variation in case of both parameters show that the values occupy the full range available for fluctuation. Results from verification dataset showed that the peaks estimated by the model were significantly different to the observed streamflow peaks. It was observed that on many occasions the predictions were out of phase indicating the incapability of averaged values to effect a suitable delay in the response.

The dimensionless baseflow coefficient (α) varied from 0.001 to 0.4. This parameter has a upper limit which is a relatively high value for the baseflow. This reflects the problem of sub surface runoff prediction with a single coefficient catering to both baseflow and interflow. The indication is that the catchment wetness fluctuations do not permit an averaged coefficient to represent the entire watershed spatially and temporally.

Another factor that could be attributed to the parameter fluctuation is the assumption of a uniform rainfall over the entire catchment and the resolution of base data being 1 day duration. These factors cause difficulties in the reproduction of streamflows from a watershed which has a significant heterogeneity.

7.3 Parameter Outliers

A study of baseflow coefficient variation during calibration showed that the values reached 0.4 only in two occasions. Investigation of these two data sets revealed that the streamflow value at the start of the dataset is small compared to that of other datasets. This requires the m_I values to be kept low but a need arose to match the direct runoff at subsequent time intervals. Accordingly the baseflow coefficient required an increase. The model showed a need to incorporate the direct runoff increase that could be noted with an increased saturation of soil.

The runoff coefficient for low rainfall (C_L) varied between 0.001 and 0.9, however values closer to 0.9 were found only in the case of four events. These four events have recorded lesser rainfall values when comparing with other events generating similar streamflows. Since the baseflow component is not adequate to represent the fluctuations in the total hydrograph, direct runoff component in the calculated hydrograph required an increase. A higher C_L values was given for the purpose of obtaining a higher direct runoff at lower rainfall conditions.

The runoff coefficient for High Rainfall (C_H) reached a value closer to unity only in one rainfall event. In all other events the values were much lower. When the behaviour of the model was evaluated, it could be noted that major contribution has been from the larger rainfall datasets which assigned larger values for the high rainfall-runoff coefficient.

In one event the threshold rainfall reached a high value when compared with the others. This is due to the incompatibility noted in the rainfall data and the associated streamflow observations. The initial moisture level reflected two outliers with relatively higher values. The need to achieve higher baseflow responses in the observed hydrographs was fulfilled by assigning large values to the initial moisture level.

7.4 Model Performance

In this work it was noted that the calibration of individual events provided the opportunity for the modeller to obtain an insight to the watershed behaviour and the appropriateness of the parameter usage to fulfil the modelling objectives. However using individual and specific datasets for model calibration and verification does not provide opportunity for a modeller to use the full potential of calibration to optimise the parameters for temporal and spatial averaging of watershed behaviour. The present work revealed difficulties with the initial moisture level, the incorporation of runoff coefficients and the issues of threshold rainfall event. Therefore the calibration of individual events could only be used to understand the watershed behaviour for a modeller to subsequently carry out continuous modelling to arrive at representative parameters.

5. Conclusions

1. Calculated streamflow of selected data sets representing hydrograph peaks could be matched with observed streamflow from the developed model with an accuracy of 0.34 MRAE for the calibration dataset.

2. Considering the highest probable parameter values obtained from 30 events, the averaged values for the baseflow coefficient (α), Runoff coefficient for low rainfall (C_L), Runoff Coefficient for High Rainfalls (C_H), Rainfall threshold value (R_0) and Initial soil moisture level (m_I) were identified as 0.01, 0.126, 0.296, 67.67mm and 265mm

3. Present work revealed that the selected event based modelling provides an insight to the watershed behaviour and to the appropriateness of model parameters, but in order to identify the spatially and temporally averaged parameters it is necessary to carryout optimisations using a lengthy continuous data series together with an appropriate model.

References

Batuwitage, L. P., Manchanayake, P., Wickramasuriya, S. S., 1986, A Comparative Study of Some Design Flood Estimation Methods for Sri Lankan Catchments, *Engineer, Journal of Institution of Engineers, Sri Lanka* , 3-13.

Chow, V.T, Maidment, D.R., Mays, L.W., (1988), Applied Hydrology, McGrow Hills

Hydrological Annual 2008/2009, 2010, Hydrology Division, Deparment of Irrigation, Colombo, Sri Lanka.

Hydrographs by Single Linear. Reservoir Model. (1980), Hydrologic Engineering Centre, U.S. Army Corps of Engineers

Maidment, David R., "Developing Spatially Distributed UH by Using GIS", Hydro GIS 93: *Application of Information Systems in Hydrology and Water Resources*, 1993

Mays, Larry W., *Water Resources Engineering*, 2005 ed., John Wiley and Sons Inc., 2005

Nandalal, H. K., Ratnayake, U. (2010). Event Based Modeling of a Watershed Using HEC-HMS. Enginer, Journal of Institution of Engineers Sri Lanka , 28-37.

Perera, K.R.J, Wijesekera, N.T.S., "Identification of Spatial Variability of Runoff Coefficients of Three Wet Zone Watersheds of Sri Lanka", *3rd International Perspective on Curren and Future State of the Water Resources and the Environment*, Chennai, India, 2010

Perera, K.R.J, "Model Development Using Geograpic Information Systems-A Comparative Analysis of Attanagalu Oya" (M.Phil Thesis), Deparment of Civil Engineering, University of Moratuwa, , 2010

Ponrajah, A.J.P., (1984), Design of Irrigation Headworks for Small Catchments, Department of Irrigation, Sri Lanka.

Ritzema, H.P., *Drainage Principles and Applications*, 2nd ed., International Institute for Land Reclamation and Improvement, Wageningen, the Netherlands, 1994

Saghafian, B., Julien, P., Rajale, H., "Runoff Hydrograph Simulation Based on Time Vriable Isochrone", *Journal of Hydrology*, 261 (2002) 193-203 , 2002

Sherman, L.K., "Stremfllow from Rainfall by Unit-Graph Method", *Engineering News Record*, 1932

Wijesekra, N.T.S., "A Comparison of Peak Flow Estimates for Small Ungauged Urban Watersheds", *Transactions, Annual Sessions of the IESL*, Institution of Engineers, Sri Lanka, October 2000

Wijesekera N.T.S., (2000), Parameter Estimation in Watershed Model: A Case Study Using Gin Ganga Watershed, Transactions, Annual Sessions of the Institution of Engineers Sri Lanka, October

Wijesekera, N. T. S. , Ghnanapala, P. P. (2003). Modelling of Two Low Lying Urban Watersheds in the Greater Colombo Area for Drainage and Environmental Improvement. Engineer .

Wijesekara, N.T.S., Perera L.R.H., Key Issues of Data and Data Checking for Hydrological Analyses - Case Study of Rainfall Data in the Attanagalu Oya Basin of Sri Lanka, "Engineer", Journal of the Institution of Engineers, Sri Lanka, Vol XXXXV, No. 02, April 2012

World Meteorological Organisation (WMO), (1986), Intercomparison of Conceptual Models Used in Operational Hydrological Forecasting, Scretatiate of the World Meteorological Organisation, Geneva, Switzerland.

Yen, B.C., Lee, K.T., UH Derivations for Ungauged Watersheds by Stream-Order Laws, *Journal of Hydrologic Engineering*, American Society of Civil Engineers, 1997

Young, A.R., "Stream flow simulation within UK ungauged catchments using a daily rainfall-runoff model", *Journal of Hydrology*, 320 (2006) 155-172, 2006

Zlatunova, D., Gergov, G. Littlewood, I.G., Preliminary assessment of a UHbased continuous flow simulation model for Bulgarian rivers, *Proceedings International Environmental Modelling and Software Society Conference*, 24-27 June 2002, Lugano, Switzerland, Vol. I, 405-409, 2002.

Acknowledgement

This research was supported by University of Moratuwa Senate Research Committee (SRC) Grant under the title "Analysis of Parameter Sensitivity and Sub Watershed Delineation when Flood Modelling with Spatially Distributed Unit Hydrographs" (SRC/LT/2011/15). The authors would like to express their sincere thanks to International Centre for Geoinformatics Applications and Training (ICGAT) of University of Moratuwa for the support and use of facilities.