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Application of SWMM for Water Resources Management by Continuous Rainfall-Runoff Modelling in the Rural Watershed of Kalu River Basin of Sri Lanka

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Abstract: Among freely available rainfall-runoff models, SWMM is described as an easy to use, semi-distributed and conceptual hydrodynamic model. However, its application has been limited to event-based analysis, especially for urban drainage management. This study aims to ascertain the applicability of the SWMM for continuous streamflow simulation in the rural watershed. As such, a watershed model with semi-distributed parameters on SWMM had been developed for the Ellagawa watershed (1342 km²) which is a predominantly rural watershed in the Kalu river basin of Sri Lanka. Observed streamflow and observed rainfall data from 2006 to 2014 of relevant gauging stations were collected and divided into calibration data sets (2006-2010) and validation data sets (2010-2014). The model was calibrated and validated combinedly with visual indicators: hydrograph matching, flow duration curve matching, mathematical indicator: Mean Ratio of Absolute Error (MRAE) and annual water balance error. The model had been calibrated with MRAE (overall: 0.39, high flow: 0.36, medium flow: 0.30 and low flow: 0.17) and an average annual water balance error of 35.5%. Similarly, the model had been validated with MRAE (overall: 0.57, high flow: 0.37, medium flow: 0.64 and low flow: 0.40) and an average annual water balance error of 10%. The hydrograph and flow duration curve matching showed that the medium and low flows are fairly estimated whereas the high flows are mostly underestimated by the model. The study concludes that SWMM is well applicable to simulate long-term continuous streamflow even for the rural watershed and can serve as an instrumental tool for water resources management, irrigation water management and environmental flow management projects.

Keywords: SWMM, rural watershed, continuous simulation, rainfall-runoff modeling

1. Introduction

The discharge of river systems around the world is being greatly impacted by various anthropogenic and natural causes. As such, hydrological models were developed to predict the river system behaviour and understand the underlying hydrological processes[1]. There are several hydrological models with different application ranges being used for these purposes. Strom Water Management Model (SWMM) developed by US EPA is one among them. SWMM is a dynamic hydrology-hydraulic model proven to be highly effective for urban and suburban watershed modelling since its conception [2]. SWMM can be used for both event-based and continuous simulation [3].

Event-based modelling requires a single event or discrete events and their applications are limited to the estimation of design storms [4] whereas continuous modelling requires a series of such events in long term continuous form. Continuous modelling not only accounts for the design storms but also estimates the frequency of such storms [5]. Hydrological problems like water resources management and flood management are generally approached by continuous rainfall-runoff models rather than traditional event-based models [6].

SWMM was primarily developed for urban watershed modelling but its applications are not limited to it [3].

The key difference between urban and rural watersheds is in the runoff generation process.

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Runoff generated from urban watersheds is more likely to have hydrographs with spikey shapes due to the channelized conveyance system of sewerage paths, or stormwater channels' whereas, in rural Watersheds, flow patterns are gradual and steady and the runoff hydrographs are more likely to have gentle shapes. Generally, rural catchments are dominated by pervious surfaces with a wide range of vegetation cover [7].

SWMM is one of the preferred models for urban watershed runoff and quality simulation and its application is more or less limited to the estimation of design floods through event-based modelling in urban catchments [8]–[12]. However, only a few applications in the rural watershed can be found in the literature. For example, SWMM had been once applied in the Sri Lankan watershed for the estimation of design storms through event-based modelling on the rural watershed (Karasnagala watershed) in Attanagalu Oya [13]. Similarly, it has been applied in the rural watershed of North Carolina Piedmont Ecoregion [14], forested reservoir watershed in Taiwan [15], and rural watershed of lower coastal plains of the US [2]. But then, the applicability of SWMM for water resources management in rural watersheds with continuous rainfall-runoff modelling is still needed to be explored.

SWMM is a catchment-scale model available in the public domain, capable of simulating single events as well as continuous time series, water quality, storage and treatment, in both urban and rural catchments. Therefore, ascertaining its potential for continuous rainfall-runoff modelling in rural watersheds would certainly benefit the scientific community. Accordingly, the study aims to develop, calibrate and validate the SWMM model for the Kalu river basin of Sri Lanka and to evaluate its application potential for water resources management.

2. Data and Methods

2.1. Study Area

Kalu River originates from the central hills of Sri Lanka, flows through Ratnapura and Horana and empties into the Indian Ocean at Kalutara with a total length of about 129 km and a catchment area of 2,690 km^2. The river basin lies entirely within the wet zone of the country. Two predominantly rural watersheds, namely Ellagawa and Ratnapura, were selected for the study. Ellagawa and Ratnapura are watersheds of the Kalu river basin with the spatial extent of 1342 km^2 and 650 km^2 respectively. The study area inset map is shown in Figure 1.

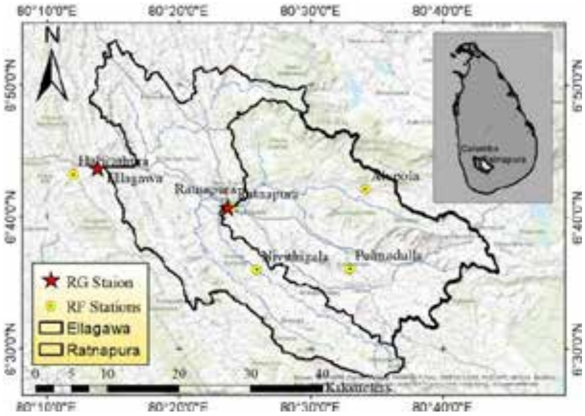

Figure 1 - Study Area Inset Map of Ratnapura and Ellagawa Watershed

Landuse analysis of the watershed gives a tentative idea of the runoff over the watershed. In general practice, it is believed that more the buildup areas or non-permeable surface the lesser the infiltration and higher the surface runoff.

The built-up areas, home sheds and rocks which can be considered as non-permeable/semi-permeable areas cover 245 km^2 (18% of total area) of the Ellagawa watershed, whereas the maximum area of the watershed is covered with cultivation: chena, paddy, rubber, coconuts, and tea together, total 60% of the total area. The forest, grasslands and water bodies in total constitute the other 18% of the total area of the watershed. There are no standardized classification parameters to distinguish urban and rural watersheds. However, it is generally accepted that the urban watershed is dominated by impervious layers whereas the rural watershed is dominated by the previous layers. So, the Ellagawa watershed in the Kalu river basin is considered a general case of a rural/non-urban watershed.

The 1:50000 land use map digitized by the Department of Survey, Sri Lanka (see Figure 2) was used for the Ellagawa watershed and its tabular breakdown is given in Table 1.

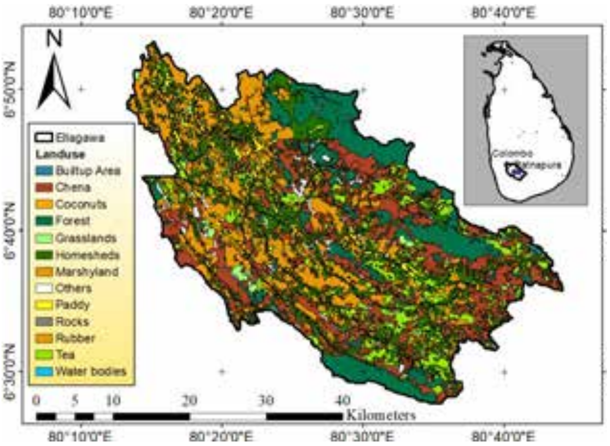

Figure 2 - Landuse Map of Ellagawa Watershed

Table 1 - Landuse Coverage on Ellagawa Watershed

Landuse	Area (km²)	Percentage
Rocks	250.2	1.86
Buildup area	12.9	0.10
Homestead	2398.7	17.87
Chena	2861.4	21.32
Paddy	925.8	6.90
Tea	1223.6	9.12
Grassland	15.18	0.11
Forest	2124.1	15.83
Coconuts	32.59	0.24
Rubber	3134.1	23.35
Water Bodies	178.5	1.33
Marshy Land	2.2	0.02
Others	262.7	1.96

2.2. Data

Data used for this study, their types, resolution and their respective sources are provided in Table 2.

Table 2 - Data Summary

Data Type	Resolution	Source
Rainfall	Daily	Dept. of Meteorology
Streamflow	Daily	Dept. of Irrigation
Topography	1:50000	Dept. of Survey
Contours	1:10000	Dept. of Survey
Landuse	1:50000	Dept. of Survey

Observed daily rainfall of 4 (four) rainfall station: Ratnapura, Alupola, Pelmadula and Nivithigala and streamflow data of 2 (two) river gauging stations: Ratnapura and Ellagawa, from 2006 to 2014, were obtained from the Department of Meteorology and the Department of Irrigation of Sri Lanka. Observed daily rainfall and streamflow data were divided into two sets: Calibration data sets (2006-2010) and Validation data sets (2010-2014).

2.3. Model Description

SWMM is a conceptual, semi-distributed hydrodynamics model capable of simulating events or continuous runoff quality and quantity [16]. The model can operate in seconds, minutes and hours (ss-mm-hh) time scales providing a wide range of scope for different engineering applications. SWMM1 model was developed by US EPA in 1977 and periodically updated several times, namely, SWWM2, SWMM3, SWMM4 and SWMM5 [3]. The SWWM5 has additional features like integrated and interactive Graphical User Interface (GUI), post-analysis options; simulation result display in graphs and tables, display of the drainage area maps, scatter plots, profile plots and many more [7]. SWMM5 is well programmed to account for the spatial variability of the watershed properties by dividing the watershed into several smaller sub-watersheds (semi-distributed approach). Precipitation input is transformed into watershed discharge at the outlet in the form of a total hydrograph through a series of interconnected compartments conceptualized in the model: Atmospheric compartment, Land surface compartment, Sub-surface compartment and conveyance compartment.

Atmospheric compartment handles meteorological data like precipitation, evaporation, and snowmelt.

Land surface compartment is directly connected with the atmospheric compartment. The meteorological inputs from the atmospheric compartment get initially transferred to this compartment. It has default non-linear reservoir model components that are responsible to generate the direct runoff (surface runoff). Most of the parameters of this model are physical: Depression storage, Area, Width, % imperviousness, Manning's n and % Zero imperviousness. Depression storage is a parameter conceptualized in the model for the initial abstraction of the precipitation. It deducts initial moisture content which results in effective rainfall. The effective rainfall gets received by the Land surface compartment's non-linear reservoir model and sends outflow in the form of evaporation back to the Atmosphere compartment, losses to the sub-surface compartment and surface runoff onto the conveyance compartment.

Losses estimates from sub-watersheds losses in the form of evaporation /evapotranspiration and infiltration. The infiltration losses from the sub-watersheds are computed using globally accepted and generally practiced methods, namely, Horton's, SCS CN and Green Ampt. Among them, Green-Ampt is physics-based whereas the SCS CN number and Hortons are the empirical methods. The SCS CN method does not take into account long term losses and computes only the direct runoff by considering available rainfall on a current day without taking into account the moisture available [17] [18]. This method is only designed for single storm events and day-to-day analysis [19]. The Horton method assumes the infiltration rate to be maximum at the beginning of a storm and decreasing exponentially with time and reaches a minimum constant or equilibrium rate when the soil gets fully saturated [7]. The exponential decay rate of Horton's method requires empirical methods of computations [20]. The Green-Ampt method of infiltration assumes that a sharp wetting front exists in the soil column, separating unsaturated soil from saturated soil. It describes the infiltration process as a balance between the changing water content of the soil over time and the change in hydraulic conductivity and diffusivity through the depth of the soil profile [7] [21].

Subsurface compartment receives the infiltration from the land surface compartment as an input. The SWMM model conceptualizes the subsurface compartment as an aquifer and divides it into two zones: unsaturated (upper zone) and saturated (lower zone). The infiltrated water from the surface reaches up to the upper unsaturated zone from which some amount of loss occurs and the remaining water enters the saturated lower zone. The recharge phenomena from the lower saturated zone to stream occur in further two steps: groundwater discharge to stream and deep percolation.

Conveyance compartment is responsible to route the surface runoff from the sub-watershed to the outlet. The additional geometric parameters like node, junction and conduit are conceptualized in the model to represent the natural stream and overland surface runoff. Regarding the flow routing process, SWMM provides three routing methods, namely, Steady flow routing, Kinematic wave routing and Dynamic wave routing. The steady flow routing is the simplest option of routing; however, it does not consider the time lag of the flow. The Kinematic wave routing solves the continuity equation and neglects the local and convective acceleration and pressure of the conduits. The Kinematic wave routing would be the best routing option for steep terrain where the effect of backwater is negligible. Dynamic wave routing on the other hand is based on 1-D Saint-Vennent's equation and produces theoretically accurate results. Dynamic wave routing would be appropriate in the rural watershed where there are terrain variation, tributary inflows, and backwater effects [3], [7], [21]. The schematic diagram of SWMM is given in Figure 3.

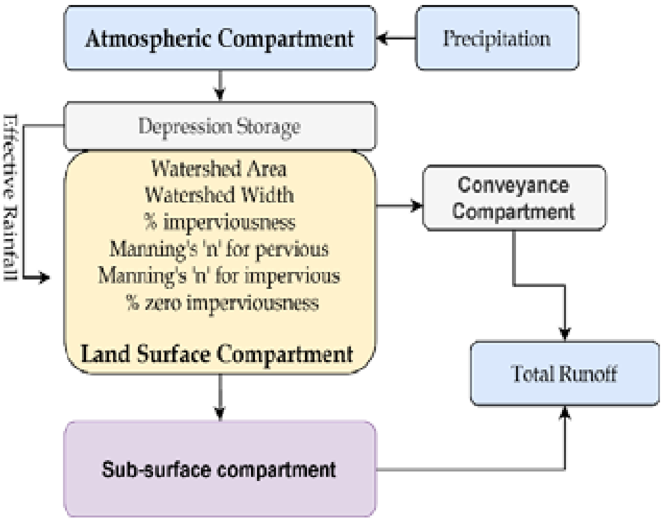

Figure 3 - SWMM Schematic

2.4 Delineation of Sub-watersheds

Sub-watershed delineation was done using Arc-Hydro tool in ArcGIS software. The input data for the delineation of the sub-watershed were 30m Digital Elevation Model (DEM) and the point data of the river gauging station as an outlet.

The method of processing DEM to delineate sub-watershed involves steps: DEM reconditioning, flow direction, flow accumulation etc., which is well depicted through the flowchart diagram in Figure 5. The watershed area was divided into three major sub-watersheds namely Ratnapura, Upper Ellagawa (Northern streams area), Lower Ellagawa (Southern streams area), as shown in Figure 4.

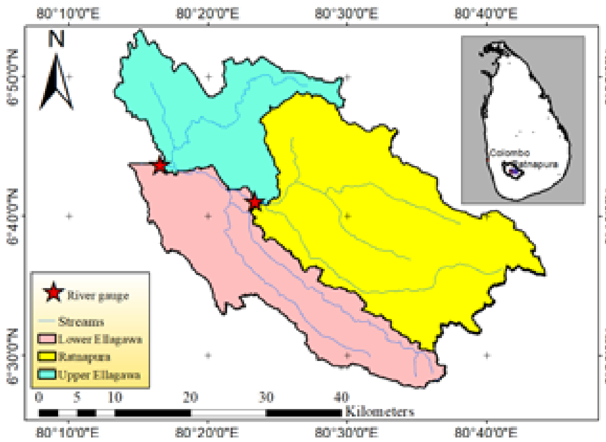

Figure 4 - Delineated Sub-Watersheds of Ellagawa Watershed

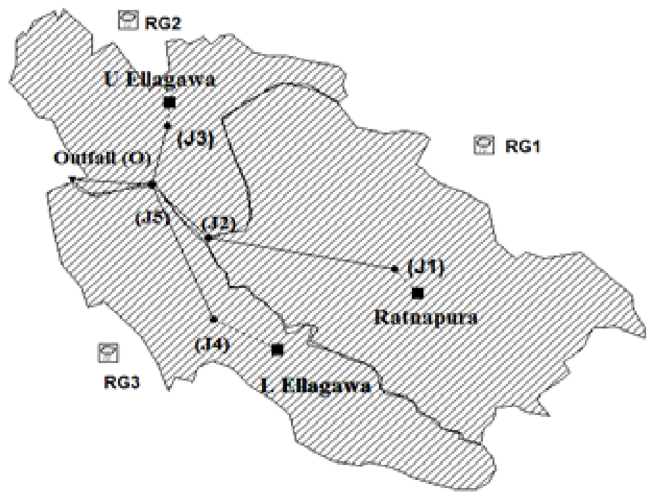

Figure 5 - The Layout of the Ellagawa Model with Sub-Watersheds in SWMM

2.5 Watershed Model Setup

A model with sub-watersheds was formed dividing the Ellagawa watershed into three sub-watersheds. Sub-watershed units are delineated based upon analysis of the areas draining towards a given discharge point. Each sub-watershed unit is attributed as a regularly shaped surface and hence, the uniform morphological and hydrological characteristics are assigned to the sub-watershed as a single unit.

The total hydrograph at the watershed outlet 'Outfall' is obtained by routing the runoff generated from each sub-watershed unit. The estimated runoff of the sub-watershed is routed to the sub-watershed outlet and then to the Outfall. The routing process in the SWMM is facilitated by nodes, junctions and conduits which represent the physical stream network of the watershed. The sub-watershed runoff is assumed to be collected at the centroid of the respective sub-watershed, hence a node is provided at the centroid of each sub-watershed. These nodes are connected to the outlet junction of each sub-watershed and finally to the watershed outlet 'Outfall'. The conduits play the role of conveyance of runoff from nodes to a junction to the outfall. Node elevation, conduit geometry, conduit roughness, and routing time step are some additional parameters to define in semi-distributed modelling. An appropriate routing process should be selected based on the nature of the flow and the watershed physical properties. For this study, the dynamic wave routing option was selected.

SWMM layout of the watershed model is given in Figure 5.

2.6 Objective Function

Hydrologic simulation models are calibrated by comparing observed data with data generated by the models. The objective function is normally defined as a function of the difference between computed and observed data during the calibration period. The choice of an objective function for any given model is a subjective decision that influences the values of the model parameters and the performance of the model. There is a definite link between the mathematical formulation of an objective function and the type of engineering application for which the model is used. Better results are obtained if the objective function is selected according to the engineering application [22].

The objective of this study is to ascertain the applicability of SWMM for water resources management in a rural watershed. Therefore, stable and consistent intermediate and low flows are prioritized. Annual water balance error and Flow duration curve (FDC) match were assigned model evaluation criteria, whereas Mean Ratio of Absolute Error (MRAE was assigned as the main objective function.

MARE compares the errors with respect to each observed flow and gives better representation when contrasting data are present in the observed data set. It is a comparatively better objective function than other commonly used objective functions like NSE, R^2, RMSE, RAEM etc., specifically for intermediate flow matching [23]. There are several studies carried out on Sri Lankan catchments with MRAE as an objective function [24] [25] [26]

$$\text{MRAE} = \frac{1}{n}\sum\frac{|\text{Qobs}-\text{Qcal}|}{\text{Qobs}}$$

where,

Qobs is the observed streamflow;

Qcal is the calculated streamflow and

n is the number of observations used for comparison.

The best fit between observed and calculated values would have a zero value of MRAE.

2.7 Modelling Approach

A semi-distributed modelling approach was followed in this study. Parameters were distributed into the sub-watershed level: Ratnapura, Upper Ellagawa and Lower Ellagawa.

Initially, lumped models were calibrated and validated for Ellagawa and Ratnapura whose parameters were then transferred as an initially estimated parameter in sub-watersheds for semi-distributed modelling.

3. Results

3.1 Calibration Results

The Ellagawa sub-watershed model has been very well-calibrated with the observed streamflow at the Ellagawa river gauging station. The comparison of simulated streamflow with respect to observed streamflow and rainfall during the calibration of the model is provided in Figure 6. The indicators assigned for the model calibration were MRAE for overall hydrograph and MRAE for each flow regimes (high, medium and low flows) as well as the Annual water balance. The respective values of model calibration indicators are given in Table 3.

Table 3 – Calibration Indicators and Results

Indicators	Results
Overall MRAE	0.29
MRAE- High flow	0.36
MRAE-Medium Flow	0.30
MRAE-Low Flow	0.17
Annual Water Balance Error	35.5%

The overall value of the Mean Ratio of Absolute Error (MRAE) during the calibration period is 0.29. The best fit MRAE value would be zero; however, the MRAE value below 0.4 is considered very good in terms of model calibration and validation [13], [23], [26] [27]. Therefore, the MRAE value of 0.29 indicates a very good result in terms of average errors in simulated streamflow. The streamflow data are classified into high, medium and low flows in terms of percentage time of exceedance. The range of streamflow data under the percentage of exceedance of 80-100% is categorized as low flows whereas those under the 10-80% range are categorized as medium flows. Similarly, the range of streamflow data under 0-10% is categorized as high flow.

The MRAE value for high, medium and low flows are 0.36, 0.30 and 0.17, respectively. This indicates that the model has been well-calibrated for all flow regimes of the hydrograph. However, the flow duration curves (FDCs) indicate that the high flows of the streamflow data are underestimated by the model. The FDCs of simulated streamflow compared to the observed streamflow during the calibration of the model are given in Figure 7. Furthermore, the model has been calibrated with an acceptable range of annual water balance error except in the years 2007-2008. In the year 2007-2008 the watershed has a high runoff coefficient which fails to reciprocate. This could be the reason for the higher value of annual water balance error during calibration. Further details are discussed in section 4.3. The year-wise breakdown of annual water balance during the calibration of the model is illustrated in Figure 8.

3.2 Validation Results

The comparison of simulated streamflow with respect to observed streamflow and rainfall during the validation of the model is provided in Figure 9. The indicators assigned for the model validation and their respective values are given in Table 4.

Table 4 -Validation Indicators and Results

Indicators	Results
Overall MRAE	0.57
MRAE- High flow	0.37
MRAE-Medium Flow	0.64
MRAE-Low Flow	0.40
Annual Water Balance Error	10%

The overall MRAE, MRAE-high flow, MRAE-medium flow, and MRAE-low flow are 0.57, 0.37, 0.64 and 0.40, respectively. The MRAE value of overall hydrograph and individual flow regimes (high flow, medium flow and low flow) shows a satisfactory result for fair validation of the model. The FDCs comparison between observed streamflow and simulated streamflow during the validation of the model shows similar results as the model calibration. Among the flow regimes (high, medium and low), high flows are underestimated by the model even during the validation. The FDCs of simulated streamflow compared to the observed streamflow during the calibration of the model is given in Figure 10. Similarly, the model has been validated with the minimum errors in annual water balance. The year-wise breakdown of annual water balance during the validation of the model is provided in Figure 6.

3.3 Calibrated Parameters

There are numerous parameters in multiple compartments of the SWMM. All these parameters are not required to be calibrated. The reason behind this is that most parameters are either physical deepening on the sub-watershed shape, size and area or completely insensitive to the model outputs. The physical parameters extracted using the ArcGIS software and other parameters with valid available information were excluded from the calibration process. Before the calibration process, an initial estimation was made based on the available literature, SWMM reference manual and other available references. Consequently, a manual, one-at-a-time sensitivity analysis was conducted. The parameter initial estimation was extrapolated in the range of -50% to +50 at a step of 10%. Then the model performance with reference to the main objective function was noted with each step of the analysis to find the sensitive parameters. Finally, the calibration was conducted using the sensitive parameters while the other parameters were set with rationalized values. The calibrated parameters, their respective compartments and their range of estimation are provided in Table 5.

Table 5 - List of Calibration Parameters

Compartment	Parameter	Range	Unit
Land surface	Manning's roughness for pervious area (N-pervious)	0.018-0.2	s/m $^{1/3}$
	Depression storage for pervious area	1.2-2.5	mm
Infiltration	Hydraulic conductivity (K)	0.315-0.612	mm /h
Groundwater	Lateral flow coefficient	(1.793-2.581) * 10^{-3}	-
	Later flow exponent	4-5	-

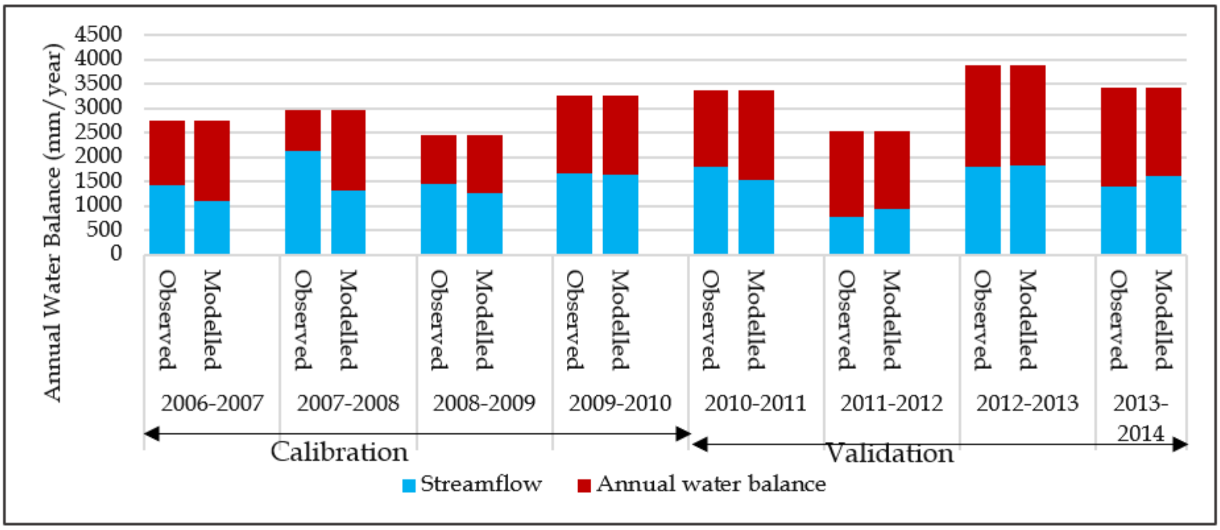

Figure 6 - Year Wise Annual Water Balance during Calibration and Validation at Ellagawa

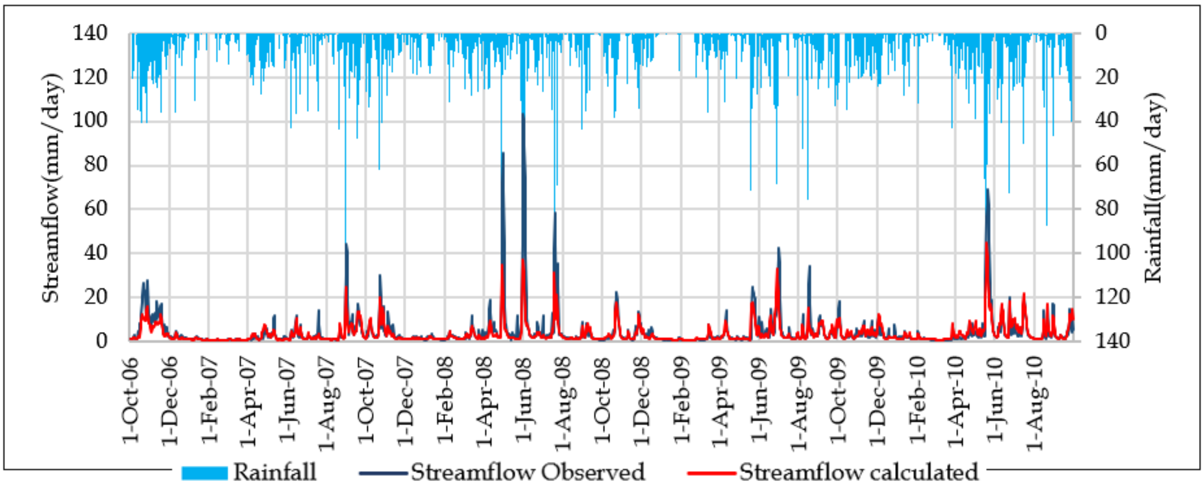

Figure 7 - Comparison of Simulated Hydrograph with the Observed Hydrograph at Ellagawa Station (Calibration Period)

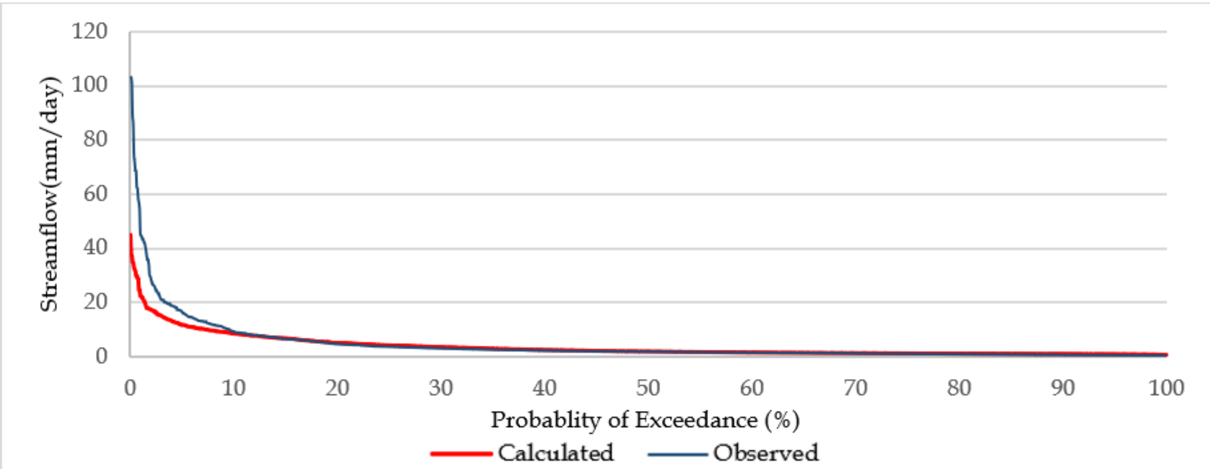

Figure 8 - Comparison of Simulated Flow duration Curve with Observed Flow duration Curve at Ellagawa Station (Calibration Period)

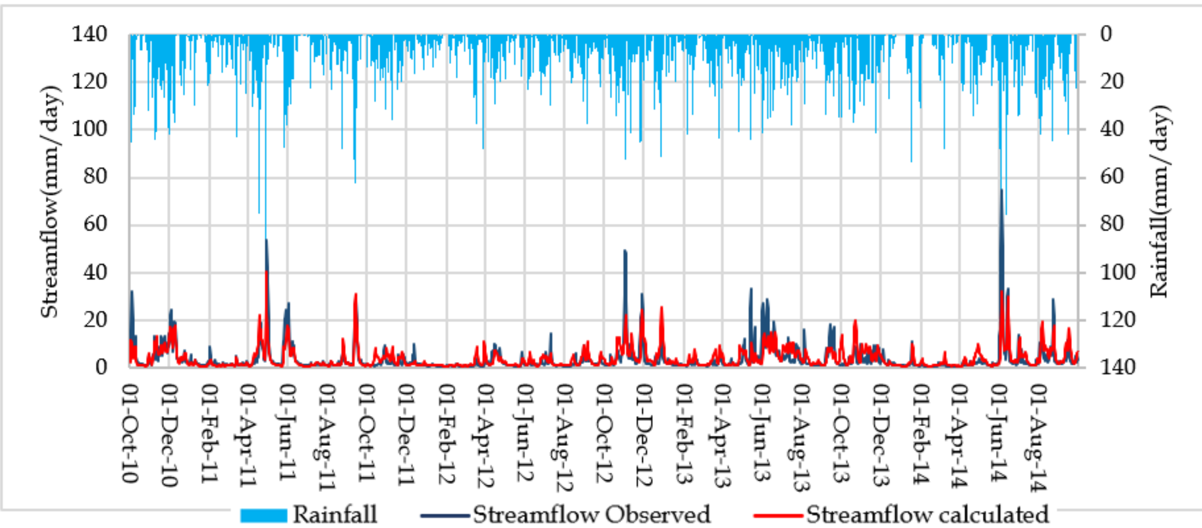

Figure 9 - Comparison of Simulated Hydrograph with the Observed Hydrograph at Ellagawa Station (Validation Period)

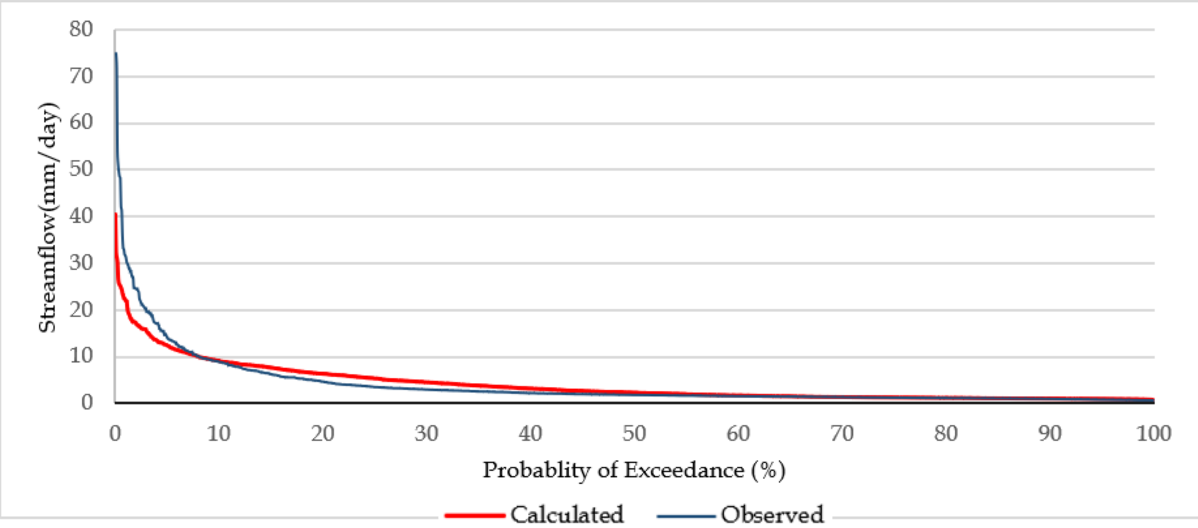

Figure 10 - Comparison of Simulated Flow duration Curve with Observed Flow duration Curve at Ellagawa Station (Validation Period)

4. Discussion

4.1 Model Application

The MRAE value for overall flow as well as all flow regimes viz; high flows, medium flows and low flows in both calibration and validation are in the acceptable range. However, comparing the observed streamflow with the modelled streamflow, it is seen that peak values of the hydrograph are often underestimated. In addition, observed and simulated FDCs of both calibration and validation periods are compared which depicted that the high flow regimes of the streamflow are often underestimated. As such, this model cannot be recommended for flood management purposes. However, medium and low flow regimes are also an imperative part of the concern of the overall flow regime. The medium and low flows are fairly estimated by the model as depicted by the hydrographs and the FDC. In addition, the model has estimated the streamflow with an acceptable range of annual water balance error. Therefore, this model can be well suited for water harnessing projects, water resources development projects, and drought management and environmental flow management projects, where low and medium flow are of imperative concern.

4.2 Data and Data issues

Continuous rainfall-runoff modelling requires a time series of the precipitation and the streamflow data. These data should be further divided into calibration and validation data sets. The long time series of data set is expected to model the watershed with a longer period of validity. Kalu River basin consist of two gauging stations, Ratnapura and Ellagawa. Ratnapura gauging station has not been functioning from 1998 to 2006. Since, 2006 both gauging stations were functioning. Therefore, the period of 2006-2014 was selected. It is better to select the recent years for the modelling because it would have more validity for forthcoming years.

There is a need for the existence of extreme years in terms of rainfall and streamflow for vigorousness in the modelling process. 20011/2012 was noted as the driest year and 2012/2013 and 2013/2014 were noted as the wettest years. The existence of contrasting weather conditions in a data set makes the model more robust.

Discrepancies between rainfall and corresponding streamflow data have been noted through the annual water balance. Though 2006/2007 and 2007/2008 had similar amounts of rainfall, the streamflow had increased in 2007/2008. The annual runoff coefficient for 2007/2008 year was found to be 0.75 which seems to be very high in a rural watershed. Similarly, in the year 2011/2012, streamflow does not seem to respond to rainfall. The number of sharp peaks without rainfall signals and flat hydrographs during the rain has been noted in visual observation of daily hydrographs.

The issue indicates that either there is inconsistency in the streamflow data or the Theissen polygon method of rainfall value averaging is not able to represent the actual situation. This type of heterogeneity in the rainfall to runoff relations are common issues being faced for which hydrological models cannot respond properly. However, there is no such strong evidence to prove the erroneousness of the observed data from the authorized department of the government. There could be multiple causes behind the heterogeneity in rainfall-runoff relation such as the antecedence of the soil moisture, inaccuracy of spatial interpolation technique to average the rainfall, drastic change in the land-use pattern with years and many more that need to be explored in the upcoming similar researches.

4.3 Uncertainty in Groundwater Model

SWMM has been widely used as an urban drainage model and its application to rural water is a new investigation. Urban sewerage and drainage systems are generally lined with concrete where groundwater recharge is negligible. Outflow from urban watersheds is generally equivalent to surface runoff. Due to these reasons, though there is adequate literature on SWMM5, no reference has cited continuous simulation with groundwater. However, the SWMM 5.1 reference manual 2015 has provided two options for the selection of the groundwater model: (i). SWMM standard ground model and (ii.) User-defined custom equation. The SWMM standard groundwater model needs large numbers of physical data to be estimated manually, whereas the user-defined custom equation conceptualizes the linear reservoir model and is much simpler compared to standard groundwater equations with limited parameters to deal with. Parameters of linear reservoirs groundwater model deal with (a) lateral groundwater discharge coefficient (b) groundwater discharge exponent.

SWMM groundwater model was simulated by observing the base flow of the hydrograph and adjusting the groundwater discharge coefficient and groundwater discharge exponent simultaneously. Even with no literature support, the groundwater compartment of this model was calibrated satisfactorily. As such, there can be some inherent uncertainties in the groundwater models which should be studied separately in future research. The groundwater model cannot be validated since the groundwater flows are not generally monitored in Sri Lanka. Therefore, it is recommended to carry out further similar studies to improve and validate the groundwater model of SWMM.

5. Conclusion and Recommendation

The Ellagawa model with semi-distributed parameters was successfully calibrated (MRAE: 0.29) and validated (MRAE: 0.57) on SWMM. Therefore, SWMM is well applicable to simulating the continuous streamflow of rural watersheds. The model performed with a good estimation of medium and low flow regimes and minimum errors in annual water balance. This implies the model is well suited for purposes like water resources management projects, irrigation planning, environmental flows and drought management. Further use of SWMM for continuous rainfall-runoff modelling in the tropical watershed is recommended to develop a better understanding of SWMM parameters and their performance.

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