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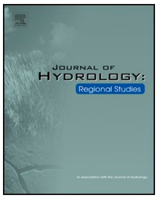

# Challenges in field approximations of regional scale hydrology

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ABSTRACT

*Study region:* Considering the availability of gauged data, the Karasnagala watershed of Attanagalu Oya located in the Gampaha district in the Western province of Sri Lanka was modeled with EPA SWMM 5.

*Study focus:* This study analyses the effect of the catchment field approximations for accurate flood hydrograph prediction. Following an event based approach, 3 days Minimum Inter event Time (MIT) and 0 mm/day Minimum inter Event Depth (MED) were used as the threshold. Fifty events were separated from 1971 to 1982 period. Four major field approximation types were identified: stream geometrical parameters approximations, soil infiltration parameter approximations, approximation of watershed intermittent storages, and subcatchment delineation approximation. Soil parameter approximations and the stream network geometry parameter approximations were verified by the field observations.

*New hydrological insights for the region:* Model calibration and verification revealed that EPA SWMM5 can be successfully used to develop regional Karasnagala watershed model with mean ratio of absolute error (MRAE) 0.289 for calibration, and 0.375 MRAE for verification. Incorporation of intermittent storages with optimized model layout obtained the best fitting of hydrograph recession MRAE 0.167. Subcatchment lumping with a 16 sub basin configuration showed the marginal increment of modeling error when compared with distributed modeling. Stream parameter approximations revealed that the head water streams/lesser order streams parameters sensitivity is higher than that of the higher order streams. In soil parameter approximations, saturated hydraulic conductivity of the soil was the most influencing parameter.

## 1. Introduction

Majority of hydrological studies aim to calculate the design flow of relevant hydraulic infrastructures (Layan et al., 2013; Zeng et al., 2016). According to Lockie (2009), in most of cases detailed hydrological and hydraulic modeling were implemented for stormwater and wastewater management to assess network performance and develop remediation options. These hydrological and hydraulic modeling studies have used a number of software products. Vaze et al. (2012), state that the model selection should follow the scope of the study, data availability, required accuracy, and user objectives. According to Zoppou (2001), the model user believes that impressive results from the model can be obtained if the user sets up a highly detailed model. However, what is actually required is an expert system, which assists the user in selecting a model that balances the modeling effort with the scope of the study (Zoppou,

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2001).

Most hydrological simulations are capable of identifying the time to peak and the peak flow, but less good in the recession. Mandeville (2016), emphasises the key role played by the slow flow component of storm runoff, which is obviously the recession that has not been given appropriate attention in the existing event-based studies in literature. However, the flood peak and the flood residence time depending on the recession behaviour are important for flood plain management. According to McIntyre et al. (2012), the impact of land use change on the shape of a hydrograph depends strongly on the properties of the channel network and hence an accurate representation of channel routing processes is critical to the assessment. For the convenience of modeling, most models approximate complex sub stream networks into simple networks. The shape, roughness, and side slopes of the modeled stream segments and the model layout are changed to represent the routing effect from the intermittent storages (Rouhani et al., 2009). Most hydrological models are characterized by a set of parameters, which are uncertain, and not directly measurable, thus obtaining an optimal model becomes a complex task (Zhan et al., 2013). When satisfying the conditions such as time efficiency and the cost efficiency in most of engineering applications, approximated values are used for both field measured and derived parameters. Generally, models solving the shallow water wave equations, are used to design storm water infrastructure (Zoppou, 2001). The cross-sectional information, roughness coefficients, boundary conditions, and the details of internal structures are the information required to solve shallow water wave equations. For some catchments, these information are not available. Generally, field parameter approximations are required in application of shallow water wave equations for the models (Zoppou, 2001).

The effects of these approximations on the model output are rarely discussed in literature. Therefore, the objectives of this study strive to analyse the applicability of an urban stormwater model (EPA SWMM 5) for a regional watershed; to analyse the effect of catchment field approximations for accurate flood hydrograph prediction; and to identify the deficiencies and possible solutions for the regional watershed modeling.

## 2. Storm water management model (EPA SWMM 5)

SWMM is a fully dynamic, deterministic, distributed, conceptual watershed simulation model for single-event or long-term simulation of runoff quantity and quality, primarily from urban areas (Gülbaz and Kazezyılmaz-Alhan, 2017). It has the capability to include urban stormwater controlling elements such as pumps, orifices, manholes, weirs, flow dividers, and conduits. Version 5 running with Microsoft Windows provides an integrated environment for editing data, running hydrologic, hydraulic and water quality simulations, and viewing of the model results (Gülbaz et al., 2019; Rossman, 2009). It conceptualizes a drainage system as a series of water and material flows between four major environmental compartments.

1 Atmosphere compartment, from which precipitation falls and generates surface and subsurface hydrographs based upon antecedent subsurface moisture conditions, soil characteristics, detention storages, land use characteristics, drainage area and topography, is known as physiographic characteristics.
2 Land surface compartment, where the pollutants are deposited is represented by subcatchment objects.
3 Groundwater compartment, which receives infiltration from the land surface compartment is based on either Green-Ampt or Horton infiltration models and transfers a portion of this inflow to the transport compartment.
4 Transport compartment, contains a network of conveyance, storage, regulation and treatment elements.

All compartments do not need to appear in a particular SWMM model (Rossman, 2009). SWMM runs according to any given time frame. There are no intrinsic limitations regulating the duration of a “continuous” simulation in the model except the time required by the computer to perform a large number of calculations. Compromising the time steps during wet and dry periods assists minimizing computing time without significant loss of information in the model output.

When rainfall input is introduced to the model, it begins a time step by the time step accounting of water movement and losses by doing various processes as runoff, infiltration, evaporation, and surface storage. In this situation, each subcatchment surface is treated as nonlinear reservoir. The capacity of the reservoir denotes the maximum depression storage consisting surface ponding, surface wetting, and interception. Surface runoff occurs when the depth of water in the reservoir exceeds the maximum depression storage (Rossman, 2009; Smith, 2004).

## 3. Study area

Catchment of Attanagalu Oya at Karasnagala (Fig. 1) located at the Gampaha district in the Western Province of Sri Lanka was selected as the study area. The highest rainfall was recorded during the Southwest Monsoon between May and November with the mean annual rainfall of 2900 mm. On average, the driest month: January, receives a monthly rainfall of 24 mm while the rainfall in the wettest month: November, is 443 mm (Ponrajah, 1984; Dharmasena, 1986; DAS, 1987). From 2006–2010 the rainfall data analysis for the same catchment reveals that wettest month has been moved to October and the driest month has been changed to February. Most of the roads are located close to the valleys. The study area is located in a hilly terrain. The major tributaries of the Attanagalu Oya were observed by performing three field visits. The watershed area is about 52.6 km$^2$ and the longest stream length is about 9.7 km (Fig. 1). The average slope along the longest stream is approximately 1.4 % and time of concentration is nearly 100 min. More than 90 % of the area is undeveloped and the major cultivation is rubber (Fig. 1). Top soil condition was dark brown sandy lean clay with occasional gravel and river bank and bed conditions were light brown silty clay with frequent small roots. Watershed at Karasnagala is gauged by the Irrigation Department of Sri Lanka. According to the Irrigation department measurements, bed

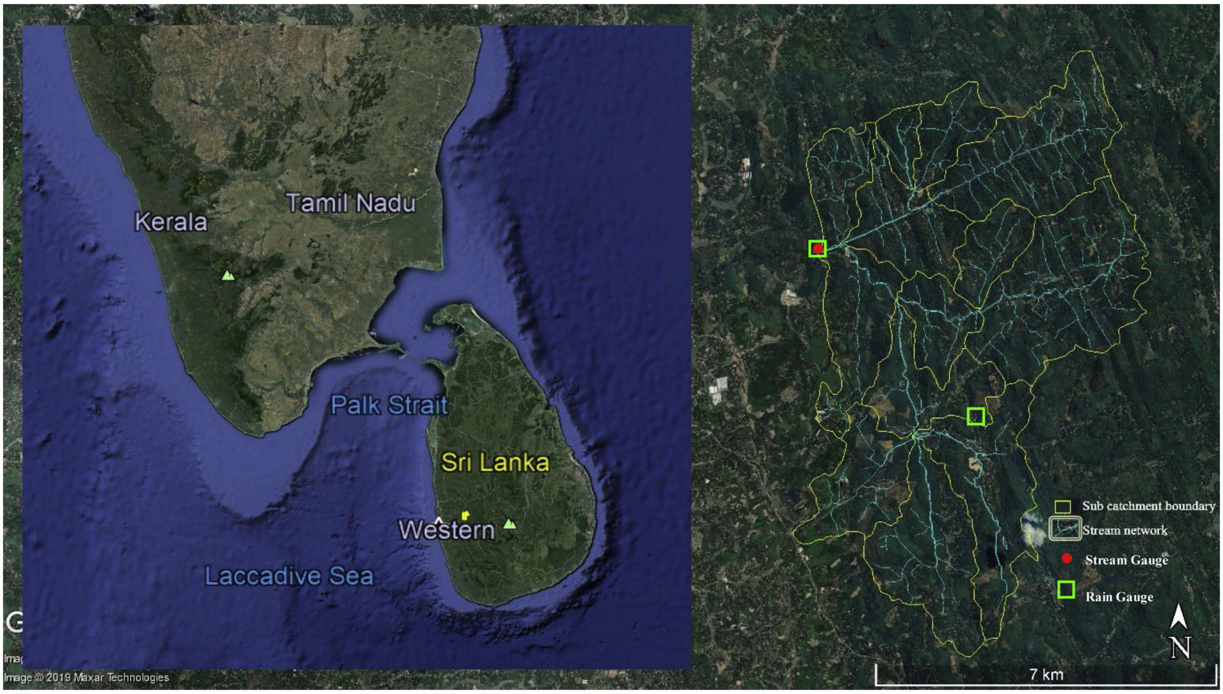


**Fig. 1.** Satellite Image of the Karasnagala Watershed.

elevation of the Attanagalu Oya at Karasnagla gauging station is 27 mMSL. The study period from 1971 to 1982 was selected due to the presence of identified data errors after 1982 (Wijesekera and Wanniarachchi, 2016). Daily data from two rain gauges at Karasnagala and Vincit stations, and streamflow gauging data at Karasnagala (7°6’44.66”N - 80°10’22.36”E) were available.

## 4. Materials & methods

### 4.1. Data

In Sri Lanka, water data of Attanagalu Oya basin are scattered among many institutions. The Meteorology Department and Irrigation Department provided the rainfall, evaporation, and streamflow data of the basin. A detailed soil map was obtained from the Survey Department. Most of rainfall and streamflow values were measured and recorded either on daily or in monthly averages. Hourly or three hourly resolution data are available only at the recently established gauging stations. 1:10,000 topographic maps were the source of updated land information. High resolution satellite images were used only to visually inspect the dynamic behaviour of land use in the catchment.

### 4.2. Field data

In order to simulate the actual field conditions, physical parameters of the major streams were measured in 100 m interval and subcatchment land use/ land cover details were recorded to the greatest possible extent. Due to the seasonal variation of the water level of the natural streams, capturing of the average stream width as a model input parameter was needed. Therefore, a stakeholder data collection was implemented to fulfill the needs. Stream type variation was another important factor observed during the fieldwork. Most of the streams observed on the topographic maps were ephemeral streams. Hand held GPS units were used to locate the places where stream shape variation were observed (Fig. 2).

### 4.3. Event separation

The event based modeling approach is closer to science and it has the capability of reasonable reflection of watershed behaviour (Tayfur and Singh, 2006; Kjeldsen et al., 2013; Efstratiadis et al., 2014; Hossain et al., 2019). In the absence of continuous data, the MIKE-NAM model with the case study of Ben Hai river basin has been calibrated and validated by Giang and Phuong (2010) using individual storm events and it was identified that the continuous simulation is impossible especially in the steep, small basins with short time of concentration. Therefore, an event based approach was followed in this study. Event identification for most of the storms can be done only with streamflow data through an analysis of the baseflow recession curves (Aksoy et al., 2001). However, for complex storms in which the identified inflection point on the receding limb is a local minimum due to another rainfall event prior to

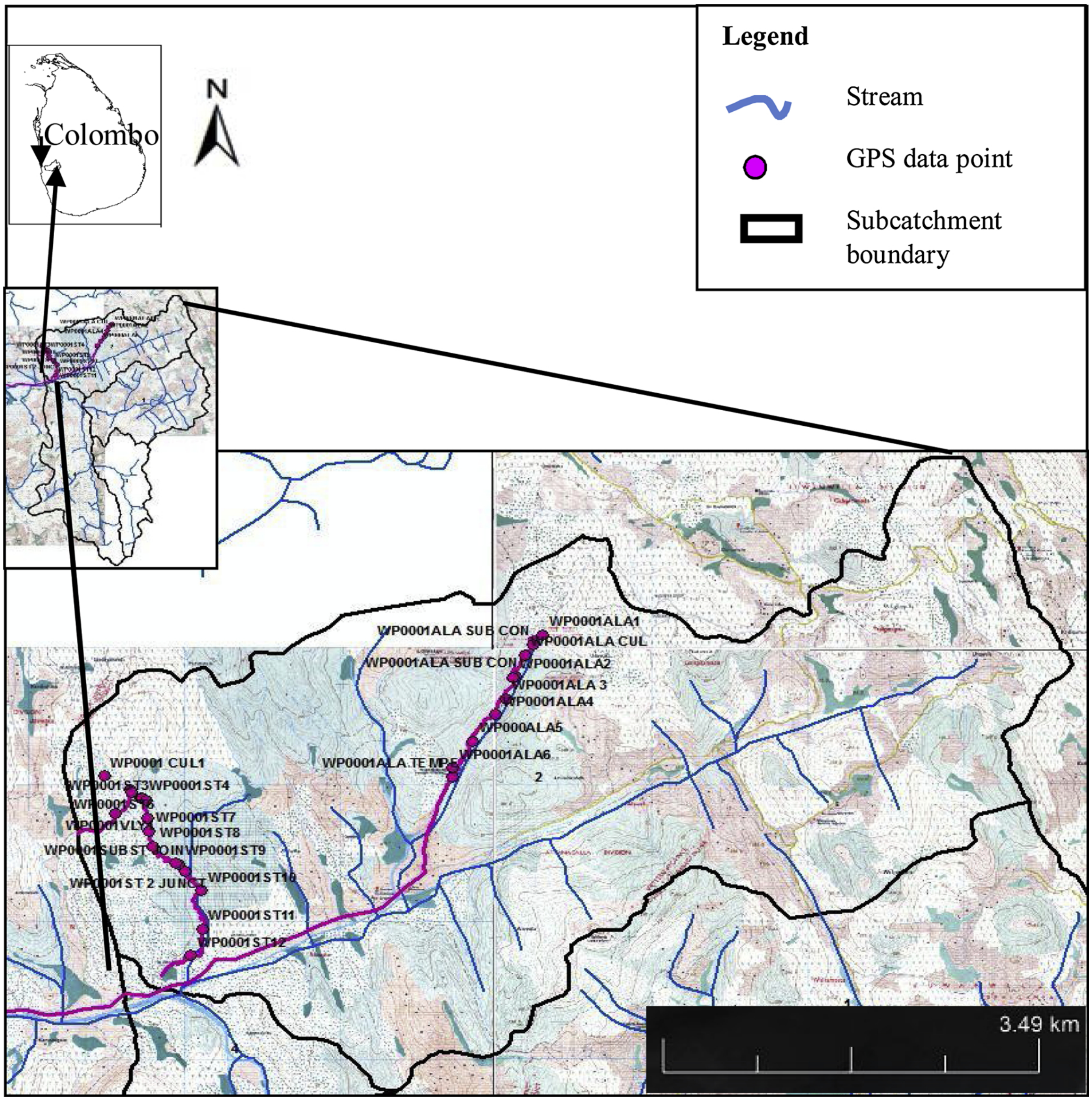


**Fig. 2.** GPS Data Collection along the Streams.

the end of the concerned event, then the identification of the end time becomes complicated (Huff and Begovich, 1976; Snyder and Curlin, 1969). Linsley et al. (1975) have described a method to demarcate the end point of the direct runoff hydrograph using the number (N) of days from the hydrograph peak or the last runoff generating rainfall. However, it has also been stated that the value of 'N' is not particularly critical when compared to the basin slope and other runoff generation factors such as the land cover and the soil type (Kohler and Linsley, 1951; Linsley et al., 1975). Assuming that the groundwater/baseflow storage is linear, Blume et al. (2007) proposed an objective, but non-physically based method, to identify the end point of event runoff. The method used by Mahe (2009) to determine the time of surface runoff disappearance has been proposed with the use of the depletion curves and the fluctuation of groundwater level observations.

Even though a threshold rainfall amount and a Minimum Inter event Time (MIT) value are required to separate rainfall events, suitable values could not be identified from the literature. Considering the time tested Unit Hydrograph (UH) method (Ritzema, 1994), the watershed response time of direct runoff for one day unit rainfall was used in order to determine the MIT for one day rainfall input. Considering the data resolution, one day synthetic unit hydrograph for Karasnagala watershed was developed (Fig. 3). Results showed that the time-base was 4 days. Hence, the MIT for this watershed was taken as 3 days, and 0 mm/day Minimum inter Event Depth (MED) was taken as the threshold rainfall value of the analysis.

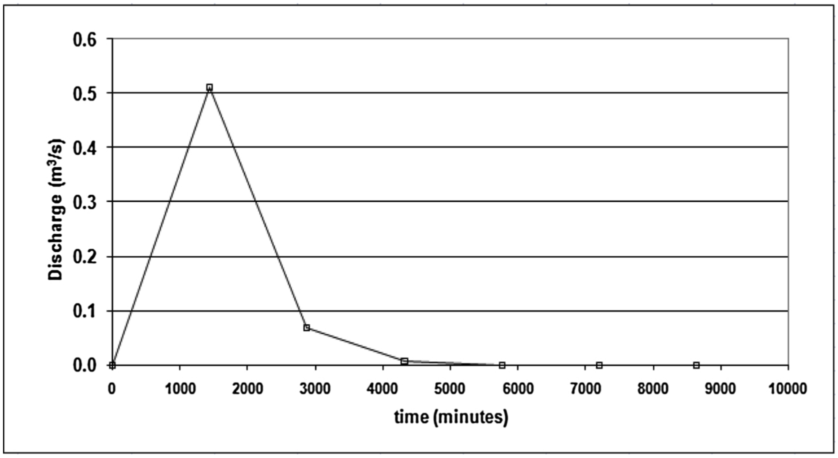


**Fig. 3.** One Day Synthetic Unit hydrograph for Karasnagala Watershed.

### *4.4. Model development*

Gülbaz and Kazezyılmaz-Alhan (2018) investigating the effect of Low Impact Development (LID) on water quality, concludes the capability of EPA SWMM 5 as a hydrological model. Applying the EPA SWMM model for Scott Creek subcatchment of the Onkaparinga River, Subhashini et al. (2013) shows the complexity and the issues encountered in modeling hydrologic response of a rural catchment and how these issues were managed to develop reliable model predictions. According to Subhashini et al. (2013), SWMM is increasingly used in rural catchment for understanding future urbanization scenarios/impacts and investigating the effectiveness of Water Sensitive Urban design (WSUD) or the Best Management Practice (BMP) measures. Therefore, in the present study, the effect of the field approximations was analysed by applying the SWMM model for an area which is not highly urbanized. Therefore, in this model layout development work, factors of the existing stormwater controlling tools of EPA SWMM 5.0 were suitably accommodated to represent a rural catchment behaviour (Table 1). Stage by stage model layout development, parameter optimization, model calibration, and verification are implemented as salient features of the methodology.

### *4.5. Subcatchment delineation*

Subwatershed delineation was the next challenge because the spatial aggregation of watershed parameters depends on the number of subdivisions. The number of subdivisions (subcatchments) in the watershed model is an important field approximation of watershed modeling. It directly contributes to the output of the model. When determining the number of subdivisions of the model, the computation time efficiency and the required accuracy of the model were compromised, while following scientific methodology for subcatchment delineation. The basis of subcatchment delineation was the stream order. When the 1st order or 2nd order stream segment were to define the subcatchment outlet, a large number of subcatchments (nearly 400) should be taken as the system. In case of 3rd order streams, only sixteen subcatchments were identified. When considering 4th order streams, only four subcatchments would be sufficient to define the system. Also approximating fully lumped layout single catchment model can be identified. The fully distributed layout for this watershed at 3rd order streams contained 16 subcatchments with 72 spatially distributed intermittent storage subcatchments while without approximations for storage area (Fig. 4 -layout **a**). When determining the semi-lumped layout, it was difficult to conceptualize the best number of subdivisions for the watershed, considering whether a layout will be classified as distributed or as lumped or as semi-lumped. However, when following the stream ordering method as the basis for subcatchment

**Table 1**
Catchment Parameters Modifications to Represent Rural Catchment Behaviou.

| Catchment parameters/ factors | Optimized parameter value | Remarks |
|---|---|---|
| Channel roughness coefficient | 0.025 | 0.013-0.1 (Application manual) |
| Overland flow roughness | 0.25 | 0.011-0.8 (Application manual) |
| Soil conductivity | 0.85 mm/hr on average | 0.3 – 30 mm/hr (Application manual - Sandy clay loam & Silty clay were the major soil types) |
| Initial deficit | 0.15 | 0.097-0.375 (Application manual) |
| Depression storage | 4.3 mm on average | 1.3–7.6 mm (Application manual - Account the canopy interception as well |
| Suction head | 273 mm | 50 – 320 mm (Application manual) |
| Intermittent storages Volume & connectivity | Catchment natural storages (Paddy lands, marshy lands, depressions) modelled with Storage unit option | Storage unit area equal to natural storages area Connectivity of the storage unit to the main stream network was used as the model layout parameter |

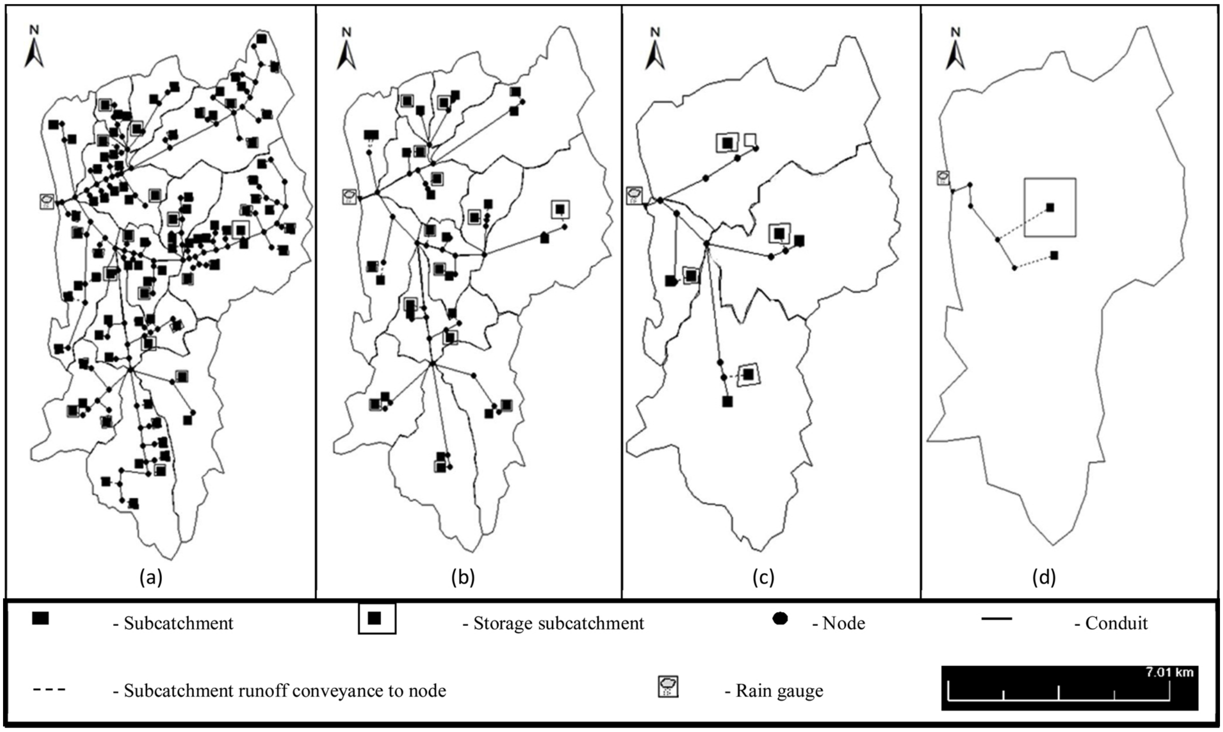


**Fig. 4.** Karasnagala watershed model layouts – Fully Distributed (a), 16 subcatchment semi-lumped (b), 4 subcatchment semi-lumped (c), and fully lumped (d).

delineation there were no combinations in between 16 subcatchment layout and 4 subcatchment layout options. The layout with 16 major subcatchments with 16 intermittent storage subcatchments (Fig. 4 -layout **b**) and layout with 4 major subcatchments with 4 intermittent storage subcatchments (Fig. 4 -layout **c**) were considered as semi-lumped layouts for this research. The selected lumped layout was with one major catchment and one storage subcatchment; which contains spatial aggregation of storage area approximations (Fig. 4 -layout **d**).

When observing the natural stream network of the Karasnagala watershed and the contour pattern, subcatchment for each single stream segment can be used with a minimum spatial aggregation. However, breaking into more subcatchments without calibrating each and every subcatchment is meaningless. If the discharge measurements were available at each subcatchment level, the fully distributed layout will be the best option. If not, it just increases the number of variables without intermittent check. However, when coming to modeling, it was a tedious task to adjust each subcatchment parameters and stream network parameters at each model run time, which in turn increased the model complexity. When the modelling approach moves from the distributed to lumped, the effect of the spatial aggregation of watershed parameters was a critical consideration.

### 4.6. Field approximations

Field approximation of subdivision level used stream bifurcations of the study area. Stream network for the model was established based on 1:10,000 topographic maps and satellite images. Also, field verification of stream network was used to apply stream ordering method. In this study, the scientific method (Strahler, 1964) was used to develop the stream network. Modeling with field approximations such as channel network arrangement, lateral connections, and intermittent storages should follow proper guidelines to represent the behaviour of the outflow hydrograph; the absence of guidelines made it a challenging task. The representation of the watershed characteristics in the model layout was the next challenge of this study. Trial and error cases were applied to identify the representative model layout. Quantitative representation and qualitative representation of the connectivity of the catchment intermittent storages were identified as the objectives of the layout parameter optimization. Then, the conceptual model layout was developed to represent the spatially distributed intermittent storages and their connections to the major stream network.

The infiltration parameters of the catchment and physical parameters of the stream network were determined using field measurements for the model. Soil parameter approximations and the stream network geometry parameter approximations were verified through the field observations and with the literature support (Chow, 1959; Chow et al., 2010; Hunukumbura, 2007; Ritzema, 1994; Rossman, 2009) there were no difficulties in approximations. Those parameter values can be identified as unique parameters corresponding to a particular watershed. Efforts and the experiences of above studies can provide the guidance, but a modeler needs to control the layout parameters such as optimum number of subdivisions, spatially distributed storages quantity and their connectivity to the stream network for optimum results. Therefore, the most important component of this study was to identify representative

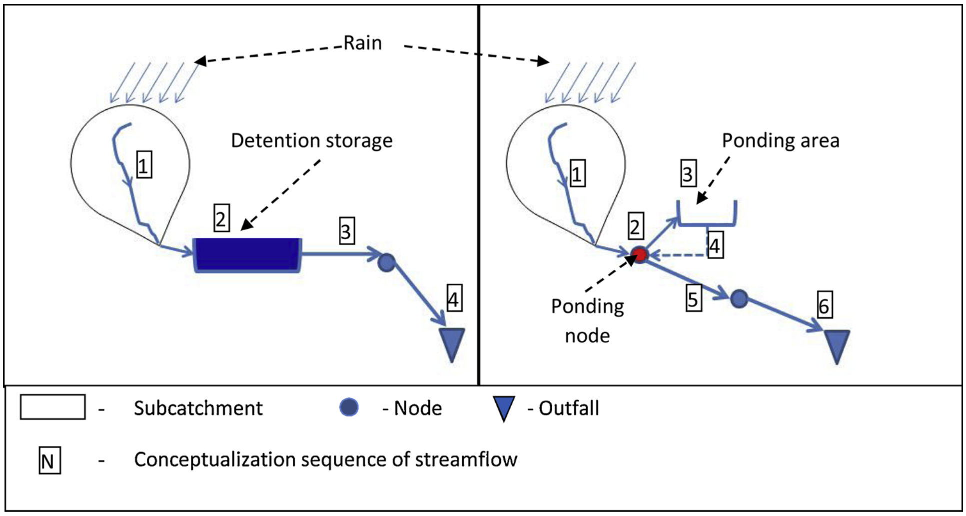


**Fig. 5.** Schematic Diagram of Detention Storage Option and Node Ponding Option.

SWMM layout for the Karasnagala watershed. After the calibration and verification of EPA SWMM model for the Karasnagala watershed, effect of the selected field approximations were analysed.

### 4.7. Storage modelling

Significant volume difference and mismatching of recession curves in observed and modeled hydrographs were the major observations with optimum subdivision level and optimized model experimental parameters. The reasons for the aforementioned behavior could be due to the model's quick response for the rainfall and misrepresentation of the catchment storages behavior. A quick response is expected as EPA SWMM 5 was specially designed for urban stormwater modeling. It was sufficiently modified with conceptual storage parameters to change the peak, and the recession which describes the withdrawal of catchment water storage. Then the paddy area, natural marshy lands and the connectivity of those areas to the stream network were modeled.

Options for the intermittent storages modeling were tested with the node ponding option and detention storage option of EPA SWMM 5.0. The detention storage option can incorporate infiltration parameters and evaporation factors to the storage unit (Rossman, 2009). However, insignificant evaporation in a flooding situation with cloudy environments and the insignificant infiltration amount in the wet soil condition reduce the effectiveness of the detention storage option. In the detention storage option, subcatchment runoff pools up in the storage area and then releases through the defined outlet. If the water depth exceeds the maximum depth of the storage unit, water will pool up on top of it and release when capacity permits (Fig. 5). However, in real situations, the water comes to the node first and if the maximum depth of the node exceeds, the node will flood and pool on top of the node. That flooded area may be the paddy land or marshy land close to the node. When the capacity permits, water is released from the flooded area to the node. In the detention storage option, this phenomena occurs in the reverse direction. The node ponding option is conceptually closer to reality than the detention storage option. Therefore, the node ponding option was used for the further modeling work. Catchment intermittent storages clustering and incorporating to the model layout were done according to the synthetic unit hydrograph theory. Accordingly, the stream length along the longest stream ($\mathbf{L_{cpd}}$), the stream length from the Centroid of the storage area to the intersection point perpendicular to the longest stream ($\mathbf{L_p}$), and the stream length from the Centroid of the catchment to the intersection point perpendicular to the longest stream ($\mathbf{L_c}$) were defined (Fig. 6).

The influence of intermittent catchment storages on model output was assessed with four model schematic diagrams (Fig. 7). Further investigation of the intermittent storages behavior has been identified that the outlet control tool should be introduced to control the storage on the node. The SWMM weir tool was used as the outlet control tool. Four model schematic diagrams were defined as schematic diagram (a) with no storage options, schematic diagram (b) with node storage direct connection, schematic diagram (c) with optimized $\mathbf{L_{cpd}}$ and $\mathbf{L_p}$, and schematic diagram (d) with optimized $\mathbf{L_{cpd}}$ and $\mathbf{L_p}$ and weir.

### 4.8. Model calibration

Model calibration and verification were done using the observed runoff data. In the model calibration, the calibration parameters were divided into two categories: controllable parameters and less controllable parameters. The watershed parameters such as depression storage, suction head, saturated hydraulic conductivity, initial deficit, and channel roughness are less controllable parameters. Boundary values and the limitations pertaining to those parameters are defined by the literature (Hunukumbura, 2007; Rossman, 2009; Chow, 1959; Chow et al., 2010). The model layout parameters such as intermittent storages and their connectivity to main stream network are controllable parameters. The model layout optimization process shows the conversion of the mathematical watershed model which was developed for urban stormwater modeling, into the regional watershed modeling. When observing the

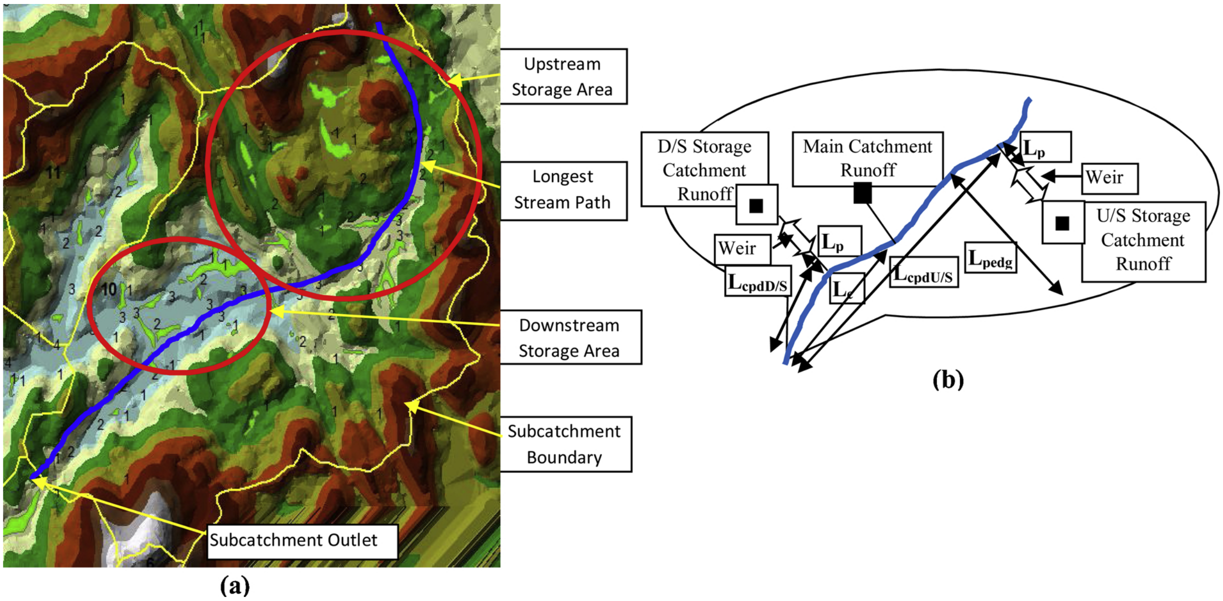


**Fig. 6.** (a) Intermittent Storage Clusters on the Subcatchment; (b) Schematic Diagram of the Connectivity of the Storages in Model Layout.

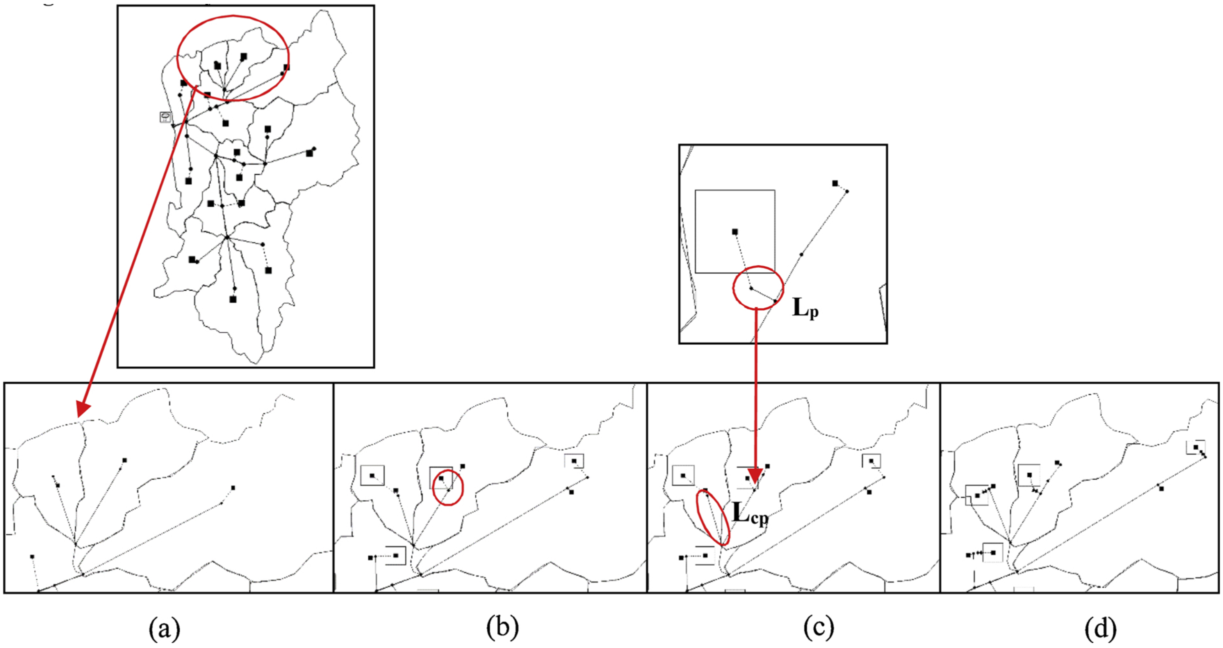


**Fig. 7.** Four Model Schematic Diagrams to Assess the Storage Contribution: Schematic Diagram (a) Without Storage Options; Schematic Diagram (b) with Node Storage Direct Connection; Schematic Diagram (c) with Optimized $L_{cpd}$ and $L_p$; Schematic Diagram (d) with Optimized $L_{cpd}$ and $L_p$ and Weir.

results, it is clear that adequate representation of the behaviour of the catchment intermittent storages in a model provided significant improvement of the hydrograph recession limb matching. A summary of the parameter values obtained for calibration events are shown in Table 4.

Numerical values were assigned for the $\mathbf{L_{cpd}}$ and $\mathbf{L_p}$ considering the average of the sixteen subcatchments values. Tables 2 and 3 show the average values used for the stream length optimization.

Assessing the goodness-of-fit of a model is done with the use of objective functions. The behaviour of the measure of the effectiveness of model output is described mathematically using objective functions. It is important to identify the actual relationship between objective function variables and the measure of efficacy (Arsham, 1994). Setting up a meaningful objective function is usually a tedious task which follows a trial and error process. The optimum parameters set minimizes the objective function that is

**Table 2**
Average $\mathbf{L_{cpd}}$ Values for the Optimization.

| Possible values | $L_{cpd}$ (m) |
|---|---|
| D/S $_{cluster}$ | 944 |
| $L_c$ | 1678 |
| $L_{cpd}$ | 1971 |
| U/S $_{cluster}$ | 2418 |
| Longest stream | 3537 |

**Table 3**
Average $\mathbf{L_p}$ Values for the Optimization.

| Possible values | $L_p$ (m) |
|---|---|
| $L_{pmin}$ | 61 |
| $L_{pavg}$ | 382 |
| $L_p$ | 532 |
| $L_{pmax}$ | 701 |
| $L_{edge}$ | 1000 |

**Table 4**
Calibration Events Optimized Parameter Values.

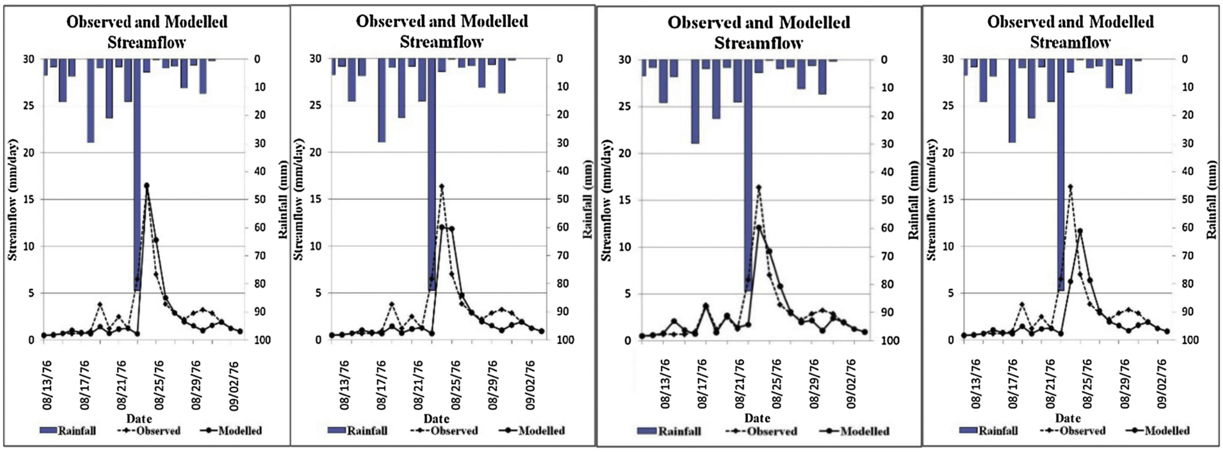
| | Event ID | Depression Storage (mm) | Suction Head (mm) | Conductivity (mm/hr) | Initial Deficit | Roughness |
|---|---|---|---|---|---|---|
| 1 | N2 | 3 | 273 | 0.75 | 0.154 | 0.025 |
| 2 | N3 | 3 | 273 | 0.762 | 0.154 | 0.025 |
| 3 | N6 | 5 | 273 | 0.6 | 0.100 | 0.025 |
| 4 | N7 | 3 | 273 | 0.5 | 0.154 | 0.025 |
| 5 | N9 + N10 | 7 | 273 | 1 | 0.154 | 0.025 |
| 6 | N13 | 3 | 273 | 0.5 | 0.154 | 0.025 |
| 7 | N17 + N18 | 5 | 273 | 1.016 | 0.154 | 0.025 |
| 8 | N23 | 7 | 273 | 0.962 | 0.154 | 0.025 |
| 9 | N35 | 3 | 273 | 1.27 | 0.154 | 0.025 |
| 10 | N36_1 | 3 | 273 | 1.016 | 0.154 | 0.025 |
| 11 | N48 | 7 | 273 | 1.27 | 0.154 | 0.025 |
| 12 | N59 | 3 | 273 | 0.945 | 0.154 | 0.025 |
| 13 | N61 | 3 | 273 | 0.65 | 0.154 | 0.025 |
| 14 | N62 | 7 | 273 | 0.1 | 0.05 | 0.015 |
| 15 | N63 | 3 | 273 | 0.6 | 0.154 | 0.025 |
| 16 | N65 | 3 | 273 | 0.785 | 0.15 | 0.025 |
| 17 | N66 | 7 | 273 | 2 | 0.2 | 0.045 |
| 18 | N67 | 3 | 273 | 0.9 | 0.154 | 0.025 |
| 19 | N68 | 7 | 273 | 1.153 | 0.154 | 0.025 |
| 20 | N71_1 | 3 | 273 | 0.735 | 0.154 | 0.025 |
| 21 | N72 + N73 | 3 | 273 | 1.016 | 0.154 | 0.025 |
| 22 | N71 | 3 | 273 | 0.6 | 0.154 | 0.025 |
| 23 | N14_1 | 7 | 273 | 0.6 | 0.154 | 0.025 |
| 24 | N12 | 3 | 273 | 0.8 | 0.154 | 0.025 |
| 25 | N30 | 3 | 273 | 0.7 | 0.154 | 0.025 |
| | **Maximum** | 7 | 273 | 2 | 0.2 | 0.045 |
| | **Average** | 4.28 | 273 | 0.849 | 0.149 | 0.025 |
| | **Minimum** | 3 | 273 | 0.100 | 0.050 | 0.015 |

discovered at the calibration process. The failure of an objective function could occur due to the selections of a wrong set of variables.

$$MRAE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{Q_{Obs(i)} - Q_{Sim(i)}}{Q_{Obs(i)}}\right| \tag{1}$$

MRAE provides the information about the predicting capability as well as the distribution of the prediction errors of the model. The best fit between the observed and calculated values would be MRAE = 0.

Majority of events the error of observed and the simulated streamflow was always higher in the high streamflow region than that of the lower flow region (Baseflow). RMSE and MRAE provide important information about the predictive capabilities of the model (He et al., 2014). The RMSE measures the goodness-of-fit relevant to high rainfall values while the MRAE provides more balanced perspective of the goodness-of-fit at a moderate value distribution of the estimation errors (Feng et al., 2014). One observation while applying the Nash-Sutcliffe (NS) efficiency is highlighting the mismatching of the peak flow region and relatively lower interpretation



(1) (2) (3) (4)

**Fig. 8.** Fully Distributed (1), 16 Subcatchment Semi-lumped (2), 4 Subcatchment Semi-lumped (3), and Fully-lumped (4) Subcatchment Model Layouts Results Comparison for Sample Rainfall-runoff Event.

of the mismatching in lower flow values. Therefore, MRAE was selected as an objective function to evaluate the goodness-of-fit of the model.

## 5. Results

### 5.1. Optimum number of subcatchments delineation

Comparison of the model generated outflow hydrograph of the fully distributed, 16 subcatchment semi-lumped, 4 subcatchment semi-lumped and fully lumped subcatchment model layouts for sample rainfall-runoff event shows in Fig. 8. According to Fig. 8, major peak matching and poor matching of initial peaks have been achieved by the fully distributed layout. A perfect initial peaks matching and poor matching of major peak have been achieved by four subcatchment semi-lumped layout. The optimization of modeling effort and modeling error has enabled the identification of optimum model layout for the Karasnagala watershed (Fig. 9). Tables 5 and 6 show the recession curve MRAE for schematic diagram (a) with no intermittent storages and schematic diagram (d) with optimized storage parameters. Figs. 10 and 11 illustrate the improvement of the results. Model calibration shows the mean ratio of absolute error (MRAE) 0.289, and 0.375 MRAE for verification. Incorporation of intermittent storages with optimized model layout improved the outflow hydrograph recession curve matching MRAE from 0.268 to 0.167 with no time lag.

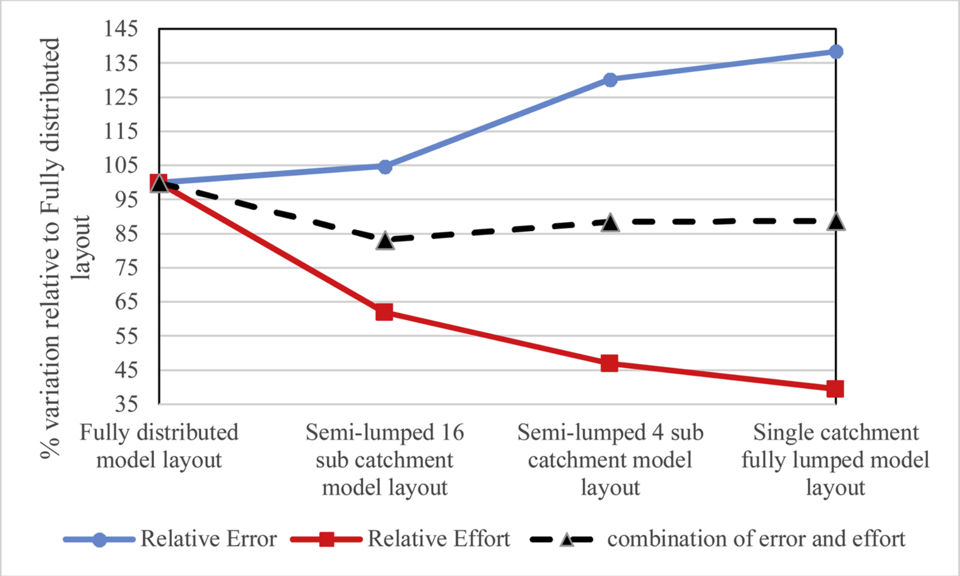


**Fig. 9.** Optimization of the Number of Subcatchments in the Model.

**Table 5**
Recession Curve MRAE of 50 Rainfall-runoff Events for Schematic Diagram (a).

| Event ID | Recession Curve MRAE | Event ID | Recession Curve MRAE | Event ID | Recession Curve MRAE |
|---|---|---|---|---|---|
| N2 | 0.072 | N66 | 0.147 | N34 | 0.299 |
| N3 | 0.325 | N67 | 0.292 | N36 | 0.181 |
| N6 | 0.147 | N68 | 0.311 | N37 | 0.302 |
| N7 | 0.127 | N71_1 | 0.244 | N38 | 0.361 |
| N9 + N10 | 0.233 | N72 + N73 | 0.201 | N45 | 0.487 |
| N13 | 0.209 | N76 | 0.357 | N46_1 + N47 | 0.371 |
| N17 + N18 | 0.311 | N80 | 0.261 | N49 | 0.197 |
| N20 | 0.161 | N80_1 | 0.317 | N51 | 0.275 |
| N30 | 0.214 | N5 | 0.389 | N54 | 0.204 |
| N35 | 0.228 | N5_1 | 0.231 | N60 | 0.341 |
| N36_1 | 0.237 | N10_1 | 0.189 | N64 | 0.183 |
| N48 | 0.346 | N11 | 0.533 | N64_1 | 0.289 |
| N59 | 0.072 | N21 | 0.292 | N69 | 0.321 |
| N61 | 0.144 | N24 | 0.219 | N70 | 0.277 |
| N62 | 0.224 | N25_1 | 0.404 | N74 | 0.321 |
| N63 | 0.566 | N27 + N28 | 0.289 | N75 | 0.143 |
| N65 | 0.392 | N33 | 0.146 | | |

**Table 6**
Recession Curve MRAE of 50 Rainfall-runoff Events for Modified Schematic Diagram (d).

| Event ID | Recession Curve MRAE | Event ID | Recession Curve MRAE | Event ID | Recession Curve MRAE |
|---|---|---|---|---|---|
| N2 | 0.023 | N66 | 0.236 | N34 | 0.208 |
| N3 | 0.111 | N67 | 0.244 | N36 | 0.043 |
| N6 | 0.086 | N68 | 0.124 | N37 | 0.174 |
| N7 | 0.135 | N71_1 | 0.11 | N38 | 0.247 |
| N9 + N10 | 0.109 | N72 + N73 | 0.13 | N45 | 0.427 |
| N13 | 0.173 | N76 | 0.22 | N46_1 + N47 | 0.239 |
| N17 + N18 | 0.116 | N80 | 0.189 | N49 | 0.135 |
| N20 | 0.083 | N80_1 | 0.167 | N51 | 0.191 |
| N30 | 0.11 | N5 | 0.259 | N54 | 0.125 |
| N35 | 0.139 | N5_1 | 0.161 | N60 | 0.209 |
| N36_1 | 0.08 | N10_1 | 0.083 | N64 | 0.102 |
| N48 | 0.222 | N11 | 0.348 | N64_1 | 0.211 |
| N59 | 0.085 | N21 | 0.142 | N69 | 0.179 |
| N61 | 0.106 | N24 | 0.119 | N70 | 0.161 |
| N62 | 0.138 | N25_1 | 0.236 | N74 | 0.269 |
| N63 | 0.356 | N27 + N28 | 0.115 | N75 | 0.065 |
| N65 | 0.314 | N33 | 0.09 | | |

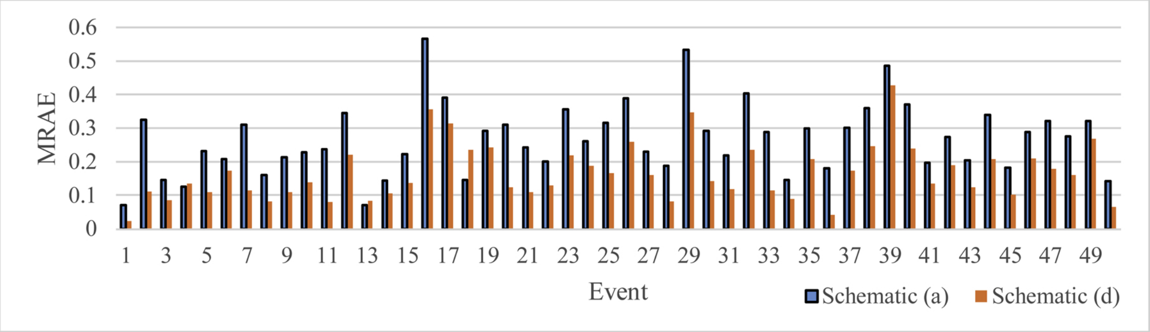
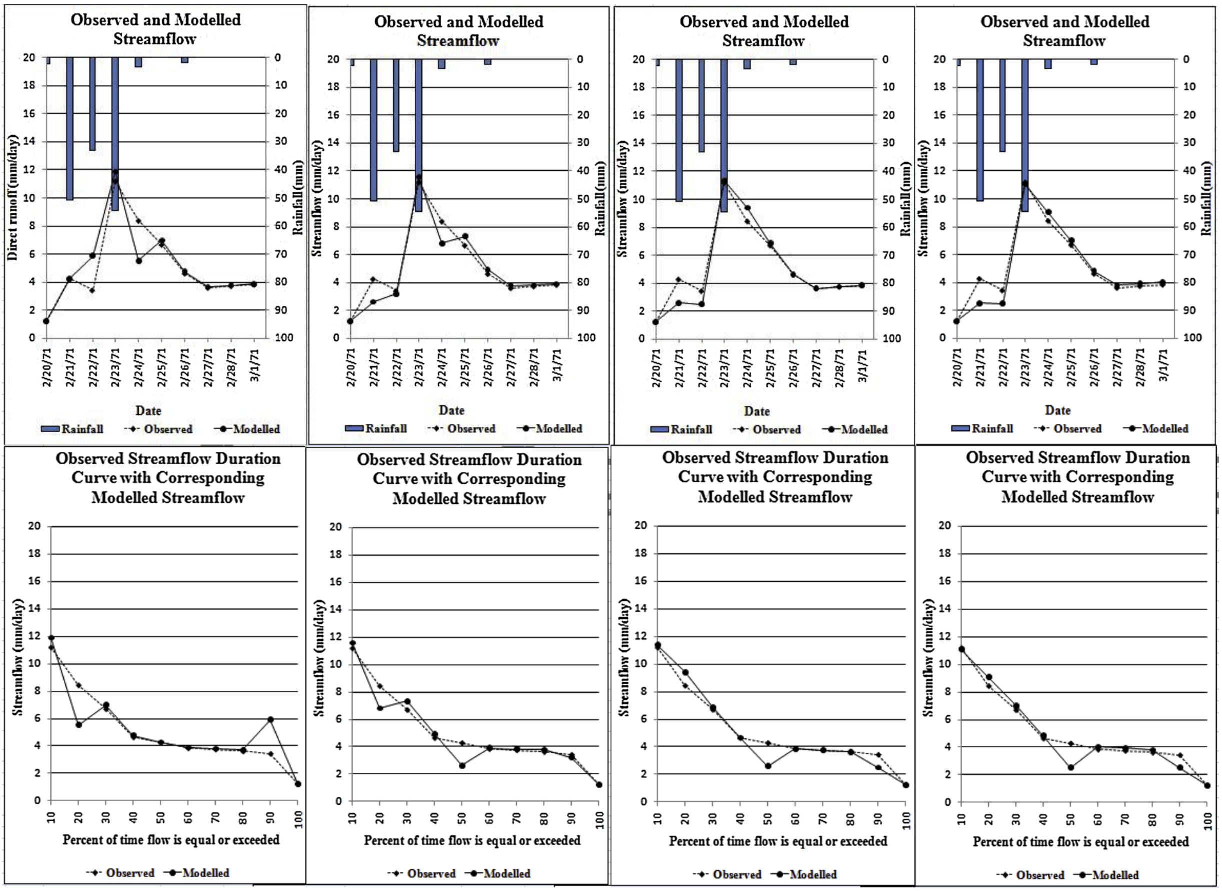


**Fig. 10.** Recession Curve MRAE Comparison for Schematic Diagram (a) and Schematic Diagram.

### *5.2. Stream parameter approximation*

The effect for 15 sample events of the stream bed and bank roughness value, when it varies ± 50 % from the field estimated roughness value is shown in Table 7. When consider the average difference it is less than 2 % variation from the modeled streamflow peak for the optimized parameters. Also it is observed that the effect of the stream bed and bank roughness on the hydrograph peak is decreasing with the increment of the stream order.



(a) (b) (c) (d)

**Fig. 11.** Schematic Diagram (a) to Schematic Diagram (d) Hydrograph Recession Improvement for Sample Event.

**Table 7**
Stream Bed and Bank Roughness Effect on Event Outflow Hydrograph Peak.

| Event ID | Observed Peak Streamflow (mm/day) | Modeled Peak Streamflow (mm/day) for the Optimized Parameters | Modeled Peak Streamflow (mm/day) | |
|---|---|---|---|---|
| | | | Roughness (-50 %) | Roughness (+50 %) |
| N2 | 11.18 | 11.59 | 11.69 | 11.48 |
| N7 | 78.53 | 68.79 | 68.83 | 68.29 |
| N17+N18 | 35.43 | 37.47 | 37.86 | 36.88 |
| N35 | 5.26 | 5.77 | 5.86 | 5.68 |
| N36_1 | 8.79 | 8.56 | 9.20 | 8.98 |
| N59 | 37.47 | 38.85 | 39.36 | 39.19 |
| N61 | 13.69 | 13.69 | 13.72 | 13.67 |
| N63 | 168.19 | 99.95 | 101.11 | 91.84 |
| N65 | 71.98 | 56.60 | 56.68 | 56.24 |
| N66 | 50.27 | 52.34 | 53.00 | 51.70 |
| N71_1 | 8.10 | 8.20 | 8.30 | 8.10 |
| N72+N73 | 57.02 | 61.54 | 61.76 | 62.44 |
| N76 | 16.57 | 18.65 | 18.81 | 18.50 |
| N80 | 28.50 | 27.02 | 27.26 | 26.79 |
| N80_1 | 41.15 | 48.40 | 48.59 | 48.12 |

## 6. Discussion

The Upstream and downstream storage area definition was based on the floodplain definition that depends on the catchment slope. DED (2013) defines floodplain area as slope less than 4 %. When the catchment slope along the main stream of each subcatchment was analyzed, storage areas contained within the floodplain are considered as downstream storage area and the rest is considered as upstream storage area.

In the iteration process, the model calculates the next time step outputs based on the current time step results. The continuous modeling, will cause the accumulation of error and would be difficult to calibrate the model with finer resolution data. Therefore, most of time, continuous modeling use the coarser resolution data. However, in event based analysis, each and every event has more degree of freedom to vary the flow governing parameters such as antecedent wetness, and event model parameters. Also, in continuous rainfall runoff modeling, usually a spin-up (warm-up) period is used before the actual calibration to establish the model parameter to adjust to the current hydrological conditions. With the spin-up period, the effects from initial values in continuous rainfall runoff modeling can be avoided. However, the determination of the spin-up period is not clearly defined (Kaffas and Hrissanthou, 2014). Comparing continuous and event based rainfall runoff modeling, Hossain et al. (2019) concludes that event-based modelling outperforms the continuous simulation approach. Therefore, an event based approach was utilized in this study. However, event-based-modeling required reliable event separation criteria suitable for the study area. There were no guidelines to determine the MIT for the Attanagalu Oya Catchment at the Karasnagala. The new approach proposed by this study is the approximation of the time-base for one day duration unit hydrograph as the direct runoff duration of one day duration rainfall.

EPA SWMM 5.0 model recommends the hourly resolution rainfall data for the analysis. Therefore, it avoids the loss of finer details of the outflow hydrograph of the model. In the absence of finer resolution data, this study used the daily resolution data. However, the majority of the events show the model generated outflow hydrograph pattern (Fluctuations) is similar to the observed streamflow hydrograph. That is due to the usage of optimum calculation time step. Considering the continuity equation and observing the model output details, trial and error calculation time step adjustments can be used to identify the optimum calculation time step.

In the subcatchment delineation process, field verified topographic map can be used as the base data. After generating the stream network, stream ordering can be used to define the subcatchments while keeping the required accuracy and the effort as the boundary conditions. Relative to the fully distributed model layout, percentage increment of MRAE in semi-lumped 16 sub catchment model layout, semi-lumped 4 sub catchment model layout, and single catchment fully lumped model layout are 21.74 %, 73.69 % and 165.94 % respectively. These values interpret the model performance in different field approximation levels of complex stream network and spatially distributed catchment parameters.

Having Karasnagala stream gauge as the only possibility to calibrate the model, there is no point of moving into finer resolution distributed subcatchement delineation without intermittent verification at each subcatchment level (Singh and Kumar, 2017; Terink et al., 2018). Therefore, when selecting the study area it is recommend to check the possibility of intermittent verification at least for one small subcatchment within major catchment boundary (Wallner et al., 2012).

## 7. Modeling errors and limitations

During the field work, a number of assumptions for the field parameter measurements and simplifications for the complex stream network were implemented to reduce the effort and time which can contribute to more errors in the model development.

The environmental protection agency which has developed this model, recommended the application of SWMM for the urban stormwater modeling. Also, past modeling experiences of the researchers were focused on the application of SWMM for urban stormwater modeling with sub-daily resolution data. However, in this study with coarser resolution input rainfall data, there was a possibility of losing important information of the model output hydrograph. The precipitation data used were obtained from two rain gauge stations and Thiessen averaged rainfall was applied uniformly over the catchment area. Theissen averaging identifies the Theissen area factors for the Karasnagala rain gauge and the Vincit rain gauge as 0.21 and 0.79 respectively. It clearly indicates the average rainfall is biased towards Vincit gauging station. Due to the spatial variation of the rain gauges, and the ambiguities in model calibration and verification reveals that the Theissen averaging may not be the best method to identify the representative rainfall for the Karasnagala stream gauge. This may add errors to the model output.

The Green-Ampt infiltration parameters were calculated by the area weighted average soil parameters, and assumed to be uniform over the entire catchment. Also, the vertical distribution of soil profile was assumed to be uniform in the unsaturated zone. These assumptions can have a significant impact on soil moisture characteristics.

## 8. Conclusions

The outflow hydrograph recession limb and the hydrograph peak behaviour depend on the catchment storage representation method, while initial peaks and the rising limb of the outflow hydrograph depend on the antecedent wetness, which is controlled by the model infiltration parameters. The key points identified from the field approximation of subcatchment delineation are that there is no combination between the 16 sub catchment model layout and semi-lumped 4 sub catchment model layout, and the effort of the 16 sub catchment model layout is marginally increased from the semi-lumped 4 sub catchment model layout.

The effect of the stream bed and bank roughness on the hydrograph peak decreases with the increment of the stream order. The main reason for this observation can be identified as the stream density. Usually the density of the lesser order streams is greater than that of the higher order streams. The conclusions of this research are as follows.

1 A qualitative evaluation of available models and the model development, calibration, & verification revealed that EPA SWMM 5 can be used to develop a rural watershed model.
2 The semi-distributed 16 sub basin configuration is more appropriate and practical model configuration for the Karasnagala catchment as this configuration only increases the error marginally compared to the fully distributed model configuration.
3 The hydrograph recession limb matching is highly correlated with the watershed intermittent storage modeling approximations, and calibration of the model conceptual parameters provided the best fitting of hydrograph recession limb with MRAE 0.167.
4 The effect of the stream bed and bank roughness on the hydrograph peak decreases with the increment of the stream order. Therefore, bed and bank roughness approximation of head water streams or the lesser order streams should be done precisely when compared with higher order streams.
5 The determination of the MIT by the Unit Hydrograph method is a reliable and rational solution for any region with similar conditions of the Karasnagala watershed.

In an event-based-modeling, identification of the end time of an event is a subjective method. It is recommend that further investigations on the defining MIT by Unit Hydrograph method should be conducted to identify end time of an event.

## Declaration of Competing Interest

I declare that I have no significant competing financial, professional, or personal interests that might have influenced the performance or presentation of the work described in this manuscript.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2019.100647.

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