IDENTIFICATION OF SUITABLE LOCATIONS FOR RUN-OF-THE-RIVER HYDROPOWER GENERATION USING GIS AND ABCD MODEL IN UPPER KELANI RIVER BASIN IN SRI LANKA

Bharat Pandit

(189245B)

Degree of Master of Science

Department of Civil Engineering

University of Moratuwa

Sri Lanka

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Bharat Pandit

(189245B)

Supervised by

Dr. R. L. H. L. Rajapakse

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UNESCO Madanjeet Singh Centre for
South Asia Water Management (UMCSAWM)

Department of Civil Engineering

University of Moratuwa

Sri Lanka

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DECLARATION

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Dr. R. L. H. L. Rajapakse Date

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ABSTRACT

Identification of Suitable Locations for Run-of-the-River Hydropower Generation using GIS and ABCD Model in Upper Kelani River Basin in Sri Lanka

The recent crisis in the energy sector has raised the need of exploration of additional renewable energy sources. Run-of-the-River (RoR) hydropower systems that harvest the energy from flowing water to generate electricity in the absence of a large dam and reservoir required in conventional impoundment hydroelectric facilities are gaining interest due to their minimum impact to the environment. Identifying suitable locations with significant potential of RoR hydropower capacity by using conventional methods is hindered in remote hilly inaccessible areas. The GIS tools and ABCD hydrologic model are used in the present study to remotely define and identify the feasible geographical features and estimate streamflow generation which governs the available hydropower capacity of potential sites in the project area.

The Upper Kelani Basin was selected as the overall project study area and two uppermost sub-catchments, namely Norwood and Holombuwa, were selected to optimize the ABCD model parameters for simulating streamflows with the selected rain gauge stations in each watershed. The ABCD daily hydrological model was calibrated using 5 years of data from 2008~2013 and validated based on four years of data from 2013~2017. The Shuttle Radar Topography Mission (SRTM) 90 m and 30 m Digital Elevation Model (DEM) terrain data was used in catchment delineation and available hydraulic head calculation along the river channel. The ABCD model parameters identified based on the two sub-catchments were progressively transferred to the downstream sub-catchments at locations where the feasible heads were available to establish potential RoR hydropower stations.

The identified *a*, *b*, *c* and *d* hydrologic parameters for Norwood and Holombuwa sub-catchments were (0.963, 398, 0.465 and 0.00001) and (0.995, 300, 0.542 and 0.0001), respectively. The Pearson's correlation coefficient (*r*) and coefficient of determination (R^2) were used as objective functions and the study found the values of ((0.825, 0.68), (0.59,0.35)) and ((0.87,0.75), (0.61,0.37)) for both calibration and validation model runs, respectively. The algorithm developed with Visual Basic for Application (VBA) Programming using extracted head from GIS tools in ArcGIS (v 10.3) platform to detect feasible sites based on river gradient coupled with flow estimates from the ABCD hydrologic model was found to be capable of remotely identifying potential locations for RoR hydropower generation. The study successfully established 36 suitable locations for RoR hydropower in the selected sub-basins.

The study shows that the proposed approach has vast advantages over the slow, cumbersome, uneconomical, conventional survey-based methods used for identification of potential RoR sites and further studies are recommended to recognize the sensitivity to terrain variations and incorporate alternatives for overall system optimization.

Keywords: Automated algorithm, Hydrological modelling, Model sensitivity and optimization

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INTRODUCTION

1.1 General

Power is certainly a catalyst for a financial boom in any nation, and shortage of adequate power will definitely slow the development of the nation (Bugaje, 2006). Energy is a major source for increasing the wealth, hence, it is the major contributing source for the economic development of the nations (Yuksel, 2010).

Geographically, South Asian countries are located in an area of various climatic situations including tropical, humid and so on, which provides a remarkable opportunity to spread renewable energy sources like hydropower. The governments of South Asian countries have initiated enacting renewable energy regulations to inspire industries and individuals to use renewable energy systems in the electricity application systems (Shukla, Sudhakar, & Baredar, 2017). Asia is experiencing a rising trend in the consumption of energy due to the increasing rate of the population and the developments in this area. It has been projected that 45 to 50 per cent of the increasing world energy demand is accounted from this area (United Nations Economic and Social Commission for Asia and the Pacific (ESCAP), 2010).

The hydropower sources are mainly divided into two types, i.e. impoundment systems and Run-of-the-River systems. Among these two types of hydropower systems, large hydropower systems have more disadvantages towards environmental protection due to its various constraints and Run-of-the-River(RoR) system of hydropower creates less effect on environmental with relatively lesser degradation impacts.

1.2 Background

Among the various source of energy, hydropower provides 16% of the total global energy and 76% of renewable energy (World Energy Council, 2015). Small hydropower covers a large amount of energy supply systems of the renewable sources in the world. The majority of the hydropower systems are of the Run-of-the-River (RoR) type (Penche & Minas, 1998). The identification of the suitable run-of-the-river (RoR) plant locations to permit high utilization of available water flows is a challenging task, in particular, due to the inherent temporal variability of the river flows (Aggidis, Luchinskaya, Rothschild, & Howard, 2010).

Among the different possibilities of developing hydropower schemes, the RoR is taken to be an impassable alternative in terms of its benefits as compared to the several other types of hydropower schemes. The selection process involves the different sets of the unknown and unseen factors that will cause more complexity in finding the exact locations of the potential RoR sites. Unavailability of the measured flow data at the required site and topographical feature data makes the site selection process more complex, hence, the recent advancements in the Geographic Information Systems (GIS) and Remote Sensing (RS) are making the process more feasible and convenient (Pasha et al., 2014).

Usually, the remoteness of the potential sites for the small hydropower (SHP) that are mainly located in mountainous areas and complicated hydrological zones create a considerable restriction for the SHP development. But, by the application of the developed hydrological tools and geospatial technique, the selection process has become relatively easier for the SHP in the recent past (Rospriandana & Fujii, 2017). Conducting a hydropower survey according to the conventional method is very tedious, slow and uneconomical. From the conventional approach, the probability of missing highly suitable sites is is very common, even with the rigorous procedures to follow. Therefore, to cater to this problem, additional support facilities of advance technology is essential for the rapid development of hydropower energy.

1.3 Status of Hydropower in Sri Lanka

Hydropower source affords to generate enormous amounts of energy in various countries in the world. More than a hundred nations, contribute to more than 15 per cent of worldwide energy production. In these countries, hydropower accounts for more than 50 per cent of overall electricity generation, such as Nepal, Iceland as an example (World Energy Council, 2013). Sri Lanka is an island having a unique, radially outward distribution of rivers in the country. Radial systems originate at the central hills and flow radially towards the ocean. These river sections, especially in the upstream hilly terrain areas, have a high potential for hydroelectricity generation. Sri Lanka's hydropower potential is estimated to be about 2,300 MW with an energy potential under average hydrological conditions. Major hydropower projects are concentrated in the central part of the country focusing on the major river systems namely Mahaweli Ganga, Kelani Ganga, Kalu Ganga, Nilwala Ganga, and Walawe Ganga. Among these river systems, Kelani Ganga hydro potential is largely developed (Old Laxapana 50 MW, Wimalasurendra 50 MW, Bowatenne 40 MW, Polpitiya 75 MW, New Laxapana 100 MW and Canyon 30 MW). In the Mahaweli basin, the Mahaweli Hydropower Complex consists of seven major power stations which have an installed capacity of 775 MWs, contributing around 15% of the electrical energy to the country annually, together with the two major hydro projects, Victoria 210 MW and Kotmale 201 MW.

1.4 Selected River Basin

For the purpose of the study, the Kelani river basin in the wet zone of Sri Lanka was selected. The river basin is mainly divided into the Lower and Upper Kelani basin. Later, only the Upper Kelani basin was examined by considering the hydro-morpho-geological requirements satisfying the criteria to establish RoR hydropower systems. The Kelani River is considered to be the fourth largest river in Sri Lanka. The river starts at the central high hills of the country and meets its final destination on the west coast in the outskirts of the capital city Colombo of Sri Lanka. The basin is surrounded by northern latitudes of 6°47' to 7°05' and eastern longitudes of 79°52' to 80°13'. The longest reach of the river is measured nearly 145 km from its origin point at the central hills at an elevation of around 2,250 m above mean sea level (m AMSL). From the administrative divisions, it originates in the Nuwara-Eliya District and travels across Kegalle, Gampaha and Colombo Districts. The river meets the Indian ocean at the outlet in Colombo District. The basin covers an approximate area of 2,230 km^2 in which 1,805 km^2 area is covered by the Upper Kelani basin and 500 km^2 is covered by the Lower Kelani basin. The basin experiences an annual average rainfall of 3,450 mm.

Geographically, the Kelani river basin has very distinct characteristics, while the Lower Kelani basin has a relatively flat area which is considered below the Hanwella river gauging station and above this station, the basin is named as Upper Kelani river basin which is elevated as compared to the lower basin area. The upper part is considered to be very suitable for the establishment of hydropower stations. Available slope and a considerable volume of discharge create the suitability for the hydropower generation of this area. The river supports the operation of the two major reservoirs and five power stations supplying a total installed power of 335 MW in this basin. The river basin provides 38% of the total hydroelectricity generated in Sri Lanka. For the development of hydro energy, the basic factor to be considered is the slope and quantity of the flow.

Hence, the basin experiences a very suitable slope, and measuring the quantity of the flow plays a vital role in finding the potential hydro energy generation capacity.

1.5 Importance of GIS and Hydrological Models in Hydropower development

Application of Geographic Information Systems (GIS) and hydrological modelling techniques are increasingly widely used in forecasting suitable sites for the hydropower generation in the last two decades. The first application of GIS tool was demonstrated in the United Kingdom (Punys, Dumbrauskas, Kvaraciejus, & Vyciene, 2011). Later, large number of researchers used this combined technique to forecast the RoR hydropower system site selection (Cuya, Brandimarte, Popescu, Alterach, & Peviani, 2013; Kayastha, Singh, & Dulal, 2018; Kusre, Baruah, Bordoloi, & Patra, 2010; Pandey et al., 2015; K. Soulis & Dercas, 2007; Zaidi & Khan, 2018). The advancement in public domain/freely available Digital Elevation Models (DEM) and GIS tools have made the selection process even robust and reliable.

1.6 Problem Statement

Identifying suitable locations with a significant potential of RoR hydropower capacity by using conventional methods is hindered in remote, hilly, inaccessible areas. Therefore, a methodology to remotely identify and estimate potential RoR capacity based on readily available GIS tools and suitable hydrologic models is required in Upper Kelani river basin where the study is undertaken.

1.7 Overall Objective and Specific Objectives

1.7.1 Overall Objective

The overall objective fo the research project is to develop a method to identify suitable locations for Run-of-the-River (RoR) hydropower generation in the Upper Kelani river basin by the combined application of GIS and suitable hydrological modelling technique.

1.7.2 Specific Objectives

1. Review of the status of the literature compared to the present status of hydropower generation and potential site selection.

2. Study of the available methods for hydropower generation and site identification based on literature.

3. Identifying the problems associated with the existing, conventional hydropower site selection process.

4. Feasibility of using GIS with an automated algorithm for site selection.

5. Identification of suitable hydrological model for flow estimation.

6. Combining above with the algorithm and verification based on the existing, pre-identified locations.

7. Deriving the conclusions and formulating recommendations based on the findings of the study.

1.8 Scope and Limitation

The scope of the present study is to show the capability of the lumped hydrological model and GIS tools to identify the suitable locations for the RoR hydropower systems. The major limitations are the application of the courser resolution of Digital Elevation Model (DEM) to identify the hydraulic head for the hydropower system and lack of data for verification purposes..

1.9 Thesis Outline

The thesis outline covers all headings of the major chapters with their contents.

1. Introduction

   The introduction section covers the general introduction about the status of the hydropower systems and why the Run-of-the-River hydropower system is important, It also describes the status of the hydropower in Sri Lanka. The topic covers the associated problems, need of the study and objectives of the study.

2. Literature Review

   The literature review is the brief study of the previously accomplished work, methods followed, tools applied and gaps in the past studies for the further improvements in the selected study. Further, this section helps to understand the established tools and procedures need to be followed for the respective study.

3. Methods and Materials

   The methods and materials are formulated with a systematic process for continuing the research in the concerned field. The methodology defines in brief the stepwise procedure to conduct the study. Moreover, this chapter discusses about the materials to be used to generate the results and data associated problems in respective systems.

4. Results and Analysis

   The results are the outcome of the developed methods and used materials towards the research goals and useful to identify the associated problems. Correspondingly, this section analyzes the results with analysis. The analysis helps to make the right decisions towards solving the associated problems and fine-tuning its solutions.

5. Discussion

   The discussion part covers the interpretation of the results and also it compares the findings with the well-accepted standards for producing concise and accurate results with the study while highlighting the causes of drawbacks.

6. Conclusions and Recommendations

   The conclusions and recommendations are the contributions from the study towards the selected goals of the research. This part covers the findings of the study, which could be applied as the new findings of the research.

LITERATURE REVIEW

2.1 General

In this recent era, an emerging need is felt for meeting the increased global energy requirements and it has led to an investigation of optimizing renewable energy sources along with Run-of-the-River hydropower projects. To derive a maximum payback for a given investment, finding the most appropriate site for a hydropower plant is basic and foremost. In the event, if the determination of potential site misses a few of the locations with indistinguishably critical hydropower potential, there is a high chance of obtaining only halfway of the possible benefits out of this investment (Zaidi & Khan, 2018). Hydropower is nowadays a key source of renewable and sustainable energy. Arefiev et al. (2015) stated hydropower potential estimation is the key component for a successful future prospective of hydropower within a selected study area. Finding a feasible location of hydropower site is crucial work in the case of RoR type of hydropower. According to Félix & Dubas (2000), exploration for exploitable locations requires a huge amount of resources and overall perception along with a concurrent comparison of energy production requirements and financial situation. Use of the Geographic Information Systems (GIS) makes it an easier and reliable process for continuation of the automatic site selection process. The GIS has the capability to cover a large area of interest with a minimum time as per the requirement. Usually, the RoR site suitability is found in the remote and inaccessible areas, and this constrains the scope of the selection process. Hence, the traditional method of selection of suitable sites for the RoR takes time and money that constrain the scope of consideration (Zaidi & Khan, 2018).

2.2 Hydropower Systems

2.2.1 General

Hydropower is the transformation of energy (Potential or Kinetic) stored within the falling or fast-moving river systems to generate or offer mechanical or electrical power. In the modern systems, hydropower is exclusively taken as hydroelectric power although some mechanical systems still remain in use. In early development age, the power (water) wheel was used to convert the mechanical energy to electric energy but now the water wheels are replaced and turbines are highly used in practice (Walker, 2018). Hydropower potential is a function of the available head and discharge at a certain flow exceedance. Hence, the power available is determined by:

$$P = \eta\ \rho\ g\ Q\ H\ \eta_t\ \eta_g \qquad \text{Eq. 1.}$$

where,

P= Power generated in watt (W),

η = Efficiency of the system (Unitless),

ρ = Mass density of water (kg/m^3),

g= acceleration due to gravity (m/s^2),

Q = Discharge (m^3/s),

H = Gross head drop (m),

η_t = Turbine efficiency = 0.85 to 0.95, and

η_g = Generator efficiency = 0.88 to 0.98.

A typical arrangement of the Run-of-the-River (RoR) system has been shown in Figure 2-1, which shows that small weir constructed in the river system and water diverted to the canal system, hence, headrace system is formed. Water collected at the forebay tank is supplied to the powerhouse by the penstock pipe to generate the electrical energy from the falling water to rotate the turbine associated in the powerhouse. The remaining water is released back to the river system. Generated electrical energy is supplied to the grid system or individual distribution systems. In these processes, the potential and kinetic power are turned into the mechanical power and again mechanical power is turned into electrical energy. The energy conversion process takes a certain amount of loss, that account for the efficiency of the system.

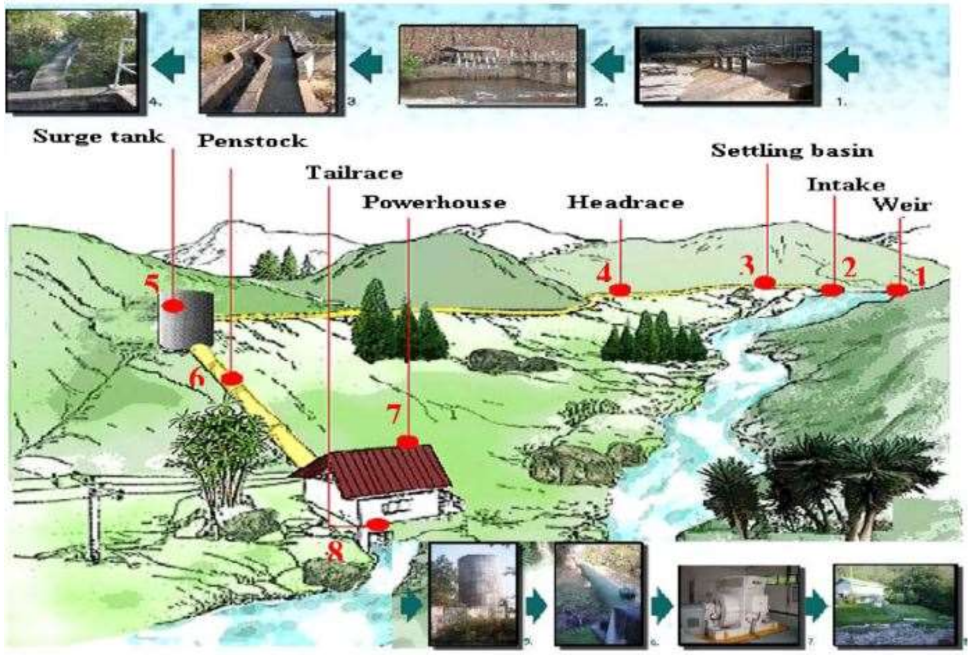


Figure 0-1. The Layout of the typical small hydropower plant (Rojanamon, Chaisomphob, & Bureekul, 2009)

Losses are occurred due to the presence of friction in supplying water from the higher head to the lower head. Other losses are due to the efficiency of generator and transmission losses are also accounted for the total efficiency of the systems. Hydraulic turbine efficiency is often in a range of 80 to 90 per cent (Paish, 2002). Good efficiency is obtained only with the overall effective layout arrangement of the total system, also the flow available, output transmission system and penstock arrangement. The selection of turbines depends on the quantity of flow. The length of the penstock is mainly responsible for the cost of the project. The simple assessment of the hydropower system mainly depends on the measurement of the flow (through the flow duration curve (FDC)) known as Q and head difference (difference of head between intake and turbine) know as H, to calculate the potential power of the river system.

Hydropower capacity ranges from the few kilowatts (kW) in small systems to gigawatts (GW) in major schemes. Hydropower stations are usually classified as Low, Medium and High head systems, where head represents the elevation difference between the water entering point to the hydropower system (i.e. Intake structure) to the outflow from the turbine (i.e. powerhouse) (Walker, 2018). Power generation capacity of the system mainly depends on the following two factors, i.e. head (*H*) and flow (*Q*). The low head systems are designed to utilize the power generation capacity of the small head intake structure but need high flow rates. The high head systems are designed in the hilly areas having higher elevation differences in the powerhouse and the intake structure locations within the shortest possible horizontal distances, and a high amount of electric energy can be achieved with comparatively less amount of the flow.

2.2.2 Run-of-the-River Hydropower

Small hydropower schemes are mainly Run-of-the-River (RoR) type with little or no reservoir impoundments and the schemes are run by the natural range of flows on the river systems. Small created dams are very favourable to maintain the natural ecosystems unaffected. The RoR hydropower can be designed as the small head type with a mild gradient and high head type with steep gradients (Yüksel, 2010). It is an extremely effective approach to harnessing renewable energy from small rivers and streams. This kind of projects is usually designed to be Run-of-the-River type projects. The water used in this system is taken back straight to the stream of the river system after utilizing by the turbine (Nasir, 2014). Development of hydroelectricity depends on the falling water system. The falling water is the main source of energy to generate hydropower energy, and without this, the system ceases to operate. Hence, evaluating this major factor of the electricity generation, the flow in the river system is a major part of the study, to fulfil the requirements of the hydropower generation. There should be an adequate amount of water available in the river to produce the hydropower in the system. For an ungauged river, where observation of extended period of long-term discharge is not available, the estimation of available flow involves the science of hydrology, the relationship of rainfall and streamflow, catchment area, its length and basin drainage measurements, evapotranspiration and geology (Penche & Minas, 1998).

The Run-of-the-River hydropower is a source to facilitate water channels or penstocks to drive a turbine in order to produce energy, and this system has no storage or only very little storage (World Energy Council, 2015). The operating of a small hydropower plant of Run-of-the-River type is exceptionally basic for the cost-effectiveness of the used fund (Anagnostopoulos & Papantonis, 2007). Run-of-river projects are classified into two types: low head and high head. Low head type is typically used for large rivers with a gentle gradient. High head type is typically used for small rivers with a steep gradient.

The Run-of-the-River hydropower points are defined as the points of the natural system with suitable head, flow and a slope that is requisite for development (Pasha et al., 2014). The river system's low flow season will not occur at the same time for powerhouse locating in different basins, hence, it can not guarantee the firm power generation system. If the hydropower generated from a system is supplied to an isolated area than to supply to a continuous power grid, to maintain an uninterrupted power supply to the corresponding area, the river should have a 90% exceedance flow in the river flow duration curve (FDC). But, even this can not guarantee the supply of energy of about 90% of the time in the area, because the FDC is related to the long-term river flow characteristics and does not necessarily apply in the dry periods (Penche & Minas, 1998). Hence, RoR is an intermittent source of energy which depends on the availability of flow, head and other satisfactory design considerations.

The configuration with a turbine design to perform high efficiency depends on the available head of water. The low flow will produce a less amount of energy but it will provide electricity throughout the year. If a project is designed based on the high flow amount, then the period the hydropower station is running will be less, and hence, it can only achieve energy targets over a lesser period of time. Kirk (1999) expressed the selection criteria of turbines for RoR hydropower systems, and they are; (a) runway safety factor and need for speed, (b) cavitation of the turbines and (c) hydraulic thrust.

2.3 Application of GIS Tools on Hydropower Assessment

The GIS allows integrating spatial and temporal data in a single organized system. It helps to analyze and organize information within the data region in the computer system. The tools perform reliable estimation of suitable hydropower generation locations for the precursory studies and large scale survey for the hydropower stations (Palla, Gnecco, La Barbera, Ivaldi, & Caviglia, 2016). A simplified geospatial assessment approach is useful to find the hydropower potential (Pasha et al., 2014). In earlier times, the hydropower site selection processes needed laborious map study and field survey, which was time taking and uneconomical.

Hall (2011) used geographic information systems (GIS) to assess the hydropower potential allover Brazil with the spatial distribution of the potential hydropower in state wise. The result was published on the internet as GIS model namely Virtual Hydropower

Prospector (VHP) to Brasil, while this presents maps, all the important features of the country like topography, hydrography, and transmission lines, etc., to determine the hydropower sites' gross power potential which was calculated by the change in elevation from upstream to downstream while the flow was calculated by using a reach average flow.

Balance et al. (2000) performed a preliminary assessment of the hydropower resources in South Africa from digital maps of slope and runoff, searching both RoR and micro-hydro and damming with a model for larger hydropower sites. The process followed a very coarse grid of 400 m by the application of GIS, using a flow value previously measured. The process established the preliminary methods of the site selection process to execute the detailing process on the field level. Palla et al. (2016) proposed a methodology on the GIS platform to identify the potential mini-hydropower sites in Italy based on the engineering, economic and environmental criteria. The proposed study was carried out on the basin level. The proposed methods examined 27-weir sections and hence, identified 640 mini-hydropower alternatives. The study also concluded that 14 basins out of 27 basins were suitable to establish the economical hydropower sites.

Setiawan (2015) presented a simple approach to finding a suitable site for RoR generation by focusing on the head and discharge data. The head is calculated by the use of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) 30 m x 30 m resolution terrain maps and for the flow calculation, Soil Conservation Service- Curve Number (SCS-CN) method was applied. Neighbourhood statistical method was used to calculate the head difference. The SCS-CN curve method was employed by using soil maps (5' x 5', spatial resolution) and land cover maps from the Ministry of Forest of Indonesia. The potential sites were mapped by the utilization of the energy formula. From the study, it was found that 18 sites were having the potential to hydropower generation from the range of 100 kW to 5.2 MW. Further, this method concluded that this is an only initial level screening and a pre-feasibility study.

Cuya et al. (2013) examined shortages and vulnerabilities of the hydropower generation capacities in the La Plata Basin. The basin covers Argentina, Bolivia, Brazil, Paraguay, and Uruguay. The study defined the future trend of the basin for the coming 30 years by establishing the relationship of electricity use of the last 20 years. The study produces the GIS-based tool VAPIDRO-ASTE, for finding the potential hydropower in the basin. This study concluded that basin has a high potentiality of hydropower and from which 40 % is already exploited and 60% is still remaining. Among this, 25% is economically unfeasible, and hence, only the remaining 35% is the feasible source to supply energy for the forthcoming period. This study basically covers the climate change parameter and its effects on the hydropower potential in the basin level.

Moiz et al. (2018) demonstrated the applicability of the GIS-based tools to identify the RoR in the Kunhar river basin in Pakistan. The study used the distributed hydrological model WEB-DHM-S. The model used the 30 m x 30 m Shuttle Radar Topography Mission (SRTM) data to evaluate the elevation profile of the river section. The tool was prepared in GIS with the help of developed criteria on python environment for the site selection. The study proposed two basic considerations to find the hydropower sites, first considering the topographic factor and the other was a combination of topography and hydrology factor. For the second case, to identify the potential hydropower locations, first, the flows at the river sections were identified by the hydrological model and then only the elevation profile was compared to decide the possibility of hydropower generation locations. The sites are selected by maximizing the head difference between the intake site and hydropower site, and then the developed FDC is employed in order to find the possible locations of RoR. The study proposed 36 small hydropower sites from an 85 km river length, considering the topographical factor. But for the same basin considering the hydrological factor and later comparing with the topographical factor, the method found 26 locations within a river length of 72 km. In both cases, the models produced the same hydropower potential of 235 MW on 70% flow exceedance. Therefore, the tools show reliable and systematic methods for preliminary site selection.

Zaidi & Khan (2018) proposed a simple methodology by use of the digital elevation model (DEM) of Advance Spaceborne Thermal Emission (ASTER) 30 m x 30 m terrain data resolution. For the flow parameter, the drainage area ration method (DAR) was employed. To develop the flow duration curve (FDC), reference data were used from the Pakistan Water and Power Development Authority (WAPDA) for the long period of 50 years and the 40-, 50- and 60 percentile discharges were produced (Q_{40}, Q_{50}, and Q_{60}). The proposed methodology was applied to the Kunhar river basin Pakistan. The 100 m interval was used to mark the elevation of the river length by the use of the construct tools on the ArcGIS editors. For the establishment of the power station, 500 m horizontal distance was employed between intake and turbine points. Further,100 m distance was used to establish two consecutive power stations. The proposed methodology evaluates the whole river system by the power potential of P_{40}, P_{50}, and P_{60} which represents flow exceedance of 40, 50 and 60 percentile discharges.

Dudhani et al. (2006) presented the applicability of the remote sensing data from the IRS-1D, LISS III satellite to use on water resources to develop the potential hydropower stations in the northeast region of India. The whole method was developed on the Visual Basic (VB) platform. Mainly, the developed methodology generates the site selection process for the best place of the RoR sites by considering the settlement patterns, vegetation cover, forest cover and snow cover area.

Kusre et al. (2010) assessed the hydropower potential of the Umkhen watershed of Kopili catchment, in North East India. It has an actual area of 2,228 km^2 but for the study, it considered only an area of 1,208 km^2 over a river length of 102 km. The methodology was developed by using a distributed hydrological model, SWAT (Soil and Water Assessment Tool) and digital elevation model (DEM) on GIS tools to develop the hydrological and topographical parameters, respectively. For the process, it used a land use map, and soil map of India having resolution 1:50,000. Further, it used the 20 m interval contour data to develop the elevation profile of the area. Flow duration curve was made by the use of 10 years of data sets. The site selection process considered the minimum of 10 m of elevation difference and 500 m horizontal distance between the intake and powerhouse area. Furthermore, the process applied the dependability of flow by using 90%, 75% and 50% exceedance. The stream point was characterized by the head and FDC, and then only used the power potential formula to calculate power available at the point of the river. This study concluded that the total power potential at the river length 132.18 MW, 18.18 MW and 9.91 MW on 50%, 75% and 90% dependability of flow exceedance.

Larentis et al. (2010) developed the Hydrospot tools by the use of FORTRAN routines integrated into the GIS. The methodology presents the inception phase automated survey process in the Brazilian basins. The methodology used the processed digital elevation model (DEM) and regional flow data for the topographical and hydrological components, respectively. The process automates the RoR system and dam system in the river basin to find the total power capacity of the basin. The study concluded that basin has 736 MW of power potential distributed in 274 locations, power varying from 10 kW to 58 MW. Among them, 199 locations out of the 274 locations were for the Run-of-the-River (RoR) systems and the remaining 99 locations were for the dam generated power plants in the area.

Punys et al. (2011) presented a study on the current scenario of uses of GIS tools on the preliminary survey of potential hydropower sites. Further, this paper discussed the growing trend of use of digital elevation models (DEM) and its accuracy and user-friendly capability to use on the hydro search possibilities. The paper concluded that over the last fifteen years, the application of DEM and GIS tool is significantly increased, and these tools are now essential basic tools for this kind of survey work.

Soulis et al. (2016) conducted a study that presents a methodology to establish large scale preliminary scale survey on poorly gauged sites in Greece. The study considered hydrological, topographical and economical factors to decide the location of suitable potential hydropower sites. The study used the course resolution SRTM Digital Elevation Model (DEM) data of 85 m x 85 m in the model and resampled data of 300 m x 300 m resolution was used for the topographical parameter estimation. The fully spatially distributed AgroHydroLogos simulation model was used to determine the flow parameters using a GIS extension. The study analyzed 2,860 sites and the details are presented in the database.

Serpoush et al. (2017) in their study developed a new methodology to find the best location of Run-of-the-River (RoR) plant according to the set engineering criteria and followed by economic criteria to finalize plant locations. The methodology was proposed by the use of ArcGIS and algorithm developed in MATLAB. The developed methodology was tested in Sifidbarg basin in Iran. The proposed methodology is based on the data of DEM and hydrometric station records of 30 years mean monthly streamflow for the determination of the topographical and hydrological features, respectively, all the processed were operated on the ArcGIS and criteria was set and executed in MATLAB algorithms. The developed methodology was used to classify distance between two hydropower sites as 1 km, 2 km, and 5 km distances. All of the distances were evaluated from the perspective of economic sites. Final results showed only four places are viable to execute for the final location of the RoR plant.

Cyr et al. (2011) presented a large-scale survey methodology to assess the hydro potential of the New Brunswick province having 71,450 km^2 area in Canada. The methodology used the synthetic hydro network (SHN) generated from the digital elevation model (DEM), which helps to determines the elevation heads of synthetic river length subtracting from the maximum to minimum elevation. The flow was determined by using the regional regression model to calculate the annual baseflow. The technical hydro potential was estimated based on the hydro head and penstock length. All the data were optimized in ArcGIS. Heads and penstock lengths were considered as 10 m and 3000 m, respectively. The result showed that 696 sites were found potential for the hydro plants, and from these, a 368 MW hydroelectricity was found feasible for the conventional reservoir type small hydropower and 58 MW was found to be feasible for the RoR type of configuration in the study area.

Pandey et al. (2015) presented a methodology on Mat river basin having an area of 47 km^2 in Southern Mizoram, India. It used SWAT (Soil Water Assessment Tool) model, satellite data and GIS tools to identify the hydro potential in the basin. The methodology employed the criteria of 20 m head and 500 m horizontal distance for finding the head of the potential sites. Head searching was started from the lowest downstream point and moved upstream. The 10 m resolution digital elevation model (DEM), land use map, a land cover map were used. A soil map was used of 1:250,000 scale. To assess the availability of the flow, the criteria was set to be 12,000 cells or more. Further, two 2^{nd} order or more rivers joining to a 3^{rd} order river is considered for the possible location of the hydro potential. The minimum distance between two consecutive sites should not be less than 500 m nor more than the 3000 m. Head selection criteria were fixed to 20 m to define the possible location of the hydropower. The model was calibrated and validated to estimate the available flow in the river system, same time head was estimated by using the DEM parameter and set criteria in the ArcGIS. After that, the energy potential formula was used to calculate the hydro potential at selected river point. The developed methodology was tested on the 50%, 75% and 90% dependability of flow from which estimated power was found to be 3,039, 1,127and 805 kW hydro potential in the river basin.

Rospriandana & Fujii (2017) developed a methodology to identify the potential hydropower locations by integrating Geographic Information Systems (GIS) and SWAT

(Soil Water Assessment Tool) model. The Digital Elevation Model (DEM) was employed to find the head criteria. The developed methodology was tested in the Ciwidey sub-watershed in Indonesia. The DEM used was of resolution of 30 m x 30 m from the USGS (United States of Geological Survey). The model was calibrated and validated for the basin and used to estimate the flow at the rivers. To estimate the hydro potential, only 2nd order and more streams were selected. The distance between each potential site was set to be a minimum of 1.0 km and the elevation drop criterion was set to a minimum of 10 m. The study concluded that the developed methodology is extremely useful to identify the hydro potential at the diverse characteristic areas, hence, it found nine potential sites with the range of 11-19 m head drop. The methodology was tested with 60%, 75% and 90% dependability of flow by which maximum potential was found to be 1.72 MW, to be harnessed in the sub-watershed.

Coskun et al. (2010) presented the methodology to assess the hydro potential on very poorly gauged catchments. Fundamentally required parameter head and flow quantity were identified from the 2.5 m finer resolution Digital Elevation Model (DEM) and Regression Model, respectively. The proposed methodology assumed the mean area, mean slope, and aerial rainfall was considered due to the data scarcity. The ability of the developed model was tested on the Solakli watershed in the Eastern Black Sea region of Turkey. The model found to be very efficient to derive data and find the locations of the hydro potential zone effectively.

Yi et al. (2010) presented the criteria and methodology to find alternative sites instead of finding the best suitable from all available alternatives. The methodology was developed to find potential sites fast and reliably. The methodology was tested in Geum river basin in Korea. Head criteria were set by the application of the DEM, with 100 m distance between the two points. The storage capacity of the dam was also tested to supply a continuous flow on the hydropower system by considering the availability of flow and elevation at the river section. For the calculation of the flow, run of the contributing area was set as the hydrologic factor. An eco-environmental factor was also considered to select alternative sites for the study. The study evaluates the Run-of-the-River type and reservoir type hydropower generation. ArcView GIS was used to analyses the DEM data. From the application of methodology on the study, it found six potential sites for the hydropower generation.

Rojanamon et al. (2009) proposed combined criteria of engineering, economic, environmental and social impact factor to develop Run-of-the-River (RoR) hydropotential at Nan river basin in Thailand. The developed methodology is integrated within GIS and for the environmental factor, a weightage was considered and also for the social impact factor, peoples participation factor focus discuss group was considered. Engineering and economic analyses were developed in the Visual Basic (VB) platform and analyzed in the ArcGIS. The GIS was used to locate the weir, surge tank, powerhouse, head race, and penstock. For the flow calculation, the regional flow model method was employed for which, all the established stational data were used to create the mean monthly flow duration curve. The model was validated to use on the ungauged locations. For the validation of digital elevation, the contour map of resolution 1:50,000 was also used. The longest distance between the weir and the powerhouse was set to 5.0 km. Only the perennial streams were selected. The installed capacity was selected in the range of 1 MW to 10 MW. The 30% dependable flow Q_{30} was selected to fix the upper level of the flow, below which the flow is not taken for the design procedure. To determine the drop of elevation profile, a DEM was employed and the drop was measured through the help of it. The economic analysis was done by considering direct and indirect cost analyses. Following all the criteria and methodology in the study area, 86 project sites were found to be feasible from the engineering criteria but later considering economic and social criteria, only 20 sites were found to be highly feasible for the final sites to establish small Run-of-the-River plant locations.

The details of the summary from different research on the study area, type of project, input data sets, spatial tools, processing unit and results obtained have been listed from 18 selected research in Table 2-1. It gives a clear idea about the use of GIS tools in different parts of the world in the identification of suitable site locations.

Table 0-1 The literature summary on the GIS tools used in hydropower surveys

SN	Researcher	Study Area	Type of Project	Input data sets	Spatial tool and processing Unit	Results
1	Hall (2011)	Brazil (National Scale)	Total power potential type projects	90 m SRTM Digital Elevation Model, mean annual flow duration curve (FDC) was prepared by Regression Equation	ArcGIS and Regression Equation	The 734638 MW power from the 818546 stream reaches, Virtual Hydropower Prospector (VHP) do Brasil
2	Balance et al. (2000)	South Africa (National Scale)	Run-of-the-River and micro and macro project with dam	Digital slope map of the country and the annual run off depth	ArcGIS	Results based of the annual energy potential, micro Excellent: ≥100,000 kWh yr^{-1} per km2 and macro hydro Excellent: >108 kWh yr^{-1}
3	Setiawan (2015)	Tanjung Lokang, South Putussibau, Indonesia	Run-of-the-River	ASTER 30-meter Digital Elevation Model (DEM), soil map 5' x 5' resolution, land cover map, average annual precipitation map	ArcGIS Arc spatial Analyst tool, SWAT and SCS-CN equation	The 18 potential site ranging power from the 100 kW to 5.2 MW
4	Cuya et al. (2013)	La Plata basin (Argentina, Brazil, Bolivia, Paraguay and Uruguay)	Potential available sites	Digital Elevation Model of resolution 900 m x 900 m, measured gauged data	GIS based tool VAPIDRO-ASTE	As results it shows 40 % already exploited and 60 % remaining out of this remaining 60 % only the 35 % is economically feasible
5	Moiz et al (2018)	Kunhar River, Northern part of Pakistan	Small hydropower SHP	SRTM- 30 m resolution data from DEM, Climatological data from 1971- 2010	GIS, hydrological model (WEB-DHM-S), Flow Duration Curve (FDC)	The 36 sites identified with power potential of total 235 MW Q_{75} flow exceedance
6	Zaidi & Khan (2018)	Kunhar River, Northern part of Pakistan, Average elevation of the watershed 2912 m MSL	Run-of-the-River	ASTER 30-meter Digital Elevation Model (DEM) and stream flow data of (1960-2009)	ArcGIS Arc Hydro tool and on ArcGIS 10, Microsoft Excel	Highest power potential of 432,050 kW from its 222 plants

SN	Researcher	Study Area	Type of Project	Input data sets	Spatial tool and processing Unit	Results
7	Kusre et al. (2010)	Kopili River basin in Assam (India), study area covers 1204 km^2	Run-of-the-River	Toposheet at 1:50,000 scale, FDC	Land use map preparation ILWIS 3.3, and GIS software and SWAT2000	A total of 107 sites on 9 streams
8	Larentis et al. (2010)	Taquari-Antas river basin, Brazil, Basin area 26,500 km^2	Run-of-the-River and reservoir type	SRTM 3" acquired in January 4, 2000, and potential flow regulation Q_{95}	Hydrospot developed in GIS environment	Initial 31266 sites, among that only feasible location were found to produce 736 MW
9	Soulis et al. (2016)	All over Greece (national scale, area =131,940 km^2)	Run-of-the- River	Soil data, land cover data, and SRTM data of resolution 85 m x 85 m and 300 m x 300 m	RESTRO Hydro, GIS hydrological model AgroHydroLogos	From the RESTOR Hydro Map 2860 sites are found and updated in the map of Greece
10	Serpoush et al. (2017)	Sefidbarg basin Nokhan, Iran, basin covers 242 km^2	Run-of-the- River	DEM of resolution 30 m and 30 years precipitation data	ArcGIS and algorithm developed in MATLAB	Total 4 Sites found to be most feasible
11	Cry et al. (2011)	Brunswick, Canada, 71450 km^2 area	Run-of-the- River and conventional reservoir system	SHN hydro network from DEM, Regional Regression Model	ArcGIS	The 696 sites found potential with power capacity of 368 MW power from reservoir type source and 58 MW from the RoR type source
12	Pandey et al. (2015)	Mat river basin India, 47 km^2 basin area	Run-of-the- River	DEM of 10 m resolution, soil map 1:250,000 scale, land use map	ArcGIS, SWAT, flow criteria set on 12,000 cell numbers	The results presented on Q_{50}, Q_{75}, Q_{90} dependable flow and power capacity found was 3093 kW, 1127 kW, 805 kW.
13	Rospriandana & Fujii (2017)	Ciwidey subwatershed, Indonesia, area - 204 km^2	Run-of-the-River	DEM OF 30 m resolution from SRTM, land use 1:25,000, soil type 1:250,000, daily precipitation 9 stations and other climatological data, river discharge data	ArcGIS and SWAT	The results presented on Q_{50}, Q_{75}, Q_{90} dependable flow and maximum potential found 1.72 MW

SN	Researcher	Study Area	Type of Project	Input data sets	Spatial tool and processing Unit	Results
14	Coskun et al. (2010)	Solakli watershed, Eastern Black Sea region Turkey, area 765.25 km^2	Run-of-the-River	DEM of 2.5 m resolution, Remote Sensing (RS), mean area, slope and aerial rainfall	ArcGIS, Regression Models	Flow estimation was done for the hydropower generation with the 4% error
15	Yi et al. (2010)	Geum River Basin in Korea,basin area 553.56 km^2	Run-of -the River and storage type	DEM and hydrologic factor as the contributing area	GSIS and ArcView	Four reservoir type and two Run-of-River type among the 100 highest searching points
16	Rojanamon et al. (2009)	Nan River Basin in Thaliland, basin area 13.026 km^2	Run-of-the-River	Topography maps 1:50,000 and Regional flow duration model	GIS tools and Weighted score method for social impact	86 possible technical location and final 20 location considering all aspect
17	Kayastha et al. (2018)	Bhote Koshi Basin, Nepal, the basin elevation ranges from 600 m - 8000 m	Run-of-the-River	DEM; ASTER-GDEM 30 m resolution	Q-SWAT, Google earth Picture and GIS and MATLAB	Here found 297 sites are highly potential sites among the 2655 number of located sites
18	Arefiev et al. (2015)	For Entire territory of Russia	Run-of-the-River	Usage of 1976's annual river runoff module (q, liters per sec. / sq. km.) map, SRTM; DEM based on digital maps (scale 1:100000)	Extension of ArcGIS as Arc Hydro tool and Python	Gross hydropower capacity = 350 GW and gross hydropower potential = 3,07*103 TWh

2.4 Digital Elevation Model (DEM) Selection

2.4.1 Introduction

The Digital Elevation Model (DEM) is a digital representation of a land surface in the digitalized version for the points having a coordinate presentation in three dimensions as X (northing), Y (easting) and Z (elevation). These are initially taken from non-uniform samples but later interpolated in a grid (Skidmore, 1989). In present time, numbers of public domain/freely available DEM's are in use, and few of them are SRTM CGIAR-CSI (Shuttle Radar Topography Mission released by the Consortium for Spatial Information (version 4.1)), ASTER GDEM2 (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (version 2)), ETOPO1 (1Arc-Minute Global Relief Model), ACE2 GDEM (Altimeter Corrected Elevations (version 2); Global Digital Elevation Model) SRTM3/DTED1 (Shuttle Radar Topography Mission 3 arc-seconds (version2.1)/Digital Terrain Elevation Data (level 1)), SRTM30/DTED0 (Shuttle Radar Topography Mission 30 arc-seconds (version2.1)/Digital Terrain Elevation Data (level 0)), ACE GDEM (Altimeter Corrected Elevations Global Digital Elevation Model), GLOBE (Global Land One-km Base Elevation Digital Elevation Model) and GTOPO30 (Global 30 Arc-second Elevation) (Rexer & Hirt, 2014). Global Digital Elevation Model (GDEM) is taken for the consideration of the current research and various kind of other users too due to its free availability and wide range of applicability (Arefi & Reinartz, 2011).

Digital Elevation Model (DEM) data are capable to derive the hydrological features of the selected area to fulfil the needs of the various hydrological models. DEMs have the capacity to derive the precise river network but this does not certainly require the high resolution of DEMs (Li & Wong, 2010). The public domain/freely available digital elevation model (DEM), ASTER GDME and SRTM are valuable elevation data. It gives satisfactory results in hilly steep sloped regions for the modelling purposes where the accurate digital elevation models are not available (W. Wang, Yang, & Yao, 2012). For the hydrological study of Upper Kelani basin, SRTM (30 m x 30 m) and (90 m x 90 m) and ASTER GDEM (30 m x 30 m) resolution data is available. Discrepancies in elevation difference depend on topographic characteristics of the area. It has a large variability of the elevation on the sloped areas. In the absence of accurate high-resolution DEMs, the ASTER GDEM (30 m resolution) and SRTM (30 m and 90 m resolutions) DEMs play a vital role in applicability on the water resources application (W. Wang et al., 2012).

2.4.2 SRTM vs ASTER Digital Elevation Models

Hirt et al. (2010) had performed an extensive comparison over the three public domain/freely available new DEMs (GEODATA DEM-9S ver3, CGIAR-CSI SRTM ver4.1, and NASA/METI ASTER GDEM ver1) over Australia, and the results concluded that SRTM was the best alternative to use as per the DEMs in that region. According to the Arefi & Reinartz (2011), the ASTER GDEM model shows the highest accuracy on spatial resolution among all the global DEMs available on the whole globe, but it has certain uncertainties on height which results from the inaccuracy in the model. Wang et al. (2012) compared public domain/freely available DEM's SRTM, ASTER GDEM and DEM5 (Digital elevation model from the high accuracy 1:50,000, contour) for glacial lake outburst flood (GOLFs) modelling, and this study concludes that SRTM overestimates and ASTER GDEM underestimates in elevation criteria, but for the flood zone extent, ASTER GDEM found to be more precise than the SRTM with comparing high accuracy DEM5. Huggel et al. (2008) compared the applicability of elevation models for a volcanic study, while it founds that SRTM had good results than the ASTER GDEM, but volcanic face angle wise result shows a difference for both models. Rexer and Hirt (2014) analyzed the three DEMs over the accurate heights of the Australian national gravity database, and the study found that Shuttle Radar Topography Mission by Consortium for Spatial Information (SRTM CGIAR-CSI version 4.1) was highly accurate as compared to Advance Spaceborne Thermal Emission Reflectometer DEM (ASTER GDEM2) and Shuttle Radar Topography Mission (SRTM) data as released by the United States Geological Survey (SRTM3 USGS version 2.1). Suwandana et al. (2012) evaluated the ASTER GDEM1, ASTER GDEM1, SRTM, and topographic maps derived DEM (Topo-DEM) against the Real-Time Kinematic differential Global Positioning Systems (RTK-dGPS) data obtained from an intensive geodetic survey which concluded that ASTER GDEM2 produced comparatively better results than the others.

Literature shows, the accuracy of the DEMs depends on the topography of the area, hence, for this Upper Kelani basin, two of the DEMs namely SRTM (30 m and 90 m) and ASTER GDEM 30 were tested to compare the topographical features of the study area.

2.5 Hydrological Models

2.5.1 Highlights of the Hydrological Model

Hydrological models are an important tool for assessing and managing water resources. It helps to understand the catchment behaviour and evaluates the effects on catchment behaviour due to various changes. Such a model helps to understand the concept of hydrological process, the mathematical interrelationship of models to the real catchment properties. The advancement in the technology for data recording and computing capacity results in the more frequent use of these models. These models are capable to produce good results on time and space domain (Martinez & Gupta, 2010). The watershed models are used to forecast the streamflow records at the point where measurement is not available. The recent advancements in computer technology and hydro climatological data facilitate the improvements on the hydrological models and development of its accuracy (Fernandez, Vogel, & Sankarasubramanian, 2000).

According to Chow, Maidment, and Mays (1988), hydrologic models can be categorized into two main categories called physical models and abstract models. The physical models represent the real physical parameters in a reduced scale while the abstract models represent the systems in terms of a set of equations which link the input and output variables.

The physical models are also known to be prototype models, the scale reduced presentation of reality in physics. But the abstract models are based on a set of equations which is based on the input and output variables. These variables may be functions of space and time and they may also be probabilistic or random variables which do not have a fixed value at a particular point in space and time but instead are described by probability distributions. Developing a model with random variables that depend on spatial variation and temporal variation and for most practical purposes, it is necessary to simplify the model by neglecting some sources of variation. Considering the randomness, the abstract models can be further classified into two types, deterministic and stochastic. The deterministic models do not consider randomness while the stochastic models do consider this randomness, although, almost all the hydrologic phenomena consist of randomness. The deterministic models can be classified to the lumped and distributed models, while stochastic models are classified into space-independent and spacecorrelated models. Further, the deterministic models can be classified as the steady flow and unsteady flow. Further, all the stochastic models can be further classified into the time-dependent and time-correlated categories.

According to Xu (2002), the two most often used classification methods for hydrological models are conceptual and physically based and according to the spatial variation of the catchment, lumped and distributed models. Theoretical models are also called white-box models or physically-based models. A theoretical model has a logical structure similar to the real-world system. Empirical models are also called black-box models or input-output models, since they do not aid in physical understanding. They contain parameters that may have little direct physical significance and can be estimated only by using concurrent measurements of input and output. Conceptual models also called as grey-box models are intermediate between theoretical and empirical models.

2.5.2 Lumped Hydrological Modeling

The significance of the application of modelling could be developed by using a smaller number of model parameters to find inherent characteristics which can change with land use and developed water resources projects (Thomas, 1981). A lumped model is used to simulate the hydrological process for the specific single point. The lumped models use developed equations to quantify the physical processes by simulating the temporal variation of various physical processes in a hydrologic system. The advantage of these models is that the conceptual parameterization is simple and computation efficient. The Lumped models have been widely used in climate, meteorological and hydrologic studies to simulate hydrologic processes (Yu, 2015).

2.5.3 Hydrologic Model Selection

Marshall, Nott and Sharma (2005) stated that selection of the suitable model has always been a challenge for the hydrologists, as none of the models can be categorised as an ideal model for a specific area of study. Hence, with the availability of the various models, it has been hard to determine a specific model for the study. Over the last several decades, a large number of models have been developed and used for the runoff generation of river basins with the view of improving the fits of simulated runoff and observed runoff hydrograph and model parameter were identified by the runoff hydrograph analysis (Ngoc, Chinh, Hiramatsu, & Harada, 2011). During the study of the model selection criteria in multi model analysis, Ye, Meyer, and Neuman (2008) stated that there are several basic criteria in practice for the model selections. They are (1) ranking of the available models as per the objective of the study, (2) eliminating the models that do not fall on the requirements as the objectives of the modelling, and is to (3) weigh and average predictions and statics for the selected models.

Considering the objective of the modelling required to use for the streamflow determination for the RoR, lumped models were selected. To select the suitable lumped model, the following criteria were formed for selecting a suitable model from the various lumped models available.

1. Objective of the modelling
2. Extent of the model
3. Capabilities of the model
4. Event based or continuous
5. Temporal resolution
6. Availability of the model
7. Data required for the model
8. User friendliness of the model
9. Details of the modelling

Hence, after evaluating the criteria selected above, the lumped non-linear ABCD model was selected and the study of further details on the selected ABCD model was carried out.

2.6 Lumped Hydrological Four Parameter ABCD Model

2.6.1 Introduction

The four-parameter ABCD hydrologic model is a non-linear, physics-based, lumped model. The model can be used either on daily or monthly time steps. This four-parameter model exhibits inherent characteristics to define the various steps present in the natural system from converting rainfall to runoff and in-between associated processes. The model is a lumped model which means the model represents the catchment as a single unit of area on its mathematical relationship. The model accepts the rainfall and potential evapotranspiration, producing output as the runoff. The model also internally represents the soil moisture storage, groundwater storage, direct runoff, groundwater outflow to the nearest outlet channel and actual evapotranspiration.

The model is capable of estimating the effect of groundwater contribution on total streamflow. The ABCD model has a separate groundwater compartment which facilitates the simulation of baseflow. The groundwater compartment of the model structure shows the capabilities to model low flows in a dry period. This capability is crucial to use the hydrologic modelling for the flow quantification required for the Run-of-the-River hydropower generation.

Martinez and Gupta (2010) discussed the advantages of the ABCD model and stated that the model is capable of predicting the streamflow under a low soil moisture condition in which the realistic representation of the infiltration process occurs.

2.6.2 The ABCD Model Structure

This model was initially developed by Thomas (1981) later this model was compared with several other water balance models considering temporal and spatial variation. The model concept structure was given by Thomas (1981), Al-Lafta et al. (2013), Fernandez et al. (2000) and Martinez and Gupta (2010), which has been presented in Figure 2-2. The model has its basic four-parameters *a*, *b*, *c* and *d* which reflect the physical interpretation of the model to present the reality of the natural system. Parameter *a* reflects the propensity of runoff to occur before the soil is fully saturated (Thomas, 1981). The parameter *b* is an upper limit on the sum of actual evapotranspiration and soil moisture storage in a given time. The parameter *b* probably shows the ability of catchment to hold water within the upper soil zone. The parameter *c* is equal to the fraction of streamflow which reflects the groundwater recharge in the given period of time. Over the long-term, *c* is then defined simply as the baseflow index (BFI), an index for defining the relationship of catchment characteristic and groundwater discharge to represent streamflow volume. The reciprocal of the parameter *d* is equal to the average groundwater residence time (Al-Lafta et al., 2013).

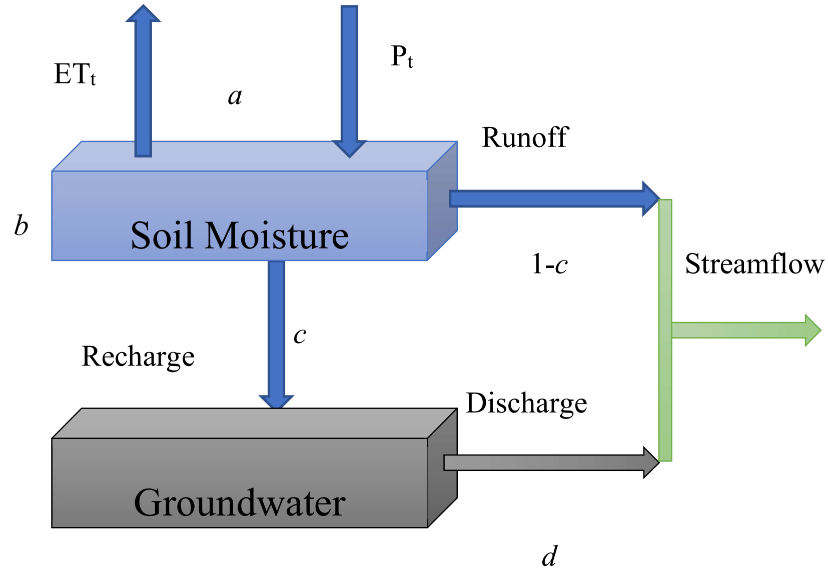


Figure 0-2 The ABCD model structure

Figure 2-2 has been used to develop the model structure and to show the basic concept of the model.

Applying the continuity equation of for the upper moisture zone,

$$P_t - ET_t - GR_t - DR_t = \Delta S_t = S_t - S_{t-1} \qquad \text{Eq. 2.}$$

where,

P_t - Precipitation during time t,

ET_t - Actual Evapotranspiration during time t,

GR_t - Groundwater Recharge for storage during time t,

DR_t -Direct Runoff during time t, and

S_t and S_{t-1}- Upper zone Soil Moisture storage at the time t and beginning of the time t.

The ABCD model defines two state variables, W_t, termed as ‘‘available water,’’ and Y_t, which is termed as ‘‘evapotranspiration opportunity’’. Hence, the above expression can be rearranged as;

$$(P_t + S_{t-1}) = (ET_t + S_t) + DR_t + GR_t \qquad \text{Eq. 3.}$$

where, $(P_t + S_{t-1})$ is "available water", (W_t) and $(ET_t + S_t)$ are the "evaporation opportunity", or (Y_t).

Now, these terms can be expressed as,

$$W_t = (P_t + S_{t-1}) = ET_t + S_t + DR_t + GR_t \qquad \text{Eq. 4.}$$

$Y_t = (ET_t + S_t)$, is the "evaporation opportunity" and can be expressed as the non-linear function of available water (W_t),

$$Y_t = \frac{Wt+b}{2a} - \sqrt{\{(\frac{Wt+b}{2a})^2 - \frac{bWt}{a}\}} \qquad \text{Eq. 5.}$$

Actual evaporation (ET_t) is expressed as a nonlinear relationship between ET_t, Potential evapotranspiration (PET_t) and Y_t,

$$ET_t = Y_t\{1 - Exp^{(-PET}t/b)\} \qquad \text{Eq. 6.}$$

Soil moisture (S_t) is given as,

$$S_t = Y_t\{Exp^{(-PET}t/b)\} \qquad \text{Eq. 7.}$$

The upper zone contribution to direct runoff,

$$DR_t = (1 - c)\,(W_t - Y_t) \qquad \text{Eq. 8.}$$

Groundwater recharge,

$$GR_t = c\,(W_t - Y_t) \qquad \text{Eq. 9.}$$

Soil moisture storage (G_t) in groundwater compartment after recharge,

$$G_t = (G_{t-1} + GR_t)\,(1+d)^{-1} \qquad \text{Eq. 10.}$$

The discharge from the lower compartment as groundwater discharge (GD_t) can be given as,

$$GD_t = d\,G_t \qquad \text{Eq. 11.}$$

Now total streamflow can be summed as,

$$Q_t = DR_t + GD_t \qquad \text{Eq. 12.}$$

The Eq. 12 gives the total volume of the simulated runoff from the model.

2.6.3 The Potential Evapotranspiration (PET) for the Model

Evapotranspiration is the major component of the hydrological cycle. To estimate the actual evapotranspiration, first, it is needed to calculate the potential evapotranspiration. The potential evapotranspiration is one of the major input of the ABCD model. Thomas (1981) had used the pan evaporation method to calculate the potential evapotranspiration (PET) for the initially developed ABCD model.

Xu and Singh (2000) based on the literature, grouped the methods of estimation of potential evaporation into seven classes. The general classification of potential evapotranspiration estimation methods is temperature based, radiation-based, evaporation based or combination type (Nikam, Kumar, Garg, Thakur, & Aggarwal, 2014).

Hargreaves and Allen (2003), Hargreaves and Samani (1985), and Thornthwaite (1948) developed models following the temperature based methods for the estimation of potential evapotranspiration. Priestley and Taylor (1972) developed the radiation-based models for the potential evaporation estimation. Allen et al. (2005) developed a combined method for the estimation of potential evaporation.

2.6.4 Hargreaves Method to Calculate Potential Evapotranspiration

Hargreaves and Samani (1985) developed a formula to compute the potential evaporation using the measured values of daily or mean values of maximum and minimum temperature. Having the scarcity of complete and reliable climatic data for estimating crop water requirements in developing countries, the developed method found to be very useful with limited data availability (Hargreaves & Samani, 1985).

$$\text{PET} = 0.0023 \times \text{So} \times (\text{Tmax} - \text{Tmin})^2 \times (\overline{\text{T}} - 17.8) \qquad \text{Eq. 13.}$$

where,

PET= Potential evaporation mm day $^{-1}$,

T_{max} and T_{min} = Daily maximum and minimum temperature in °C,

$\overline{T}$ = Average daily temperature in °C,

S_0 = Water equivalent of extraterrestrial solar radiation calculated in mm day $^{-1}$,

The extraterrestrial is calculated by using the methodology given by the Allen , Pereira, Raes and Smith (1998), according to developed methodology the S_0 is calculated by the formula,

$$S_0 = \frac{24 \times (60)}{\pi} G_{sc} \, d_r \left[\omega_s \sin(\Phi).\sin(\delta) + \cos(\Phi).\cos(\delta).\mathrm{Sin}(\omega_s) \right] \quad \text{Eq. 14.}$$

where,

G_{sc} is solar constant = 0.0820 (MJm^{-2} min^{-1}), d_r is inverse relation distance earth-sun equation, ω_s is sunset hour angle, Φ is the latitude (rad), and δ is the solar declination (rad). Also, S_0 is extraterrestrial radiation is expressed in MJm^{-2} day^{-1} the corresponding equivalent evapotranspiration in mm day $^{-1}$ is obtained by multiplying the S_0 by 0.408.

$$dr = 1 + 0.33 \cos\left(\frac{2\pi}{365} J\right) \quad \text{Eq. 15.}$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right) \quad \text{Eq. 16.}$$

J = Julian day

The sunset angle hour angle ω_s is given by the,

$$\omega_s = \arccos\left[-\tan(\Phi).(\delta) \right] \quad \text{Eq. 17.}$$

As the minimum and maximum temperature records are readily available for the study area, this is a very straightforward method. Hence, this method was used to develop the model structure.

2.6.5 The Application ABCD Model

The model was initially introduced by Thomas (1981) using an annual time step. Later, the model was improved and recommended by a number of researchers including Alley (1984), Fernandez et al. (2000) and Vandewiele and Ni-Lar-Win (1998). Fernandez et al.

(2000) reviewed the ABCD model used up to this moment and found the numerous applicability as a water balance model. Vandewiele et al. (1992) tested the model results compared with other several models and found that the model is favourably comparable to all other water balance models. The ABCD model has a term for soil moisture storage, which helps to understand the process on the actual evapotranspiration since the actual evapotranspiration depends on the soil moisture and potential evapotranspiration. In the previous times, various research had tested the ABCD model in different parts of the world (Alley, 1984; Block, Souza Filho, Sun, & Kwon, 2009; Martinez & Gupta, 2010; Sankarasubramanian & Vogel, 2002; Vandewiele & Ni-Lar-Win, 1998; Vandewiele et al., 1992; Q. J. Wang et al., 2011). Gunasekara and Rajapakse (2018) successfully applied the ABCD model in the Kalu Ganga and Gin Ganga basins in Sri Lanka for determining the application potential for the water resources investigation.

2.6.6 The ABCD Model Parameters from Literature

The properties of the catchment can be predicted from the model parameters. It is because each parameter in the model reflects each of different specific characteristics of catchment. Hence, finding the parameter range and specific value for modelled catchments is important in hydrological modelling. Initial values of the parameter help to expedite the calibration process and provides reliability checks for the parameters.

According to Vandewiele et al. (1992), Alley (1984), Martinez and Gupta (2010) and Al-Lafta et al. (2013), the model parameters had different distinct values on different studied catchments.

Table 0-2. The ABCD model parameters from the literature

References	**No. of basins**		***a***	***b***	***c***	***d***
Vandewiele et al. (1992)	79	**Range**	0.66-0.999	260-1900	0.04-0.7	0.0003-0.415

		Mean	0.986	475	0.270	0.110
Al-Lafta et al. (2013)	2	**Mean**	0.994	700	0.100	0.030
Alley (1984)	10	**Range**	0.975-.999	14-50	0.01-0.46	0.07-1.00
		Mean	0.992	30	0.160	0.260
Martinez and Gupta (2010)	127	**Range**	0.837-0.999	133-922	0-1	0-1
		Mean	0.977	393	0.229	0.350

2.7 Data Period for the Hydrologic Modeling

Selection of the data period should be based on the propose of the study and the other hydrological characters of the selected catchment. In this section, the data period considered by the various researchers have been studied and concluded.

Al-Lafta, Al-Tawash, and Al-Baldawi (2013) applied the ABCD model for transferring the applicability of parameters of the model to other basins, and the authors calibrated and validated three major basins, namely St. Johns River catchment, Kickapoo River catchment and Leaf River catchment. These basins have an area of the 7940 km^2 while catchment encompasses 4,369 km^2 and 290 km long river sections, respectively. The daily data of precipitation, evapotranspiration and streamflow were taken for 17 years and that was afterwards converted to monthly data. Later, the data were divided for the calibration and validation of ten and seven years, respectively. Alley (1985) used 50 years of temperature, precipitation and streamflow data for the New Jersey Catchment to perform the parameter estimation to forecast the streamflow records one month ahead. All the data was of monthly time scale and it was divided into the half-half years for the calibration and validation, respectively. Ten streamflow gauging stations were selected for taking the monthly streamflow data. Vogel and Sankarasubramanian (2003) used a

37-year period, with 1951–1988 year data for precipitation, temperature and streamflow records for the two catchments, Coosawhatchi River near Hampton, South Carolina and the St. Johns River near Deland, Florida. Sankarasubramanian, Vogel and Limbrunner (2001) used the 20 years of monthly data of streamflow, precipitation, minimum temperature, maximum temperature and the average monthly temperature which had already been collected. The data of 1,291 gauged river basins over the United States of America was collected to use in the two lumped models for the purpose of identifying climate change effect on the streamflow generation. The ABC and ABCD lumped models were used to compare the results. Vandewiele and Ni-Lar-Win (1998) defined water balance models are of two kinds, i.e. they are P and PE. The P models require only the precipitation to generate streamflow from model and PE models need both precipitation and potential evapotranspiration. The study had been carried out by using eight PE models and three P models. The models are then applied to 55 river basins in 10 countries with widely diverging climates and soil conditions. The data period taken ranged from 5 to 24 years in different countries and catchments. Fernandez et al. (2000) evaluated ABCD model parameters for regionalization using 33 basins in the southeastern region of the United States by comparing simulations using the regional models for three catchments which were not used to develop the regional regression equations. The model used a time series of monthly precipitation, potential evapotranspiration, streamflow and temperature data to enable calibration and validation. The records collected for the 33 stations ranged from 19 to 37 years, with an average of 30.4 years of data.

Martinez and Gupta (2010) concluded that considerable changes will not be there after ten years of calibration periods for data. It was identified from the study of improved identification of hydrological models, using monthly four-parameter lumped non-linear ABCD model for the 40 years of data. The methodology was employed for the calibration and validation with different temporal variations to identify the effect of calibration and validation data period.

From the above study and literature findings, it was concluded that the data periods depend on the objective of the modelling. A number of researchers have used different numbers of years as the data period. Further, the study of the literature concluded that for the calibration and validation, the data of more than 10 years would not make a considerable change in results of model outputs when using monthly time step data.

Hence, for the daily data resolution of nine years was taken. From this data set, the first five years of data was used for the calibration and the other four years of data set was used in the validation purpose.

2.8 Application of Hydrological Models in Kelani River Basin

Hydrology is the science of water occurrence, movement and transport in nature. It deals with the physical and chemical relationship within its cycle. In general, it is concerned with natural events such as rainfall, runoff, drought, flood and runoff, groundwater occurrences, their control, prediction, and management (Şen, 2014). Most of the research is carried out to understand the phenomena of the rainfall-runoff modelling for the hydrological system. Understanding this system plays a vital contribution to the science of hydrology (Minns & Hall, 2010). The hydrological models have a wide range of applicability for simulating a natural hydrological process. In general, modelling is the process of transforming the knowledge of hydro climatological data to hydrometric data.

Most of the hydrological systems are extremely complex. It is very hard to understand its process in detail. The catchment modelling is to understand primarily two objectives; one is understanding hydrological phenomena and effect on these phenomena by its changes while the other important objective is to produce the synthetic sequences of hydrologic data for the design and forecasting (Xu, 2002). The primary objective of modelling in the Upper Kelani river basin was to create the synthetic streamflow data forecasting for evaluation of Run-of-the-River (RoR) hydropower generation at the Upper Kelani river basin. Application of the hydrological modelling for the synthetic streamflow data generation from using the metrological data is a crucial activity. For the synthetic river flow preparation, ABCD lumped model was used. For the model parameter optimization in the Upper Kelani basin, two sub-catchments were selected to minimize the possible error occurrence. Norwood and Holombuwa were the selected sub-catchments. For the selection of the catchment, two basic criteria were set for diminishing errors. The first one was the catchment without any reservoirs or waterbodies and the second criteria, it should be in the upstream of the basin. For the calibration and validation on both sub-catchments, two river gauging stations were selected at the end (outlet) of each sub-catchment.

Hydrological forecasting is very convenient in the management of water resources, a series of hydrological forecasting and many applications (Hingray, Picouet, & Musy, 2001). The ABCD model parameters are already tested in the Upper Kelani river basin which provides applicable results (Sasanka & Rajapakse, 2018).

2.9 Parameter Optimization

According to Wijesekera (2000), mathematical functions help to find out the best fit for the modelled and simulated hydrographs, but it needs to evaluate the model streamflow to the rainfall and also needs to observe the water balance along with mathematical objective function used in the model structure for the best optimization of the model.

2.9.1 Objectives of using Hydrological Models

The objective of any hydrologic analysis is to estimate the values of certain hydrological quantities that could be analyzed at given space and time. The estimation may be concern amount of resources available, for example, the amount of inflow for the Run-of-the-River (RoR) hydropower generation (Hingray et al., 2001). With the recent advancements of the watershed models, their applicability is continuously increasing (Al-Lafta et al., 2013). A hydrologic mathematical model has a variety of applications. It depends on the purpose of the research and the problem needs to be solved. Proper formulation of a model concept helps to understand its uncertainties and future prospective of the catchments. As per the objective, the modelling is based on temporal and spatial variability. The objective of the hydrological modelling is listed as to ascertain the impact of human activities and the impact of climate change. Hence, this hydrological modelling helps to characterize and ascertain its impact on the catchment level with analyzing climate change and other uncertainties presents. The main purpose of using the model in the Upper Kelani basin for the study was to generate the synthetic streamflow to develop possible suitable Run-of-the-Rive hydropower locations.

2.9.2 Objective Functions

Hydrologic simulation models are calibrated by observed data with the model's simulation results data. The objective function is defined as the function of the difference between observed and simulated results data during calibration (Deskin & Simon, 1977). Usually, the accuracy of the model is defined by the objective function. In general, results are compared and contrasted by its value of better goodness of fit to that of the used objective functions. Gao et al. (2014) stated hydrological model parameter estimation is highly affected by calibration objectives, therefore the selection of calibration objective should be considered as an important factor in modelling. The selection of the objective function differs from the objective of the modelling. Deskin and Simon (1977) stated that the selection of the objective function for modelling is a subjective criterion which influences model parameter values for the model performances. The modelling has the proper link between its mathematical formulation of an objective and type of model application. The basic two methods available in the parameter optimization are the manual and automatic methods. The manual optimization method provides a good set of results but depending on the size of data, time and computerized methods availability automatic methods were considered useful. The automatic optimization method is reliable and fast (WMO, 1975). Boyle et al. (2000) argued on the automatic calibration process, and stated that automatic calibration process has speed and power of the computers, however, it will not provide the considerable acceptable parameter optimization as required to the hydrologist. In addition to that, the paper presents the manual calibration method on optimization by the computerized process.

Green and Stephenson (1986) collected extensive literature and analyzed 21 available objective functions. This study concludes that the selection of the objective function depends on the objective of the modelling. And also, it contrasts that if the researcher is looking for one aspect of the flow for an example, high flow than there is no point to look after the low flow indices on the flow hydrograph. Hence, it concludes that all the objective function selection depends on the objective and the interest of the modeller for the specific purpose of the modelling. The modelling study was based on the single event modelling to define the criteria to select the hydrograph behaviour.

Engeland and Hisdal (2009) stated that the study of low flows is the most important to manage the water resources for uses such as hydroelectricity and other water consumption uses. The low flow can be identified from the mean annual minimum discharge and the percentile from the flow duration curve (FDC). Garcia et al. (2017) defined the criteria used for the goodness of fit which are based on the objective function used but to analyze the robustness of the parameter for finding the low flow is very hard by this objective. As found from developed evaluation criteria, RMSE is the best suitable objective function for the low flow indices. Pushpalatha et al. (2012) evaluated the criteria suitable for the low flow simulation based on two rainfall-runoff models on 940 catchments throughout France, by using RMSE for the simulation of the low flow.

2.9.2.1 Root mean square error (RMSE)

Root mean square error (RMSE) is widely used for the modelling purposes of the low flow (Garcia et al., 2017; Houghton-carr, 1999; Pushpalatha et al., 2012) simulation especially to use on the streamflow determination for the various purposes like hydropower, irrigation and other water use projects. RMSE measured the difference between values from observed and values from the model simulated. Root mean square error is the standard deviation of residual prediction error (Observed value- Simulated value) and is defined by;

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(Qo,i-Qs,i)^2}{n}} \qquad \text{Eq. 18.}$$

where Q_o: observed discharge, Q_s: simulated discharge, n: is the total number of observations. The RMSE evaluates the average measurement of the error in the simulation but it fails to evaluate any information on differences in simulation uncertainties (Boulariah, Longobardi, & Meddi, 2017).

2.9.2.2 Pearson's correlation coefficient *r*

Pearson's correlation coefficient (r) describes the degree of co-linearity between the observed and simulated data. This correlation coefficient was always taken as a basic statistic test and excepted to followed by almost all the modellers (Legates & McCabe, 1999). Pearson's correlation coefficient (r) was developed by the Pearson (1895), and afterwards, it came into wide practice. Aghakouchak and Habib (2010) describes the ability of the Pearson’s correlation coefficient for the modelling of the conceptual hydrologic HBV model performances on the calibration and validation. In different modelling works, various personals had used the r as the objective function for optimization of models (Aghakouchak & Habib, 2010; Block et al., 2009; Krause, Boyle, & Bäse, 2005).

Block et al. (2009) used the Pearson's correlation coefficient r for the calibration and validation of the four parameters lumped ABCD model and SMAP model. This study showed that the Pearson's correlation coefficient *r* is useful as the objective function for the ABCD model optimization. In Sri Lanka, Perera and Rajapakse (2018) used the correlation coefficient *r* for the modelling of the ABCD model on three sub-catchment of the Kelani river basin. Wijesekera and Rajapakse (2013) had used the Pearson's correlation coefficient *r* for the mathematical watershed model optimization.

The value of the Pearson correlation coefficient varies from the -1 to 1, and the negative value shows the negative relationship and positive value shows the best relationship of the model, as represented by;

$$r = \frac{\sum_{i=1}^{n}(Qo - \bar{Q}o) \times \sum_{i=1}^{n}(Qs - \bar{Q}s)}{\sqrt{\sum_{i=1}^{n}(Qo - \bar{Q}o)\,2} \times \sqrt{\sum_{i=1}^{n}(Qs - \bar{Q}s)\,2}} \qquad \text{Eq. 19.}$$

where Q_o means observed, Q_s means the simulated flow and $\bar{Q}$ mean flow.

2.9.2.3 Mean ratio absolute error (MRAE)

Mean ratio absolute error has been defined as below,

$$\text{MRAE} = \frac{1}{n}\left[\Sigma \frac{|\,Qo - Qs|}{Qo}\right] \qquad \text{Eq. 20.}$$

The objective efficiency criteria indicates the degree of matching of observed and simulated streamflow hydrographs while this gives an average relative error of simulated output with reference to given observed streamflow (Wijesekera, 2000).

Wijesekera (2000) concluded from its application on the model that the objective function performs with good results to simulate the high, medium and low flow optimization. Further, Gunasekara and Rajapakse (2018) concluded from the study that MRAE performs very good on the high and medium flow as compared to low flow when it is used on the ABCD model. The MRAE is commonly used by the various researchers for model optimization purposes (Gunasekara & Rajapakse, 2018; Wijesekera, 2000; Wijesekera & Rajapakse, 2013).

2.9.2.4 Coefficient of determination (R^2)

The coefficient of determination (R^2) is the objective function which measures the goodness-of-fit for the model evolution (Fernandez et al., 2000). The coefficient of determination (R^2) was used as a measure of the goodness-of-fit not because it is the best overall criterion, but because it provides an equal weighting scheme for the two upstream parameters as high and low flow scheme (Vogel, 2005).

According to the findings on literature and applicability on the model, the objective function was selected as Pearson's correlation coefficient (r) and the coefficient of determination (R^2) for the parameter optimization of the four-parameter ABCD lumped hydrological model, and;

$$R^2 = \left(\frac{\sum_i^n (Oi-\bar{O})(Pi-^{-})}{\sqrt{\sum_i^n (Oi-\bar{O})^2}\sqrt{\sum_i^n (Pi \quad \bar{P})^2}} \right)^2 \qquad \text{Eq. 21.}$$

where, O is the observed value and the P is the predicted value and $\bar{O}$ and $\bar{P}$ is the mean value of the observed and the predicted value of the runoff.

2.9.2.5 Nash- Sutcliffe efficiency

Nash Sutcliffe efficiency coefficient is the normalized statistic that represents the one minus square of residual of observed and simulated value normalized by the residual of the observed value and the mean of observed value (Nash & Sutcliffe, 1970), given as;

$$\text{NSE} = 1 - \left(\frac{\sum_{i=1}^n (Qo-Qs)^2}{\sum_{i=1}^n (Qo-Qm)^2} \right) \qquad \text{Eq. 22.}$$

where, Q_o is the observed runoff and Q_s is the simulated runoff from the model and Q_m is the mean flow from observed discharge.

A majority of research had suggested the NSE as a good objective function but it has been specifically used for the high flow determination; i.e. for the flood analysis or some high flow parameter analysis. Krause et al. (2005) urged that when using NSE as the objective function, the larger values in the time series would be overestimated while the lower values in the time series would be neglected. This is because of the structure of the NSE is composed of observed minus simulated values are squared and normalized by the square of the observed value and observed mean value. Hence, it was urged as the main drawback of the objective function. But instead of this, many researchers have used this for modelling purposes (Bai et al., 2016; Martinez & Gupta, 2010; Pushpalatha et al., 2012).

2.9.3 Criteria for Selection for the Objective Functions

The objective function was selected considering the main three criteria (1) Mathematical functions, (2) Flow regime, and (3) Purpose of the modelling in the basin. Hence, based on the formed criteria and detailing made in the Chapter 2.9.2 the Pearson correlation coefficient (r) and Coefficient of determination (R^2) were selected as the objective functions.

2.10 Warm-up Period and Initial Values for Soil Moisture and Groundwater Storage of the Model

The ABCD model structure has soil moisture and groundwater compartment, since, it needs to provide initial values for the soil moisture and the groundwater storage. According to Thomas (1981), the model includes variables required to groundwater storage and in the soil moisture, it does not requires the observe data of these quantities to fit and use in the model. But, later it raised the state of confusion on the model application process, first optimized value of initial soil moisture values exceeded the fitted value of b. Second, it raised the issue of unclarity when the model was used on different temporal scales, which values should be used. Third, the value of initial storage accounts for the effect on the total volume of streamflow. Hence, considering all these, the modeller needs to have some idea of the initial soil moisture and groundwater recharge value.

Alley (1984) used the initial one year of period accounting for the initial soil moisture and groundwater storage for both the calibration and validation periods. According to Xiong and Guo (1999), the initial value of the soil moisture content has some effect on model performance, for the case of the less data period. Hence, the study considers a re-estimation method by using the mean value of the soil water content and it should not be very different from the soil water content of the month having the same rank within a year, for the identification of the initial soil moisture content. Xiong and Guo (1999) estimated the initial soil moisture content by considering the mean value of the month over the whole period, as;

$$(S) = \sum_{1}^{m} \frac{S(j \times 12)}{m} \qquad \text{Eq. 23.}$$

where m is the number of years of the calibration data series, i.e. $m = N_c/12$. And, N_c is the number of calibration data.

For this study, the initial soil moisture and groundwater storage volume was put to zero initially and changed during the optimization process by looking at the equal value of soil moisture and groundwater storage for the best fit of simulated and observed data set.

2.11 Rainfall Interpolation Method

Interpolating a climatic variable such as rainfall and other variables are challenging due to the nature of the established meteorological process, effects of different geology and terrain and difficulty in establishing representative stations. Further, interpolation models are used to reduce these effects (Plouffe, Robertson, & Chandrapala, 2015).

According to the Plouffe et al. (2015), methods for the interpolation can be classified into four categories: Global methods (trend surfaces and regression models), Local methods (Thiessen polygons, Inverse Distance Weightage (IDW), and splines), Geostatistical methods (Kriging) and Mixed methods. Dirks, Hay, Stow, and Harris (1998) studied on the interpolation method of rainfall data for the Norfolk Island, Australia, by using a rainfall interpolation method as areal mean, Kriging, IDW and Thiessen polygon methods. From this study, it is concluded that Kriging is the least suitable when IDW found to be highly suitable for the study area. Zeinivand (2015) compared the rainfall interpolation methods for the hydrological component using a physical based spatial model in Iran. The compared interpolation models were Thiessen polygon methods, Universal Kriging method and Inverse Distance Weighting (IDW) method. Among these models, Thiessen polygon method was found to produce good results on basis of set criteria. Jayawardene, Sonnadara and Jayewardene (2005) used the spatial interpolation methods for the dry zone of Sri Lanka for the weekly rainfall data by using a Kriging interpolation method and Inverse Distance Weightage method. The study found that IDW is the best for the spatial interpolation for the rainfall data.

Along with above discussed methods, a number of researchers have used the Thiessen polygon spatial rainfall interpolation method for the different parts of Sri Lanka (Gunasekara & Rajapakse, 2018; K. R. J. Perera & Wijesekera, 2012; Wijesekera &

Rajapakse, 2013). By analyzing the model availability, applicability and simplicity, here the Thiessen method was selected for the interpolation of spatial rainfall data.

2.12 Review of Selected Criteria for Run-of-the-River Hydropower Generation

Criteria selection is the process of establishment of methodology to develop for RoR hydropower in the selected study area and all other applicable areas. Criteria selection process defines the constraints and framing of methods for selecting the appropriate locations for the hydropower generation.

Kusre et al. (2010) established a set of criteria to select the RoR hydropower station locations. It was based on four basic criteria; i.e. order of stream, bottom gradient, minimum hydropower site interval and minimum available head. For the site selection, hydrological modelling with SWAT was used and to ensure the sufficient amount of flow, only the fifth order of streams were selected and river bed gradient was selected to be more than the 2%, the minimum powerhouse distance was selected as the 500 m interval and the minimum head difference was considered 10 m. Rojanamon et al. (2009) limited the length of the powerhouse and intake structure as a maximum of 5 km, and also defined that penstock length should be as short as possible. The range of the hydropower capacity was fixed in 1 MW to 10 MW in order to limit the study to only mini and micro hydropower.

Yi et al. (2010) found from a study that when using a 30 m resolution DEM, the 100 m minimum head extraction point was sufficient to find the head in the river bed profile. Further, the study stated that to find a higher capacity, the site selection process should start from the lowermost outlet of the river. Setiawan (2015) calculated the head of the river bed profile by the use of the neighbourhood tool in ArcGIS (ESRI, USA). The study considered a minimum head difference of 20 m between intake structure and powerhouse site. Minimum powerhouse capacity to be analyzed was fixed in the order of 100 kW. Serpoush et al. (2017) used all the general criteria fixed by Yi et al. (2010), but in addition to that, the study fixed the maximum distance between intake structure and powerhouse, selecting 1 km, 3 km and 5 km. Kayastha et al. (2018) also fixed the criteria of 500 m minimum distance between powerhouse and intake structure and at the same time, the maximum search radius was selected as a maximum of 10 km. Bayazıt, Bakış and Koç (2017) used the focal statistic tool in ArcGIS to find the possible head for the hydropower generation. Zaidi and Khan (2018) divided equal distance of 100 m by the use of Construct Point tool in ArcGIS to calculate the head difference between each 100 m difference in the river bed profile. The study also suggested that minimum distance between the intake structure and the powerhouse should be 500 m and the minimum distance between two powerhouses was selected of 100 m. Pasha et al. (2014) had used 150 m horizontal distance interval to find the elevation difference between each point on the river bed. The study also presented three methods of stream reach selection procedure by looking at the factors, equal reservoir length approach, full development approach and merit matrix-based approach. In addition to that, the study confirmed that to find the maximum power available as the RoR at the river channel, the site selection process should start from the downstream of the river.

Moiz et al. (2018) presented a methodology coupled in ArcGIS by considering the range of hydropower capacity from 2 MW to 25 MW. This selection criterion for the RoR hydropower generation was made by considering stream densification point in the interval of 500 m, minimum and maximum stream length of 2000 m to 5000 m, respectively. And the minimum of head criteria should meet to 30 m and a minimum slope of 2% is considered for finding the appropriate sites for the hydropower generation. Pandey et al. (2015) considered the site selection process, assuming that the consecutive distance between the two powerhouses should not be less than 500 m and not more than 3000 m. The selected site had an elevation drop of more than 20 m. To maintain the adequacy of flow, the 3rd order of stream was selected and the number of flow accumulation cells was selected to be more than 12,000 cells.

From the study of the literature, it was found that the site selection process is highly spatial dependent. The selection process varies depending on location, environmental law and other considerations. The different researchers from different parts of the world have considered different factors. Hence, for this study, it has been developed following the parameters considering all the factors associated in the Upper Kelani river basin for the Run-of-the-River (RoR) site selection. The consecutive minimum distance between hydropower houses should not be less than 500 m and the maximum distance should not be more than 2000 m. The minimum hydraulic head was fixed as 25 m for the selection of a site. For the calculation of the head difference, the head between each 100 m was generated. The selection process for finding the possible locations of the hydropower was commenced from the upper part of the river section. Also, for the selection of the hydropower sites, the minimum flow volume was selected as 0.5 m^3/s.

METHODOLOGY AND MATERIALS

3.1 Introduction to Methodology

An overall introduction of the methodology concerning to each step has been provided under the subsequent headings.

3.1.1 Methods to Identification of Research Problem and Objectives

The research problem identification was mainly based on the background study in Sri Lanka and the associated region with a growing trend of the power demand and difficulties present in the hydropower site selection process. After finding the research problem, the overall objective was developed by considering the findings of the background study for the associated problems. Henceforth, specific objectives were formulated to meet the goals of the overall objective. The study area was selected based on the problem-solving approach and associated power capacity available in the Sri Lankan basins. Hence, by the background study of the power production capacity and associated topographic features of the area, Kelani basin was selected for the study.

3.1.2 Methods and Consideration to the Literature Survey

After the establishment of the research problem, a literature survey was conducted considering the main aspects of the developed specific objectives by considering the solution of the identified problem. First, a literature survey was conducted on the hydropower systems, types of hydropower, the site selection process for the hydropower generation and their pros and cons by establishing the different types of the hydropower systems; i.e. Reservoir systems and Run-of-the-River (RoR) hydropower systems.

After the initial study on the hydropower site selection process, the Geographic Information Systems (GIS) based methods were found to be the prominent methods for the site selection process, hence, to confirm the initial findings, a detailed study on the application of GIS tools in the hydropower site selection was conducted. The methods applied, tools used, the area considered and findings from the study were reviewed carefully. During the study of the application of GIS tools, it was found that Digital Elevation Models (DEM), their spatial resolutions, types available and their suitability for different areas were the important factors to be considered for the selection of the

DEM. Hence, the study was conducted on the type of DEMs available and used in the previous research and applicability of the DEMs for the selected catchments was analyzed. From the analysis, it was found that the Shuttle Radar Topography Mission (SRTM) 30 m resolution data set is the most suitable. Therefore, the SRTM terrain data set was selected and it was also compared with 90 m resolution SRTM data and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) 30 m resolution DEM data.

For evaluation of the hydropower capacity, it is well known that the river head and the flow quantity are the key factors required for calculating the power available in river sections. One of the main parameters, the available head, was estimated by using the selected DEM and for the estimation of the flow available in the river section, a hydrologic model was required. Hence, it needed to study on the available hydrological models for conducting the study. Hence, a literature review was conducted for the types of the hydrological models, its highlighted features and capacity and applicability in the present study. During the study, it was found that models with a lesser number of parameters also produce acceptable results in the data scarce, ungauged and remote regions for conducting the hydropower sites. Hence, the ABCD Lumped Model was selected for the study. The details of the ABCD model, its structure, required equations, assumptions, parameters from the literature, objective functions for the modelling and study on the warmup period were conducted to maintain the accuracy of the hydrological results for the selected objectives. Subsequently, a study on the data length was also undertaken from the consideration of the model requirements to generate the streamflow for the RoR analysis. Finally, the review study was conducted on the previously selected criteria for hydropower site selection process. During the process of study of the site selection criteria, it was found that the site selection process is a spatial process and each study area differs significantly from each other. Hence, the criteria needed to be unique to suit the topography, local rules/regulations and hydrological characteristics of the study area.

3.1.3 Methods to Data Collection and Pre-processing for Modelling

The model inputs and its lengths were identified during the literature survey process using findings, the consideration of the availability and the data inputs of the model. Data were collected from the 2008/2009 to 2016/2017 considering water year. The main data considered were the precipitation, streamflow, temperature and evaporation. Further, the Digital Elevation Model (DEM) was compiled from the public domain/freely available sources (USDA/USGA). Accuracy of the meteorological data was checked before putting on the models and subsequent corrections were incorporated by using various methods available, including regression methods.

3.1.4 Methodology used for the GIS Operations

The study was mainly divided into two parts; one was the available head determination and the other was the available flow estimation in the river sections. For the determination of the available heads, GIS operations were conducted using ArcGIS (v10.3; ESRI, USA), for the stream network and watershed delineation. For this purpose, the arc-hydro tool kit was used up to the watershed delineation and stream network generation. The raster stream network was converted to the vector file by using a tool features tool under the hydrology tool. The longest and main river features at the Upper Kelani Ganga were merged and made into a single line feature. Then, the points were added with the spacing differences of 100 m on the river network by using the Construct Point network tool. Hence, to extract the elevation at that point, Add Surface Information tool was employed under the 3D Analyst Functional Surface and Add Surface Information tool. The surface elevation was extracted from the digital elevation models (DEM). The minimum available head was limited to 25 m and higher values were allowed to proceed as per the availability in the study area and the minimum and maximum distance between consecutive powerhouses were limited to 500 m and 2000 m, respectively. Figure 3-1 represents the steps followed in the watershed delineation process.

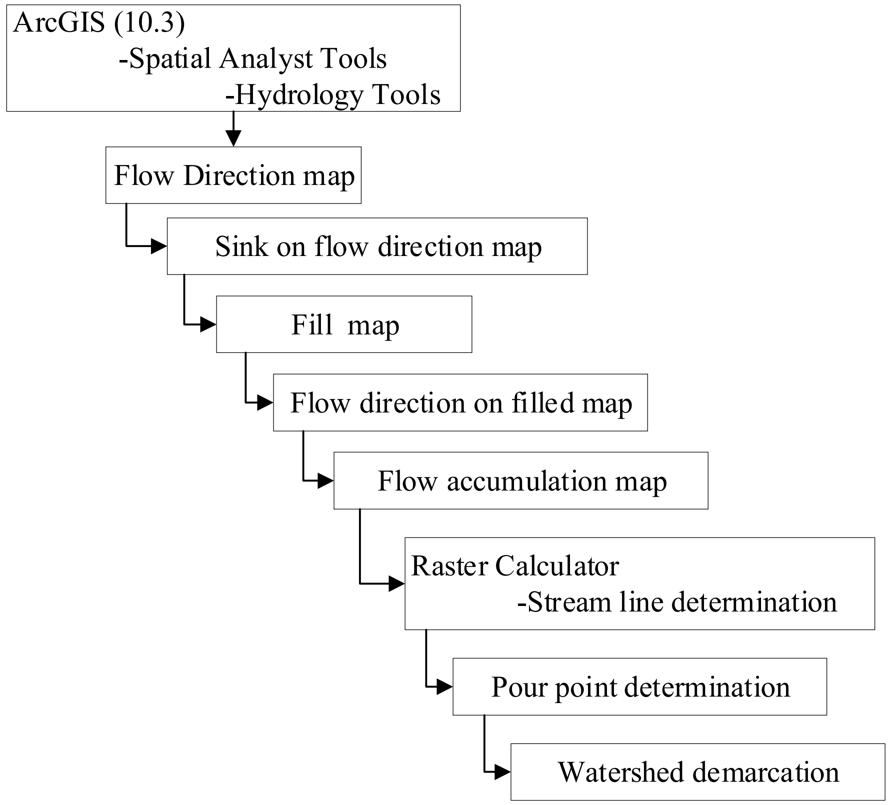


Figure 0-1 The tools and process for the watershed delineation

3.1.5 Methodology used on the Visual Basic for Application (VBA) Program

For the analysis of the identified head, at each of the 100 m interval of the river sections derived from the ArcGIS, the MS Excel Spreadsheet operation was performed by using a Visual Basic for Application (VBA) program. The VBA helps to simplify the complex calculation process in the simple order of magnitude with the efficiency of time for the development of the complex relationship. The head searching algorithms for identification of the criteria of the head on the river bed profile was developed in the Visual Basic environment in Excel Macros based on the developed criteria. Figure 3-2 represents a schematic diagram of the developed criteria for available head determination.

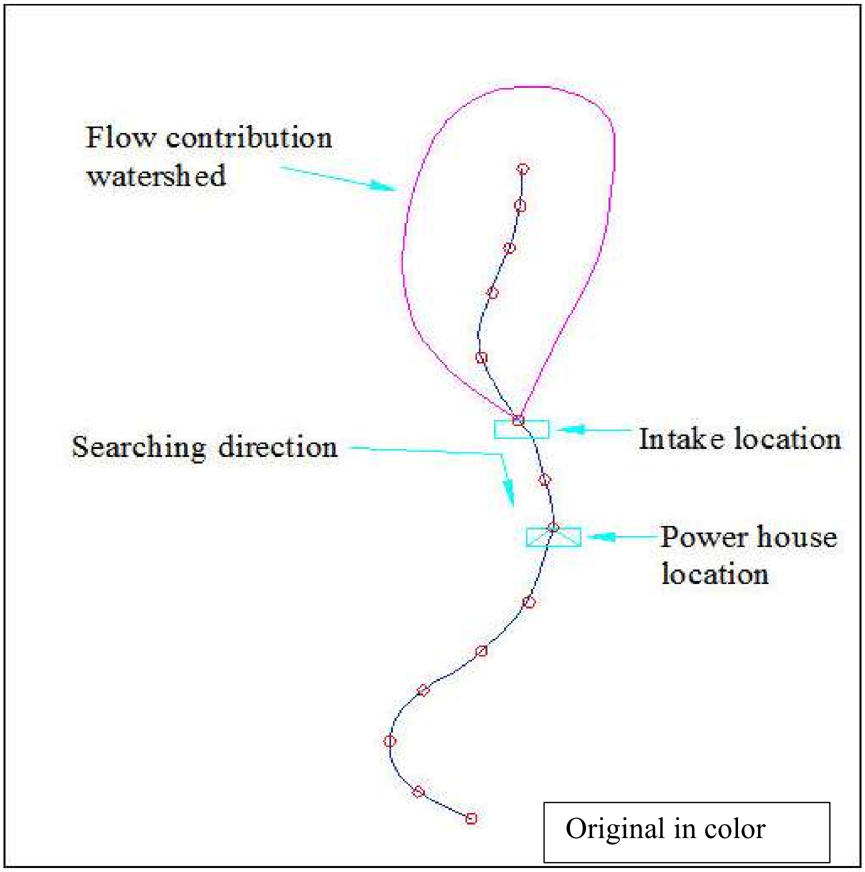


Figure 0-2 The searching algorithm for selecting a suitable location of the Run-of-the-River hydropower head in the river profile

3.1.6 Methods to Combine Application of GIS and Hydrological Model

The catchment area identification for the hydrological modelling and hydrological model application were performed simultaneously with the process of the head identification. Hence, the corrected data set was divided subsequently into two parts for the calibration and the validation for this study while the calibration period of five years was selected from the year 2008/2009 to 2012/2013 and for the validation, four years of data from the year 2013/2014 to 2016/2017 was selected. The uppermost two sub-catchments, Norwood and Holombuwa were selected for the model calibration and validation to establish the model parameters for subsequent using in the basin. After the successful establishment of the model parameters, those parameters were averaged to be used in the whole Upper Kelani basin and model parameters were transferred to estimate the quantity of the flow at the locations of the identified head points in the river intake area.

After the successful application of the model parameters for the whole Upper Kelani basin, the successful identification of the intake points on the river section was carried out by applying the selected head criteria on the first set of the points as explained in the methodology. The ABCD model was established at each point of the selected intake locations by using the full set of data. Hence, the flow duration curve was compiled for each intake station. The minimum flow criteria was limited to the 0.5 m^3/s. Hence, only 100 kW power site was selected as a feasible site.

Obtained results were analyzed and discussed with its various aspects and results were also compared with the existing locations. Hence, based on the study, the conclusions were derived and subsequently, the additional recommendations were included.

The details of the developed methodology have been presented in Figure 3-3, hence, according to the developed methodology, all the processes were followed step by step following the process presented in the methodology flow chart. This chart gives the details in the stepwise process governing the study methodilogy.

3.2 Methodology Flow Chart

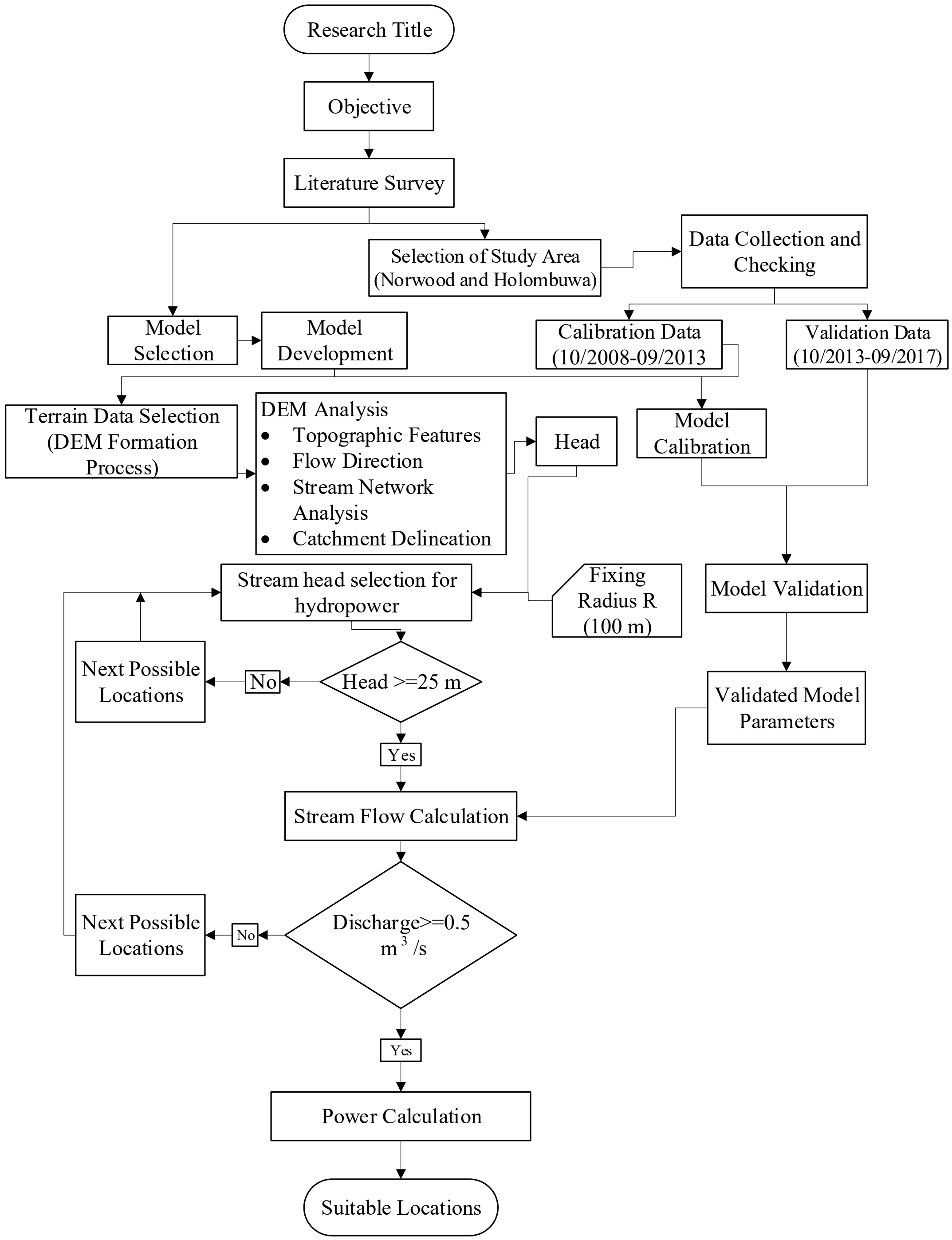


Figure 0-3 Methodology flow chart

3.3 Study Area

The selected study site area was Upper Kelani basin. The study area is divided into three segments for the purpose of modelling. The two sub-catchments of the Upper Kelani basin were selected for the modelling to establish the model parameters for the whole basin. The Norwood and Holombuwa sub-catchments were selected for the modelling, which lies in the upper east side and upper north side of the Kelani basin, respectively. The averaged values of the model parameters from two sub-catchments were used to establish the model on the whole Upper Kelani basin and it was named as the third (combined) study area for the model application. Hence, the Upper Kelani river basin was used for the application of the model to find the possible locations of the Run-of-the-River (RoR) hydropower generation. The first two basins were accordingly used for the ABCD model calibration and validation. The third area covers the whole basin which was tested for finding the possible run-of-the-river (RoR) hydropower sites. Data were collected from the total seven precipitation stations, and one evaporation station, one temperature measuring station and two-stream gauging stations from the Department of Meteorology and Department of Irrigation. The data was taken from 2008 to 2017 (water years). Details of the locations and their coordinates are presented in Table 3-1 and Table 3-2. The details of the data stations and study area map have been shown in Figure 3-2, highlighting the Upper Kelani basin, Norwood sub-catchment, Holomobuwa sub-catchment, located all inside the Kelani river basin. Figure 3-4 shows the details of the selected locations and the other details of the basin.

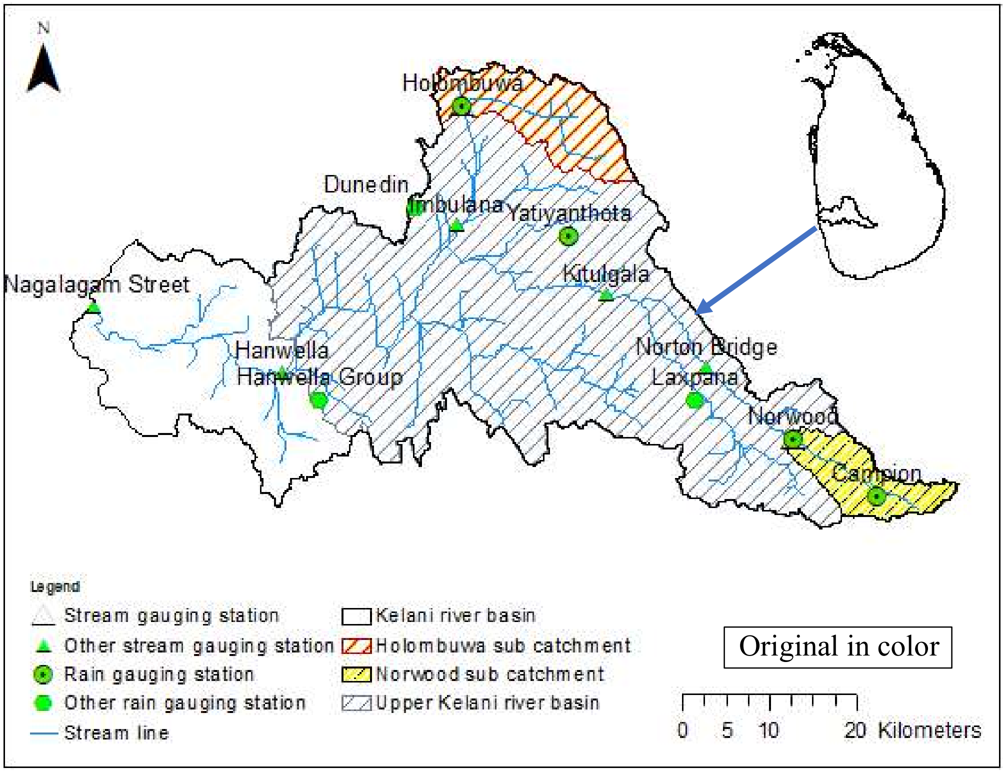


Figure 0-4 The map of the Kelani river basin

Table 0-1 Coordinates of meteorological data (Rainfall stations)

Purpose of the catchment	Sub-catchment	Names of the Stations	Locations	
			Latitudes	**Longitudes**
Hydropower Analysis	Norwood	Norwood	6° 50' 22" N	80° 36' 44" E
		Campion	6° 46' 48" N	80° 42' 00" E
	Holombuwa	Holombuwa	7° 11' 07" N	80° 15' 53" E
		Yatiyanthota	7° 03' 00" N	80° 22' 48" E
	Remaining stations	Laxpana	6° 52' 48" N	80°30'36" E
		Dunedin	7° 04' 48" N	80° 13' 12" E
		Hanwella group	6° 52' 48" N	80° 07' 12" E

Table 0-2 Coordinates of the meteorological stations (Streamflow, Temperature, and Evaporation)

Data type	Sub catchment	Name of Stations	Location	
			Latitudes	Longitudes
Streamflow	Norwood	Norwood	6° 50' 22" N	80° 36' 44" E
	Holombuwa	Holombuwa	7° 11' 07" N	80° 15' 53" E
Temperature	All catchment	Nuwara-Eliya	6° 58' 12" N	80° 46' 12" E
Evaporation	All catchment	Ratnapura	6° 40' 48" N	80° 24' 00" E

3.3.1 Norwood Sub-catchment

The Norwood sub-catchment is the sub-watershed of the Upper Kelani basin in the upper east side of the main basin, which is shown in Figure 3-5.

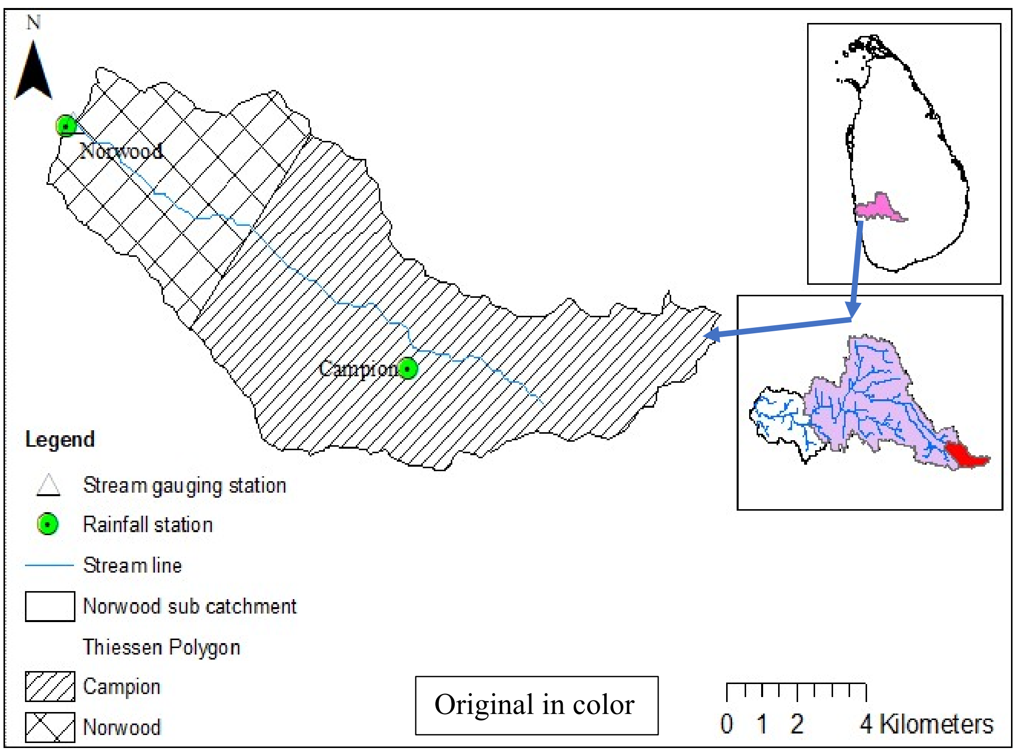


Figure 0-5 The study area Norwood sub-catchment, in Upper Kelani basin

The study area comprises an area of 97 km^2, spreading under the Nuwara-Eliya district of the Central province. The sub-catchment falls in the wet zone of the country.

Topographically, this sub-catchment has a highly elevated terrain. As area falls under the wet zone of the country, it receives around 2,650 mm of average annual precipitation. Being in the elevated terrain, this sub-catchment comprises of the average temperature of around 16°C considering the Nuwara-Eliya station. The steep slopes and low flow availability are the main identified characteristics of this area in the perspectives of the hydropower generation.

3.3.2 Holombuwa Sub-catchment

The Holombuwa sub-catchment is the sub-watershed of the Kelani basin in the upper north side of the main basin which is shown in Figure 3-6.

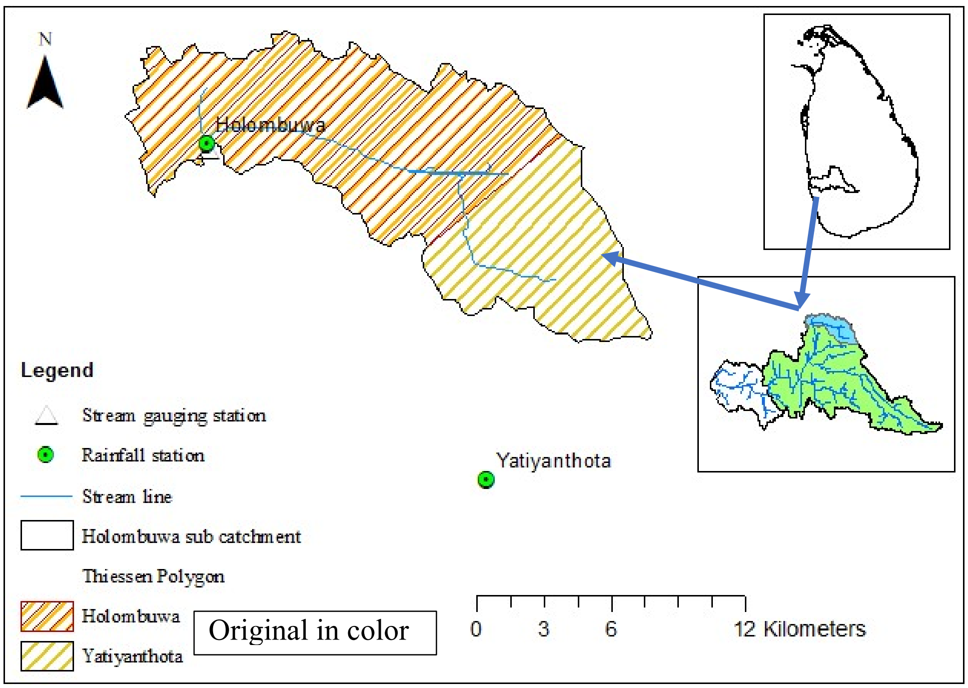


Figure 0-6 The Study area Holombuwa sub-catchment, in Upper Kelani basin

The study area comprises an area of 155 km^2, spreading under the mainly Kegalle district of the Sabaragamuwa province. The sub-catchment falls in the wet zone of the country. Topographically this sub-catchment has a medium elevated terrain. As area falls under the wet zone of the country, it receives around 3,850 mm of average annual precipitation. For the catchment modelling, the Nuwara-Eliya temperature measuring station was selected in this sub-catchment with the average temperature of around 16°C. The medium steep slope and high flow availability are the main identified characteristics of the Norwood sub-catchment in the perspectives of the hydropower generation.

3.3.3 Upper Kelani Sub-catchment (Model Application)

The Kelani basin is mainly divided into the upper and lower parts of the catchment. The study area comprises the Upper part of the Kelani basin. The study area comprises the fourth-largest river basin of the country. The main geographical extent of the catchment lies in the wet zone of the country which mainly contributes to the overall catchment characteristics. The Upper Kelani basin has a diverse range of topographical features. The details of the other extents are given in Figure 3-4.

3.4 Data Collection

The data collection was carried out by selecting data station guidelines complying to the WMO (2009) standards and by considering modelling approach, for the modelling of the representative catchment by examining modelling objectives, the upper part of the sub-catchment was selected as the representative catchment. The data period was selected from the 2008/2009 to 2016/2017 (water year) for the study. For the selection of catchment, basic two criteria were formed, i.e. the catchment should be in the upper part of the basin and the selected catchment should not contain any reservoirs and water bodies. This criterion was formed to reduce the possible discrepancies in the ABCD lumped modelling. The selected data and stations are discussed under the subsequent sub-headings in detail.

3.4.1 Data Collection for the Norwood Sub-catchment

The Norwood sub-catchment is situated in the upper east side of the Kelani basin, and the sub-catchment is situated just above the Castlereigh reservoir. This is comparatively a very small catchment as compared to the guidelines of the WMO (2009), and it would have been adequate to use data from one precipitation measuring station but instead of one station here, two stations were selected, namely Norwood and Campion stations to better represent the rainfall spatial variability in the area.

Table 0-3 Data sources and data availability for the Norwood sub-catchment in Upper Kelani basin

Stations/Data type	Temporal resolution	Data period (Water year)	Data source
Precipitation			
Norwood	Daily	2008-2017	Department of Meteorology
Campion	Daily	2008-2017	Department of Meteorology
Streamflow			
Norwood	Daily	2008-2017	Department of Irrigation
Temperature (Temp. max and Temp. min)			
Nuwara-Eliya	Daily	2008-2017	Department of Meteorology
Evaporation			
Ratnapura	Daily	2008-2017	Department of Meteorology

The Norwood stream gauging station was selected at the end outlet of the catchment. The nearby temperature and evaporation measuring stations were selected. The temperature and evaporation data were collected from the Nuwara-Eliya and Ratnapura station, respectively. Other details of the stations and data have been presented in the Table 3-3 above.

3.4.2 Data Collection for the Holombuwa Sub-catchment

The other selected catchment for the ABCD modelling was the Holombuwa catchment. The Holombuwa sub-catchment lies in the upper north side of the Kelani basin. The area of sub-catchment comprises only 155 km^2. Hence, for this small sub-catchment as compared to the guidelines of the WMO (2009), it would have been enough to use only one precipitation measuring station, but instead of one station, two-precipitation stations were selected, namely Holombuwa and Yatiyanthota. The Holombuwa stream gauging station was selected at the end outlet of the catchment. The nearby temperature and evaporation measuring stations were selected. The temperature and evaporation data were collected from the Nuwara-Eliya and Ratnapura stations, respectively. Other details of the stations and data have been presented in the below Table 3-4.

Table 0-4 Data source and availability for the Holombuwa sub-catchment in Upper Kelani basin

Stations/Data type	Temporal resolution	Data period (Water year)	Data source
		Precipitation	
Holombuwa	Daily	2008-2017	Department of Meteorology
Yatiyanthota	Daily	2008-2017	Department of Meteorology
		Streamflow	
Holombuwa	Daily	2008-2017	Department of Irrigation
		Temperature (Temp. max and Temp. min)	
Nuwara-Eliya	Daily	2008-2017	Department of Meteorology
		Evaporation	
Ratnapura	Daily	2008-2017	Department of Meteorology

3.4.3 Data Collection for the Upper Kelani Sub-catchment (Model Application)

The basic input requirements for the Four-parameter ABCD model is the precipitation and potential evapotranspiration. Here for the modelling, the precipitation was directly taken as a meteorological input data and temperature data were collected from the respective stations for calculation of the Potential Evapotranspiration (PET). The model evaluation is one of the important factors for the model application, hence, for the validation of the model, stream gauging station was required. But this is only the model application part in this catchment, and the model is calibrated and validated using the data in the above two sub-catchments in the Norwood and Holombuwa. Hence, only the calibrated and validated parameters were transferred from above sub-basins for the development of the model in this catchment. For maintaining the accuracy of the modelling and precipitation station densification, some extra precipitation data was selected in the basin. Further, for the temperature data, the same station was used as in the model verification process. Details of the selected stations are given in Table 3-5.

Table 0-5 Data source and availability for the Upper Kelani sub-catchment in Kelani basin

Stations/Data type	Temporal resolution	Data period (Water year)	Data source
		Precipitation	
Laxapana	Daily	2008-2017	Department of Meteorology
Dunedin	Daily	2008-2017	Department of Meteorology
Hanwella Group	Daily	2008-2017	Department of Meteorology
		Temperature (Temp. max and Temp. min)	
Nuwara-Eliya	Daily	2008-2017	Department of Meteorology

3.5 Data Checking

3.5.1 General

For evaluating a satisfactory result from the modelling, the input data should be free of the discrepancies and reliable time series data are the key basis for the modelling. Maintenance of data quality and satisfactorily estimation of missing time series data in the hydrology series is of significant importance in the hydrological computation of any hydrological parameter. Hence, to find the inaccuracies present in the data, the single mass curve check, double mass curve check, the visual interpretation of rainfall versus streamflow and Thiessen averaging were followed. Further, the data station was checked against the compliance of the WMO (2009) guidelines for the data collection for the modelling purpose.

First, the data was plotted in the time series and missing time periods were counted and the percentage of data missing periods was recorded. Initially, the data were checked separately for each modelling sub-catchment to find the discrepancies and interrelationships of the data for the specific sub-catchment. Further, all the precipitation data were gathered together later on for the whole Upper Kelani basin and checked against it, to compute the double mass curve. The details of the missing data in the time series are discussed in Table 3-6, Table 3-7, and Table 3-8.

Table 0-6 The missing data details in Norwood sub-catchment, Upper Kelani basin

Stations/ Data types	Number of missing days	Percentage of missing (%)
Precipitation		
Norwood	0	0.00
Campion	30	0.91
Streamflow		
Norwood	0	0.00
Temperature (Temp. max and Temp. min)		
Nuwara-Eliya, T_{max}	1	0.03
Nuwara-Eliya, T_{min}	3	0.09
Evaporation		
Ratnapura	92	2.80

Table 0-7 The missing data details in Holombuwa sub-catchment, Upper Kelani basin

Stations/ Data types	Number of missing days	Percentage of missing (%)
Precipitation		
Holombuwa	0	0.00
Yatiyanthota	153	4.65
Streamflow		
Holombuwa	0	0.00
Temperature (Temp. max and Temp. min)		
Nuwara-Eliya, T_{max}	1	0.03
Nuwara-Eliya, T_{min}	3	0.09
Evaporation		
Ratnapura	92	2.80

Table 0-8 The Missing data details in the Upper Kelani basin (Model purpose)

Stations/ Data types	Number of missing days	Percentage of missing (%)
Precipitation		
Laxpana	61	1.90
Dunedin	544	16.60
Hanwella Group	92	2.80
Temperature (Temp. max and Temp. min)		
Nuwara-Eliya, T_{max}	1	0.03
Nuwara-Eliya, T_{min}	3	0.09

The data checking process started with the finding of the missing data in the series and their percentage of missing values. The percentage of the missing data criteria helps to find a possible gap-filling method for data replacement. From the visual inspection and excel sheet operation on the time series data of the precipitation, streamflow, temperature and evaporation data, it was found that there were numbers of missing data on the time series. The maximum number of missing data (16.6%) in time series was found in the Dunedin station, which was used for the model application. The stations selected for the model verification was found to be with the percentage of missing data less than 5% in both sub-catchments for the precipitation records. The streamflow records have no missing data. The missing data of maximum temperature, minimum temperature and evaporation data were found 0.03 %, 0.09 %, and 2.8 %, respectively.

The distribution of the precipitation gauging stations, streamflow gauging station, temperature gauging station and evaporation measurement station were checked with respect to the guidelines provided by the WMO (2009) and found to be in acceptable extents. Details of the distribution of gauging stations have been presented in Table 3-9, Table 3-10, and Table 3-11.

Table 0-9 The distribution of the gauging station at Norwood sub-catchment in Upper Kelani basin

Data types	Number of stations	Station density (km^2/station)	WMO standard (km^2/station)
Precipitation	2	47.70	575.00
Streamflow	1	95.40	1875.00
Temperature	1	95.40	-
Evaporation	1	95.40	-

Table 0-10 The distribution of gauging stations at Holombuwa sub-catchment in Upper Kelani basin

Data types	Number of stations	Station density (km^2/station)	WMO standard (km^2/station)
Precipitation	2	77.20	575.00
Streamflow	1	154.40	1875.00
Temperature	1	154.40	-
Evaporation	1	154.40	-

Table 0-11 The distribution of gauging stations at Upper Kelani sub-catchment in Kelani basin (Model application)

Data types	Number of stations	Station density (km^2/station)	WMO standard (km^2/station)
Precipitation	7	257.20	575.00
Temperature	1	1801.00	-

3.5.2 Thiessen Average Rainfall

For the hydrological analysis, data are required in single time series format though it has been used data from several station records for the purpose of the analysis. As per the literature review, the selected best approach for the averaging of the rainfall was found to be Thiessen averaging. Hence, the averaging was done by the application of Thiessen averaging method. The Thiessen averaging was done for the first selected ABCD modelling sub-catchments separately and later Thiessen averaging was carried out considering all the precipitation stations for the model application. The details of the Thiessen averaging have been presented in Figure 3-7, Figure 3-8 and Figure 3-9.

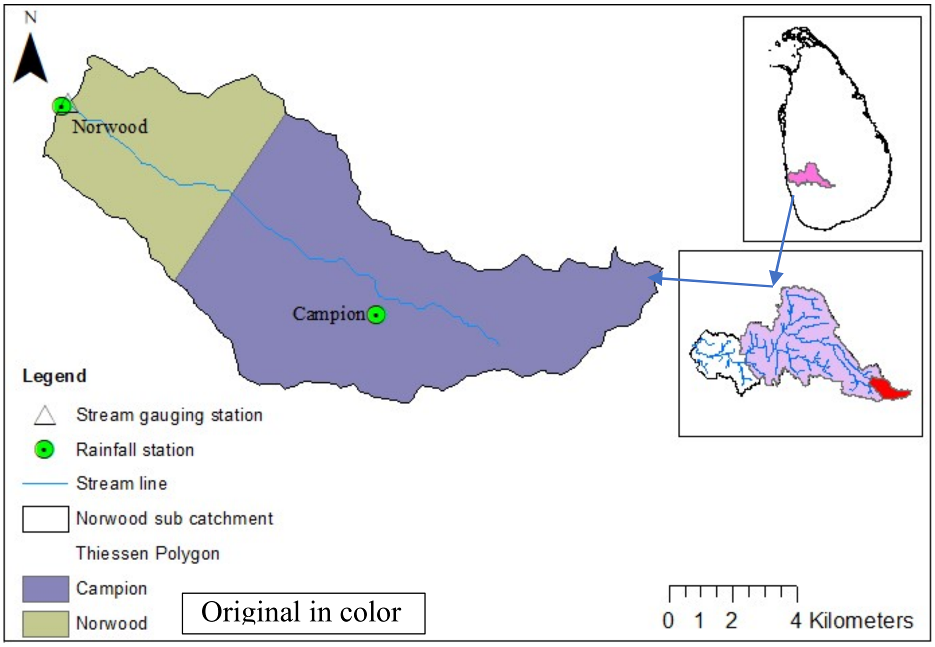


Figure 0-7 Thiessen polygons for the Norwood sub-catchment in Upper Kelani basin

The details of the Thiessen weights have been presented in Table 3-12, and from the table it is concluded that the maximum weight is contributed by the Campion precipitation station and at the same time, the least weight is contributed by the Norwood precipitation gauging station.

Table 0-12 The Thiessen polygon areas and weights for Norwood sub-catchment in Upper Kelani basin

Rain gauging stations	**Thiessen area (km^2)**	**Thiessen weight**
Norwood	28.75	0.30
Campion	66.66	0.70

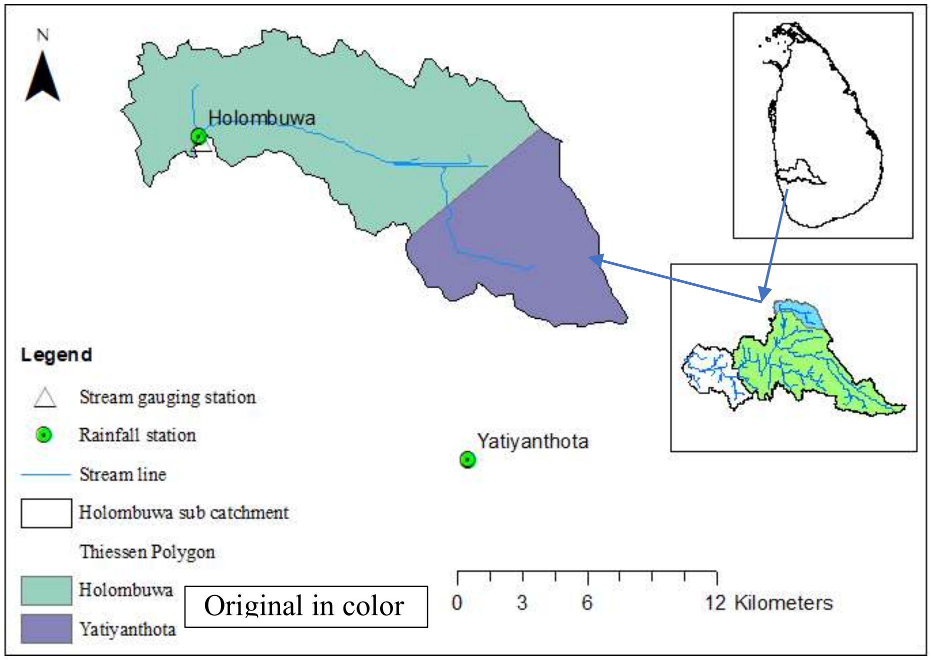


Figure 0-8 Thiessen polygon for the Holombuwa sub-catchment in Upper Kelani basin

The details of the Thiessen weights are presented in the Table 3-13, and this shows that the maximum weights are contributed by the Holombuwa precipitation station and at the same time, the least weight was contributed by the Yatiyanthota precipitation gauging station.

Table 0-13 The Thiessen polygon areas and weights for Holombuwa sub-catchment in Upper Kelani basin

Rain gauging stations	Thiessen area (km^2)	Thiessen weight
Holombuwa	102.97	0.67
Yatiyanthota	51.44	0.33

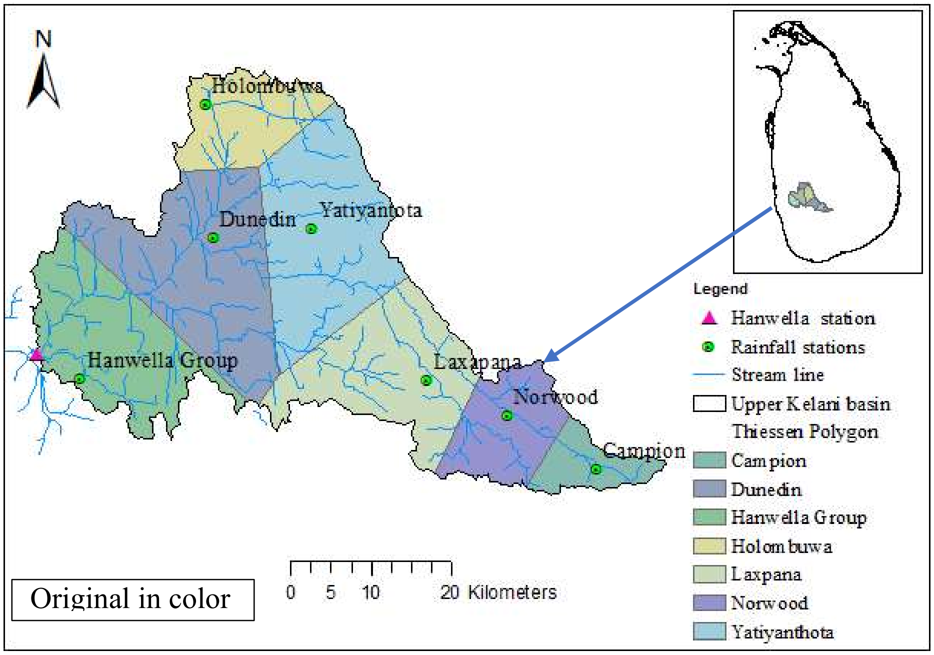


Figure 0-9 Thiessen polygon for the Upper Kelani sub-catchment in Kelani basin

The details of the Thiessen weights are presented in Table 3-14, and this shows that, the maximum weight was contributed by the Dunedin precipitation station and at the same time, the least weight was contributed by the Campion station.

Table 0-14 The Thiessen polygon areas and weights for the Upper Kelani basin (Model application) in Kelani basin

Rain gauging stations	Thiessen area (km^2)	Thiessen weight
Norwood	160.84	0.09
Campion	78.56	0.04
Holombuwa	165.67	0.09
Yatiyanthota	371.82	0.21
Laxpana	308.44	0.17
Dunedin	409.99	0.23
Hanwella Group	306.36	0.17

3.5.3 Visual Data Checking

Visual data checking was carried out to observe inconsistencies between the rainfall and streamflow data. The visual process is the manual process though it helps to identify the discrepancies in the rainfall and streamflow records. It is the simple graphical checking process on which rainfall is plotted in a bar chart and streamflow is plotted in a line graph.

The daily missing data were calculated in each station to find the percentage of the missing records in the time series data and to make sure that is within an acceptable range for the hydrological computation.

Initially, the daily precipitation data with missing data in each station were plotted with respect to the data from streamflow gauging station in the same sub-catchment to analyze the response of streamflow to the precipitation at each station.

Missing daily rainfall data were filled by using the method of multiple linear regression, for each year of data were tested for its 'goodness of fit' i.e. R^2 value. Then the missing data were computed with the index station data by taking the highest R^2 value.

After filling the missing data, Thiessen average daily precipitation data were plotted with respect to the streamflow data of the respective sub-catchment. Then, the visual discrepancies were analyzed accordingly by looking at the response of streamflow to the rainfall. By the visual checking process, the large discrepancies were observed, and in the process of data checking, many of the stations were found to be with erroneous data. In some of the stations, it was found that streamflow data to be over responsive for the rainfall and some of the stations were found to be extremely less responsive.

The comparison for the daily rainfall versus streamflow was conducted and when found to be erroneous, details are given in Figure 3-10 and Figure 3-11. Basically, it is seen that it is an error on the streamflow measuring data presented by the red dotted circle. It is found that the data were recorded same for the period of three months of the period for the years of 2009. Hence, it is treated as missing streamflow data and filled by using the regression analysis.

Details of Thiessen average rainfall vs streamflow for the Norwood and Holombuwa sub-catchments have been shown in Appendix A and Appendix B, respectively.

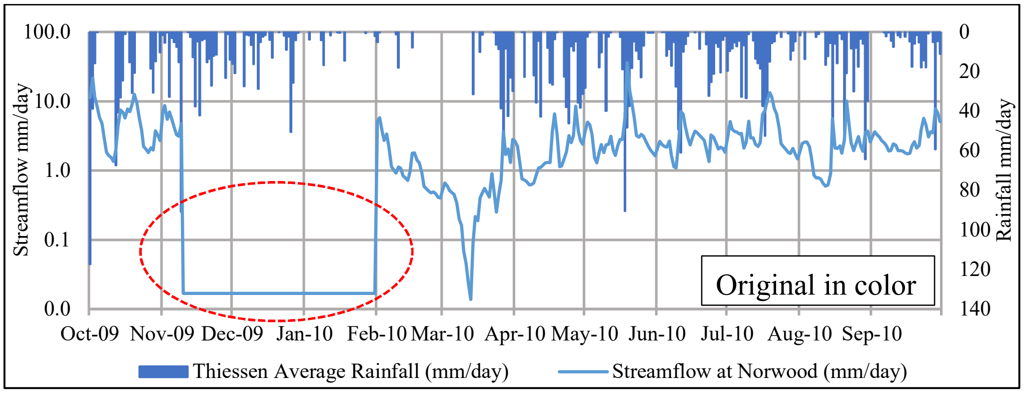


Figure 0-10 The rainfall versus streamflow comparison for the year of 2009 at the Norwood sub-catchment

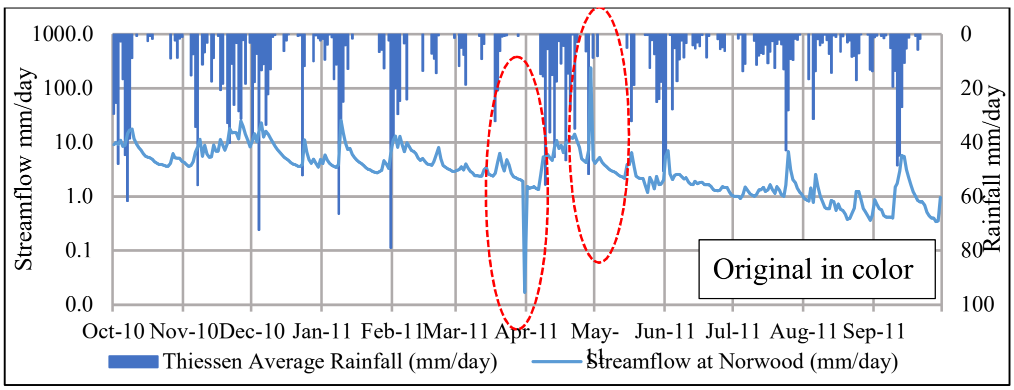


Figure 0-11 The rainfall versus streamflow comparison for the year of 2010 at the Norwood sub-catchment

After finding the discrepancies in the daily streamflow and rainfall comparisons, the annual responses of each sub-catchment were also checked with respect to the streamflow, as in Figure in 3-12 and Figure 3-13 for the Norwood and Holombuwa sub-catchments, respectively. Here, the yearly responses seem to be visually comparable to their rainfall – streamflow relationship.

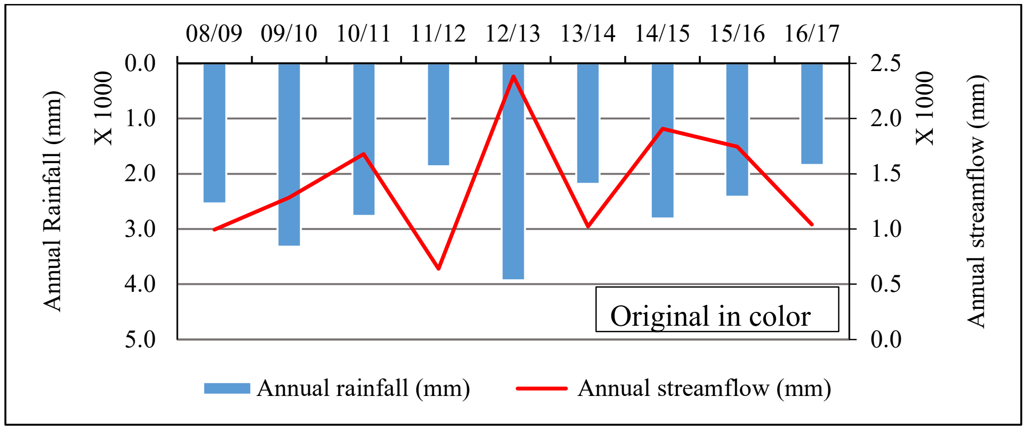


Figure 0-12 The annual comparison of the annual rainfall and streamflow at the Norwood sub-catchment

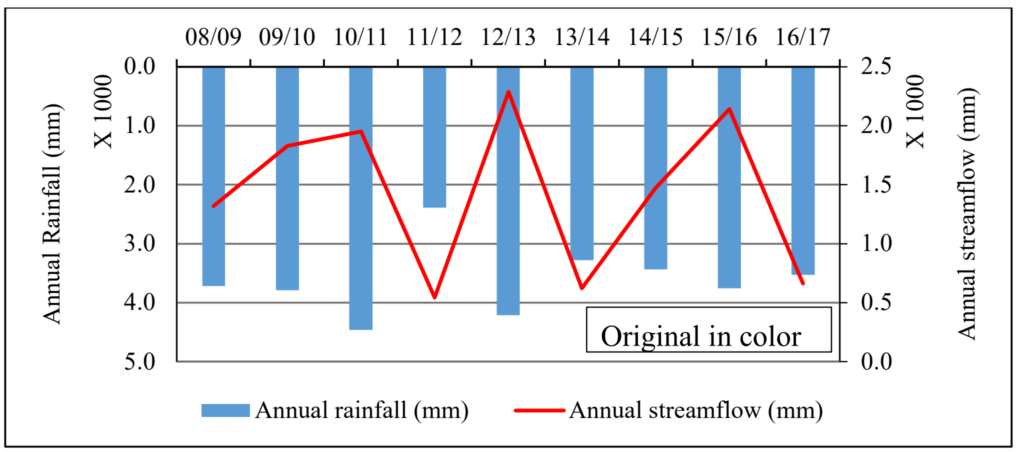


Figure 0-13 The annual comparison of the annual rainfall and streamflow at Holombuwa sub-catchment

Annual rainfall was plotted in the Figure 3-14 to compare the co-relationship between all the rainfall stations in the study area with annual rainfall at Yatiyanthota, and it was found to be higher and Laxpana station has seen the second-largest rainfall measuring station. The graph shows that the rainfall pattern is the same and following the same seasonal pattern for all the stations.

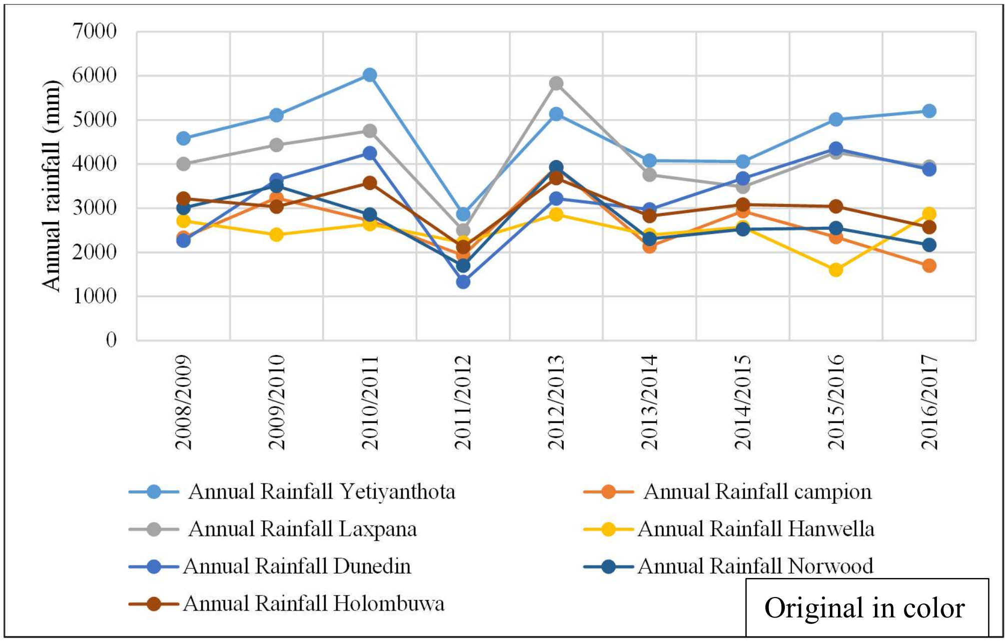


Figure 0-14 The annual rainfall of all the stations in the Upper Kelani river basin used in the study

3.5.4 Co-relationship between Rainfall and Streamflow

The co-relationship between the rainfall and streamflow was checked after filling in the missing data in the daily precipitation and streamflow time series for both sub-catchments. Here, it is observed that there was a slightly weaker relationship between the rainfall and streamflow in both sub-catchments. The coefficient of determination R^2 for the Norwood catchment found to be the 0.264 and also, for the Holombuwa sub-catchment, the coefficient of determination R^2 value was found to be 0.192, the result showing clearly the weak relationship between the data series. Figure 3-15 and Figure 3-16 show the respective correlation plots of the rainfall and streamflow for both sub-catchments.

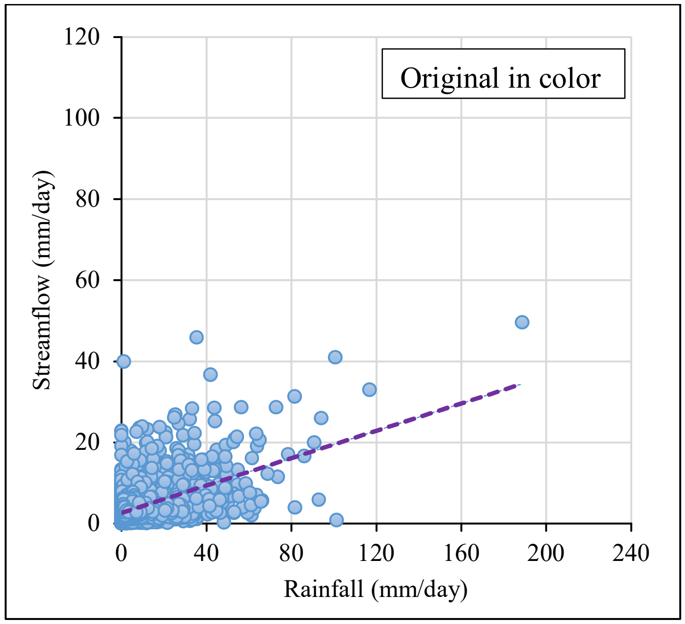


Figure 0-15 The co-relationship between daily rainfall and streamflow records at the Norwood sub-catchment

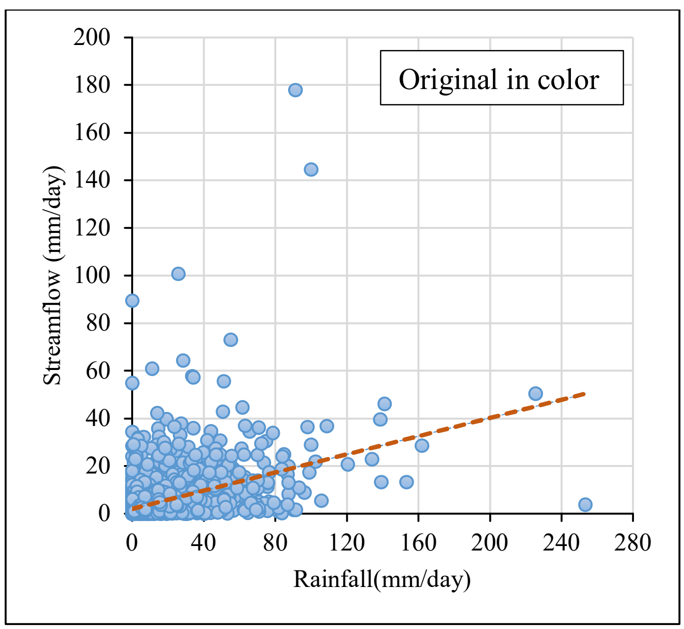


Figure 0-16 The co-relationship between daily rainfall and streamflow records at the Holombuwa sub-catchment

3.5.5 Single Mass Curve Analysis

For determining the discrepancies present at the meteorological data, single mass curve analysis was performed for the rainfall, temperature and evaporation data. The single mass curve was plotted for determining the inconsistency present in the data series, and this can be visualized by the sudden change (inflections) in the angle of the graph.

3.5.5.1 Single mass curve analysis of the precipitation

The single mass curve analysis was carried out for all the rainfall stations used in the study area. Hence, the single mass curve analysis was carried for the sub-catchment used for the model calibration and validation and model application in the study area. The single mass curve is plotted for all station in one graph. Figure 3-17 shows the single mass curves for the selected stations. The dotted red circle shows the sudden change (inflections) in the slope of the mass curve lines indicating possible discrepancies in data series.

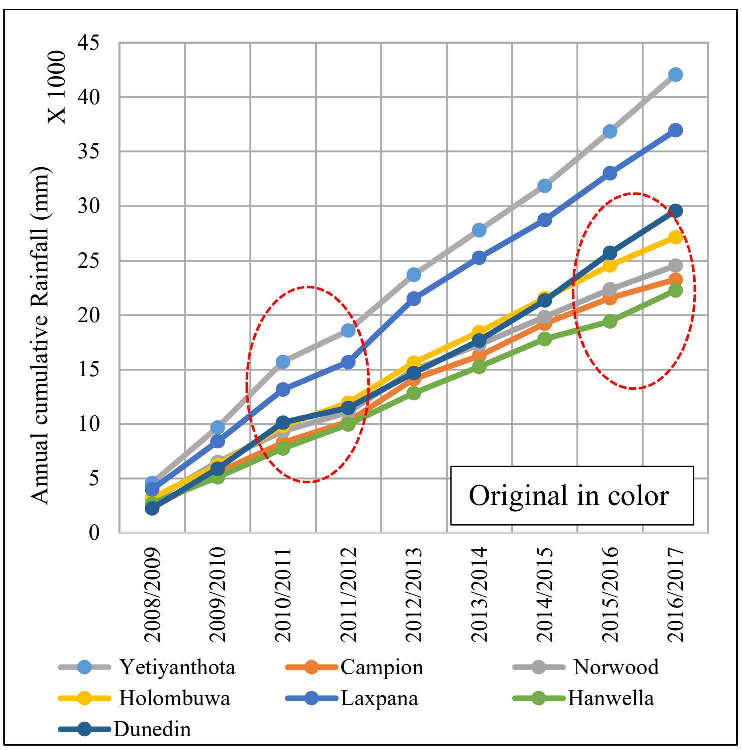


Figure 0-17 Single mass curve analysis of the rainfall data in Upper Kelani basin

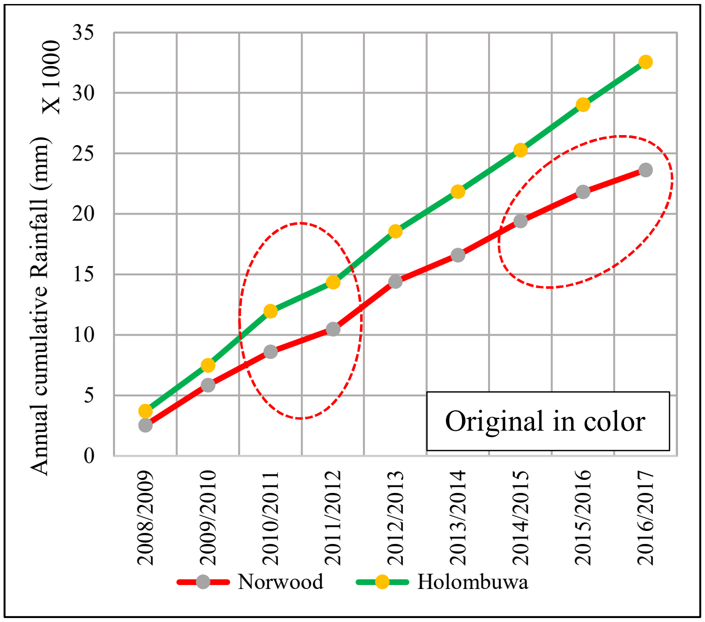


Figure 0-18 The single mass curve on Thiessen Average rainfall for both modelled catchments (Norwood and Holombuwa)

The single mass curve of the Thiessen average rainfall in Figure 3-18 for the modelled catchment at the Norwood shows possible deflection in year 2010/2011 to 2012/2013 but, at Holombuwa catchment, the breakpoint of inclination shows in the year 2010/2011. The red dotted circles indicate the sudden changes of the slope in the mass curve lines indicating possible discrepancies in data series.

3.5.5.2 Single mass curve analysis of the evaporation

To check the possible inconsistencies in the evaporation data series, the single mass curve was plotted. The single mass curve of the Ratnapura station was found to be straight without having any such deviations in the curve. And the missing data were below 5 %. Hence, missing data were filled with monthly average data. The single mass curve analysis has been shown in Figure 3-19.

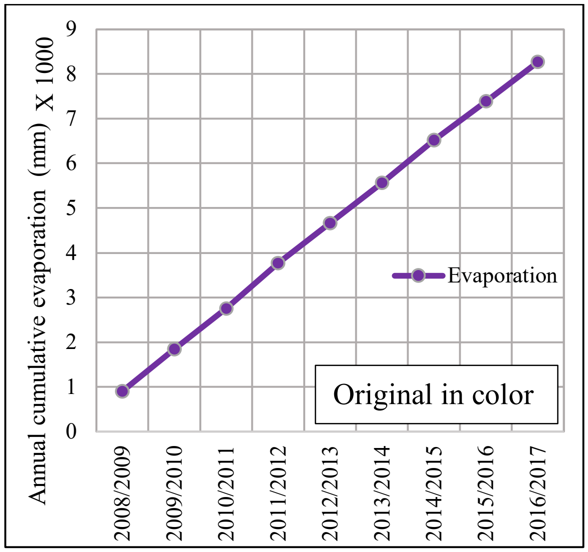


Figure 0-19 The single mass curve analysis of the evaporation for the Ratnapura Station

3.5.5.3 Single mass curve analysis of the temperature

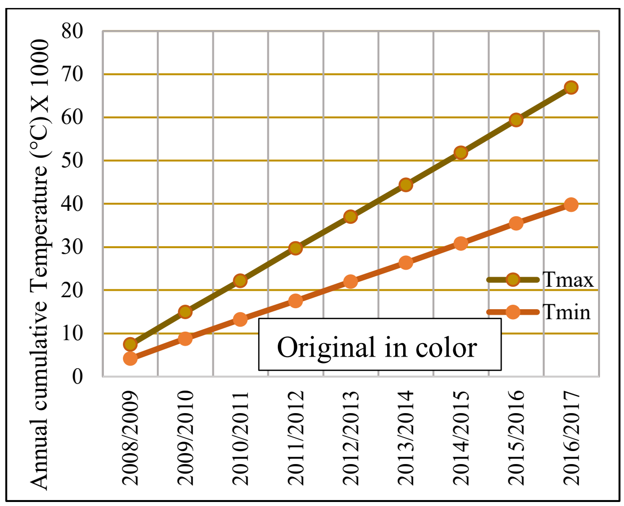


Figure 0-20 The single mass curve analysis for maximum and minimum temperature for the Nuwara-Eliya station

The single mass curve analysis of the T_{max} and T_{min} were found to be consistent when the single mass curve analysis was performed on the data series. Hence, it shows that the data is consistent over the period under consideration. The single mass curve analysis of temperature data has been presented in Figure 3-20.

3.5.6 Double Mass Curve Analysis

Consistency of the selected data was further checked by the double mass curve analysis. Homogeneity of the data can be checked by the double mass curve analysis.

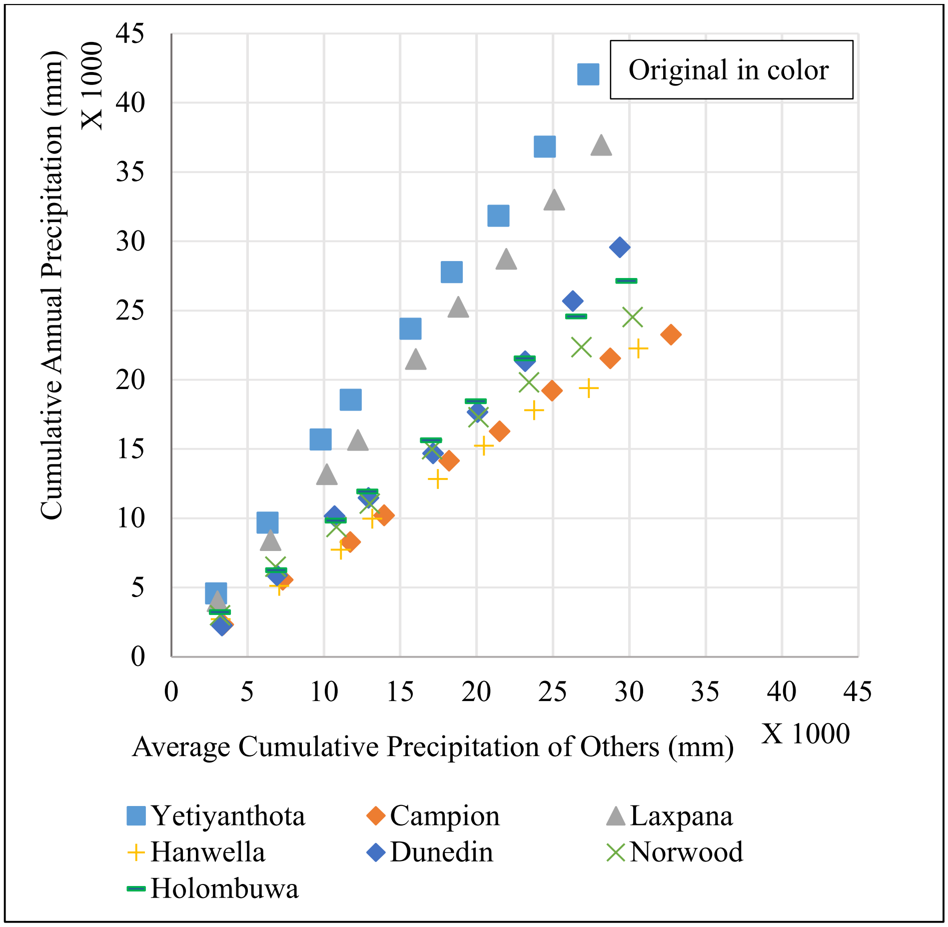


Figure 0-21 The double mass curve analysis of all the rainfall station at the study area in Upper Kelani basin

The double mass curve analysis was also conducted separately for modelled sub-catchments initially and inconsistency of the data were checked for the individual sub-catchments. But, later the test was carried out for all stations in the Upper Kelani sub-catchment. All the data stations used for the study were grouped together and the data consistency was checked by plotting the double mass curve. Figure 3-22 shows the double mass curve analysis by using all the stations together. This shows that the close relationship and consistency between the five stations, Norwood, Holombuwa, Campion, Hanwella Group and Dunedin. The highest total annual rainfall was recorded at Yetiyanthota station while the lowest was observed at Laxpana station.

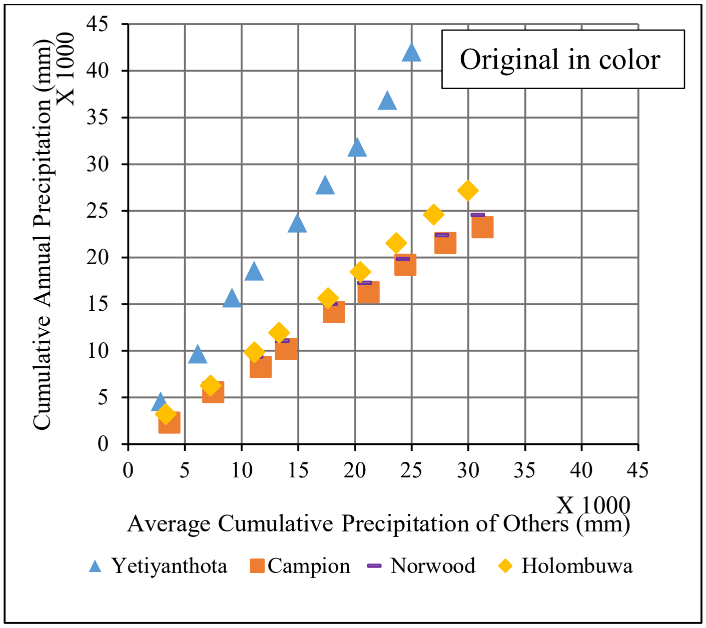


Figure 0-22 The Double mass curve analysis for the precipitation data in the modelled sub-catchments in Norwood and Holombuwa

3.5.7 Annual Water Balance Analysis

The annual water balance study was carried out separately for the Norwood and Holombuwa sub-catchments. The annual water balance was conducted to find the annual runoff coefficient and the variation of the rainfall, streamflow and evaporation rates. The runoff coefficient is one of the most important factors indicating the characteristics of the study sites. Wijesekera (2000) had also applied the water balance study concept to compare the model results and find the catchment characteristics for the study area.

The water balance study is a very straight forward concept to analyse the water budget of the sub-cacthment based on the total inflow, outflow and change in storage.

i.e. Inflow - Outflow = Change in storage, and the basic contributor of the system is the precipitation, runoff and evapotranspiration. The runoff could be calculated in two parts; one is surface runoff and the other is the groundwater flow. And also, the evapotranspiration could be calculated in two parts that are evaporation from the surface of the earth and vegetation.

Simplifying it,

Inflow - Outflow = Change in storage Eq. 24.

Precipitation (P) - Surface runoff (R) - Groundwater flow(G) - Evaporation (E) - Transpiration (T) = Change in storage (ΔS)

i.e., $P - R - G - E - T = \Delta S$ Eq. 25.

Hence, here Neglecting the Small change in the storage, the equation could be written as the,

$P - (R + G) - (E + T) = 0$ Eq. 26.

Hence, again re-arranging the equation,

Precipitation – Total runoff = Evapotranspiration

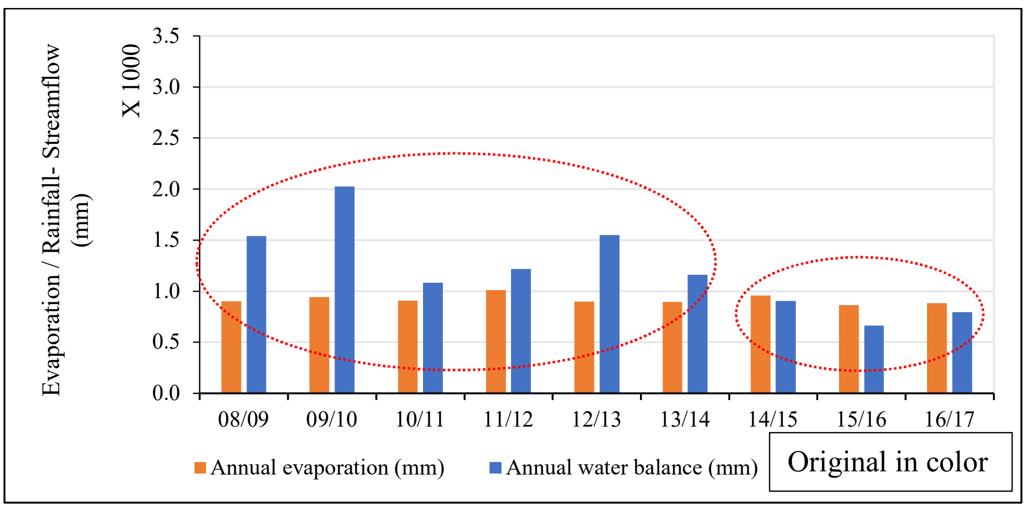


Figure 0-23 Annual water balance at the Norwood sub-catchment in Upper Kelani basin

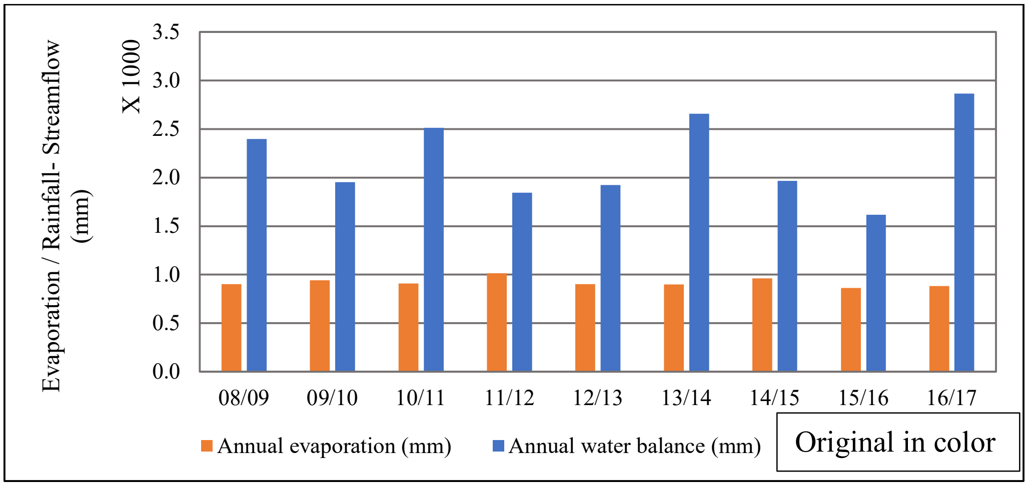


Figure 0-24 Annual water balance at Holombuwa sub-catchment in Upper Kelani basin

The water balance study on these two sub-catchments shows different behaviours, while the Norwood sub-catchment shows an increasing behaviour of the Rainfall-Streamflow (Water balance) relationship up to the year 2013/2014 but after that, the annual evaporation rate was higher than the annual net streamflow, which in turn caused a reduction in the flow in the river. The water balance study at the Holombuwa sub-catchment shows an increased ratio of the evaporation and rainfall-streamflow (Water balance) relationship. This all can be clearly seen in Figure 3-23 and Figure 3-24.

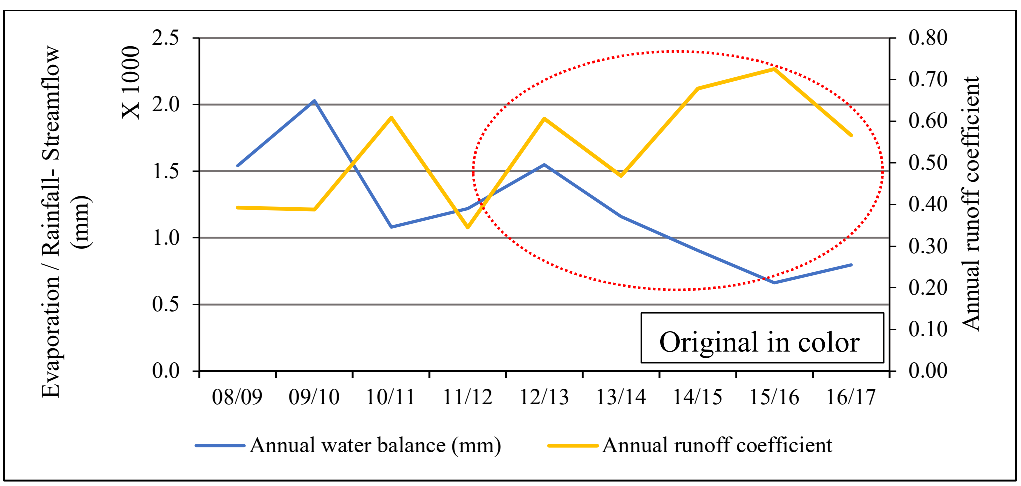


Figure 0-25 The relationship of the annual water balance and annual runoff coefficient in Norwood sub-catchment in Upper Kelani basin

The annual runoff coefficient has started to suddenly increase after the 2010/2011, and this may be due to the change in the vegetation cover in the sub-catchment, and the change in runoff coefficient is shown in Figure 3-23. But for the period of 2008/2009 to 2016/2017, the water balance and runoff coefficient in the Holombuwa sub-catchment show no such change in the sub-catchment, and Figure 3-26 shows no change in the Holombuwa sub-catchment.

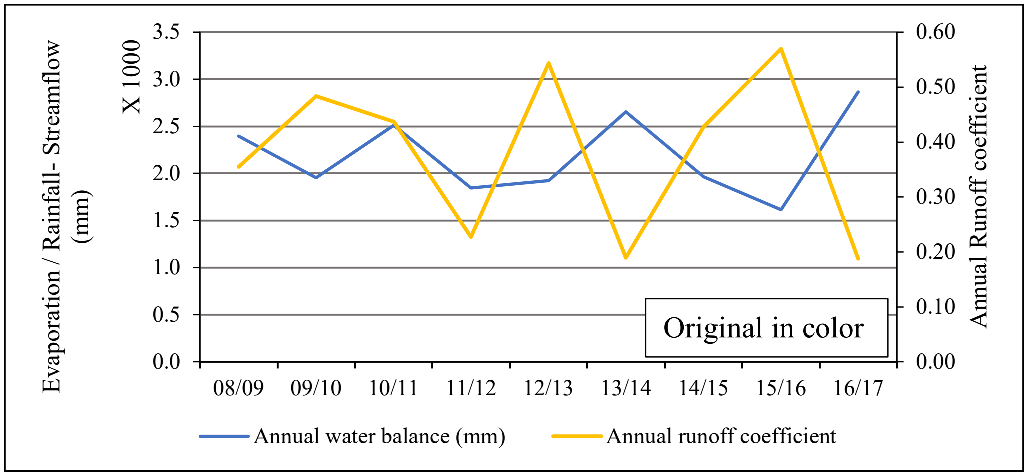


Figure 0-26 The relationship of the annual water balance and annual runoff coefficient in Holombuwa sub-catchment in Upper Kelani basin

Table 0-15 The annual water balance study in Norwood sub-catchments in Upper Kelani basin

Norwood water Balance					
Water Year	**Annual Streamflow (mm/annum)**	**Annual Evaporation (mm/annum)**	**Annual rainfall (mm/annum)**	**Annual runoff coefficient**	**Annual water balance (mm/annum)**
2008/09	994.76	902.41	2536.01	0.39	1541.25
2009/10	1286.21	942.56	3314.48	0.39	2028.27
2010/11	1679.04	908.49	2761.34	0.61	1082.29
2011/12	640.98	1011.85	1858.79	0.34	1217.81
2012/13	2380.49	899.88	3929.28	0.61	1548.79
2013/14	1023.61	897.36	2184.58	0.47	1160.98
2014/15	1907.67	959.04	2812.40	0.68	904.74
2015/16	1746.64	863.67	2409.17	0.72	662.52
2016/17	1041.14	881.45	1838.19	0.57	797.05
Average	**1411.17**	**918.52**	**2627.14**	**0.53**	**1215.97**

The total runoff coefficient in the Norwood sub-catchment is 0.53.

Table 0-16 The annual water balance study in Holombuwa sub-catchments in Upper Kelani basin

Holombuwa water Balance					
Water year	**Streamflow (mm/annum)**	**Annual Evaporation (mm/annum)**	**Annual rainfall (mm/annum)**	**Annual runoff coefficient**	**Annual water balance (mm/annum)**
2008/09	1318.60	902.41	3714.69	0.35	2396.09
2009/10	1830.80	942.56	3784.86	0.48	1954.06
2010/11	1950.21	908.49	4462.57	0.44	2512.36
2011/12	543.38	1011.85	2390.24	0.23	1846.86
2012/13	2286.85	899.88	4209.09	0.54	1922.24
2013/14	621.57	897.36	3277.46	0.19	2655.89
2014/15	1470.14	959.04	3436.56	0.43	1966.42
2015/16	2140.83	863.67	3756.29	0.57	1615.46
2016/17	661.77	881.45	3525.41	0.19	2863.64
Average	**1424.90**	**918.52**	**3617.46**	**0.38**	**2192.56**

The average runoff coefficient in Holombuwa sub-catchment is 0.38, and the details of this study conclude that a noticeable change in runoff coefficient occurs in the Norwood sub-catchment but, in Holombuwa sub-catchment such variation was not seen in the study period. And the annual runoff coefficient of the Norwood sub-catchment was found to be 0.53 but in Holombuwa sub-catchment, the average annual runoff found was found to be 0.38 only.

3.5.8 Flow Duration Curve

The flow duration curve (FDC) is one of the foremost important graphical representation tools that is capable to show the complete behaviour of the flow regime at the given station location. It is capable to indicate the low and high flows present in the river regime. It shows the complete clear description of the available flow and its reoccurrences in the given period of time (Smakhtin, 2001). The total period of flow duration curve in the Norwood and Holombuwa have been presented in Figure 3-27 and Figure 3-28 for the period of 2008-2017 considering the water year.

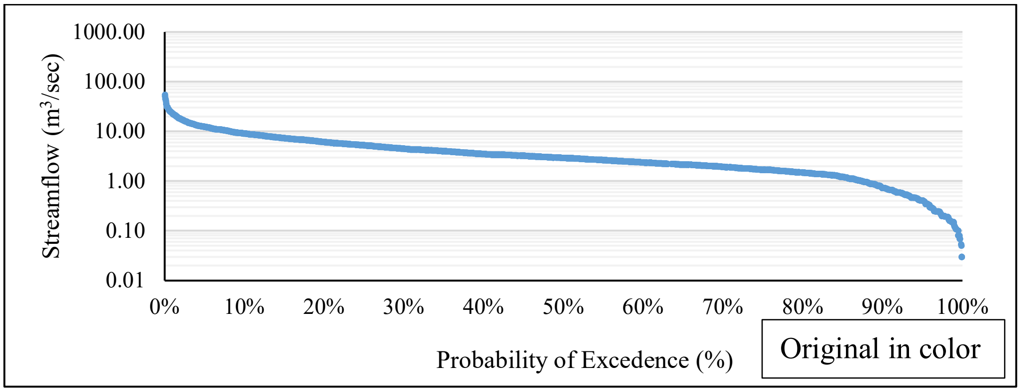


Figure 0-27 The flow duration curve for the total data period (2008/2009-2016/2017) at the Norwood sub-catchment

The flow duration curve was constructed by using the ranked flows in the regime and its probability of percentage exceedance of distribution is given by the Weibull (1951) to construct the flow duration curve. Smakhtin (2001) suggested the logarithmic graph to plot the flow duration curve. Hence, the total flow in m^3 /sec was plotted against the probability of exceedance percentage.

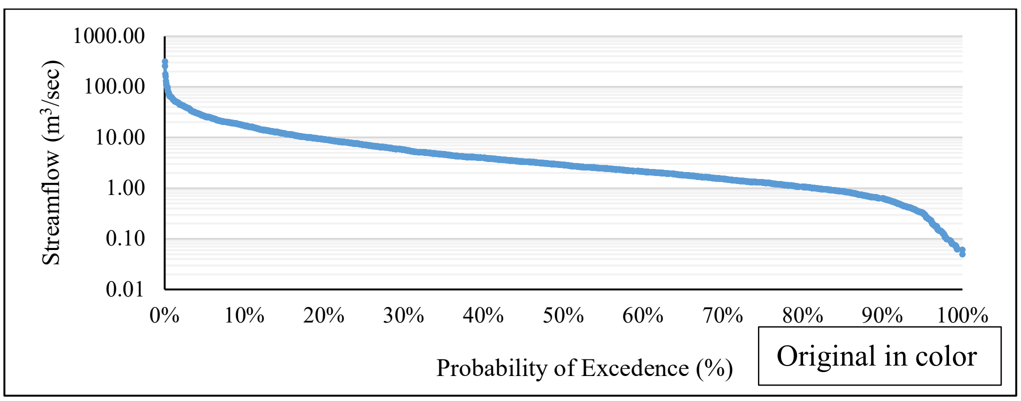


Figure 0-28The flow duration curve for the total data period (2008/2009-2016/2017) at the Holombuwa sub-catchment

Smakhtin (2001) stated that the flow duration curve is the foremost easy and applicable way to represent the total flow in a flow regime. The most descriptive way to present the graph of the flow duration curve is the log-normal probability plot, which is capable to linearize a low and high flow at the starting end and start of the graph, respectively.

RESULT AND ANALYSIS

4.1 Hydrological Model

4.1.1 Potential Evapotranspiration (PET) Calculation

The literature review was conducted for selecting the methods to be applied for finding potential evapotranspiration. The potential evapotranspiration (PET) is one of the main components of the model input to the ABCD model. From the literature review, the method provided by the Hargreaves and Samani (1985), was used for the PET estimation. The methodology was developed to estimate the PET by using the air temperature from the meteorological station's data. For estimating the PET, it requires the minimum temperature, maximum temperature and average temperature. The model itself is used as a daily model and hence, the data acquired was also daily resolution. For estimation of the PET from these methods, it requires the extraterrestrial solar radiation. For this, the methodology developed by the Allenet al. (1998) was used, and the equation used to calculate the extraterrestrial solar radiation needs to provide the location of the basin. For providing this location point, one needs to be very careful about the positive and negative sign. If the location falls in the Northern hemisphere, then the sign should be taken positive and if the point falls in the Southern hemisphere, the sign should be taken as negative. The study area falls on the Northern hemisphere so it was taken as a positive value. The location point for the computation of the location data was taken at the outlet location of each sub-catchment. The formula provides its values on the $MJm^{-2} day^{-1}$ for estimation of the extraterrestrial solar radiation and hence, to convert it to the required mm day^{-1} units, the conversion factor of 0.408 given by the Allen et al. (1998) was used. This PET calculation method was found to be easy and useful in the model development process.

4.1.2 Warm-up Period, Initial Soil Moisture Content and Initial Groundwater Storage

The ABCD model requires the initial values of the moisture content and the groundwater. Thomas (1981) had used arbitrary values to develop the model. Further, for the development of two-parameter model, Xiong & Guo (1999) have used arbitrary values in the same manner.

Hence in this study, to determine the initial values and its characteristics, the calibration set of data from 2008/2009 to 2012/2013 was used and five initial warm up cycles of the run were made. The observation found that the quasi-steady state was reached after the first one set of model runs except for the Norwood groundwater storage G_{t-1}. But for all the other values of the soil moisture storage S_{t-1} and groundwater storage G_{t-1}, the quasi-steady state was reached after the first set of model run. For the Norwood sub-catchment, groundwater storage reached quasi state at only after the 20 times of model runs. Figure 4-1 to Figure 4-4 show the model warmup period for the respective catchments for the initial soil moisture and the groundwater storage.

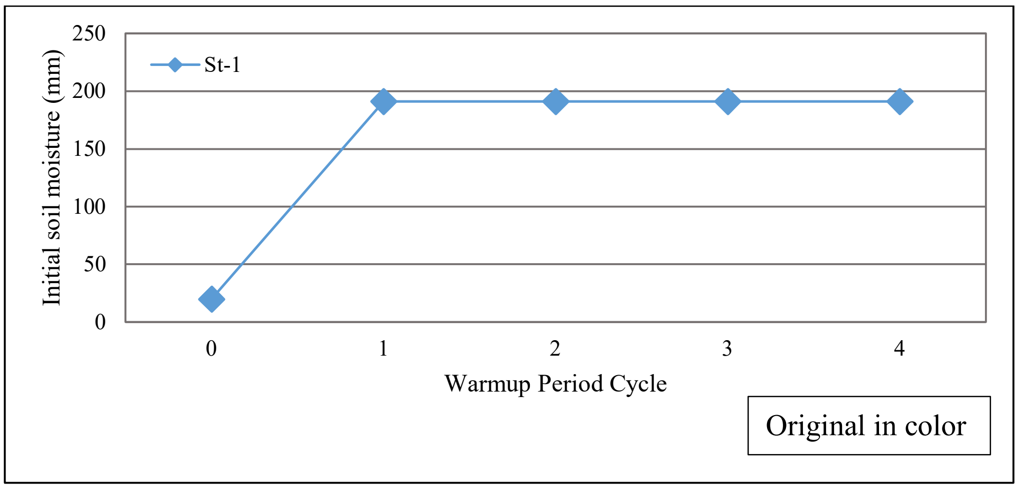


Figure 0-1 Warm-up period and corresponding soil moisture storage at the Norwood sub-catchment in Upper Kelani basin

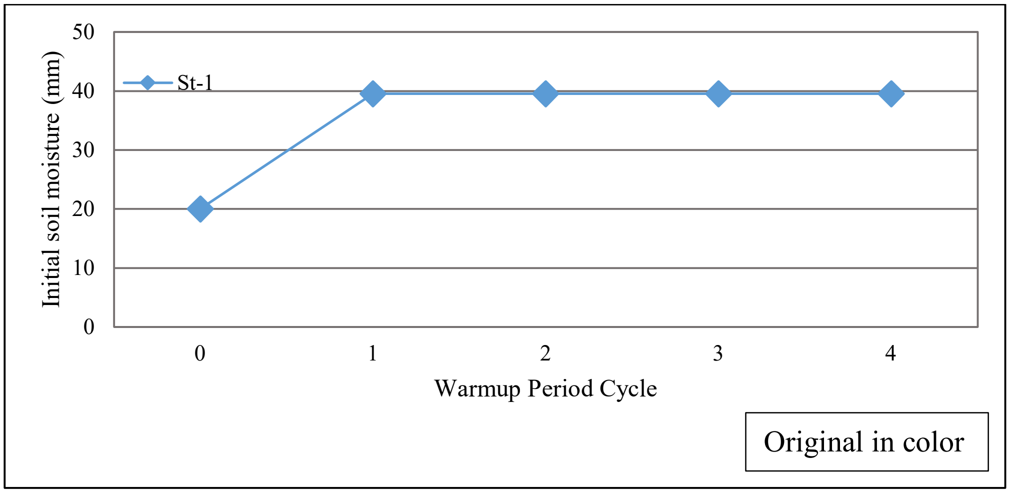


Figure 0-2 Warm-up period and corresponding soil moisture storage at the Holombuwa Sub- catchment in Upper Kelani basin

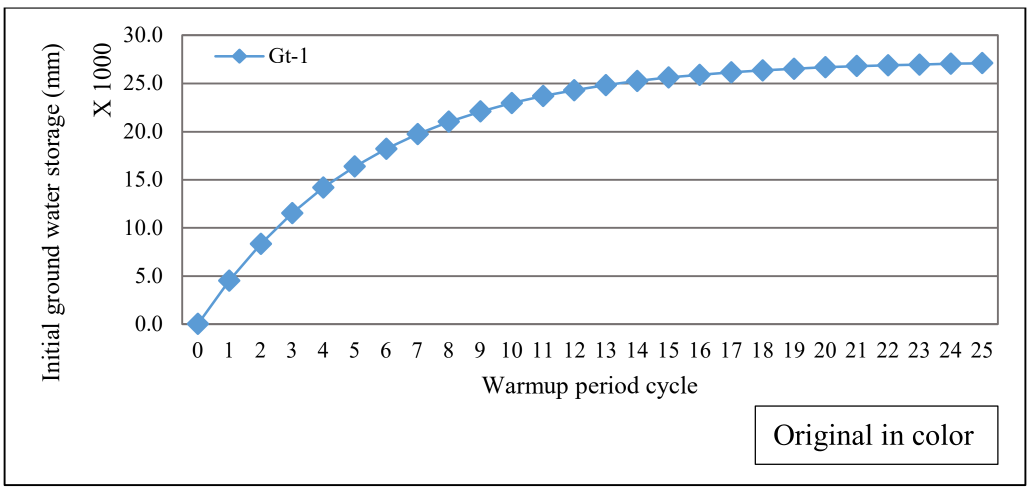


Figure 0-3 Warm-up period and corresponding groundwater storage at the Norwood sub-catchment in Upper Kelani basin

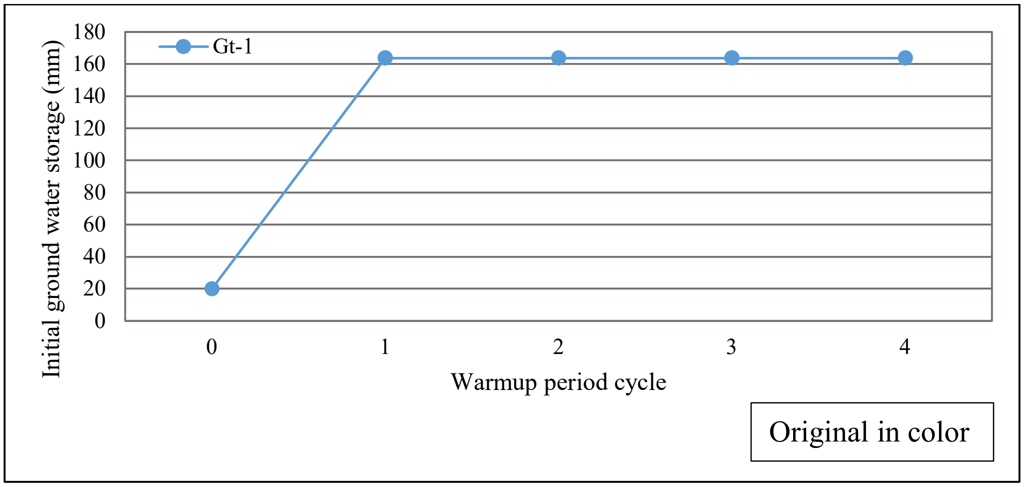


Figure 0-4 Warmup period and corresponding groundwater storage in the Holombuwa sub-catchment in Upper Kelani basin

4.1.3 Calibration and Validation of the ABCD Four-parameter Hydrological Model

4.1.3.1 Initial values of model run

The initial values for the model running, the parameter *a, b, c* and *d* was used considering the range from the literature study considering a model objective function as the Pearson correlation coefficient, *r.* Table 4-1 shows the initially used model parameters to run the model. The model requires the initial values which were used from the 5th cycle of model runs, as it was used to determine the initial soil moisture quantity and groundwater storage. The initial run of the model shows a relatively good correlation in the Norwood sub-catchment but in the Holombuwa sub-catchment, it shows a very good relationship to the observed flow at the watershed outlet. The model was run using a co-relation coefficient *r* with another reference of the coefficient of determination R^2. The developed excel spreadsheet of the model was run by using solver function available in excel and another evolutionary method, the goal seek function available in Excel. The model was run first trying to balance the individual parameters and later it was optimized by looking at the response of the flow hydrograph and its corresponding parameters to control the resultant flow in the sub-catchment. After the model calibration, the same values were used to validate the model and found a good response from the model runs with the objective function used.

Table 0-1 The initial values of the model parameter used in the first set of the model runs in both sub-catchments

Model parameter	**Range from the literature**	**Initial values used in the model**	
		Norwood	**Holomobuwa**
a	0.873-0.999	0.936	0.936
b	14-4000	260.000	130.000
c	0-1.000	0.001	0.500
d	0-1.000	0.001	0.001

The model performance was checked from the visual compatibility as well. The model in the first set of runs in the calibration period was not found to in good compatibility with the observed flows. The below Figure 4-5 and Figure 4-6 show the model visual compatibility following the initial run in Norwood and Holombuwa sub-catchments, respectively. The objective function value available from the first run of the model is presented in Table 4-2.

Table 0-2 The objective function at the initial run in the model for both sub-catchments in Upper Kelani basin

Sub-catchment	**Correlation Coefficient *r***	**Coefficient of determination R^2**
Norwood	0.82	0.67
Holombuwa	0.60	0.36

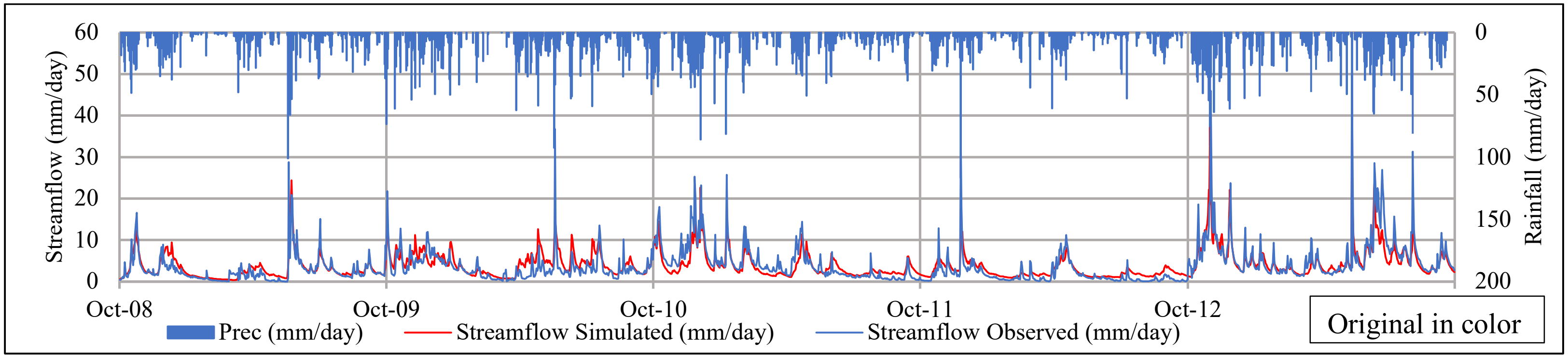


Figure 0-5 The model initial run for the calibration period on the Norwood sub-catchment in Upper Kelani basin

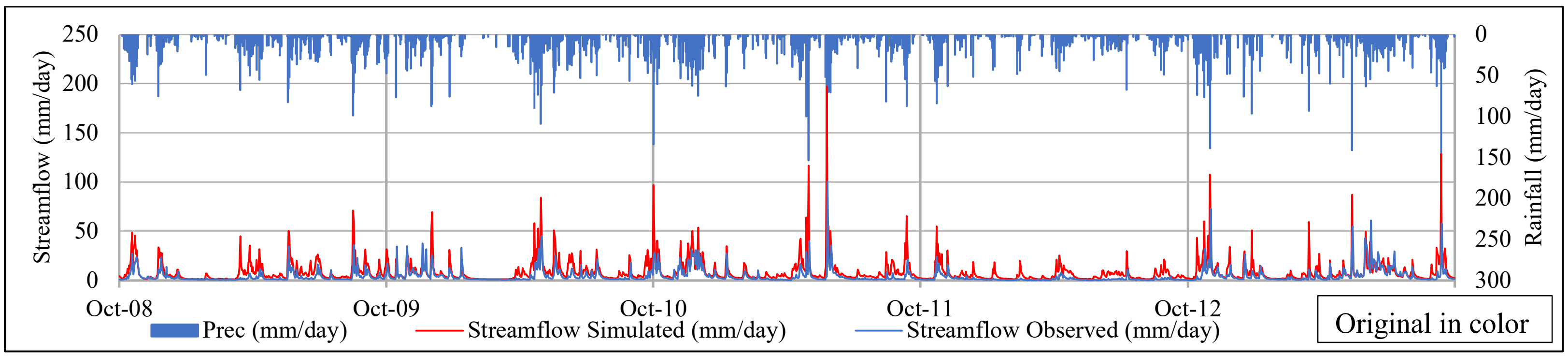


Figure 0-6 The model initial run for the calibration period on the Holombuwa sub-catchment in Upper Kelani basin

After the initial run of the model, according to the methods described with the use of the Excel solver and Goal Seek functions available in Excel, the model was calibrated first, and then the parameters were optimized one by one, The model was further optimized by looking at the model response to the respective model parameters. Manual optimization and visual optimization processes were also applied to get the best match in the observed and simulated hydrograph. After finding the optimum match in hydrograph and obtaining the maximum range of objective function, the parameters were transferred for the model verification. The model was run for the 2008/2009 to 2012/2013 period for the calibration and 2013/2014 to 2016/2017 period for the validation of the model on both catchments. The optimized parameters for both sub-catchments have been listed in Table 4-3.

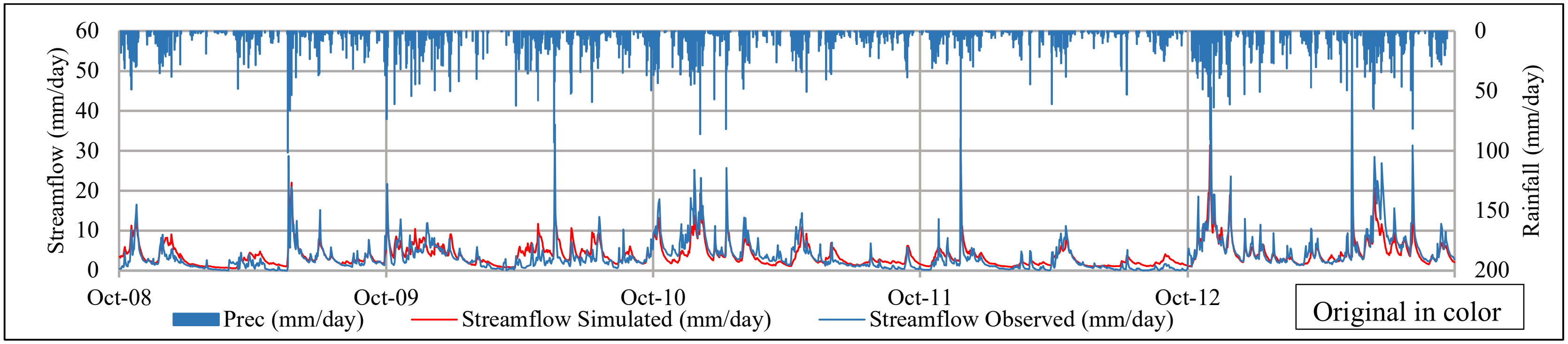
Table 0-3 Model parameters obtained in the optimization process

Sub-catchment	**Parameter**	**Parameter value**	**Objective functions**			
			Calibration		**Validation**	
			r	R^2	***r***	R^2
Norwood	*a*	0.963	0.83	0.68	0.87	0.75
	b	398				
	c	0.465				
	d	0.00001				
Holombuwa	*a*	0.995	0.59	0.35	0.61	0.37
	b	300				
	c	0.542				
	d	0.0001				

The corresponding hydrographs of simulated vs. observed and the rainfall-runoff relationship have been shown under the below subsequent sub-headings.

4.1.3.2 Simulated and observed flow hydrograph from the calibration and validation in both sub-catchments

After the model runs for the initial simulation and finding an initial soil moisture content and groundwater storage, the model is optimized by using Excel Solver and evolutionary Goal Seek methods along with the visual compatibility check. Hence, from this iterative process, the objective function values obtained have been shown in Table 4-3 for both catchments.



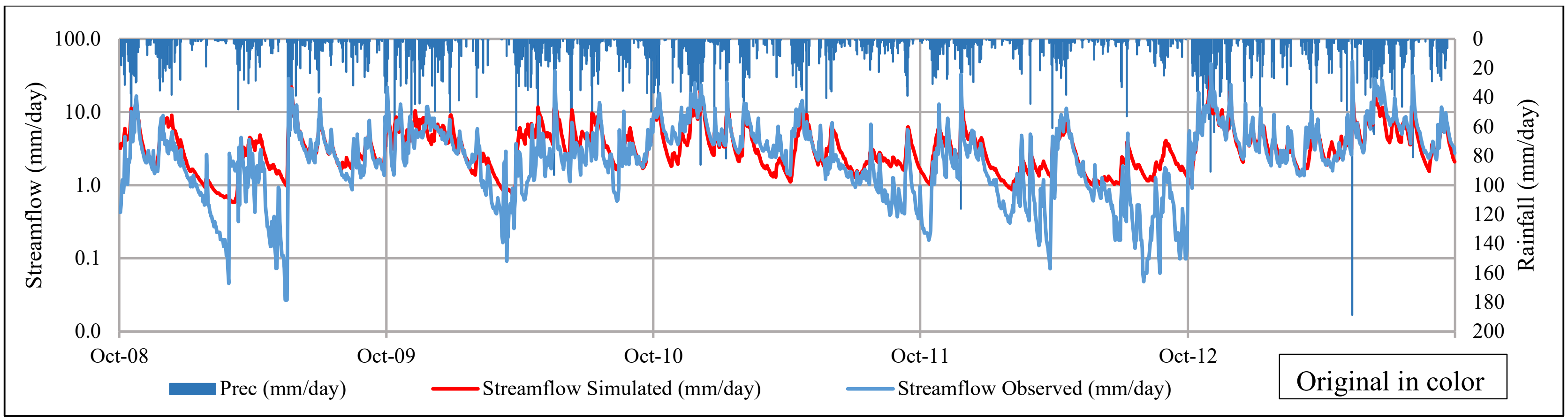


Figure 0-7 The calibration results on normal and log plots of the Norwood sub-catchment in Upper Kelani basin

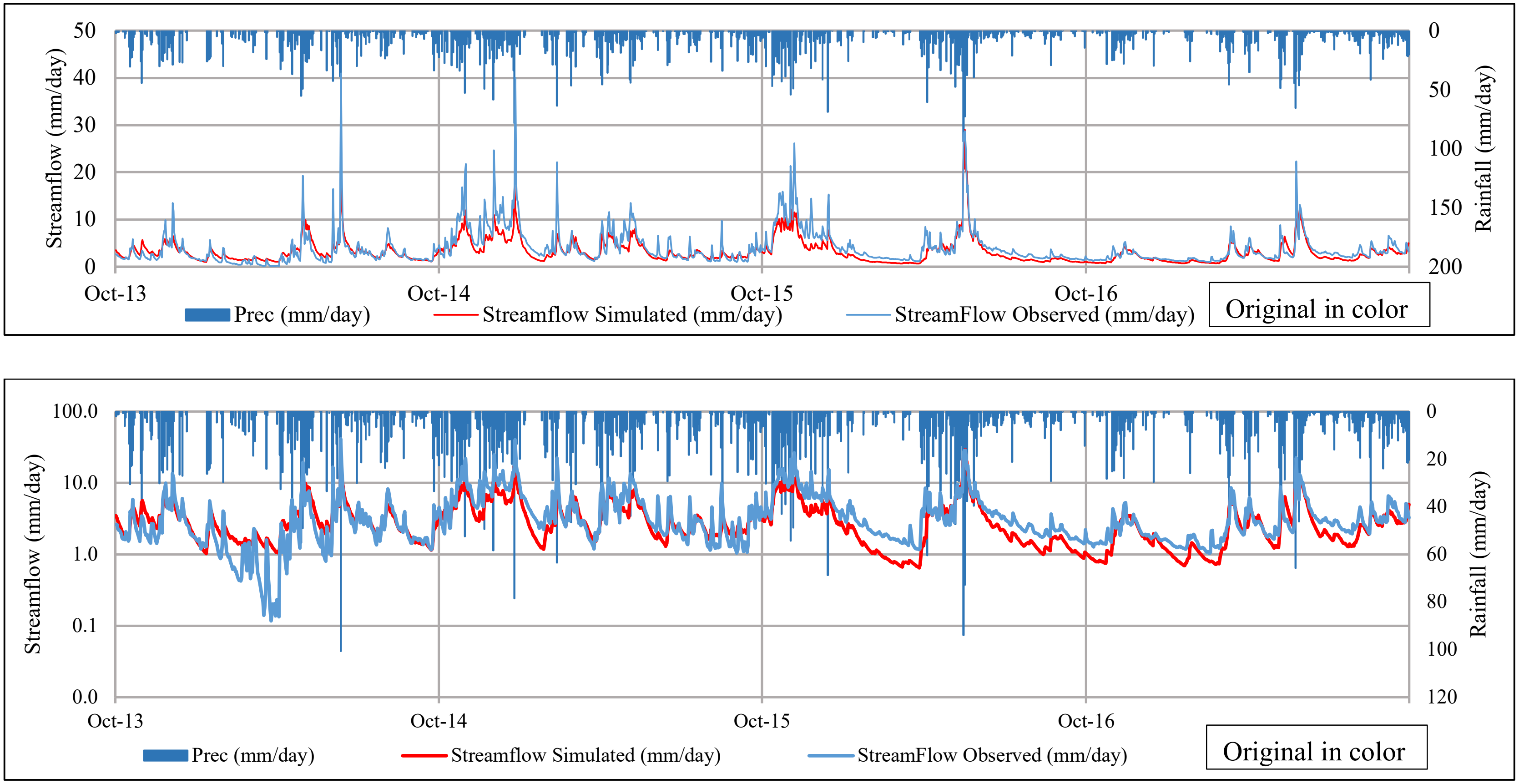


Figure 0-8 Validation results on normal and log plots of the Norwoodsub-catchment in Upper Kelani basin

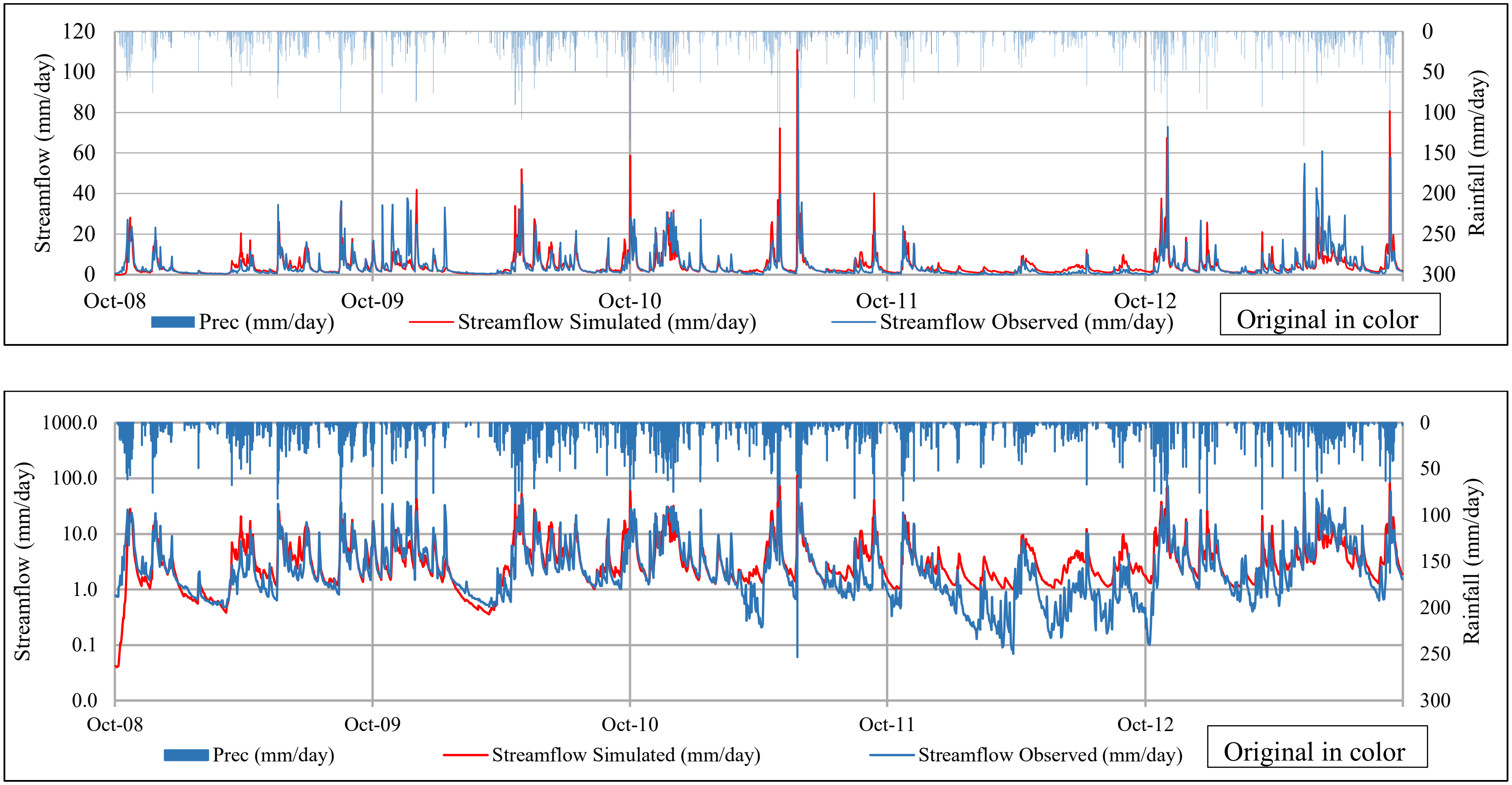
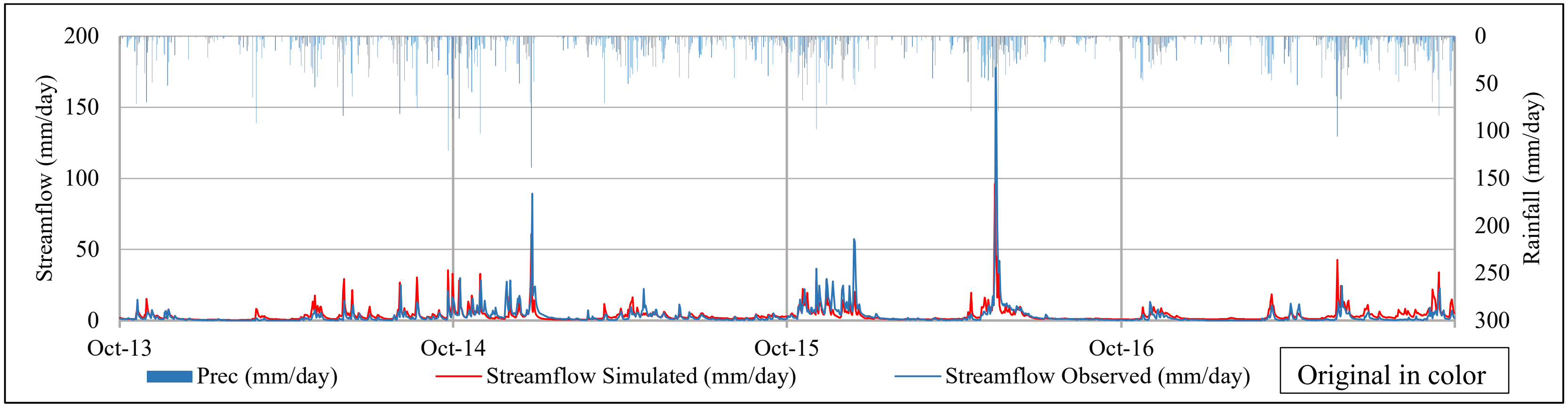


Figure 0-9 The calibration results on normal and log plots of the Holombuwa sub-catchment in Upper Kelani basin



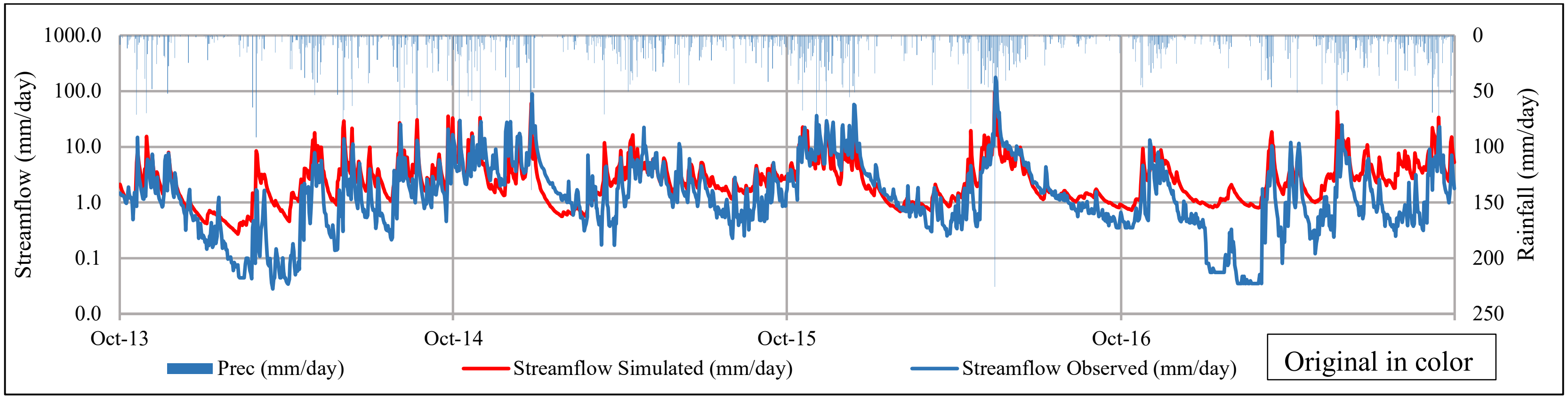


Figure 0-10 Validation results on normal and log plots in the Holombuwa sub-catchment in Upper Kelani basin

4.1.4 Relationship between Observed and Simulated Streamflow

The observed and simulated runoff relationship can be plotted in the scatter plot to see the relationship between them. Figure 4-11 to Figure 4-14 show the calibration and validation relationship in the Norwood and Holombuwa sub-catchments, respectively.

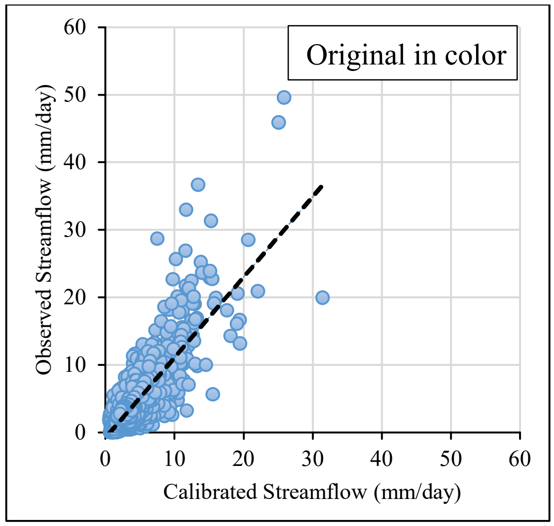


Figure 0-11 The observed and simulated streamflow relationship for calibration in Norwood sub-catchment

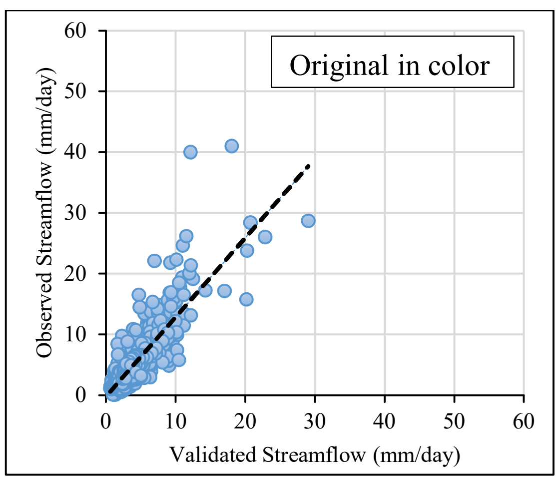


Figure 0-12 The observed and simulated streamflow relationship for validation in Norwood Sub-catchment

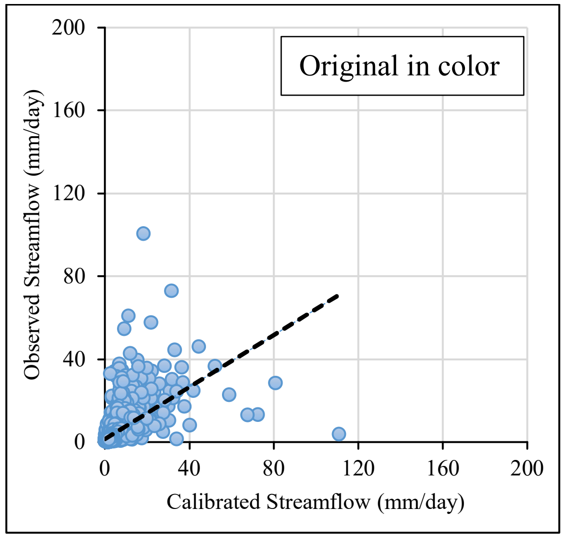


Figure 0-13 The observed and simulated streamflow relationship for calibration in Holombuwa sub-catchment

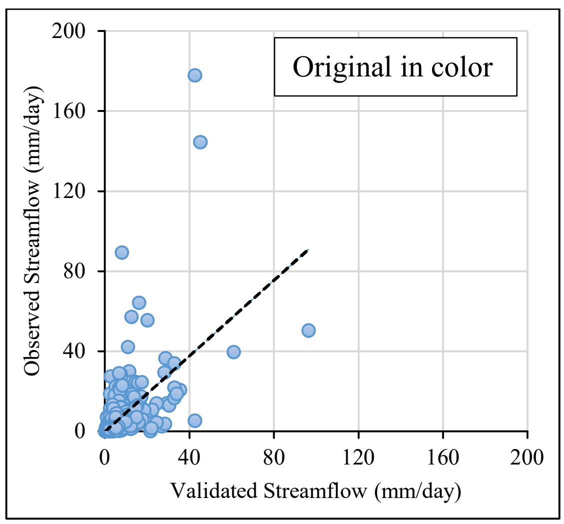


Figure 0-14 The observed and simulated streamflow relationship for validation in Holombuwa Sub-catchment

4.1.5 Flow Duration Curve Analysis for the separation of Low, Medium and High Flow

4.1.5.1 Introduction to flow separation by using flow durationcurve

The shape of the flow duration curve is capable to define the particular characteristic of the catchment, its upper zone evaluates the high flow ranges and lower zone evaluates the low flow ranges (Gunasekara & Rajapakse, 2018). This study was based on daily resolution. Hence, daily flow records are used to draw the flow duration curves. This curve shows the percentage of time during which the specified flow rates are exceeded. The shape of the FDC curve in high flow region shows the flood condition in the rainy season and the shape at the low flow region shows the capability to sustain flow in the dry period in the river system. For the Run-of-the-River hydropower design, the low flow is the interest of the hydrologist. As the hydropower is based on the run-of-the-river system, it is very much important to characterize the low flow in the river system. For defining the regime characteristic from the flow duration curve, the slope is the main parameter to be considered. The steep slope of the FDC shows that the catchment is highly runoff dependent and a short period of the heavy rainfall can cause the flood in the catchments area.

The development of the flow duration curve was carried out by using the daily streamflow records. The streamflow records were arranged in the descending order irrespective of the date in the column and then the flow was ranked. To find the probability of exceedance, Weibull (1951) formula was used. The expression was given by Weibull (1951),

$$P = \frac{r}{(n+1)} \times 100 \qquad \text{Eq. 27.}$$

where *r* is the rank number and the *n* are the total number of statistical parameters present in the study. The probability is expressed as the percentage of exceedance (%).

4.1.5.2 Flow duration curve for Norwood sub-catchment

The flow duration curve for the Norwood sub-catchment has been plotted in the normal plot and the logarithmic plot (Figs. 4-15 and 4-16). The streamflow versus the probability of exceedance was plotted. The separation of low, medium and high flow was done by looking at the sudden change in the slope of the FDC. The flow duration curve analysis was undertaken separately for the calibration and validation periods.

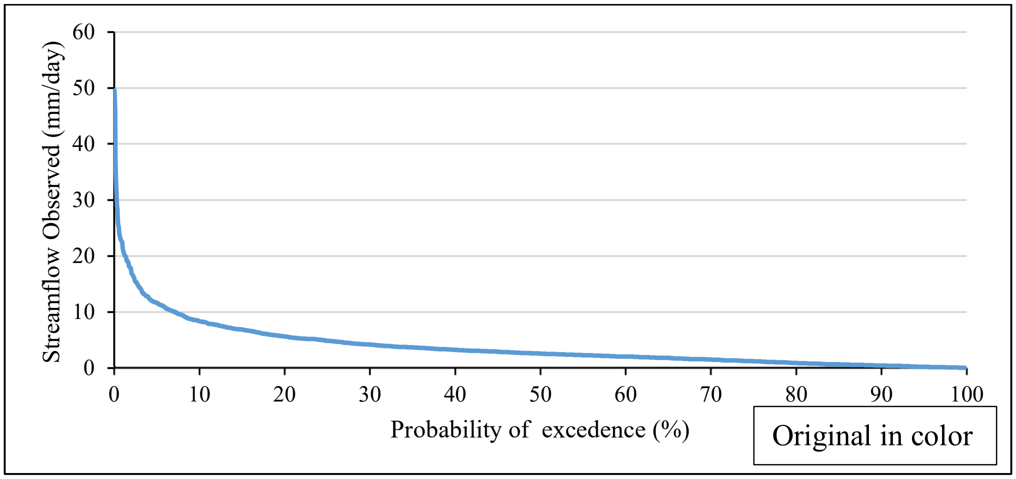


Figure 0-15 The normal plot of the flow duration curve of the Norwood sub-catchment for calibration data

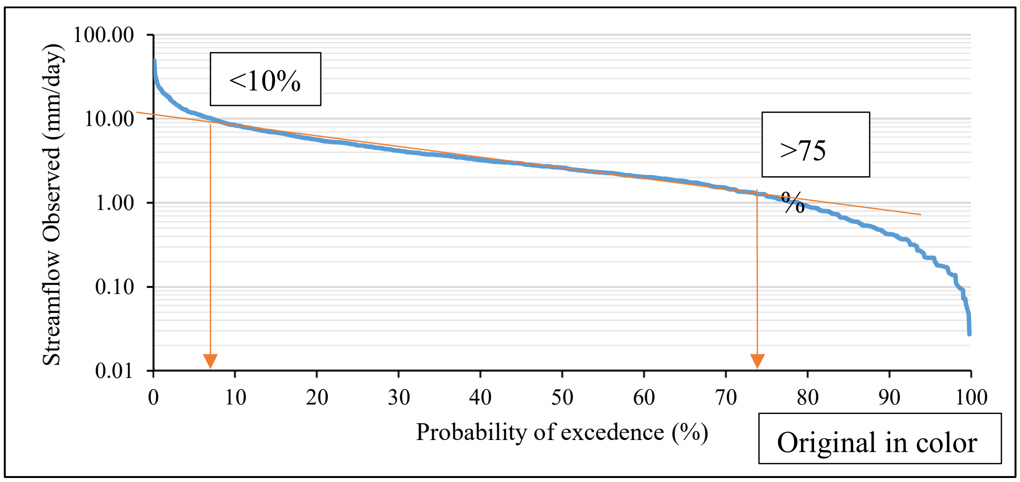


Figure 0-16 The logarithmic plot of flow duration curve of the Norwood sub-catchment for calibration data

Figure 4-15 and Figure 4-16 show the flow duration curve for the calibration period for the Norwood sub-catchment from 2008/2009 to 2012/2013 year.

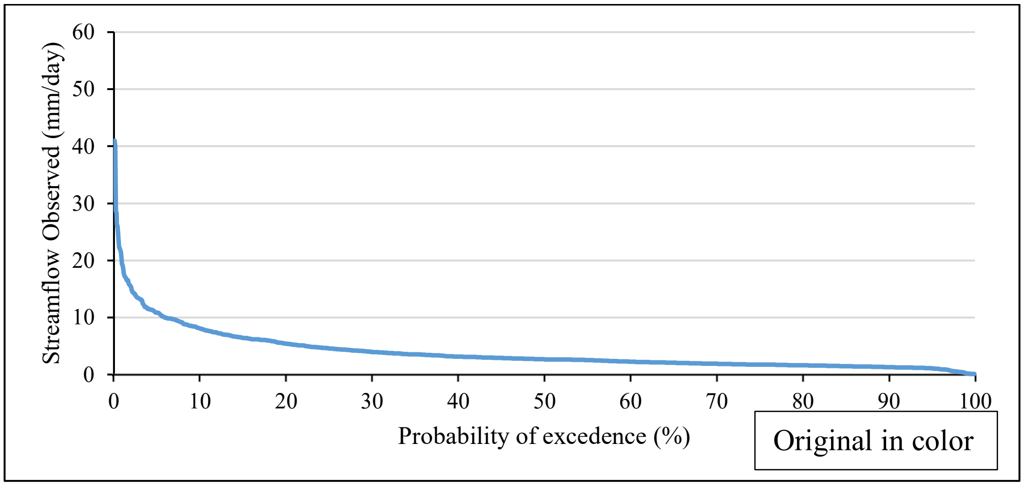


Figure 0-17 The normal plot of the flow duration curve of the Norwood sub-catchment for the validation period

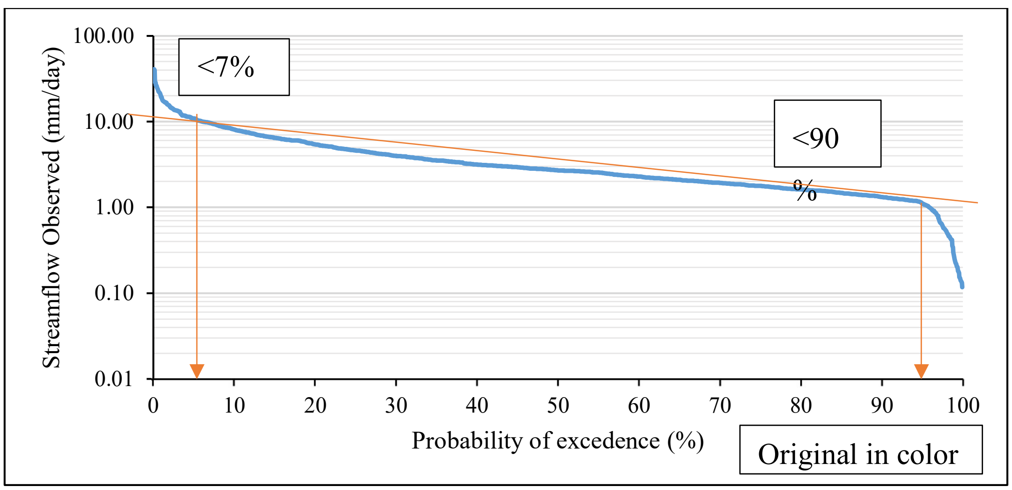


Figure 0-18 The Logarithmic plot of flow duration curve of the Norwood sub-catchment for the validation period

Figure 4-17 and Figure 4-18 show the flow duration curve for the validation period for the Norwood sub-catchment from 2013/2014 to 2016/2017 year.

4.1.5.3 Flow duration curve for Holombuwa sub-catchment

The flow duration curve for the Holombuwa sub-catchment has been plotted in the normal plot and the logarithmic plot. The streamflow versus the probability of exceedance percentage was plotted. The separation of low, medium and high flow was done by looking at the sudden change in the slope in the flow duration curve. The FDC analysis was carried out separately for the calibration and validation period.

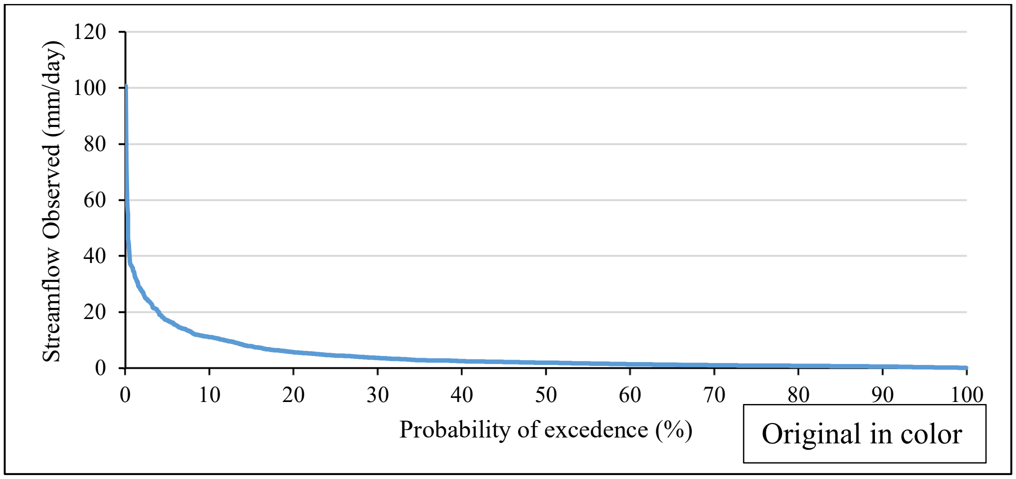


Figure 0-19 The normal plot of the flow duration curve of the Holombuwa sub-catchment for the calibration period

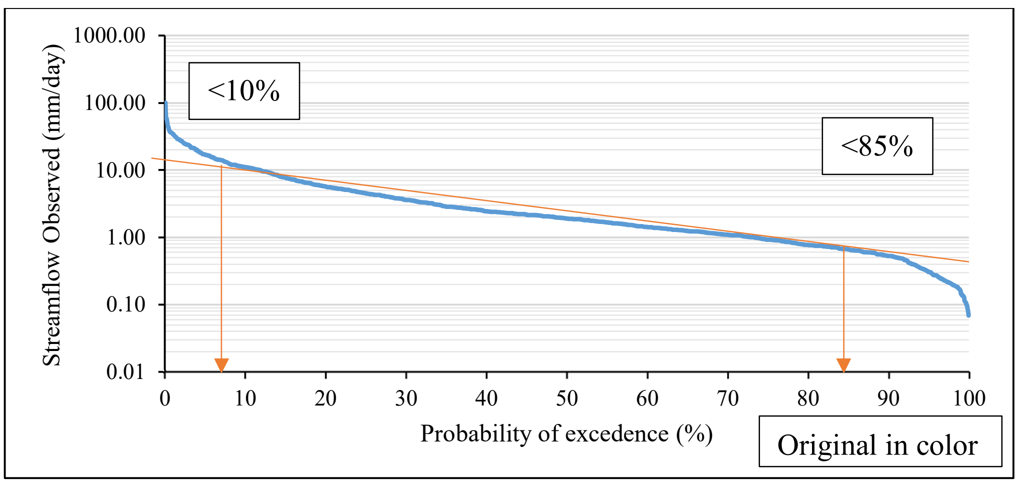


Figure 0-20 The logarithmic plot of the flow duration curve of the Holombuwa sub-catchment for the calibration period

Figure 4-19 and Figure 4-20 show the flow duration curve for the calibration period for the Holombuwa sub-catchment from 2008/2009 to 2012/2013 year.

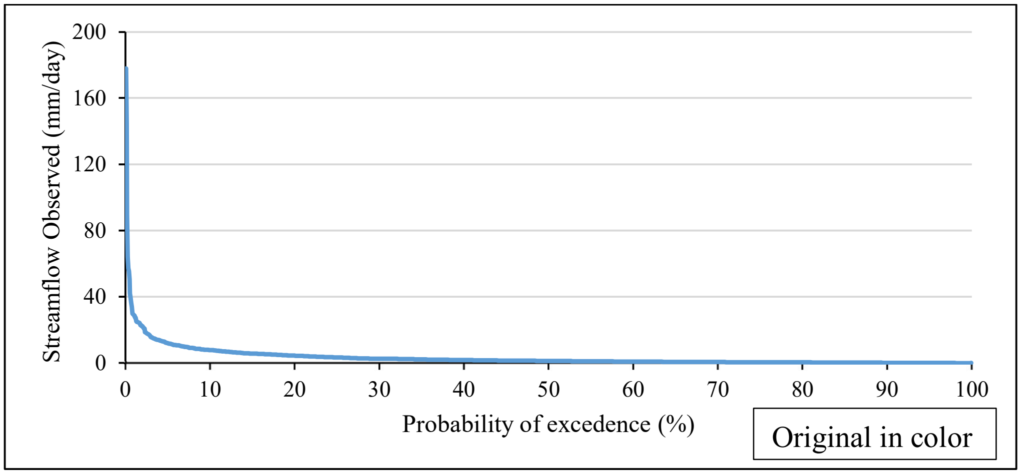


Figure 0-21 The normal plot of the flow duration curve of the Holombuwa sub-catchment for the validation period

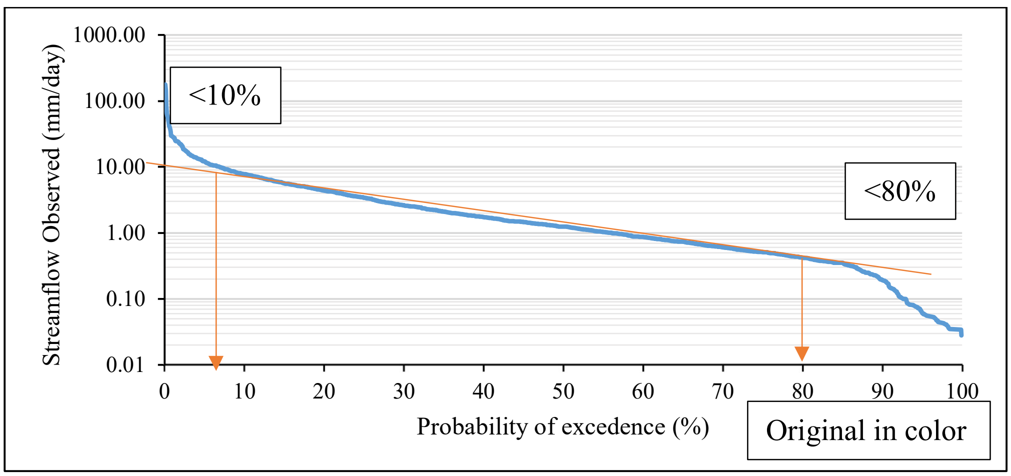


Figure 0-22 The logarithmic plot of the flow duration curve of the Holombuwa sub-catchment for the validation period

Figure 4-21 and Figure 4-22 show the flow duration curve for the validation period for the Holombuwa sub-catchment from 2013/2014 to 2016/2017 year.

4.1.5.4 Flow separation based on the Flow Duration Curve

The catchment flow variation was determined by the visual inspection over the logarithmic curve by checking its changes (inflections) in the slope of the flow duration curve. The details of the findings have been presented in Table 4-4.

Table 0-4 The low, medium and high flow variation in both sub-catchments

Sub-catchment		Flow in stream	Exceedance Probability (%)	Relevant Discharge (mm/day)
Norwood	Calibration	High	< 10	>8.37
		Medium	10-75	1.2-8.37
		Low	<75	<1.2
	Validation	High	<7	>9.55
		Medium	7-90	1.31-9.55
		Low	<90	<1.31
Holombuwa	Calibration	High	< 10	>11.13
		Medium	10-85	0.65-11.13
		Low	<85	<0.65
	Validation	High	<10	>7.88
		Medium	10-80	0.42-7.88
		Low	<80	<0.42

4.1.6 Flow Duration Curve analysis for Norwood and Holombuwa Sub-catchments with Simulated flow

The purpose of the analysis of the flow duration curve was to inspect the visual compatibility of the flow duration curve over each other based on the observed and simulated flows. For this purpose, the simulated flow was plotted on top of the observed flow duration curve in the calibration and validation process. The details of the flow duration curve and its compatibility has been presented in the subsequent below sub-headings for both sub-catchments.

4.1.6.1 Flow duration curve analysis for the Norwood sub-catchment

The observed flow was separated for the calibration period and validation period for the Norwood sub-catchment. Then the data were treated as an isolated series for the other computation processes. The daily flow was ranked by the ranking process and the probability of exceedance percentage was computed by using Weibull (1951) formula. The normal plot and logarithmic plot have been presented (Figs. 4-23 and 4-24).

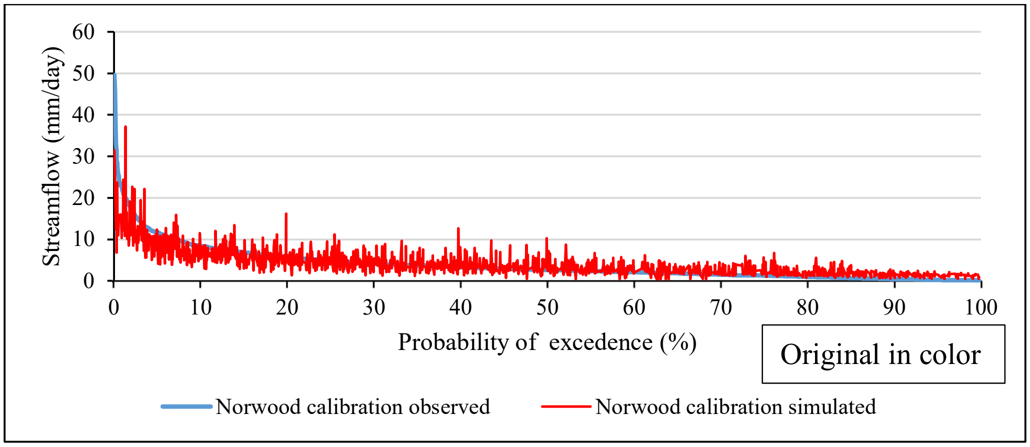


Figure 0-23 The Normal plot of observed and simulated flow duration curve for the calibration period in Norwood sub-catchment

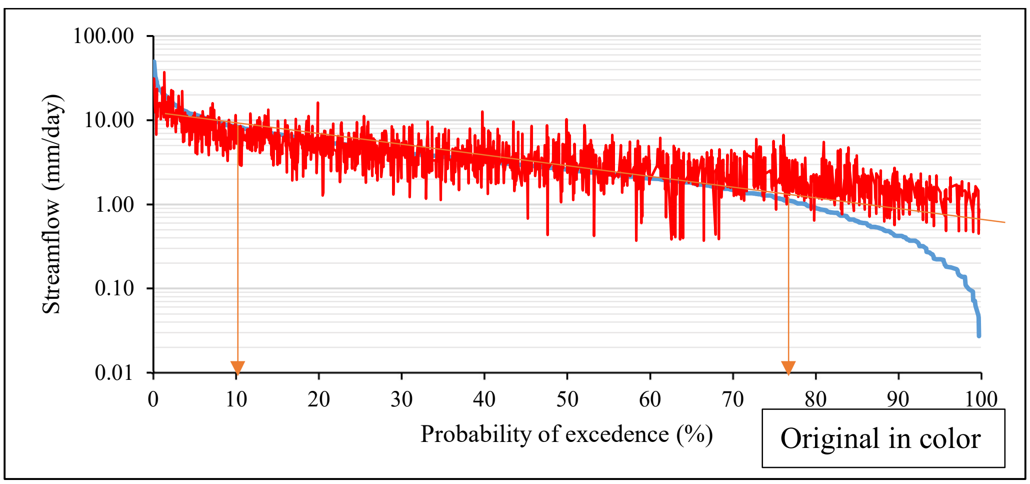


Figure 0-24 The logarithmic plot of observed and simulated flow duration curve for the calibration period in Norwood sub-catchment

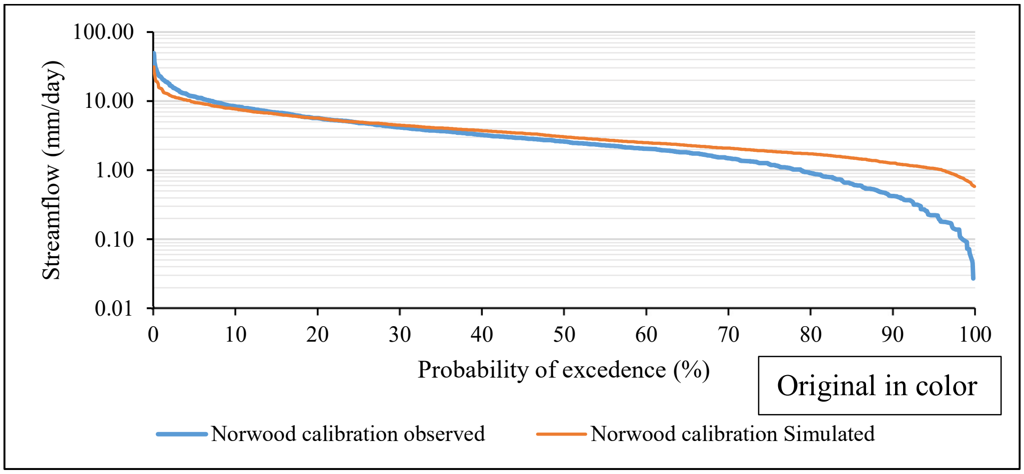


Figure 0-25 The logarithmic plot of observed and simulated flow duration curve for the calibration period in Norwood sub-catchment

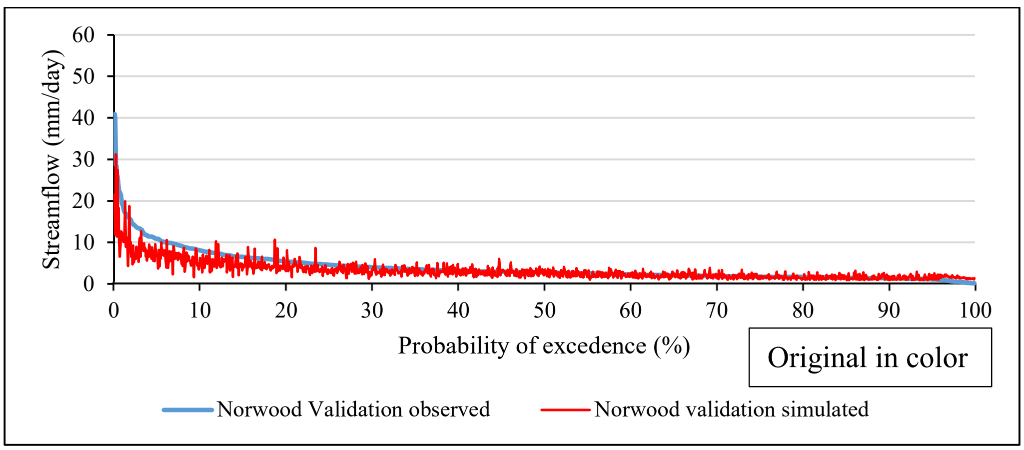


Figure 0-26 The Normal plot of observed and simulated flow duration curve for the validation period in Norwood sub-catchment

Figure 4-23 and Figure 4-24 show the normal plot and logarithmic plot during the calibration period for the observed and simulated values. Figure 4-23 represents the plot with both series sorted separately to compare but Figure 4-24 shows the observed data is ranked but the simulated data is left as per the results obtained at the exact respective date, which indirectly shows the variation in temporal scale. The same sequence of the pattern is followed in the representation of the data in Figure 4-25 to Figure 4-35.

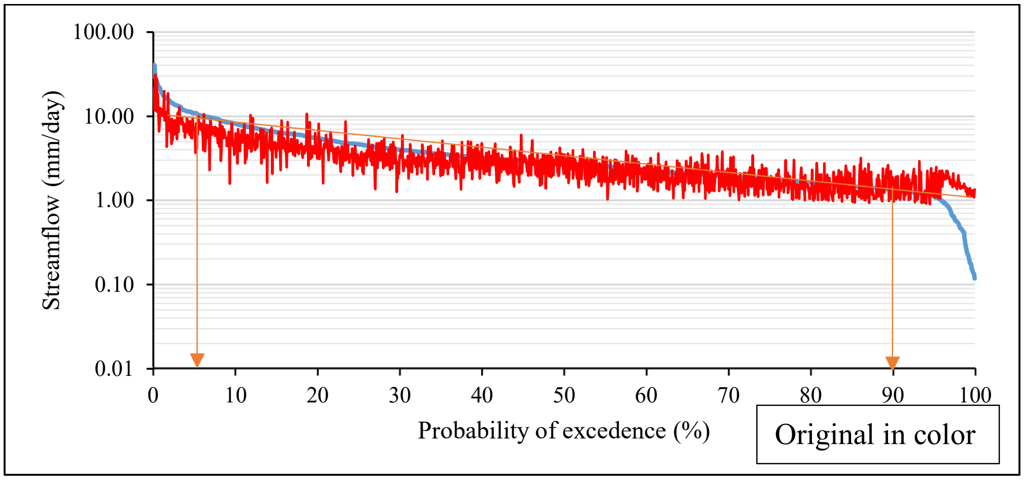


Figure 0-27 The logarithmic plot of observed and simulated flow duration curve for the validation period in Norwood sub-catchment

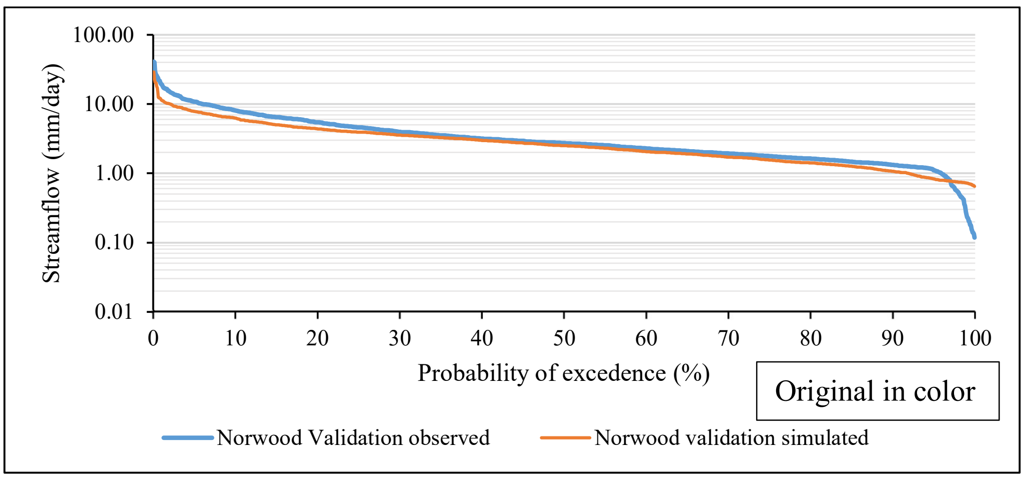


Figure 0-28 The logarithmic plot of observed and simulated flow duration curve for the validation period in Norwood sub-catchment

4.1.6.2 Flow duration curve analysis for the Holombuwa sub-catchment

The observed flow was separated for the calibration period (2008/2009-2012/2013) and validation period (2013/2014-2016/2017) for the Holombuwa sub-catchment. Then the respective data series was treated as an isolated series for the other computation processes. The daily flow was ranked by the ranking process and the probability of exceedance percentage was computed by using the Weibull (1951) formula. The normal plot and logarithmic plot have been presented.

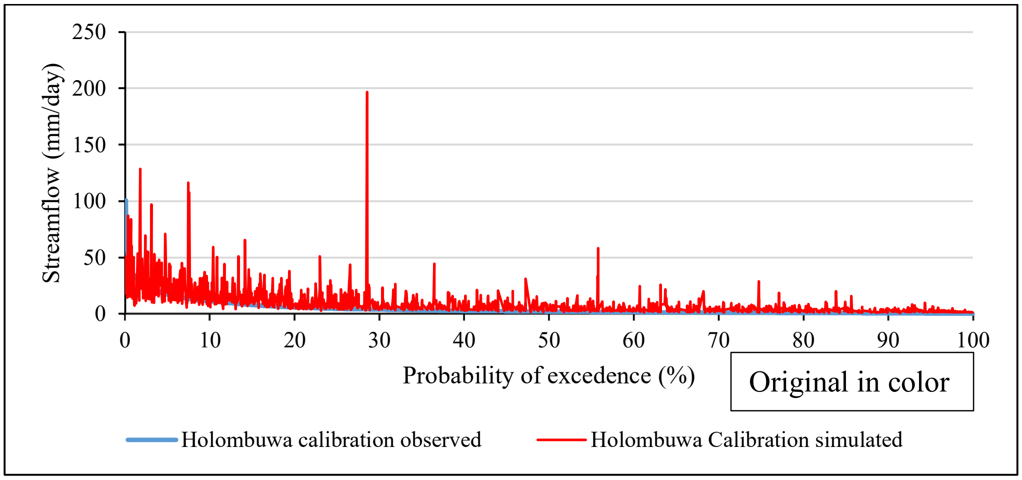


Figure 0-29 The Normal plot of observed and simulated flow duration curve for the calibration period at Holombuwa sub-catchment

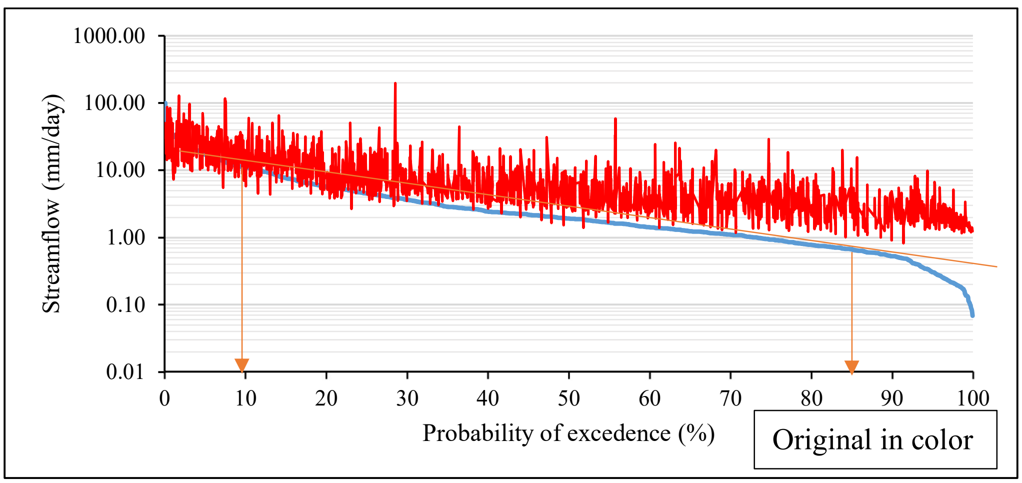


Figure 0-30The logarithmic plot of observed and simulated flow duration curve for the calibration period at Holombuwa sub-catchment

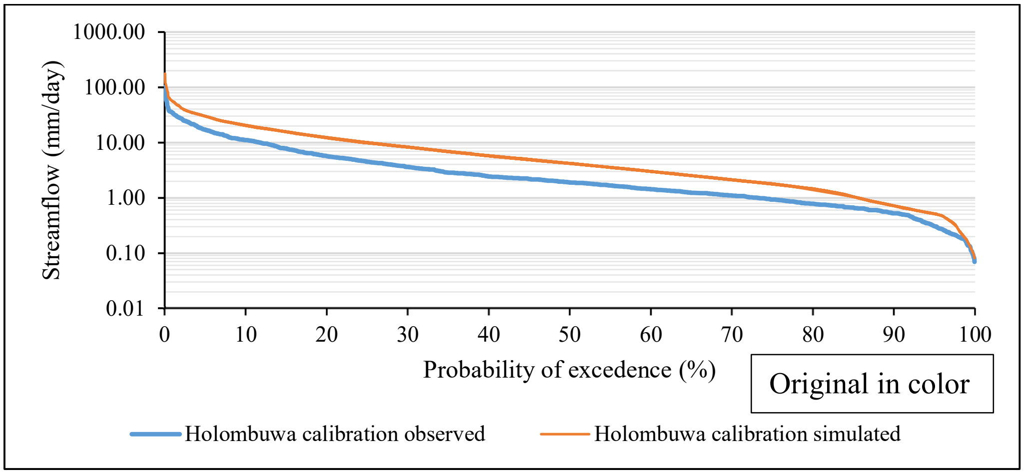


Figure 0-31 The logarithmic plot of observed and simulated flow duration curve for the calibration period at Holombuwa sub-catchment

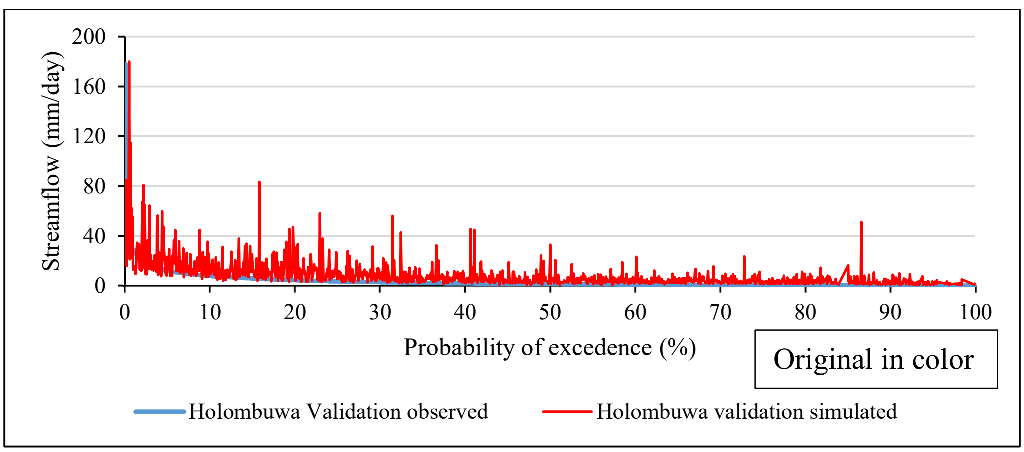


Figure 0-32 The Normal plot of observed and simulated flow duration curve for the validation period at Holombuwa sub-catchment

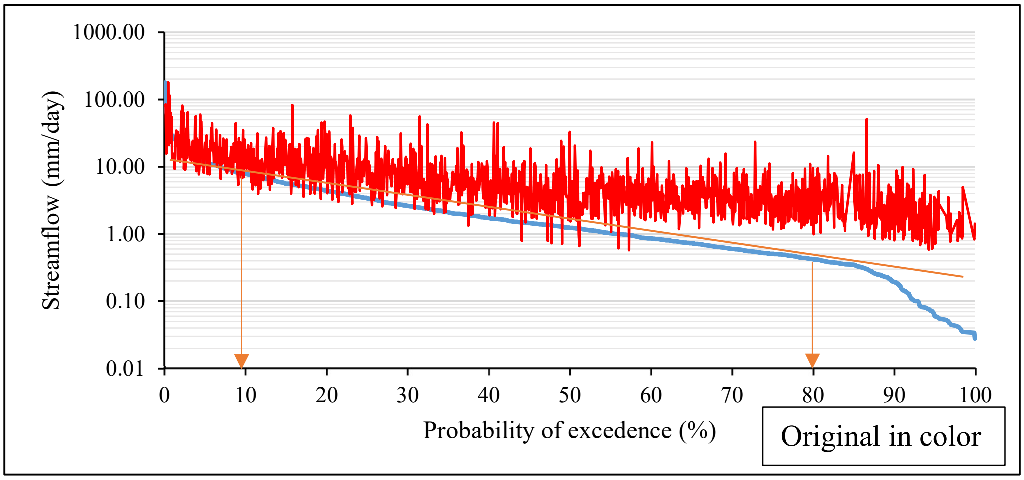


Figure 0-33 The logarithmic plot of observed and simulated flow duration curve for the validation period at Holombuwa sub-catchment

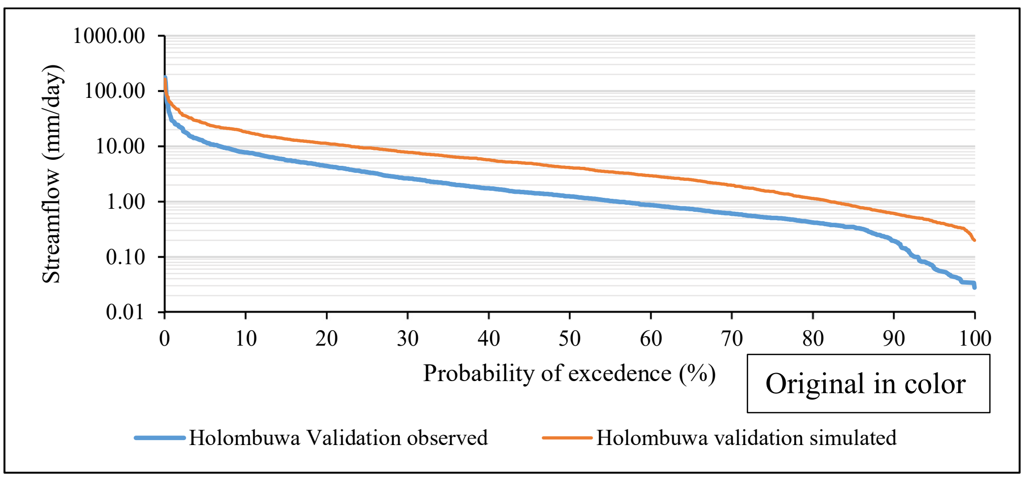


Figure 0-34 The logarithmic plot of observed and simulated flow duration curve for the validation period at Holombuwa sub-catchment

4.1.7 Annual Water Balance

The annual water balance was checked after model calibration and validation. The annual water balance was performed separately for calibration and validation periods. The annual water balance was estimated using Thiessen average rainfall, pan evaporation, streamflow observed and streamflow simulated, the resultant water balance between the observed and simulated water balance was calculated and plotted in the graph. Figure 4-35, Figure 4-

36, Figure 4-37 and Figure 4-38 show the annual water balance for the calibration and validation periods in both sub-catchments.

4.1.7.1 Annual water balance in Norwood sub-catchment

The annual water balance for the period of calibration and validation was conducted on the Norwood sub-catchment and the respective graphs were plotted accordingly. Figure 4-35 and Figure 4-36 show the annual water balance for calibration and validation periods in Norwood sub-catchment.

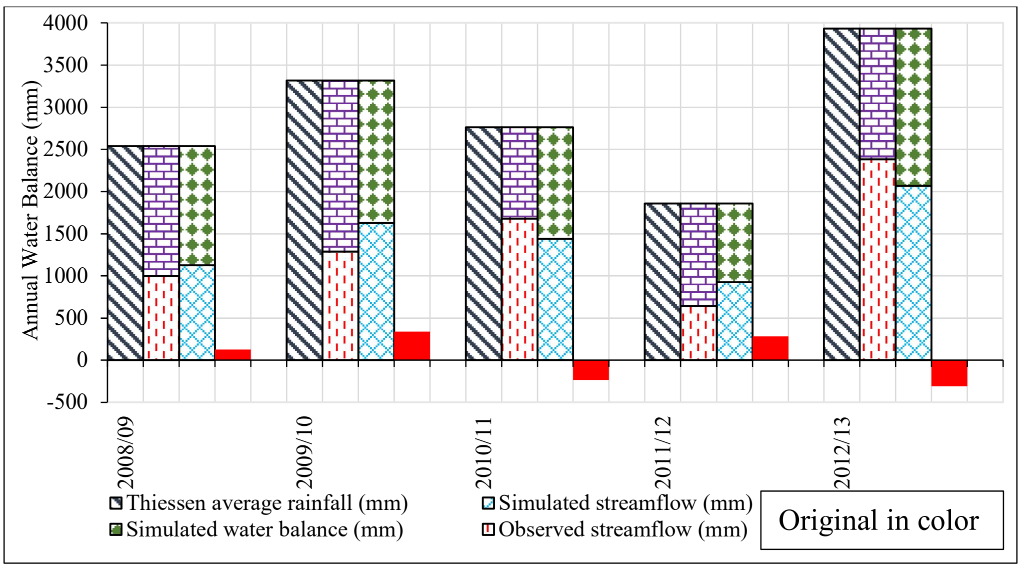


Figure 0-35 Annual water balance in Norwood sub-catchment for the calibration period

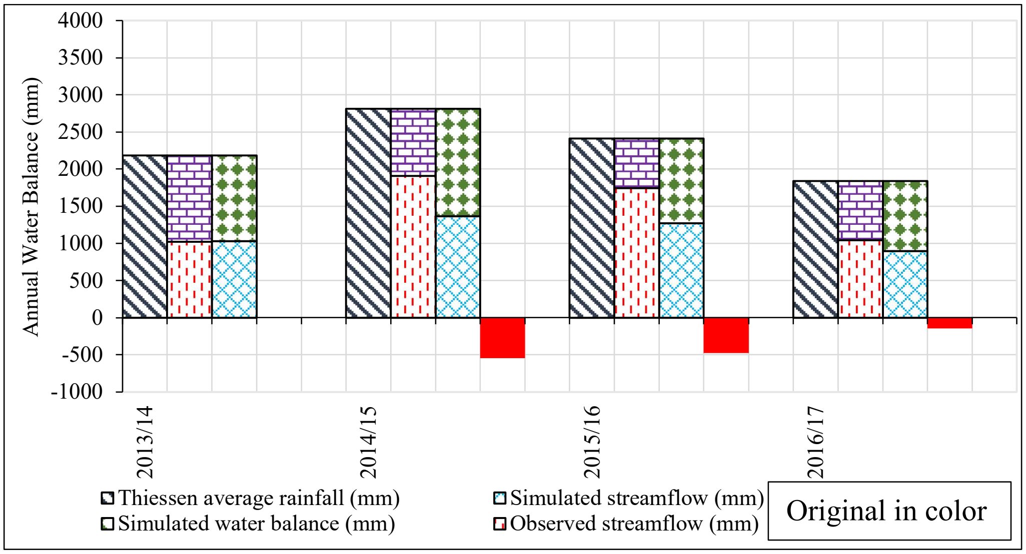


Figure 0-36 Annual water balance in Norwood sub-catchment for the validation period

4.1.7.2 Annual water balance in Holombuwa sub-catchment

The annual water balance for the period of calibration and validation was conducted in the Holombuwa sub-catchment and the respective graphs were plotted accordingly. Figure 4-37 and Figure 4-38 show the annual water balance during calibration and validation periods for the Holombuwa sub-catchment.

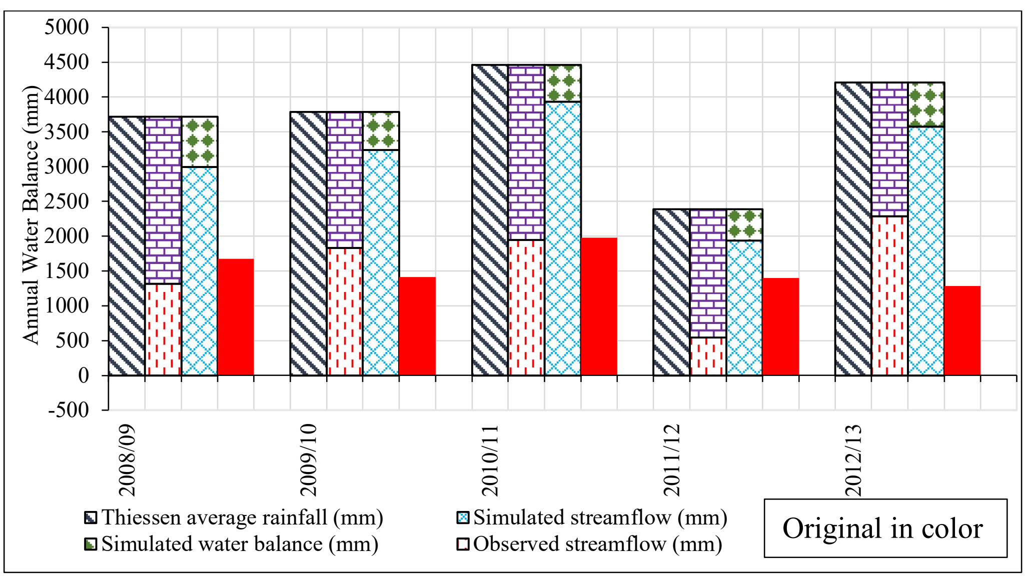


Figure 0-37 The annual water balance in Holombuwa sub-catchment for the calibration period

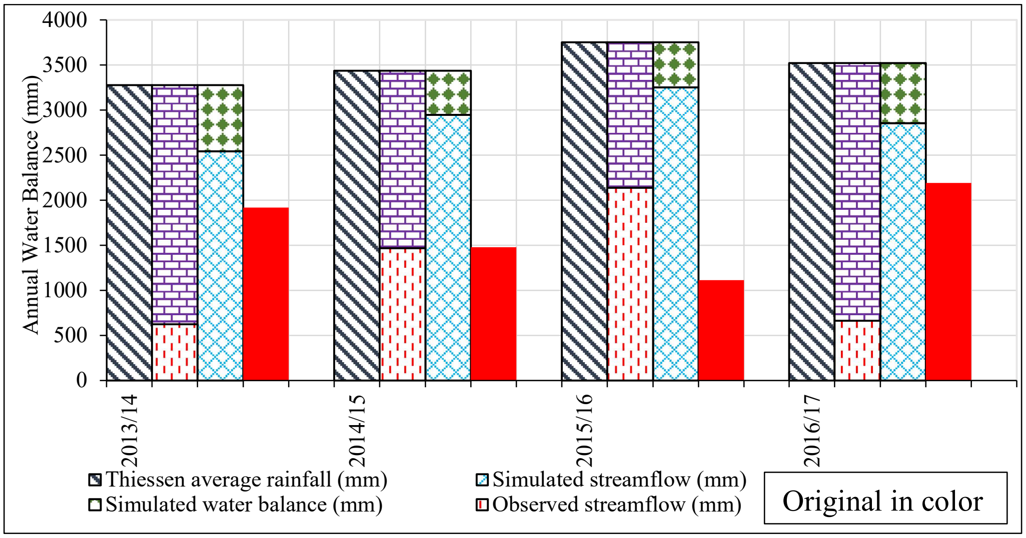


Figure 0-38 The annual water balance in Holombuwa sub-catchment for the validation period

4.1.8 Model Parameter Sensitivity Analysis

The model parameters are the main governing factors in the model contributing to the change in the average model simulation results. Hence, the analysis could be better performed by considering the sensitivity of the parameters and this achieved by changing the parameters one-at-a-time for each model parameter. The initial value of groundwater storage and initial soil moisture storage had no effect on modelling when used in the ABCD hydrological lumped model (Marinou, Feloni, Tzoraki, & Baltas, 2017). Hence, considering one-at-a-time process for each model parameter, a sensitivity analysis was conducted to determine the effect and characteristics of the model parameters in both sub-catchments. Figure 4-39 to Figure 4-42 show the graphs for the parameter sensitivity in both sub-catchments.

4.1.8.1 Model parameter sensitivity analysis for Norwood sub-catchment

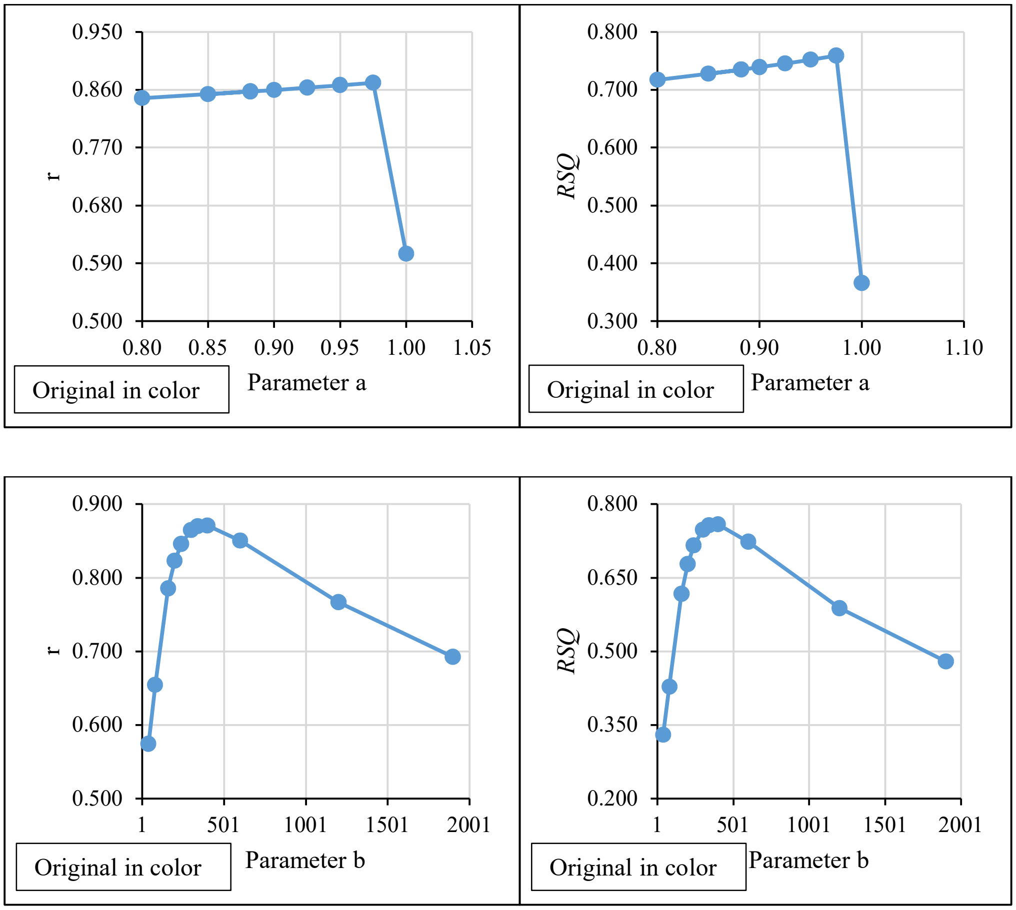
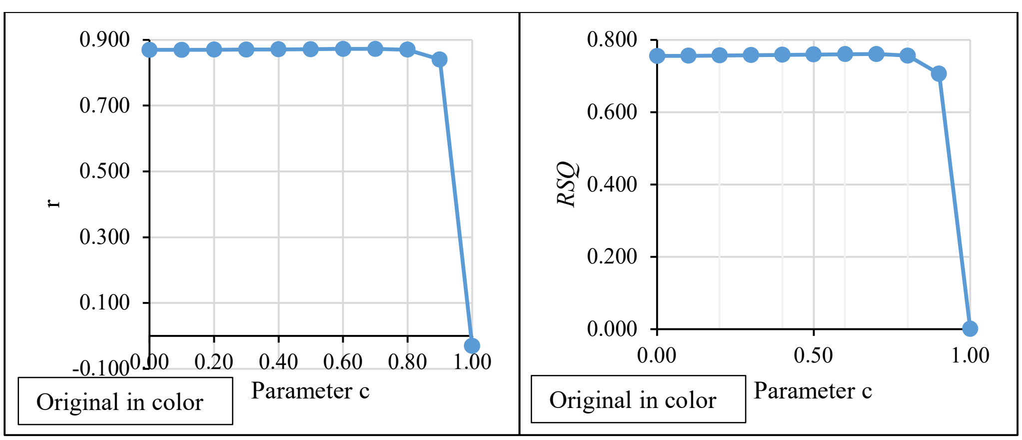


Figure 0-39 Sensitivity of the parameter *a* and *b* in Norwood sub-catchment



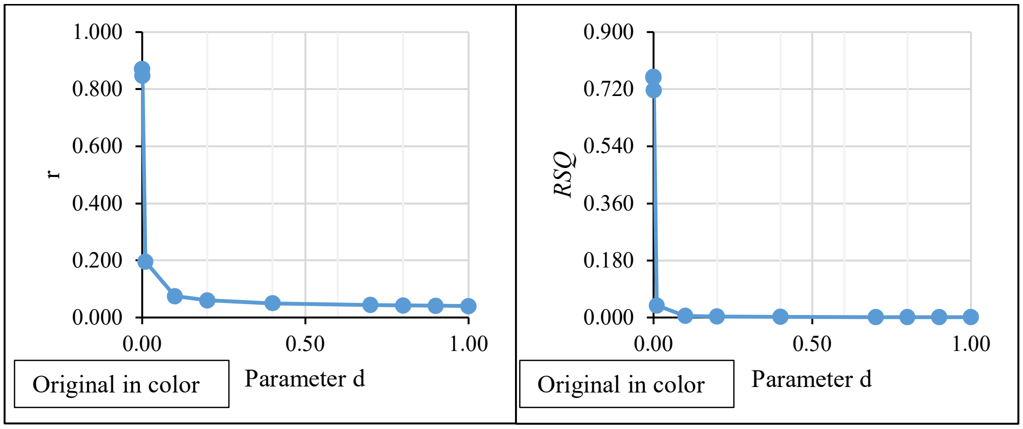


Figure 0-40 Sensitivity of the parameter *c* and *d* in Norwood sub-catchment

4.1.8.2 Model parameter sensitivity analysis for Holombuwa sub-catchment

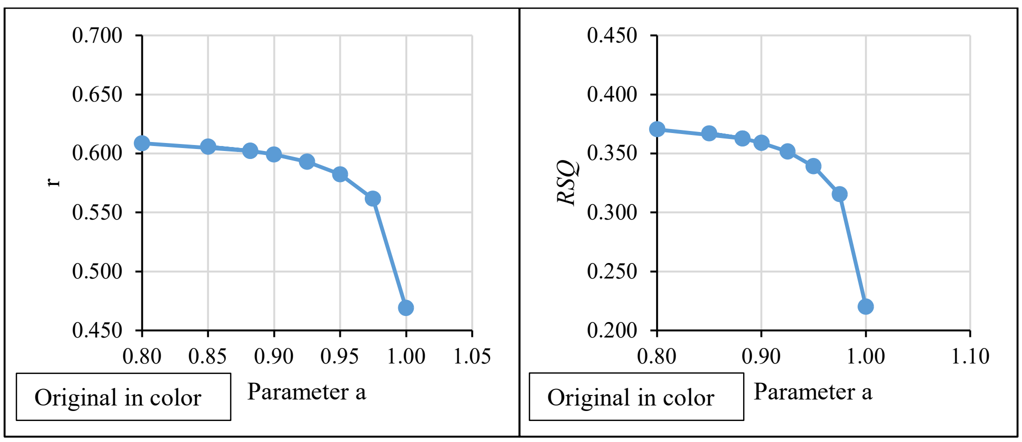
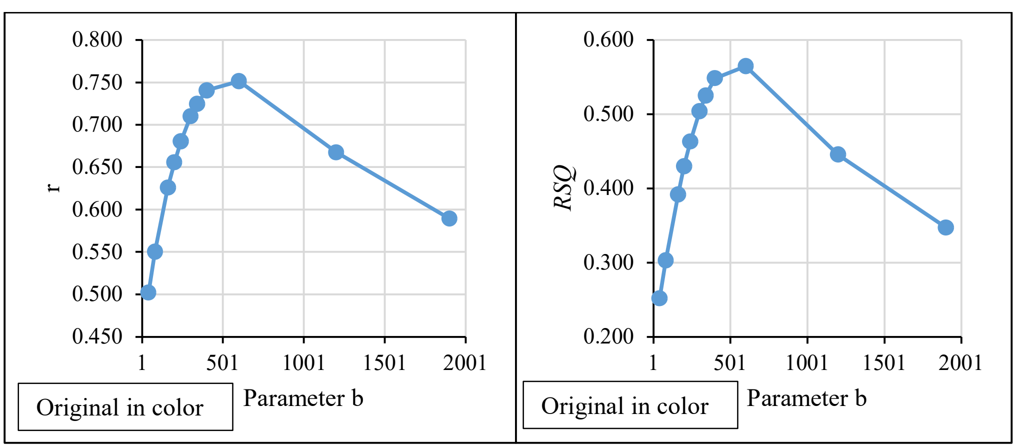


Figure 0-41 Sensitivity analysis of parameter *a* at Holombuwa sub-catchment



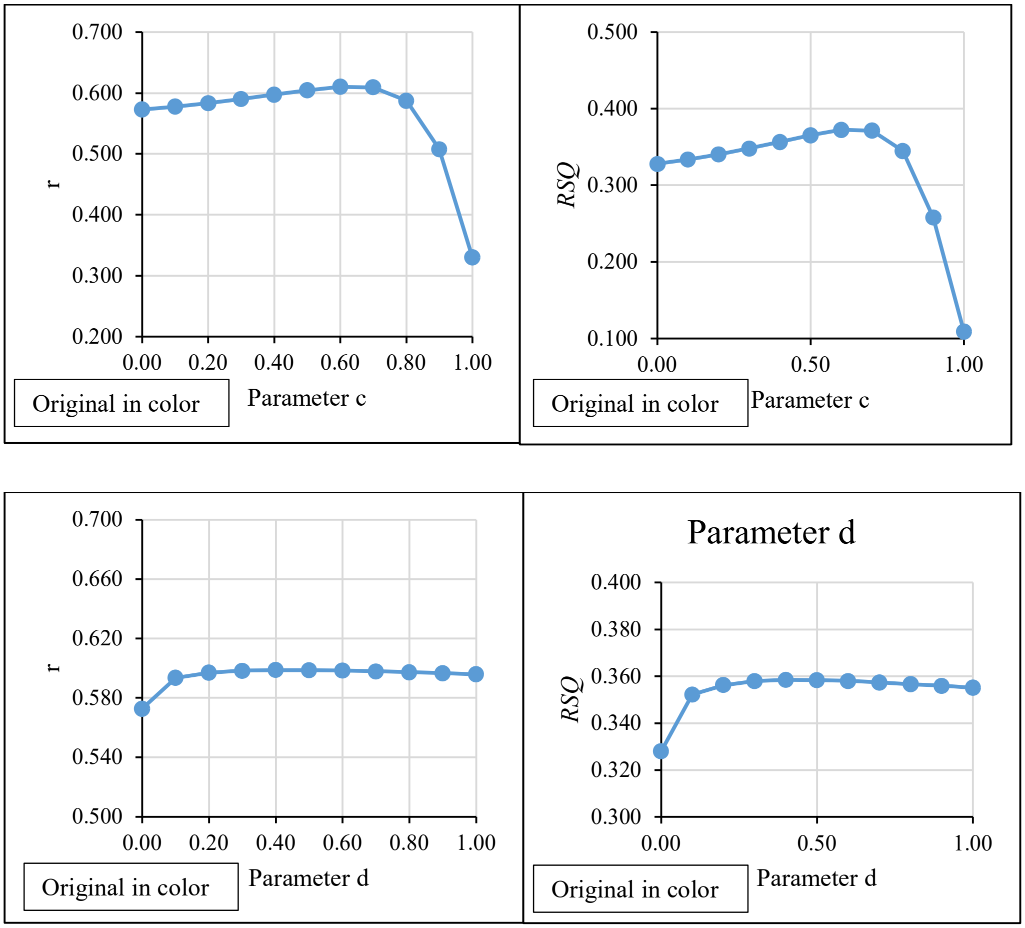


Figure 0-42 Sensitivity analysis of the parameter *b*, *c,* and *d* in Holombuwa sub-catchment

4.2 GIS Analysis

4.2.1 Introduction to Results from Overall GIS Analysis

After the initial literature survey for the methodology and associated research findings, the GIS analysis was started based on the literature survey for the suitable selection of the Digital Elevation Model (DEMs). During the literature survey, it was found that different literature suggested different DEMs for the analysis of gross head in the study.

Hence, in the present study, the initial analysis, flow direction, sink fill, flow accumulation, stream network generation and watershed demarcation were carried out by using three different DEMs. The used DEMs were the Shuttle Radar Topography Mission (SRTM) 30 m and 90 m resolution and the other was the Advance Spaceborne Thermal

Emission and Reflection Radiometer (ASTER) 30 m resolution DEMs. The details of the findings have been discussed in the following chapter.

4.2.2 Digital Elevation Model Interpretation and Comparison with Agrarian Basin Map

For the initial stage of the demarcation of the watershed, three available DEMs were analyzed by comparing with the basin maps produced by the Agrarian Services Department (ASD), Sri Lanka. The results of the comparisons found that SRTM 90 m DEM gives better results in the overall watershed generation, but very less accuracy in the elevation profile determination. The SRTM 30 m resolution DEM provides good results for the elevation profile determination but when producing the watershed, it shows more discrepancies in the map when compared with the ASD maps. The ASTER DEM gives comparable results where the elevation accuracy is better but after reaching the medium flat area, it shows a higher deviation in streamflow paths as compared to the ASD maps. Hence, the maps generated from the ASTER DEMs have not been presented here. The results from the SRTM 30 m and 90 m resolution DEMs have been presented in Figure 4-43 and Figure 4-44. Finally, comparing overall accuracy, the SRTM 30 m resolution DEM was selected for the gross head determination process.

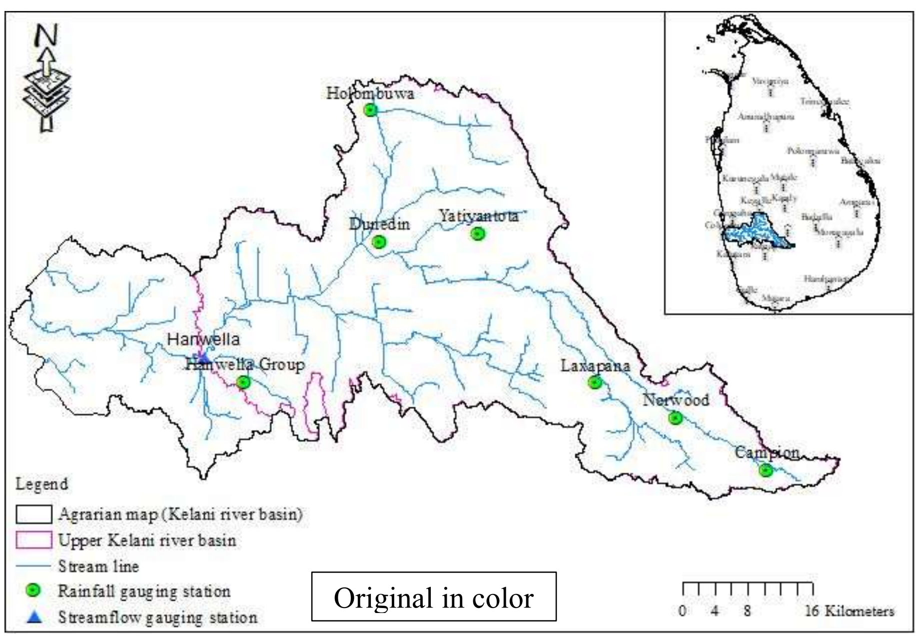


Figure 0-43 The map generated from using the SRTM 30 m resolution Digital Elevation Model (DEM)

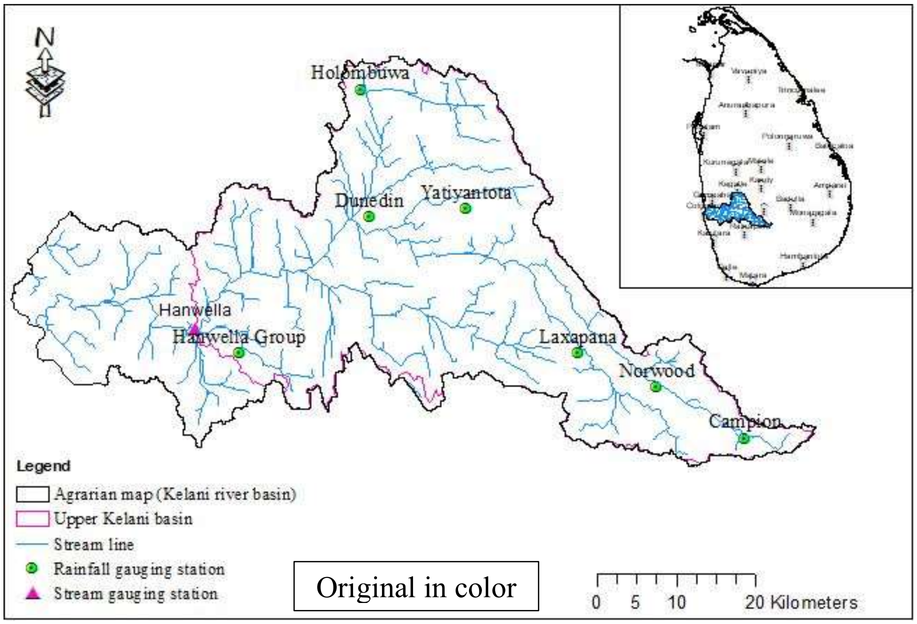


Figure 0-44 The map generated from using the SRTM 90 m resolution Digital Elevation Model (DEM)

4.2.3 Stream Network Generation and Watershed Delineation

The stream network was initially generated from the three DEMs (SRTM 30 m, SRTM 90 m and ASTER 30 m) as discussed in the Chapter 4.2.2. All the processes were undertaken in the ArcGIS 10.3 (ESRI, USA), using Spatial Analyst Tools in Arc Hydrology Tools.

Initially, all the steps were executed for both SRTM 30 m and 90 m resolution DEMs but after finding more inaccuracies in the head parameter from the 90 m DEM, its further analysis was stopped. All the maps prepared from the SRTM 30 m DEM has been shown in Figure4-45 to Figure 4-49.

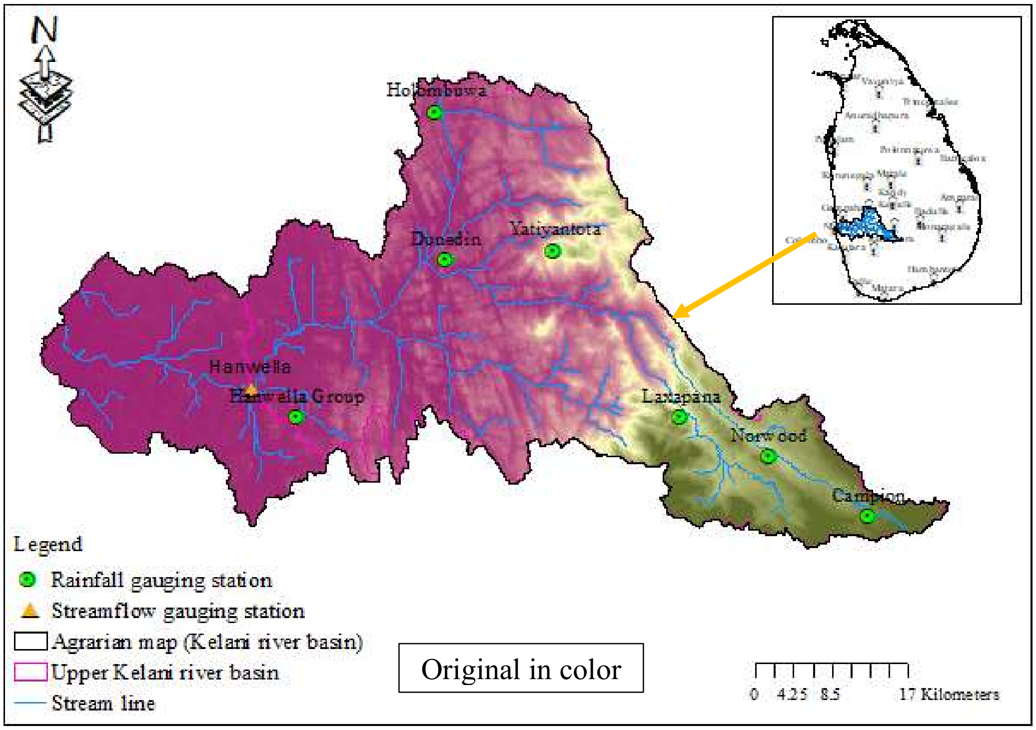


Figure 0-45 The SRTM 30 m DEM for the Kelani river basin

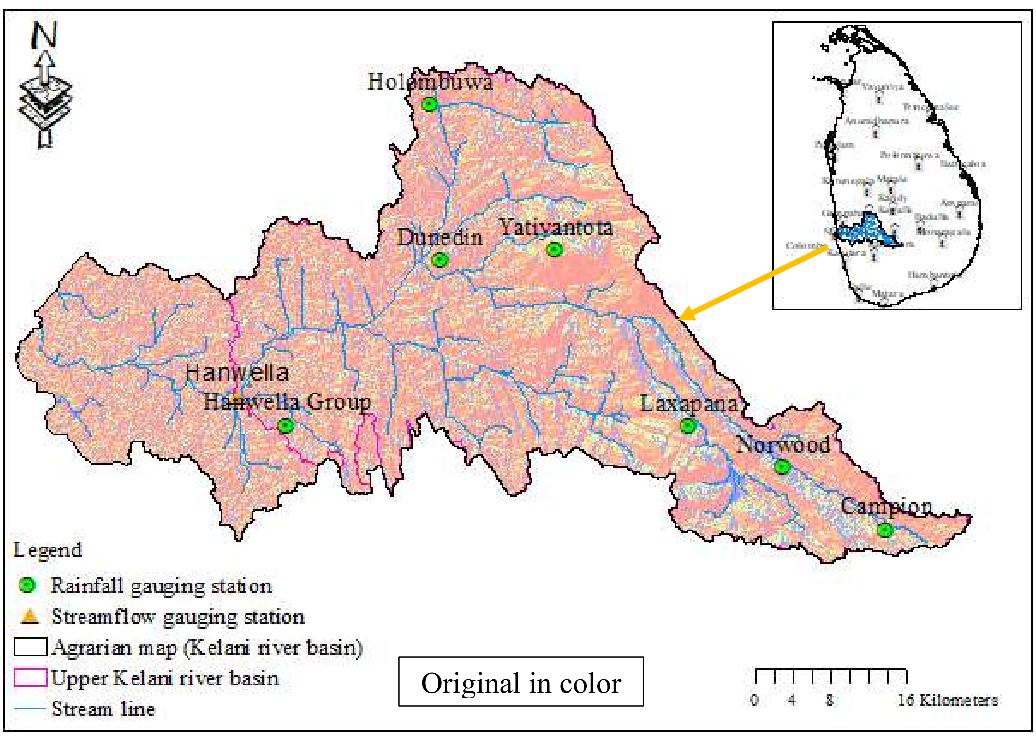


Figure 0-46 Flow direction map (before filling) of the Kelani river basin

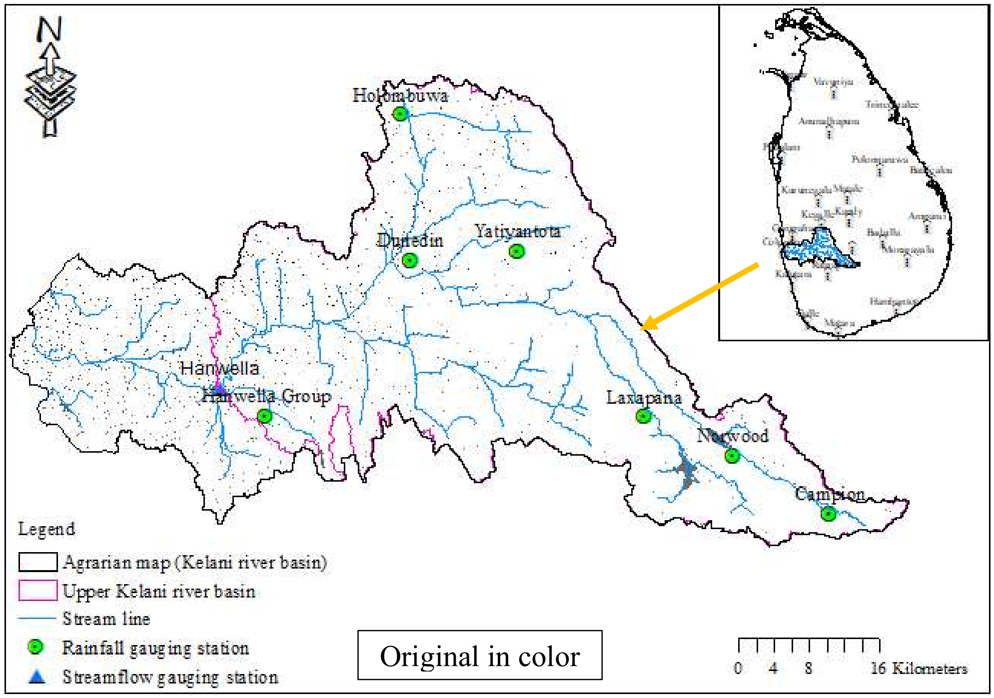


Figure 0-47 The sink map of the Kelani river basin

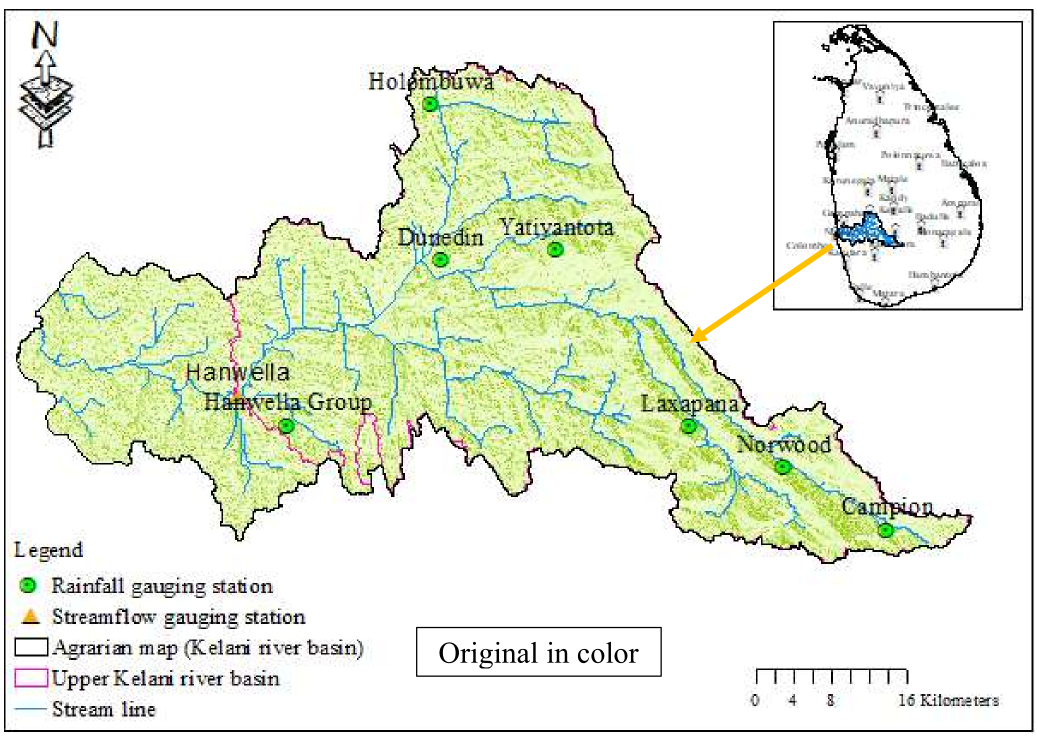


Figure 0-48 The flow direction map for the filled DEM

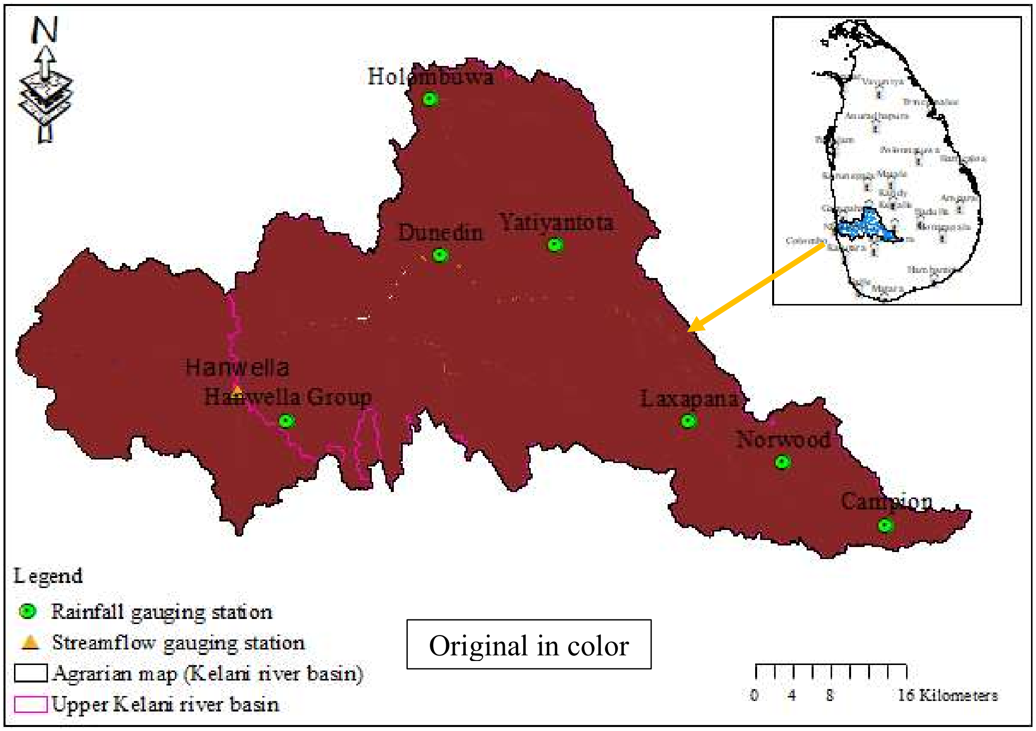


Figure 0-49 The flow accumulation map of the Kelani basin

The remaining upper Kelani basin maps and the streamlines have been shown on each map except in the flow accumulation map.

4.2.4 Head Extraction in River Bed Profile

Initially, the raster layer of stream file was converted from the stream to feature option from the hydrology tool and then the river section was merged for the required length of the study area and converted to a single river section. Construct point tool was used to determine the 100 m difference sections along the river section. For that, the identified points along the river section, XY coordinates were added from the data management tool in the ArcGIS. After locating the co-ordinate, the elevation parameters were added to that point from the 3D Analyst tool, Functional surface and Add surface tools. The results of the identified gross head have been presented in Figure 4-51 for the SRTM 30 m DEM and Figure 4-52 for the SRTM 90 m DEM. Figure 4-51 and Figure 4-52 have been presented for the comparison purpose. For the rest of the calculation of gross head, SRTM 30 m resolution data were used.

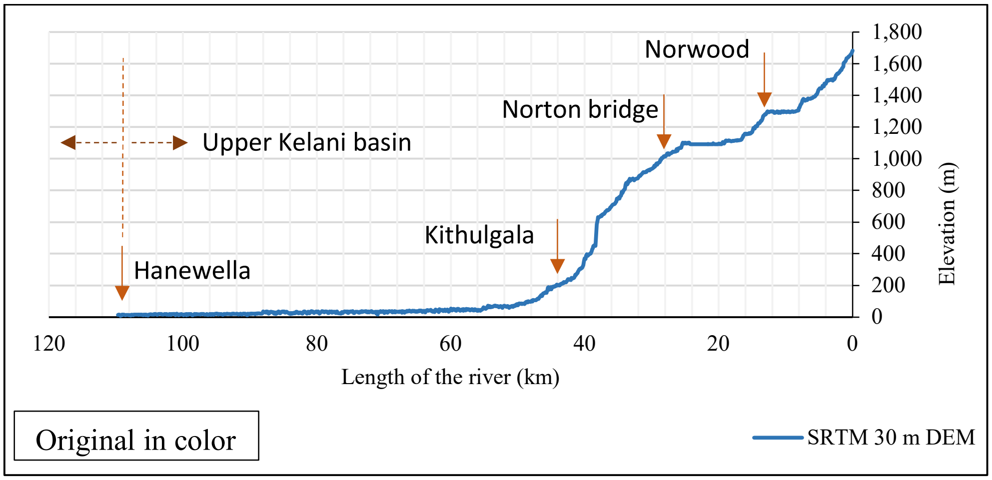


Figure 0-50 The river profile from the SRTM 30 m resolution DEM

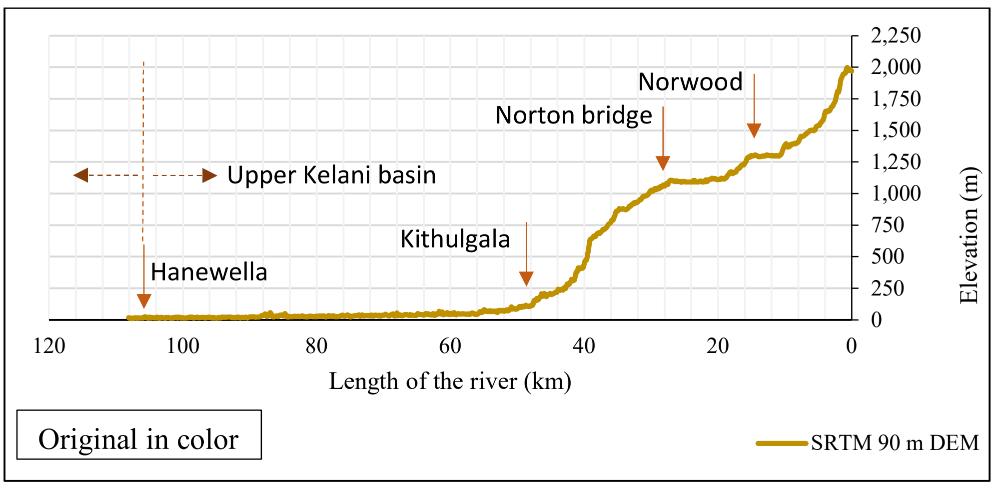


Figure 0-51 The river profile from the SRTM 90 m resolution DEM

4.2.5 Suitable Locations for the Hydropower Analysis (Gross Head Criteria)

For the identification of the gross head-on the river profile, the selected criteria were used as per those defined in Chapter 2.8 in the literature review section and as per the developed methodology. From using this methodology, initially 46 sites were identified and the flow was computed for those identified points. Further, as per the methodology developed, low flow points were discarded and only the technically feasible points were selected and presented. Hence, the points suitable based on the criteria of head and flow were further analyzed for the further additional classification of the hydropower generation capacity available at particular selected the river section.

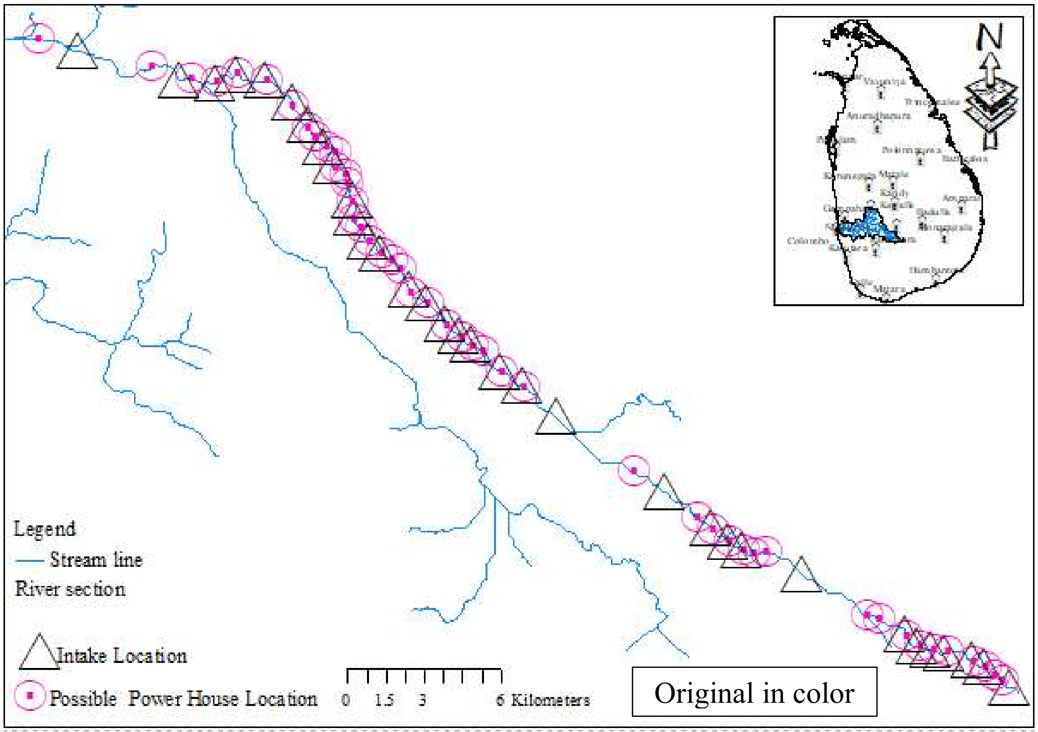


Figure 0-52 The possible hydropower intake locations in the Upper Kelani basin

Figure 4-52 shows the zoomed view of some of the identified points as per the gross head criteria for the location of the hydropower site selection. Further, the possible locations were analyzed from the criteria of the flow and only the points with both conditions satisfied were marked as the potential Run-of the-River hydropower points.

Figure 4-53 shows more specifically zoomed view for the identified locations for the intake structures and the powerhouse locations. Further, Figure 4-54 shows the overall presentation of the availability of the powerhouse locations and intake locations.

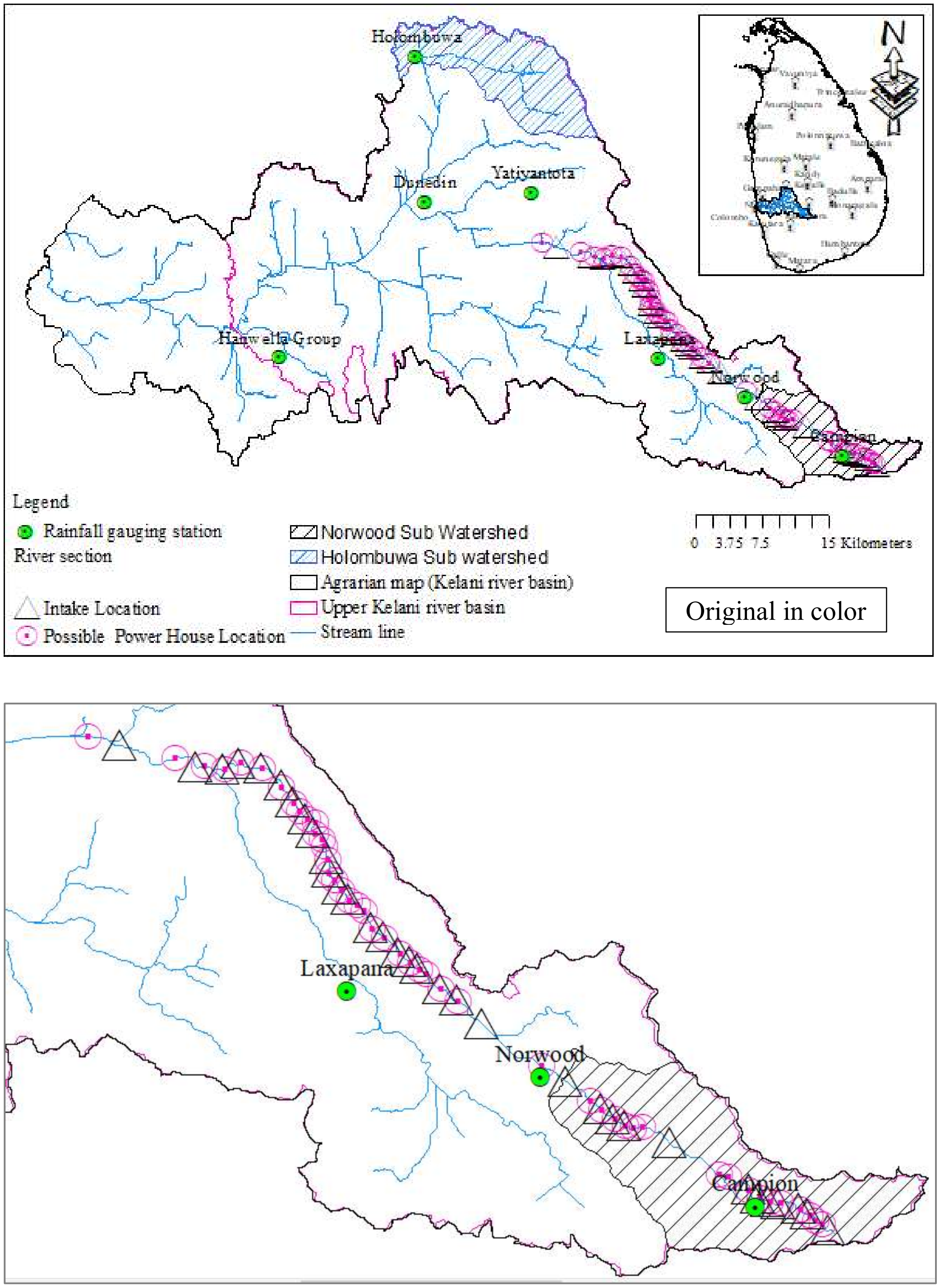


Figure 0-53 The total hydropower locations and intake stations identified in the Upper Kelani river basin

4.3 Suitable Locations for Hydropower Sites

The first set of criteria were to identify the available head at the river section, which was as concluded in Section 4.2.5, i.e. the available head above 25 m and the points were only selected to satisfy the additional conditions that the minimum distance between two consecutive stations is 500 m and the distance between intake and powerhouse should not be more than 2000 m. Hence, after establishing the successful possible hydropower locations from the gross head criteria, the ABCD model was established for estimating flow at each point where the head was identified. As per the developed methodology and criteria, those points where the flows more than 0.5 m^3/s for the Q_{95} dependable flow were available were selected. Initially, 46 sites were found from the head criteria but later after checking against the flow criteria, only 37 locations were found as the possible locations of the RoR hydropower installations. Details of the results have been shown in Table 4-5. Altogether, 46 Flow Duration Curves (FDC) were prepared for each identified site. Figure 4-54 to Figure 4-57 show the details of all FDCs for the selected points.

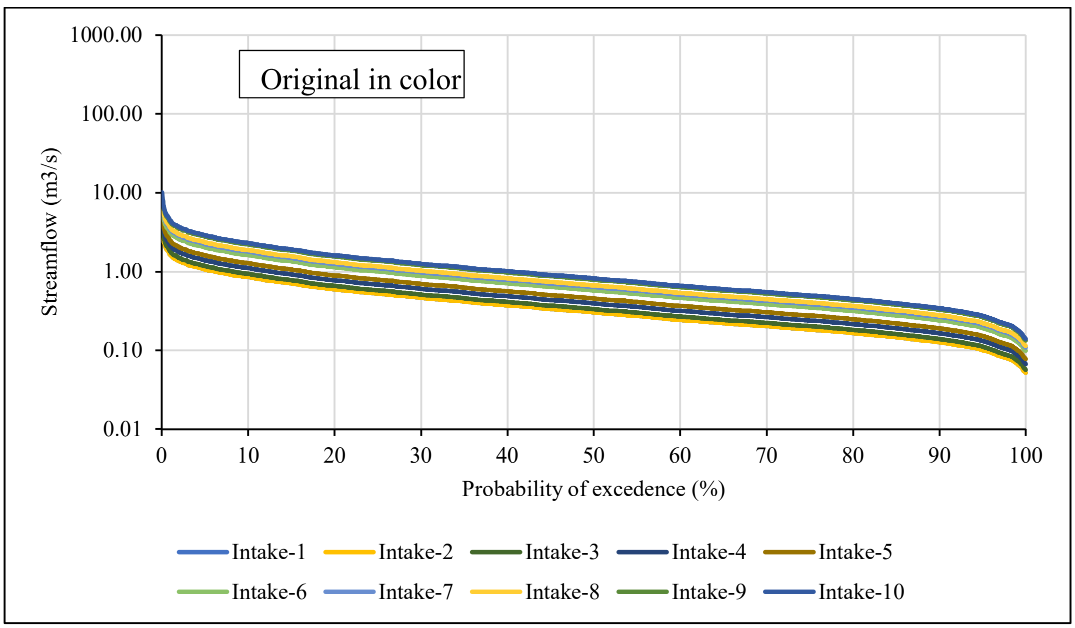


Figure 0-54 Flow duration curve for the identified points from Intake-1 to Intake-10

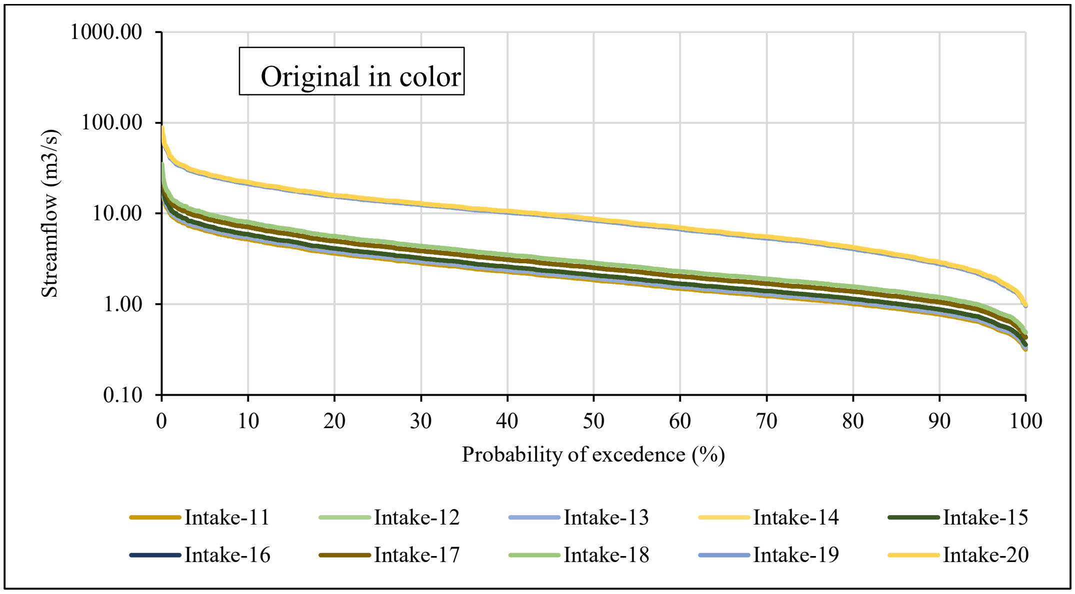


Figure 0-55 Flow duration curves for the identified point from Intake-11 to Intake-20

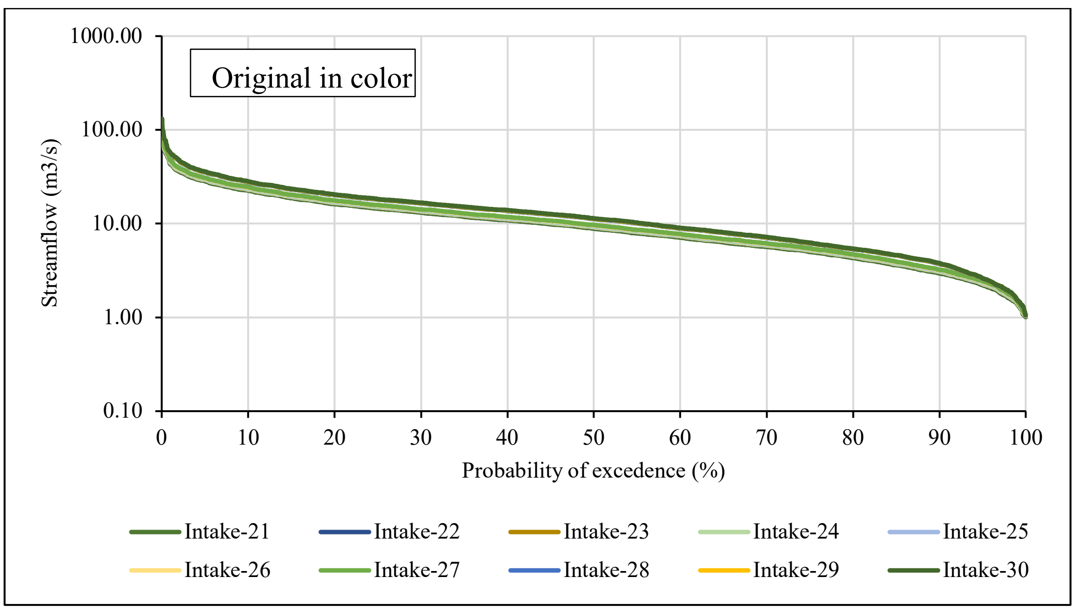


Figure 0-56 Flow duration curves for the identified point from Intake-21 to Intake-30

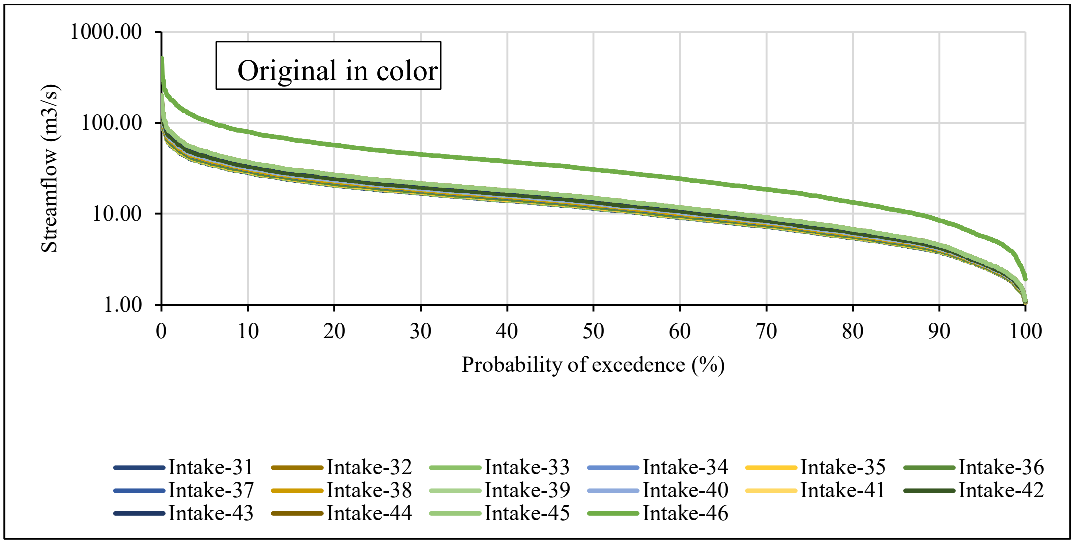


Figure 0-57 Flow duration curves for the identified points from Intake-31 to Intake-46

Table 0-5 The potential hydropower locations from the final results of the analysis

Power House No.	Chainage	Coordinate X	CoordinateY	Catchment Area (km^2)	Dependable Flow Q_{95}, (m^3/s)	Power (kW)	Power (MW)
Power House 1	08+010	490,236.26	477,251.93	27	0.28	111	0.11
Power House 2	13+020	486,267.95	479,711.93	61	0.64	137	0.14
Power House 3	13+070	485,792.80	479,651.93	64	0.67	188	0.19
Power House 4	14+020	485,414.93	479,801.93	64	0.67	142	0.14
Power House 5	14+090	484,851.62	480,131.93	69	0.73	201	0.20
Power House 6	15+080	484,192.70	480,586.67	69	0.73	167	0.17
Power House 7	16+060	483,589.56	481,061.93	83	0.87	231	0.23
Power House 8	20+010	481,065.73	482,891.93	83	0.87	181	0.18
Power House 9	25+090	476,814.67	486,164.70	94	0.99	218	0.22
Power House 10	27+010	475,944.77	486,791.93	142	2.16	540	0.54
Power House 11	28+040	475,175.43	487,563.94	148	2.26	510	0.51
Power House 12	28+090	474,795.73	487,811.93	151	2.30	553	0.55
Power House 13	29+050	474,349.99	488,141.93	153	2.35	506	0.51
Power House 14	30+030	473,797.41	488,611.96	154	2.36	492	0.49
Power House 15	31+060	473,030.30	489,439.07	155	2.38	573	0.57
Power House 16	32+050	472,390.89	489,898.48	159	2.45	582	0.58
Power House 17	33+060	471,973.69	490,825.67	161	2.47	522	0.52
Power House 18	34+010	471,609.84	491,111.93	163	2.50	773	0.77
Power House 19	34+060	471,221.68	491,381.93	172	2.71	873	0.87
Power House 20	35+030	470,790.79	491,861.93	173	2.72	839	0.84
Power House 21	36+000	470,427.44	492,391.88	174	2.73	639	0.64
Power House 22	36+050	470,157.44	492,727.33	175	2.74	605	0.61
Power House 23	37+030	470,114.42	493,434.95	176	2.75	614	0.61
Power House 24	38+010	469,917.44	494,128.50	176	2.75	723	0.72
Power House 25	38+060	469,811.87	494,517.50	178	2.77	3768	3.77
Power House 26	39+010	469,444.38	494,794.98	178	2.77	1110	1.11
Power House 27	39+090	469,437.44	495,390.27	180	2.79	825	0.82
Power House 28	40+040	469,046.38	495,551.93	185	2.84	1298	1.30
Power House 29	41+010	468,631.42	495,967.95	186	2.86	784	0.78
Power House 30	41+060	468,357.44	496,336.89	190	2.91	709	0.71
Power House 31	42+080	467,727.44	497,188.07	191	2.91	700	0.70
Power House 32	44+040	466,749.83	498,161.93	192	2.96	653	0.65
Power House 33	45+070	465,621.67	498,431.93	195	2.96	981	0.98
Power House 34	46+080	464,791.31	498,105.80	207	3.09	766	0.77
Power House 35	48+000	463,754.46	498,251.93	209	3.12	672	0.67
Power House 36	50+000	462,237.72	498,702.21	210	3.12	658	0.66
Power House 37	55+040	457,791.29	499,781.93	411	5.89	1290	1.29

DISCUSSION

5.1 Hydrological Model

The selected hydrological model was the ABCD non-linear model, which was successfully calibrated and validated in the uppermost two sub-catchments in the Upper Kelani river basin. The main objective of the model application in the two sub-catchments was to evaluate the possibility of model parameter transferability with better performance of the model considering the spatial variability within the catchments. Hence, it helped obtaining better results by averaging the model parameters in the basin. The details of model selection, model development and identifying its behaviour in the sub-catchments have been discussed in subsequent Section 5.1.1 to 5.1.5.

5.1.1 Hydrological Model Selection

The application of the hydrological model is to generate the synthetic river flows for the hydropower generation. In data scarce regions, where the measured stream runoff data are not available in the required locations, it provides a way of replacing measurement data in the section of the river, and hence, it help overcoming this challenge. The hydrological model plays a crucial role to compute the streamflow at the desired location in the basin. This helps to identify the required quantity of the flow at the specific point of the basin.

Being one of the major parameters of the hydropower design, the simulation of the streamflow should be accurate to represent reality with reasonable accuracy. Finding simulated streamflow to the closest possible to the reality or the hypothetical or missing observed streamflow plays an important role in establishing the potential hydropower. Further, for finding such a good result with the influences of time, data availability, application and basin characteristics add more to the complexity in the model selection process. Another main consideration is the model parameters and previous results if any for the same catchment plays a crucial part in the selection process. Rinsema, Franks and Mekonnen (2014) defined that when selecting the inflow model for estimating the flow at a hydropower production site, it depends on the experience of the modeller. The selection of the model differs in each catchment.

Rinsema et al. (2014) evaluated three (3) lumped models for determining the inflow for the hydropower development, and showed that the Four- parameter GR4J model produced the best results in the catchment. For the study in the Kelani river basin focusing on hydropower generation, the lumped Four-parameter ABCD model was selected, by considering its applicability to produce the river flow, availability of the data and model efficiency for the desired purpose.

5.1.2 Model Inputs

The basic inputs of the model were the rainfall and potential evaporation of the area. Among these major inputs, the rainfall was collected and analyzed, but for the computation of the potential evapotranspiration, the minimum and maximum temperature and average temperature were used based on Hargreaves and Samani (1985). For the model calibration and verification purposes, the observed streamflow records were used for both the sub-catchments. The details of each input have been discussed correlating to the literature and used model inputs for the model developments.

5.1.2.1 Rainfall gauging station locations

The rainfall gauging stations were optimally tried to locate inside the modelled catchment for both Norwood and Holombuwa sub-catchments considering the optimum uniform distribution of rainfall over sub-catchment and availability of the gauging stations. For the Norwood sub-catchment, the selected stations fall inside the sub-catchment area but for the Holombuwa sub-catchment the two stations were not available inside the sub-catchment, hence, one was taken at the end of the sub-catchment and the other was taken at the outside of the catchment area. Hence, for this reason, the selected rainfall was checked with the long-term isohyetal maps and the result shows only 5% variation for the long-term average annual isohyetal rainfall and selected Thiessen average rainfall. Figure 5-1 shows the variation of the isohyetal rainfall for the Kelani basin and from that Norwood and Holombuwa basins were selected and for each sub-cacthment, the average rainfall was calculated.

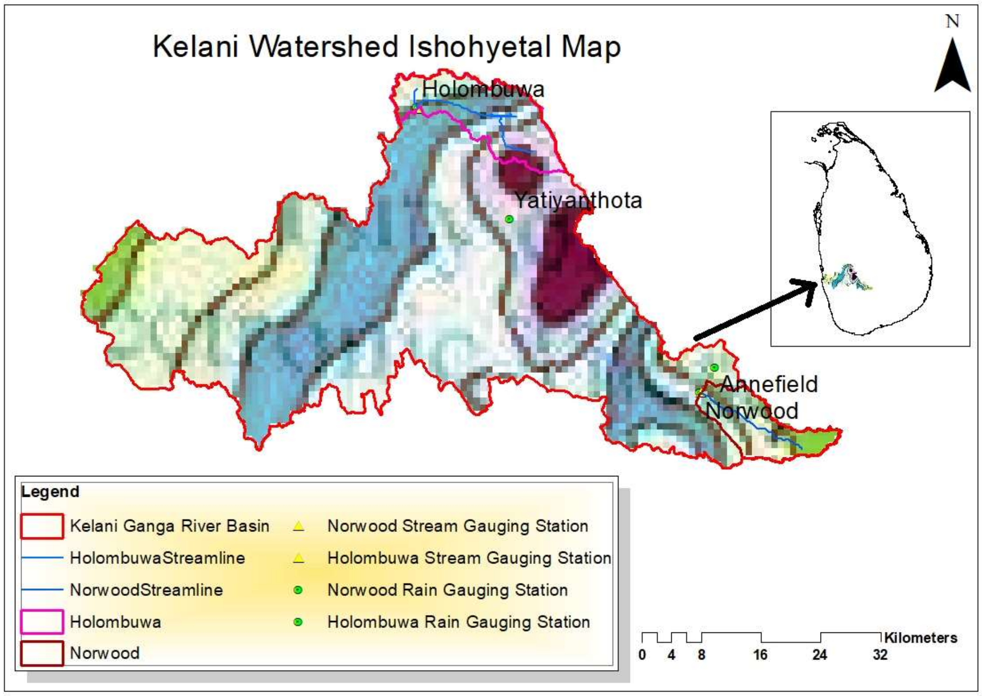


Figure 0-1 The long-term isohyetal rainfall for the Kelani river basin

5.1.2.2 Thiessen average precipitation

Precipitation is one of the main inputs for the hydrologic simulation. The precipitation data were collected for the different gauging stations for each simulated sub-catchment and during the model application, data from another three stations was collected considering the guidelines given by the WMO (2009), and checking the isohyetal maps of the precipitation variation in the region. The precipitation averaging method was reviewed during the literature survey. The finding of the literature for the rainfall averaging was the Thiessen averaging method. Here, in this study for the modelling of Norwood sub-catchment, two rainfall gauging stations were considered namely Norwood and Campion. And for the Holombuwa sub-catchment, another two rainfall stations were considered namely Holombuwa and Yatiyanthota stations. Further, for the model application, another three stations were considered along with the rainfall stations considered for the model calibration and validation. The catchment rainfall density maps were checked to assure the realistic representation of the averaged data. Hence, as per the findings from the literature, Thiessen rainfall averaging method was used for rainfall spatial averaging. The Thiessen averaging was carried out using the ArcGIS (V10.3).

The Thiessen average map of the Norwood sub-catchment was presented as shown in Figure 3-5 and respective Thissen weights were tabulated in Table 3-12. From the selected stations, Norwood was towards the upstream end of the catchment and Campion was in the upper mid part of the sub-catchment. According to the Thiessen weights, Norwood and Campion rainfall stations contribute 0.3 and 0.7, respectively.

The Thiessen average map of the Holombuwa sub-catchment was presented as shown in Figure 3-6 and respective Thissen weights were tabulated in Table 3-13. From the selected stations, Holombuwa was at the upstream end of the catchment and Yatiyanthota was located outside of the sub-catchment area but it falls within the same isohyetal zone for the upper part of the Holombuwa sub-catchment. Hence, even though it was taken at the downside of the catchment, it is presumed that there is no influence due to the selection of the rain gauge stations. According to the Thiessen weights, the Holombuwa and Yatiyanthota rainfall stations contribute 0.67 and 0.33, respectively.

For the model application, an extra three rainfall stations were considered along with the stations initially considered for the model calibration and validation to cover the whole of Upper Kelani basin. The Thiessen average map of the Upper Kelani basin was presented in Figure 3-9 and respective Thissen weights were tabulated in Table 3-14. From the selected stations, Dunedin has the highest and Campion has the least Thiessen weights for the rainfall averaging. These values were 0.23 and 0.04, respectively.

The annual average rainfall of the Norwood and Holombuwa sub-catchments were found to be 2,726 mm and 3,016 mm, respectively. An analysis on seasonal rainfall variation (based on the four-seasons) on the Thiessen rainfall was also carried out after the filling in the missing data and correction of the rainfall series. The results of the seasonal variation in the Norwood and Holombuwa have been shown in Figure 5-2 and Figure 5-3.

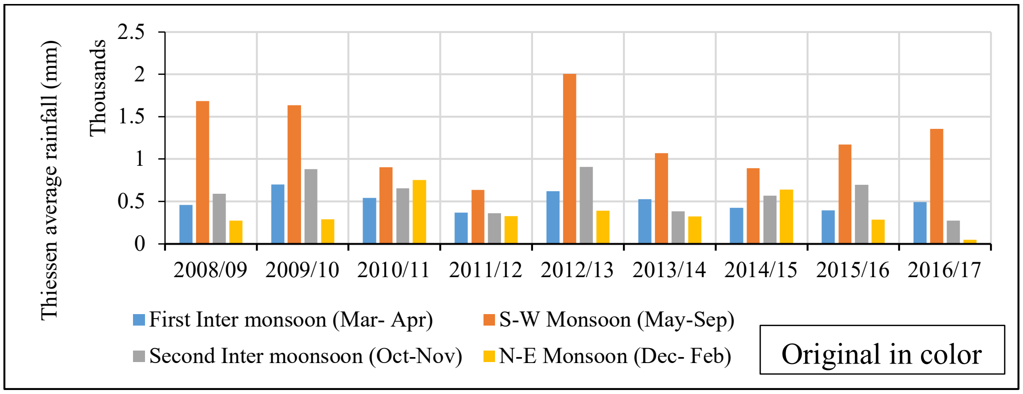


Figure 0-2 Thiessen average seasonal rainfall in the Norwood sub-catchment

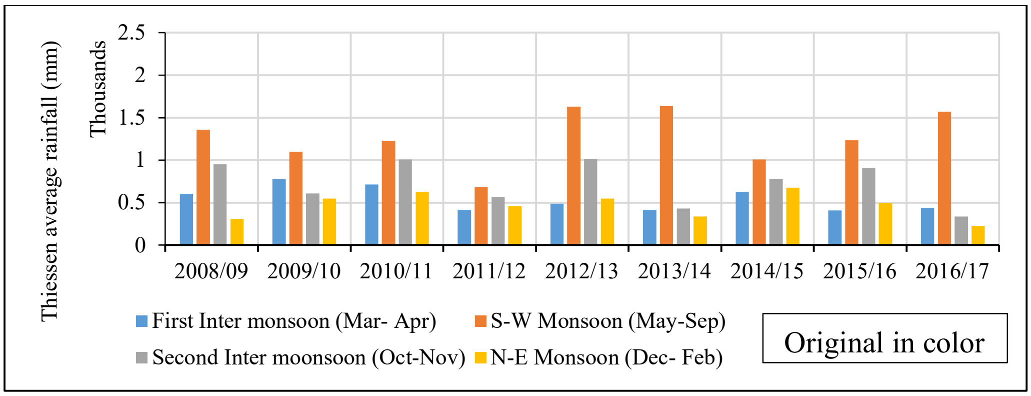


Figure 0-3 Thiessen average seasonal rainfall in the Holombuwa sub-catchment

The seasonal variation of the rainfall makes an influence on the availability of the streamflow and seasonal variation in the simulated flow. For these both sub-catchments, the high variation was observed during the season of the southwest monsoon (May-Sep). Further, the second effective rainfall season is the second inter monsoon (Oct- Nov) in this region.

5.1.2.3 Temperature

For the calculation of the Potential Evapotranspiration (PET), the temperature data are extremely useful where the complex type of data is not available in the ungauged catchments and it produces the satisfactory results for the PET-based runoff models (Bai et al., 2016).

The temperature was one of the important factors for the simulation of the flow in the sub-catchment. Although temperature data was not a direct input of the model, it was essential for the computation of another important major input, i.e. 'potential evapotranspiration' PET, hence, for the computation of the PET, the temperature data was used.

Initially, the available methods to compute PET and data availability were reviewed in Chapter 2.6.3. From the findings of the literature, temperature methods for estimation of the PET were used. To estimate the potential evapotranspiration, the Hargreaves method was found to be easy and applicable for the modelling. For the calculation of the PET from the method of Hargreaves, it requires the extraterrestrial radiation for this location at the end of the catchment. The extraterrestrial radiation was computed from the methods of Allen et al. (1998), given in the FAO guideline. Details of this method and all the formula have been discussed in Chapter 2.6.4.

The temperature data was collected from Nuwara-Eliya station from the year of Oct-2008 to Sep-2017 and during this period, the maximum temperature data was found to be 26°C and minimum temperature was found to be 2°C, and these are the extreme values present in the catchment. But calculating the average and maximum and minimum temperature was found to be 20.35°C and 12.15°C. The temperature data collected from the Nuwara-Eliya station was used for the modelling in both sub-catchments and also to the model application in the catchment. Figure 5.1 shown below represents the data of maximum and minimum temperature of the station after filling in the missing data in the temperature data series.

The variation of the temperature effects the variation in the actual evapotranspiration, hence, in overall it creates an effect on the simulated streamflow in the catchment. As the temperature is raised in the catchment, it consequently raises the evapotranspiration. As the catchment lies in the wet zone of the country, its PET and actual evapotranspiration ET_o is not much high as compared to the dry zone of the county. Hence, from Figure 5-3, the average temperature variation of the measured data of the catchment was also not high.

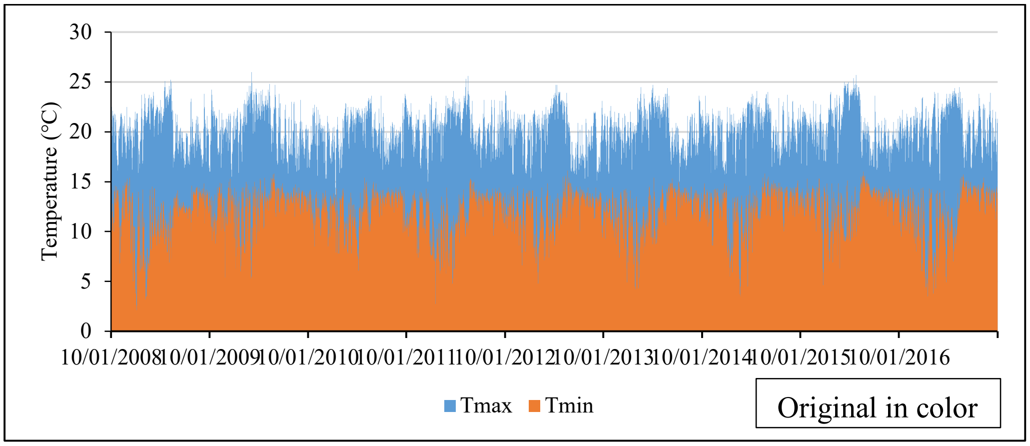


Figure 0-4 The daily minimum and maximum temperature data from the period of Oct-2008 to Sep-2017

5.1.2.4 Streamflow

The streamflow data were collected separately for each sub-catchments from the outlet of the catchment for model calibration and validation. The data period was from Oct-2008 to Sep-2017 for both sub-catchments. From this data, five years of data for the periods of Oct-2008 to Sep-2013 was selected for calibration and rest of the data of the remaining four years was kept for the validation period, that is the data of the period from Oct-2013 to Sep 2017. The data resolution was a daily time step.

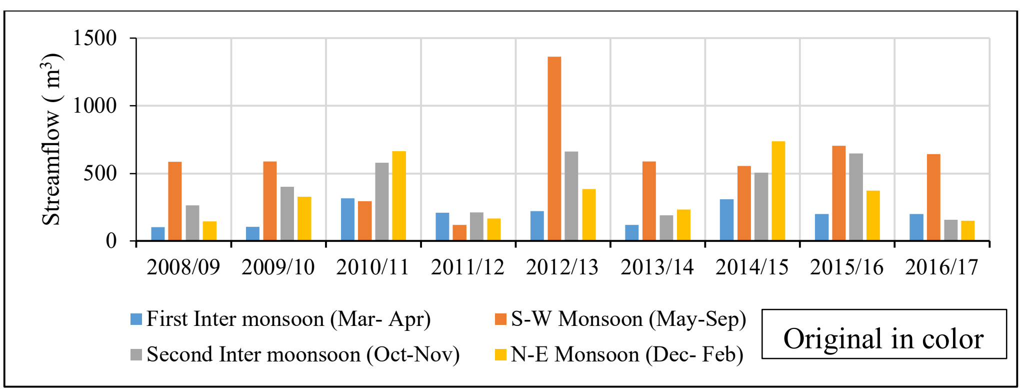


Figure 0-5 The seasonal streamflow data of the Norwood sub-catchment

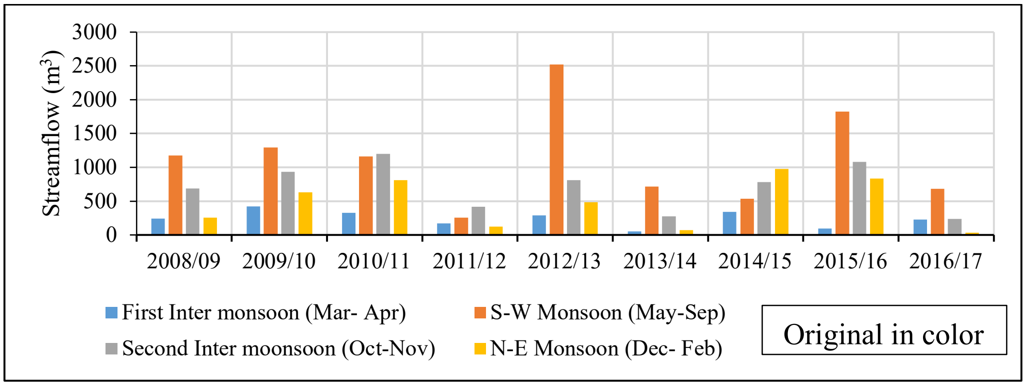


Figure 0-6 The seasonal streamflow data of the Holombuwa sub-catchment

As the streamflow available in the river section is the main key parameter to generate the Run-of-the-River hydropower, the low flow was the main concern in the river section Hence, the flow depends on the season of the rainfall. The seasonal plots shown in Figure 5-5 and Figure 5-6 confirm that South-west monsoon has the maximum streamflow. But, the least flow in Norwood was found during the first inter monsoon (Mar-Apr) and for the Holombuwa sub-catchment, the least flow season was found to be in the North-east monsoon (Dec- Feb). In overall, the simulated, as well as the observed flows, were found to have the same patterns in the flow in both sub-catchments.

5.1.3 Model Performance

For the model performance, the objective function was applied to check the correlation of the observed and simulated flows. For this purpose, the correlation coefficient r and coefficient of determination R^2 were selected. The ABCD model was calibrated and validated based on the Pearson correlation coefficient r and also the value of the coefficient of determination R^2 were also checked. As given in Table 4-3, the optimized value of the model was successfully achieved.

The final values of the a, b, c and d parameters for the Norwood sub-catchment was found to be 0.983, 398, 0.465 and 0.00001, respectively. For the same values, the correlation coefficient r was found to be 0.87 and the coefficient of determination R^2 was found to be 0.75. Hence, the model produced quite comparable results on the specified catchment. The optimized graph is shown in Figure 4-7 and Figure 4-8 shows that the model, overestimated low flows and high flow estimation was slightly underestimated. But, the overall criteria were found to be in the acceptable range as the Pearson correlation coefficient *r* was found to be in the acceptable range. The Norwood catchment lies in the upper part of the basin having an area only 95 km^2. The outlet of the basin is at the inlet of the Casterleigh reservoir, hence, the water flowing from this catchment feeds the downstream reservoir. The flow duration curve was prepared by comparing the simulated flow and the observed flow, which are shown in Figure 4-23 to Figure 4-28. These further demonstrate that the low flow is overestimated in the Norwood sub-catchment.

Further, the scatter plot graph between the observed and simulated flow was plotted to determine their relationship, and for the Norwood sub-catchment, it shows a good relationship between the simulated and the observed flows. Figure 5-7 shows the calibration and validation graphs for the respective periods which clearly demonstrate this result in the catchment.

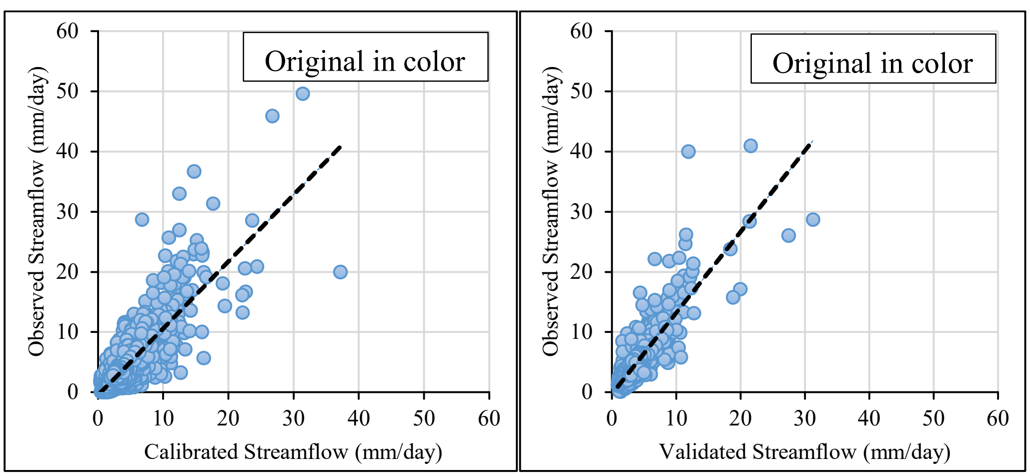


Figure 0-7 The relationship between observed and simulated streamflow for the period of the calibration and validation in Norwood sub-catchment

The final values of the *a*, *b*, *c* and *d* parameters for the Holombuwa sub-catchment were found to be 0.995, 300, 0.542 and 0.0001, respectively. For the same values, the correlation coefficient *r* was found to be 0.61 and the coefficient of determination R^2 was found to be 0.37. The model shows the comparably good relationship with the Pearson correlation coefficient but the coefficient of the determination R^2 shows a quite weak relationship between observed and simulated streamflows. The optimized graph is shown in Figure 4-9 and Figure 4-10 shows that the model overestimated high flows and low flow was also not estimated properly. But the overall criteria were found to be in the acceptable range as the Pearson correlation coefficient *r* was found to be in the acceptable range. The Holombuwa catchment lies in the North upper part of the basin having an area of only a 155 km^2. The flow duration curve was prepared by comparing the simulated flow and the observed flow, which are shown in Figure 4-29 to Figure 4-34. These also demonstrate that the high flow has been overestimated in Holombuwa sub-catchment.

Further, the scatter plot graph between the observed and simulated flow was plotted to examine their relationship, and for Holombuwa sub-catchment, it shows only a fair relationship for the simulated and the observed flow. Figure 5-8 presented here for the calibration and validation period graph clearly demonstrates this result in the catchment.

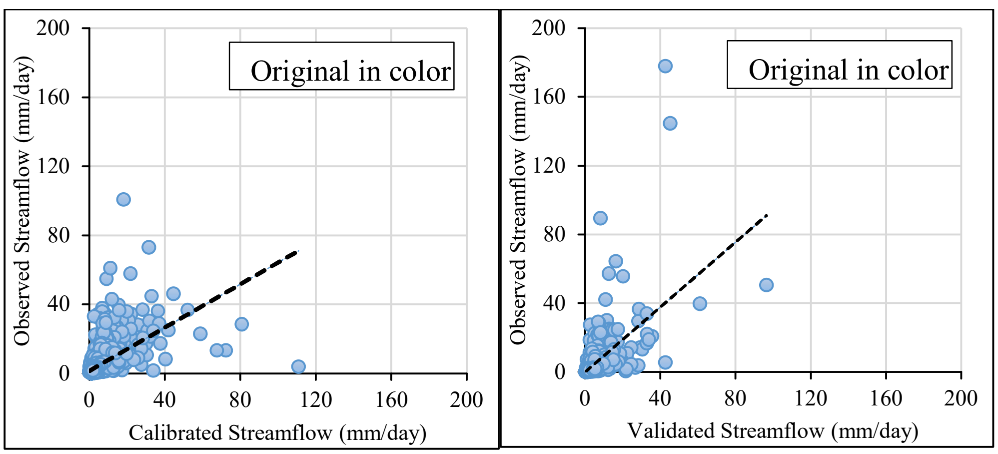


Figure 0-8 The relationship between observed and simulated streamflow for the period of the calibration and validation in Holombuwa sub-catchment

5.1.4 Model Parameters and Behavior

Here, the model applied was the Four- parameter ABCD lumped hydrologic model. The model has the main four parameters, namely *a*, *b*, *c* and *d*, which behave as their specific physical interpretation to catchment for different processes of runoff generation. The parameter identification and understanding their behaviours are key features of the model development.

Initially, for the model development, the literature was studied for finding the model equations and the characteristics of the model parameters were studied in detail. It was found that the model has a different range of values for the model parameters. Hence, for the initial development of the model, near middle or middle value was taken from the literature as the initial value for a particular parameter and the model was optimized thereafter to fine-tune the parameter value. These parameters have their own characteristics for different catchments. The parameter depends on the various catchment related conditions and factors, hence, the model shows various parameter values and ranges to the different types of catchments. The different parameter values have a different set of behaviours, and hence, it has been discussed below.

The parameter *a* is the propensity of runoff before the soil gets fully saturated (Thomas, 1981). The parameter *b* is the upper limit of the evapotranspiration and soil moisture storage (Al-Lafta et al., 2013). Hence, this parameter *b* reflects the ability to hold the water in the upper part of the soil i.e. for the ABCD model, this reflects the Upper compartment of the model. The parameter *c* is the fraction of the streamflow from the groundwater recharge and when the value subtracting with unity it represents the direct surface flow in the stream. The value *d* represents the fractional multiplicative factor for the groundwater discharge. Further, its reciprocal shows that average groundwater residence time.

The optimized parameter value *a* obtained in Holombuwa sub-catchment was found lower than the optimized *a* in Norwood sub-catchment, and this shows that the Norwood sub-catchment will discharge more water as runoff but as per Thomas (1981), the value of *a* will reach close to the unity as it is further raised (i.e. representing the urbanization effect) and on the opposite, the deforestation instead will lead to a low drainage generation density. Hence, in this case, the Norwood catchment lies in a less human influenced area in the upper part of the catchment but the Holombuwa lies in the little downstream and a more human-influenced area. This can also be caused due to various other factors as well. Therefore, it needs to be further investigated about the observed different flow generation characteristics in the two sub-catchments.

The optimized parameter value of the parameter *b* was obtained similarly for the Norwood and Holambuwa sub-catchments. The value *b* was found to be 398 and 300 for the

Norwood and the Holombuwa sub-catchments, respectively. Hence, it shows that both sub-catchments have a similar water holding capacity but the Norwood has a slightly higher water holding capacity in the upper soil zone.

The optimized parameter value of *c* was found to be 0.465 and 0.542 for the Norwood and the Holombuwa sub-catchments, respectively. As the range of literature value for *c* is 0 – 1, the value found in this study comes in the range of the medium values which symbolizes that when the rainfall occurs, roughly a half of that will contribute for the runoff discharge and the rest half of will go for the groundwater storage and recharge, as the soil water storage in the catchment is nearly half or 0.5.

The parameter *d* is responsible for the amount of groundwater discharge in contribution to streamflow. The value of this parameter found in these catchments are extremely different and the values found are 0.00001 and 0.0001 for the Norwood and the Holombuwa sub-catchments, respectively. The parameter *d* was found to be extremely sensitive in Norwood catchment but in Holombuwa sub-catchment, the it was found to be less sensitive. The reason behind this sensitivity may be the Norwood catchment is in the extreme upstream with higher altitude as compared to Holombuwa catchment, which is also with more vegetation in the catchment.

The model initial parameter values and their ranges obtained from the literature and optimized values have been presented in Table 5-1. This gives a clearer picture of the value distribution in catchments.

Table 0-1 The model parameters and their behavior in the sub-catchments

Model Parameter	**Range from the Literature**	**Model Initial Values**		**Optimum Parameter Value**	
		Norwood	**Holombuwa**	**Norwood**	**Holombuwa**
a	0.837-0.999	0.936	0.936	0.963	0.995
b	14 - 4000	260	130	398	300
c	0 - 1.000	0.001	0.500	0.465	0.542
d	0 - 1.000	0.001	0.001	0.00001	0.0001

5.1.5 Parameter Sensitivity

The main interest in the parameter sensitivity analysis was finding the most effective parameter among *a, b, c* and *d* on the model result (streamflow). The model parameter is the most influencing factor to determine the streamflow in the catchment. Hence, finding its effect is essential for hydrologic modelling. According to the Al-Lafta et al. (2013), the main idea of the parameter sensitivity analysis is to distinguish the most effective factor contributing strongly to the variability of simulated streamflow, i.e. input - output analysis. McCUEN (1973) stated that parametric sensitivity plays an important role in the model optimization technique, and it is very useful in the model calibration and the validation process.

Song et al. (2015) stated that sensitivity helps to identify the key parameters that play the main role for the model parameterization, calibration, validation and the uncertainty identification in the modelling. Hence, parameter optimization is essential to model reality and finding catchment properties.

For the Norwood and the Holombuwa sub-catchments, the sensitivity analysis was carried out by changing the model parameters in the full range of parameters found out in literature against the correlation coefficient r and coefficient of determination R^2, and both values were recorded during the parameter sensitivity process. The model parameter values were changed one at a time during the sensitivity process. The graphs plotted for the sensitivity analysis have been shown in Figure 4-39 to Figure 4-42.

The parameter value a was found to be equally sensitive for both Norwood and the Holombuwa sub-catchments. The value of the b was found to be relatively less sensitive for both catchments in comparing with the r and R^2 values. The parameter c was found to be equally less sensitive for both sub-catchments when analyzing against the r and R^2 values. The parameter d was found to be very sensitive to the Norwood sub-catchment but at the same time, the parameter d was found to be less sensitive in the Holombuwa sub-catchment.

Considering all above, the parameter a and d were found to be the most sensitive as compared to the other parameters (c and d). Both of these parameters are directly responsible to generate the streamflow in the catchment.

5.1.6 Selection of Catchments

Al-Lafta et al. (2013) applied the ABCD model in large size catchments with snow and without snow, and the study shows that the ABCD model does not work properly in the continental and snow feed climates. Further, Martinez and Gupta (2010) stated that during a study of the ABCD model, the model does not perform well in the areas where reservoirs and water bodies were presents. Hence, considering all the previous research towards the improvement of the ABCD model and its applicability, for this study, two uppermost sub-catchments of the Upper Kelani basin were selected to avoid the presence of the water bodies in the catchments selected for the model calibration and validation. The selection decision was found to be useful during the analysis process for the catchment analysis. Moreover, another cause of selecting two catchments was to average the model parameters for their subsequent applications in the hydropower inflow analysis in the Upper Kelani basin.

5.2 GIS Tools

5.2.1 Stream Network Generation and Watershed Delineation

The stream network generation and watershed delineation play a crucial role in the identification of suitable potential locations for the hydropower installations in the study area. In this study, public domain/freely available 30 m spatial resolution Digital Elevation Model (DEM) from SRTM was used, as described in Chapter 4.2.3. The DEM was used to stream network generation and watershed delineation. All the process was carried out by using the ArcGIS (v10.3) by using an associated hydrology tool (Arc Hydro Tool). Figure 4-42 to Figure 4-46 show all steps involved in the stream network generation and watershed delineation. For the stream network delineation, a combination of the different threshold was set and the final selection was made by selecting the 10,000-cell threshold.

5.2.2 Head Optimization Problem

The realistic representation of synthetic river profile is one of the foremost important criteria for the determination of the head in the suitable hydropower site selection process. The topographic features of the study area are presented by using different available topographic data. The spatial resolution of the topographic data plays a crucial role in the determination of stream network which will help extraction of the correct river profile. Locating the river bed profile at the right location is of foremost importance because it may affect the determination of the correct elevation in the river profile for subsequent procedures.

For the head optimization, SRTM 30 m resolution data was analyzed. Further, those data were used for the determination of the elevation (Head) along the river profile. The elevation was extracted for every 100 m of horizontal distances from the starting point of the river reach. The elevation difference was calculated by deducting the head for the consecutive points. Hence, a suitable location was identified from the developed criteria focusing on the selected catchment.

The main problem faced during the determination of the exact head on the river bed profile was the spatial resolution of the topographic data for the correct generation of the stream network and consequently, its determination of the associated head along the river profile.

5.3 Visual Basic for Application (VBA) Program Analysis

For the analysis of the head derived from the ArcGIS, the Excel spreadsheet operation was done by using a Visual Basic for Application (VBA) program. This helps to simplify the complex calculation process in the simple order of magnitude with the efficiency of time for the development of the complex relationship. The head searching algorithms for identification of the criteria of the head along the river bed profile was developed on the Visual Basic environment using the Excel Macros. Yan-fen (2006) stated that Microsoft Excel and the attached program Visual Basic for Application (VBA) is a powerful tool for the solution of the complex problem, and it shows the huge advantage in showing simultaneous graphics for the visualization of the problems.

Visual Basic for Application (VBA) program helps to solve the complex process of the hydropower site selection, and it demonstrates the powerful function for analyzing the complex computation, visualizing and secondary data processing (Yan & Hongliang, 2012) which was used and applied in the study.

The proposed Visual Basic for Application (VBA) program analyze the elevation (head) data of river profile extracting elevation data from SRTM 30 m resolution terrain with the help of the ArcGIS (v10.3) tools under the developed criteria for the Run-of-the-River suitable site selection process. The head searching program starts from the start point of the river and the first point identified was considered as the intake point and after that, if it meets the head criteria, then it is fixed as a suitable location, and otherwise, the algorithm starts to search for another location by moving one step down from the last selected point till the meeting of 25 m or more elevation criteria. But if it could not find the required head drop within pre-specified 2000 m consecutive distance, then it will skip the location and will start from the next point onward to search for finding the next suitable location of the hydropower according to the head criteria.

5.4 Discussion on Combined Selected Criteria

This study considered head and flow criteria only. These criteria were established taking references from several past studies in the literature and considering other site-specific criteria for the Upper Kelani basin and specifically designed for the site-specific area. But this same process may not be adequate for the site selection process in a complicated area where it needs to consider the environmental and social factors also concurrently for the hydropower site analysis and also local laws and regulations need to be considered for the detailed study of the hydropower site selection process. moreover, the economic and cost-benefit factors should also be analyzed properly.

Since this method was established for the pre-feasibility and preliminary site selection process, it is acceptable in this stage and further analysis should be performed on the identified locations. This method is concluded as a fast and reliable process for the initial site selection process only.

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

1. The applicability of the ABCD lumped model was established on the daily resolution in two sub-catchments of the Upper Kelani river basin on the wet zone of Sri Lanka to use for the suitable Run-of-the-River hydropower power site selection. The selected upper sub-catchments were Norwood and Holombuwa.

2. The daily ABCD model can be successfully developed and applied with the 2008-2017 (water year) for the period of the nine-year by using precipitation, streamflow and minimum, maximum and with average air temperature in daily resolution data.

3. The optimized averaged parameter *a, b, c* and *d* values considering Norwood and Holombuwa sub-catchment were found to be 0.979, 349, 0.504 and 0.00005 with correspondence optimized correlation coefficient *r* and coefficient of determination R^2 values of 0.87, 0.75 and 0.61, 0.37, respectively.

4. For both sub-catchments, the parameter *a* was found to be more sensitive. For the Norwood sub-catchment, the parameter *d* was found to be very sensitive but for the Holombuwa sub-catchment, *d* was not found to be that much sensitive as compared to the Norwood sub-catchment. Rest of the values were found to be not much sensitive for both sub-catchments.

5. The proposed methodology facilitates to generate the flow duration curve (FDC) in the ungauged catchments for the determination of the available discharge at the selected specific points of the river using the developed VBA program algorithm.

6. The proposed suitable site selection process for the Run-of-the-River hydropower projects was designed to overcome the issues in the traditional process of the hydropower survey, and to identify the suitable sites by simultaneously considering the constraints on the head and flow data over the river profile in any watershed.

7. The study delineates the suitable hydropower locations by the use of the lumped ABCD flow model and the head extraction process with the GIS tools using SRTM 30 m resolution publich domain topographic terrain data.

8. The spatial resolution of the topographic data is very important to identify the best suitable elevation drop at the river section and also to determine the correct overall representation of the watershed.

9. The Visual Basic for Application (VBA) programming is a powerful tool which helps to solve the complex problems in a simplified way by using the Excel Macros.

10. The proposed methodology overcomes the issues in traditional time taking process for the suitable site selection of Run-of-the-River hydropower site.

6.2 Recommendations

1. The simple lumped hydrological ABCD model would be adequate to evaluate synthetic streamflow for determining the suitable potential locations for the RoR hydropower sites with the optimized model parameter values *a, b, c* and *d* in the range of *a* (0.963-0.995), *b* (300-398), *c* (0.465 – 0.542) and *d* (0.00001 – 0.0001).

2. The public domain/freely available topographic data sets would be adequate to analyze the suitable location of the RoR sites in the preliminary and pre-feasibility phase of the hydropower surveys for the rapid identification of the suitable potential locations for the further analysis.

3. The quality of the topographic data plays a crucial role in determining the suitable locations of the potential hydropower sites hence, it is advised that high accuracy data with ground verification is used for the better performance of the model.

4. The ABCD model is recommended to be used in areas with no reservoirs for the better performance of the model. In this study, the selection of the upper sub-catchments was specifically due to this reason.

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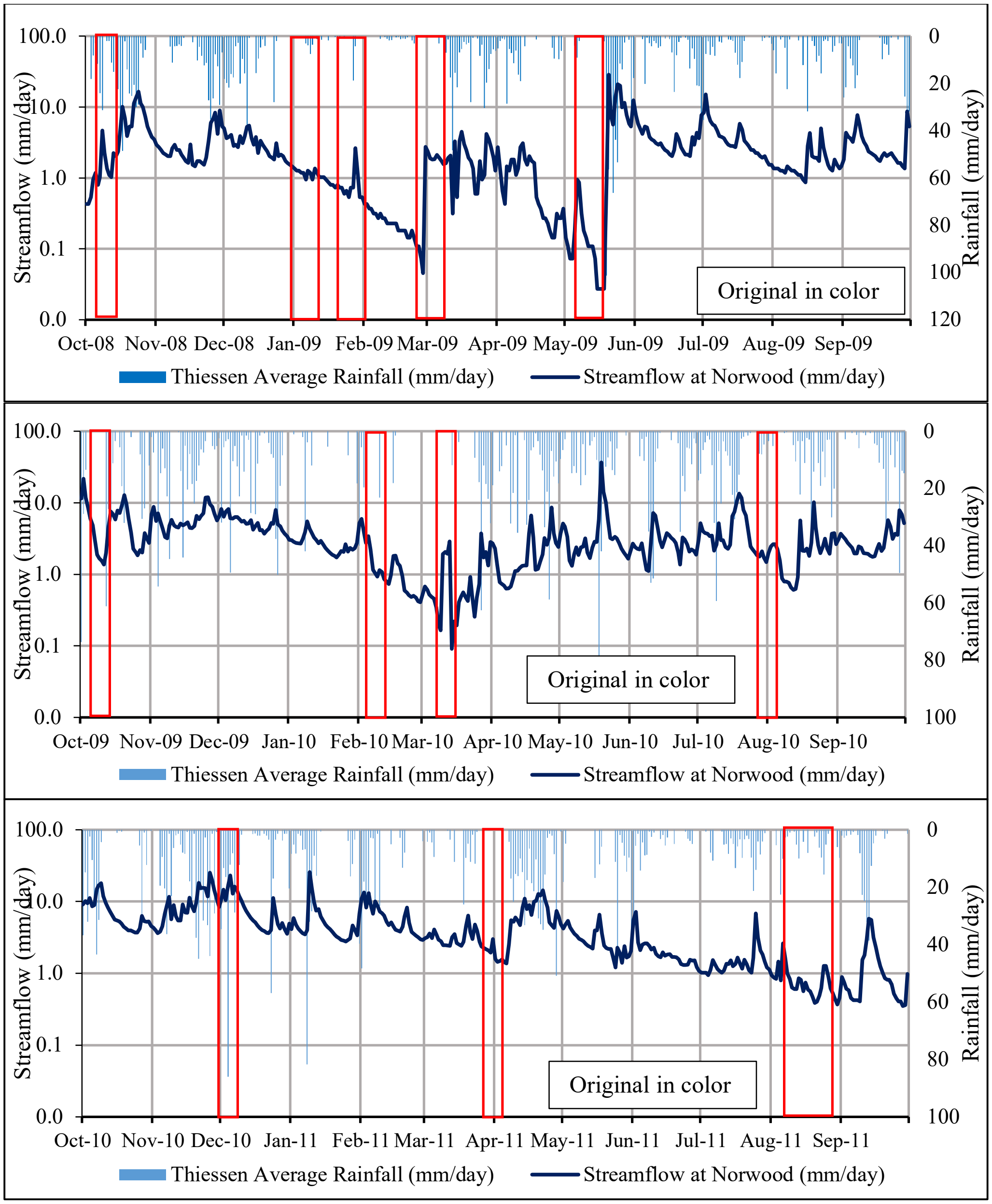
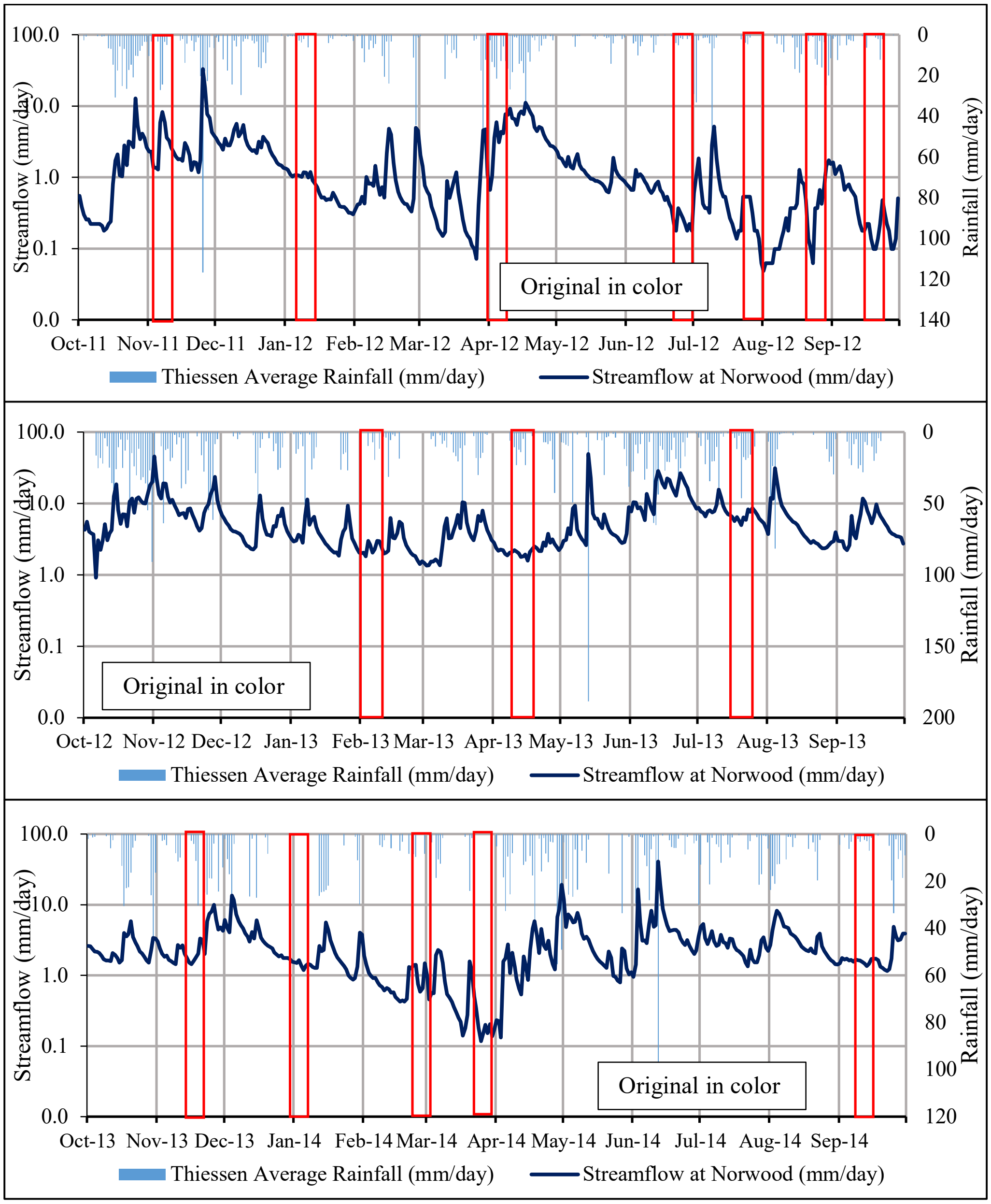
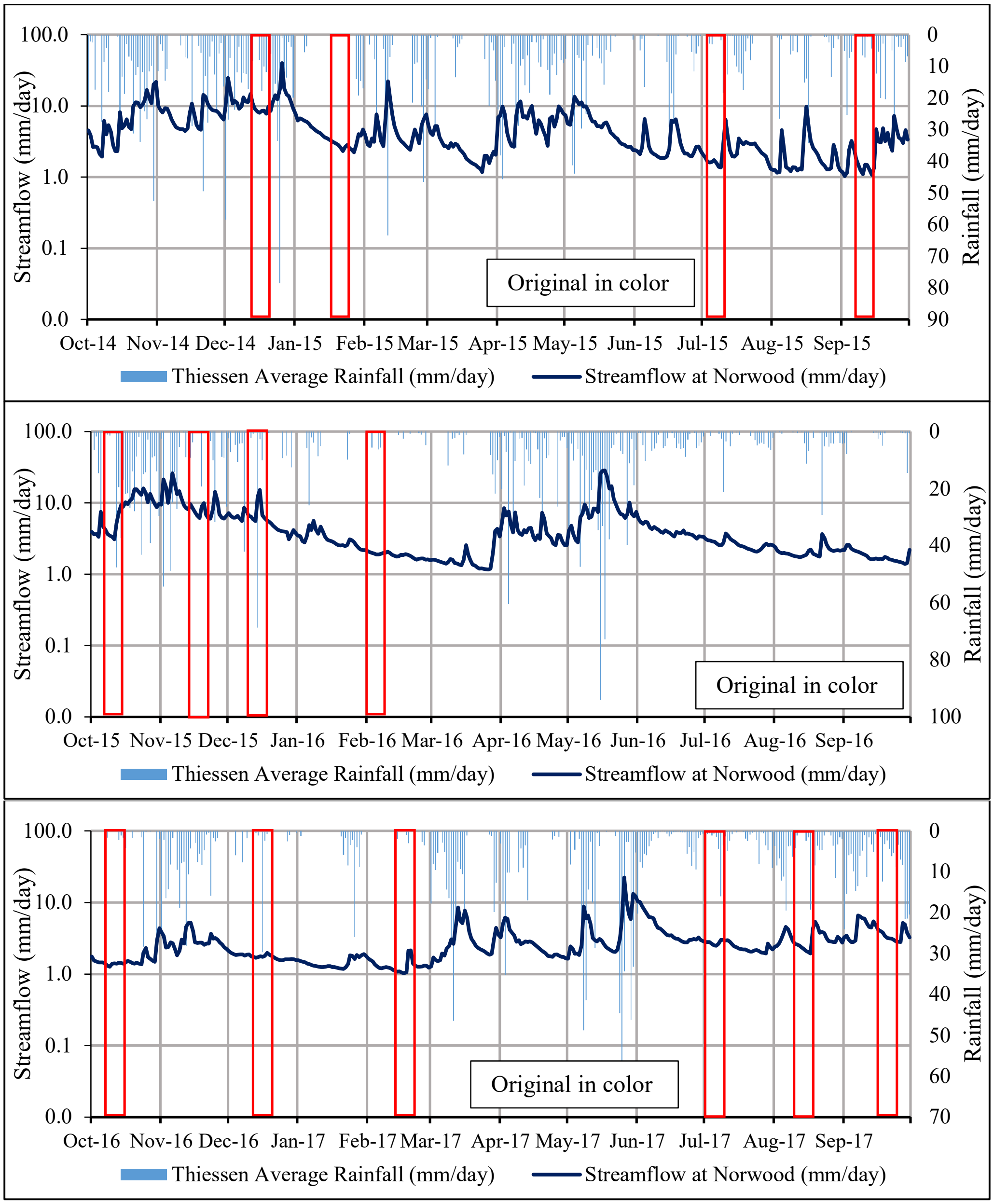
APPENDIX A: VISUAL DATA CHECKING IN NORWOOD SUB-CATCHMENT



APPENDIX A - 1 Streamflow response for Thiessen average rainfall in Norwood Sub-catchment (1-3)

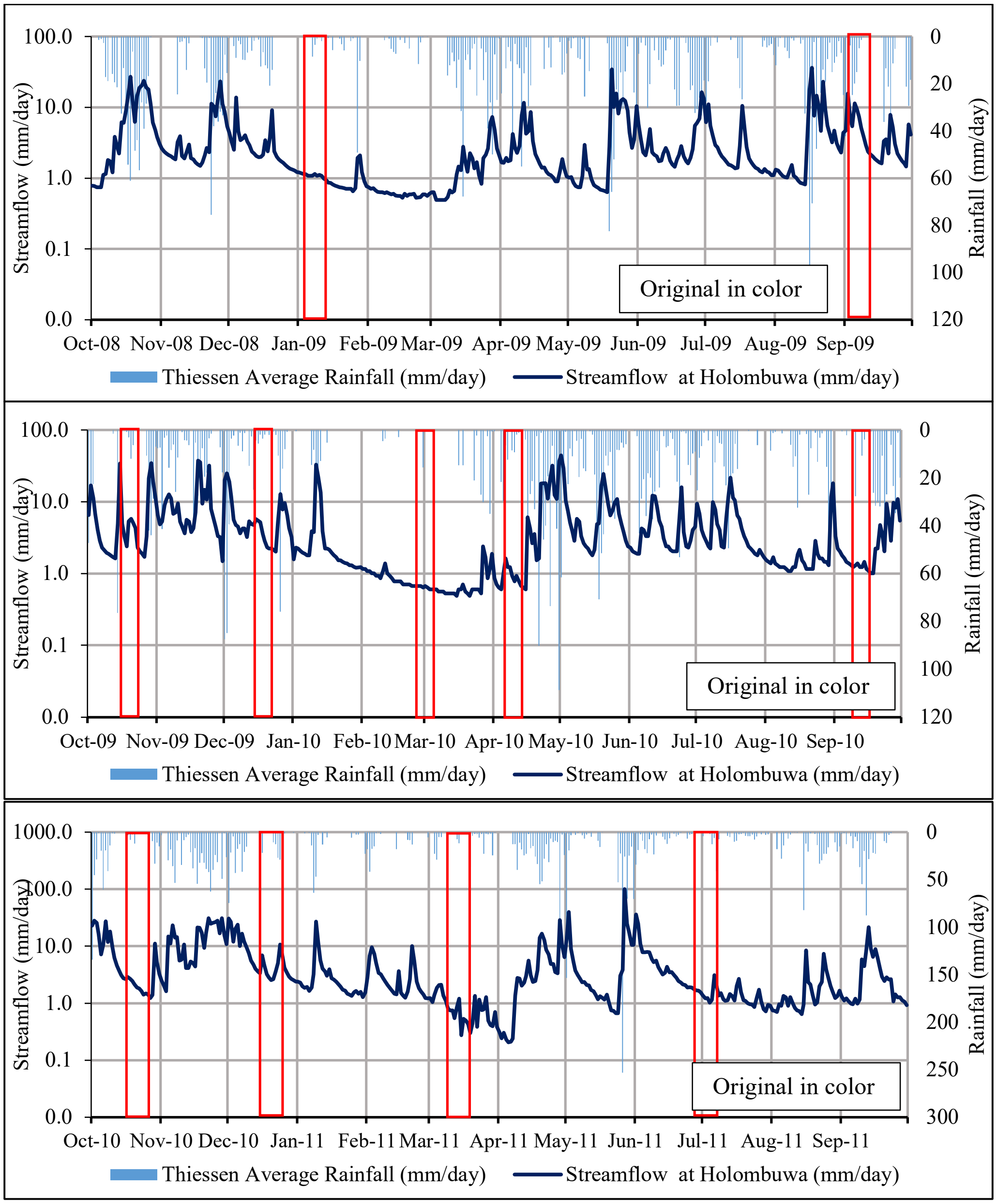


APPENDIX A - 2 Streamflow response for Thiessen average rainfall in Norwood Sub-catchment (4-6)

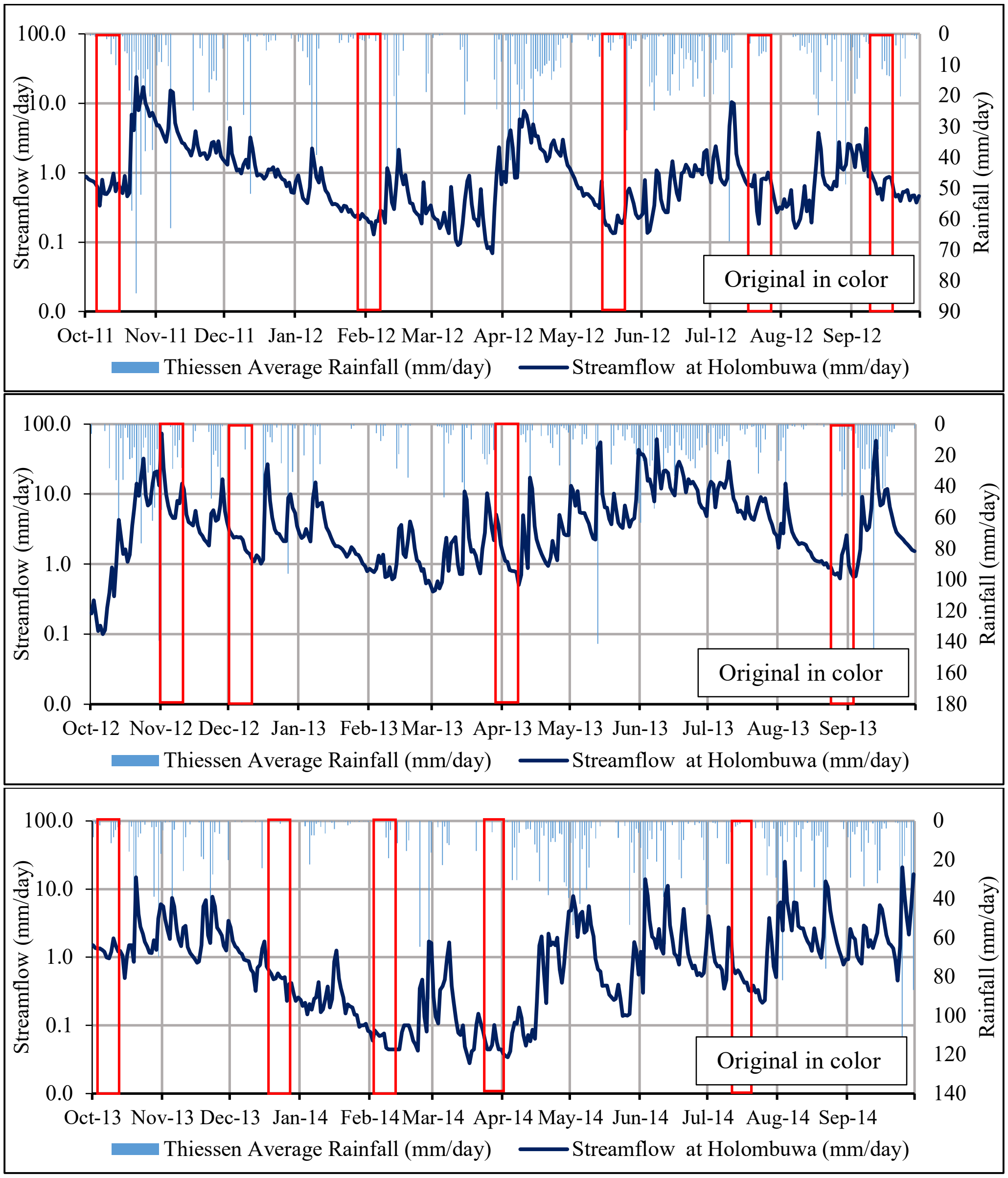


APPENDIX A - 3 Streamflow response for Thiessen average rainfall of Norwood Sub-catchment (7-9)

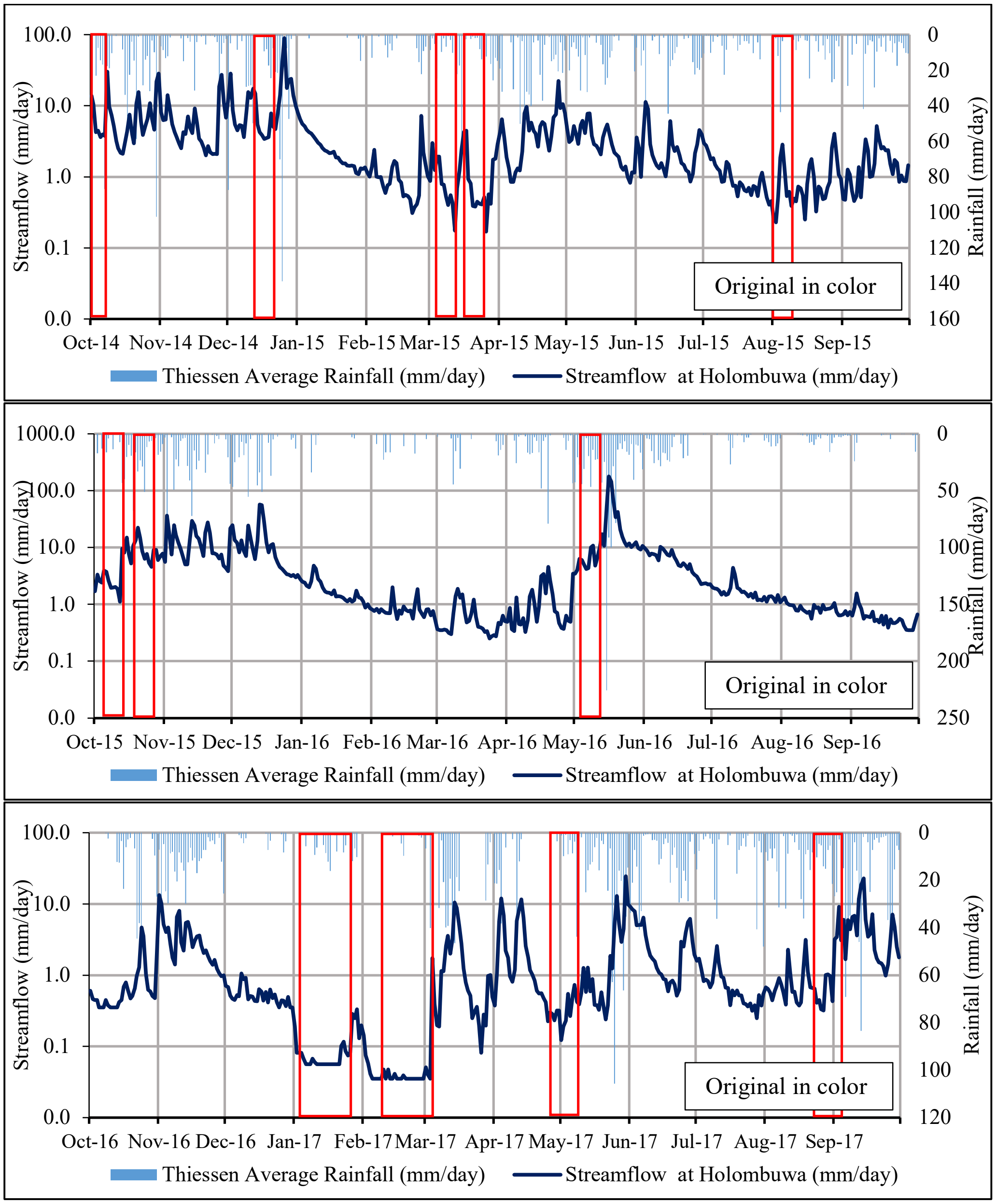
APPENDIX B: VISUAL DATA CHECKING IN HOLOMBUWA SUB-CATCHMENT



APPENDIX B - 1 Streamflow response for Thiessen average rainfall in Holombuwa Sub-catchment (1-3)

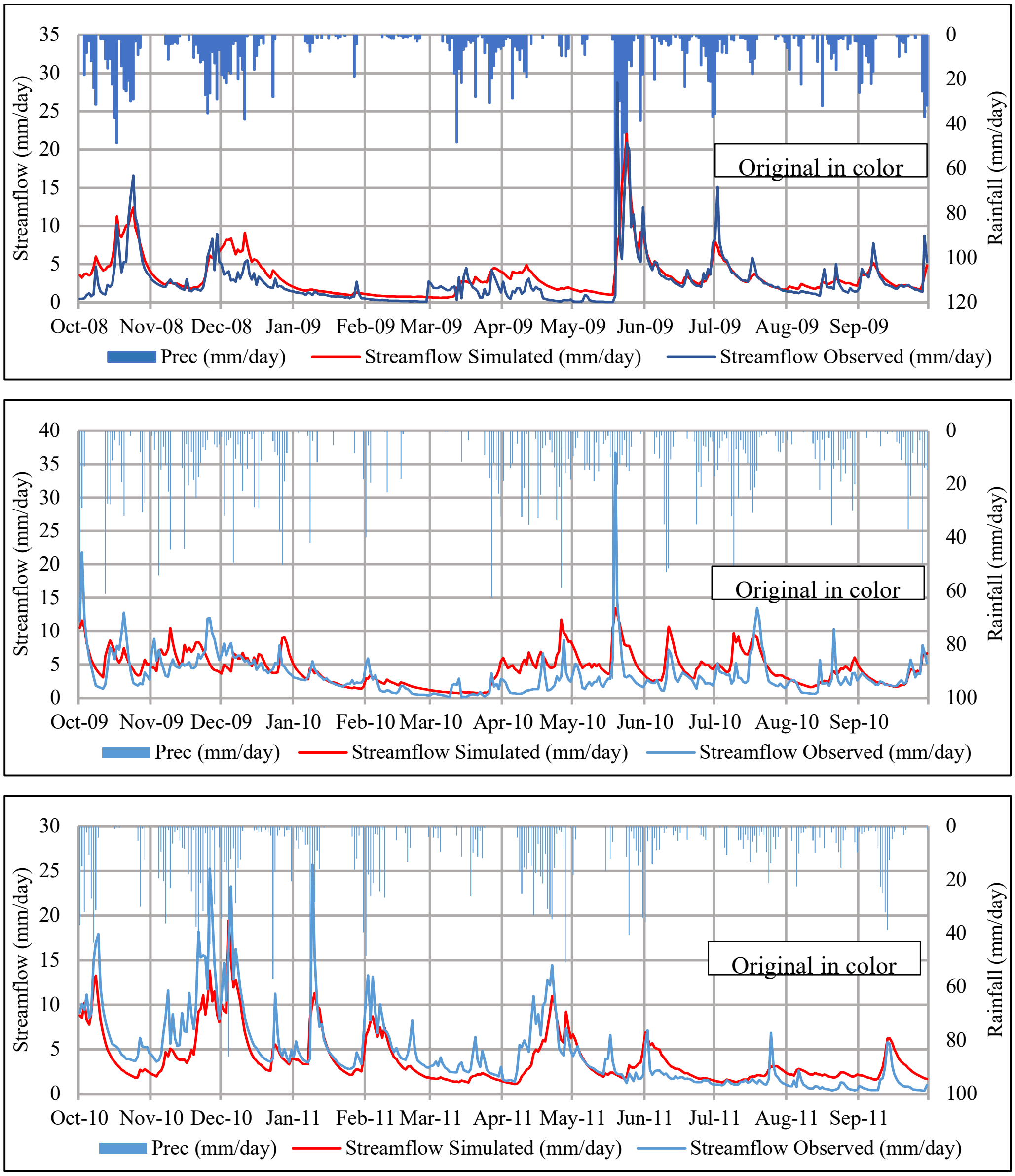


APPENDIX B - 2 Streamflow responses for Thiessen average rainfall in Holombuwa Sub-catchment (4-6)

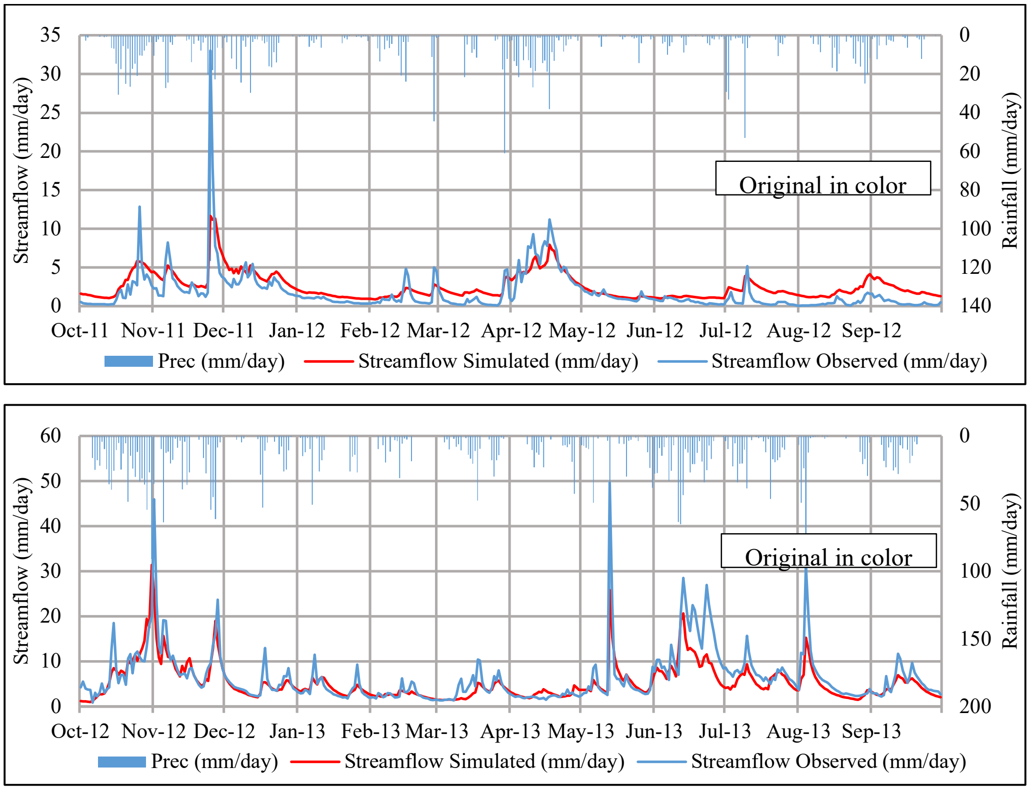


APPENDIX B - 3 Streamflow responses for Thiessen average rainfall in Holombuwa Sub-catchment (7-9)

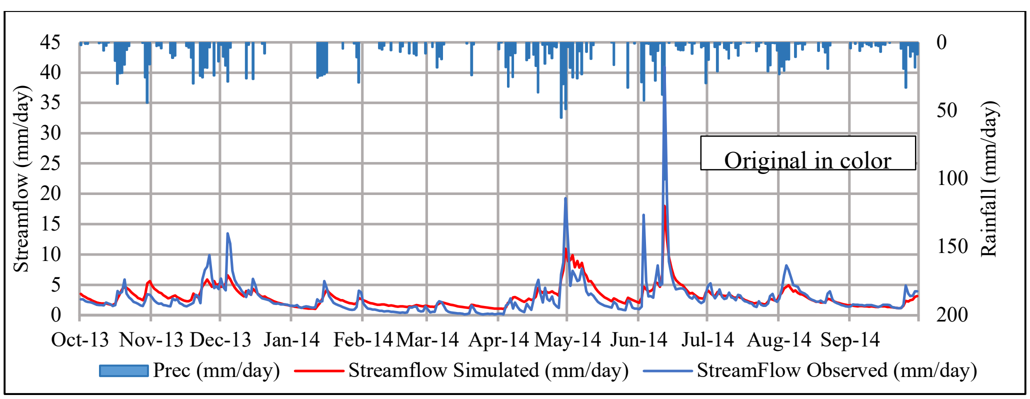
APPENDIX C: YEARLY HYDROGRAPH FOR CALIBRATION AND VALIDATION PERIODS IN NORWOOD SUB-CATCHMENT



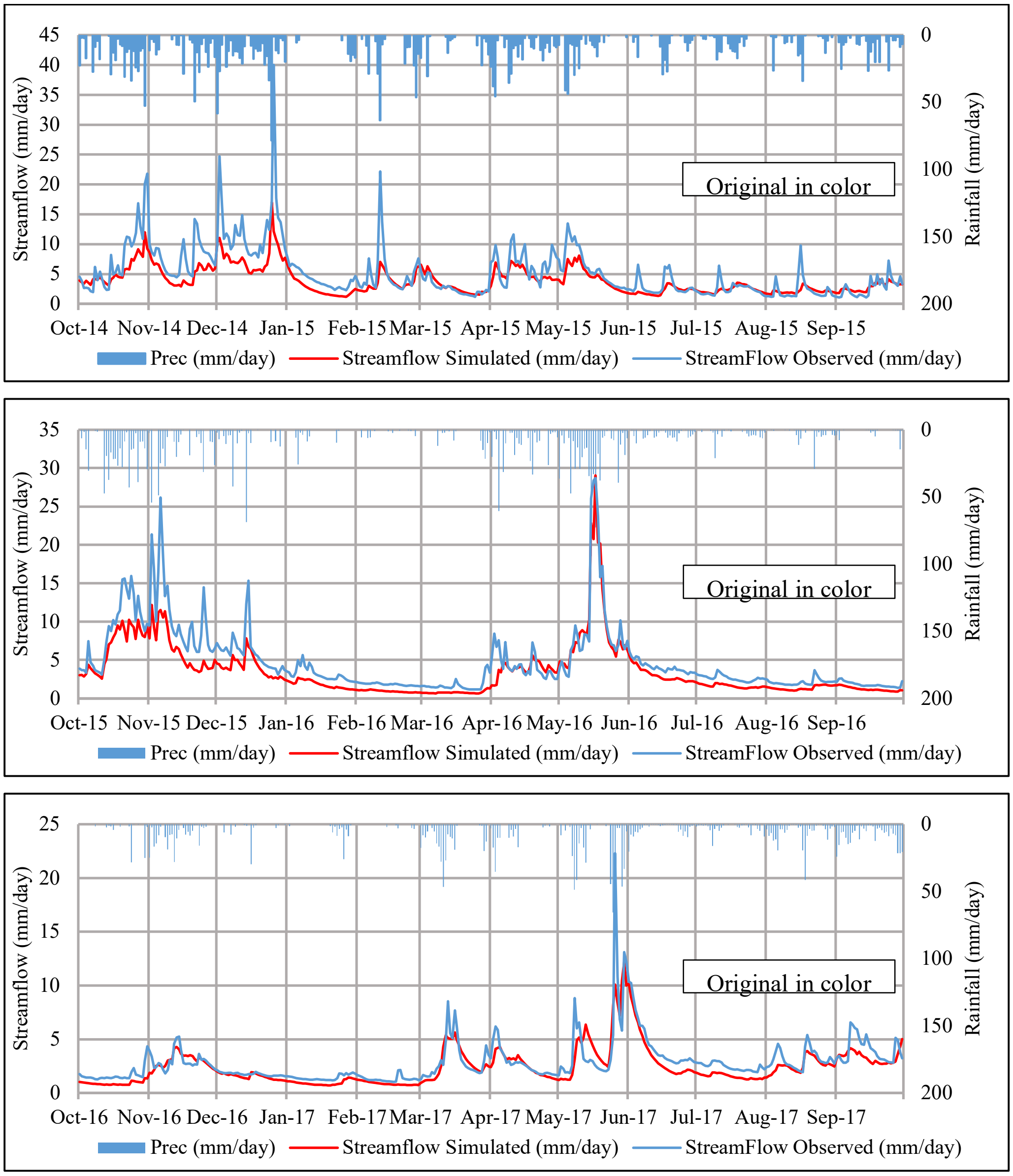
APPENDIX C - 1 The hydrograph for the calibration period from the 2008/2009 to 2010/2011 in Norwood Sub-catchment



APPENDIX C - 2 The hydrograph for the calibration period from the 2011/2012 to 2012/2013 in Norwood Sub-catchment

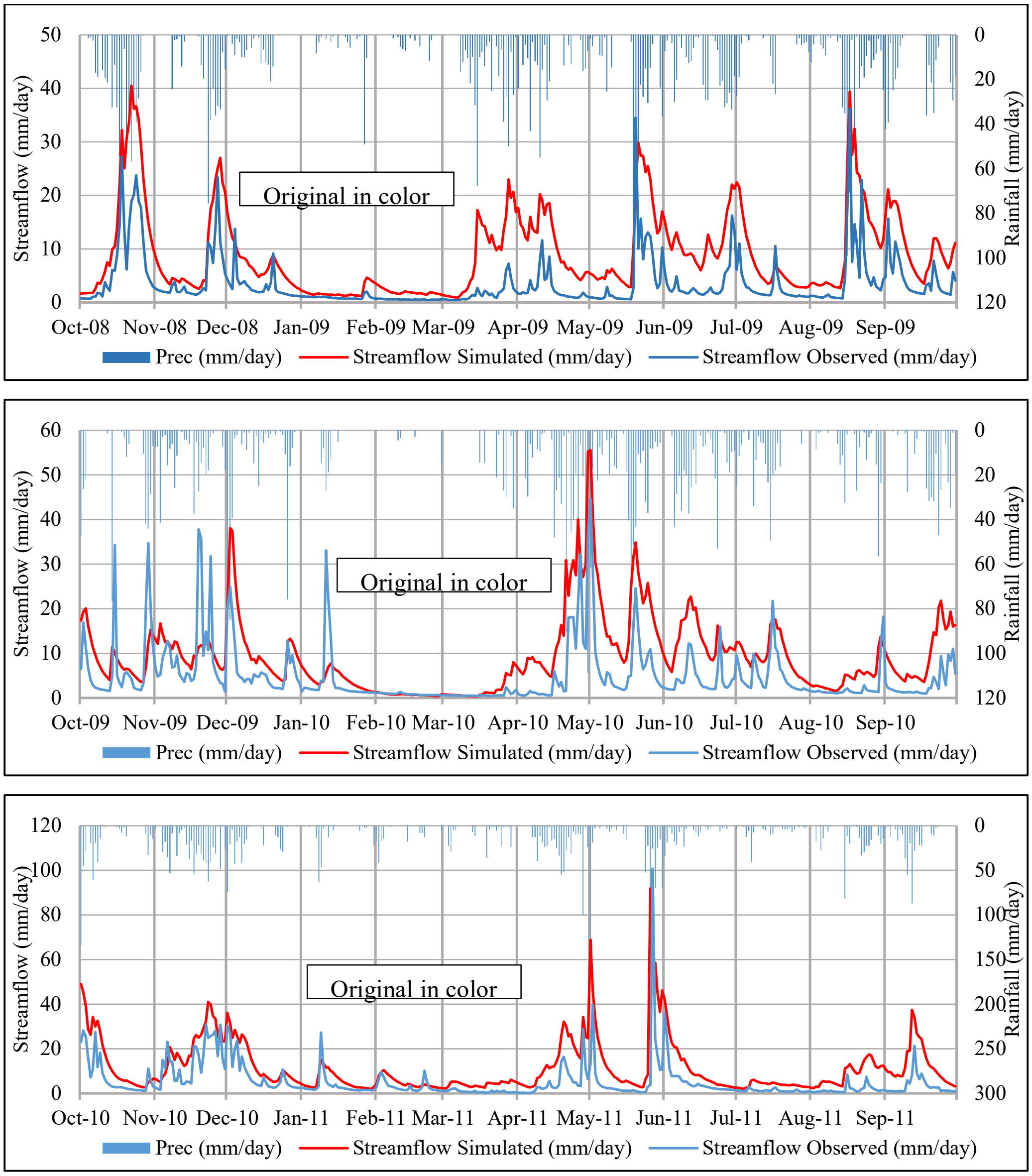


APPENDIX C - 3 The hydrograph for the validation period from the 2013/2014 in Norwood Sub-catchment

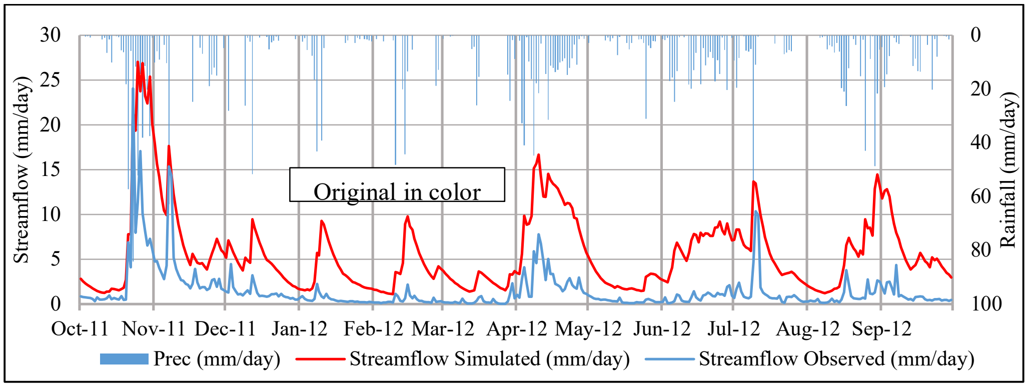


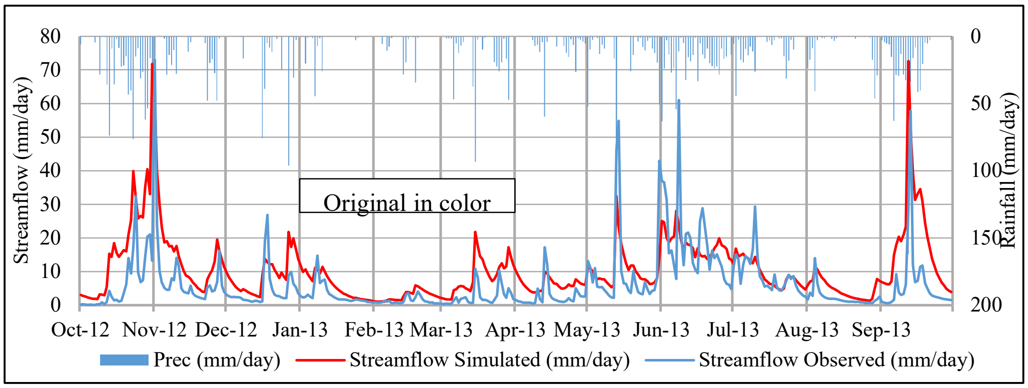
APPENDIX C - 4 The hydrograph for the validation period from the 2014/2015-2016/2017 in Norwood Sub-catchment

APPENDIX D: YEARLY HYDROGRAPH FOR CALIBRATION AND VALIDATION PERIODS IN HOLOMBUWA SUB-CATCHMENT

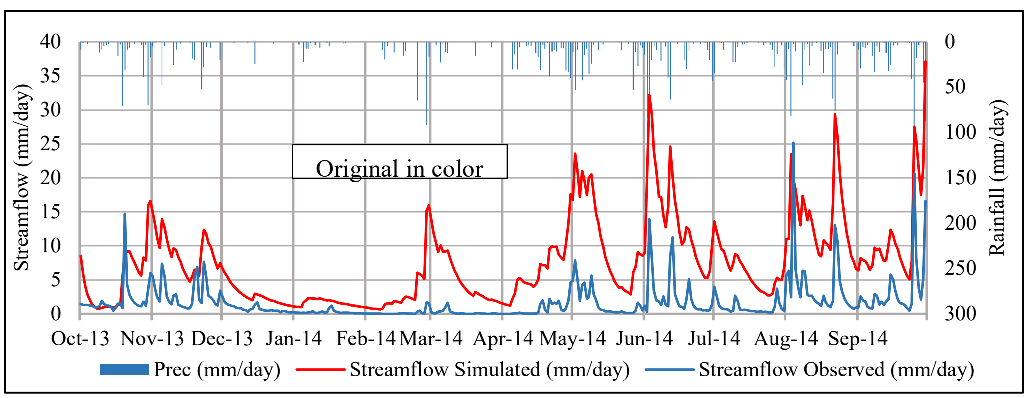


APPENDIX D - 1The hydrograph for the calibration period from the 2008/2009 to 2010/2011 on Holombuwa Sub-catchment

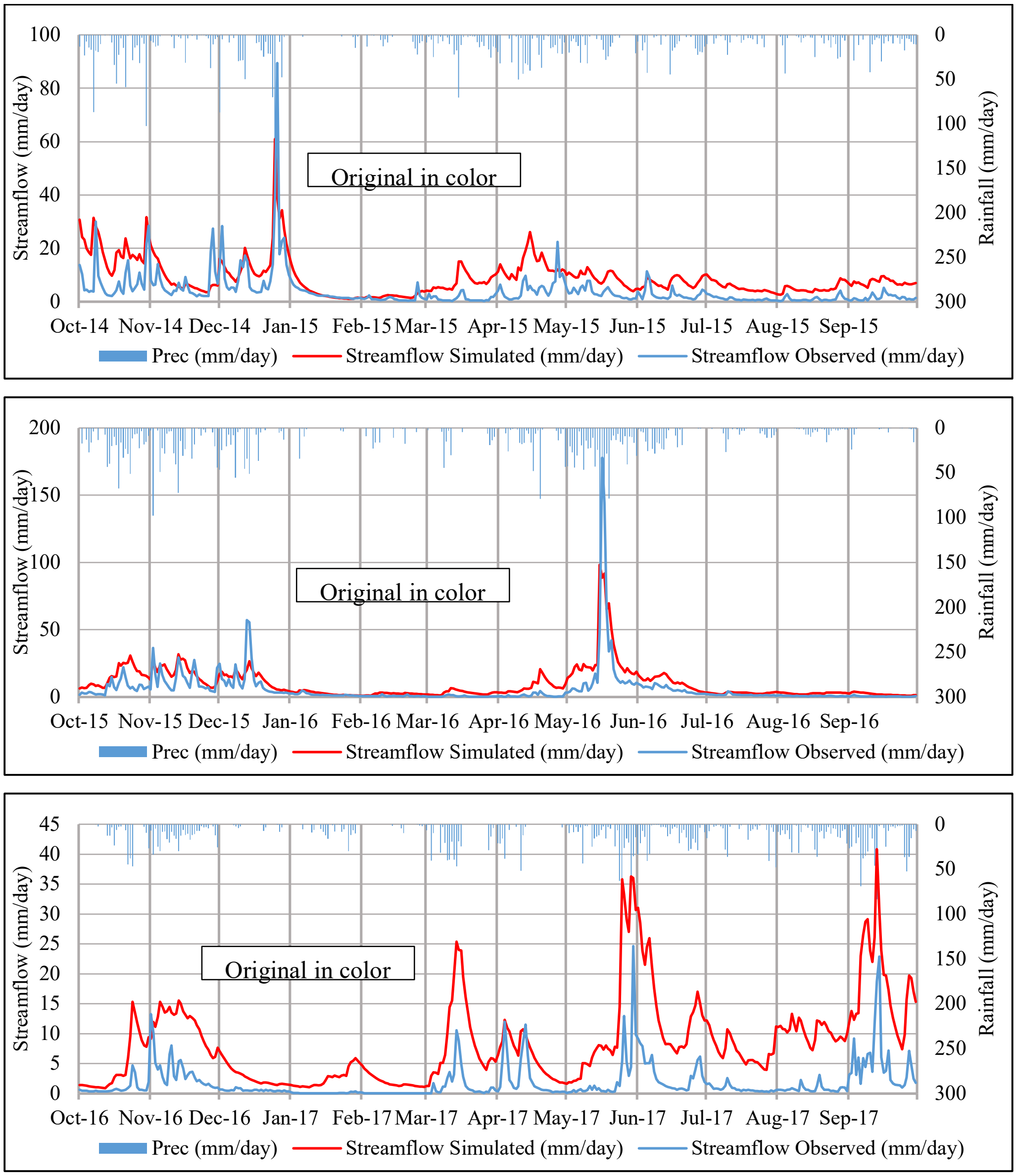




APPENDIX D - 2 The hydrograph for the calibration period from the 2011/2012 to 2012/2013 in Holombuwa Sub-catchment



APPENDIX D - 3 The hydrograph for the validation period from the 2013/2014 in Holombuwa Sub-catchment



APPENDIX D - 4 The hydrograph for the validation period from the 2014/2015-2016/2017 in Holombuwa Sub-catchment