EVALUATION OF MODELS FOR YIELD COMPUTATION IN UNGAUGED WATERSHEDS FOR IRRIGATION INFRASTRUCTURE DESIGN

Sasiri Tharasara Siriwardana

(158567D)

Degree of Master of Science

Department of Civil Engineering

University of Moratuwa
Sri Lanka

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Sasiri Tharasara Siriwardana

(158567D)

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Supervised by
Professor N.T.S. Wijesekera

Department of Civil Engineering

University of Moratuwa
Sri Lanka

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DECLARATION

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ABSTRACT

In any country water management and water infrastructure development activities are mostly associated with ungauged watersheds. Yield computation method recommended by Irrigation Guideline of Sri Lanka does not provide sufficient evidence to ascertain the accuracy of the estimations. Unavailability of a reliable yield calculation method for a practicing engineer to plan, design, construct and manage water infrastructure in ungauged catchments, affects planning, and design of infrastructure and carrying out efficient water management. Therefore a comparison of available yield models and a verification of model outputs with observed values is required to fill a much needed gap in reliable yield estimations for water resources engineering and management. Moreover, the seasonal yield limitations in the Irrigation Department guideline (1984) should be verified to assess the need of changes to the thresholds. IGM is empirical. HEC-HMS, UH are two other catchment yield models commonly used for water engineering applications. These three models were selected and evaluated with observed daily streamflow data of two watersheds from Attanagalu Oya and Kalu River basins.

The present work at first attempted to evaluate the capability of an ungauged catchment modeler to accurately estimate the yield for water infrastructure planning and design. Subsequently these results were evaluated with the actual observations in order to make suitable recommendations. The period of comparisons in the Attanagalu Oya and Kalu river basins were from 2005-2015 and 2006-2014 respectively.

Three spreadsheet models were developed by using the parameters reported in the literature. Lack of recommended methods were overcome by evaluating literature recommendations and incorporating the best engineering judgement. Model parameters were identified by making best estimations from available literature. Seasonal yield thresholds of IGM were checked with observed yield values. Comparison of model estimations with the observations was done using annual water balance and flow duration curves while using Mean Ratio of Absolute Error as the indicator.

According to the state of art review, Irrigation department yield estimation model (IGM) is the best available watershed yield estimation model. Comparison of three models revealed that IGM is the closest monthly yield estimation model with 12.5% and 22.5% annual difference in estimation for Dunamale and Ellagawa watersheds respectively. HEC model over estimates streamflows by 53.2% and 25.7% in Dunamale and Ellagawa watersheds respectively while the UH model overestimates the streamflow of Ellagawa by 101% and underestimates the streamflow by 16.7% in Dunamale watershed. IGM underestimates the streamflow in rainy months and overestimates during relatively dry months and the threshold time of exceedance is 60% for both Dunamale and Ellagawa watersheds. The use of HEC and UH model results create significant ambiguities when compared with the IGM because of the unreliability associated with the process and parameters in the guidance material. Yield model estimates when compared with the observations show that in all three models the antecedent rainfall acts as a key factor influencing model overestimation and underestimations. IGM, HEC-HMS and UH model development and parameter estimations need better reference material to arrive at accurate watershed yield values. It is therefore important to systematically determine design safety factors to account modelling uncertainties.

Key words: Yield computation, ungauged watersheds, Infrastructure design, hydrological models

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LIST OF ABBREVIATIONS

Abbreviation	Description
IGM	Irrigation Guideline Model
HEC	HEC-HMS model
UH	Unit Hydrograph model
FDC	Flow Duration Curve
PoR	Period of Record
PDSE	Percentage Difference of Streamflow Estimation
RF	Rainfall
AMC	Antecedent Moisture Conditions
BFI	Baseflow Index
MRAE	Mean Ratio of Absolute Error
WMO	World Meteorological Association

1 INTRODUCTION

1.1 General

Sri Lanka is a country located in the Indian Ocean in between latitudes of 5°N - 10°N and longitudes of 79° E-82° E. As a result of the location of Sri Lanka, the country gets rainfall by two monsoon seasons called South west (April to September) monsoon and the North East (October to March) monsoon and two inter-monsoon seasons.

Sri Lanka is mainly an agro economy since historical period and rice is the main crop. Rubber, coconut, tea, cinnamon and chena cultivation are also popular in Sri Lanka. Due to land use pattern changes and climate change, water stress situation and yield reduction can be seen in almost all parts of Sri Lanka. Therefore an accurate yield computation method is needed for better water management and irrigation and infrastructure design.

Irrigation guideline developed by Eng. A.J.P. Ponraja is presently used for yield calculations and estimations by the Department of Irrigation, Sri Lanka. Iso-yield curves are used to calculate monthly and seasonal yield and the curves are given as a guideline. The two factors for limiting yield values include the upper as 35% and the lower as 7.5% of the seasonal rainfall. Determination of these factors appear as an exercise based on experience. There is a lack of documentary evidence to justify the verification of these thresholds. Therefore the seasonal yield limitations in the Irrigation Department guideline (1984) needs verification.

There are many recently popular rainfall runoff estimation models such as HEC, SWMM, Unit hydrograph (UH), rational method etc., (Trommer, Loper, & Hammett, 1996). Accuracy and reliability of yield estimations by these models need to be checked for the possibility to use in designs corresponding to ungauged catchments. Evaluation of existing yield estimation methods to be used by an ungauged catchment modeler in a practical situation is a need for better water resources management.

1.2 Significance of the Study

In a country, almost all irrigation water management, planning and infrastructure design and development are associated with ungauged watersheds. Considering Sri Lankan conditions, more than 60% of river basins are ungauged. Many researchers have identified decreasing rainfall trends in Sri Lanka (Herath & Ratnayake, 2004;Eriyagama, Smakhtin, & others, 2009;Eriyagama & Smakhtin, 2010;Piyasiri, Peiris, & Samita, 2004). Due to the human activities, land use pattern changes, and global warming, rainfall patterns have changed. Impervious areas have increased and infiltration reduced. With these changes, there is a water stress and a big question mark for accurate and reliable yield computation.

Currently, in Sri Lanka, yield estimations are done based on the time tested irrigation guideline or by using modern hydrological models. When applying these two methods in a practical situation, a practising engineer face a dilemma whether to choose a time tested guideline method or a modern hydrological model.

Irrigation guideline model is an empirical model that is developed using the data up to 1984. Many formulae, equations and charts including iso-yield curves, 75% rainfall values, iso-yield values and yield limitations have been developed by using those data before 1984 and do not provide sufficient documentary evidence to ascertain accuracy.

Literature review does not directly indicate yield computation models. HEC-HMS and Unit Hydrograph are two other catchment rainfall runoff models which are freely available, easy to handle and commonly used for water engineering applications and the capability of these models for design yield estimation in an ungauged catchment need to be tested.

Therefore unavailability of a reliable yield calculation method for a practicing engineer for planning and design purposes for efficient water management is the gap that needs to be filled.

1.3 Problem Statement

This research is carried out with the purpose of fulfilling the gap of unavailability of a comparative evaluation for a practicing engineer for planning and infrastructure design purposes for efficient water management. In this research Irrigation guideline model, HEC-HMS model and Unit Hydrograph model were compared considering two case studies; Kalu river basin and Attanagalu basin. The main reason for selecting these basins is data availability. No study has done up to the date for investigation and comparison of available yield calculation models.

1.4 Objective of the Study

1.4.1 Overall objective

The overall objective of the present study is to investigate and compare present yield calculation models with observed yield to evaluate the capability of an ungauged catchment modeler in order to accurately estimate the yield for water management, infrastructure design and planning by carrying out in Kalu river and Attanagalu oya basins.

1.4.2 Specific objectives

Specific objectives of the present study are:

i. Study of yield application models and select appropriate models
ii. Develop computer models and application
iii. Analysis of generated monthly, seasonal and annual yields for different scenarios
iv. Evaluation and making recommendations for an engineer to practice in the field.

1.5 Study Area

The study area considered for the research is Dunamale watershed in Attanagalu oya river basin and Ellagawa watershed in Kalu river basin. Both basins are situated in the wet zone of Sri Lanka.

1.5.1 Dunamale watershed in Attanagalu oya river basin

Attanagalu oya river basin is located in between of 7° 00´ and 7° 17´N latitudes and 79°50´ and 80° 15´E longitudes. Watershed area is about 854 Ha. Diyella oya and Uruwal oya are main tributaries of Attanagalu oya.

Dunamale which is a sub-watershed of Attanagalu basin, (Figure 1-1) is considered for the present study, considering the data availability. The area of Dunamale watershed is 157.5 km^2.

This watershed is comprised of three agro ecological regions as WL3, WL2, and WL1. Cultivations are done for Yala (April – September) and Maha (October – March) seasons and paddy farming takes a major portion. Dunamale watershed does not consist reservoirs and the water supplying and controlling for irrigation purposes is done through an anicut system (Manchanayake & Madduma bandara, 1999).

1.5.2 Ellagawa watershed in Kalu river basin

Kalu river basin is located in between latitudes of 6° 20´ and 6° 55´N, longitudes of 79°55´N and 80° 45´E and the catchment area is about 2816 km^2. Kuda Ganga from Millakanda is the main tributary of Kalu River. Recurrent flooding and inundation of downstream is a main problem for cultivations and approximately 50% of paddy cultivation is affected by the flood (Manchanayake & Madduma bandara, 1999).

Considering the data availability, Ellagawa watershed (Figure 1-2) of Kalu river basin was selected as the study area for the present study. The area of Ellagawa watershed is 1446.4 km^2.

The annual rainfall is between 2600 mm-4000 mm. The upper part of the watershed has steep slopes (Ampitiyawatta & Guo, 2010) and Tea and Rubber are major cultivations (Manchanayake & Madduma bandara, 1999). Lower part of the watershed consists of mild gradients (Ampitiyawatta & Guo, 2010) and Coconut, rubber, tea and paddy cultivations are agricultural land uses in the watershed.

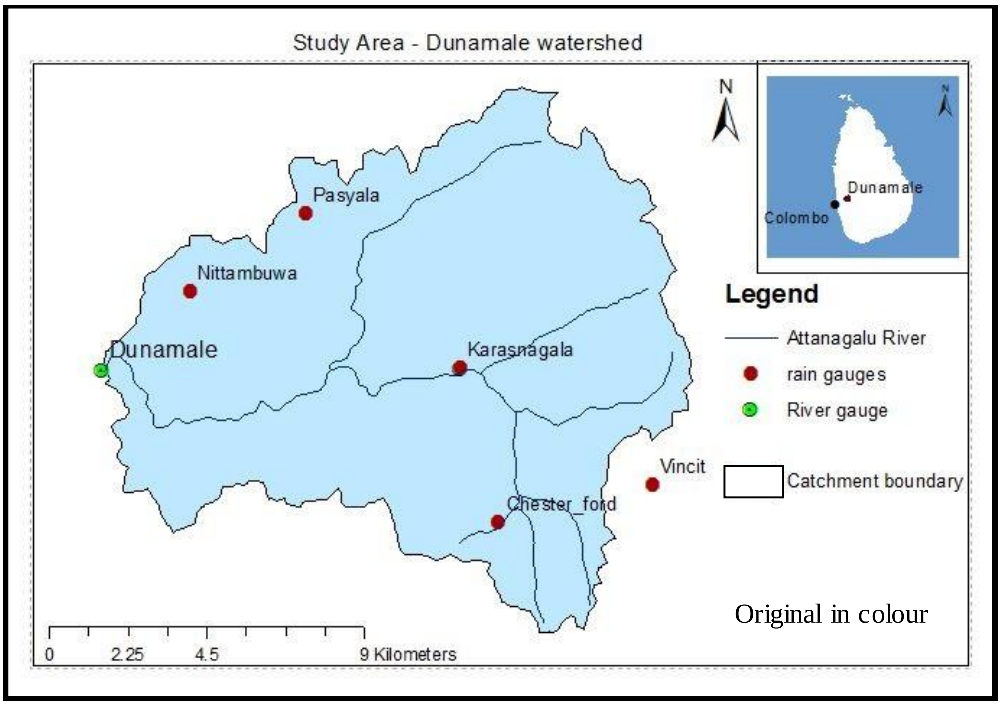


Figure 1-1: Study area - Dunamale watershed

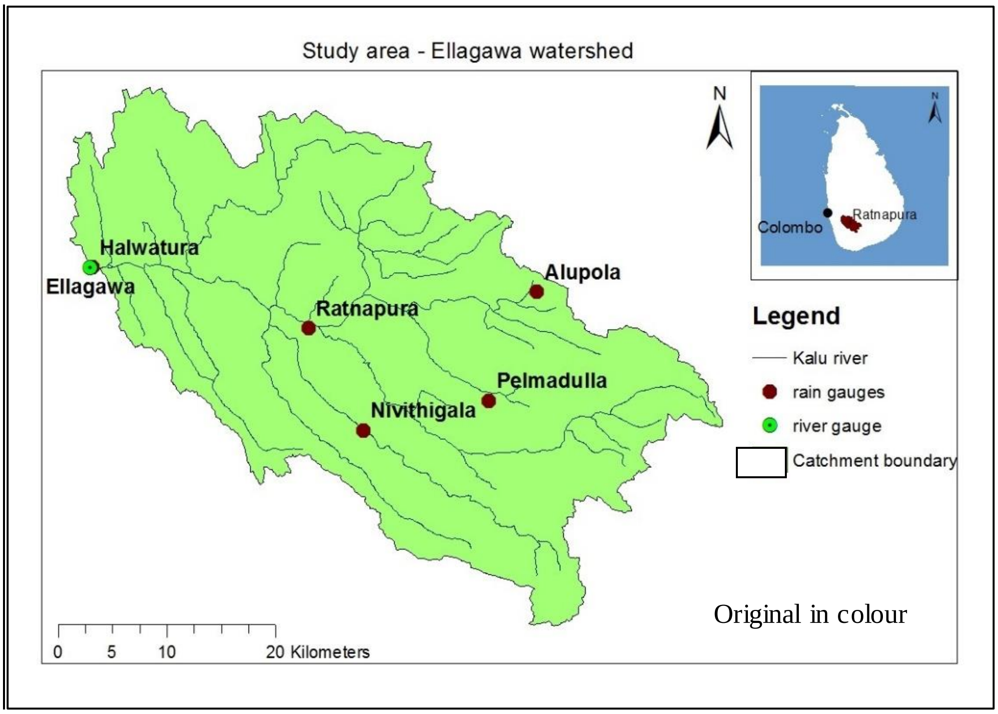


Figure 1-2: Study area -Ellagawa watershed

2 LITERATURE REVIEW

2.1 General

Irrigation systems are considered as the backbone of many nations because of their contribution to food security and the strength they provide to the large farming communities to survive amidst difficult living conditions. Reliable estimation of streamflow from watersheds is a key factor when carrying out planning and design of irrigation systems (Smakhtin, 2001). Streamflow gauging is a rarity, therefore world over, irrigation infrastructure development other than in the case of operation and maintenance projects is mostly on ungauged watersheds. In case of ungauged watersheds within a gauged watershed or otherwise, reliable streamflow extrapolation methods are required for rational engineering design. Even in the case of gauged watersheds the streamflow estimations are mentioned as unreliable due to poor monitoring of streams and lack of sufficient records to enable estimations (Ouarda, Charron, Hundecha, St-Hilaire, & Chebana, 2018).

Irrigation systems are large infrastructure investments for hundreds of years and cover vast extent of land. Hence, the reliability and accuracy of water yield estimation with magnitudes and patterns is one of a major concern for the sustainability of the systems. Value and the demand of water is rising with population increase and natural scarcity when demand rises with population increase. As a result, accurate yield estimation is a greater challenge faced by ungauged watershed managers and engineers. Hence, design yield for practical applications in ungauged watersheds need to identify a watershed model that will ensure the accuracy of estimations while incorporating appropriate safety factors.

In case of watershed streamflow estimations, on one hand, there are time tested and coarse resolution empirical models while on the other hand there are most recent generalized process based hydrologic models which can provide distributed outputs at finer temporal and spatial resolutions. Presently available guidelines show a clear necessity to provide adequate details for comparative evaluations in order to make a selection. Even at locations where models can be calibrated and verified, there is a need for the explicit identification of safety factors. The desire of practicing engineers and managers to use modelling advances for their work, makes it an urgent need to establish guidelines when design watershed yields are computed.

2.2 Watershed Yield and Uncertainties

Water yield form watersheds is the main factor for rational water use decisions. Hence watershed yield is the most important input for reservoir systems that treat water as a resource. Dependable yield is useful and important in water management systems especially during droughts (Ward & Trimble, 1995). In literature, water yield is referred to as watershed yield, watershed runoff, streamflow, watershed outflow, catchment inflow to reservoirs etc. Watershed yield is the amount of streamflow accumulated over a time period and at a particular geographic location. Rainfall and the rainfall distribution over the catchment (Ponrajah, 1984), soil type, vegetation, Slope and catchment size, surface roughness, land use pattern (Mungai, Ong, Kiteme, Elkaduwa, & Sakthivadivel, 2004) are the factors affecting for seasonal runoff yield.

Design watershed yield corresponds to the streamflow from a watershed which is considered as the inflow for engineering infrastructure designs. In order to ensure safe designs, it is necessary to accommodate safety factors to account for real world uncertainties.

Streamflow assessments for water use is mainly associated with medium and low flows (Ouarda et al., 2018). Accordingly, planning and engineering for water use is concerned with the complete streamflow hydrograph over a representative period of several years (Chow, Maidment, & Mays, 1988). The evaluations and recommendations for water use are commonly based on either monthly or seasonal temporal scales (Beard, 1972; Beard, 1967; Beard et al., 1977). Guideline of the Irrigation Department of Sri Lanka (Ponrajah, 1984), the references corresponding to India (Bureau of Indian Standards, 1974), and many others for water planning in irrigation and associated development are for monthly or coarser time resolutions(Department of Irrigation, Nepal, 1990; Irrigation Branch, Pakistan, 1943; Field and Collier, n.d.)

Watershed yield estimations face two main types of uncertainties, one is the uncertainty associated with respect to the determination of watershed rainfall. The other is the uncertainty associated with respect to the model chosen to represent the watershed heterogeneity and associated hydrologic and hydraulic processes (Griffiths et al., 2008; Bourdin and Stull, 2013; Olsson and Lindström, 2008). Issues such as inadequate representation of hydrologic processes, lack of guidance on parameter values, optimization deficiencies coupled with the mathematical algorithms etc., cause uncertainties that need to be considered when converting model outputs as design watershed yield (Troin et al., 2017; Pathiraja et al., 2018).

Considering rainfall related uncertainties, there are two types, (1) watershed averaged rainfall with point measurements (2) uncertainty due to occurrence of rainfall. . In hydrologic computations, uncertainty of rainfall is dealt by considering the probability of occurrence. The same of a selected model is taken care of by considering the accuracy of model estimations. However in the conventional design processes of water resources engineering projects, only the rainfall measurement and computational uncertainties are considered by selecting a large return period and artificially considering this design level as a safety factor (Chow et al., 1988; Shaw et al., 2010; Mays, 2004).

Design watershed yield corresponds to the streamflow from a watershed which is considered as the inflow for engineering infrastructure designs. In order to ensure safe designs, it is necessary to accommodate safety factors to account for real world uncertainties.

2.3 Yield Computation Options

2.3.1 General

Watershed yield calculation options in guidelines and textbook references are either direct, empirical, or simple conceptual models (Ward and Trimble, 1995; Chow et al., 1988; Ponrajah, 1984; Department of Irrigation, Nepal, 1990; Irrigation Branch, Pakistan, 1943; Shaw et al., 2010; Drainage services department, Hong Kong, 2018; Viesseman and Lewis, 2003; Wurbs and James, 2002). Direct methods use streamflow observations at the site of interest; empirical methods recommend derived relationships between observed streamflow and watershed parameters; the mathematical methods propose hydrologic models which rely on fundamental laws of known physics.

Watershed yield calculation methods have developed from the use of regression type (Chow et al., 1988; Haan, 1972; Haan and Allen, 1972), to sophisticated process based hydrologic models such as Hydrologic Engineering Centre – Hydrologic Modelling System (HEC-HMS), Soil Water Assessment Tool (SWAT), Storm Water Management Model (SWMM). These methods which vary between empirical and mathematical models are either available as guidelines (Chow et al., 1988; Bureau of Indian Standards, 1974; Irrigation Branch, Pakistan, 1943; Shaw et al., 2010; Viesseman and Lewis, 2003, Willardson et al., 2006; IOWA Department of Natural resources, 2007; Minnesota Stormwater Steering Committee, 2008; Department of Irrigation and Drainage, Malayasia, 2000) or can be found as research publications (Cunderlik and Simonovic, 2004; Abushandi and Merkel, 2013; Sampath et al., 2014; Wang et al., 2014; Wang and Altunkaynak, 2012; Liong S. Y. et al., 1991;Bhunya, 2011;Anderson M. L. et al., 2002)

Rydzewski (1987) describes the options under the direct method category that could be applied with either observed or generated data. In general, historical repetition methods, random generation techniques, and persistent methods are the Synthetic streamflow generation methods (Chow et al., 1988; Viesseman and Lewis, 2003; Subramanya, 2014; Chow et al., 1988) recommends the use of synthetic streamflow generation and random number generation to prepare synthetic streamflow records that are statistically equivalent to historical records.

Empirical methods are mostly rainfall and streamflow correlations while there are several with relationships using rainfall and other climatic or watershed characteristics (Subramanya, 2014; Khopade and Oak, 2014; Reddy, 1993). Hydrologic Engineering Centre guidance material on reservoir yield estimation combine to introduce empirical inflow estimation methods (Beard, 1972; Beard, 1967; Beard et al., 1977).

Binnie's percentages (Annual runoff), Inglis and DeSouza formula (Annual runoff), Barlow's tables (seasonal runoff), Strange's tables (daily runoff), Khosla's formula (monthly & annual runoff) are some common empirical formulas used for estimate catchment yield in India and Pakistan (Irrigation Branch, Pakistan, 1943; Subramanya, 2014; Reddy, 1993;Tabesh and Bhave, 2015; Bavishi, 2017). Parkers formulae for Britain, Germany and East USA (annual runoff) are other common empirical formulae (Reddy, 1993; Bavishi, 2017).

2.3.2 Guideline recommendations

2.3.2.1 Irrigation guidelines in different countries

Saudi Arabia (Hussain, Alquwaizany, & Al- Zarah, 2010), British Colombia (Tam, Nyvall, & Brown, 2005), and water requirements for European union (Wriedt et al., 2008) does not provide a method for catchment yield estimation. Irrigation guide of Natural resources conservation service, USDA, 1997 provides calculation methods of crop water requirement, soil water requirement and water balance methods, but does not recommend a yield estimation method. Guidelines for agriculture based South Asian countries such as India (Bureau of Indian Standards, 1974), Pakistan (Irrigation Branch, Pakistan, 1943) and Nepal (Department of Irrigation, Nepal, 1990) provide yield calculation options. According to Indian standard, flow forecasting and yield estimation is done based on previous data records, by using rainfall runoff coaxial relations and unit hydrograph method (Bureau of Indian Standards, 1974). A format for 12 hour unit hydrograph calculation is given in the guideline. Vermeule formula and Khosla’s formula are main formulas that based on precipitation and a temperature factor, used for estimation of runoff in Pakistan. Maximum discharge from a catchment is calculated by Inglis formula, Khangar and Gullhati’s formula (Irrigation Branch, Pakistan, 1943). These empirical formulas seem to have some safety factors embedded.

In Nepal guideline, ungauged catchment runoff is estimated by 2 methods as (1) WECS regional regression for long term (mean and low) flows, (2) MIP design manual method for mean 80% flows. According to WECS method, mean monsoonal precipitation iso-lines that had been developed for the entire country and monthly flow is calculated by use of monthly coefficient constant. According to MIP method, Country is divided for 7 regions & mean monthly flow and 80% reliable flow charts have been developed. 80% monthly flow value is taken for design criterion for irrigation schemes for the reliability of full supply. The concept of "hydrologically similar catchments" is used for getting runoff values when there is a lack of data (Department of Irrigation, Nepal, 1990). Nepal guideline provides mean monsoon precipitation isolines and typical hydrographs for Karnli river at Chisapani and Sabhaya Khola at Hokse. And also it provides options and constraints for estimation of flow. Regional hydrographs for mean monthly flow are also providing for different regions.

Storm water drainage manual, Hong Kong (Drainage services department, Hong Kong, 2018) while recommending the use of many statistical and deterministic models, highlights the details of common deterministic models (rational method, time area method, UH method and reservoir routing models). Australian Rainfall Runoff guidelines (Institution's technical committee on Stormwater standards, 1972; Ball et al., 2016) provide methodologies on estimation of rainfall, flood estimation and surface runoff estimation. Areal reduction factor, that can be considered as a safety factor for rainfall is provided in both editions. Though simple and design event hydrograph estimation methods provided in the old edition (Institution's technical committee on Stormwater standards, 1972), Ensemble and Monte Carlo methods are included in the new guideline (J. Ball et al., 2016). Uncertainty in design rainfall estimation and design flood estimation is discussed in both guidelines.

Los Angeles Hydrology manual (Willardson et al., 2006) states rational method and modified rational method as yield estimation methods and pros and cons of each methods are described. According to urban stormwater management manual (Department of Irrigation and Drainage, Malayasia, 2000), IDF curves, rainfall pattern tables, rational formula, SCS curve number based unit hydrograph were recommended for yield estimation. Minnesota storm water manual (Minnesota Stormwater Steering Committee, 2008), IOWA stormwater management manual recommends runoff coefficient and rational method for yield estimation. Also, are many literature recommending unit hydrograph approach for yield estimation (IOWA Department of Natural resources, 2007; Willardson et al., 2006; Minnesota Stormwater Steering

Committee, 2008; Bay of Plenty Regional Council, 2012; Hydrologic research laboratory, US, 1972; SEMSWA Board of Directors, City of centennial, 2012).

2.3.2.2 Irrigation guideline in Sri Lanka

A large number of technical notes and guidelines relevant to Sri Lanka had been prepared by the Designs Branch of the Irrigation Department in the period of Eng. A.J.P. Ponraja and published in 1984 relevant to catchments less than 52 square kilometres (Ponrajah, 1984). This guideline is presently used for irrigation design purposes of Sri Lanka.

Reservoir capacity and irrigable extent depends on the amount of rainfall, runoff and the distribution of rainfall over the crop season. Seasonal yield means the seasonal runoff. Iso-yield curves in Irrigation guideline facilitate the calculation of seasonal runoff. Iso-yield curves had been developed by considering main monsoon seasons (Yala and Maha) in Sri Lanka. (Ponrajah, 1984).

Rainfall and the rainfall distribution over the catchment (Ponrajah, 1984), soil type, vegetation, slope and catchment size, surface roughness, land use pattern (Mungai et al., 2004) are the factors affecting for seasonal runoff yield. Irrigation guideline of Sri Lanka has provided a method to calculate monthly and seasonal yield. According to the irrigation guideline, the net catchment area multiplied by the specific seasonal yields, gives the seasonal yield for Yala and Maha seasons (Ponrajah, 1984). Net catchment area is the net area obtained by removing catchments of all established and operating works in the gross catchment. In the irrigation guideline, immediate upstream fields were assumed as contributing to the yield and 20% of the irrigation water supply was observed reusable. 75% rainfall is used for yield calculations. Sri Lanka is divided in to 25 agro- ecological regions and 75% probability is calculated for each region. With the purpose of prevailing economic and social factors, irrigation guideline has recommended 75% probable rainfall for design purposes. Long Term Monthly Rainfall (LTMR) records show a probability of 40% -50% and it gives higher rainfall values than 75% rainfall. According to the Irrigation guideline, success of cultivation will be 75% of total success and certain percentage additional. Seasonal yield calculations have safety factor limitations of 35% as the upper limit and 7.5% as the lower limit. The reason for the limitations is that, Iso-yield curves have been developed extrapolating from larger catchments to small catchments (<20 square miles) and there was a need to levy upper and lower limits to the seasonal rainfall.

Several researchers showed the need of verification of design parameters of present Irrigation guideline (SL) due to climatic changes and land use pattern changes, changes of irrigation practices (Nawaratne and Gunawardene, 1999; Wijesekera and Wickramaarachchi, 2003a). In the guideline, apportioning to months and application threshold recommendations are expected to lead the computation of safe watershed yield.

Nawaratne and Gunawardene, (1999) has done a study for verification of design parameters of Irrigation design guideline for operational studies of minor tanks of dry zone considering two minor tanks in Anuradhapura district. Reservoir operations were done considering inflow, outflow and water losses measured during a period of 3 years. Results showed that the existing 75% probability rainfall does not represent DL1 agro ecological region mainly due to spatial variation of the rainfall. According to the research, existing procedure given by (Ponrajah, 1984) tends to overestimate the water available for irrigation and the reason is under estimation of seepage and percolation losses. Wijesekera and Wickramaarachchi, (2003b) has done a research to evaluate water use practices in irrigation schemes of Mahaweli H and concluded that canal efficiency assumptions are different, land preparation water use and quantity are dissimilar, water releases do not consider much about growth stages. They finally recommended that there is a need for a critical evaluation of guidelines and present practices of cultivation.

2.4 Modern Hydrological Models

2.4.1 Setting

There are many streamflow estimation computer models which facilitate detailed modelling of many hydrological processes in a watershed at high spatial and temporal resolutions. There are brief text book references to popular models such as HEC-HMS, SWMM, SWAT, TR20, TR55, HSPF (Mays, 2004; Viesseman and Lewis, 2003; Wurbs and James, 2002; Subramanya, 2014; Ali, 1993). These and many other popular computer based watershed models which provide individual detailed technical documentation on the incorporation and use of hydrologic rationalizations in model computations.

UH is a popular recommendation among the guidance materials on watershed runoff estimation. Snyder's Synthetic Unit hydrograph (Snyder, 1938), the Soil Conservation Service (SCS) Unit Hydrograph (United States. Soil Conservation Service., 1972) and Clarks' unit hydrograph method, Grays' method etc., are commonly selected streamflow computation methods (Salami et al., 2009a; Yen and Lee, 1997; Yang and Han, 2006). Derivation of a composite hydrograph by using a series of unit hydrographs enables the generation of streamflow times series. Chow et.al., (Chow et al., 1988) provide details on the potential of using UH for the generation of hydrograph and the use of Kinematic Wave method for routing along stream channels to capture the hydrograph at a desired location. There is a wide variety of research that had taken place on UH applications, parameter optimization, parameter identification with physical characteristics, parameter transferability etc., (Meier, 1964;Yang and Han, 2006; Agirre et al., 2005; Da Ros and Borga, 1997; Darya et al., 2018; López et al., 2005; Permatasari, 2017; Thapa, 2015; Tobgay, 2015).

One of the popular generalized water resources engineering models is the package consisting of the Hydrologic Modelling System (HEC-HMS) and River Analysis System (HEC-RAS) developed by the Hydrologic Engineering Center (HEC). HEC-HMS , which is capable of handling any watershed and a river system (Wurbs & James, 2002) and recommended after many research (Cunderlik and Simonovic, 2004; Abushandi and Merkel, 2013; Scharffenberg and Fleming, 2006; Sardoii et al., 2012; Derdour et al., 2018; Gumindoga et al., 2017). HEC model can be used for both continuous and event based modelling (Cunderlik & Simonovic, 2004) and simplified model formulation gives quick, precise, accurate results (Scharffenberg & Fleming, 2006). Many researchers had used HEC-HMS modelling for different catchments all over the world and obtained acceptable results (Abushandi and Merkel, 2013; Anderson M. L. et al., 2002; Sardoii et al., 2012; Derdour et al., 2018; Gumindoga et al., 2017; Chu Xuefeng and Steinman Alan, 2009). HEC-1 (Hydrologic Engineering Centre Flood hydrograph package) is recommended by several authors (Ali, 1993;

Zakaria, 2015; Yusop et al., 2007) for runoff estimation. There are many Sri Lankan applications for HEC-HMS model for Kalu (Jayadheera, 2016; Kanchanamala et al., 2016) Kelani (Silva, Weerakoon, & Herath, 2014), Deduru (Sampath et al., 2014) Nilwala (Ratnayake, Sachindra, & Nandalal, 2010) and Attanagalu (Halwatura & Najim, 2013) river basins. These reported research works are with individual preferences for process model selections and a wide variety of model parameters.

2.4.2 HEC-HMS modelling

HEC-HMS model can be used for both continuous and event based model development (Cunderlik & Simonovic, 2004) and has simplified model formulation, simplified flow representation; simplified model formulation gives quick, precise accurate results while simplified flow representation shows efficient process and reduces duplication (Scharffenberg & Fleming, 2006).

2.4.2.1 Model structure

According to the manual of the software, HEC-HMS has three basic model components as, (1) basin model, (2) meteorological model, (3) control specification. Basin model is to convert atmospheric conditions in to streamflow at specific locations of the watershed. Meteorological model is for preparing meteorological boundary conditions to sub-watersheds. HEC-HMS supports one evapotranspiration method and six different precipitation methods. Control specifications control the simulation time span. Precipitation loss method, Transform method, Base flow method are main components of the basin model. There are 12 different precipitation loss methods in HEC-HMS and the purpose is to simulate the actual surface runoff, reducing the infiltration. Infiltration, surface runoff and subsurface processes acting together in the real world. Transform method is created to perform actual surface runoff calculations. There are 8 different transform methods in HEC-HMS. Base flow method is created to simulate subsurface processes and 6 different methods are provided in the software. Short wave radiation method, Precipitation method, Evapotranspiration method and snow melt method are main components of meteorological model. Depending on the application, hydrologic modelling in HEC-HMS can be event based (Silva et al., 2014) or continuous (Silva et al., 2014).

2.4.2.2 Model application studies

HEC- HMS is a freely available simple software. Therefore it has been applied for many cases.

Abushandi & Merkel, (2013) has applied HEC-HMS model to Wadi Dhuliel catchment in Jordan to simulate a single streamflow event. Hourly data resolution was used and calibration and validation was done using observed streamflow data. SCS Unit hydrograph method used as transform method while using SCS Curve number method for loss method. Calibrated data set fitted well with the observed data set.

Sardoii, Rostami, Sigaroudi, & Taheri, (2012) has done a comparison of different methods for runoff loss evaluation in Amirkabir watershed in Iran that covers 778 km^2 of area. They have used Green and Ampt, Initial constant and SCS curve number method as loss methods. Seven rainfall events were used for simulation and one for validation. According to the results, Green and Ampt method showed the least error percentage among other two.

2.4.2.3 Reviewing HEC-HMS model applications for Sri Lanka

Considering the present available literature, HEC-HMS model development applications were reviewed and model parameters were selected (Table 2-1).

2.4.3 Unit hydrograph model (UH)

Unit hydrograph concept was first proposed by Sherman in 1932 using observed rainfall runoff data with the purpose of rainfall runoff simulation in ungauged catchments (Yen & Lee, 1997). Chow, Maidment, & Mays, (1988) recommends this method for watersheds of area equal or less than 5180 square kilometers. Bhunya, (2011) states that to avoid the data availability requirement, the Synthetic Unit Hydrograph (SUH) concept was developed to derive a unit hydrograph synthetically considering catchment characteristics.

2.4.3.1 Unit Hydrograph Basic Assumptions and Applicability

Uniform distribution of constant excess rainfall intensity and unchanged catchment characteristics within the rainfall period is assumed in unit hydrograph derivation (Chow et al., 1988). Common base time and ability for super imposing are other assumptions. The unit hydrograph is inapplicable for runoff generated from snow or ice, when drainage area is too large to be covered by nearly uniform distribution of rainfall, when watershed has an appreciable storage and when channel conditions changed (Chow et al., 1988).

2.4.3.1 Synthetic Unit Hydrograph

Uniformity of rainfall throughout the entire catchment, constant hydrograph base time for a given rainfall, and unchanging characteristics of a given watershed have been described as the assumptions that can limit the use of the unit hydrograph and applicability of superposition is assumed, the composite hydrograph is a linear combination of the unit hydrograph ordinates (Chow et al., 1988)

There are many techniques to derive synthetic unit hydrograph and they are such as Snyder’s method, SCS curve number method, Clarks’ unit hydrograph method, Grays’ method etc. (Salami et al., 2009b). Comparison of different UH methods are in Table 2-4.

Table 2-1: HEC-HMS model applications for Sri Lanka

Basin	**Reference**	**Data period**	**Calibration and Validation**	**Loss method**	**Transform method**	**Base flow method**
Kalu river basin	(Jayadheera & Wijesekara, 2016)	2006-2014	Calibration 2006-2010, Validation 2010-2014	Deficit & constant	SCS UH	Recession
	(Kanchanamala, Herath, Nandalal, 2016)	1986-1995	Calibration 1986-1990, Validation 1991-1995	Deficit & constant	Snyder's UH	Recession
Deduru Oya	(Sampath, Weerakoon, Herath, 2015)	1986-1989	3 months calibration – 3 years validation	Five layer moisture accounting	Clark UH	Recession
Kelani basin	(De Silva, Weerakoon, Herath, 2014)	4 extreme events, (November 2005, April-May & May-June-2008, May 2010)	Calibrated for extreme event of November 2005 and validated for other events	Green & Ampt	Clark UH	Recession
Nilwala basin	(Kanchanamala, Herath, Nandalal, 2010)	Extreme events (September 1974, May 1975, May 1978, June & September 1979, July 1984)	3 extreme events for calibration, 3 extreme events for validation (1974-1984)	Green & Ampt	Clark, Snyder, SCS UH methods	Recession
Attanagalu	(Halwatura & Najim, 2013)	2005-2010	Calibration 2005-2007 Validation 2008-2010	SCS curve number, Deficit & constant	Clark, Snyder UH methods	Not mentioned

2.4.3.2 Cp and Ct – Regional parameters

The main coefficients of Snyder's method are Ct which is a coefficient representing variations of watershed slope and storage and Cp which is a coefficient accounting for flood wave and storage conditions (Salami et al., 2009b). Ct and Cp are non-dimensional constants in Snyder's unit hydrograph method and varies in the range of 1.8-2.2 and 0.56-0.69 respectively (Bhunya, 2011). According to Miller, Kerr and Spaeder (1983) (as cited in Bhunya, et al., 2011) Ct varies in between 1.01-4.33 while Cp is in the range of 0.23-0.67. According to Hudlow & Clerk (1969) 0.4-2.26 is the range of Ct and Cp varies in between 0.31-1.22 (Table 2-2). Regional parameters for Sri Lankan watersheds are stated in Table 2-3.

Considering inconsistencies in Snyder's method, (Bhunya, 2011) states that,

a) An error can occur due to manual fitting of the characteristic points because a great degree of subjectivity and a trial and error procedure is needed.
b) Ct and Cp changes differ from region to region
c) The time base is always greater than 3 time units, when deriving the unit hydrograph and therefore the method can be used only for fairy large watersheds.

Table 2-2: Regional parameter ranges from different literature

Reference	**Cp range**	**Ct range**
Bhunya, (2011)	0.56-0.69	1.8-2.2
Miller, Kerr and Spaeder (1983)	0.23-0.67	1.01-4.33
Hudlow & Clerk (1969)	0.31-1.22	0.4-2.26

Table 2-3: Regional parameter values for Sri Lankan watersheds

Reference	**Basin**	**Cp**	**Ct**
Thapa Gautham., (2014)	Karasnagala	0.38	3.75
Wijesekera, (2000)	Kalu basin	0.47	8.7
	Maha Oya	0.9	1.67
	Kelani Ganga	0.55	3.76
Ponrajah, (1984)	Putupaula	0.47	8.7
	Holumbuwa	1.0	2.52

Table 2-4: Comparison of Different Unit Hydrograph Models

Snyder's UH	**SCS UH**	**Gray method**	**Taylor and Schwarz (TS) Model**
Simple and easy	Simple and easy	Model is complex	Simple and easy
Less data requirement	More data equirement	More data requirement	More data requirement
Catchment characteristics accounting	Catchment characteristics accounting	Catchment characteristics accounting	Catchment characteristics accounting
Less number of parameters (Cp, Ct)	Less number of parameters (CN)	More parameters (2 parameters in γ, shape parameter, γ')	Less number of parameters (m1,m2)
Ct and Cp vary over wide range and from region to region, and may not be equally suitable for all the regions	SCS method overestimates the Peak discharge, underestimates the rising limb, and closely matches with the recession limb of the hydrograph.	over-estimates the peak discharge, under-estimates discharges in both rising and receding phases of the hydrograph, and reduces the time base	Parameters vary over wide range and from region to region, and may not be equally suitable for all the regions
reasonable for fairly large watersheds only	application to large and midsize watersheds may lead to erroneous results	empirical relationships are watershed size specific, and should be used with in the area limits for which these are developed	reasonable for fairly large watersheds only
manual fitting of the characteristic points needed great degree of subjectivity and trial and error, and may involve error	SCS method fixes the ratio of time base to time to peak (tb/tp) for triangular UH equal to 2.67 (or 8/3), ratios other than this may lead to the other shapes of the UH		manual fitting of the characteristic points needed great degree of subjectivity and trial and error, and may involve error
Literature available for Sri Lankan studies	Literature available for Sri Lankan studies	Literature not available for Sri Lankan studies	Literature not available for Sri Lankan studies

Ranking of methods: 1-Snyders' UH, 2-SCS UH, 3- Taylor and Schwarz (TS) Model, 4 – Gray method

2.4.4 Effective rainfall

The rainfall that is contributing to the direct runoff, without retaining in the land surface or infiltrated in to the soil is defined as effective rainfall (Chow et al., 1988). There are numerous methods to estimate effective rainfall and direct measurement techniques, empirical equations and soil water balance methods are some of them (Patwardhan, Nieber, & Johns, 1990). Φ- index is a simple method to estimate effective rainfall and it is defined as the constant rate of abstractions that will yield an excess rainfall hyetograph with a total depth equal to the depth of direct runoff over the watershed (Chow et al., 1988).

Soil water balance is considered as the best technique to calculate effective rainfall, while it considering all necessary components of water balance (Patwardhan et al., 1990). Hershfield nomograph estimates the effective rainfall (Patwardhan et al., 1990) by using mean annual rainfall, mean annual evapotranspiration and net irrigation amounts, but the method is not suited for rice growing lowlands (Mohan, Simhadrirao, & Arumugam, 1996). USDA- SCS method calculates effective rainfall and developed with water balance calculations of 50 years (Patwardhan et al., 1990) shows under predicted values for South Indian watersheds (Mohan et al., 1996). Irrigation department guideline shows an empirical equation methodology to estimate effective rainfall considering lowland and upland areas of Sri Lanka (Ponrajah, 1984). Integrating gauge, Ramdas apparatus, Lysimeters, Drum technique, Evapotranspiration to precipitation ratio and empirical methods from India, Japan, Vietnam and Burma are some other techniques for calculating effective rainfall (Dastane & Nations, 1974). According to Dastane & Nations, (1974) evaluation of different effective rainfall methods is shown in Table 2-5.

Table 2-5: Evaluation of effective rainfall techniques (Dastane & Nations,1974)

Methods	**Factors taken in to account**				**Special equipment**	**Accuracy**	**Remarks**
	R	**S**	**A**	**C**			
Field studies on soil moisture	+	+	+	+	+	Very high	Good for verify other methods, practicability is low
Daily soil water balance with ETa	-	+	+	+	+	Very high	Practicability is medium
Integrating gauge	-	+	+	+	+	Medium	Needs careful standardization
Ramdas apparatus	-	+	+	+	+	High	Practicability good
Lysimeters	-	+	+	+	+	Very high	Practicability is medium. Good to check other methods
Drum technique	+	+	+	+	+	Very high	Practicability high
Renfro equation	-	B	+	-	+	Low	Too empirical
US bureau reclamation method	+	-	-	-	-	Low	Not suitable for wide use
Ratio of ETp to precipitation	B	B	+	-	-	Medium	Satisfactory for preliminary planning purposes
USDA, SCS method	-	B	+	B	-	Medium	Good for areas with low intensity of rainfall and high soil infiltration rate
Empirical methods	B	B	B	B	-	Medium	Practicability is very high

(Dastane & Nations,1974)

R – Runoff, S – Soil, A – Aridity, C - Crop, B – First approximation, + (positive), - (negative)

A comparative study of effective rainfall calculation methods considering USDA-SCS, Indian1(FAO), Indian2(FAO), Vietnam(FAO), soil water balance and rainfall ratio methods for South Indian watersheds shows the results of Indian 2, rainfall ratio and soil water balance methods show comparatively similar results (Mohan et al., 1996). For Sri Lankan case studies, Manchanayake (1985) has stated average loss rates calculated by two different methods for 9 Sri Lankan watersheds. Average loss rate for Karasnagala watershed is calculated and verified as 1.2 mm/hr by Thapa (2015).

2.4.5 Baseflow estimation

Baseflow is the water discharged from groundwater storage which reacts slowly to rainfall and contributes to the streamflow (Eckhardt, 2008). There are three main techniques for baseflow analysis as baseflow separation, frequency analysis and recession analysis (Brodie & Hostetler, 2005). Empirical relationships, constant discharge, constant slope, concave, trends of falling limbs in hydrograph are some graphical separation methods and smoothed minima technique, local minimum method, fixed interval method, sliding interval method, streamflow partitioning method and filtering separation methods (Brodie & Hostetler, 2005).

Flow duration curves, low flow frequency curves, spell durations and deficiency volumes can be categorised as frequency analysis methods (Nathan & McMahon, 1992). Recession curves, storage outflow models, plotting flow ratios, correlation methods, recession ratio methods fall under recession analysis methods (Brodie & Hostetler, 2005).Traditional recession curves are based on nonlinear and static linear reservoir models and they work well for groundwater dominated recession curves, but when the direct runoff part is significant, models do not work well (Hammond & Han, 2006). Peña-Arancibia, Van Dijk, Mulligan, & Bruijnzeel, (2010) have estimated recession coefficients using 167 tropical catchments and the overall recession coefficient was 0.08 ± 0.053 day^{-1}. Among different regions, for continental Southeast Asia, the recession coefficient was estimated as 0.04-0.07day^{-1} (Peña-Arancibia et al., 2010).

Baseflow estimation for ungauged watersheds is a difficult task due to lack of suitable data (Nathan & McMahon, 1992). River regime groups, Baseflow indexes, Storage yield analysis and Recession methods can be used for ungauged catchments depending on data availability (Nathan & McMahon, 1992). A global classification of river regimes and seasonal flow classification was done by (Haines, Finlayson, & McMahon, 1988) considering the regions of Asia, Africa, North America, South America, Europe and Oceania. Welderufael & Woyessa, (2010) has done a baseflow separation methods comparison for Modder river basin in Central South Africa by using Nathan & McMohan equation, Chapmen equation, Smatkin & Whatkins method and frequency duration analysis. Results showed that all the methods other than Smatkin & Whatkins method show a higher percentage of low flow component (65% to 84%). Smatkin & Whatkins method underestimates the low flow. Baseflow index (volume of baseflow divided by the volume of total flow) is another low flow estimation method based on the concept of permeability index (Longobardi & Villani, 2008) that can be used for ungauged catchments (Nathan & McMahon, 1992). Accurate catchment geology spatial variability will reduce baseflow index error by 23% 14%. Annual baseflow index was calculated in Michigan using 17 gauged watersheds and their characteristics by Zhang, Ahiablame, Engel, & Liu, (2013) and observed the baseflow variation from 162 to 345 mm and BFI variation from 0.45-0.8 during 1967-2011.

Yoshida & Troch, (2016) evaluated the hydrological response of 14 volcanic catchments of different ages in Japan by using water balance, Baseflow Index and flow duration curves. Results showed a decrease in baseflow and the drainage density with the catchment age, and baseflow index values were changed from 0.533 to 0.835.

Lacey & Grayson, (1998) has studied the influence of vegetation, geology, catchment properties, topographic and climatic influences for baseflow index by considering 114 catchments in Victoria, Australia ranging from 0.05-192 km^2. According to results, baseflow index had a strong relationship with vegetation-geology groups and no relationship with topographic parameters. A weak relationship was shown with climatic parameters.

Bloomfield, Allen, & Griffiths, (2009) used linear regression method to quantify BFI in 44 natural catchments from Thames river basin, UK. The mean observed BFI for

Thames basin was 0.65. Model calibration by 44 catchments and the validation by 110 other variably impacted catchments chowed a correlation of modelled and observed BFI. However observed BFI was significantly higher than modelled BFI.Global patterns in Baseflow index were studied by Beck et al., (2013) by using the observations from 3394 catchments for various parts of the world, including a Sri Lankan wet zone catchment. Considering climatic and physiographic characteristics, 13 categories were selected and wet zone of Sri Lanka was included to "Tropical rainforest" category where median BFI for tropical rainforest was 0.77 while tropical monsoon BFI was 0.74.

Table 2-6: Literature reported BFI values

Study Area	**BFI value**	**Reference**
River Thames (44 small catchments)	0.65	(Bloomfield et al., 2009)
UK catchments	0.41-0.98	(Johnes, 2006)
Agricultural catchments, Ohio, USA (28 catchments)	0.4-0.7	(Longobardi & Villani, 2008)
114 Catchments, Victoria, Australia (0.05 km^2 to 192 km^2 area)	0.49	(Lacey & Grayson, 1998)
14 Volcanic catchments, Japan	0.533-0.85	(Yoshida & Troch, 2016)
Zimbabwe	0.05-0.3 -Cristalline rocks 0.5-0.7 – Well watered eastern highlands	(Mazvimavi, Madamombe, & Makurira, 2007)
World	tropical, rainforest -0.77 tropical, monsoon -0.74 tropical, savannah -0.71 arid, desert -0.49 arid, steppe -0.57 temperate, dry summer -0.65 temperate, dry winter -0.67 temperate, no dry season -0.63 cold, dry summer -0.77 cold, dry winter -0.74 cold, no dry season -0.74 polar, tundra -0.64 polar, frost 0.70	(Beck et al., 2013)

Considering Sri Lankan case studies, (Wanniarachchi, 2016; Thapa, 2015) and (Tobgay, 2015) used concave method for baseflow separation in their studies. Wijesinghe & Wijesekera, (2014) used linear baseflow concept for separating baseflow in Karasnagala-Attanagalu basin. The term average non-separated flow based on many assumptions and catchment characteristics of large number of British watersheds were used for baseflow estimation in six sub catchments in Victoria, Randenigala and Rantambe sanctuaries by Dhanapala & Jayasena, (1998).

In literature, there are no BFI values for Sri Lanka. Values found in the literature are presented in Table 2-6.

2.4.6 Model application studies

Unit hydrograph modelling is a popular method used for ungauged catchments due to less data requirement, simplicity (Bhunya, 2011) and no requirement for calibration. Therefore many studies have been done in various parts of the world using this concept. Salami et al., (2009) has studied catchments of eight rivers in South west, Nigeria using synthetic unit hydrographs developed by Snyder, Soil Conservation Service and Gray's method. Return periods of 20-year, 50-year, 100-year, 200-year, 500-year had been used to compare peak flows. According to the results, unit hydrograph developed by using SCS method had given the most acceptable results for actual conditions.

Yen & Lee, (1997) has done a study of unit hydrograph derivation for ungauged catchments by using stream order. Geomorphologic instantaneous unit hydrograph method had been used for this study. Selected study area were two hilly watersheds in eastern United States and two flat-slope watersheds in Illinois. Results had shown that the hydrologic response to rainfall excess has a link to the geomorphological structure of the watershed. In this study comparison of hydrographs concluded that GIUH method is applicable for rainfall- runoff modelling.

Yang & Han, (2006) has done a study on derivation of unit hydrograph by using transfer function approach by using two events in England for demonstrating application of the model. The proposed model structure was based on removing the negative UH ordinates and guarantee a smooth curve. A discrete transfer function in the time domain was used and a model of physically realizable, numerically stable, easy implementing and parameter updating was derived.

A unit hydrograph application based on sub-catchment division was done by Aggire, et al., (2005) (Aggire, Goni, Lopez, & Gimena, 2005)using Aixola catchment in Gipuzkoa (Northern Spain). A geomorphology based unit hydrograph was used for the study. 18 observed rainfall events had been used. Linear reservoir methodology was applied for each sub-catchment and the results were compared with Nash's instantaneous unit hydrograph. Results showed similarities in GUHR model developed and the Nash's IUH model. Analysis of a unit hydrograph model considering the watershed as a cascade reservoir was done by López, Gimena, Goñi, & Agirre, (2005) considering 169 small agricultural watersheds in Central Navarre (Spain). By forming the structured sub-catchments along the drainage network and by limiting the area by iso-distance curves, the cascade had been determined.

2.5 Design Yield/ Yield Thresholds

In literature there is a clear deficiency of methods to compute the design yield from a watershed. Many point out the need for design yield computations to carefully examine the dependability of mathematical models and associated simplifications with regards to the reliability of streamflow estimations (Chow et al., 1988; Beard, 1972; Beard, 1967; Beard et al., 1977; Konukcu et al., n.d.; Mujumdar and Kumar, n.d.; Mujumdar and Ramesh, 1997).

Troin, Arsenault, Martel, & Brissette (2017) in their work stating that hydrologic model structure contributes most to uncertainty on the projected streamflow, indicate the importance to determine appropriate safety factors when determining design watershed yields. Bourdin and Stull, (2013); Olsson and Lindström, (2008); Mays,(n.d.) highlights the uncertainty in both the meteorological input and the hydrologic model discuss the importance of an appropriate final value for the hydrological forecast. Turner and Jeffrey, (2015) recognized the importance of clearly expressing methods to overcome the modelling uncertainties in order to make appropriate planning decisions associated with the development of water resources. Konukcu et al.,(n.d.) recognized the increased reservoir costs of reservoirs and the environmental hazards in agricultural area, due to over prediction of water yield by a method used by Turkish General Directorate of Rural Services.

2.5.1 Guideline recommendations

The need of judgement and experience, the inclination to err on the side of over estimating, and the incorporation of conservative factors (Drainage services department, Hong Kong, 2018; Argue et al., 2009; Wang and Singh, 2018; Xie et al., 2018) points to the adhoc approaches currently used for the determination of design watershed yield values.

Design streamflow estimation methods using the Hydrology Manual for Public Works (Willardson et al., 2006) considers only the rainfall uncertainty. Uncertainties and effects due to rainfall distribution over a catchment has been discussed with respect to watershed response (J. E. Ball, 1994); the need of further evaluation of rainfall distributions considering inter-event dry periods for the reliability of runoff predictions had been identified (Hvitved-Jacobsen & Yousef, 1988); the importance of design rainfall for hydrologic and hydraulic design calculations (J. C. Guo & Hargadin, 2009) are stated in literature but the lack of clear statements regarding design catchment yield must be noted.

There are practical situations that had considered only a percentage of dependable annual yield to cater to the randomness of watershed yield estimated either by using empirical or mathematical models (Khopade & Oak, 2014). A direct method to determine water availability at reservoir sites endorsed by the National Water Development Agency (NWDA) of the Ministry of Irrigation/ Water Resources, India has a design consideration which uses the 75% probable natural streamflow value in the multiplication factor that caters to inflow uncertainties ("(nwda.gov.in/upload/uploadfiles/files/5290347981.pdf). - Google Search," n.d.; Juharsyah, 2002). Irrigation guideline in Nepal uses 80% dependable yield for planning purposes (Department of Irrigation, Nepal, 1990)

The direct method of estimation from historical yield values recommended by the Irrigation Department guidelines of Sri Lanka uses 75% probable rainfall to apportion seasonal values to monthly values and then incorporates two percentage thresholds to avoid extremely high or low design yield values. Welsh Water Resources Planning guideline (Environment Agency, Ofwat, Defra and the Welsh Government, n.d.) which is one of the documentations that emphasizes a rational risk factor for the hydrological yield when determining the Deployable Output (DO), does not lead a practicing person with technical guidance for computations.

There are many empirical black box models based on regression method (Ward and Trimble, 1995; Department of Irrigation, Nepal, 1990; Bourdin and Stull, 2013; Haan and Allen, 1972), in literature as, box-jenkins time series regression, auto regressive moving average (Bourdin & Stull, 2013), WECS regional regression method (Department of Irrigation, Nepal, 1990), USGS empirical regression method (Ward & Trimble, 1995). Some models use rainfall as the only input and some other models use several inputs other than rainfall. Other than regression models, there are many empirical equations developed for regions. Inglis formula is developed for Ghatt areas and non Ghatt areas (Reddy, 1993) is widely used for many application and is mentioned in Irrigation guideline in Pakistan (Irrigation Branch, Pakistan, 1943). Parkers formula is developed for British isles, USA and Germany(Reddy, 1993).

Many guidelines own empirical methods for catchment yield estimation in south Asian region (Ponrajah, 1984; Department of Irrigation, Nepal, 1990; Irrigation Branch, Pakistan, 1943) and many of them are associated with rainfall and coefficients based on catchment characteristics. Nepal guideline has developed iso lines for annual rainfall and provide coefficients to convert them to monthly yield(Department of Irrigation, Nepal, 1990) Sri Lankan irrigation guideline has developed iso lines for yield (Ponrajah, 1984) and provide coefficients for distribute for monthly yield and safety factors are embedded to the calculation method. Pakistan uses annual yield estimation empirical formulas.

Monthly water balance model developed by USGS is a black box model considers the water balance of catchment, using monthly total precipitation, mean monthly temperature and latitude of the location. This model owns various components of the hydrological cycle, driven by a graphical user interface and easily applied for the countries that the snow fall is applicable (McCabe & Markstrom, 2007)

Though empirical methods are practiced in specific geographical region, there are advantages as being a direct method and time tested for better results. Rainfall and streamflow uncertainties are considered in several guidelines(Drainage services department, Hong Kong, 2018; Department of Irrigation, Nepal, 1990) and some implicit safety factors are embedded (Ponrajah, 1984; Department of Irrigation, Nepal, 1990).

Though the need of incorporating a rational risk factor for water yield is stressed in many guidelines/manuals there is no guidance of an appropriate range of risk factors.

2.5.2 Modern hydrological models

Due to uncertainty of parameters, interdependency of parameters, dependency of parameters on the model and objective functions (Bárdossy, 2007), unavailability of data for calibration (Beven, 2011), expensiveness of models, availability of higher number of parameters (Post & Jakeman, 1999) it is difficult to use many models for a practicing engineer for general conditions.

Considering the increasing importance of water due to factors such as population increase, growing needs and challenging climates, there is a clear necessity to incorporate appropriate safety factors in order to arrive at the optimum design streamflow value. There is lack of methods for the identification of suitably chosen factors for the determination of design streamflow or watershed yield either cause conservative uneconomical infrastructure or estimates with higher risks.

Watershed streamflow estimation models frequently cited in Guidelines are restricted to a few models such as empirical regression type models, rational method, Unit Hydrograph method, SCS Curve number method. The empirical methods in guidelines not only appear to use probable rainfall in design inputs but also consider thresholds for streamflow estimations. These thresholds appear as implicit safety factors.

2.5.3 Safety factors

Engineering designs for infrastructure construction always embed safety factors to cater to the uncertainties. Margins of safety are usually conceptualized by considering the associated uncertainties. Though rainfall and watershed process conceptualizations are known to possess uncertainties, none of the literature provided explicit guidance for a design engineer to perform infrastructure designs by using the outputs from hydrologic models. There is not any explicit indication of safety factors in water resources design guidelines found, other than rainfall adjustment factors (Drainage services department, Hong Kong, 2018; Department of Irrigation and Drainage, Malayasia, 2000; Xie et al., 2018). Though some literature state uncertainties of design flood estimation methods (Viesseman and Lewis, 2003; Yin et al., 2018; Guo et al., 2018) there is no guidance at design catchment yield estimation. This factor leads to a drawback when a designer has to decide whether to use a streamflow from a traditional model or a recent model.

2.6 Data Checking

Hydrological data that is used for water managing purposes need to be consistent, stationary and homogeneous (Dahmen, Hall, & others, 1990). Data screening, Plotting the data and visual checking, checking the correlation and double mass analysis for relative consistency and homogeneity are basic data checking methods widely used (Dahmen et al., 1990). Other than those checks, Spearman's rank correlation test, Standard Normal homogeneity test, Test for stability of variance (F test), Test for stability of mean (t test), Cumulative residuals (Wijesekera & Perera, 2016), Monte Carlo simulations, Mann –Kendall test (Renard et al., 2008), are used for data checking. For handling missing data Arithmetic mean method, Normal ratio method (De Silva, Dayawansa, & Ratnasiri, 2007), Inverse distance method (Suhaila, Sayang, & Jemain, 2008), homogeneity analysis and regression method (Wijesekera & Perera, 2016) can be used.

A study of rainfall data in 18 stations in Attanagalu basin from 1970-2001 by Wijesekera & Perera, (2016) shows variation of results for different statistical tests and regression analysis has shown good results with many stations. Pasyala was identified the most significant rainfall station of the stations considered and it shows an inhomogeneity with the other stations.

3 METHODOLOGY

Problem identification, objective and specific objectives were determined and literature review was carried out to identify present status and existing knowledge regarding yield models, model applications, and basin characteristics.

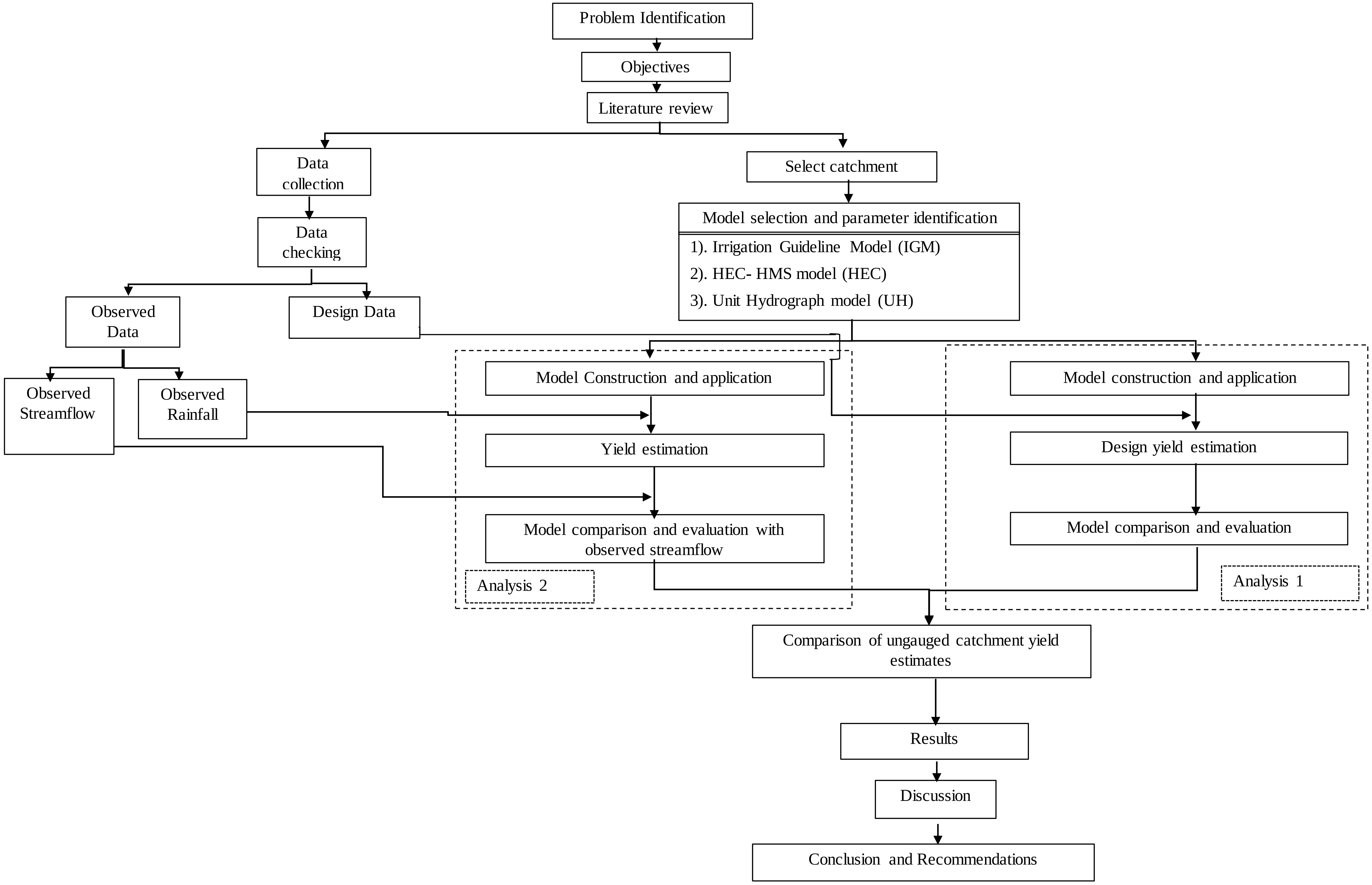
Design data were collected from Irrigation guideline and available literature. Rainfall and evaporation data were collected from Department of Meteorology and Streamflow data were collected from Irrigation Department.

Visual checking, annual water balance, and double mass curve were used for data checking. Missing data were estimated using normal ratio method, regression analysis, and slope proportional analysis. Thiessen polygon method was used to obtain rainfall distribution. For Attanagalu basin weighted Thiessen average method was used to calculate areal rainfall.

Irrigation model, HEC-HMS and Unit hydrograph models and model parameters evaluated and selected by available best literature. Design data was applied and compared for planning purposes and then observed rainfall data was applied for models to compare with observed yield. Annual baseflow index method used for baseflow estimation and Φ index method was used for effective rainfall estimation in Unit hydrograph method.

Hydrographs obtained from design rainfall input were compared based on order of magnitude and runoff coefficient, and decisions have taken for the best suitable model for an ungauged catchment by a qualitative assessment. Hydrographs obtained from observed rainfall data input were compared and analysed with observed runoff. Comparison of Analysis part 1 results and analysis part 2 results were done. Key factors for variations of different hydrographs were identified and discussed.

3.1 Methodology Flowchart



4 DATA AND DATA CHECKING

4.1 Data

Main data used for the research are in Table 4-1 and 4-2.

Table 4-1: Data collection details for Dunamale watershed of Attanagalu basin

Data	Gauging station	resolution	period	source
Rainfall	Nittambuwa	daily	2005-2015	Department of Meteorology
	Pasyala	daily	2005-2015	
	Vincit	daily	2005-2015	
	Chester-ford	daily	2005-2015	Irrigation Department
	Karasnagala	daily	2005-2015	
Streamflow	Dunamale	daily	2005-2015	Department of Meteorology
Evaporation	Colombo	daily	2005-2015	Department of Meteorology

Table 4-2: Data collection details for Ellagawa watershed of Kalu River basin

Data	Gauging station	resolution	period	source
Rainfall	Halwatura	daily	2006-2014	Department of Meteorology
	Alupola	daily	2006-2014	
	Pelmadulla	daily	2006-2014	
	Niwithigala	daily	2006-2014	
	Ratnapura	daily	2006-2014	
Streamflow	Ellagawa	daily	2006-2014	Irrigation Department
Evaporation	Ratnapura	daily	2006-2014	Department of Meteorology

4.1.1 Rainfall data

Daily data of 5 rainfall stations in Ellagawa watershed (2006-2014) and Dunamale watershed (2005-2015) were collected. The primary data source was Meteorological department, Sri Lanka. Station locations are in Table 4-3 and 4-4.

Table 4-3: Rainfall stations at Dunamale watershed

Rainfall station	Location coordinate
Karasnagala	79^0 58’ 48” E 7^0 6’ 0” N
Nittambuwa	80^0 6’ 0” E 7^0 7’ 48” N
Pasyala	80^0 7’ 48” E 7^0 9’ 0” N
Vincit	80° 11’ 56” E 7° 5’ 24” N
Chesterford	80° 10' 60" E 7° 4' 0" N

Table 4-4: Rainfall stations in Ellagawa watershed

Rainfall station	Location coordinate
Halwatura	80^0 21’ 36’’ E 6^0 48’ 0’’ N
Ratnapura	80^0 24’ 0’’ E 6^0 5’ 30’’ N
Alupola	80^0 34’ 48’’ E 6^0 43’ 12’’ N
Pelmadulla	80^0 31’ 48’’ E 6^0 37’ 12’’ N
Nivithigala	80^0 15’ 36’’ E 6^0 21’ 36’’ N

4.1.2 Streamflow data

Daily stream flow data in Ellagawa (2006-2014) and Dunamale (2005-2015) were collected from the Irrigation department. Station locations are in Table 4-5.

Table 4-5: Stream gauge stations and locations

Stream flow gauge	Location coordinate
Ellagawa	80^0 12’ 36” E 6^0 43’ 55” N
Dunamale	80^0 04’ 50” E 7^0 06’ 56” N

4.1.3 Evaporation data

Daily evaporation data in Colombo (2005-2015) and Ratnapura (2005-2015) were collected from the Meteorological department.

4.1.4 Topographic data

Revised topographic and land use maps of 1:50,000 scale were collected. Land use pattern for Dunamale watershed is in Table 4-6 and Figure 4-1 while the same for Ellagawa watershed is in Table 4-7 and Figure 4-2.

Table 4-6: Land use pattern of Dunamale watershed

Land use type	Area (sqkm)	Area percentage
Homestead	55.2	35.1%
Paddy	19.1	12.1%
Coconut	32.9	20.9%
Rubber	38.0	24.1%
Forest	1.8	1.2%
Other	10.4	6.6%

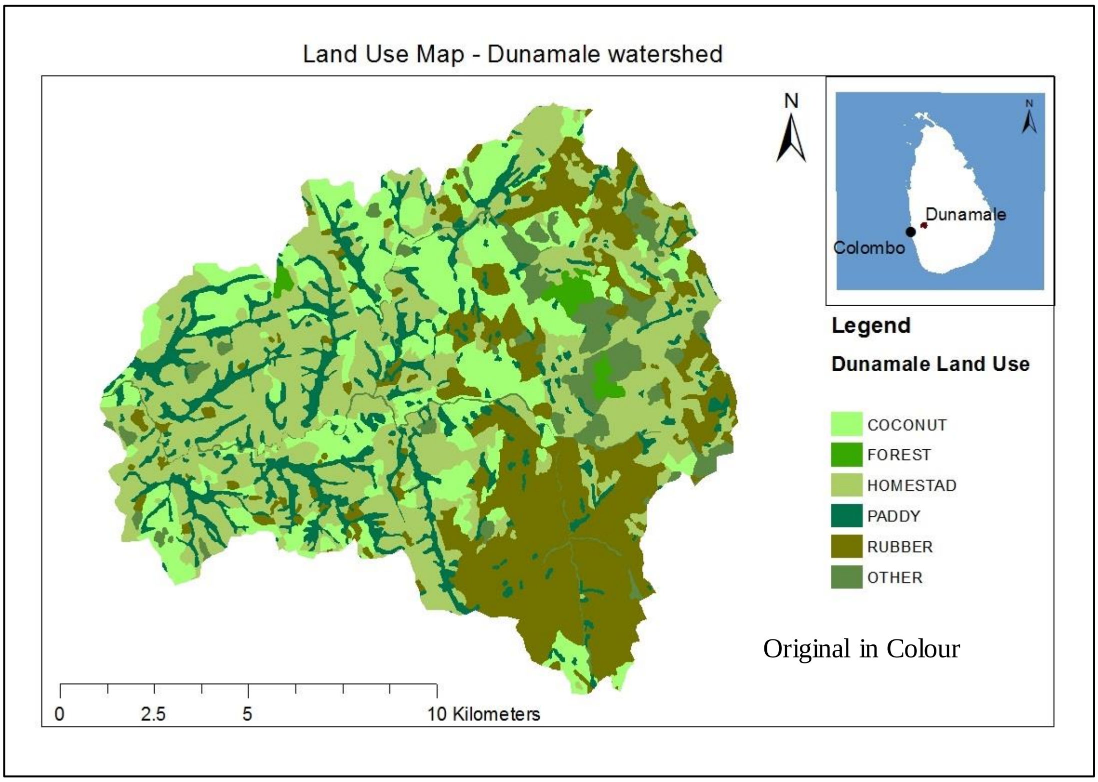


Figure 4-1: Land use map of Dunamale watershed

Table 4-7: Land use pattern of Ellagawa watershed

Land use type	**Area (sqkm)**	**Area percentage**
Homestead	255.8	17.7%
Built up	1.4	0.1%
Coconut	3.7	0.3%
Tea	126.5	8.8%
Rubber	358.7	24.8%
Paddy	97.1	6.7%
Forest	231.0	16.0%
Chena	293.5	20.3%
Other	78.2	5.4%

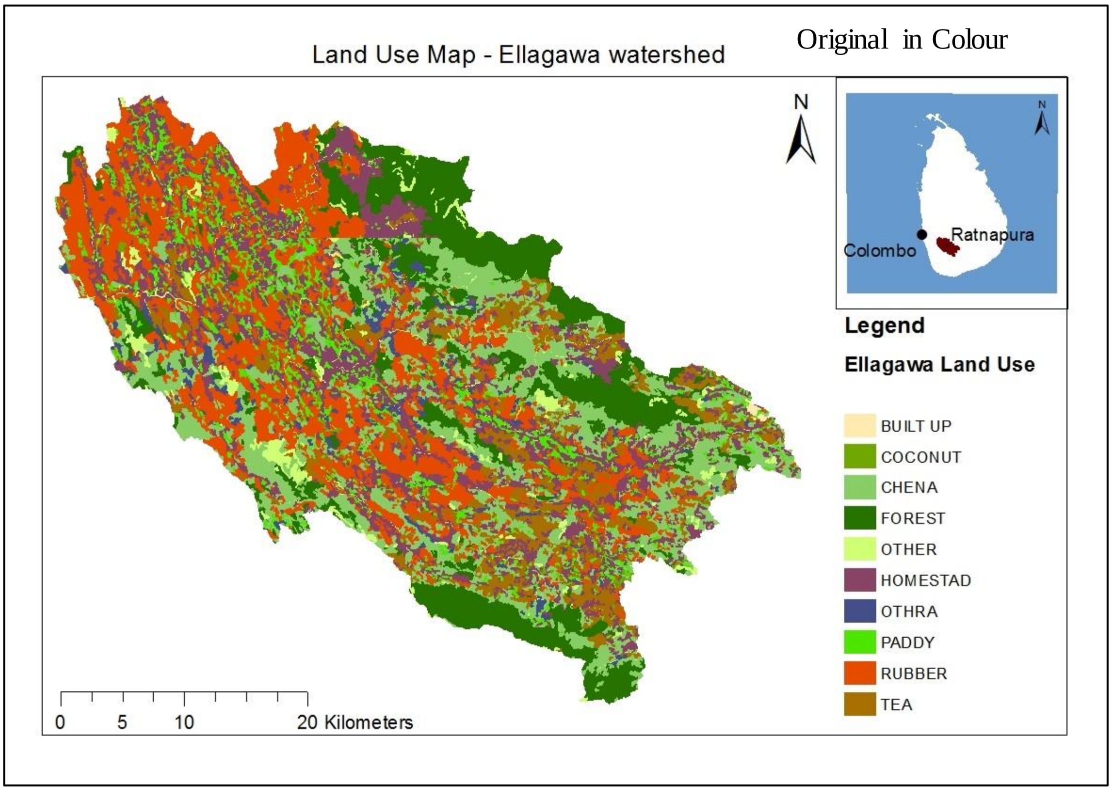


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Figure 4-2: Land use map of Ellagawa watershed

4.2 Data checking

4.2.1 Station density

As the first step, the data was checked whether there are sufficient gauging stations for the spatial extent. World meteorological Organization standard was used as a limit. Station densities fulfilled the WMO standards (Table 4-8, 4-9).

Table 4-8: Distribution of gauging stations – Dunamale watershed

Description	**No of stations**	**Station density (sqkm/station)**	**WMO standards (sqkm/station)**
rainfall	5	31.5	575
streamflow	1	157.5	1875
Evaporation	1	157.5	

Table 4-9: Distribution of gauging stations - Ellagawa watershed

Description	**No of stations**	**Station density (sqkm/station)**	**WMO standards (sqkm/station)**
rainfall	5	289.2	575
streamflow	1	1446.4	1875
Evaporation	1	1446.4	

4.2.2 Visual checking

Visual checks on the rainfall corresponding to annual streamflow was carried out (Figure 4-3). These checks using Thessen rainfall were carried out for each station in Ellagawa watershed and Dunamale watershed.

Inconsistencies and outliers in rainfall and stream flow were marked (Figure 4-3, 4-4, 4-5). In some cases, streamflow is much higher compared to the rainfall and in some cases there is a very high rainfall with either little or no streamflow. Results are given in Appendix A and Appendix B.

4.2.2.1 Thiessen rainfall and streamflow comparison

Considering Dunamale watershed in Attanagalu basin, several inconsistencies can be seen (Figure 4-3, 4-4, 4-5). In December, January-February, July 2005/2006, in between December-January in 2006/2007, in between December- January in 2008/2009, February 2010/2011 and December- January in 2012/2013 shows streamflow variation, but there is no rainfall. For the rainfall event in March 2006/2007, there in not a streamflow response.

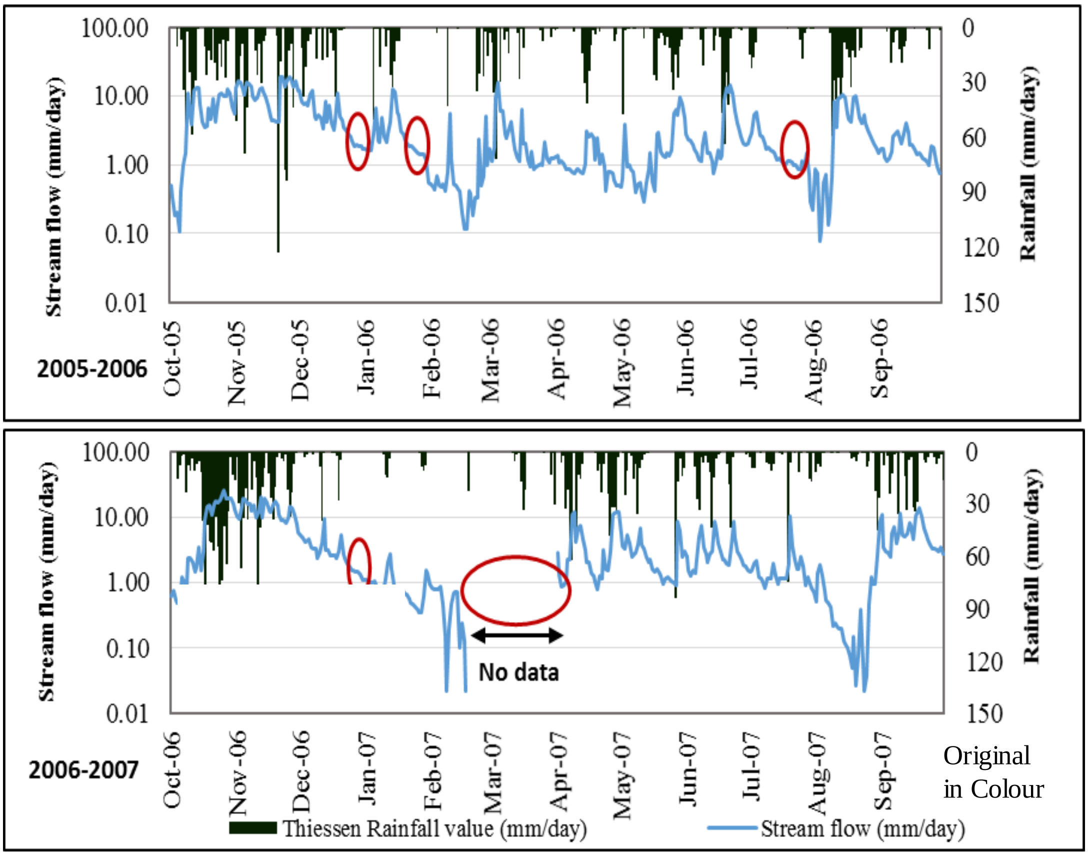

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Figure 4-3: Thiessen average rainfall and streamflow – Dunamale watershed - (2005-2007)

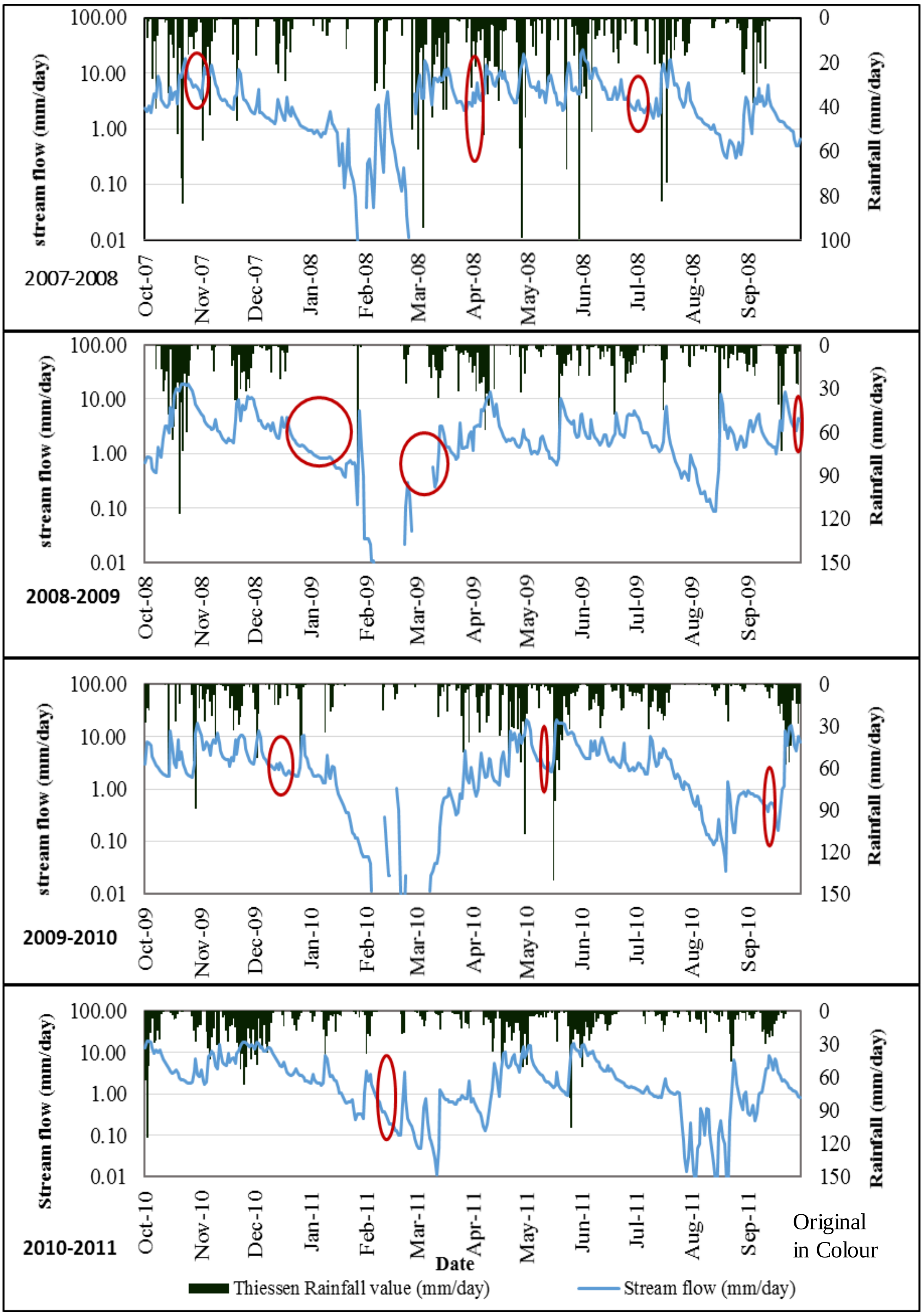

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Figure 4-4: Thiessen average rainfall and streamflow – Dunamale watershed - (2007-2011)

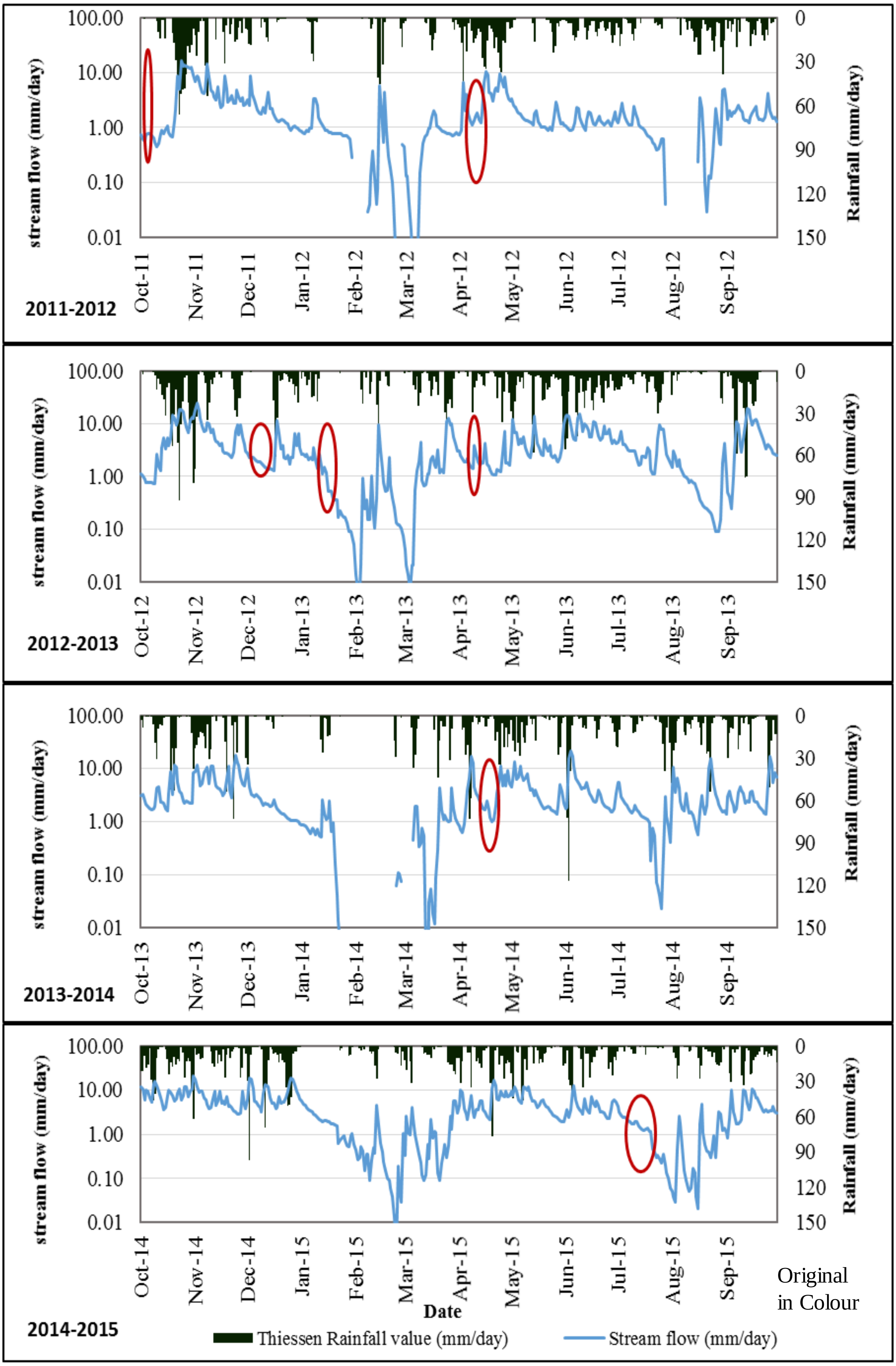

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Figure 4-5: Thiessen average rainfall and streamflow – Dunamale watershed - (20011-2015)

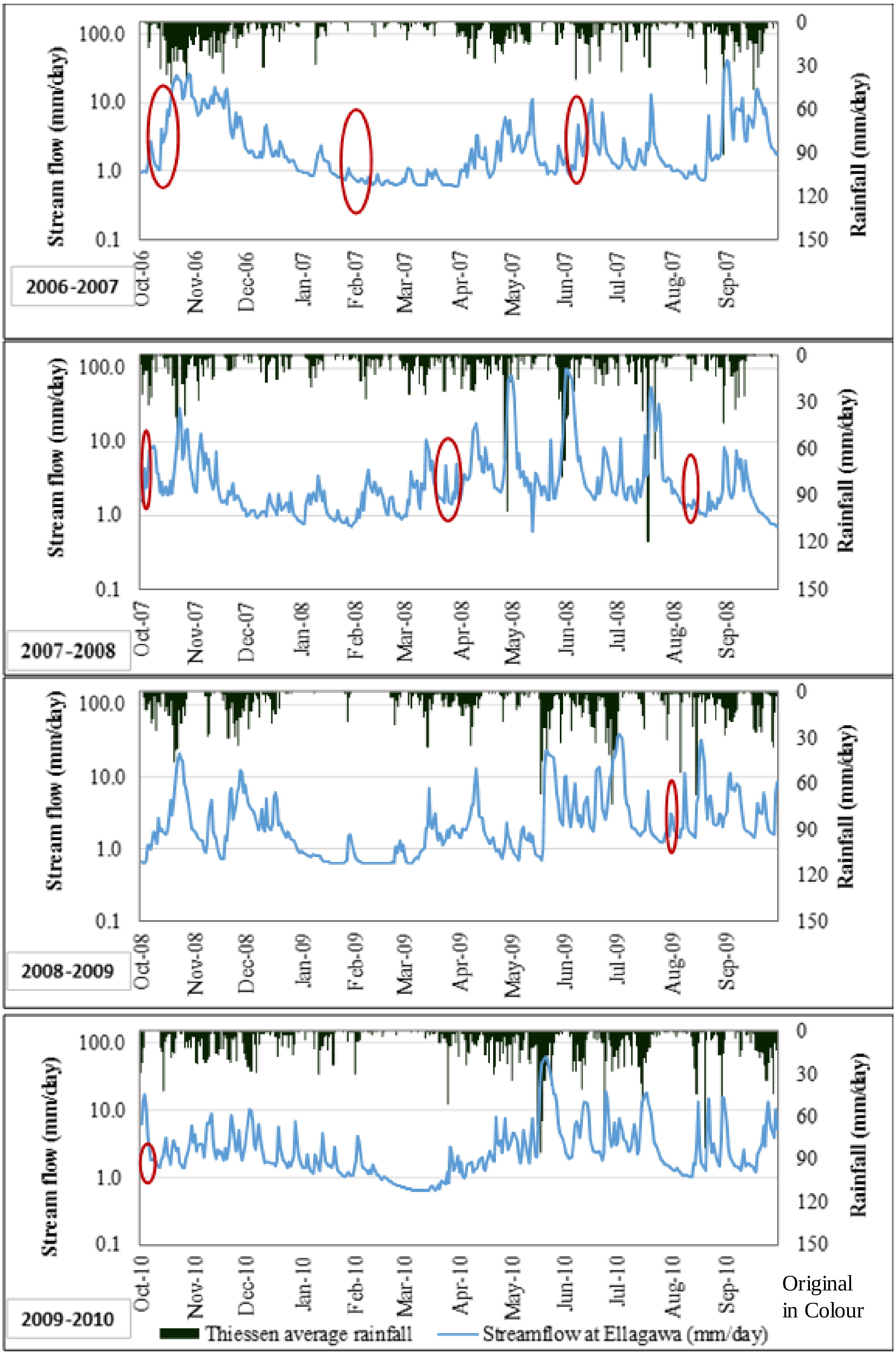

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Figure 4-6: Thiessen average rainfall and streamflow – Ellagawa watershed - (20006-2010)

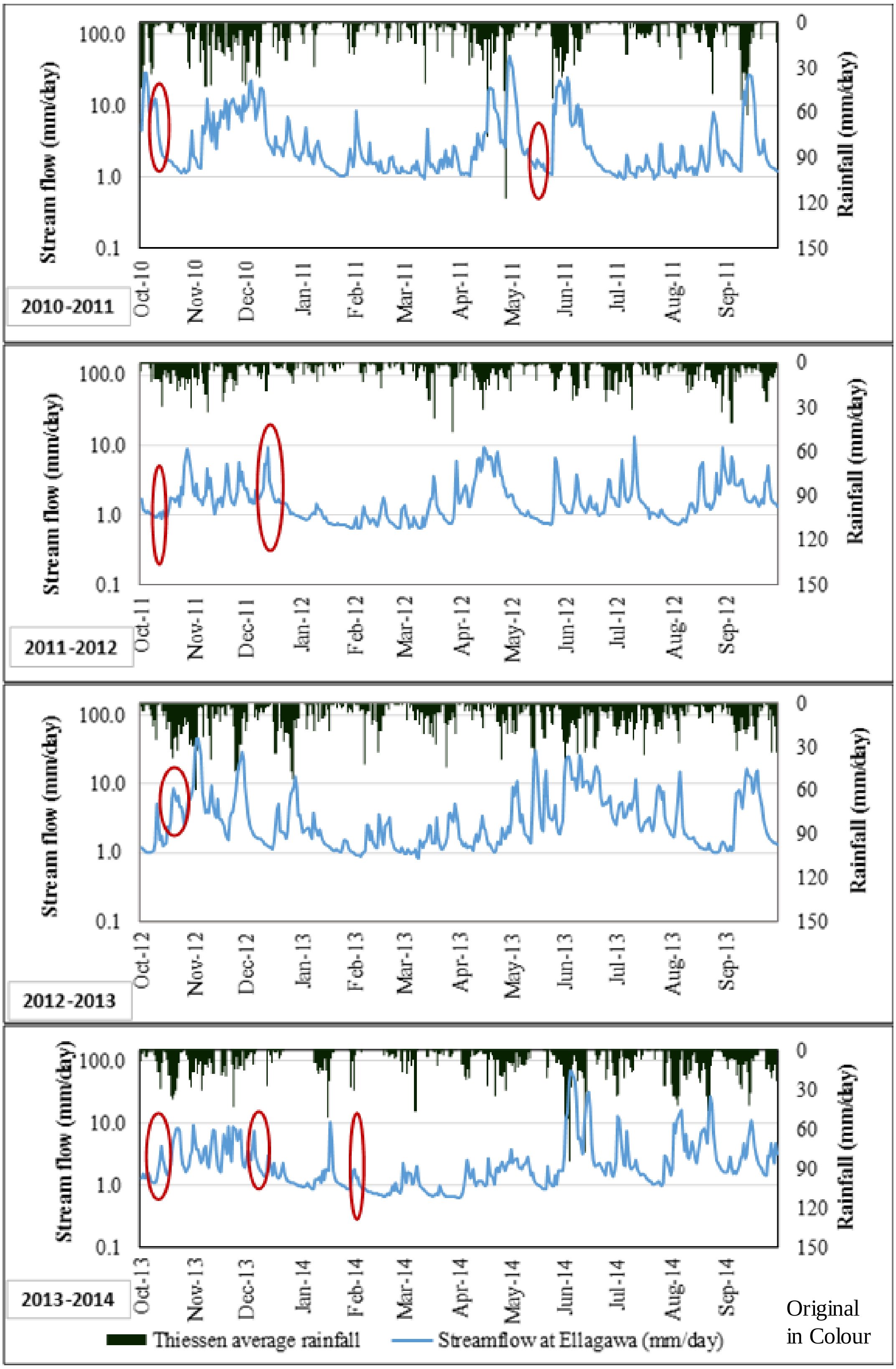

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Figure 4-7: Thiessen average rainfall and streamflow – Ellagawa watershed - (20010-2014)

The comparison of streamflow variation with Thiessen average rainfall for Ellagawa watershed is in Figure 4-6, 4-7. The comparison shows that there are several inconsistencies and mismatches of rainfall and streamflow variation in every year. Some rainfall events are not clearly indicate by streamflow variation

4.2.2.2 Comparison of rainfall variation in different stations

Rainfall variation in different rainfall stations in each watershed was checked using monthly aggregated rainfall data.

Considering Attanagalu watershed, monthly rainfall in Nittambuwa, Pasyala, Vincit, Chesterford and Karasnagala rainfall station patterns were compared. According to the comparison Chesterford shows higher precipitation than other stations. Comparing with Kalu river basin, rainfall patterns are more consistent. Missing data can be seen in many months and 2005/2006 shows the largest number of missing data values. 2008/2009 precipitation values are comparatively lower than other years.

Comparing with other years 2012/2013 the rainfall in different stations in Ellagawa sub-basin have a large variation and does not show a proper pattern. In 2007/2008 from October to March, the precipitation in Alupola is comparatively higher than other stations, but shows the same pattern. Comparing with many years, South West monsoon period precipitations are higher than North East monsoon period precipitations.

4.2.3 Missing data

Missing data for both rainfall data and streamflow data was checked for Ellagawa sub-basin in Kalu River and Dunamale sub-basin for Attanagalu River for the considering data period for the research and calculated the error percentage.

4.2.3.1 Missing data in Dunamale watershed

Considering Attanagalu basin, there are missing rainfall values for consecutive months. For Dunamale river gauge, the flow variation shows that there is no daily flow for some days in February and March in many years. However, 2007 March, shows no streamflow value to whole month and it was considered as missing data. Number of missing data and percentages are in Table 4-10.

Table 4-10: Missing data percentage in Attanagalu basin

Data type	Station	Number of missing Data	Percentage
Rainfall data	Nittambuwa	120	3%
Rainfall data	Pasyala	214	6%
Rainfall data	Vincit	517	14%
Rainfall data	Karasnagala	518	14%
Rainfall data	Chester-ford	621	17%
Streamflow data	Dunamale	31	0.85%

Since the missing data percentage in Vincit, Karasnagala and Chesterford is higher than the allowable percentage of missing data according to WMO standard (10%), Thiessen rainfall was calculated by changing the Thiessen weightage for analysis works. Regression method was used for filling the missing rainfall data to obtain double mass curve.

4.2.3.2 Missing data in Ellagawa watershed

According to Kalu basin data set, only 3 rainfall data are missing and no any streamflow data is missing. Missing data and percentage is presented in Table 4-11.

Normal ratio method is a common method recommended for intermediate zone. Since the percentage of missing data is less, normal ratio method has used to estimate missing rainfall data. Double mass curve was obtained after filling the missing rainfall data.

Table 4-11: Missing data in Kalu river basin

Data type	Station	Number of missing Data	Percentage
Rainfall data	Halwatura	0	0%
Rainfall data	Ratnapura	0	0%
Rainfall data	Alupola	2	0.07%
Rainfall data	Pelmadulla	0	0%
Rainfall data	Nivithigala	1	0.03%
Streamflow data	Ellagawa	0	0%

4.2.4 Thiessen average rainfall

Catchment average rainfall was calculated using Thiessen average method (Chow, Maidment, & Mays, 1988) Thiessen polygons were created and Thiessen average rainfall was calculated for Ellagawa watershed in Kalu River and Dunamale watershed for Attanagalu River.

Table 4-12 and Figure 4-8 shows the Thiessen weightages and Thiessen polygon for Dunamale watershed. Figure 4-9 and Table 4-13 show the same for Ellagawa watershed.

Table 4-12: Thiessen weights of rain gauging stations – Dunamale watershed

Rainfall station	**Area (km^2)**	**Total area (km^2)**	**Thiessen weight**
Nittambuwa	26.3	157.5	0.17
Pasyala	34.5	157.5	0.22
Karasnagala	59.5	157.5	0.38
Vincit	13.5	157.5	0.08
Chester-ford	23.5	157.5	0.15

Table 4-13: Thiessen weights of rain gauging stations – Ellagawa watershed

Rainfall station	**Area (km^2)**	**Total area (km^2)**	**Thiessen weight**
Halwatura	240	1446.4	0.16
Ratnapura	434.8	1446.4	0.30
Alupola	225.4	1446.4	0.16
Pelmadulla	363.6	1446.4	0.25
Nivithigala	182.6	1446.4	0.13

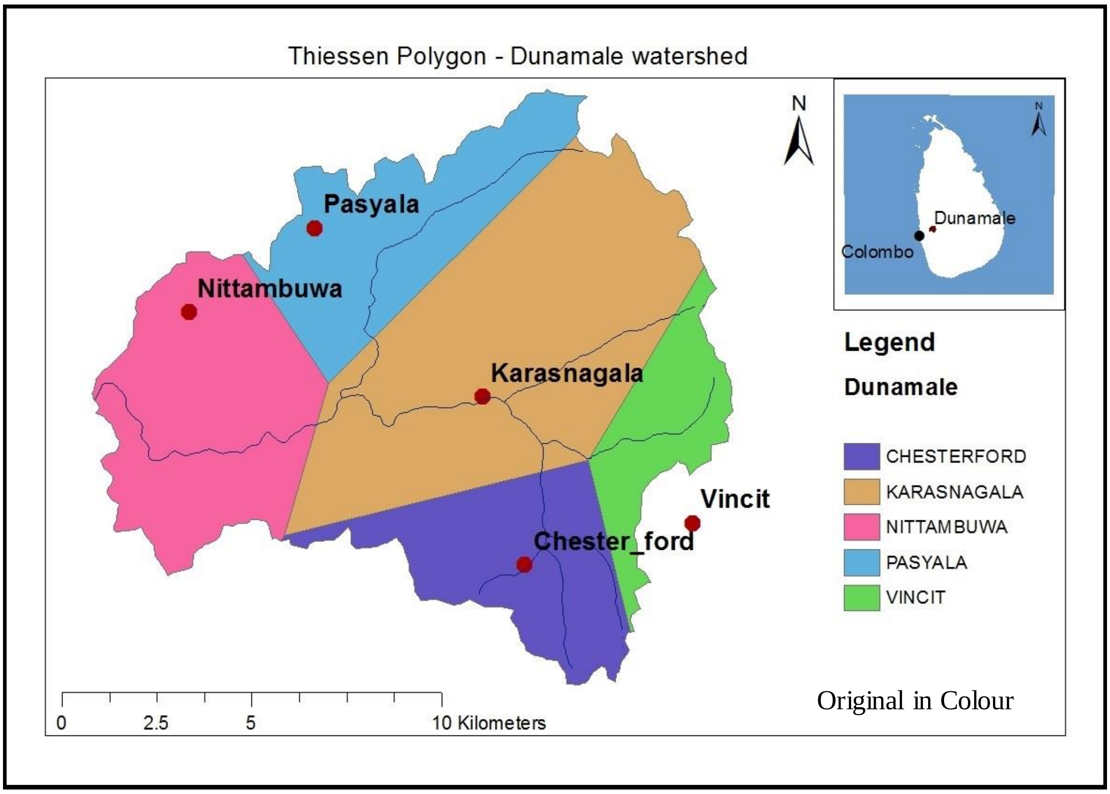

Figure 4-8: Thiessen polygon of Dunamale watershed

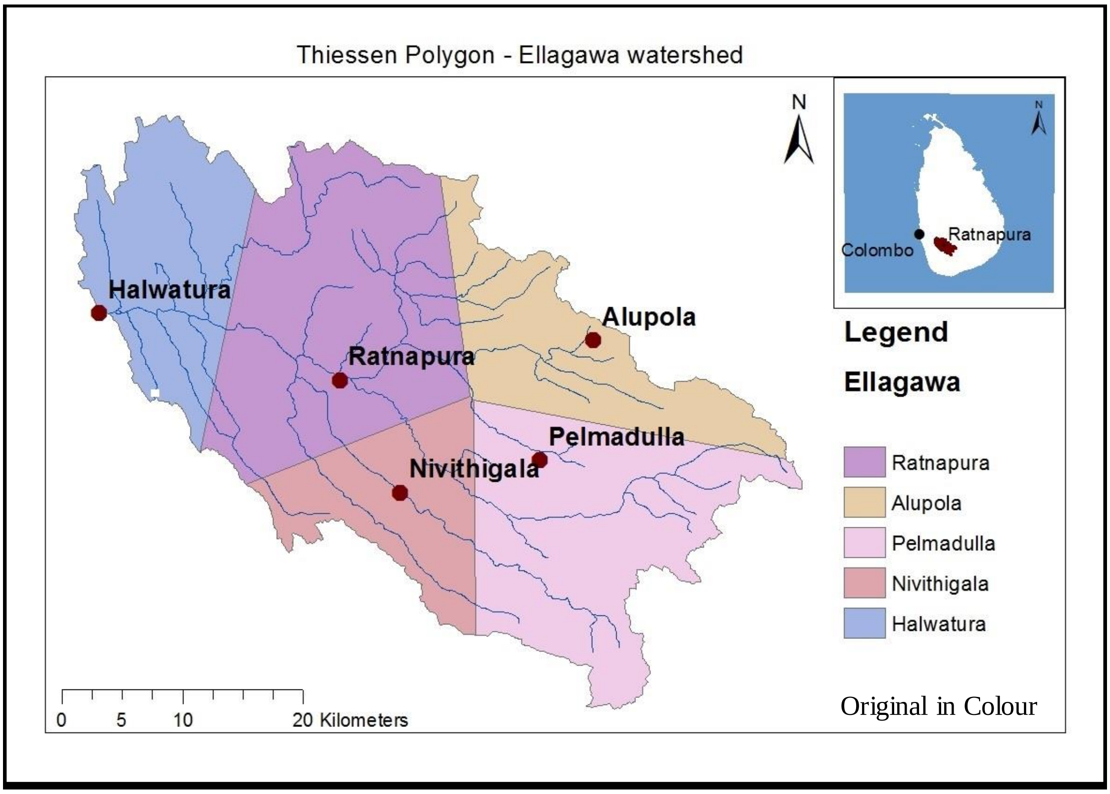

Figure 4-9: Thiessen polygon of Ellagawa watershed

4.2.4.1 Calculating Thiessen Average Rainfall

Considering Dunamale waterhsed, there are missing rainfall values for consecutive months. Therefore Thiessen rainfall was calculated by changing the Thiessen weightage. Table 4-14 gives further details.

In 2006 September, Thiessen weightage was calculated considering only Pasyala and Nittambuwa rainfall stations which are located in downstream side of the watershed. Other 3 upstream rainfall stations data were missing. Therefore in that month, the homogeneity of the rainfall in Thiessen polygon might not be seen.

Table 4-14: Thiessen weightages for Dunamale watershed

Data period	**Thiessen weights**				
	Vincit	**Nittambuwa**	**Pasyala**	**Karasnagala**	**Chester-ford**
2005 Oct 1 – Dec 30	0.00	0.28	0.00	0.72	0.00
2005 Dec 31	0.16	0.28	0.00	0.56	0.00
2006 Feb – Aug	0.38	0.27	0.36	0.00	0.00
2006 Sep	0.00	0.28	0.72	0.00	0.00
2011 Nov, 2013 Nov	0.23	0.45	0.00	0.00	0.32
2013 Dec	0.00	0.28	0.00	0.53	0.18
2010 Sep, 2014 Sep, 2015 Apr	0.09	0.00	0.35	0.42	0.15
2006 Jan, 2009 Apr- Jul, 2010 Nov, 2014 Feb, 2014 Apr	0.16	0.22	0.17	0.46	0.00
2008 Feb, 2011 (Jan, Jul, Oct), 2012 (Jun- Jul, Sep, Nov-Dec), 2014 (Jan, Nov)	0.00	0.22	0.17	0.43	0.18
2010 Apr, 2013 Oct	0.09	0.28	0.00	0.48	0.15
2006 Oct – Nov, 2008 March, 2009 Nov- Dec, 2010 Jul, 2013 (Jan, Aug), 2015 May – Jul	0.17	0.23	0.32	0.00	0.27
(2005 Oct – 2015 Sep) Rest all	0.09	0.22	0.17	0.38	0.15

In Ellagawa watershed data set, only three rainfall data are missing. Therefore those data were estimated and daily Thiessen average rainfall was calculated by 5 rainfall stations.

4.2.5 Annual water balance

Annual water balance was done for analysing rainfall, runoff and evapotranspiration values and then the actual evapotranspiration value was compared with observed pan evaporation value, considering the multiplication coefficient. Considering Dunamale watershed in Attanagalu basin, average annual runoff coefficient is 0.41 and from 2006/2007 to 2014/2015 each year the annual water balance is higher than observed pan evaporation. Table 4-15, 4-16 and Figure 4-10, 4-11 shows the annual water balance results for Dunamale and Ellagawa watersheds.

Table 4-15: Annual water balance in Dunamale watershed

year	**Thiessen average rainfall (mm)**	**Annual streamflow (mm)**	**Annual observed pan evaporation (mm)**	**Water Balance (mm)**	**Annual Runoff co-efficient**
2005/2006	2549.6	1368.0	1217.00	1181.6	0.54
2006/2007	3179.1	1360.9	1276.55	1818.2	0.43
2007/2008	3480.1	1543.5	1218.85	1936.6	0.44
2008/2009	3067.5	1046.7	1299.02	2020.8	0.34
2009/2010	3298.0	1300.1	1263.27	1997.9	0.39
2010/2011	3590.5	1366.9	1202.85	2223.6	0.38
2011/2012	2456.0	728.6	1301.63	1727.5	0.30
2012/2013	3501.8	1439.3	1236.44	2062.5	0.41
2013/2014	2736.2	1122.5	1335.76	1613.8	0.41
2014/2015	3123.9	1551.1	1256.34	1572.8	0.50

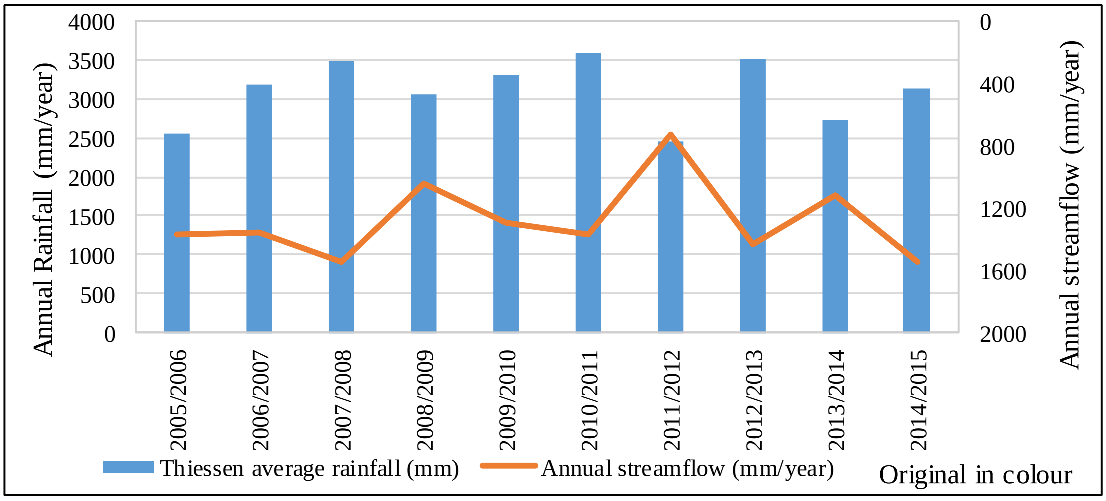

Figure 4-10: Annual rainfall, streamflow variation in Dunamale watershed

Considering the annual water balance results, for Dunamale basin, annual runoff coefficient varies from 0.3-0.54 in the considered 10 years. 2005/2006 shows the maximum annual runoff coefficient and 2011/2012 shows the minimum annual runoff coefficient in Dunamale basin. In Kalu river basin, also the minimum annual runoff coefficient appears in 2011/2012 as 0.23 and maximum runoff coefficient is in 2007/2008 as 0.78. Hence 2011-2012 can be considered as a dry year. Higher runoff coefficient can occur due to data inconsistencies. Jayadheera, (2015) who has done a research using same period of data in Kalu river basin also shows the same pattern as maximum annual runoff coefficient in 2007/2008 and minimum runoff coefficient is in 2011/2012.

Considering Ellagawa sub-basin in Kalu river basin, average annual runoff coefficient is 0.51 and from 2006/2007 to 2013/2014 each year the annual water balance does not show any contradiction. Comparing with the annual aggregated pan evaporation values, only 2007/2008 shows observed pan evaporation is higher than the calculated evapotranspiration by the annual water balance. 2011/2012 year shows the highest difference in between annual pan evaporation and annual water balance.

Table 4-16: Annual water balance - Ellagawa watershed

year	Thiessen average rainfall (mm)	Annual streamflow (mm)	Annual observed pan evaporation (mm)	Water balance (mm)	Annual runoff coefficient
2006/2007	2737.6	1323.1	952.10	1414.5	0.48
2007/2008	2542.4	1982.4	924.07	560.0	0.78
2008/2009	2594.5	1331.4	1060.59	1263.1	0.51
2009/2010	2703.2	1538.8	944.03	1164.4	0.57
2010/2011	2607.3	1679.9	869.18	927.4	0.64
2011/2012	3039.6	710.4	994.01	2329.2	0.23
2012/2013	3372.6	1671.5	870.27	1701.2	0.50
2013/2014	3236.4	1283.5	898.86	1952.9	0.40

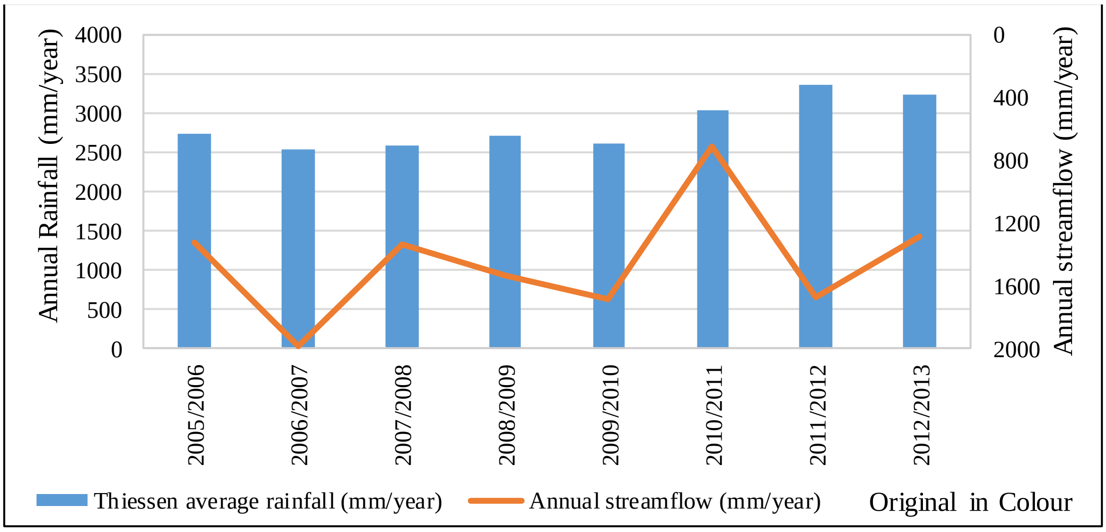

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Figure 4-11: Annual streamflow and rainfall variation in Ellagawa watershed

4.2.6 Double mass curve

Double mass curve technique is a common method that is used for analysing the consistency of hydrological data. Cumulative precipitation in one station was plotted against average cumulative precipitation of other stations in the same basin. This process was done for each and every rainfall station in each basin. Double mass curve results are shown in Appendix C.

Considering double mass curves in Dunamale watershed, Nittambuwa, Pasyala, Chesterford and Karasnagala station double mass curves does not show a visible inconsistency, however Vincit double mass curve shows a change of the slope. The reasons for that change is need to be found. All the slopes of double mass curves are comparatively same.

Considering the Double mass curves in Ellagawa sub-basin, Kalu basin, Halwatura, Alupola, Ratnapura, Pelmadulla and Nivithigala station double mass curves doesn’t show a visible inconsistency, however the slopes of the Pelmadulla and Nivithigala double mass curves are low compared with other stations.

4.2.7 Data checking summary

Data checking summary is presented in Table 4-17.

Table 4-17: Summary of Data checking

Data checking method	**Remarks**		**Judgement**
	Dunamale watershed	**Ellagawa watershed**	
Checking for station density	Both rainfall and streamflow gauges are according to WMO standards	Both rainfall and streamflow gauges are according to WMO standards	Number of Rainfall and streamflow gauges are enough to represent actual conditions
Visual checking	• December, January-February, July 2005/2006, December-January in 2006/2007, December- January in 2008/2009, February 2010/2011 and December- January in 2012/2013 rainfall missing • March 2006/2007, no streamflow response to rainfall	• February 2006/2007, October 2009/2010 and December-January, February 2013/2014 no streamflow response to rainfall.	Considering the data period and data resolution, data set inconsistencies are not much significant, but need to reconsider with the model results
Annual water balance	• 2011/2012 – Low annual streamflow	• 2007/2008 – Low annual water balance (%) • 2011/2012 – High annual streamflow (%)	• 2011/2012 can be considered as a dry year • 2007/2008 - Can be a data error in Kalu river basin. Need to reconsider with model results
Double mass curve	• No visible inconsistency	• No visible inconsistency	Data are consistent

5 ANALYSIS AND RESULTS

5.1 General

The main purpose of the present research is to evaluate options available for an ungauged watershed modeller to estimate watershed yield for irrigation planning and design. Literature review identified that there are two major gaps with respect to the determination of design yield for the development of infrastructure. The first is the lack of guidelines for a practicing engineer to select a yield computing method without carrying out further research. The other is the lack of case studies where the outputs from existing methods have been subjected to a comparison with observations.

In the present work, the above-mentioned concerns were subjected to a two staged analysis. Analysis Part 1 deals with the evaluation of available models for design yield computation when there are no gauged streamflow records. Generally, a practicing engineer facing this situation would have access to guidelines, reviewed publications and physical data of the watershed. Though modern hydrological models do not have yield thresholds, Irrigation guideline model has yield thresholds. In this analysis the applicability of yield thresholds for the modern hydrological models was evaluated.

In Analysis Part 2, design yield computations carried out for two watersheds were compared with the gauged streamflow to evaluate the best option for sustainable irrigation infrastructure designs. Applicability of yield thresholds is checked and verified.

5.2 Qualitative Analysis of Literature

The present work in its attempt to establish the state-of-the-art design yield computation methods reviewed 15 number of related guidelines, 10 books, 18 monographs/Thesis and 56 peer reviewed journal publications (Figure 5-1). In this list of documents, the balance of coverage between flood and yield estimation references is shown by Figure 5-2. Figure 5-3 shows the total summary of runoff estimation references.

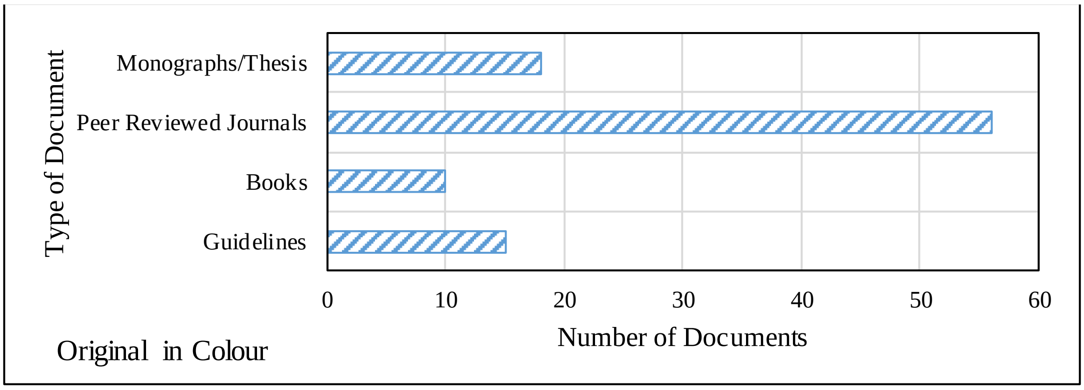

Figure 5-1: Summary of literature reviewed

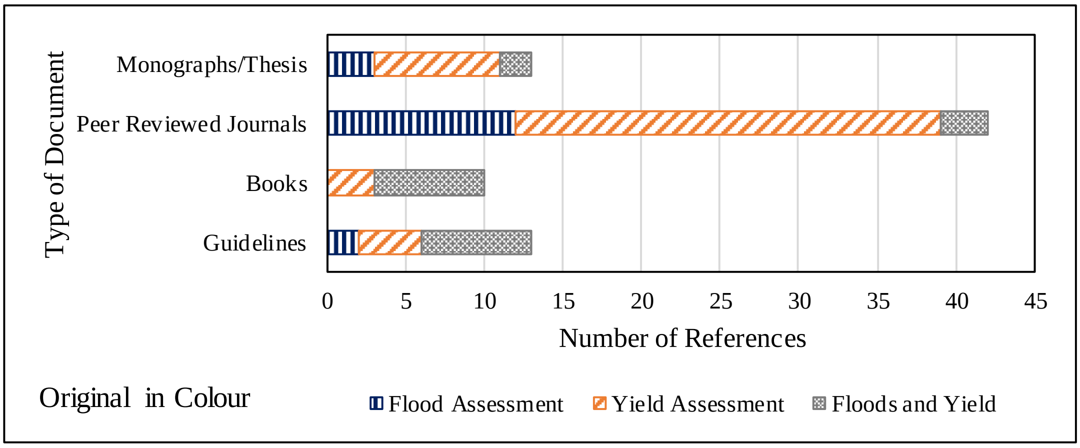

Figure 5-2: Coverage of references

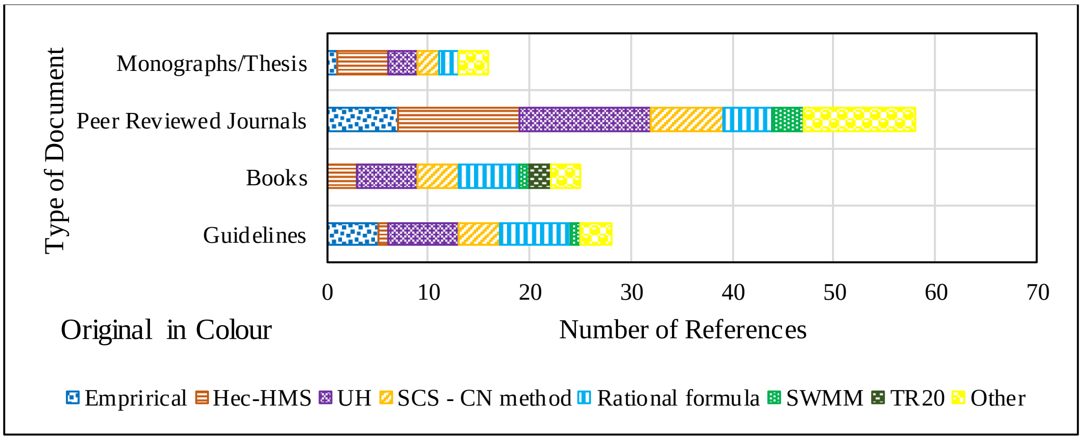

Figure 5-3: Summary of runoff estimation references

The qualitative evaluation based on the findings in the work is shown in the Table 5-1. Weightages were given considering high, medium, low categorization for each criteria. The demarcation given for High (H), Medium (M), and Low (L) categorization for each criteria is presented in Table 5-2.

Table 5-1: Demarcation for criterion for qualitative assessment of literature

Criteria	High (H)	Medium (M)	Low (L)
monthly estimates possible	explicit equations or monthly factors available	generating hydrograph and flow can be divided/ summed in to monthly	Not clear whether monthly estimates possible
availability of safety factors for rainfall	safety factors/probable rainfall available	Literature states that probable rainfall is available	No safety factors or probable rainfall recommendation in literature
availability of runoff safety factors	safety factors explicitly identified	Safety factors are implicit	Safety factors cannot be identified
application simplicity	empirical equations and simple calculations available	Mathematical model with assumptions available	Black box type models
availability in country guide or research paper	Guideline recommended method	Text books and research papers recommended method	No recommendation in guidelines or other literature
Data demand	data available in guideline	Data not available in guideline and less data requirement	more data requirement and data not available in guideline

According to the results Sri Lankan ID yield calculation method gets first priority (weightage 17), and guideline recommended methods clearly show a higher priority than other hydrological models.

Table 5-2: Qualitative assessment regarding yield models

Weightage: H - 3, M - 2, L- 1							
model	**monthly estimates possible**	**Rainfall safety factors available**	**Streamflow safety factors available**	**Application simplicity of model**	**Availability in country guide or research paper**	**Data demand**	**Total weightage**
Sri Lanka	H	H	M	H	H	H	17
Nepal	H	L	M	H	H	H	15
India	M	M	L	M	H	L	11
Pakistan	L	L	M	H	H	M	12
Hong Kong	H	H	L	M	H	L	13
ARR (2016)	M	H	L	M	H	H	14
ARR (1972)	M	H	L	M	H	H	14
HEC HMS	M	L	L	L	M	L	8
UH	M	L	L	M	H	L	10
SCS	M	L	L	M	H	L	10

5.3 Design Yield Option Comparison – Analysis part 1

5.3.1 General

Main objective of the Analysis Part 1 is the evaluation of options available for a practising engineer to compute design yield in ungauged watersheds. This is a key problem faced by the current practice of irrigation infrastructure design. In order to evaluate the options, the Dunamale watershed in Attanagalu Oya basin and Ellagawa watershed in Kalu river basin (Figure 1-1, Figure 1-2) were selected based on data availability.

A critical literature review carried out for the present work recognised that Irrigation guideline model (IGM), HEC-HMS model and Unit hydrograph (UH) model are the best available models for the computation of design watershed yield. In this analysis, the objective is to apply the said models to the two catchments, evaluate and discuss the results to facilitate the decision making of a practising engineer or a watershed manager.

As the analysis part 1 is for ungauged catchments, it is necessary to consider the available options for design rainfall. Ponrajah, (1984) provides sufficient data to determine the design rainfall for irrigation infrastructure design. Accordingly, the computations in the Analysis 1 used the 75% probable rainfall as the input design rainfall for all three models. Guidelines indicate the use of 75% probable value as a design recommendation to incorporate the rainfall uncertainty.

5.3.2 Irrigation Guideline Model (IGM)

The iso yield map of irrigation department is an empirical method to determine seasonal yield at a given geographic location. The method of using this model for design yield values is termed “Irrigation Guideline Model”. IGM as directed in Irrigation guideline, Sri Lanka (Ponrajah, 1984) was used in the computation of design yield values for Dunamale and Ellagawa watersheds. IGM recommendations were used for the computation of design rainfall. In a similar manner, seasonal yields computed with the iso yield curves were converted to monthly design yield values. Agro ecological zone map (Ponrajah, 1984) was used to determine the composite zoning indicator for each watershed.

5.3.2.1 Watershed Design Rainfall

The design rainfall is a function of agro-ecological region. Each of the selected watersheds fall into several agro-ecological regions. Area weighted design rainfall for each watershed was used in the computations. The agro ecological regions falling within Dunamale basin are WL1, WL2 and WL3. In the Ellagawa basin, there are 6 agro-ecological regions and they are WL1, WL2, WM1, WM3, IL1, WU1.

5.3.2.1.1 Dunamale Watershed

Agro-ecological regions and the corresponding design rainfall values of Dunamale watershed are in Figure 5-4 and Figure 5-5 respectively. Extents under WL1, WL2 and WL3 are 40.2, 98.2 and 19.1 km2 respectively. Summary of weighted average design rainfall is in Table 5-3.

5.3.2.1.1 Ellagawa watershed

Ellagawa basin consists of areas belong to six agro ecological regions as WL1, WL2, WM1, WM3, IL1, WU1 and presented in Figure 5-7. Figure 5-6 includes monthly design rainfall values for corresponding agro ecological regions. Summary of design rainfall values for Ellagawa basin is presented in Table 5-4.

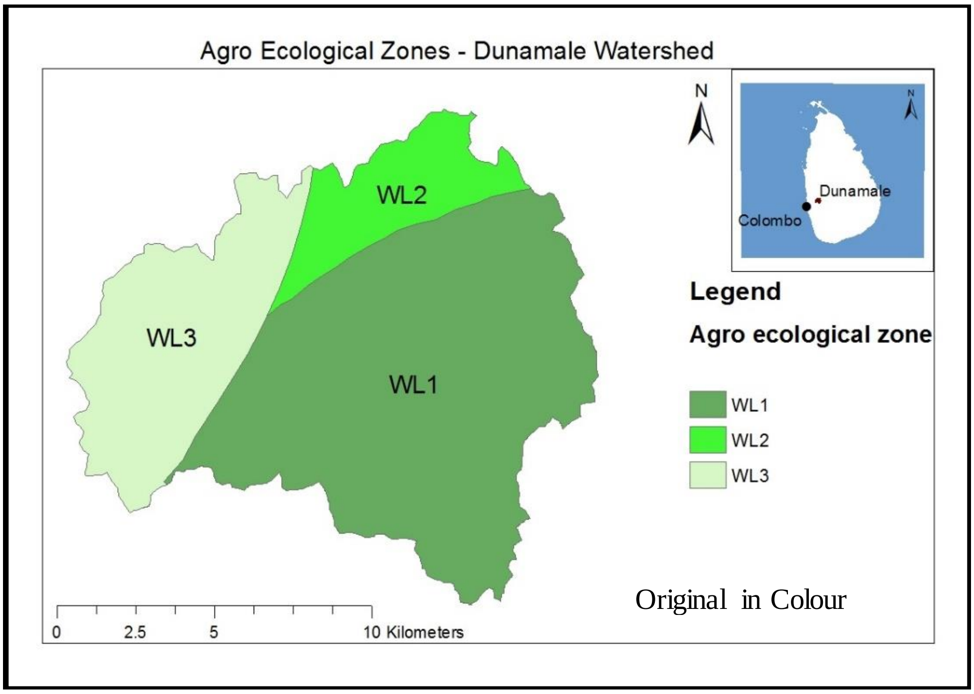

Figure 5-4: Agro ecological regions - Dunamale watershed

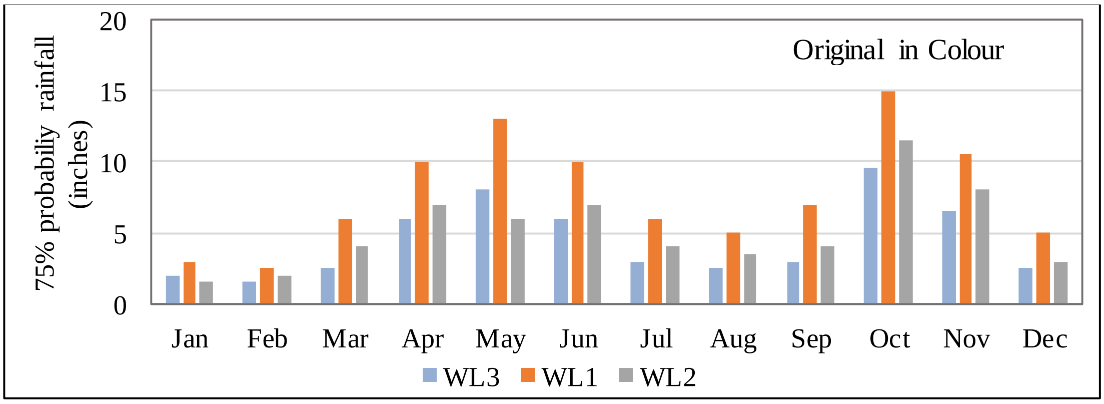

Figure 5-5: Monthly design rainfall values for agro ecological regions in Dunamale watershed

Original in Colour

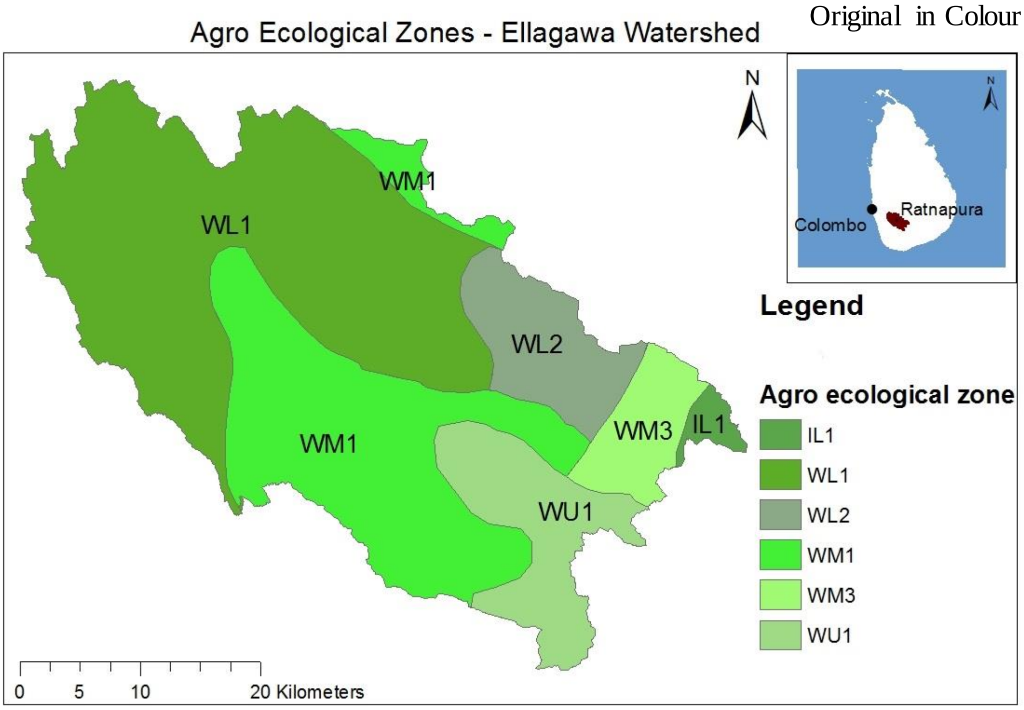

Figure 5-6: Agro ecological regions – Ellagawa basin

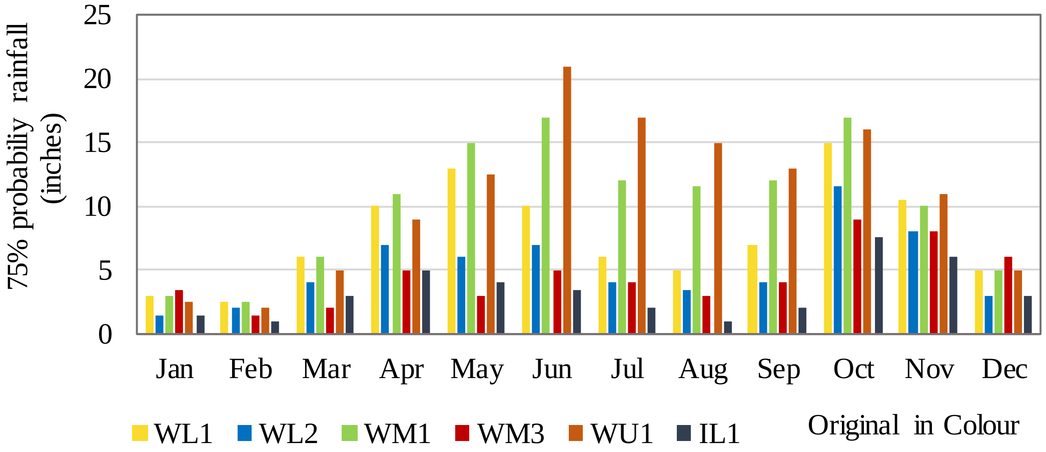

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Figure 5-7: Monthly design rainfall values for agro ecological regions in Ellagawa watershed

Table 5-3: Summary of design rainfall for Dunamale watershed

	Area weight	**75% rainfall (mm) (Ponraja, 1984)**											
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
WL3	0.26	50.8	38.1	63.5	152.4	203.2	152.4	76.2	63.5	76.2	241.3	165.1	63.5
WL1	0.62	76.2	63.5	152.4	254	330.2	254	152.4	127	177.8	381	266.7	127
WL2	0.12	38.1	50.8	101.6	177.8	152.4	177.8	101.6	88.9	101.6	292.1	203.2	76.2
Watershed rainfall		65.1	55.5	123.5	218.8	276.2	218.8	126.8	106.2	142.6	334.6	233.1	104.6

Table 5-4: Summary of design rainfall for Ellagawa watershed

	Area weight	**75% rainfall (mm) (Ponraja, 1984)**											
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
WL1	0.36	76.2	63.5	152.4	254	330.2	254	152.4	127	177.8	381	266.7	127
WL2	0.08	38.1	50.8	101.6	177.8	152.4	177.8	101.6	88.9	101.6	292.1	203.2	76.2
WM1	0.28	76.2	63.5	152.4	279.4	381	431.8	304.8	292.1	304.8	431.8	254	127
WM3	0.18	88.9	38.1	50.8	127	76.2	127	101.6	76.2	101.6	228.6	203.2	152.4
WU1	0.09	63.5	50.8	127	228.6	317.5	533.4	431.8	381	330.2	406.4	279.4	127
IL1	0.01	38.1	25.4	76.2	127	101.6	88.9	50.8	25.4	50.8	190.5	152.4	76.2
Watershed rainfall		74.0	56.5	127.5	229.3	282.7	300.3	207.5	184.3	207.3	362.1	247.2	127.2

5.3.2.2 Watershed parameters

Watershed boundaries were mapped and extents were computed by using 1: 50,000 maps and ArcGIS software. Geo referenced iso yield maps were used to ascertain the seasonal yield at each watershed. Watershed area, Maha (October to March) and Yala (April-September) iso yield values are in the Table 5-6.

Table 5-5: Watershed Parameters for Dunamale and Ellagawa Watersheds

#	**Dunamale Watershed**	**Ellagawa Watershed**
Watershed area	157.5 km^2	1446.4 km^2
Iso -yield value in Maha	1750 Ac. ft/ sq. mile (833,432 m3/km2)	2500 Ac.ft/ sq.mile (1,190,618 m^3/km^2)
Iso -yield value in Yala	2000 Ac. ft/ sq. mile (952,494 m3/km2)	3000 Ac.ft/ sq.mile (1,428,741 m^3/km^2)

5.3.2.3 Model Construction and application

Design yield computation model was developed using Microsoft Excel spreadsheet. Initially the pattern of respective design rainfall values were used to apportion the seasonal yield values to corresponding monthly values. Ponrajah (1984) recommends to apply upper and lower thresholds for the apportioned yield values. The apportioned yield values for each watershed prior to the application of thresholds (named as “Without Thresholds”) and after the application (named as “With Thresholds”) are shown in Figures 5-8 and 5-9 for Dunamale and Ellagawa watersheds respectively. In order to overcome the inherent limitations in the preparation of iso-yield curves by extrapolating observations from larger watersheds, the guidelines recommend the use of upper and lower limits to the seasonal yield values. Accordingly, the upper and lower bounds of the seasonal runoff coefficients are 35% and 7.5% respectively.

The monthly variation of yield values with and without thresholds and the percentage changes are in Table 5-7. The changes in case of Dunamale amounts to 61.5% Maha and 60.7% Yala seasons. In Ellagawa the change amounts to 70.8%, Maha and Yala seasons.

Table 5-6: Monthly Yield of Dunamale and Ellagawa Watersheds – IGM

Season	**Month**	**Dunamale Watershed**				**Ellagawa Watershed**			
		75% Probable Rainfall (mm)	**Watershed Yield (mm/ month)**			**75% Probable Rainfall (mm)**	**Watershed Yield (mm/ month)**		
			Without Thresholds	**With Thresholds**	**% Change**		**Without Thresholds**	**With Thresholds**	**% Change**
Maha (October – March)	October	334.56	304.3	117.1	61.5%	362.09	433.6	126.7	70.8%
	November	233.07	212	81.6	61.5%	247.16	295.9	86.5	70.8%
	December	104.63	95.2	36.6	61.5%	127.15	152.3	44.5	70.8%
	January	65.1	59.2	22.8	61.5%	74	88.6	25.9	70.8%
	February	55.48	50.5	19.4	61.6%	56.48	67.6	19.8	70.8%
	March	123.55	112.4	43.2	61.5%	127.46	152.6	44.6	70.8%
	Total	916.38	833.44	320.7	61.5%	994.35	1190.6	348.0	70.8%
Yala (April - September)	April	218.83	191.3	76.6	60.0%	229.28	274.5	80.2	70.8%
	May	276.22	241.5	96.7	60.0%	282.67	338.5	98.9	70.8%
	June	218.83	191.3	76.6	60.0%	300.25	359.5	105.1	70.8%
	July	126.79	110.9	44.4	60.0%	207.54	248.5	72.6	70.8%
	August	106.17	92.8	37.2	60.0%	184.29	220.7	64.5	70.8%
	September	142.63	124.7	49.9	60.0%	207.25	248.2	72.5	70.8%
	Total	1089.47	952.5	381.3	60.0%	1411.29	1689.9	494.0	70.8%
Annual		2005.85	1785.94	702.0	60.7%	2405.64	2880.5	842.0	70.8%

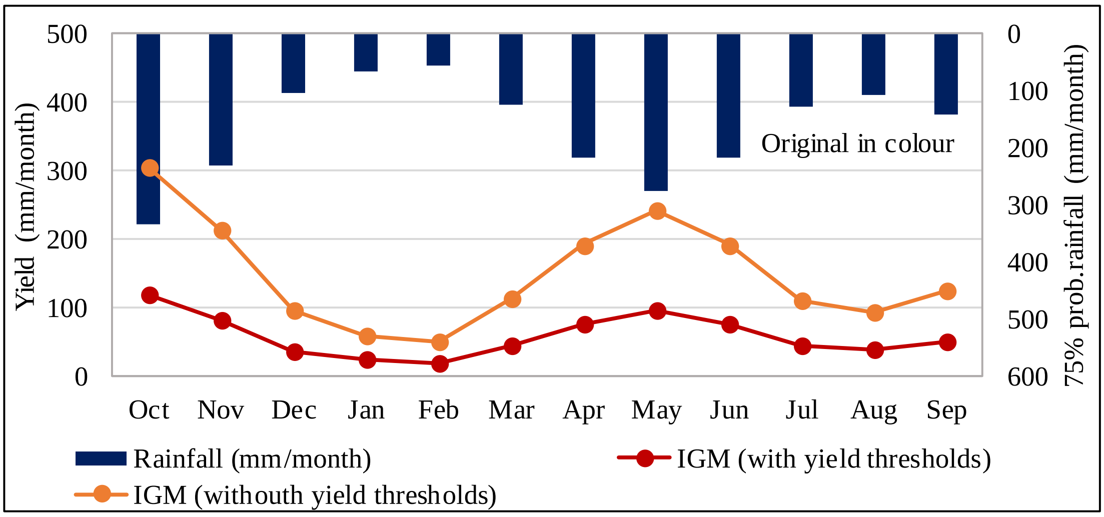

Figure 5-8: Monthly Design Rainfall and IGM Yield Variation - Dunamale Watershed

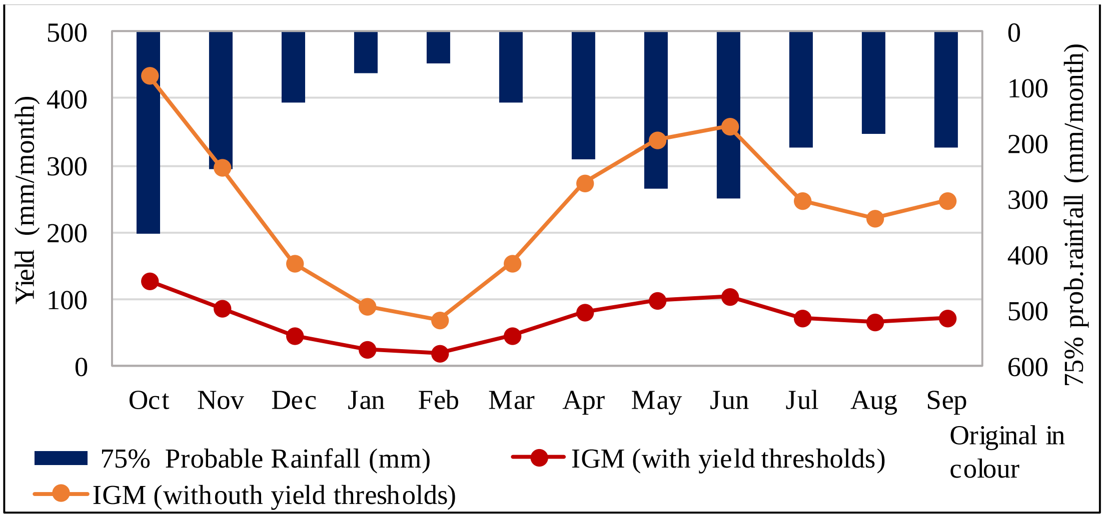

Figure 5-9: Monthly design rainfall and IGM yield - Ellagawa watershed

5.3.3 HEC-HMS Model

HEC HMS application was carried out at a daily temporal resolution. Irrigation guideline design rainfall data for each catchment are at a monthly temporal resolution. Evaporation values in the irrigation guidelines are at a monthly resolution. In order to run a daily HEC HMS model, it was assumed that both monthly rainfall and evaporation values are evenly distributed within each month. In the guideline, evaporation station at Colombo was the closest location for both watersheds. Hence monthly evaporation data of Colombo were used (Table 5-7). Considering the lack of data and the disadvantages during parameter optimisation, the watershed was modelled as a single lumped entity.

Table 5-7: Monthly Evaporation (Colombo)

Season	**Month**	**Evaporation (mm/month)**	**Season**	**Month**	**Evaporation (mm/month)**
Maha	Oct	93.27	Yala	Apr	93.88
	Nov	93.88		May	104.85
	Dec	106.07		Jun	97.54
	Jan	101.19		Jul	78.64
	Feb	95.10		Aug	77.72
	Mar	89.00		Sep	89.00
Total		578.51	Total		541.63

5.3.3.1 Model Components and Parameters

A practicing engineer has the option of either using a HEC-HMS calibrated and verified for the same watershed or to use parameters from a model developed for an adjacent basin or extrapolated from those reported in reviewed literature. This because attempting parameter calibration demonstrates the lack of understanding of model development for ungauged watershed. As such model components selection was based on the literature review. There are many HEC-HMS model applications carried out for Sri Lankan watersheds. These were evaluated and selected by considering the success of application and the data availability. Selection of model parameters for both watersheds were based on (1) Literature preferred methods, (2) Number of parameters, (3) Parameter availability and (4) Applicability for continuous modelling, Deficit and constant method recommended as the appropriate loss method by many researchers (Jayadheera, 2016, Kanchanamala et al., 2016, Halwatura and Najim, 2013). SCS curve number method and Snyder's UH method were the most recommended options for transform method (Jayadheera, 2016, Kanchanamala et al., 2016, Halwatura and Najim, 2013). In almost all Sri Lankan applications, Recession method was used as the baseflow method (Table 2-1).

Table 5-8: HEC Process models used and recommended in Siri Lankan Studies

Reference	**Loss Model**		**Transform Model**		**Recession method**		**Usage**
	Model	**Parameters**	**Model**	**Parameters**	**Model**	**Parameters**	**U/NI/R**
(Jayadheera, 2016)	Deficit & constant	Constant loss, initial deficit	SCS UH	Lag time	Recession	Initial discharge, recession constant	U & R
(Kanchanamala et al., 2016)	Deficit & constant		Snyder's UH		Recession		NI & R
(Sampath et al., 2014)	Five layer moisture accounting	canopy interception, surface depression storage, soil, upper groundwater, and lower Groundwater.	Clark UH	Time of concentration, storage coefficient	Recession	Initial discharge, recession constant	U & NI
(Silva et al., 2014)	Green & Ampt	Initial loss, Moisture deficit, suction head, conductivity, imperviousness	Clark UH	Time of concentration, storage coefficient	Recession	Initial discharge, recession constant	U
(Ratnayake et al., 2010)	Green & Ampt		Clark, Snyder, SCS UH methods		Recession		NI
(Halwatura & Najim, 2013)	Deficit & constant	initial deficit (mm), maximum storage (mm), constant rate (mm/h), Imperviousness (%)	Snyder UH methods	standard lag (h), peaking coefficient	Not mentioned		U & R

Note: Notation: U/NI/R denotes, Used/Not Indicated/Recommended

When selecting model components, the priority was given for selecting same loss, transform and baseflow methods for both basins, but different transform methods were selected for two basins due to availability of literature. The summary of models used in Sri Lankan studies is in the Table 5-8. Considering the merits and Demerits the Process models and parameters used for Dunamale watershed and Ellagawa watershed are shown in Table 5-9 and 5-10.

Table 5-9: HEC-HMS model Parameters for Dunamale watershed

Model component	**Name of Parameter**	**Value**	**Unit**	**Remarks (Reason for Selection)**
Loss method	Constant loss	0.487	mm/hr	Hydrologically similar catchments (Jayadheera, 2016)
	Initial deficit	3.384	mm	Hydrologically similar catchments (Jayadheera, 2016)
Transform method	Standard lag	41.1	hr	Parameter availability (Halwatura & Najim, 2013)
	Peaking Coefficient	0.2		Parameter availability (Halwatura & Najim, 2013)
Recession method	Recession constant	0.907		Hydrologically similar catchments (Jayadheera, 2016)
	Threshold ratio	0.151		Hydrologically similar catchments (Jayadheera, 2016)

Table 5-10: HEC-HMS model Parameters Ellagawa watershed

Model component	**Name of parameter**	**Value**	**Unit**	**Remarks (Reason for Selection)**
Loss method	Constant loss	0.487	mm/hr	Parameter availability (Jayadheera, 2016)
	Initial deficit	3.384	mm	Parameter availability (Jayadheera, 2016)
Transform method	Lag time	2677	minutes	Parameter availability (Jayadheera, 2016)
Recession method	Recession constant	0.907		Parameter availability (Jayadheera, 2016)
	Threshold ratio	0.151		Parameter availability (Jayadheera, 2016)

5.3.3.2 HEC-HMS model construction and application

The model was downloaded (US Army Corps of Engineers, 2016) and installed in a lap top computer with a windows Operating system. The schematics of the developed lumped models for Dunamale and Ellagawa watersheds are in Figure 5-10 and Figure 5-11 respectively. For each watershed, the initial storage and initial discharge were set to zero and then several dry runs were performed to warmup the model. The initial storage percentage and initial discharge of Dunamale watershed at the beginning of the model runs were 0.95% and 1.7 m3/s respectively. The respective initial storage percentage and initial discharge values for Ellagawa watershed were 0.69% was 11.5 m^3/s respectively.

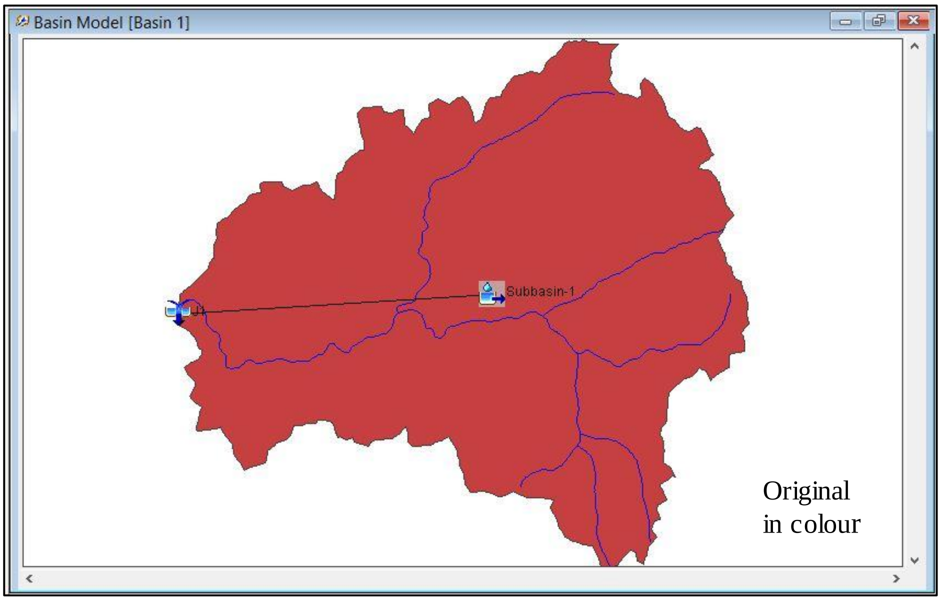

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Figure 5-10: Schematic HEC-HMS Model – Dunamale watershed

5.3.3.1 Yield Estimated by HEC-HMS model

Model outputs in the daily temporal scale were aggregated to monthly scale for comparison with the IGM. The yield computations for Dunamale and Ellagawa watersheds with and without thresholds are shown in Table 5-11. Design rainfall and corresponding yield values of Dunamale and Ellagawa watersheds are in Figure 5-12 and Figure 5-13.

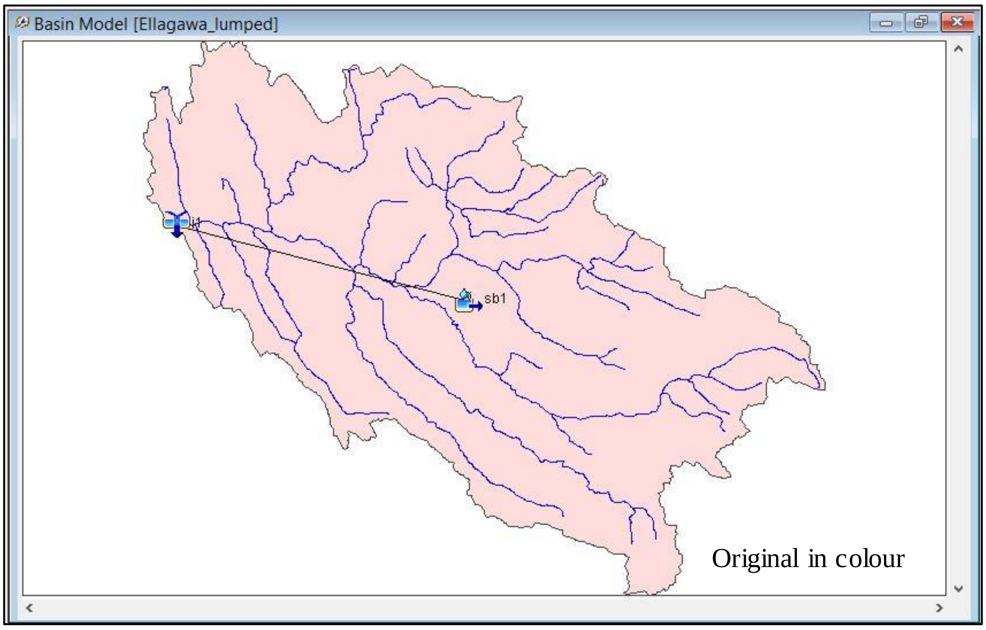

Figure 5-11: Schematic Diagram in HEC-HMS – Ellagawa watershed.

Maha season shows 184.9 mm/season yield and Yala season shows 216.69 mm/season yield for Dunamale watershed for both with and without threshold conditions and Ellagawa watershed shows 105 mm/season for Maha and 140 mm/season for yala for both conditions. Annual yield is 401.6 mm/year for Dunamale basin and 245.0 mm/year for Ellagawa watershed. HEC-HMS yield results fall under the yield thresholds. Hence, one graph generates for yield with and without thresholds.

Table 5-11: Monthly Yield of Dunamale and Ellagawa watersheds HEC HMS Model

Season	**Month**	**Dunamale Watershed**				**Ellagawa Watershed**			
		75% Probable Rainfall (mm)	**Watershed Yield (mm/ month)**			**75% Probable Rainfall (mm)**	**Watershed Yield (mm/ month)**		
			Without Thresholds	**With Thresholds**	**% Change**		**Without Thresholds**	**With Thresholds**	**% Change**
Maha (October – March)	October	334.56	57.5	57.5	0%	362.1	40.0	40.0	0%
	November	233.07	51.8	51.8	0%	247.2	25.7	25.7	0%
	December	104.63	27.9	27.9	0%	127.2	13.6	13.6	0%
	January	65.1	15.1	15.1	0%	74.0	7.8	7.8	0%
	February	55.48	11.0	11.0	0%	56.5	5.6	5.6	0%
	March	123.55	21.6	21.6	0%	127.5	12.3	12.3	0%
	Total	916.38	184.9	184.9	0%	994.3	105.0	105.0	0%
Yala (April - September)	April	218.83	38.5	38.5	0%	229.3	22.0	22.0	0%
	May	276.22	52.6	52.6	0%	282.7	27.9	27.9	0%
	June	218.83	46.4	46.4	0%	300.3	29.8	29.8	0%
	July	126.79	30.4	30.4	0%	207.5	21.4	21.4	0%
	August	106.17	22.4	22.4	0%	184.3	18.5	18.5	0%
	September	142.63	26.4	26.4	0%	207.3	20.4	20.4	0%
	Total	1089.47	216.7	216.7	0%	1411.3	140.0	140.0	0%
Annual		2005.9	401.6	401.6	0%	2405.6	245.0	245.0	0%

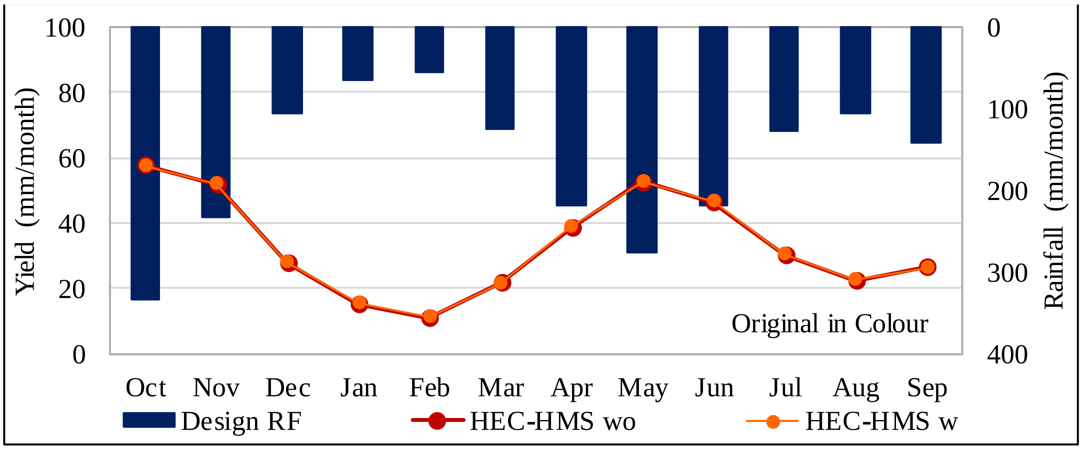

Figure 5-12: Monthly design rainfall and HEC HMS yield variation - Dunamale watershed

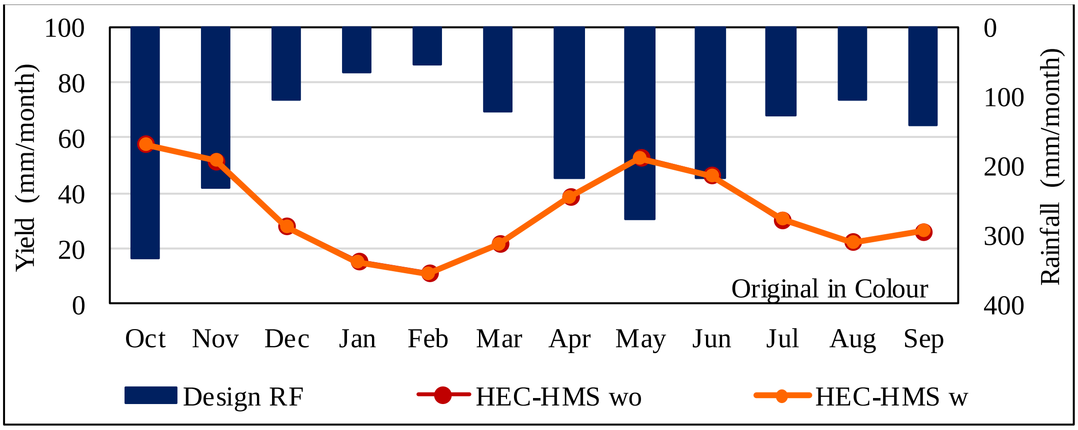

Figure 5-13: Monthly design rainfall and HEC HMS yield variation - Ellagawa watershed

5.3.4 Unit hydrograph model

Unit hydrograph is an event based synthetic flow generation model that has been successfully applied for continuous modelling. Different unit hydrograph methods were reviewed for the selection of a suitable model for computation of design yield values. Model selection was based on the consideration of (1) Availability of Sri Lankan literature, (2) Easiness for applicability (3) number of parameters, (4) Applicability for selected catchments (5) Accountability of catchment characteristics. Table 2-4 shows the evaluation and prioritisation of the models by considering advantages and disadvantages. Snyder's synthetic unit hydrograph method that had more merits was selected for the comparison. The Snyder's synthetic unit hydrograph model is a direct runoff generation model, therefore it is necessary to compute the baseflow for the estimation of continuous streamflow.

5.3.4.1 Design rainfall

75% probable rainfall used for the previous two models was the input selected for the Unit Hydrograph (UH) model. As in the case of HEC HMS, the monthly values were uniformly distributed within each month to determine the daily design rainfall values. UH model requires the input as effective rainfall. Following the evaluation of several available loss models, the Φ index method was selected as the most suitable to compute the rainfall loss values. Loss rate computations used a 24 hour day (Thapa, 2015), a comparison with physical runoff coefficient (Chow et al., 1988), rationality of outputs by considering a match with reality, and consideration of annual water balance.

5.3.4.1.1 Dunamale watershed

Φ index average loss rate values were selected as 1.2 mm/hr for Duanamale watershed from the literature considering the data period considered to calculate the loss rate. (Thapa G, 2015). In the application of unit hydrograph, monthly design rainfall was generalised to days and wet days, dry days and wet hours, dry hours were not considered. Literature selected loss rate was generalised considering average wet days and dry days of selected 10 years, but the generated hydrograph did not give acceptable results. Average wet hours and dry hours were considered and generalised, but the generated hydrograph results were not acceptable. Hence, the loss rate was back calculated considering the average percentage of effective rainfall from 2005-2015. For Dunamale watershed, 5.9 mm/day loss rate was used for calculating effective rainfall in design rainfall application.

5.3.4.1.2 Ellagawa watershed

For Ellagawa watershed, no direct literature support was found for Φ index values. Therefore by considering similar catchment characteristics, Φ index values were obtained from literature considering similarity of wet zone watersheds as present in Table 5-12.

Loss rate depends on the soil type and slope of the watershed. Considering those factors, Karasnagala watershed in Attanagalu basin was selected that has more similarities for Ellagawa watershed in Kalu River. Considering the data period used for calculation of loss rate, 1.2 mm/hr loss rate was selected to be applied for Ellagawa watershed.

Table 5-12: Pi-index values selected for effective rainfall calculation

Φ index value	**Reference**	**Basin**	**Period**
19.4 mm/hr	(Manchanayake et. al., 1985)	Mahaweli (watawala)	Sep, 1975
36.3 mm/hr			June, 1973
4.8 mm/hr	(Manchanayake et. al., 1985)	Nilwala (Bopagoda)	May, 1977
5.2 mm/hr	(Manchanayake et. al., 1985)	Attanagalu (Karasnagala)	Nov, 1975
1.2 mm/hr	(Thapa G, 2015)		1971-1989
0.6 mm/hr	(Manchanayake et. al., 1985)		June, 1979

In the application of unit hydrograph, monthly design rainfall was generalised to days and wet days, dry days and wet hours, dry hours were not considered. Literature selected loss rate was generalised considering average wet days and dry days of selected 8 years, but the generated hydrograph did not give acceptable results. Average wet hours and dry hours were considered and generalised, but the generated hydrograph results were not acceptable. Hence, the loss rate was back calculated considering the average percentage of effective rainfall to the annual rainfall from 2006-2014. Loss rate was 7.9 mm/day for calculating the effective rainfall for Ellagawa watershed by using Φ index method in design rainfall application.

5.3.4.2 Model parameters

The watershed geometric parameters for the UH method were extracted using ArcGIS software. Different researchers have found the ranges of regional parameters and Table 2-2 summarises those ranges. Basic regional parameters were selected for Ellagawa and Dunamale watersheds considering the parameter ranges used for Sri Lankan case studies for Snyder’s unit hydrograph. Calibrated and verified regional parameter values from Sri Lankan case studies are present in Table 2-3. The regional parameters Ct and Cp (Chow et Al, 1988) of the synthetic UH for each watershed was determined by using Irrigation Guideline (1984) (Ponrajah, 1984). Considering proximity to watersheds, the Ct and Cp values of Karasnagala (Thapa, 2015) and Putupaula (Ponrajah, 1984) were selected for Dunamale and Ellagawa respectively. Table 5-14 shows the geometric and regional parameters for both watersheds. Figure 5-14, 5-15 show catchment parameters required for UH model application for Dunamale and Ellagawa watersheds.

5.3.4.3 Baseflow Computation

Unit hydrograph only provides direct runoff. Therefore base flow component is need to be added for direct runoff to obtain yield. Different base flow calculation methods were checked considering literature and Baseflow index method was identified as possible to apply for the study area. Since literature does not provide baseflow index values for Sri Lanka directly, baseflow index value for tropical rainforest – 0.77 (Beck et al., 2013) was selected for both watersheds considering literature. Calculated annual baseflow was divided into months considering the proportionality of total monthly rainfall and then added to monthly direct runoff to obtain the yield. The obtained yield values were compared with the observed yield.

Table 5-13, Figure 5-14 and Figure 5-15 summarises catchment parameters for UH model for both Dunamale and Ellagawa watersheds.

Table 5-13: Unit Hydrograph parameters for Dunamale and Ellagawa watersheds

Parameter	**Dunamale watershed value**	**Remarks**	**Ellagawa watershed value**	**Remarks**
Catchment area (A)	157.5 sqkm	Figure 5-14	1446.4 sqkm	Figure 5-15
Length of the longest river (L)	22.55 km	Figure 5-14	74.03 km	Figure 5-15
Length of the river from centroid/ near centroid (Lc)	12.67 km	Figure 5-14	29.23 km	Figure 5-15
Regional Parameter Ct	0.38	(Thapa, 2015)	0.47	(Ponrajah, 1984)
Regional Parameter Cp	3.78	(Thapa, 2015)	8.7	(Ponrajah, 1984)
Baseflow Index	0.77	(Beck et al., 2013)	0.77	Beck et al., 2013)

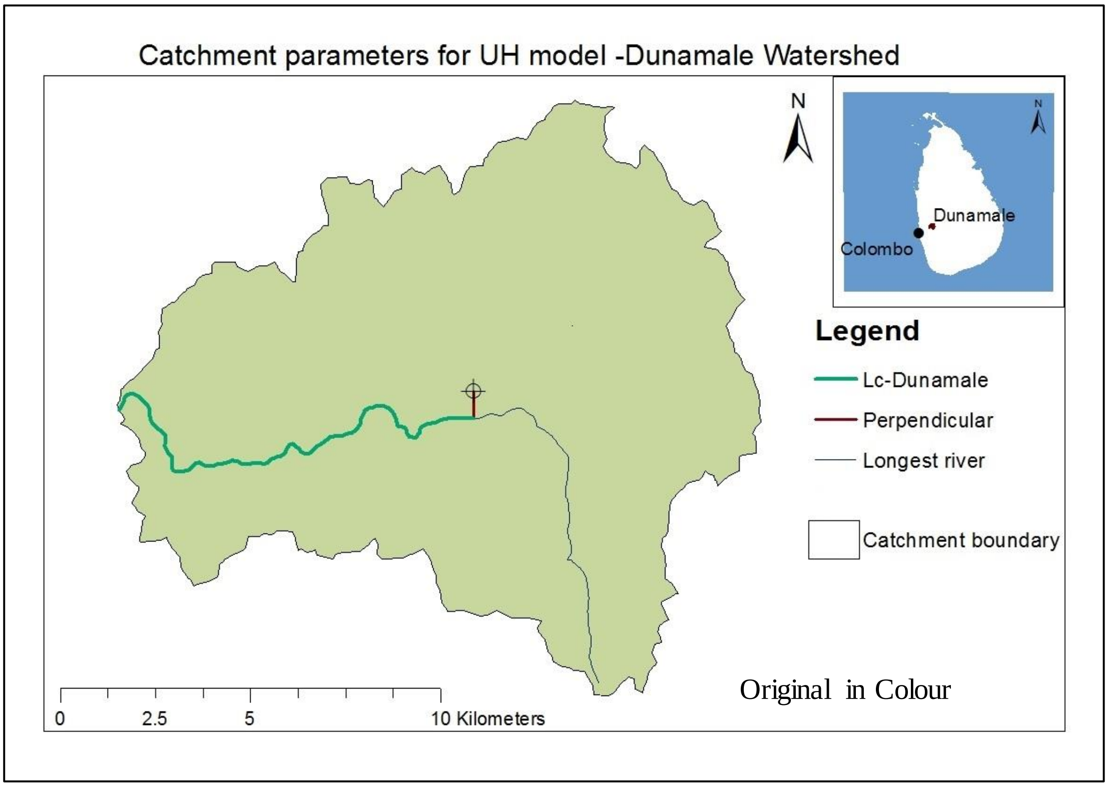

Figure 5-14: Catchment parameters for UH model - Dunamale watershed

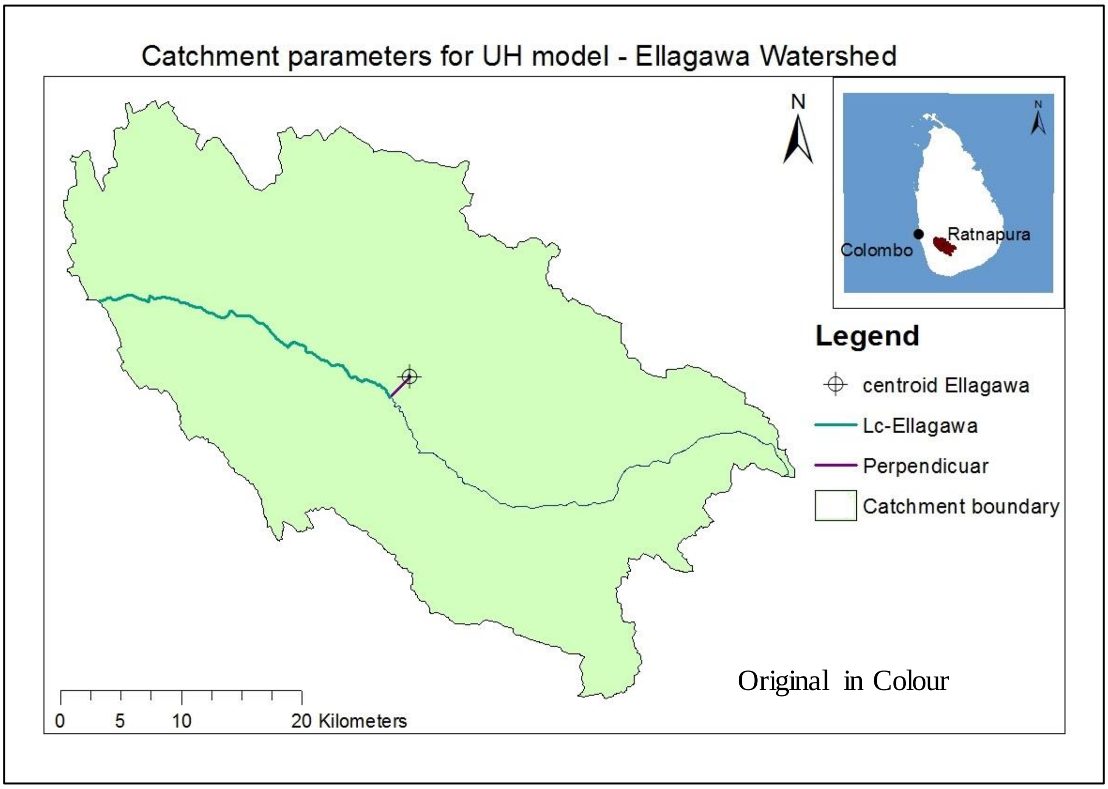

Figure 5-15: Catchment parameters for UH model - Ellagawa watershed

5.3.4.4 Model construction and application

A UH model at a daily temporal resolution and spanning over the design year was developed using Microsoft excel spreadsheet. The standard Empirical equations for Snyder's Synthetic Unit Hydrograph (Chow et al., 1988) were used to derive the standard UH and the watershed specific UH for a 24 hour duration. The 24 hour triangular hydrograph was to the converted as a curvilinear UH by following the practice of US Soil Conversion Service (Chow et al., 2013). The computed UH parameters are in Table 5-14. Triangular and Curvilinear UH developed for both watersheds are shown in Appendix F.

Table 5-14: Standard and 24 Hr unit hydrograph results – Dunamale and Ellagawa watersheds

#	**Notation**	**Description**	**Dunamale Watershed**	**Ellagawa Watershed**
Standard Unit Hydrograph	t_p	Basin lag (standard hydrograph)	928min	3920.15 min
	t_r	Standard effective rainfall duration	168.7 min	712.75 min
	q_p	Peak discharge (standard hydrograph)	0.07m^2/s.km^2.cm	0.0198 m^2/s.km^2.cm
24 Hour Unit hydrograph	t_{pR}	Basin lag (required hydrograph)	20.8 hr	68.37 hr
	q_{pR}	Peak discharge (required hydrograph)	7.93 m^3/s.cm	27.345 m^3/s.cm
	t_b	Base time	110.46 hr	294.09 hr
	T_p	Standard basin lag	32.76 hr	80.37 hr

5.3.4.5 UH model application results

UH model yield computations for Dunamale and Ellagawa watersheds with and without thresholds are shown in Table 5-15 and Figure 5-16 and 5-17. Yield variation with rainfall considering baseflow, direct runoff, effective rainfall and losses is presented Appendix F.

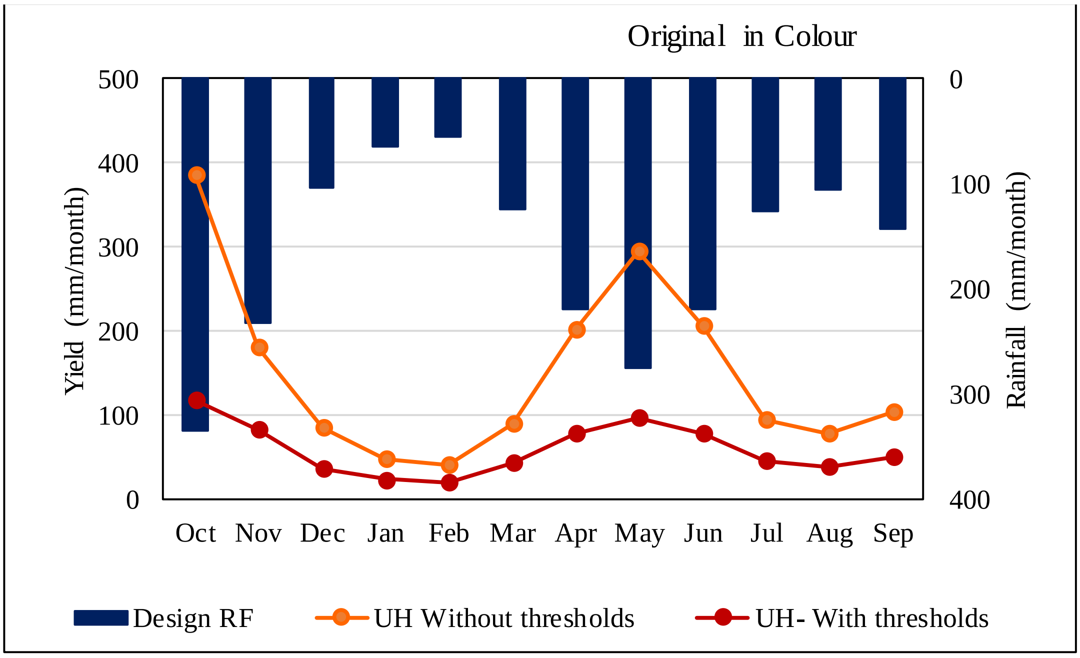

Figure 5-16: UH yield variation for Dunamale watershed

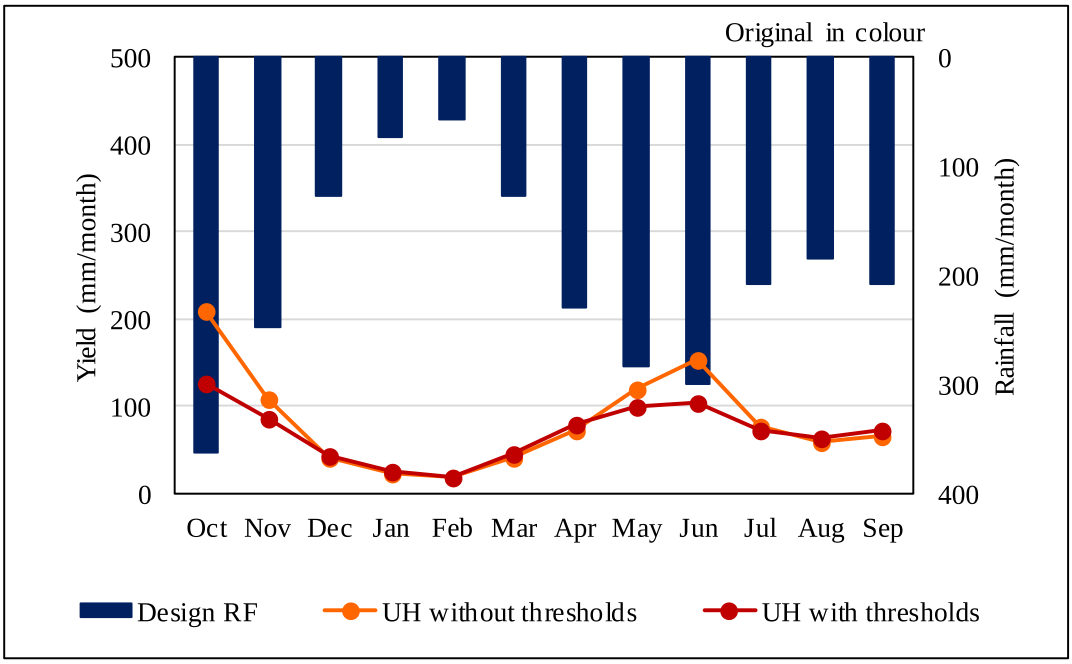

Figure 5-17: UH yield variation for Ellagawa watershed

Table 5-15: Monthly yield of Dunamale and Ellagawa watersheds UH model

Season	Month	Dunamale Watershed						Ellagawa Watershed					
		75% Probable Rainfall (mm)	Effective RF	Direct Runoff	Watershed Yield (mm/ month)			75% Probable Rainfall (mm)	Effective RF	Direct Runoff	Watershed Yield (mm/ month)		
					Without Thresholds	With Thresholds	% Change				Without Thresholds	With Thresholds	% Change
Maha (October – March)	Oct	334.6	151.9	141.9	377.7	117.10	70%	362.1	117.8	94.6	209.5	126.73	39%
	Nov	233.1	99.0	105.6	176.3	81.57	55%	247.2	9.0	30.6	108.6	86.51	21%
	Dec	104.6	0.0	9.0	83.6	36.62	57%	127.2	0.0	1.9	42	44.50	-6%
	Jan	65.1	0.0	0.0	46.5	22.79	52%	74.0	0.0	0.0	23.3	25.90	-11%
	Feb	55.5	0.0	0.0	39.6	19.42	52%	56.5	0.0	0.0	17.7	19.77	-11%
	Mar	123.5	1.4	0.0	88.2	43.24	52%	127.5	0.0	0.0	40.2	44.61	-11%
	Total	916.4	252.3	256.5	811.88	320.74	60%	994.3	0.0	127.0	441.3	348.02	21%
Yala (April to September)	Apr	218.8	43.6	40.5	195.9	76.59	74%	229.3	37.2	0.0	72.4	80.25	-11%
	May	276.2	91.4	92.3	287.6	96.68	53%	282.7	63.0	31.1	120.3	98.93	18%
	Jun	218.8	40.6	45.7	200.9	76.59	19%	300.3	0.0	58.5	153.3	105.09	32%
	Jul	126.8	0.0	2.4	92.9	44.38	43%	207.5	0.0	10.9	76.8	72.64	5%
	Aug	106.2	0.0	0.0	75.8	37.16	64%	184.3	0.0	0.0	58.7	64.50	-11%
	Sep	142.6	0.0	0.0	101.9	49.92	94%	207.3	126.8	0.0	65.9	72.54	-11%
	Total	1089.5	175.6	181.0	955.05	381.31	61%	1411.3	100.2	100.4	547.4	493.95	10%
annual		2005.9	427.9	437.4	377.7	702.0	61%	2405.6	227.0	227.4	988.7	842.0	15%

Effective rainfall computed after the reduction of losses from the design rainfall was used as the input rainfall for the model. Baseflow was added to the computed direct runoff to obtain the total watershed runoff. In this computation evaporation was assumed as a loss when calculating effective rainfall. UH model computations were aggregated to monthly, seasonal and annual values. Watershed yield components which consist of baseflow and direct runoff together with design rainfall consisting of effective rainfall and losses are shown in the Appendix F. Both UH models of Ellagawa and Dunamale supports for annual water balance.

5.3.5 Evaluation of yield estimations

5.3.5.1 Evaluation Methodology

The computational flow of evaluation is presented in Figure 5-18.

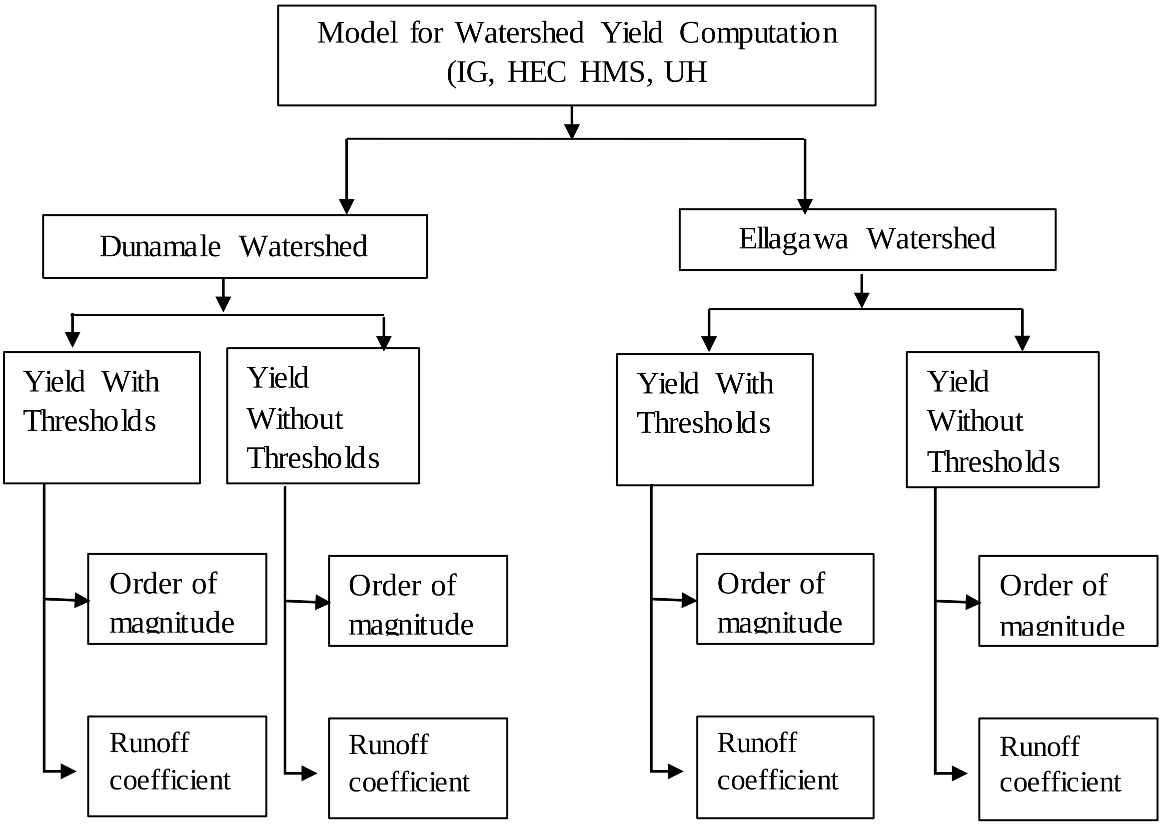

Figure 5-18: Computational Flow for Evaluation of Yield Computation Option

Since the Analysis 1 is to evaluate the best option available for a practicing engineer, the evaluation of alternatives can only be judgemental. Hence two main aspects were considered. One is the comparison of yield magnitudes to assess the differences between each alternative. Other is the comparison of runoff coefficients to assess the acceptability of computed values. Therefore, the Order of Magnitude of watershed yield estimations and the corresponding runoff coefficients were evaluated for with and without threshold considerations. In case of runoff coefficients the comparisons were done with the runoff coefficients computed with physical parameters (Chow et al., 1988).

5.3.5.1 Model comparison without yield thresholds

5.3.5.1.1 Magnitude of Watershed Yield

Model computations without thresholds indicate the yield estimation for the design rainfall. Hence this evaluates the estimated streamflow by each model. Comparison of yield for Duanamale and Ellagawa watersheds without thresholds and for different temporal resolutions is shown by Figure 5-19, Figure 5-20 and Table 5-19. In case of both watersheds the HEC HMS estimates were the lowest. In Dunamale watershed, yield estimates of both IG and UH models were having the same order of magnitude. In case of Ellagawa watershed the IGM model estimations were approximately 3 times the UH model estimations while they were approximately 12 times higher than those of the HEC HMS.

5.3.5.1.2 Watershed Runoff Coefficient

Runoff coefficient provides an indication of the realistic nature of the yield estimates. The associated monthly, seasonal and annual runoff coefficients of IGM, HEC-HMS and UH model results are in Table 5-18. In case of Dunamale Watershed the monthly runoff coefficients from IGM vary between 0.87 and 0.91 while the same from UH model vary between 0.71 and 1.04. HEC –HMS shows a comparatively lower runoff coefficient variation from 0.16-0.27. In the Ellagawa watershed the IGM estimates are with a runoff coefficient of 1.2, UH vary from 0.31-0.51, HEC-HMS vary from 0.10-0.11. The runoff coefficient values greater than one are conceptually unacceptable. Comparison of values in references (Subramanya, 2014, Chow et al., 1988) reveal that runoff co-efficients in the range of 0.9 are highly unrealistic for watersheds with physical parameters similar to Dunamale and Ellagawa watersheds. In order to evaluate with the values quoted references, the physical characteristics of two watersheds were used to compute the runoff coefficients as guided by Chow et Al, (1988). This reference which provides guidance for drainage designs, lists runoff coefficient values for events corresponding to return periods between 2 and 500 years. These values enable to comprehend the range of runoff coefficients that may be acceptable to evaluate yield estimations. Details are in Tables 5-16, 5-17 and Figure 4-1 and 4-2 Composite runoff coefficients for Dunamale and Ellagawa watersheds are 0.50 and 0.54 respectively. The guidance material followed is Chow et.al, 1988. When calculating physical runoff coefficients, it was assumed antecedent moisture content is 2, soil condition of both catchments are shallow loess, sandy loam category and by using SCS curve number method, slope was calculated. Slope in both catchments were in between 2%-7%. Return period of 25 years was considered for the calculation.

5.3.5.1.3 Evaluation of Dunamale Watershed

The runoff coefficient value obtained by following the guidance of Chow et Al 1988 shows that the IGM and UH model estimations for Dunamale is much higher and unacceptable as realistic estimates. The HEC HMS model estimations with an average runoff coefficient of 0.20 indicates that the estimated yield value is much lower than the expected values. Annual water balance of Dunamale watershed shows that average annual evapotranspiration value is approximately 1610 mm. Evaporation values in the ID guideline shows that the annual evapotranspiration value at Colombo (The closest station) is approximately 1120 mm. This also shows that the HEC HMS estimates are about 45% of the expected yield from Dunamale watershed. Therefore, in case of Dunamale watershed the watershed yield estimations by the IDM and UH model lead to significant over estimations. Comparison of runoff coefficient values with the HEC HMS model estimations clearly shows that the yield values from model are significantly under estimated. Since over estimations lead to over expenditure of resources, the under estimations lead to increased risks of failure. Hence none of the three models can be used for estimation of watershed yield.

5.3.5.1.4 Evaluation of Ellagawa Watershed

IGM yield estimations with a runoff coefficient of 1.2 is conceptually unacceptable. Runoff coefficient of Ellagawa watershed computed using guideline reference (Chow et Al 1988) is approximately 1.3 times the average runoff coefficient shown by UH model estimations. The same is 5 times the average runoff coefficient displayed by the HEC HMS model estimations. Water balance computed with the UH model yield values shows that annual evapotranspiration is approximately 1420 mm. This is 300 mm lesser than that recorded at the nearby Colombo gauging station (Ponrajah 1984). Comparison of the water balance values and evapotranspiration shows that the UH model estimated watershed yield values are approximately 77% of the expected yield computed using the watershed runoff coefficients.
The HEC HMS model estimations with an average runoff coefficient of 0.10 indicates that the estimated yield value is approximately 18% of the than the expected values from physical runoff coefficients. Annual water balance of Ellagawa watershed shows that average annual evapotranspiration value is approximately 2158 mm. Evaporation values at the closest station as per ID guideline indicate that the annual evapotranspiration of Ellagawa is approximately 1120 mm. This shows that the UH model estimates are about 28% of the expected yield from Ellagawa watershed.

These assessments indicate that the IDM watershed yield estimates for Ellagawa are unrealistically high. The yield estimate using HEC HMS model has shown a significant under estimation. Most comparable watershed yield for Ellagawa as estimated by the UH model is 28% higher than that estimated using the physical runoff coefficient.

Therefore, in case of Dunamale watershed the watershed yield estimations by the IDM and UH model lead to significant over estimations. Comparison of runoff coefficient values with the HEC HMS model estimations clearly shows that the yield values from model are significantly under estimated. Since over estimations lead to over expenditure of resources, the under estimations lead to increased risks of failure. Hence none of the three models can be used for estimation of watershed yield.

Table 5-16: Watershed Physical Parameters and associated Runoff Coefficients – Dunamale

#	**Paved**	**Homestead**	**paddy**	**Coconut**	**Rubber**	**Forest**	**Total**
Area extent (sqkm)	10.4	55.2	19.1	32.9	38	1.9	157.5
Area percentage (%)	6.6%	35.0%	12.1%	20.9%	24.1%	1.2%	100%
Runoff CN	85	65	75	72	72	55	-
Area percentage (%) X Runoff CN	5.61	22.78	9.10	15.04	17.37	0.66	70.56
Weighted CN							70.56
Slope (inch)							4.17
Slope range							2%-7%
Runoff coefficient	0.85	0.5	0.48	0.46	0.46	0.3	-
Area % weighted runoff coefficient	0.06	0.18	0.06	0.10	0.11	0.00	0.50
Physical runoff coefficient							0.50

Table 5-17: Watershed Physical Parameters and associated Runoff Coefficients – Ellagawa watershed

#	**Paved**	**homestead**	**paddy**	**coconut**	**rubber**	**tea**	**forest**	**chena**	**Total**
Area extent (sqkm)	79.6	255.8	97.1	3.7	358.7	126.6	231	293.5	1446
Area percentage (%)	5.5%	17.7%	6.7%	0.3%	24.8%	8.8%	16.0%	20.3%	100%
Runoff CN	85	65	75	72	72	75	55	65	-
Area percentage (%) X Runoff CN	4.68	11.50	5.04	0.18	17.86	6.57	8.79	13.19	67.80
Weighted CN									67.80
Slope (inch)									4.75
Slope range									2%-7%
Runoff coefficient	0.85	0.5	0.48	0.46	0.46	0.44	0.3	0.85	-
Area % weighted runoff coefficient	0.05	0.09	0.03	0.00	0.11	0.04	0.05	0.17	0.54
Physical runoff coefficient									0.54

Table 5-18: Runoff Coefficients of Dunamale and Ellagawa watersheds

	Dunamale Watershed			**Ellagawa Watershed**		
	IGM wo	**HEC wo**	**UH wo**	**IGM wo**	**HEC wo**	**UH wo**
October	0.91	0.16	1.13	1.20	0.12	0.58
November	0.91	0.22	0.76	1.20	0.10	0.44
December	0.91	0.27	0.80	1.20	0.11	0.33
January	0.91	0.23	0.71	1.20	0.11	0.31
February	0.91	0.20	0.71	1.20	0.10	0.31
March	0.91	0.17	0.71	1.20	0.10	0.32
April	0.87	0.18	0.90	1.20	0.10	0.32
May	0.87	0.19	1.04	1.20	0.10	0.43
June	0.87	0.21	0.92	1.20	0.10	0.51
July	0.87	0.24	0.73	1.20	0.10	0.37
August	0.87	0.21	0.71	1.20	0.10	0.32
September	0.87	0.19	0.71	1.20	0.10	0.32
Maha	0.91	0.20	0.89	1.20	0.11	0.44
Yala	0.87	0.20	0.88	1.20	0.10	0.39
Annual	0.89	0.20	0.88	1.20	0.10	0.41
Min	0.87	0.16	0.71	1.20	0.10	0.31
Max	0.91	0.27	1.04	1.20	0.11	0.51

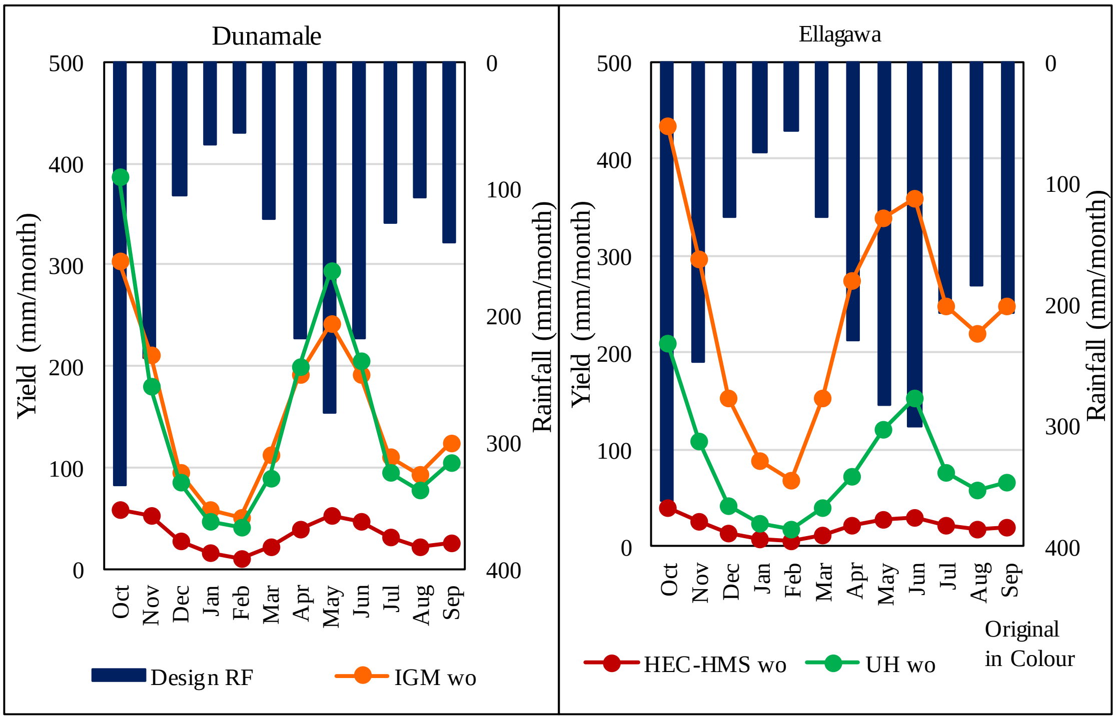

Figure 5-19: Model yield comparison without thresholds

Table 5-19: Comparison of Dunamale and Ellagawa watersheds without threshold yield

	Dunamale Watershed				**Ellagawa Watershed**			
	Design Rainfall	**IGM wo**	**HEC wo**	**UH wo**	**Design Rainfall**	**IGM wo**	**HEC wo**	**UH wo**
October	334.6	304.3	53.7	377.7	362.1	433.6	42.9	209.5
November	233.1	212	51.6	176.3	247.2	295.9	25.8	108.6
December	104.6	95.2	27.8	83.6	127.2	152.3	13.6	42
January	65.1	59.2	15.1	46.5	74.0	88.6	7.8	23.3
February	55.5	50.5	11	39.6	56.5	67.6	5.6	17.7
March	123.6	112.4	21.6	88.2	127.5	152.6	12.3	40.2
April	218.8	191.3	38.5	195.9	229.3	274.5	22.0	72.4
May	276.2	241.5	52.6	287.6	282.7	338.5	27.9	120.3
June	218.8	191.3	46.4	200.9	300.3	359.5	29.8	153.3
July	126.8	110.9	30.4	92.9	207.5	248.5	21.4	76.8
August	106.2	92.8	22.4	75.8	184.3	220.7	18.5	58.7
September	142.6	124.7	26.4	101.9	207.3	248.2	20.4	65.9
Maha	916.4	833.6	180.8	811.9	994.3	1190.6	108.0	441.3
Yala	1089.5	952.5	216.7	955.1	1411.3	1689.9	140.0	547.4
Annual	2005.86	1786.1	397.5	1766.9	2405.6	2880.5	248.0	988.7

wo - Without Yield Thresholds

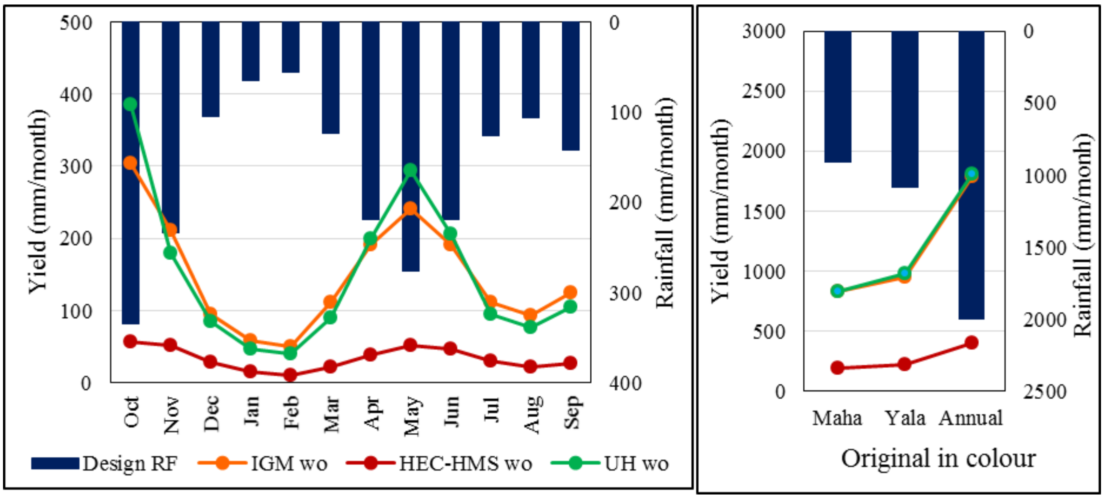

Figure 5-20: Monthly, Seasonal and Annual yield comparison without yield thresholds – Dunamale

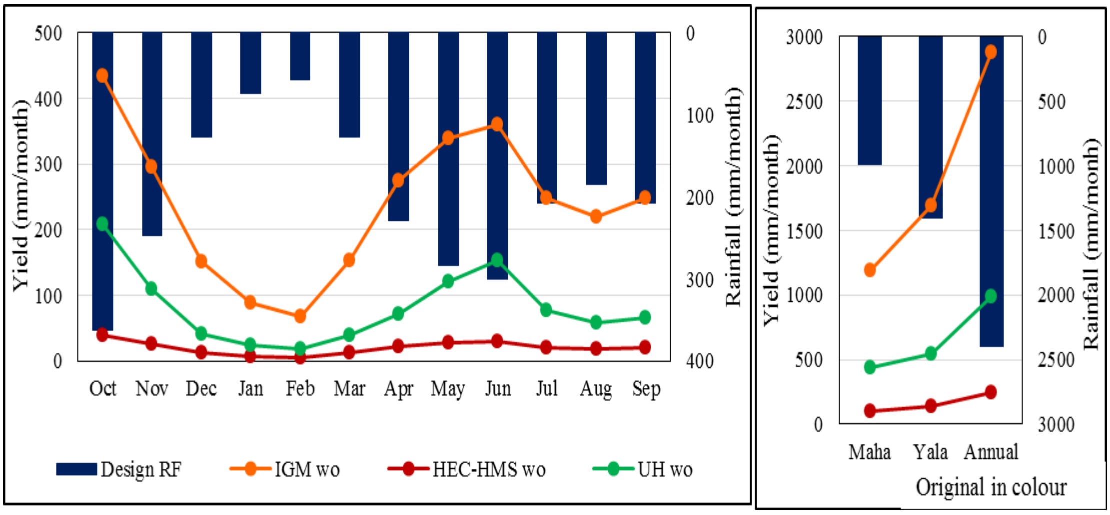

Figure 5-21: Monthly, Seasonal and Annual yield comparison without yield thresholds - Ellagawa Watershed

5.3.5.2 Comparison of Watershed Yield with yield thresholds

Yield thresholds are incorporated to IGM model to overcome the uncertainties in the iso-yield curves. Application of HEC HMS model has many uncertainties because of the assumptions made in the selection of process models, model parameters, and data conversion from a coarser to a finer resolution. UH model computations also have the above uncertainties plus others due to conversion of total rainfall to effective rainfall and then computing the total streamflow from direct runoff. In the HEC HMS or UH model descriptions (Scharffenberg and Fleming, 2006; Snyder, 1938) there are no indications or guidance for the incorporation of factors to safeguard the estimates against uncertainties in the assumptions. Many literature point out the need for design yield computations to carefully examine the dependability of mathematical models and associated simplifications with regards to the reliability of streamflow estimations (Chow et al., 1988 ;Beard, 1972;Beard, 1967; Beard et al., 1977 ;Konukcu et al., n.d. ;Mujumdar & Kumar, n.d.; Mujumdar & Ramesh, 1997). Troin, Arsenault, Martel, & Brissette (Troin et al., 2017) in their work stating that hydrologic model structure contributes most to uncertainty on the projected streamflow, indicate the importance to determine appropriate safety factors when determining design watershed yields. Chow et Al 1988, indicate the necessity to incorporate safety factors when determining values for infrastructure designs. Therefore in the absence of other guidance material on the threshold values to convert model outputs to design values, the present work used the Ponrajah 1984 guide for all three models. Yield values after the application of thresholds are shown in Figure 5-22 (Dunamale watershed), and Figure 5-23 (Ellagawa watershed). Corresponding values are in the Table 5-21.

Comparison of watersheds for models with yield thresholds for design rainfall application is shown in Figure 5-24. Runoff coefficients for models considering yield thresholds is in Table 5-22.

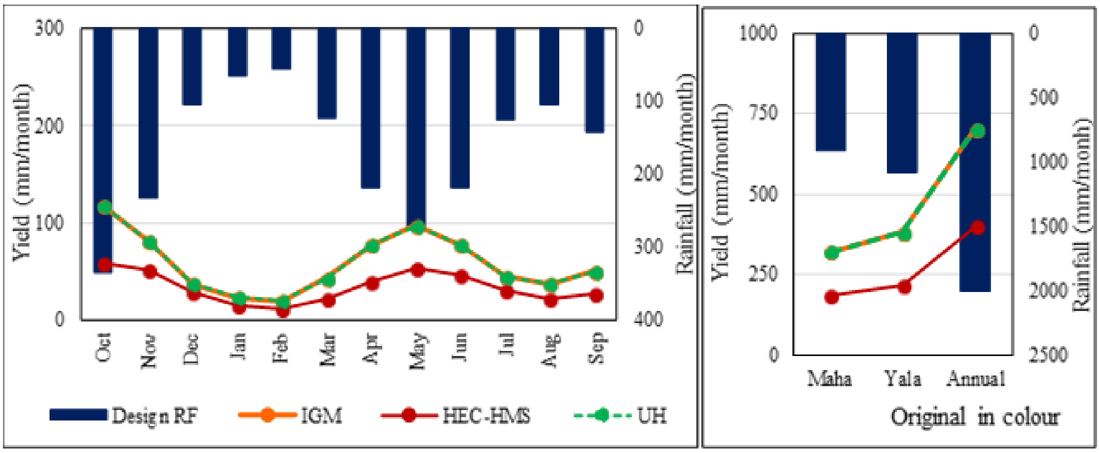

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Figure 5-22: Monthly, Seasonal and Annual yield comparison with yield thresholds - Dunamale watershed

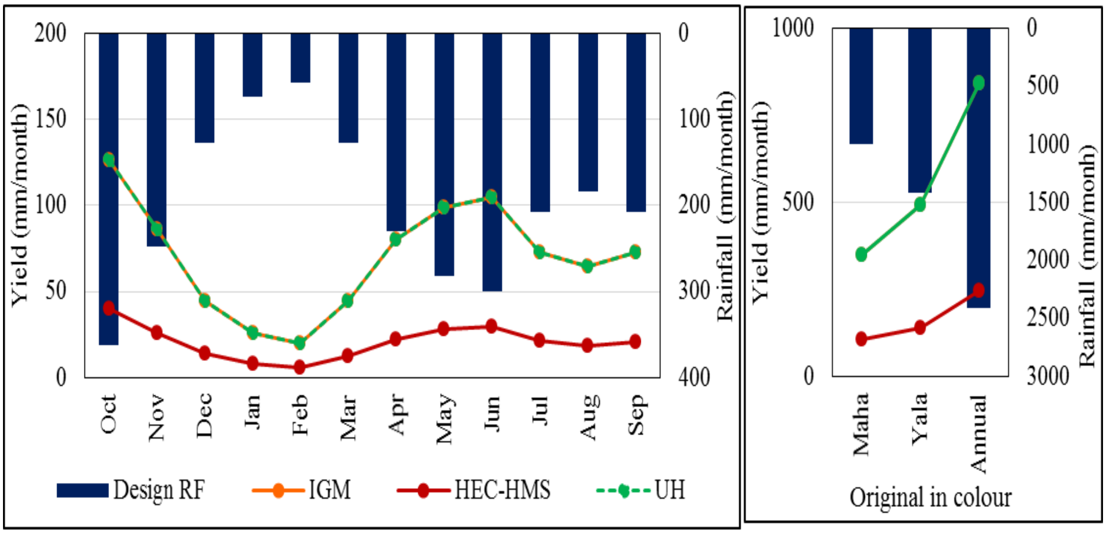


Figure 5-23: Monthly Seasonal and Annual yield comparison with yield thresholds - Ellagawa watershed

Table 5-20: Yield Comparison of Dunamale and Ellagawa Watersheds with Thresholds

	Dunamale Watershed				**Ellagawa Watershed**			
	Design Rainfall	**IGM w**	**HEC w**	**UH w**	**Design Rainfall**	**IGM w**	**HEC w**	**UH w**
October	334.56	117.10	53.70	117.10	362.09	126.73	42.90	126.73
November	233.07	81.57	51.60	81.57	247.16	86.51	25.80	86.51
December	104.63	36.62	27.80	36.62	127.15	44.50	13.60	44.50
January	65.10	22.79	15.10	22.79	74.00	25.90	7.80	25.90
February	55.48	19.42	11.00	19.42	56.48	19.77	5.60	19.77
March	123.55	43.24	21.60	43.24	127.46	44.61	12.30	44.61
April	218.83	76.59	38.50	76.59	229.28	80.25	22.00	80.25
May	276.22	96.68	52.60	96.68	282.67	98.93	27.90	98.93
June	218.83	76.59	46.40	76.59	300.25	105.09	29.80	105.09
July	126.79	44.38	30.40	44.38	207.54	72.64	21.40	72.64
August	106.17	37.16	22.40	37.16	184.29	64.50	18.50	64.50
September	142.63	49.92	26.40	49.92	207.25	72.54	20.40	72.54
Maha	916.39	320.74	180.80	320.74	994.34	348.02	108.00	348.02
Yala	1089.47	381.31	216.70	381.31	1411.28	493.95	140.00	493.95
Annual	2005.86	702.05	397.50	702.05	2405.62	841.97	248.00	841.97

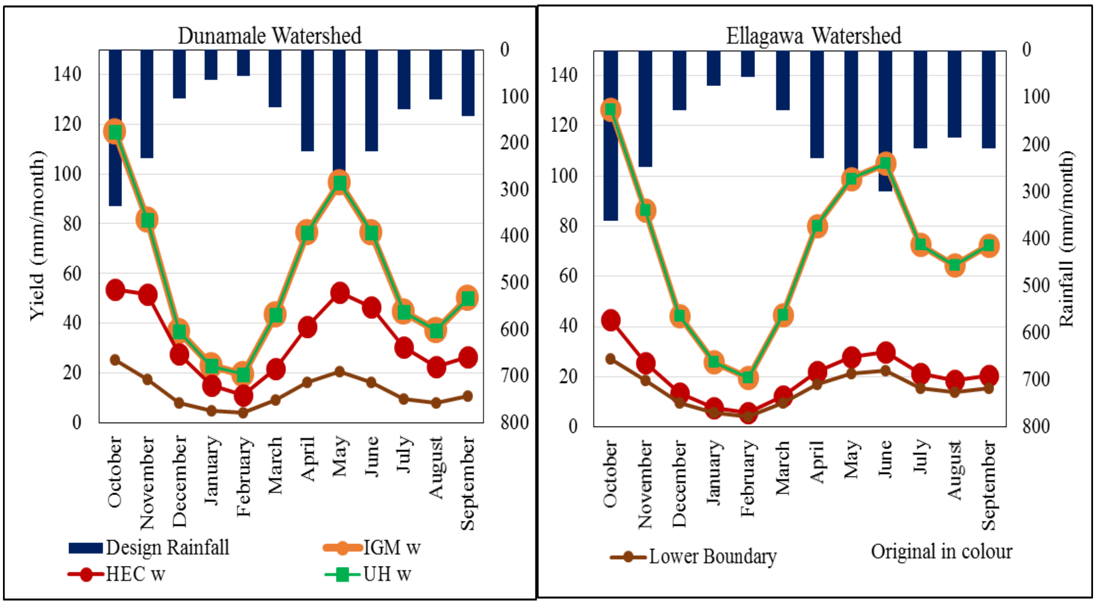


Figure 5-24: Comparison of watersheds for models with yield thresholds

Table 5-21: Runoff coefficient comparison of Dunamale and Ellagawa watersheds with thresholds

	Dunamale Watershed			**Ellagawa Watershed**		
	IGM w	**HEC w**	**UH w**	**IGM w**	**HEC w**	**UH w**
October	0.35	0.16	0.35	0.35	0.12	0.35
November	0.35	0.22	0.35	0.35	0.10	0.35
December	0.35	0.27	0.35	0.35	0.11	0.35
January	0.35	0.23	0.35	0.35	0.11	0.35
February	0.35	0.20	0.35	0.35	0.10	0.35
March	0.35	0.17	0.35	0.35	0.10	0.35
April	0.35	0.18	0.35	0.35	0.10	0.35
May	0.35	0.19	0.35	0.35	0.10	0.35
June	0.35	0.21	0.35	0.35	0.10	0.35
July	0.35	0.24	0.35	0.35	0.10	0.35
August	0.35	0.21	0.35	0.35	0.10	0.35
September	0.35	0.19	0.35	0.35	0.10	0.35
Maha	0.35	0.20	0.35	0.35	0.11	0.35
Yala	0.35	0.20	0.35	0.35	0.10	0.35
Annual	0.35	0.20	0.35	0.35	0.10	0.35
Min	0.35	0.16	0.35	0.35	0.10	0.35
Max	0.35	0.27	0.35	0.35	0.11	0.35

Incorporation of yelds indicated the over estimated seasonal yields reaching a limit of 35% of rainfall. The IGM and UH models outputs that had shown abnormally high runoff coefficients were reduced by restricting the runoff coefficient to the upper threshold. Estimation of both these models for Maha and Yala seasons indicated yield values above the upper boundary of estimates. HEC HMS model outputs revealed that the yield values in both seasons and for both watersheds were between the lower and upper bounds of yield limittions in Ponrajah 1984. Hence the with and without yield estimates of HEC HMS model remained the sme. Therefore the HEC HMS values remain unajusted for modelling uncertainties that had been noted during computations.

In case of Dunamale watershed, the HEC HMS yield estimates are with an averge runoff coefficient of 0.27 which is approximately midway between the upper and lower thresholds. The estimates of Ellagawa shows an averge runoff coefficient of 0.11 which is almost reaching the lower threshold. In the present work, the computaions discueed the ambiguities and the techniques used to overcome those to arrive at the best yield estimates from the HEC HMS model. Therefore, utilisation of yield values in designs without considering the modelling uncertainties would require better justifications.

5.3.5.3 Overall Evaluation – Analysis 1

An evaluation of options available for a practicing engineer to estimate watershed yield requires the identification of associated decision parameters. These are associated with the uncertainties related to inputs, modelling of hydrologic processes, determination of model parameters and methods used to deal with uncertainities. Guidelines become the prime resource for practical engineering applications and in the absense of such guidance, the praticing engineers have to make judgements based on engineering knowledge and available reviewed literature. This becomes a task that requires substantial rationalisation. In the preent study a qualitative evaluation was done by using the experiences from the application of three selected models on two watersheds. The summary is as given below.

5.3.5.3.1 Application of ID model

In case of the ID model, the most valuable factor is the availablity of an application guideline. The next most important factor is that almost all irrigation infrastructure construction by the department of irrigation for the entire country is based on this guideline without any revisions. One drawback is that this guideline dates back to 1984. Another is the lack of details about the use of refereed documentation when determining the embedded design methods and values.

In the two case applications the ID model input is 75% probable monthly rainfall and the guideline clearly indicate that it is to fulfill the planning requirements. The yield model is a dierct technique and hence the process model or parameter uncertainties are non existence. However the yield curves are based on large watershed data and there is an uncertainty that is looked after by imposing the streamflow threholds. Data in the guidelines are at a monthly resolution which matches the temporal resolution required for watershed yield computation. Yield estimations for both watersheds were significant over estimations whih either higher than or nearly equal to the input rainfall. Water balance computations also revealed that the yield estimations were high.

5.3.5.3.2 Application of HEC HMS Model

Available model application guidelines are by the tool developers and hence coverage is general. Selection of hydrological processes within the model was based on a limited number of Sri Lankan applications. Many reported international applications are available as peer reviewed publications. Model parameter selection is either based on other models calibrated for nearby or similar watersheds. Monthly rainfall and evaporation inputs were uniformly distributed to daily values. Rainfall uncertainty was considered similar to the ID model. There are no yield limiation guidelines specificallly for the HECHMS model. Yield values for both case studies were inbetween the two thresholds indicated in the irrigation department guidelines. The runoff coefficient and water balance showed that the computed yield values for Dunamale watershed were within a reasonable range while same for Ellagawa were closer to the lower bounds.

5.3.5.3.3 Application of UH model

Model application guidelines are general and avilable in common hydrological text books. Irrigation department guideline provides limited guidance on the regional paramters and method of application. Only a limited number of peer reviewed publications are available as Sri Lankan case studies. Model is for event based application. Hence assumptions on a sequence of events, incorporation of baseflow etc., are needed for a continuous longterm application. Assumptions are necessary to convert guideline based monthly rainfall as daily inputs. Baseflow incorporation requires the selection of a baseflow model. Effective rainfall needs a rational loss model. In the absence of guidance material to incorporate uncerainties related to rainfall, modelling processes and paramters, the present work followed the ID guideline recommendations. 75% probable rainfall and yield thresholds are the two considerations used. Application on the Dunamale watershed revealed unreliable yield values with very high runoff coeffieicnts and unacceptale waterbalance. In case of Ellagawa watershed, the yield estimates were higher than those computed with physical parameter based runoff coefficients. Irrigation department thresholds also indicated that the runoff ratios are high.

5.3.5.4 Qualitative Assessment

A qualitative assessment was carried out by assigning ranks for uncertainties associated with the design yield computations. Ranks were assigned by using a 5 class Likett scale. Relationship between the rank and uncertainty are in Table 5-22. Considered factors, assigned ranks and the aggregation to provide a guidance for a practicing engineer are shown in the Table 5-23. The normalised ranking indicated that the ID model is with moderate unceraintyy while the UH model is with the highest uncertaintly. Therefore the best available option for a practicing engineer is to use the ID model evan with the prevailing drawbacks. Also it is important to note that an accurate judgement can be made only after a comparative evaluation with the observed yield values.

Table 5-22: Rank for qualitative assessment of models

Rank	**Description**
1	Lowest Uncertainty
2	Uncertainty between Lowest and Moderate
3	Moderate Uncertainty
4	Uncertainty between Moderate and Highest
5	Highest Uncertainty

Table 5-23: Qualitative ranking of models based on case study applications

#	Uncertainty Factor associated with Yield Computation	Qualitative Ranking based on Case Study Applications - Dunamale and Ellagawa Watersheds			
		ID model	**HEC HMS Model**	**UH Model**	**Remarks/Rationalisation**
1	Rainfall Input Conversion	1	3	5	ID model needs no conversion, UH model conversion has more assumptions than HEC HMS Conversion requirements
2	Process Selection	1	3	5	ID method is direct, HEC HMS with continuous capability is less uncertain than with Event based UH for Continuous modelling
3	Parameter Selection	2	4	5	ID model has to deal with low resolution seasonal iso yield maps, HEC model has reasonable nearby watershed applications, UH model has many sub model parameters to select
4	Yield Threshold Selection	1	3	3	ID model has specific guidance, Use of same thresholds for HEC HMS and UH models can be justified
5	Example Application Cases	4	3	5	Based on reviewed publications and priority for Sri Lankan case studies
6	Guideline Availability	1	3	3	ID models has a clear guideline, other two models with general and text book guides
7	Time Tested Practice	1	4	4	Absence of literature evidence of using HEC HMS and UH models in official practice, ID model in Sri Lankan official practice since 1984
8	Order of Magnitude of Computed Yield	5	4	5	Based on relative reliability or acceptability of computed yield values without Thresholds
9	Comparison with Physical Runoff Coefficient	5	4	5	Based on relative reliability or acceptability of computed yield values without Thresholds
10	Comparison with Water Balance	5	4	5	Based on relative reliability or acceptability of computed yield values without Thresholds
11	Computations after Threshold Applications	3	4	5	ID model have specific thresholds but they are seasonal and needs updating, the others do not have any specific attachment, HEC HMS values are within the lower and upper bounds
Normalised Uncertainty Ranking		3	4	5	

5.4 Yield Comparison – Analysis Part 2

5.4.1 General

Design yield computation option comparison with available information revealed the merits and demerits of each option. The qualitative analysis also indicated the need to make comparisons with observed streamflows for conclusive selections. Therefore, two watersheds were selected to carry out a comparative evaluation. Observed streamflow of Dunamale watershed in Attanagalu oya basin and Ellagawa watershed in Kalu river basin were collected to compare the estimated yield values from the available modelling options. Irrigation guideline model (IGM), HEC-HMS (HEC) model and Unit hydrograph (UH) model were used for yield estimations. In this analysis, first major step is to apply the said models to the two catchments using observed rainfall and evaporation data and generate model yield values. Then, model results obtained by applying observed data, were compared with observed yield with the verification purpose.

5.4.2 Data availability

5.4.2.1 Rainfall, Streamflow, Evaporation

Yield estimation with observed daily rainfall for 10 years (2005-2015) for Dunamale basin and 8 years (2006-2014) for Ellagawa basin was done with the purpose of comparing the model yield with observed yield. Thiessen average method was used to compute areal average rainfall of each watershed. Daily rainfall values were used as inputs for the HEC HMS and UH models while monthly values were the input for the IGM. As the objective of the analysis is to compare model estimations with the actuals, the computations were carried out with the observed rainfall and evaporation values. Evaporation station at Ratnapura and at Colombo were the closest locations for Ellagawa and Dunamale watersheds respectively. Daily Evaporation data were used for HEC-HMS model while monthly aggregated values were used for the IGM model.

Monthly Evaporation Variation at Ratnapura and Colombo stations is shown by Figure 5-25 and in Table 5-24.

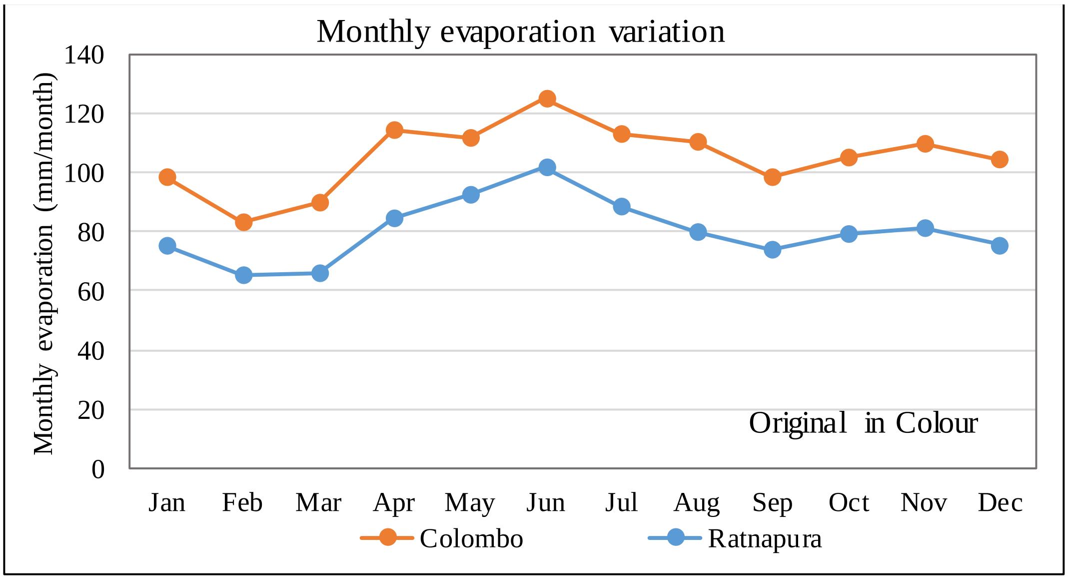


Figure 5-25: Monthly evaporation variation - Colombo and Ratnapura

Table 5-24: Monthly evaporation variation - Colombo and Ratnapura

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Colombo	98.3	82.9	89.8	114.1	111.4	124.7	113.1	110.1	98.4	105.2	109.8	104.6
Ratnapura	75.2	64.9	65.8	84.3	92.2	101.6	88.5	79.7	74.0	79.1	81.2	75.5

5.4.2.2 Thiessen Rainfall

Daily Thiessen rainfall values of 10 years from 2005-2015 in Dunamale watershed and 8 years from 2006-2014 in Ellagawa watershed were aggregated for monthly rainfall values and applied to the model. Figure 5-26, Table 5-25 and Table 5-26 show the Thiessen average rainfall values for each year. Thiessen polygons for each watershed and the monthly rainfall, evaporation and streamflow data variations are shown in Figure 4-9 and 4-10. Rain gauge station locations and Thiessen weights are presented in Table 4-3, Table 4-4, Table 4-12 and Table 4-13.

Table 5-25: Observed Thiessen averaged rainfall - Dunamale watershed

Year	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Maha**	**Yala**	**Annual**
2005-2006	462.4	687.7	195.6	180.2	152.6	232.4	145.7	275.9	239.5	91.9	349.8	99.9	1910.9	1202.7	3113.5
2006-2007	861.1	626.1	93.4	62.0	22.9	128.7	494.5	244.5	243.0	184.8	156.8	291.0	1794.2	1614.6	3408.8
2007-2008	457.4	263.8	155.0	48.0	224.1	495.0	589.0	429.5	275.0	368.9	95.4	142.8	1643.3	1900.7	3544.0
2008-2009	700.5	318.0	99.4	85.8	45.7	254.0	384.9	241.1	264.1	159.1	234.0	326.8	1503.3	1609.9	3113.2
2009-2010	339.5	319.3	250.8	75.3	43.3	192.6	384.9	593.5	246.1	234.1	79.8	365.2	1220.9	1903.5	3124.4
2010-2011	453.4	694.5	343.5	165.2	132.9	133.3	481.0	482.2	247.2	97.7	220.1	271.8	1922.9	1800.0	3722.9
2011-2012	465.2	271.8	93.8	64.4	167.4	87.7	487.5	104.5	211.2	108.9	292.9	175.7	1150.3	1380.6	2530.9
2012-2013	652.2	323.7	213.6	93.5	160.8	287.9	190.7	406.1	489.7	237.3	88.5	434.8	1731.6	1847.0	3578.7
2013-2014	305.3	405.7	57.7	77.6	48.6	218.9	417.6	246.2	348.4	179.2	315.4	303.4	1113.8	1810.2	2924.0
2014-2015	507.0	233.6	568.2	22.9	109.4	223.4	412.8	246.2	339.0	179.2	222.1	288.7	1664.5	1688.2	3352.7
Average	520.4	414.4	207.1	87.5	110.8	225.4	398.8	327.0	290.3	184.1	205.5	270.0	1565.6	1675.7	3241.3

Table 5-26: Observed Thiessen averaged rainfall - Ellagawa watershed

Year	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Maha**	**Yala**	**Annual**
2006-2007	484.8	367.4	130.8	82.8	29.7	68.3	334.0	174.5	247.5	171.7	300.5	345.6	1163.7	1573.9	2737.6
2007-2008	399.5	169.9	110.6	104.9	165.4	254.3	436.7	288.3	277.3	361.9	157.4	164.6	1204.6	1686.1	2890.7
2008-2009	370.2	285.3	154.3	25.1	51.8	205.1	198.2	341.1	502.0	141.0	309.7	337.7	1091.8	1829.8	2921.5
2009-2010	255.9	344.7	233.0	140.9	60.2	122.6	338.9	580.2	409.9	330.7	302.9	311.4	1157.3	2274.0	3431.2
2010-2011	331.4	486.0	329.1	154.4	118.4	185.3	561.9	289.6	169.9	164.5	248.2	328.2	1604.6	1762.3	3366.9
2011-2012	310.2	279.6	149.8	86.2	109.3	261.3	293.2	123.7	259.0	208.0	288.9	279.4	1196.4	1452.2	2648.5
2012-2013	452.9	484.1	399.2	144.2	191.1	337.0	209.6	324.3	476.3	383.1	182.0	393.1	2008.5	1968.5	3977.0
2013-2014	368.5	366.1	83.7	252.5	60.4	130.9	330.5	216.2	555.8	228.4	480.9	388.0	1262.1	2199.9	3462.0
average	371.7	347.9	198.8	123.9	98.3	195.6	337.9	292.2	362.2	248.7	283.8	318.5	1336.1	1843.3	3179.4

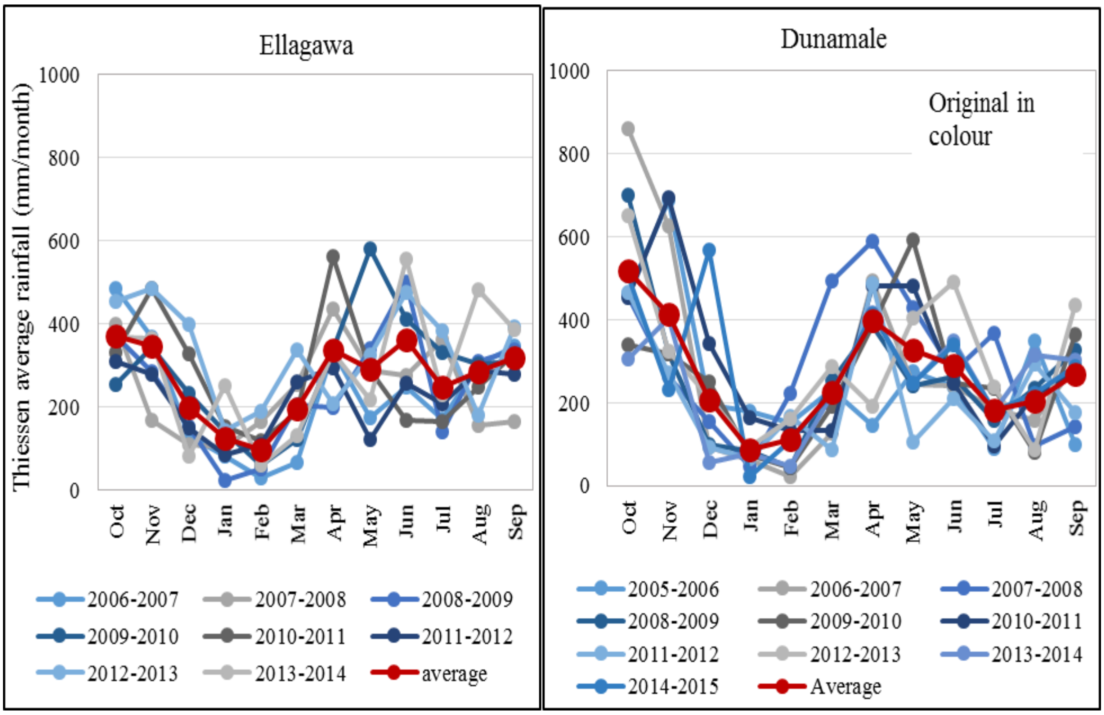


Figure 5-26: Monthly Thiessen average rainfall for Dunamale and Ellagawa watersheds

5.4.3 Irrigation guideline model (IGM) - Dunamale watershed

Iso-yield maps in Irrigation Department guideline, Sri Lanka (Ponrajah, 1984) were used to the computation of seasonal yield values for Dunamale watersheds. Table 5-6 presents the yield parameters.

5.4.3.1 IGM Yield Model without Thresholds

Monthly yield of Dunamale Watershed without considering yield thresholds are presented in Table 5-27, and in Figure 5-27.

Comparison of the IGM estimations with the observed monthly streamflow and the Thiessen Average rainfall for the entire data period (Figure 5-28 and Table 5-27) and the comparison of Period of Record (PoR) Flow Duration Curves (FDC) (Figure 5-29) indicate significant over estimation of yield values. The annual FDC are shown in Figure 5-30. These results clearly indicate an over estimation of streamflow over the period.

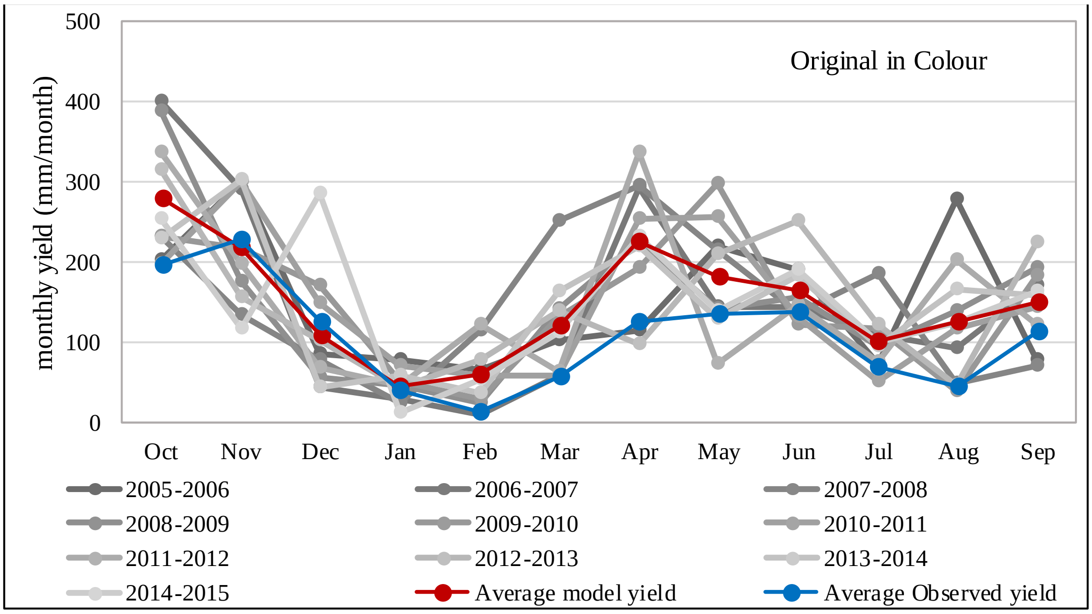


Figure 5-27: Monthly yield variation - Irrigation model without yield thresholds - Dunamale watershed

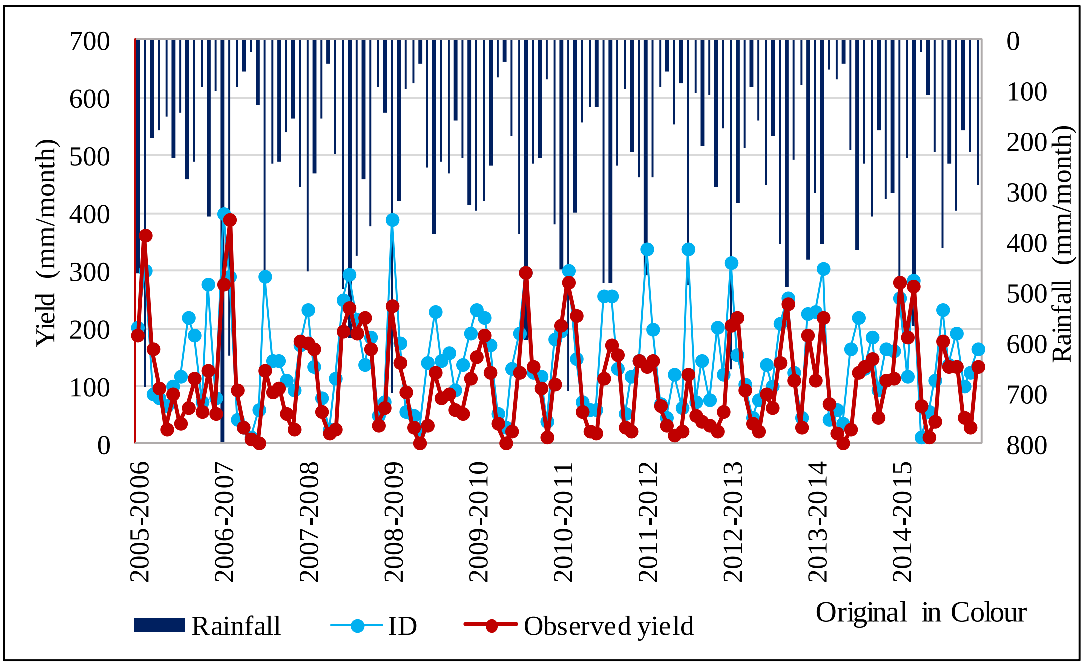


Figure 5-28: Thiessen Average Rainfall, Observed and IGM monthly yield for Dunamale Watershed

Table 5-27: Monthly, seasonal and annual yield variation (mm) – without yield thresholds - Dunamale basin

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Maha	Yala	annual
2005-2006	201.7	299.9	85.3	78.6	66.5	101.3	115.4	218.5	189.7	72.8	277.0	79.1	833.4	952.5	1785.9
2006-2007	400.0	290.8	43.4	28.8	10.6	59.8	291.7	144.3	143.3	109.0	92.5	171.7	833.4	952.5	1785.9
2007-2008	232.0	133.8	78.6	24.3	113.7	251.1	295.2	215.3	137.8	184.9	47.8	71.6	833.4	952.5	1785.9
2008-2009	388.4	176.3	55.1	47.5	25.3	140.8	227.7	142.6	156.2	94.1	138.4	193.3	833.4	952.5	1785.9
2009-2010	231.8	218.0	171.2	51.4	29.6	131.5	192.6	297.0	123.2	117.1	39.9	182.7	833.4	952.5	1785.9
2010-2011	196.5	301.0	148.9	71.6	57.6	57.8	254.5	255.2	130.8	51.7	116.5	143.8	833.4	952.5	1785.9
2011-2012	337.0	196.9	68.0	46.7	121.3	63.5	336.3	72.1	145.7	75.1	202.1	121.2	833.4	952.5	1785.9
2012-2013	313.9	155.8	102.8	45.0	77.4	138.6	98.3	209.4	252.5	122.4	45.6	224.2	833.4	952.5	1785.9
2013-2014	228.4	303.6	43.2	58.1	36.4	163.8	219.7	129.5	183.3	94.3	165.9	159.7	833.4	952.5	1785.9
2014-2015	253.9	116.9	284.5	11.5	54.8	111.9	232.9	138.9	191.3	101.1	125.3	162.9	833.4	952.5	1785.9
average	278.3	219.3	108.1	46.4	59.3	122.0	226.4	182.3	165.4	102.3	125.1	151.0	833.4	952.5	1785.9

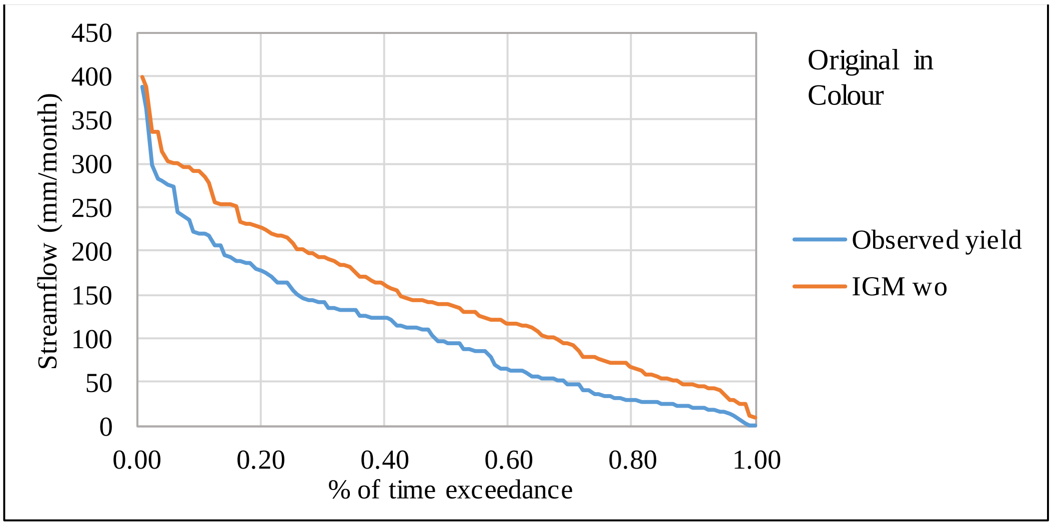


Figure 5-29: Monthly PoR FDC for Dunamale Watershed

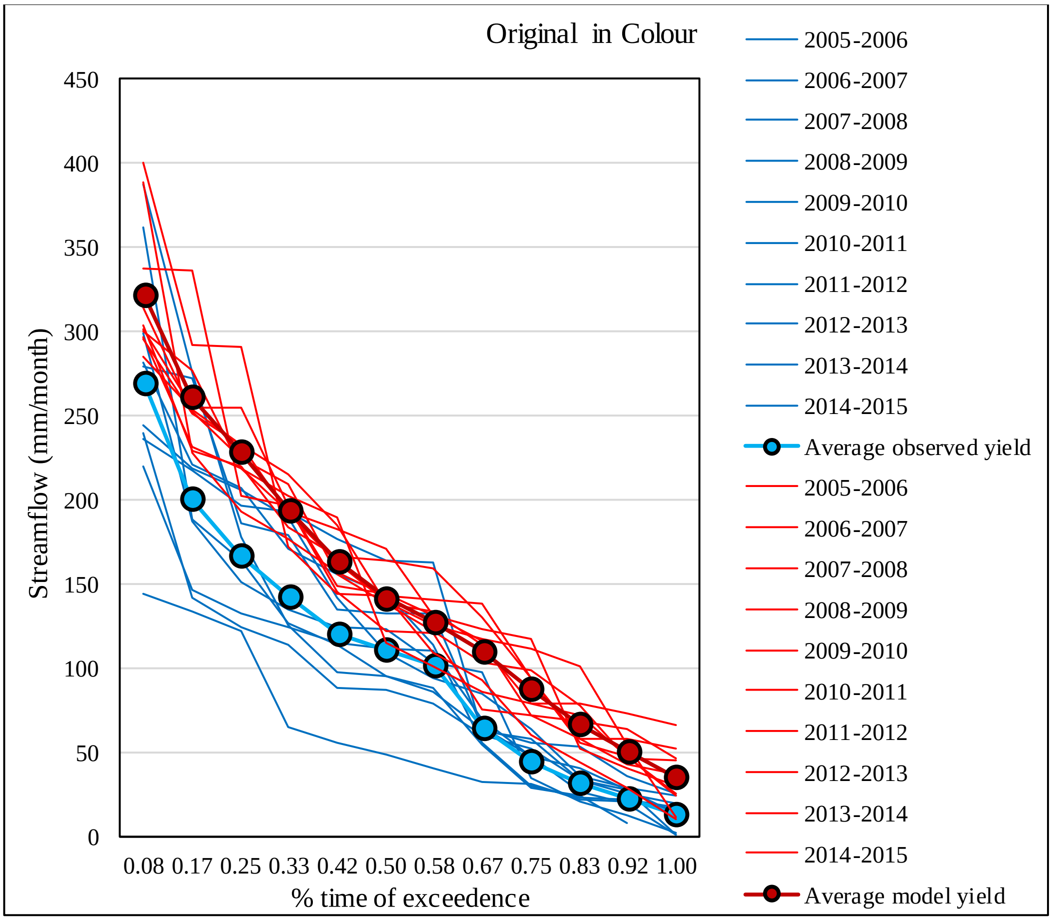


Figure 5-30: Annual FDC of monthly streamflow - Dunamale Watershed

5.4.3.2 Comparison of Numerical Indicators

Comparison of numerical indicators corresponding to IGM streamflow estimations and the observed values indicate a significant over estimation (Figure 5-31, Table 5-28, Table 5-29).

Water balance is defined as the balance of observed and estimated yield as equation 1.

$$Water\ balance = (Observed - Estimated)\ Streamflow \tag{1}$$

The overall hydrograph matching shows a significant mismatch both in the magnitude and the timing of watershed response reflected by the model. The IGM FDC shows a significant over estimations while the seasonal water balance values show an even distribution of over estimation across both monsoons. Observed streamflow data of March in water year 2006/2007 was missing.

Table 5-28: Seasonal and Annual Water Balance Difference IGM without Threshold - Dunamale

	Water balance in mm		
	Water Balance Difference-Maha	**Water Balance Difference-Yala**	**Water Balance Difference-Annual**
2005-2006	87.49	-505.37	-417.89
2006-2007	-39.43	-385.62	-425.05
2007-2008	-195.83	-46.59	-242.42
2008-2009	-302.54	-436.64	-739.17
2009-2010	-314.47	-181.32	-495.78
2010-2011	-28.88	-316.72	-345.60
2011-2012	-422.42	-634.91	-1057.33
2012-2013	-170.57	-176.00	-346.57
2013-2014	-386.75	-276.71	-663.46
2014-2015	22.47	-298.24	-275.77
Mean	-175.09	-325.81	-500.90

Average water balance error and Mean Ratio of Absolute Error (MRAE) was calculated for the comparison purposes (Table 5-30).

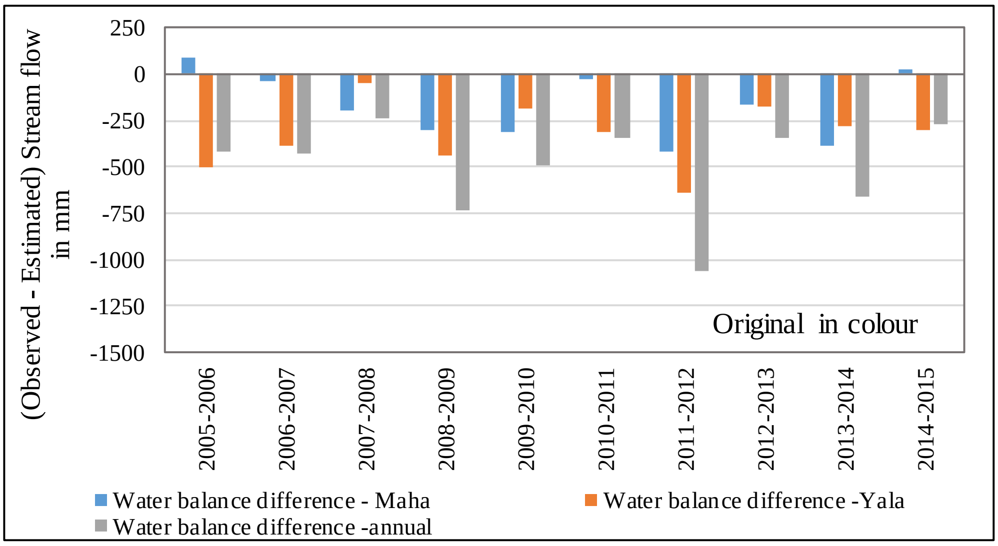


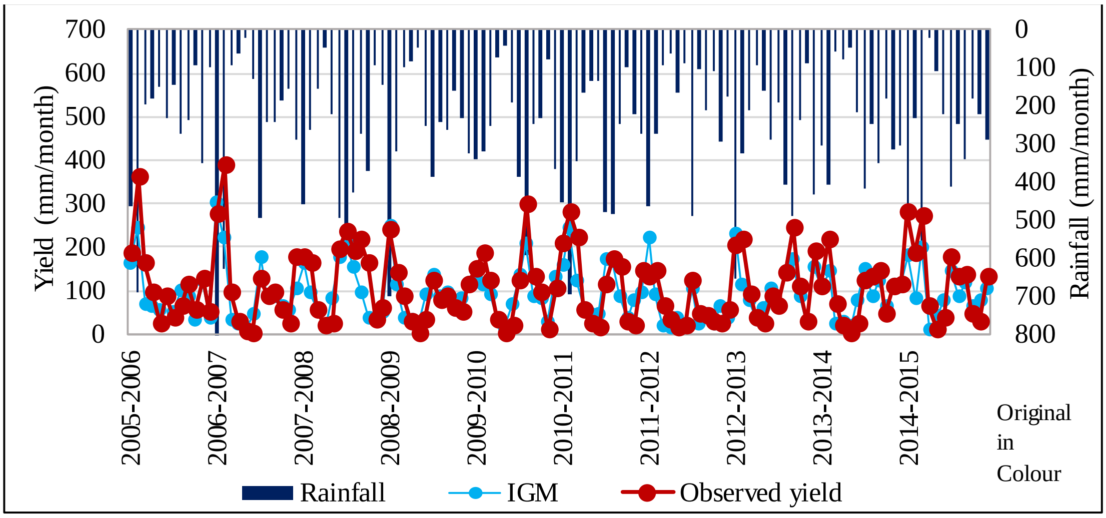
Figure 5-31: Seasonal and Annual water balance difference IGM without Threshold – Dunamale

Table 5-29: Numerical Indicators of IGM Model Estimations - Dunamale basin

Numerical indicators	**Dunamale Watershed**
Average Annual Water Balance Error (mm)	-500.9
Average Maha Season Water Balance Error (mm)	-175.09
Average Yala Season Water Balance Error (mm)	-325.81
Percentage error of annual average runoff coefficient	-38.98
MRAE overall hydrograph	2.2066
MRAE PoR FDC	41.59
MRAE Annual FDC	1.922

5.4.3.3 IGM Yield Model – With Thresholds

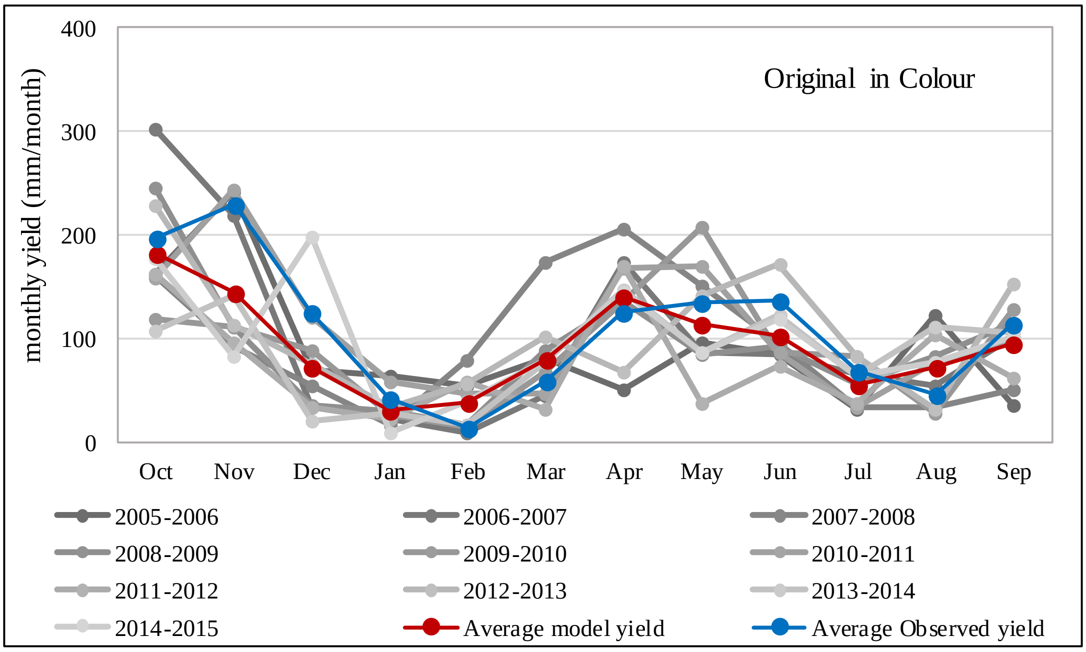
Seasonal yield thresholds were applied for Irrigation model and evaluated. Since the selected watershed located in wet zone, only upper threshold limit was applied where necessary. Lower threshold limit is already fulfilled. Figure 5-32, 5-33 and Table 5-30 indicate the results.



Original in Colour

Figure 5-32: Thiessen Average Rainfall, Observed and IGM monthly yield with thresholds for Dunamale Watershed

An under estimation of high flows in the monthly streamflow hydrograph and also in the monthly average flow variations was observed. The duration curve indicated an under estimation in the high-intermediate flow values.



Original in Colour

Figure 5-33: Monthly yield variation - Irrigation model with yield thresholds - Dunamale watershed

Table 5-30: Monthly, seasonal and annual yield variation (mm) – with yield thresholds - Dunamale basin

Year	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Maha**	**Yala**	**annual**
2005-2006	161.8	240.7	68.5	63.1	53.4	81.3	51.0	96.6	83.8	32.2	122.4	35.0	668.8	420.9	1089.7
2006-2007	301.4	219.1	32.7	21.7	8.0	45.0	173.1	85.6	85.0	64.7	54.9	101.9	628.0	565.1	1193.1
2007-2008	160.1	92.3	54.2	16.8	78.4	173.3	206.1	150.3	96.2	33.4	33.4	50.0	575.1	569.5	1144.6
2008-2009	245.2	111.3	34.8	30.0	16.0	88.9	134.7	84.4	92.4	55.7	81.9	114.4	526.2	563.4	1089.6
2009-2010	118.8	111.8	87.8	26.4	15.2	67.4	134.7	207.7	86.1	81.9	27.9	127.8	427.3	666.2	1093.5
2010-2011	158.7	243.1	120.2	57.8	46.5	46.7	168.4	168.8	86.5	34.2	77.0	95.1	673.0	630.0	1303.0
2011-2012	162.8	95.1	32.8	22.5	58.6	30.7	170.6	36.6	73.9	38.1	102.5	61.5	402.6	483.2	885.8
2012-2013	228.3	113.3	74.8	32.7	56.3	100.8	66.7	142.1	171.4	83.0	31.0	152.2	606.1	646.4	1252.5
2013-2014	106.8	142.0	20.2	27.2	17.0	76.6	146.1	86.2	121.9	62.7	110.4	106.2	389.8	633.6	1023.4
2014-2015	177.5	81.7	198.9	8.0	38.3	78.2	144.5	86.2	118.7	62.7	77.7	101.0	582.6	590.8	1173.4
Average model yield	182.1	145.0	72.5	30.6	38.8	78.9	139.6	114.4	101.6	54.9	71.9	94.5	547.9	576.9	1124.9

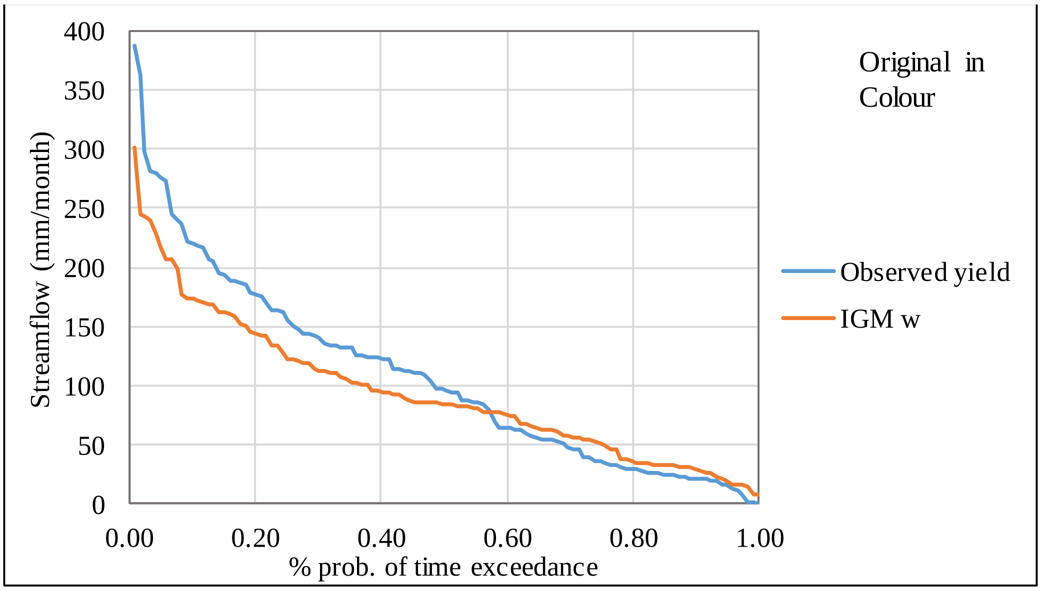


Figure 5-34: Monthly PoR FDC for IGM with thresholds Dunamale Watershed

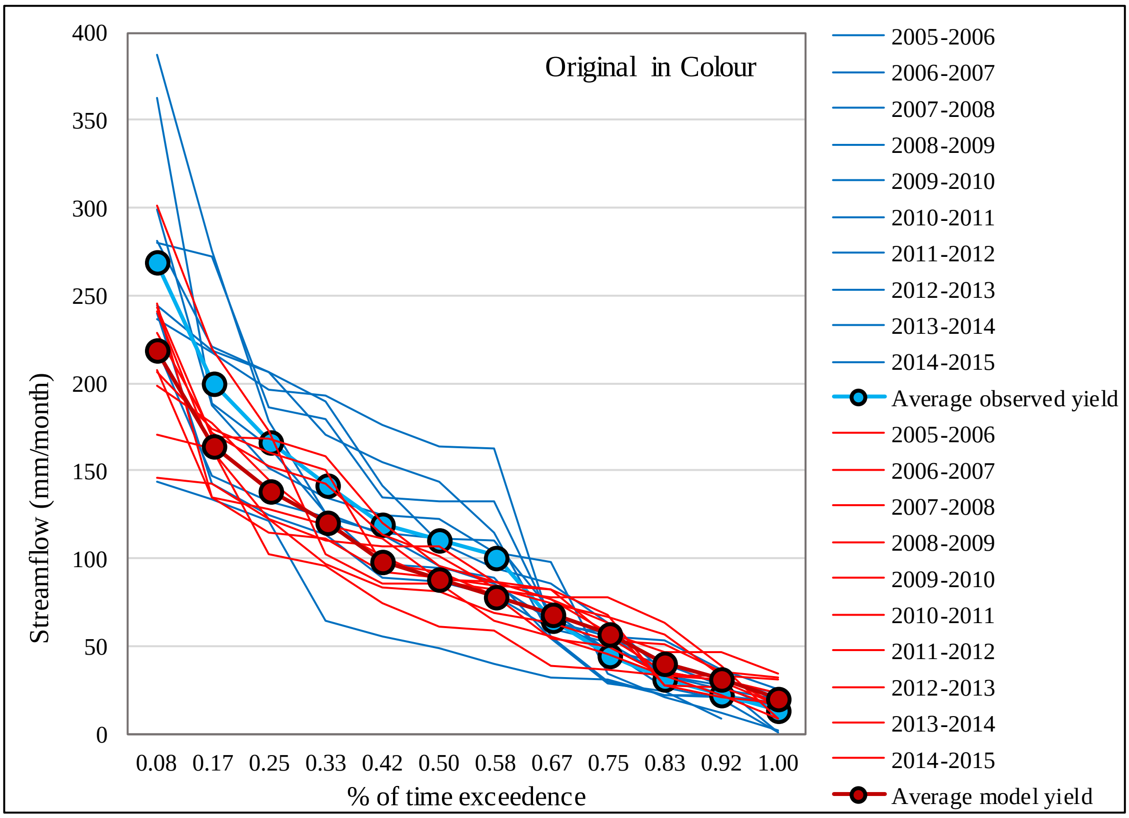


Figure 5-35: Annual FDC of monthly streamflow for IGM with thresholds - Dunamale watershed

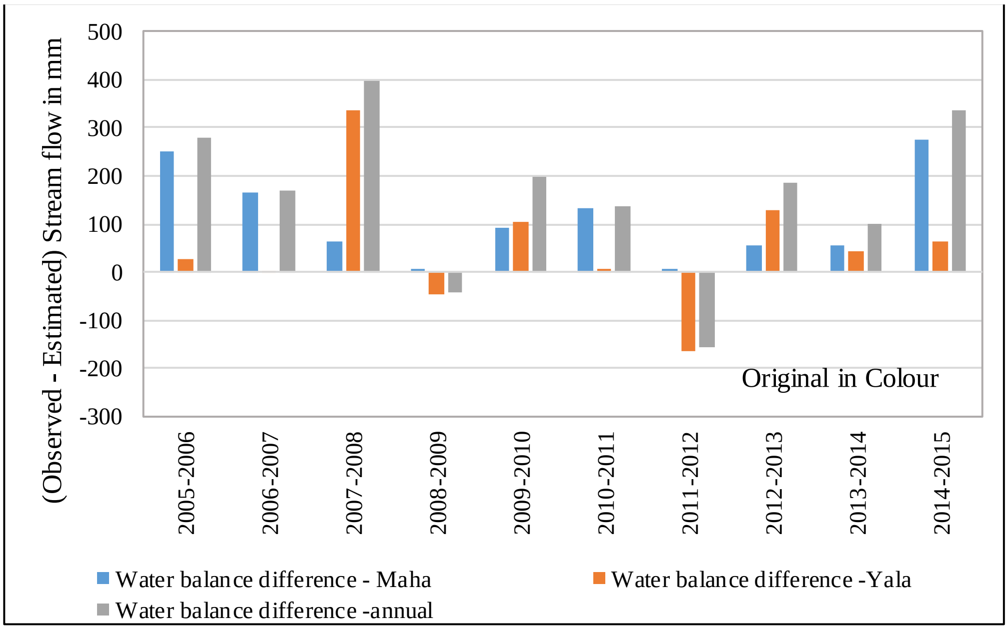


Figure 5-36: Seasonal and Annual water balance difference IGM with threshold – Dunamale

Figure 5-34 and Figure 5-35 presents the FDC for period of record and the annual FDC. The variation of flow duration curve shows an under estimation of high, medium flows. Low flows varies slightly higher values than observed yield.

Figure 5-36 and Table 5-31 presents seasonal and annual water balance results. Seasonal and annual water balance also indicates that in 8 years IGM with thresholds under estimates yield values.

Table 5-32 shows the numerical indicators for IGM with thresholds for Dunamale basin. The values show that the application of yield thresholds give comparatively better results for IGM. Annual water balance error, Mean ration of Absolute error (MRAE) defined as the difference between calculated and observed flow with respect to the particular observation was calculated for the comparison purposes (equation 2).

$$MRAE = \frac{1}{n}\sum \frac{|Qobs - Qmodel|}{Qobs} \qquad (2)$$

Table 5-31: Seasonal and annual water balance difference IGM with thresholds - Dunamale

	Water balance difference in mm		
	Water Balance Difference-Maha	**Water Balance Difference-Yala**	**Water Balance Difference-Annual**
2005-2006	252.12	26.17	278.30
2006-2007	166.03	1.78	167.80
2007-2008	62.45	336.38	398.83
2008-2009	4.73	-47.60	-42.87
2009-2010	91.65	104.94	196.60
2010-2011	131.56	5.76	137.31
2011-2012	8.42	-165.63	-157.21
2012-2013	56.79	130.04	186.83
2013-2014	56.83	42.22	99.05
2014-2015	273.33	63.39	336.72
Average	110.39	49.75	160.14

Table 5-32: Numerical Indicators of IGM Model Estimations with thresholds - Dunamale basin

Numerical Indicators	**Dunamale Watershed**
Average Annual Water Balance Error (mm)	160.14
Average Maha Season Water Balance Error (mm)	110.39
Average Yala Season Water Balance Error (mm)	49.75
Percentage error of annual average runoff coefficient	12.46
MRAE overall hydrgraph	1.09
MRAE PoR FDC	21.3
MRAE Annual FDC	0.882

5.4.3.4 Comparison – Dunamale Watershed

5.4.3.4.1 Effect of Yield Thresholds

Irrigation Department guideline, Sri Lanka (Ponrajah, 1984) clearly indicates that seasonal yield values extracted from the iso-yield curves require adjustments with the incorporation of threshold values. This was investigated by evaluating the monthly yield values with and without yield threshold against the observed yield values. Monthly, seasonal and annual yield value comparison with respective Thiessen rainfall is shown in Figure 5-37, Figure 5-38.

Observed Annual and Yala yield values together with Maha yield values except for one year, indicate that the iso-yield curve based values without thresholds are comparatively lower than the observations. This supports the guideline recommendation to incorporate yield threshold values. Analysis of monthly values indicate that in some years, months of November, December and January, the observed streamflow is higher than the yield values without thresholds. In all other months the observed streamflow is lower than the yield values without thresholds.

The yield values from IGM model with yield threholds closely represent the observed yield values in monthly, seasonal and annual temporal resolutions. Out of the 10 year study duration the annual total streamflow in the years 2008/2009, and 20011/2012 were less than the yield values of IGM model with thresholds. In case of Maha season all years indicated higher observed seasonal streamflow than the IGM model values with thresholds. In the Yala season comparison, except 2008/2009 and 2011/2012 all years were with higher observed streamflow values than the IGM model values. Monthly average values over the study period showed that the model values with thresholds were higher during months with lower streamflow and lower during months with higher streamflow. These results confirm that the IGM Model with yield thresholds provide the closest yield estimates for the Dunamale watershed. Therefore, in the present work the comparative evaluation of models considered that IGM model is the use if iso-yield curves with yield thresholds.

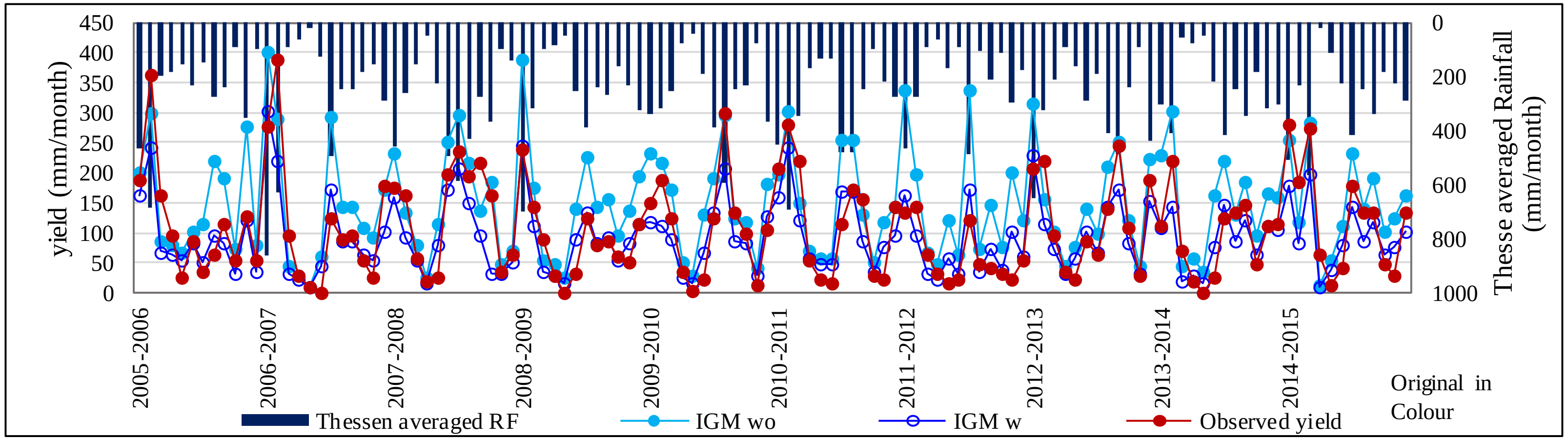


Figure 5-37: Comparison of Average Monthly Observed and Modelled Yield Values with Average Thiessen Rainfall (2005/2006-2014/2015)

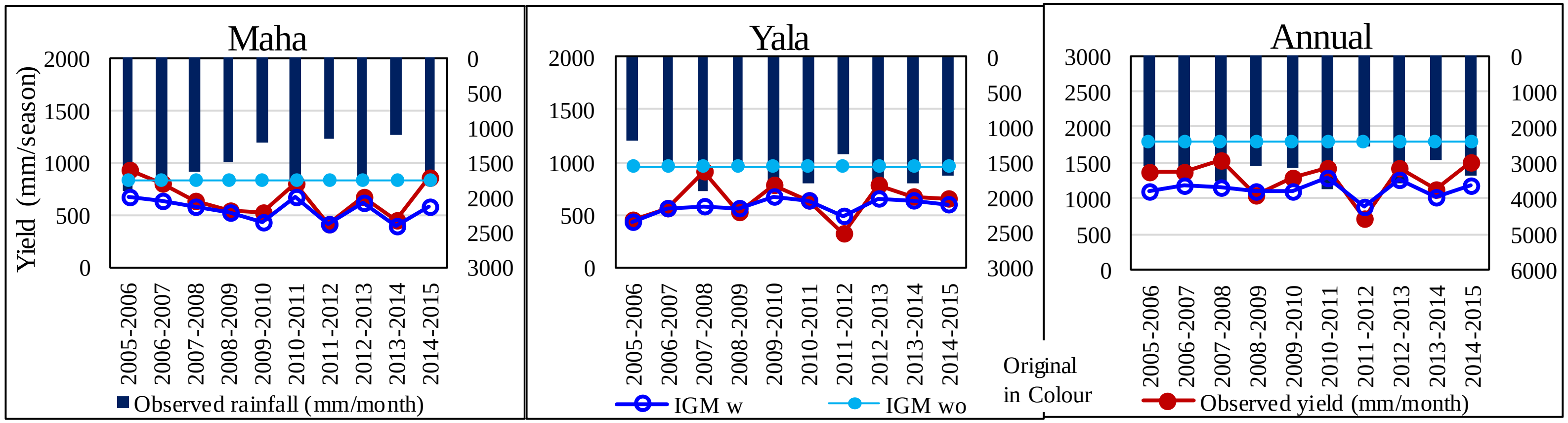


Figure 5-38: Maha, Yala and Annual Yield Comparison - Dunamale watershed

5.4.3.4.2 Hydrograph Comparison

Estimation errors between the IGM with yield thresholds and the observed streamflow were compared at monthly, seasonal and annual temporal resolutions by aggregating the values of monthly streamflow hydrographs of Dunamale watershed. Percentage Difference in Streamflow Estimates (PDSE) was defined as the difference between the observed and modelled values as percentage of the observed value (Equation 3).

$$PDSE = \left[\frac{Observed\ Streamflow - Modelled\ Streamflow}{Observed\ Streamflow}\right] x100\% \qquad (3)$$

Incase of IGM model, PDSE_IGM represents the values after the application of Threshold values. Monthly, Seasonal and Annual PDSE_IGM values of each year are shown in the Figure 5-39. Average, maximum, minimum of each year are shown in the Figure 5-39 and Table 5-33.

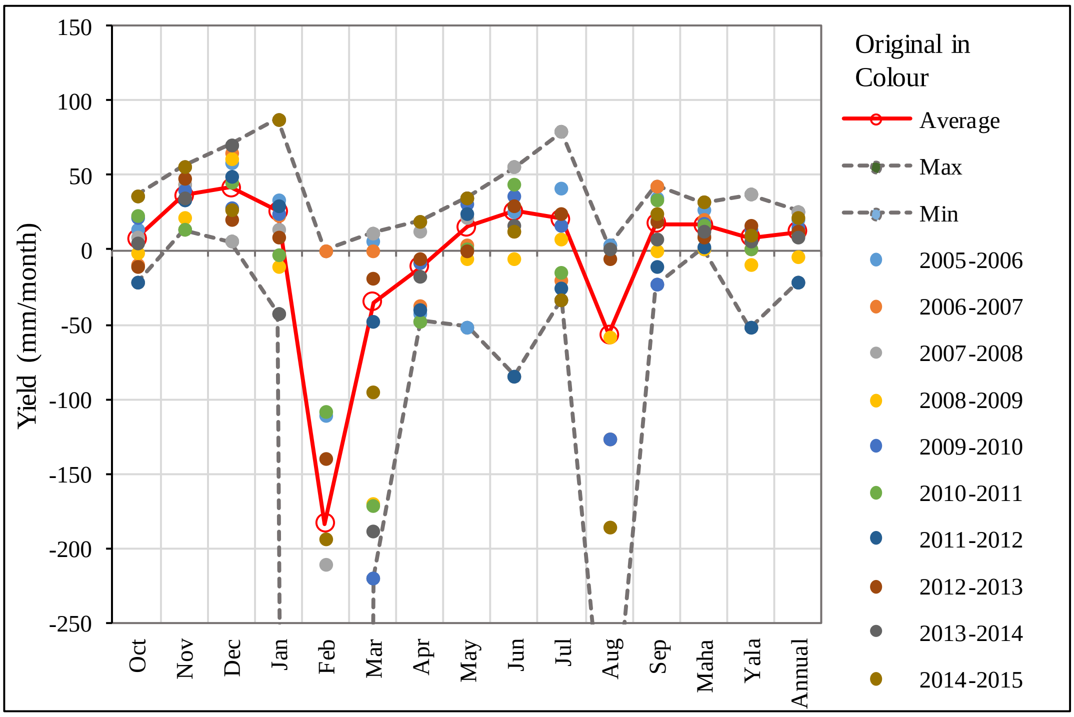


Figure 5-39: Monthly, Seasonal and Annual PDSE_IGM – Dunamale Watershed

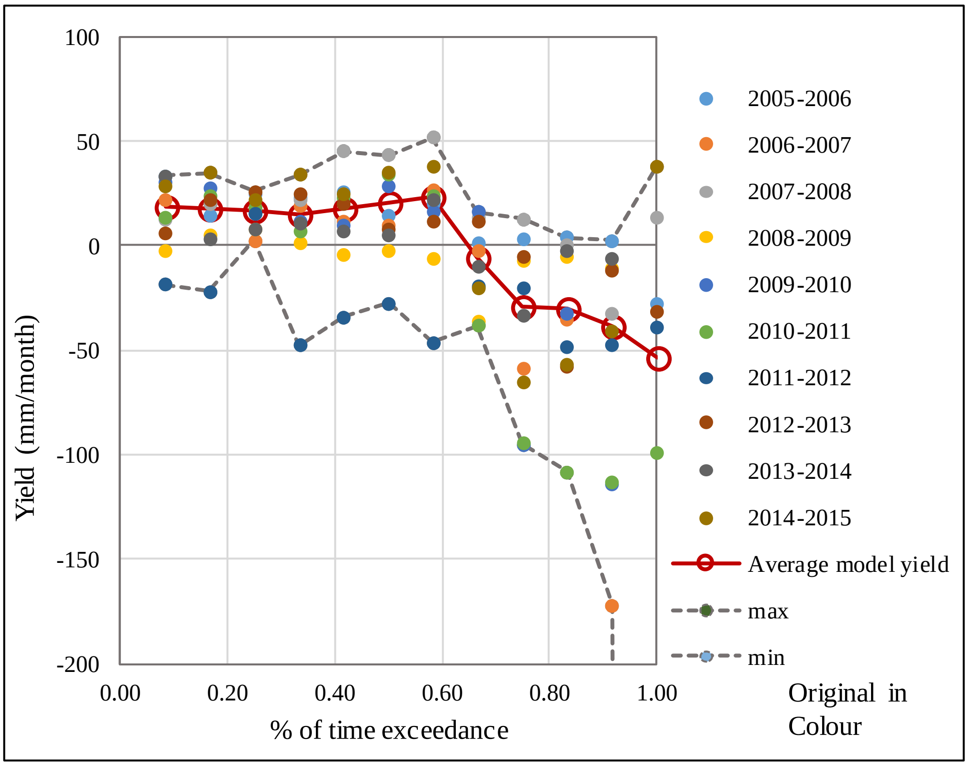
Table 5-33: Average Monthly, Seasonal and Annual PDSE_IGM – Dunamale Watershed

Year	**Average PDSE_IGM value**
Oct	7.4
Nov	36.7
Dec	41.9
Jan	25.7
Feb	-183.6
Mar	-35.1
Apr	-11.7
May	15.1
Jun	25.9
Jul	20.9
Aug	-56.8
Sep	17.6
Maha	16.8
Yala	7.9
Annual	12.5

Average values show that in both Maha and Yala seasons the observed streamflow values are 16.8% and 7.9% higher than the model estimates. The annual yield values show a 12.5% higher observed streamflow than the IGM model estimate. Monthly values are the most important estimates for successful water resources infrastructure planning. In case of February, March, April and August months the model on average, overestimated the watershed yield values while the average model estimates in the other months were either close or lower than the average of observed streamflow. The minimum PDSE_IGM values of February and August indicated issues of missing and questionable data.

5.4.3.4.3 Duration Curve Comparison

Variation of PDSE_IGM values corresponding to the annual flow duration curves are shown by the Figure 5-40 and Table 5-34. The flow duration curve matching of each year clearly shows that in most of the years the high flow periods corresponding to the time of exceedance values below 60% had received streamflow values higher than the model estimates. The minimum values also reflected the missing and questionable data.



Original in Colour

Figure 5-40: PDSE_IGM values and % Time of Exceedance – Dunamale Watershed

Table 5-34: Average PDSE_IGM values and % Time of Exceedance – Dunamale Watershed

% Time of Exceedance	8%	17%	25%	33%	42%	50%	58%	67%	75%	83%	92%	100%
Average	18.7	17.9	16.7	15.2	17.9	20.2	23.1	-5.5	-28.8	-30.1	-39.0	-53.6

5.4.3.4.4 Evaluation Summary – Dunamale Watershed

On average, IGM Model estimates in Maha and Yala seasons are 16.8% and 7.9% lower than the observed streamflow of Dunamale watershed. However, both monthly averages from hydrograph analysis and duration curve comparisons indicate that high flows are under estimated while the low flows are over estimated. On average the highflow (0%-60%) over estimation is approximately 18.5 % while the lowflow (60% -100%) under estimation is 31.4%. A comparison of the average yield estimation error in each month with the average Thiessen rainfall of the previous month indicated that an approximate average antecedent rainfall value of 225 mm/month, acts as the threshold between under estimation and over estimation. (Figure 5-41).

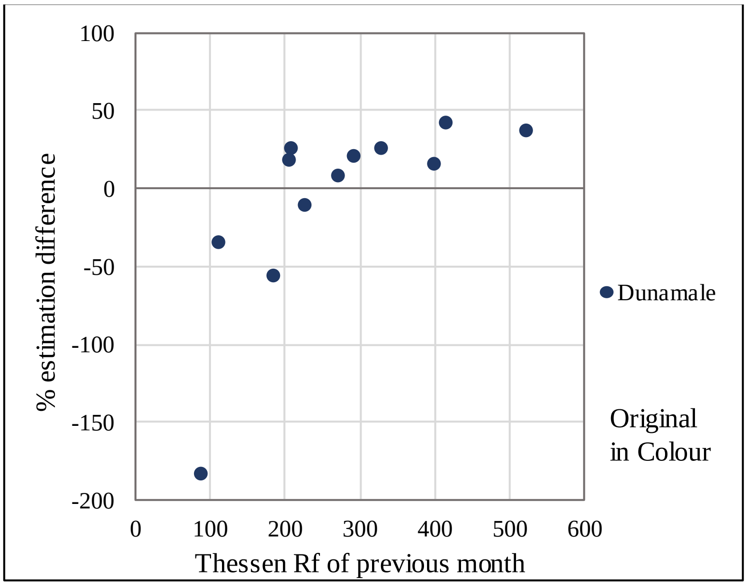


Figure 5-41: Average estimation difference % of yield with RF of previous month – IGM with thresholds

5.4.4 Irrigation Guideline Model (IGM) - Ellagawa Watershed

Irrigation Guideline model was applied to Ellagawa watershed. Table 5-36 presents the yield parameters for Ellagawa watershed.

5.4.4.1 Yield model without Threshold.

Monthly yield for each year computed for Ellagawa Watershed without considering yield limitations are presented in Figure 5-42 and in Table 5-35.

Table 5-35: Monthly, seasonal and annual yield variation (mm) – without yield thresholds – Ellagawa watershed

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Maha	Yala	annual
2006-2007	496.0	375.9	133.8	84.7	30.4	69.8	303.2	158.5	224.7	155.9	272.8	313.7	1190.6	1428.7	2619.3
2007-2008	394.9	167.9	109.3	103.7	163.5	251.4	374.4	247.2	237.8	310.2	134.9	124.3	1190.6	1428.7	2619.3
2008-2009	403.8	311.1	168.3	27.3	56.4	223.7	154.8	266.3	392.0	110.1	241.9	263.7	1190.6	1428.7	2619.3
2009-2010	273.6	321.8	249.1	150.7	64.4	131.1	212.9	364.5	257.6	207.7	190.3	195.6	1190.6	1428.7	2619.3
2010-2011	245.9	360.6	244.2	114.6	87.8	137.5	455.5	234.8	137.7	133.4	201.3	266.1	1190.6	1428.7	2619.3
2011-2012	308.7	278.3	149.0	85.8	108.7	260.0	288.5	121.7	254.8	204.6	284.2	274.9	1190.6	1428.7	2619.3
2012-2013	268.5	287.0	236.6	85.5	113.3	199.8	152.1	235.4	345.7	278.1	132.1	285.3	1190.6	1428.7	2619.3
2013-2014	347.6	345.4	78.9	238.2	57.0	123.5	214.7	140.4	361.0	148.3	312.3	252.0	1190.6	1428.7	2619.3
average	342.4	306.0	171.2	111.3	85.2	174.6	269.5	221.1	276.4	193.5	221.2	246.9	1190.6	1428.7	2619.3

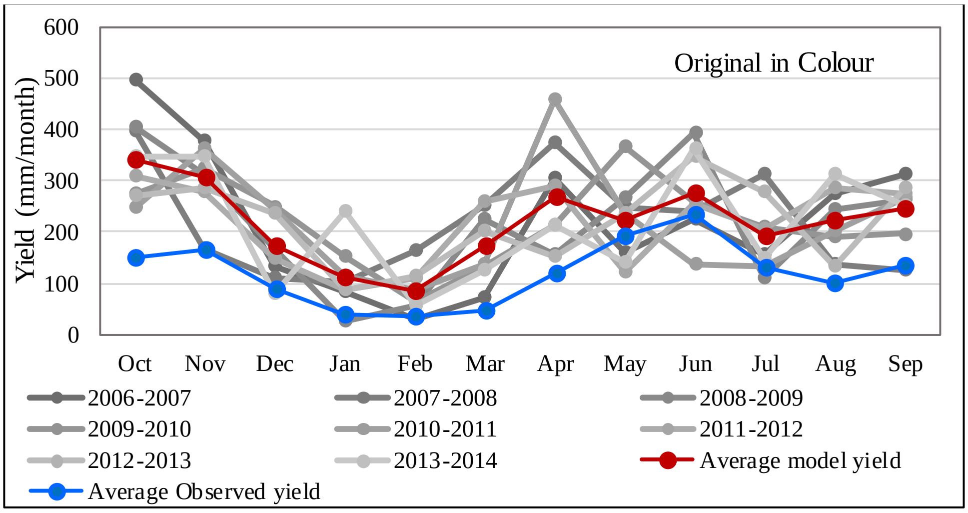


Figure 5-42: Monthly yield variation - Irrigation model without yield limitations - Ellagawa watershed

Comparison of the IGM estimations with the observed monthly streamflow and the Thiessen Average rainfall for the entire data period (Figure 5-43 and Table 5-35) and the comparison of Period of Record (PoR) Flow Duration Curves (FDC) (Figure 5-44) indicate significant over estimation of yield values. The annual FDC are shown in Figure 5-45. These results clearly indicate an over estimation of streamflow over the study period.

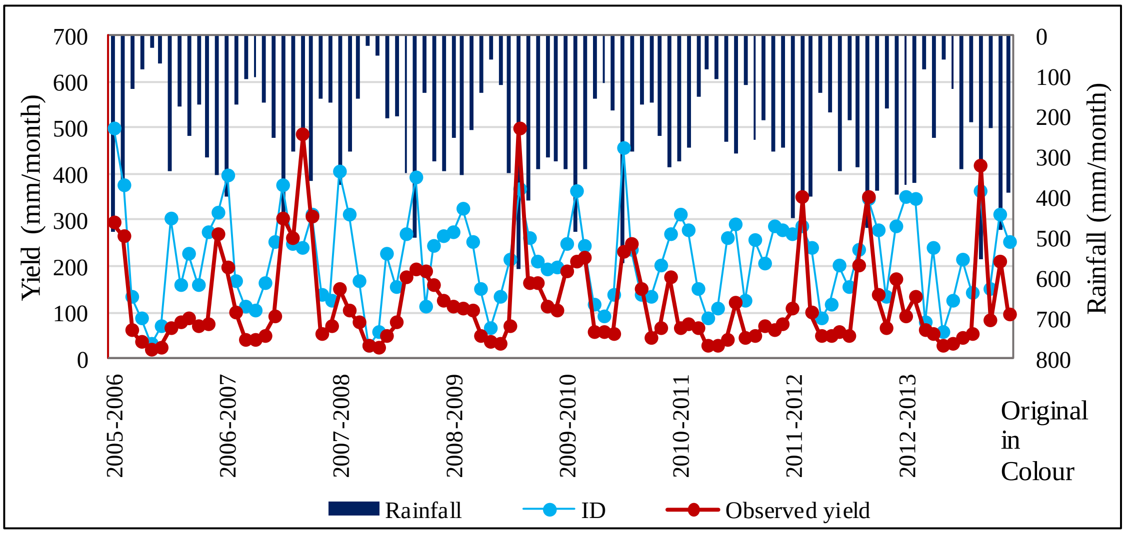


Figure 5-43: Thiessen Average Rainfall, Observed and IGM monthly yield without thresholds for Ellagawa Watershed

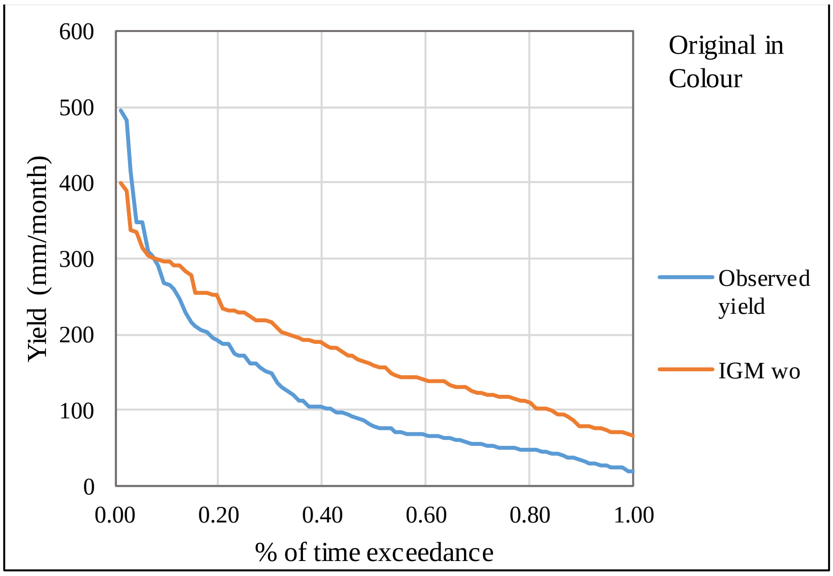


Figure 5-44: Monthly PoR FDC for Ellagawa watersheds without threshold

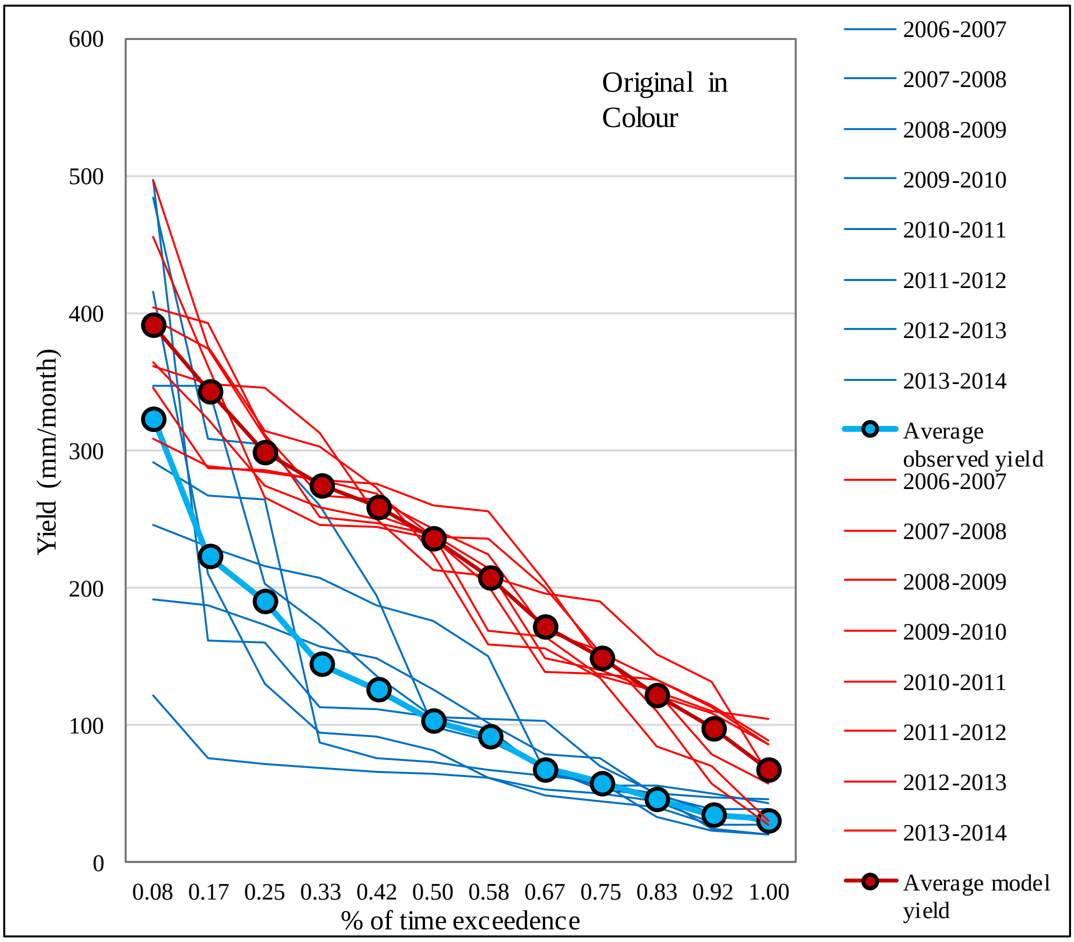


Figure 5-45: Annual FDC of monthly streamflow without thresholds - Ellagawa Watershed

5.4.4.2 Comparison of Numerical Indicators

Comparison of numerical indicators corresponding to IGM streamflow estimations and the observed values show a significant over estimation (Figure 5-46, Table 5-36). The overall hydrograph matching shows a significant mismatch both in the magnitude and the timing of watershed response that was reflected by the model. All seasonal and annual estimations show that an over estimation of model yield without thresholds than observed yield, except in 2007/2008 Yala season. The IGM Flow duration curve shows a significant over estimations while the seasonal water balance values show an even distribution of overestimation across both monsoons. Observed streamflow data of March in water year 2006/2007 was missing. Table 5-37 shows numerical indicators for IGM model without thresholds for Ellagawa basin.

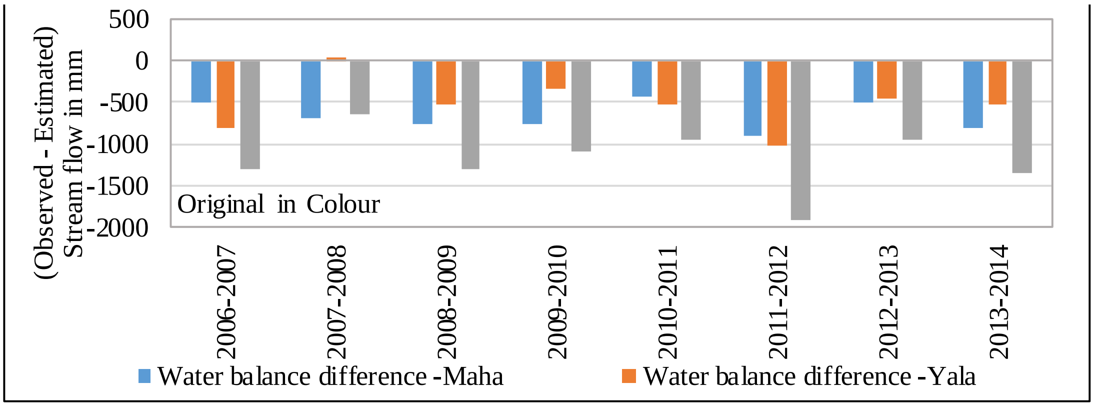


Figure 5-46: Seasonal and annual water balance difference IGM without Threshold – Ellagawa watershed

Table 5-36: Seasonal and annual water balance difference IGM without threshold – Ellagawa watershed

	Water balance difference in mm		
	Water Balance Difference-Maha	**Water Balance Difference-Yala**	**Water Balance Difference-Annual**
2006-2007	-499.32	-796.95	-1296.26
2007-2008	-684.80	47.85	-636.96
2008-2009	-768.57	-519.35	-1287.92
2009-2010	-755.40	-325.12	-1080.52
2010-2011	-420.74	-518.70	-939.43
2011-2012	-897.30	-1011.64	-1908.94
2012-2013	-489.28	-458.56	-947.85
2013-2014	-804.18	-531.61	-1335.79
Average	-664.95	-514.26	-1179.21

Table 5-37: Numerical Indicators of IGM Model Estimations without thresholds - Ellagawa watershed

Numerical indicators	Ellagawa Watershed
Average Annual Water Balance Error (mm)	-1179.21
Average Maha Season Water Balance Error (mm)	-664.95
Average Yala Season Water Balance Error (mm)	-514.26
Percentage error of annual average runoff coefficient	-81.88
MRAE overall hydrograph	1.47
MRAE PoR FDC	1.47
MRAE Annual FDC	1.34

5.4.4.3 IGM Yield Model – With Thresholds

IGM model with yield thresholds was applied and evaluated. Figure 5-47, 5-48 and Table 5-38 presents the results.

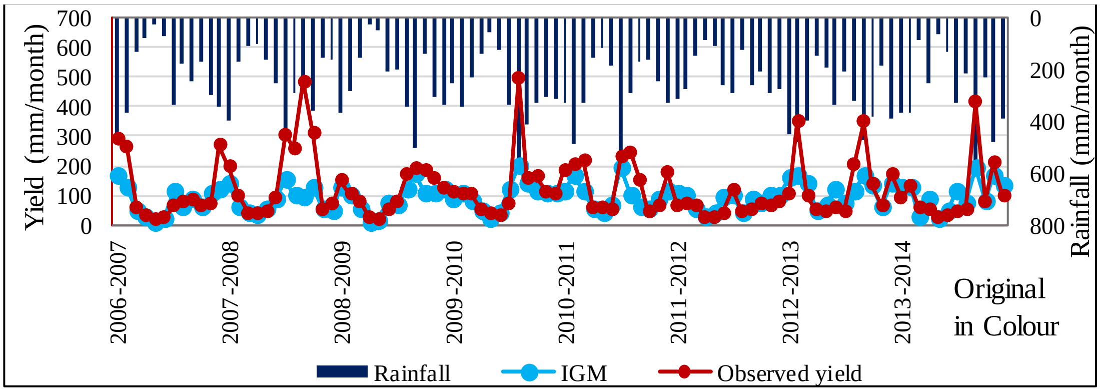


Figure 5-47: Observed yield variation with IGM yield with thresholds - Ellagawa watershed

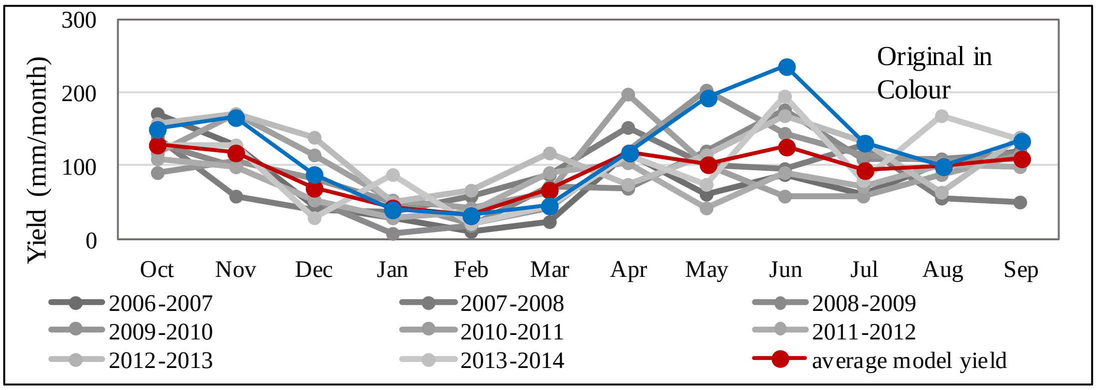


Figure 5-48: Monthly model yield variation with average observed yield- Ellagawa watershed

IGM model with yield thresholds was applied and evaluated. Figure 5-47, 5-48 and Table 5-38 presents the results. An under estimation of high flows in the monthly streamflow hydrograph and also in the monthly average flow variations can be seen. The duration curve indicated an over estimation in the high-intermediate flow values.

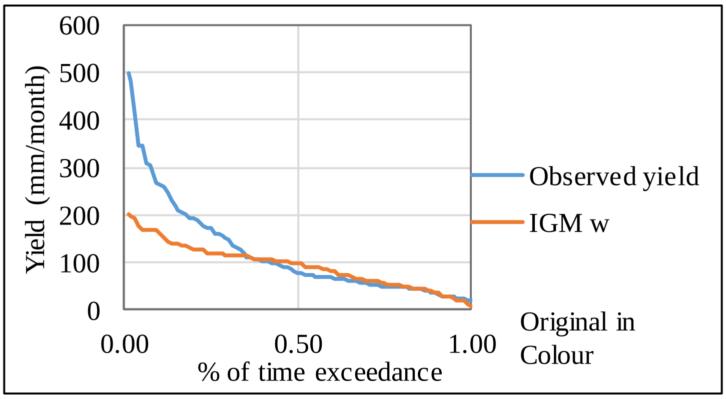


Figure 5-49: Overall FDC IGM with thresholds for Ellagawa watershed

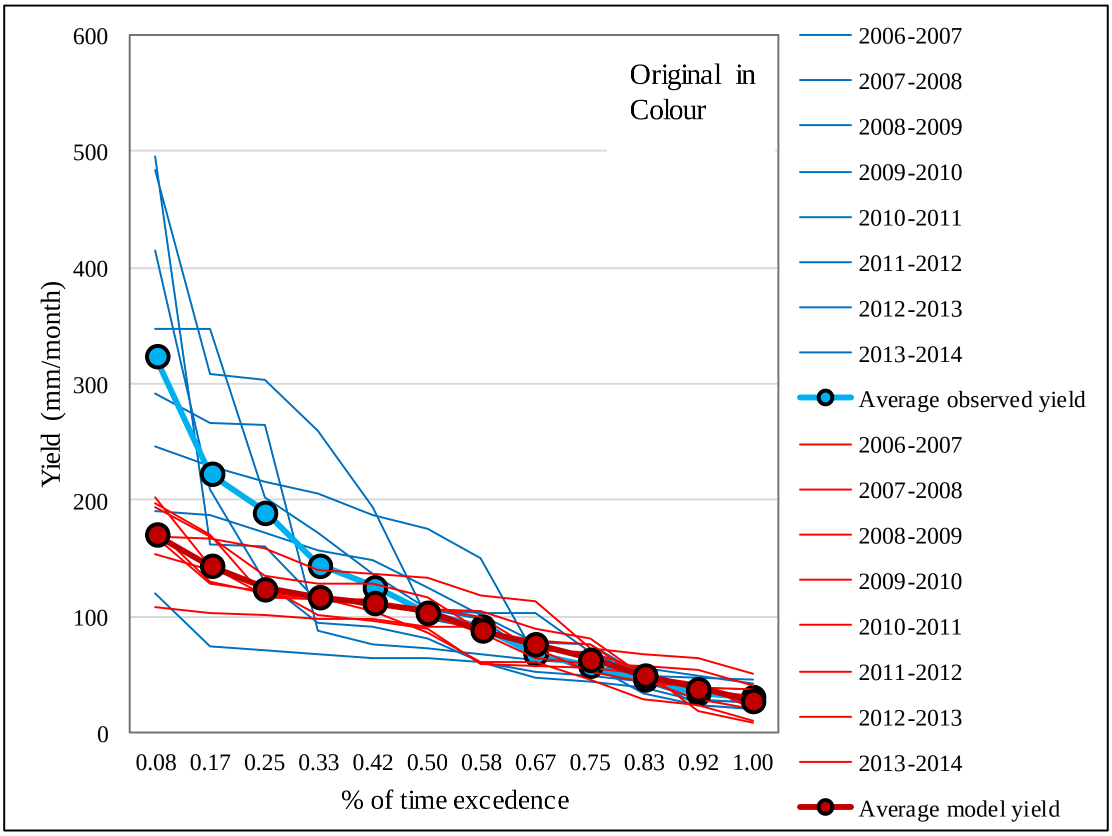


Figure 5-50: Annual FDC for IGM with thresholds - Ellagawa watershed

Table 5-38: Model results for IGM with yield thresholds - Ellagawa basin

Year	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Maha**	**Yala**	**annual**
2006-2007	169.7	128.6	45.8	29.0	10.4	23.9	116.9	61.1	86.6	60.1	105.2	121.0	407.3	550.8	958.1
2007-2008	139.8	59.5	38.7	36.7	57.9	89.0	152.8	100.9	97.1	126.6	55.1	50.7	421.6	583.3	1004.9
2008-2009	129.6	99.8	54.0	8.8	18.1	71.8	69.4	119.4	175.7	108.4	108.4	118.2	382.1	699.5	1081.6
2009-2010	89.6	105.3	81.5	49.3	21.1	42.9	118.6	203.1	143.5	115.7	106.0	109.0	389.7	795.9	1185.6
2010-2011	116.0	170.1	115.2	54.0	41.4	64.9	196.6	101.4	59.5	57.6	86.9	114.9	561.6	616.8	1178.4
2011-2012	108.6	97.9	52.4	30.2	38.2	91.5	102.6	43.3	90.6	72.8	101.1	97.8	418.7	508.2	927.0
2012-2013	158.5	169.4	139.7	50.5	66.9	118.0	73.4	113.5	166.7	134.1	63.7	137.6	703.0	689.0	1391.9
2013-2014	129.0	128.1	29.3	88.4	21.2	45.8	115.7	75.7	194.5	79.9	168.3	135.8	441.7	770.0	1211.7
average model yield	130.1	119.8	69.6	43.4	34.4	68.5	118.3	102.3	126.8	94.4	99.3	110.6	465.7	651.7	1117.4

Figure 5-49 and Figure 5-50 show PoR FDC and annual FDC for IGM with thresholds. After applying yield thresholds the observed yield and model yield come closer to each other for intermediate and low flows. However, the difference between observed high flow and modeled high flow has remained as high. Figure 5-51 and Table 5-39 indicates seasonal and annual water balance difference. Only in the year 2011/2012, seasonal and annual water balance difference has shown a minus value. According to the data checking, the lowest runoff coefficient was observed in 2011/2012.

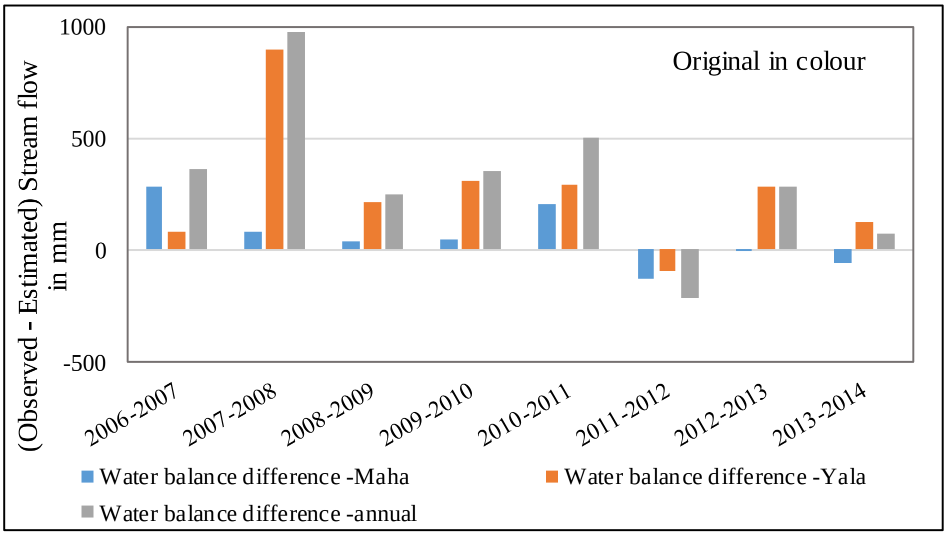


Figure 5-51: Seasonal, annual water balance difference IGM with Threshold – Ellagawa

Table 5-39: Seasonal, annual water balance difference IGM with threshold - Ellagawa

	Water balance difference in mm		
	Water Balance Difference-Maha	**Water Balance Difference-Yala**	**Water Balance Difference-Annual**
2006-2007	284.00	80.94	364.94
2007-2008	84.20	893.30	977.50
2008-2009	39.93	209.91	249.84
2009-2010	45.47	307.73	353.20
2010-2011	208.27	293.24	501.52
2011-2012	-125.42	-91.16	-216.58
2012-2013	-1.64	281.19	279.55
2013-2014	-55.32	127.16	71.85
Average	59.94	262.79	322.73

Table 5-40: Numerical Indicators of IGM Model Estimations - Ellagawa watershed

Numerical indicators	**Ellagawa Watershed**
Average Annual Water Balance Error (mm)	322.73
Average Maha Season WaterBalance Error (mm)	59.94
Average Yala Season Water Balance Error (mm)	262.79
Percentage error of annual average runoff coefficient	22.41
MRAE overall hydrograph	0.35
MRAE PoR FDC	0.35
MRAE Annual FDC	0.27

5.4.4.4 Comparison Ellagawa Watershed

5.4.4.4.1 Effect of Yield Thresholds

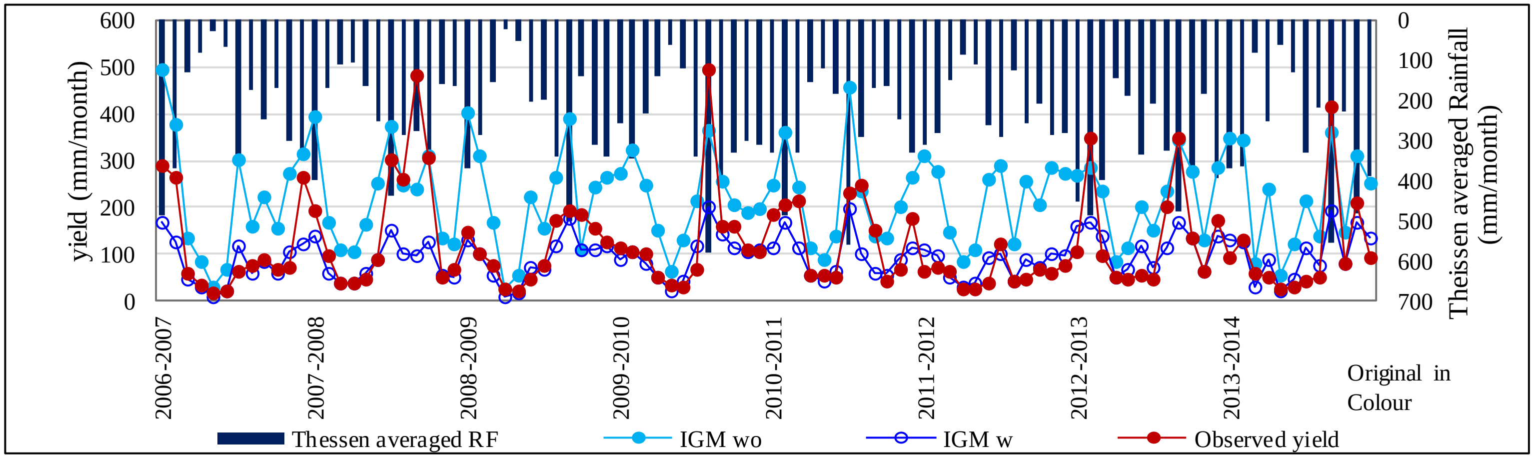
Monthly, seasonal and annual yield value comparison with respective Thiessen rainfall is shown in Figure 5-52, 5-53 and Table 5-38. In all the years, Maha season has shown over estimation in the yield without thresholds. Without threshold yield except in 2007-2008 Yala season has shown overestimated yield values. This supports the guideline recommendation to incorporate yield threshold values. Analysis of monthly values indicate that in many months the observed streamflow is much lower than the yield values without thresholds. The yield values from IGM model with yield thresholds closely represent the observed yield values in monthly, seasonal and annual temporal resolutions. Out of the 8 year study duration, the annual total streamflow in the year 2011-2012 were less than the yield values of IGM model with thresholds. In case of Maha season 2011-2014 years indicated lower observed seasonal streamflow than the IGM model values with thresholds. In the Yala season comparison, 2011-2012 year were with lower observed streamflow values than the IGM model values. Monthly average values over the study period showed that the model values with thresholds were higher during months with lower streamflow and lower during months with higher streamflow. It seems that there is a data uncertainty in 2011-2012 year because the observed streamflow is very much less compared to observed rainfall. These results confirm that the IGM Model with yield thresholds provide the closest yield estimates for the Ellagawa watershed. Therefore, in the present work the comparative evaluation of models considered that IGM model is the use if iso-yield curves with yield thresholds. Considering Yala season in 2007-2008, observed yield show a peak without comparable rainfall event. This seems due to data uncertainty noticed during visual checking.

5.4.4.4.1 Hydrograph Comparison

Percentage Difference in Streamflow Estimates (PDSE) was defined as the difference between the observed and modelled values as percentage of the observed value (Equation 2). Incase of IGM model, PDSE_IGM represents the values after the application of Threshold values. Monthly, Seasonal and Annual PDSE_IGM values of each year are shown in the Figure 5-54. Average, maximum, minimum of each year are shown in the Figure 5-54 and Table 5-41. Monthly values are the most important estimates for successful water resources infrastructure planning. In case of January and March, the model on average had overestimated the watershed yield values while the average model estimates in the other months were either close or lower than the average of observed streamflow.

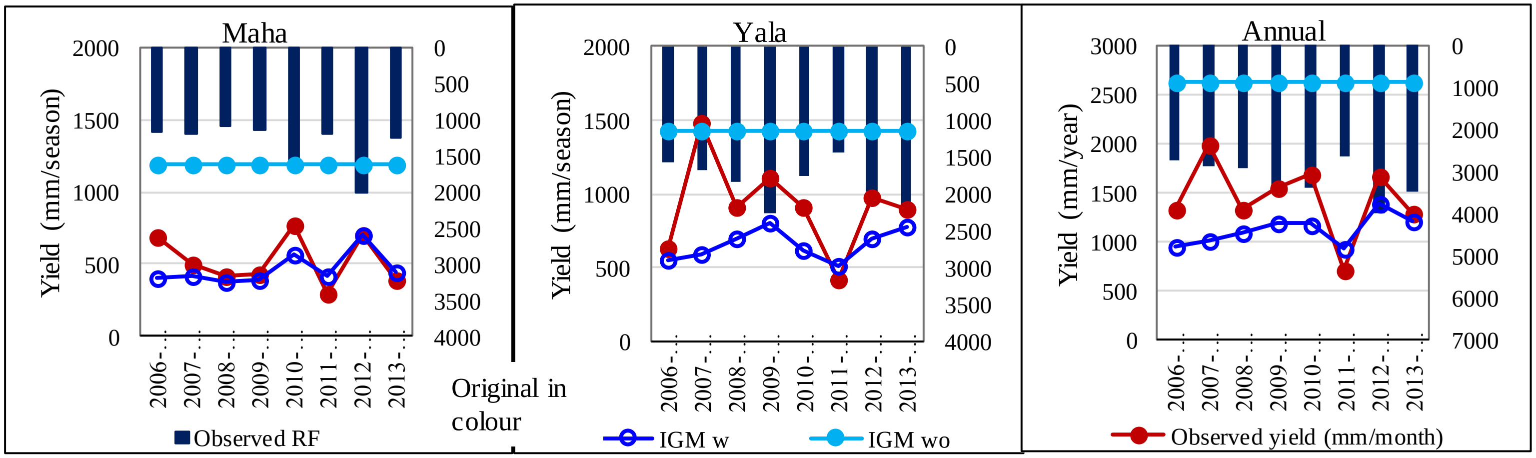
Table 5-41: Average Monthly, Seasonal and Annual PDSE_IGM – Ellagawa Watershed

Year	Average PDSE_IGM
Oct	12.9
Nov	27.6
Dec	22.5
Jan	-5.9
Feb	0.4
Mar	-50.5
Apr	0.8
May	47.2
Jun	46.1
Jul	28.2
Aug	0.2
Sep	18.2
Maha	11.4
Yala	28.7
Annual	22.4



Original in Colour

Figure 5-52: Comparison of Average monthly observed and modelled yield values with average Thiessen rainfall – Ellagawa watershed (2006/2007-2013/2014)



Original in colour

Figure 5-53: Maha, Yala and Annual Yield Comparison -Ellagawa watershed

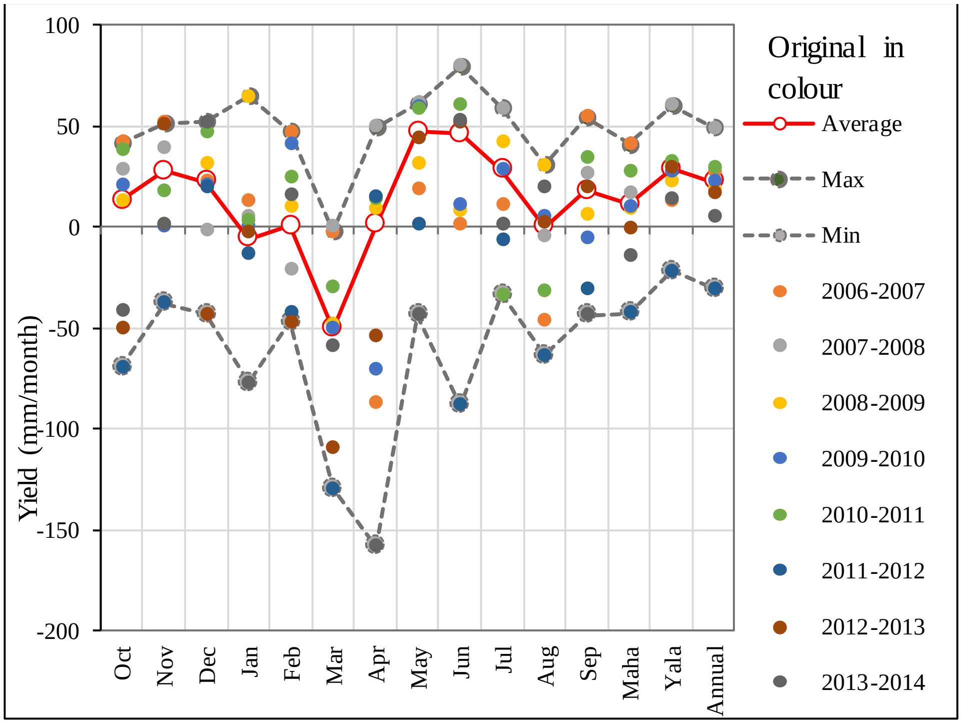


Figure 5-54: Monthly, Seasonal and Annual PDSE_IGM – Ellagawa Watershed

5.4.4.4.2 Duration Curve Comparison

Variation of PDSE_IGM values corresponding to the annual flow duration curves are shown by the Figure 5-55 and Table 5-42. The flow duration curve matching of each year clearly shows that in most of the years the high flow periods corresponding to the time of exceedance values below 60% had received streamflow values higher than the model estimates. The minimum values reflected the missing and questionable data.

Table 5-42: Average PDSE_IGM values and % Time of Exceedance – Ellagawa Watershed

% Time of Exceedance	8%	17%	25%	33%	42%	50%	58%	67%	75%	83%	92%	100%
Average	18.7	17.9	16.7	15.2	17.9	20.2	23.1	-5.5	-28.8	-30.1	-39.0	-53.6

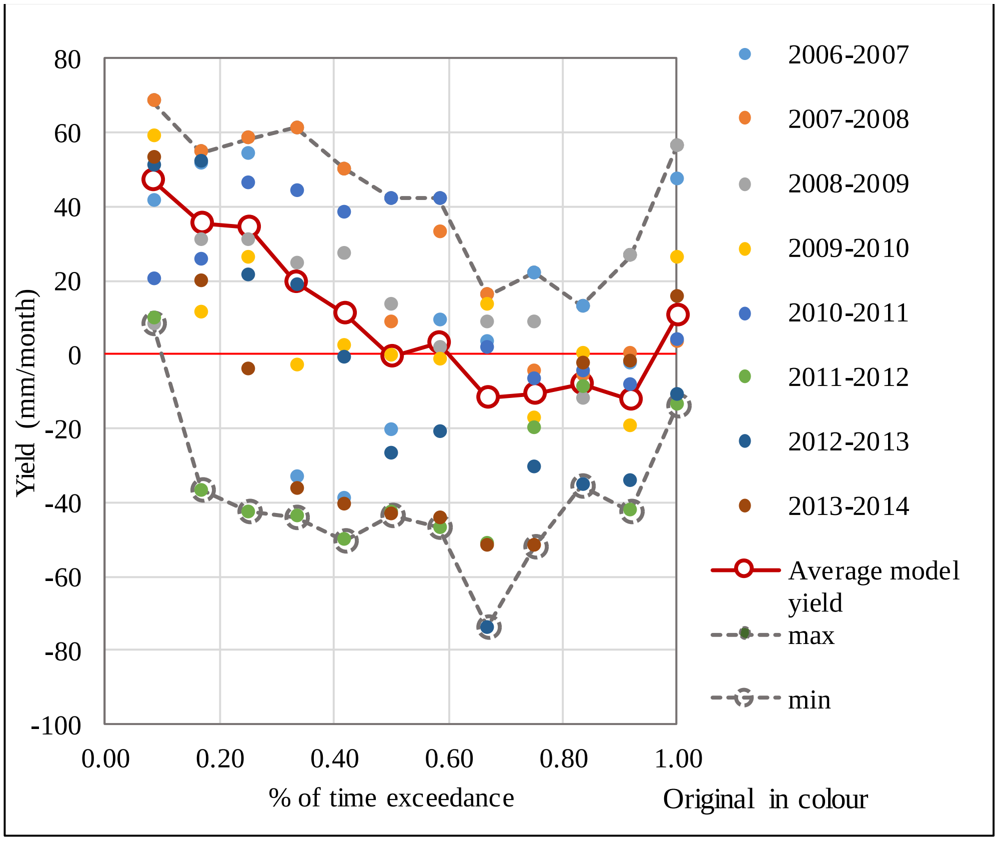


Figure 5-55: PDSE_IGM values and % Time of Exceedance – Ellagawa Watershed

5.4.4.4.3 Evaluation Summary Ellagawa

On average, IGM Model estimates in Maha and Yala seasons are 11.4% and 28.7% lower than the observed streamflow of Dunamale watershed. However, both monthly averages from hydrograph analysis and duration curve comparisons indicate that high flows are under estimated while the low flows are over estimated. On average the highflow (0%-60%) under estimation is approximately 21.4 % while the lowflow (60%-100%) over estimation is 6.39%. A comparison of the average yield estimation error in each month with the average Thiessen rainfall of the previous month indicated that an approximate average antecedent rainfall value of 250 mm/month, acts as the threshold between under estimation and over estimation (Figure 5-56).

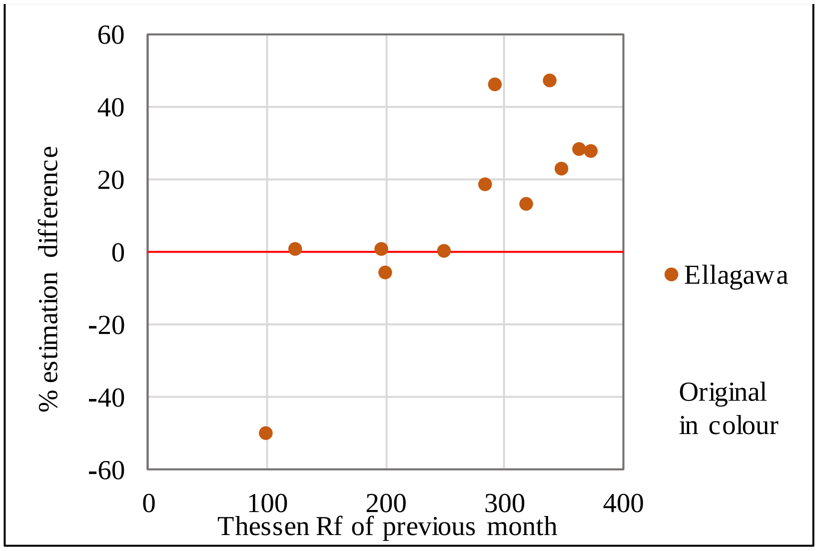


Figure 5-56: Average estimation difference % of yield with RF of previous month – IGM with thresholds – Ellagawa basin

5.4.5 HEC-HMS Model (HEC)- Dunamale Watershed

5.4.5.1 HEC Model application

Monthly, seasonal and annual HEC model results were analysed. Monthly variation of HEC model results is presented in Figure 5-57, 5-58 and Table 5-43. Monthly hydrograph results show that in almost all years, model results are higher than the observed yield. Figure 5-59 and Figure 5-60 presents FDC for Period of Record and annual FDC respectively. FDC variation indicates that HEC-HMS model over estimates the high flow, medium flow and low flows. Appendix D shows daily model yield and observed yield variation with Thiessen averaged rainfall.

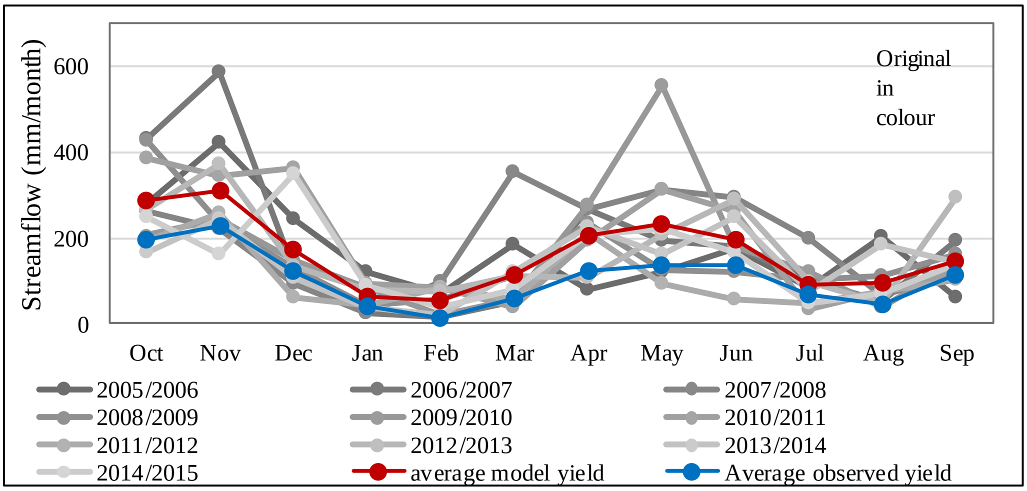


Figure 5-57: Monthly yield variation - HEC model - Dunamale watershed

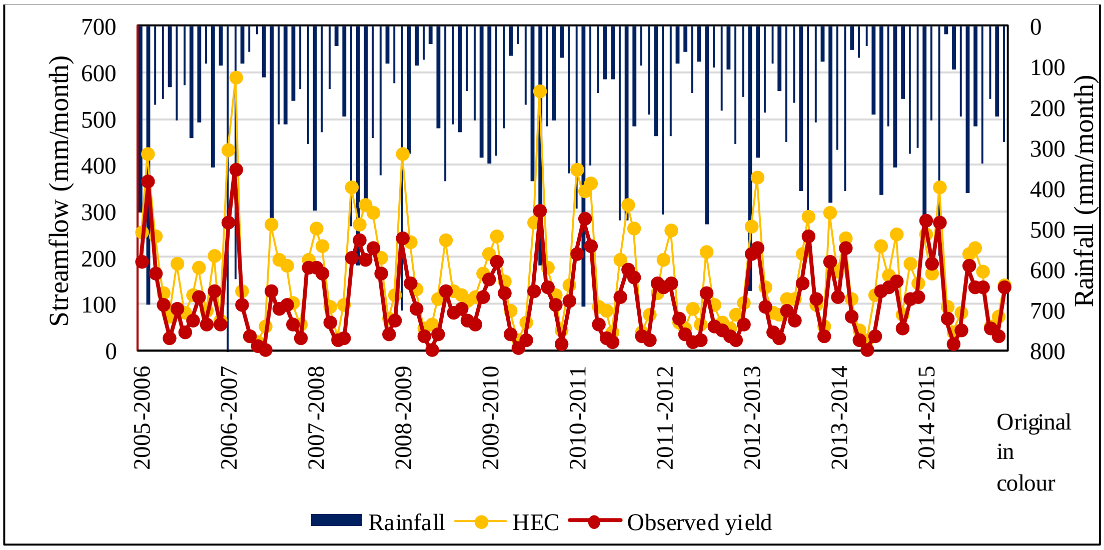


Figure 5-58: Thiessen average rainfall, observed and HEC – HMS monthly yield for Dunamale watershed

Table 5-43: Monthly, seasonal and annual yield variation (mm) – HEC model- Dunamale watershed

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Maha	Yala	annual
2005-2006	277.9	421	243.4	120.1	72	184.5	79.8	119.1	175.4	82.9	203.8	60.8	1318.9	721.8	2040.7
2006-2007	430.3	585.1	126.6	26.3	16.8	51.5	267.6	195.3	179.4	100.7	54.1	193.2	1236.6	990.3	2226.9
2007-2008	261.1	221.2	93.8	26.3	95.8	351.9	267.6	313.1	293.7	196.8	65.8	116	1050.1	1253.0	2303.1
2008-2009	423.6	233.3	128.9	43.3	55.1	109.8	236.2	126	118.7	102.7	111	162.7	994.0	857.3	1851.3
2009-2010	204.8	242.9	146.4	85.3	19.3	57.8	274.2	555.6	177.7	119.3	39.7	139.2	756.5	1305.7	2062.2
2010-2011	387	341.7	360.2	93.5	82.6	38.8	191.5	310.7	262.9	35.6	76.6	120.7	1303.8	998.0	2301.8
2011-2012	193.7	258.8	59.4	43.5	85.7	55.6	211.1	94.7	57	47.5	76.5	102	696.7	588.8	1285.5
2012-2013	266.4	370.3	132.4	79.7	74.7	109.7	108.1	206.4	287.9	95.8	49.5	294.4	1033.2	1042.1	2075.3
2013-2014	166.3	241.4	107.8	39.6	19.7	118.3	224.2	160.6	246.6	72.9	185.4	141.3	693.1	1031.0	1724.1
2014-2015	247.8	162.5	348.9	90.2	38.9	77.5	206	218.9	165.9	48.5	72.1	139.8	965.8	851.2	1817.0
average	285.89	307.82	174.78	64.78	56.06	115.54	206.63	230.04	196.52	90.27	93.45	147.01	1004.87	963.92	1968.79

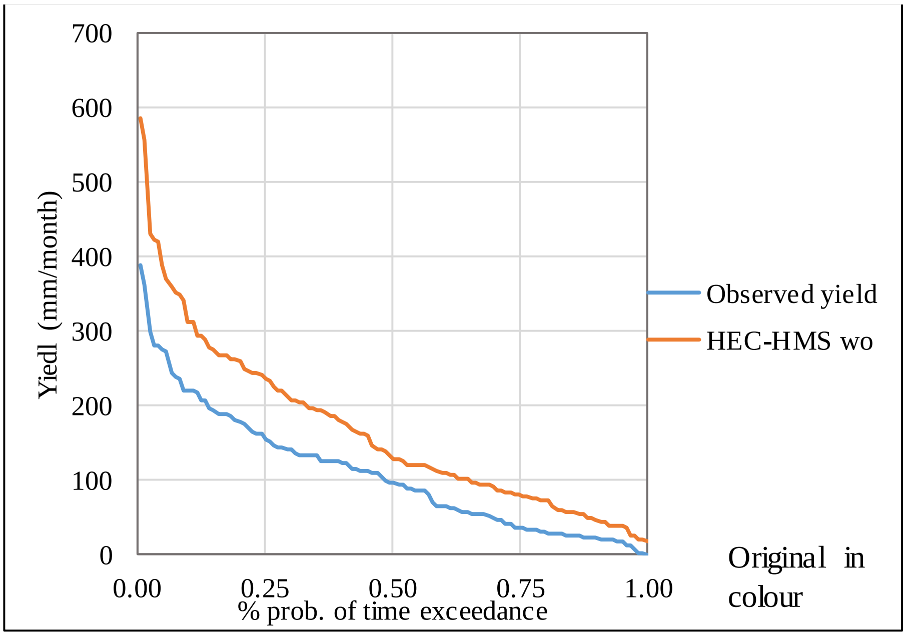


Figure 5-59: Monthly PoR FDC for HEC model Dunamale Watershed

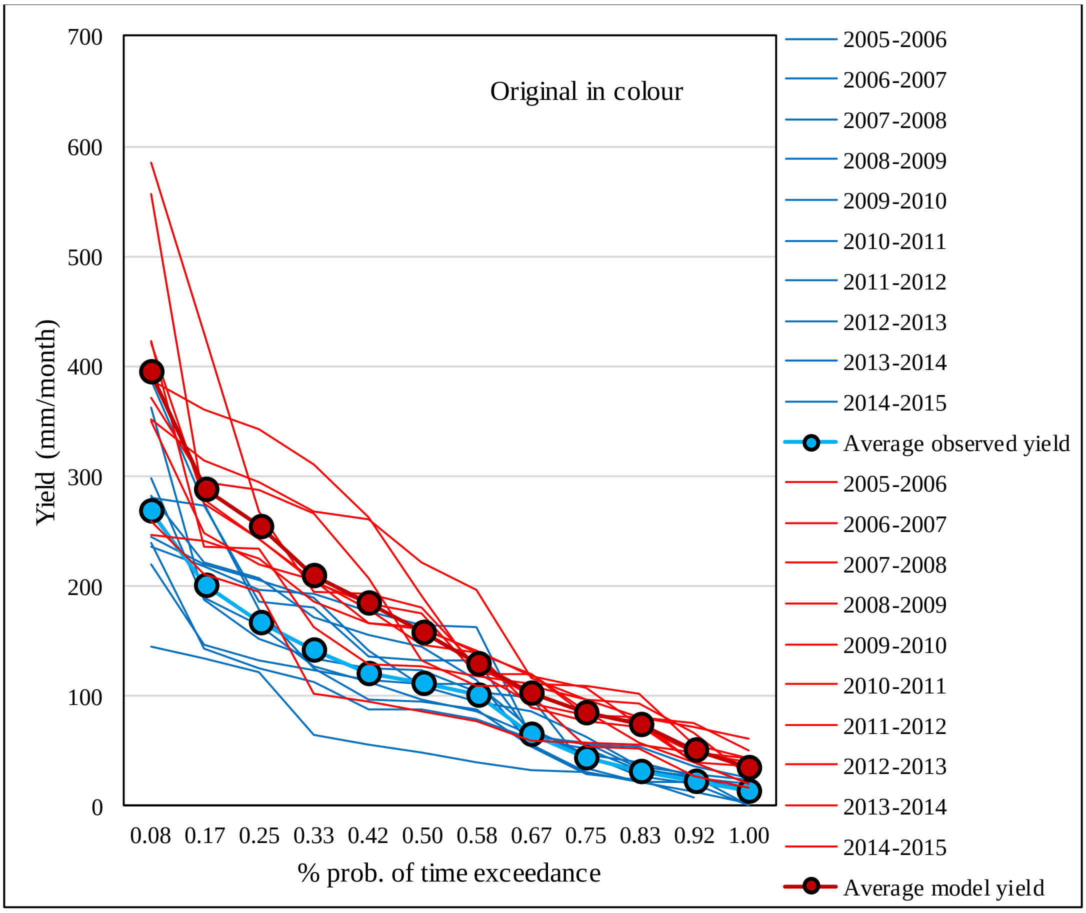


Figure 5-60: Annual FDC for HEC model and monthly streamflow - Dunamale Watershed

5.4.5.2 Comparison of Numerical Indicators

All the seasons in all years during the study period shows a negative water balance difference indicating the overestimated yield values of the model (Figure 5-61, Table 5-44). Hence the analysis results in Dunamale watershed show the need of correction factors to avoid the estimation of design yield by the HEC-HMS software.

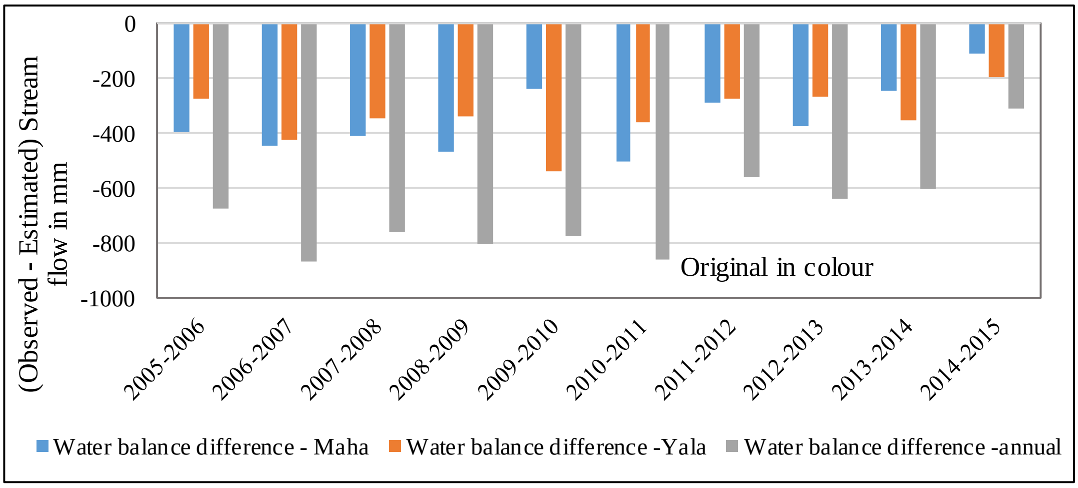


Figure 5-61: Seasonal and Annual Water Balance Difference HEC model– Dunamale

Table 5-44: Seasonal and Annual Water Balance Difference HEC model - Dunamale

	Water balance in mm		
Year	**Water Balance Difference-Maha**	**Water Balance Difference-Yala**	**Water Balance Difference-Annual**
2005-2006	-397.99	-274.69	-672.68
2006-2007	-442.61	-423.43	-866.04
2007-2008	-412.51	-347.11	-759.62
2008-2009	-463.11	-341.46	-804.57
2009-2010	-237.55	-534.53	-772.08
2010-2011	-499.26	-362.24	-861.50
2011-2012	-285.70	-271.23	-556.93
2012-2013	-370.35	-265.61	-635.96
2013-2014	-246.43	-355.22	-601.65
2014-2015	-109.91	-196.96	-306.87
Average	-346.54	-337.25	-683.79

Numerical indicators of HEC-HMS model estimations is presented in Table 5-45.

Table 5-45: Numerical Indicators of HEC-HMS Model Estimations - Dunamale watershed

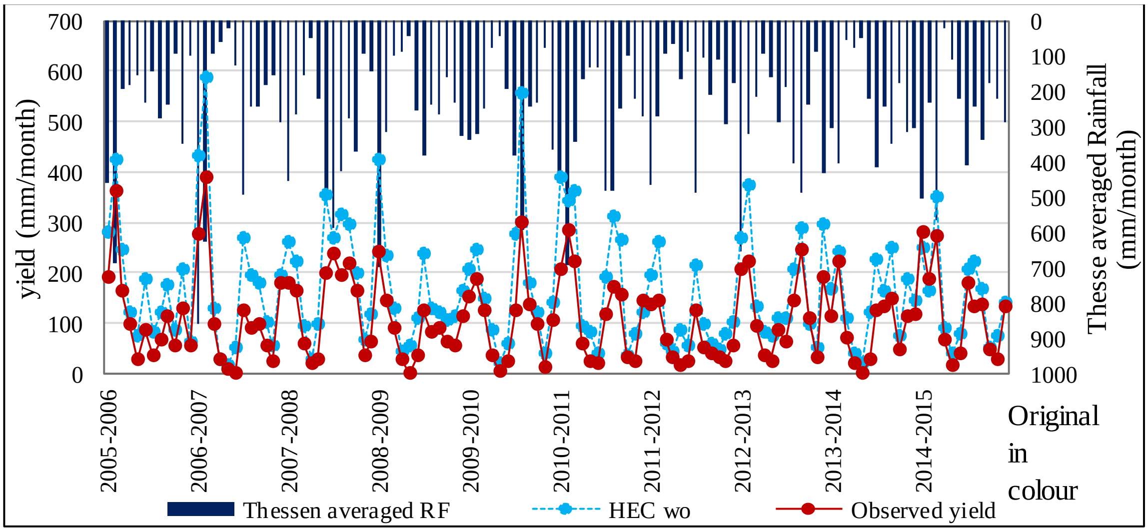
	Dunamale Watershed
Average Annual Water Balance Error (mm)	-1854.17
Average Maha Season Water Balance Error (mm)	-935.53
Average Yala Season Water Balance Error (mm)	-918.05
Percentage error of annual average runoff coefficient	-53.21
MRAE overall hydrograph	1.90
MRAE PoR FDC	1.90
MRAE Annual FDC	1.72

5.4.5.1 Comparison – Dunamale Watershed

Even though the HEC model that over estimates the watershed yield, the monthly, seasonal and annual flow patterns of estimations and observations are similar. Model yield is approximately 1.5 times higher than the observed yield. Hence, it is clear that yield thresholds are needed to be applied for HEC-HMS model applications.

5.4.5.1.1 Effect of Yield Thresholds

Monthly, seasonal and annual average yield comparison of HEC-HMS model and observed values is in Figure 5-62 and 5-63.



Original in colour

Figure 5-62: Comparison of Average Monthly Observed and Modelled Yield Values with Average Thiessen Rainfall (2005/2006-2014/2015)

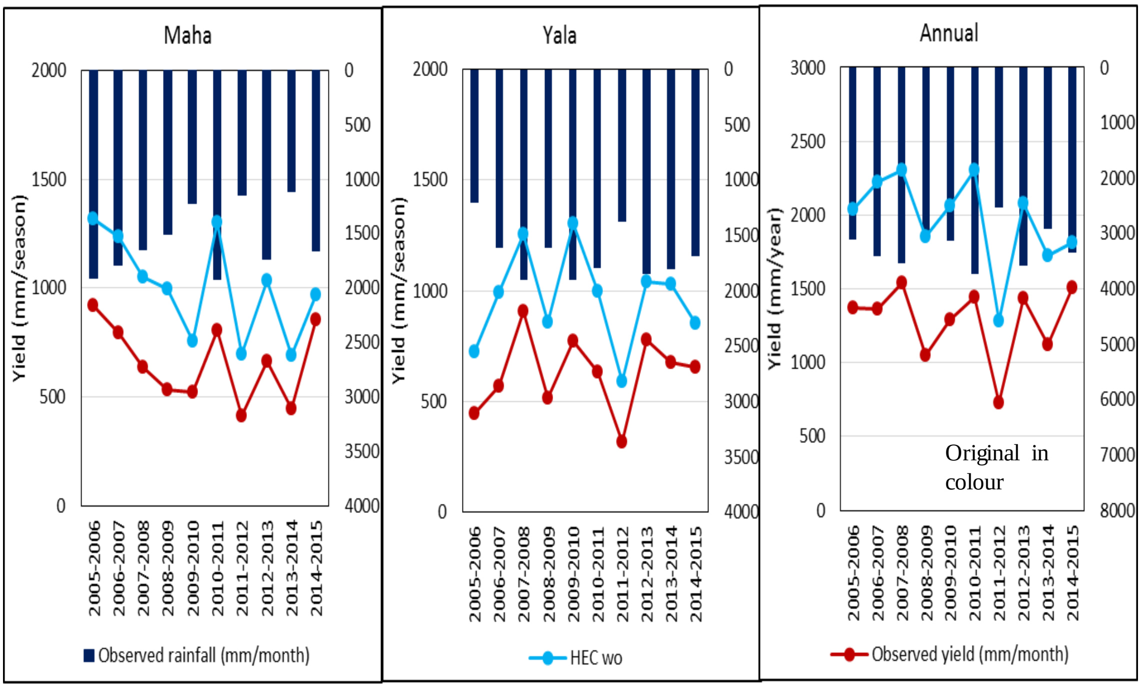


Figure 5-63: Maha, Yala and Annual Yield Comparison HEC model – Dunamale watershed

5.4.5.1.2 Hydrograph Comparison

Hydrograph comparison relative to observed yield for HEC-HMS model is in Figure 5-64 and Table 5-46.

Monthly, Seasonal and Annual PDSE of HEC model show that during all the months, model over estimates the streamflow. For relatively dry months as February and August, over estimation is comparatively higher than other months. Seasonal and annual over estimation is approximately 53%.

Hence, it is clear that there is a need for applying correction factors for yield estimation for HEC-HMS model for Dunamale watershed.

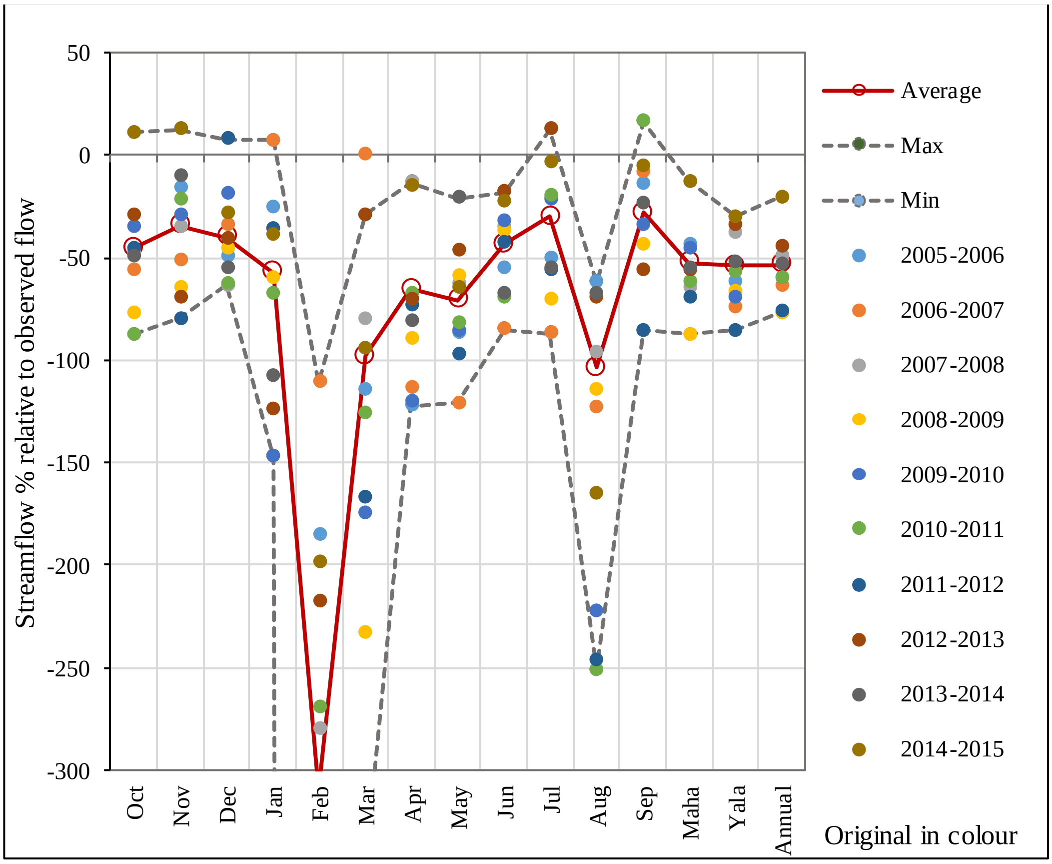


Figure 5-64: Monthly, seasonal and annual PDSE_HEC – Dunamale watershed

Table 5-46: Average Monthly, seasonal and annual PDSE_HEC – Dunamale watershed

#	**Average yield % relative to observed yield**
Oct	-45.3
Nov	-34.3
Dec	-40.0
Jan	-57.1
Feb	-310.1
Mar	-97.8
Apr	-65.4
May	-70.6
Jun	-43.4
Jul	-30.2
Aug	-103.7
Sep	-28.3
Maha	-52.6
Yala	-53.8
Annual	-53.2

5.4.5.1.3 Duration Curve Comparison

Variation of PDSE_IGM values corresponding to the annual flow duration curves are shown by the Figure 5-65 and Table 5-47.

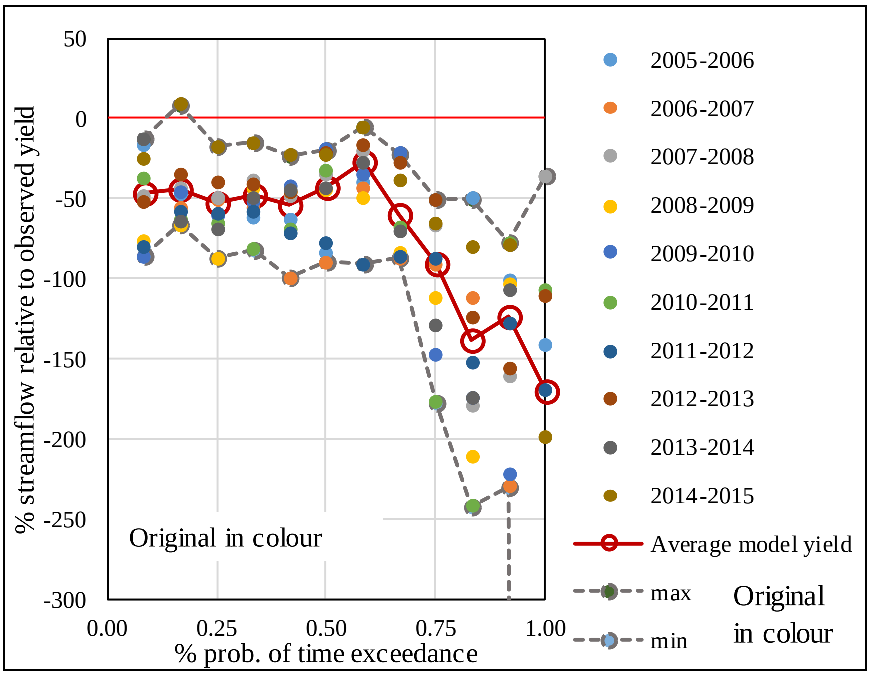


Figure 5-65: PDSE_HEC values and % time of exceedance – Dunamale watershed

Table 5-47: Average PDSE_HEC values and % time of exceedance – Dunamale watershed

% time exceedance	**average model yield**
8%	-46.64
17%	-44.04
25%	-52.92
33%	-48.22
42%	-53.41
50%	-42.53
58%	-27.46
67%	-60.48
75%	-90.80
83%	-138.31
92%	-124.20
100%	-170.46

The flow duration curve matching of each year clearly shows that in most of the years the high flow periods corresponding to the time of exceedance values below 60% are varying between 0 -100 range. However, a very high over estimation of can be seen after 60% time of exceedance. The minimum values also reflected the missing and questionable data.

5.4.5.1.4 Evaluation Summary – Dunamale Watershed

On average, HEC Model estimates in Maha and Yala seasons are 52.6% and 53.8% higher than the observed streamflow of Dunamale watershed. Monthly averages from hydrograph analysis and duration curve comparisons indicate that streamflow of dry months are significantly over estimated. A comparison of the average yield estimation error in each month with the average Thiessen rainfall of the previous month indicated that all the streamflow values are overestimated and the percentage estimation difference varies in the range of 0 to -100. Higher deviations show missing or questionable data (Figure 5-66).

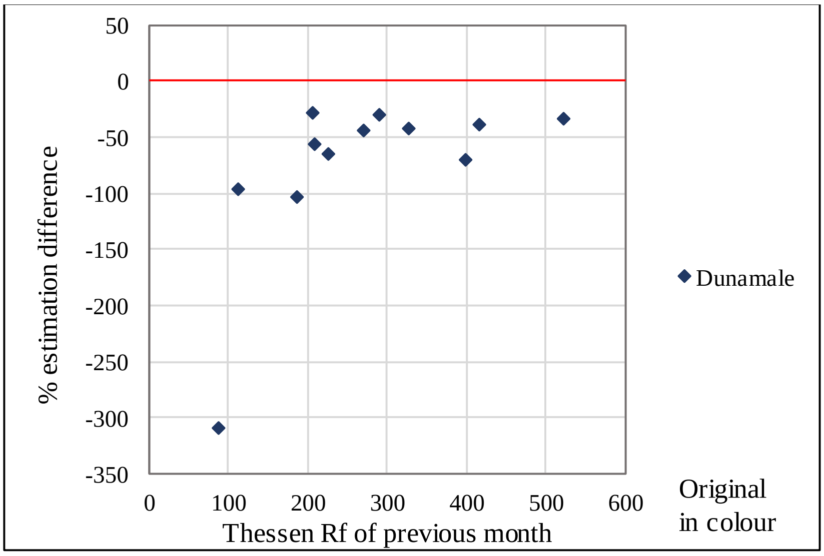


Figure 5-66: Average estimation difference % of yield with RF of previous month – HEC with thresholds – Dunamale watershed

5.4.6 HEC- HMS Model (HEC) - Ellagawa Watershed

Monthly, seasonal and annual HEC model results were analysed. Monthly variation of model results are presented in Figure 5-67 and Table 5-48. Results show that in most of the years model results are higher than the observed yield. Hydrograph of Figure 5-68 shows a time lag in HEC model estimations.

5.4.6.1 HEC model Results

Monthly yield comparison for the PoR is showed in Figure 5-68. Figure 5-69 and Figure 5-70 presents FDC for Period of Record and annual FDC respectively. FDC variations indicate that model over estimates the flow in all high, medium, low flows. The percentage of over estimation is less in high flows. Annual FDC variation in Figure 5-70 shows that the over estimation is less in both high flows and low flows.

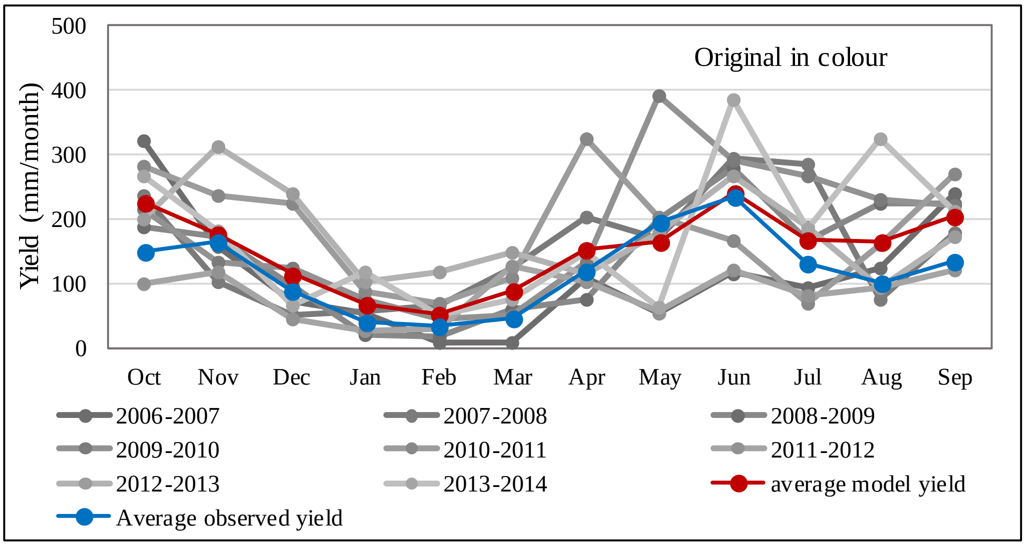


Figure 5-67: Monthly yield variation - HEC model - Ellagawa watershed

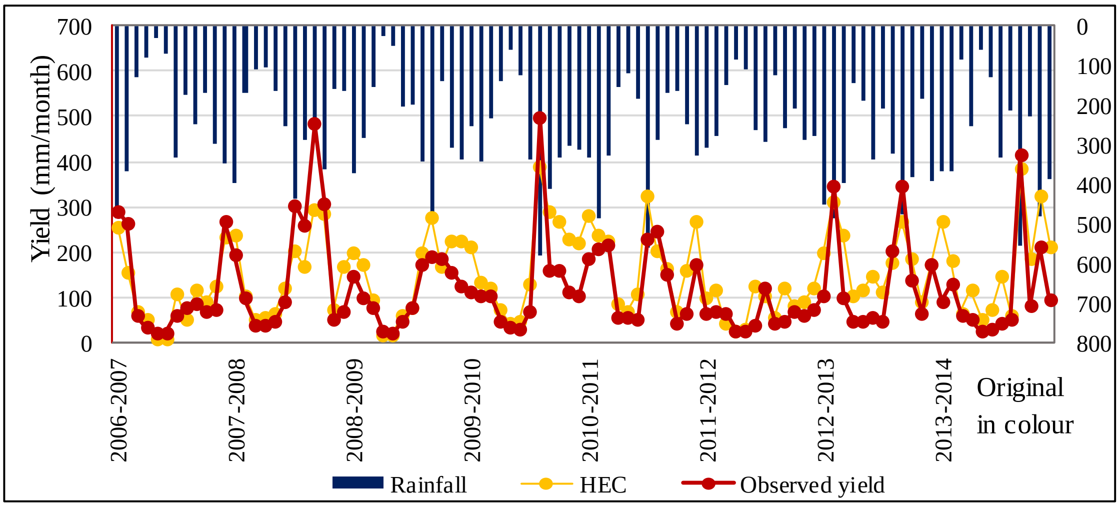


Figure 5-68: Thiessen Average Rainfall, Observed and HEC monthly yield for Ellagawa Watershed

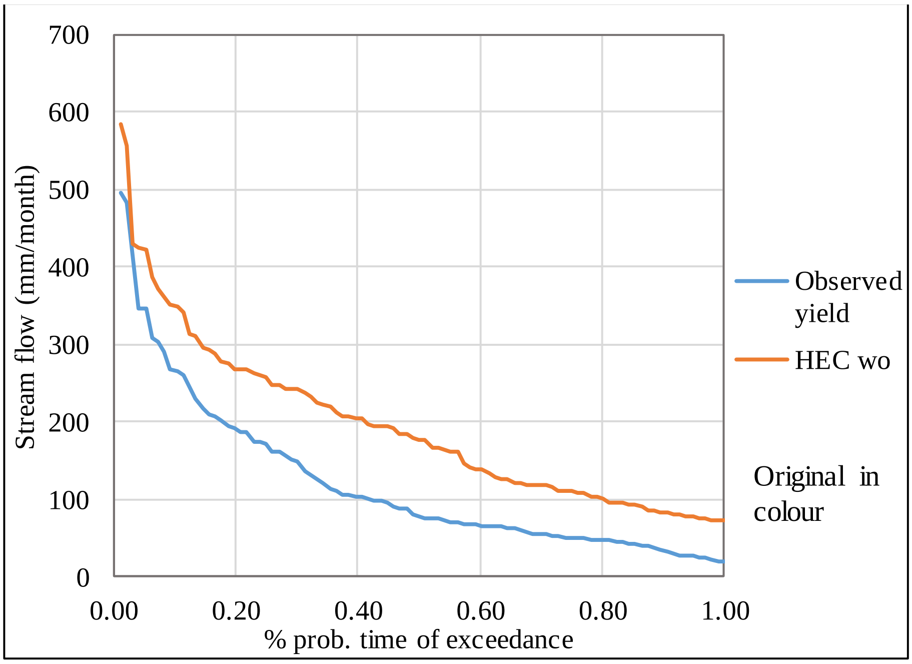


Figure 5-69: Monthly PoR FDC for Ellagawa Watersheds HEC model

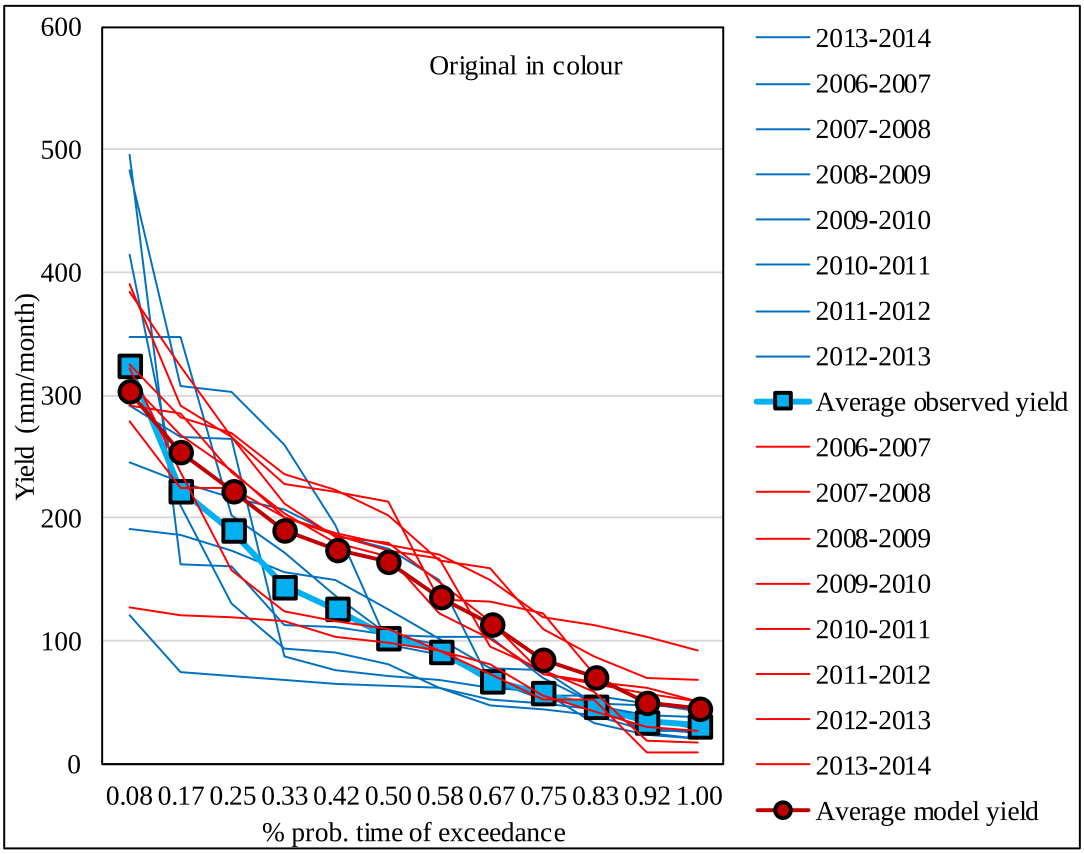


Figure 5-70: Annual FDC of HEC model monthly streamflow - Ellagawa Watershed

Table 5-48: Monthly, seasonal and annual yield variation (mm) – HEC-HMS– Ellagawa watershed

Year	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Maha**	**Yala**	**annual**
2006-2007	321.3	157.1	72.7	52.9	9	8.5	109	52.2	115.7	91.6	123.4	238	621.5	729.9	1351.4
2007-2008	237.1	101.8	50.6	57.2	65.8	122.2	203.7	169.5	292.4	285.7	73.3	179.3	634.7	1203.9	1838.6
2008-2009	186.9	173	96.1	19	17.6	58.8	76	200.5	278.5	166.7	224.7	223.8	551.4	1170.2	1721.6
2009-2010	213.9	133	122.3	73.7	44.9	49.5	131.6	389.8	291.5	266.5	228.4	220.8	637.3	1528.6	2165.9
2010-2011	282.1	235.7	222.9	86.9	69.4	109.1	325.1	202.3	166	68.1	158.6	269.5	1006.1	1189.6	2195.7
2011-2012	98.1	116.5	42.9	26.7	30.1	127.3	102.8	55	121	80.4	92.5	119.9	441.6	571.6	1013.2
2012-2013	200.5	311.5	239.4	103.2	118.6	148.9	112.8	178	267.4	187.2	92.7	171.1	1122.1	1009.2	2131.3
2013-2014	266.8	179.7	66.8	116.6	51.1	73.6	147.3	62.2	383.9	185.3	323.2	212.2	754.6	1314.1	2068.7
average	225.84	176.04	114.21	67.03	50.81	87.24	151.04	163.69	239.55	166.44	164.60	204.33	721.16	1089.64	1810.80

5.4.6.2 Comparison of Numerical Indicators

Figure 5-71 and Table 5-49 shows the seasonal and annual water balance error. Seasonal and annual water balance error shows that all the years after 2007-2008, model over estimates the yield. In 2006-2007 Maha and 2007-2008 Yala and annual yield values are lower than the observed yield. The variation shows the need of applying thresholds for estimation of yield by using HEC-HMS model for Ellagawa watershed. Numerical indices are presented in Table 5-50.

Table 5-49: Seasonal and Annual Water Balance Difference HEC - Ellagawa

		Water balance difference in mm	
Year	**Water Balance Difference-Maha**	**Water Balance Difference-Yala**	**Water Balance Difference-Annual**
2006-2007	69.79	-98.12	-28.33
2007-2008	-128.90	272.67	143.78
2008-2009	-129.36	-260.83	-390.19
2009-2010	-202.09	-424.99	-627.09
2010-2011	-236.23	-279.57	-515.80
2011-2012	-148.30	-154.51	-302.81
2012-2013	-420.78	-39.03	-459.81
2013-2014	-368.18	-416.98	-785.16
Average	-195.51	-175.17	-370.68

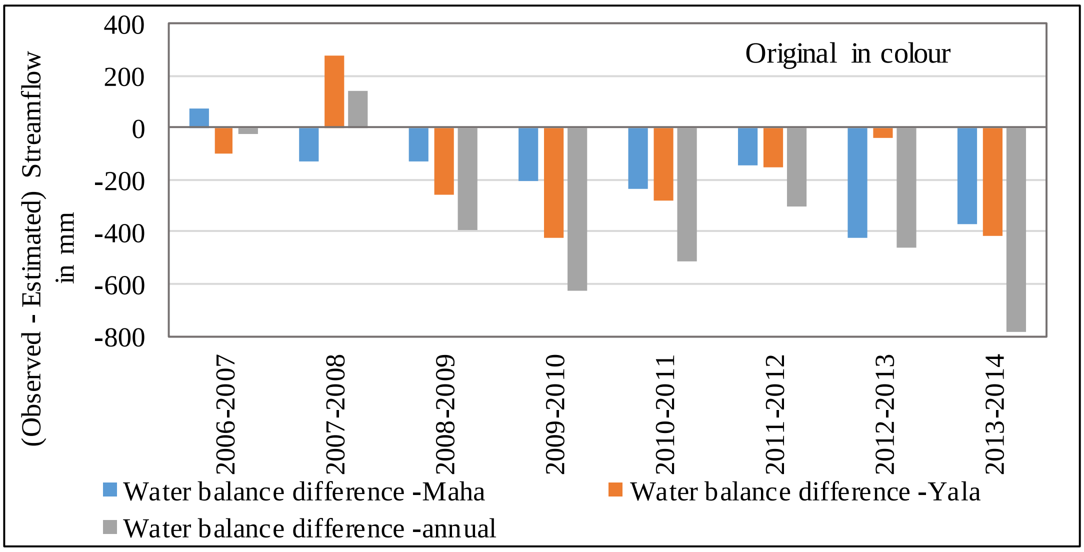


Figure 5-71: Seasonal and annual water balance difference HEC - Ellagawa

Table 5-50: Numerical indicators of HEC-HMS model estimations - Ellagawa basin

Numerical Indicators	**Ellagawa Watershed**
Average Annual Water Balance Error (mm)	-370.68
Average Maha Season Water Balance Error (mm)	-195.51
Average Yala Season Water Balance Error (mm)	-175.17
Percentage error of annual average runoff coefficient	-25.74
MRAE overall hydrograph	0.58
MRAE PoR FDC	0.57
MRAE Annual FDC	0.51

5.4.6.3 Comparison Ellagawa Watershed

5.4.6.3.1 Effect of Yield Thresholds

Figure 5-72 and 5-73 show monthly, seasonal and annual hydrographs.

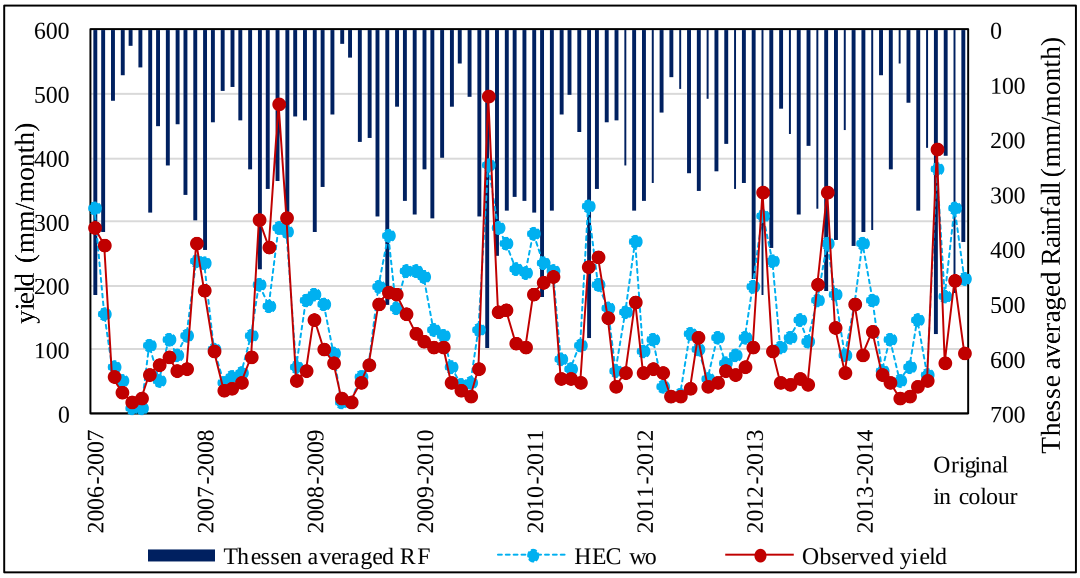


Figure 5-72: Comparison of Average Monthly Observed and Modelled Yield Values with Average Thiessen Rainfall – Ellagawa watershed (2006/2007-2013/2014)

Considering hydrograph variation, it is clear that observed yield of Yala season in 2007-2008 shows an unacceptable variation. This was noticed during data checking (chapter 4) and this data inconsistency might be the reason. Observing the yield variation of other years, it is clear that HEC model estimates show a pattern closer to that of observed streamflow values. The need of a correction factor is evident from the flow variations.

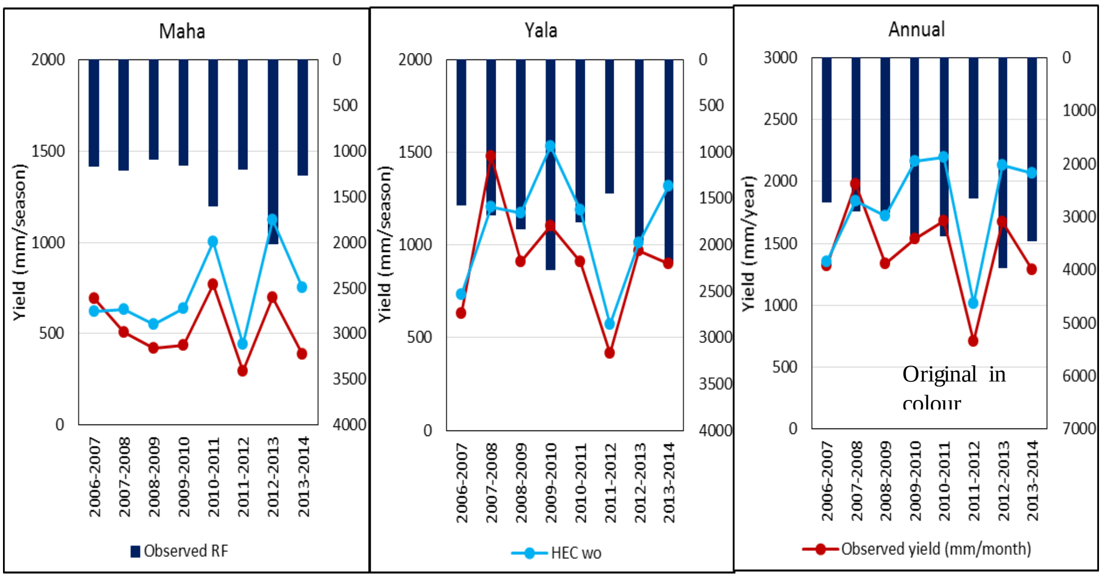


Figure 5-73: Seasonal and annual HEC model yield comparison - Ellagawa watershed

5.4.6.3.2 Hydrograph Comparison

Figure 5-74 and Table 5-52 show the percentage estimation difference of model yield relative to observed yield.

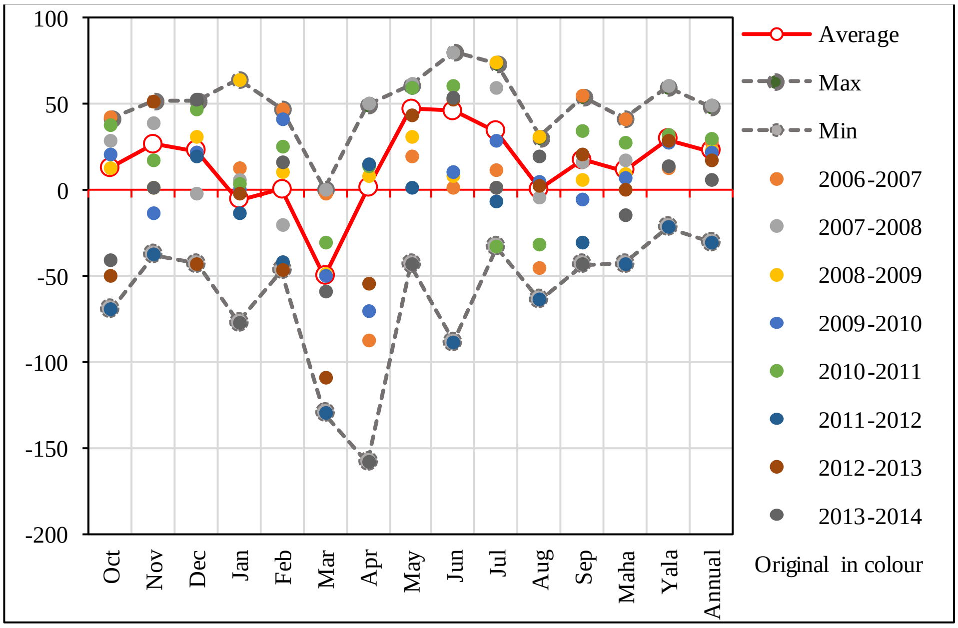


Figure 5-74: Monthly, Seasonal and Annual PDSE_HEC – Ellagawa Watershed

Table 5-51: Average Monthly, Seasonal and Annual PDSE_HEC – Ellagawa Watershed

#	**Average yield % relative to observed yield**
Oct	-51.2
Nov	-6.4
Dec	-27.2
Jan	-63.7
Feb	-47.1
Mar	-91.8
Apr	-26.8
May	15.5
Jun	-1.8
Jul	-26.5
Aug	-65.4
Sep	-51.1
Maha	-37.2
Yala	-19.2
Annual	-25.7

Monthly, seasonal and annual PDSE of HEC model with thresholds show that except May, all the other months, model on average over estimates the Maha season flow by 37% and Yala season flow by 19%. Annual average over estimation of the model yield is 25%. Hence, the need of a correction factor for rational applications.

5.4.6.3.3 Duration Curve Comparison

Variation of PDSE_IGM values corresponding to the annual flow duration curves are shown by the Figure 5-75 and Table 5-52. The flow duration curve matching of each year clearly shows that in most of the years the high flow periods corresponding to the time of exceedance values below 60% had varied in between 0 to -100. After 60% of time of exceedance, the graph shows a steep slope and higher over estimation of model yield. The minimum values reflect the deviations due to missing and questionable data.

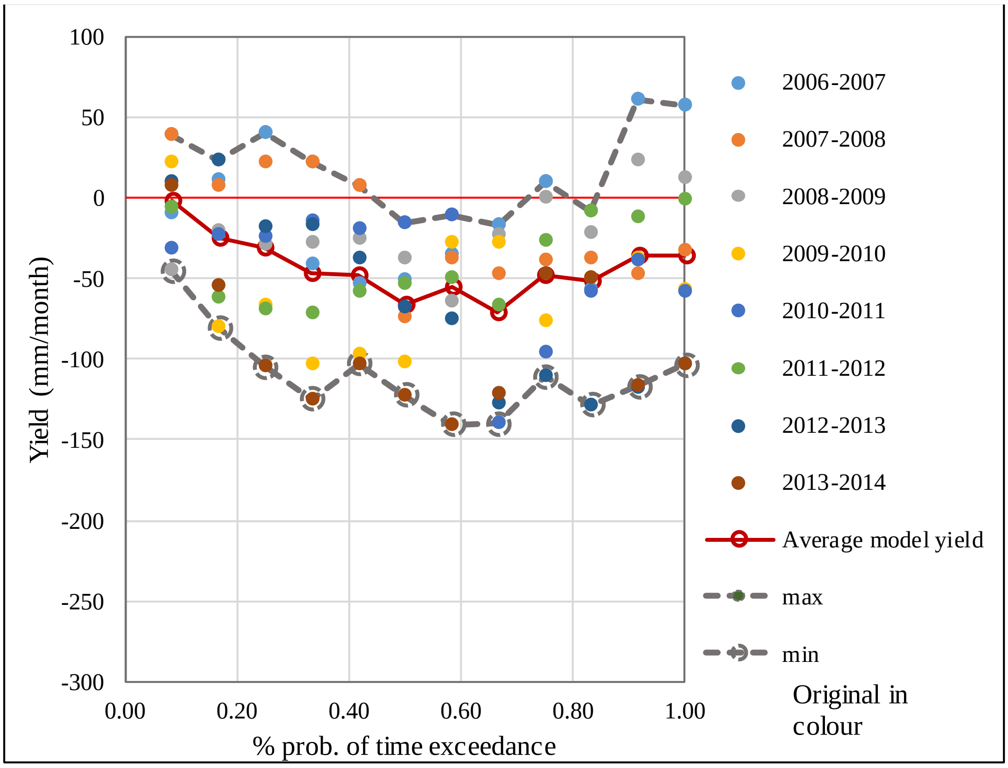


Figure 5-75: PDSE_HEC values and % Time of Exceedance for HEC-HMS model – Ellagawa Watershed

Table 5-52: Average PDSE_HEC values and % Time of Exceedance for HEC-HMS model – Ellagawa Watershed

% of time exceedance	**average model yield**
0.08	-1.83
0.17	-24.76
0.25	-31.26
0.33	-47.07
0.42	-48.28
0.50	-65.58
0.58	-55.28
0.67	-71.29
0.75	-48.18
0.83	-51.02
0.92	-35.72
1.00	-35.83

5.4.6.3.4 Evaluation Summary Ellagawa watershed

On average, HEC Model estimates in Maha and Yala seasons are 37.2% and 19.2% higher than the observed streamflow of Ellagawa watershed. However, both monthly averages from hydrograph analysis and duration curve comparisons indicate that low flows are highly over estimated. A comparison of the average yield estimation error in each month with the average Thiessen rainfall of the previous month indicated that an approximate average antecedent rainfall value shows a threshold between under estimation and over estimation (Figure 5-76).

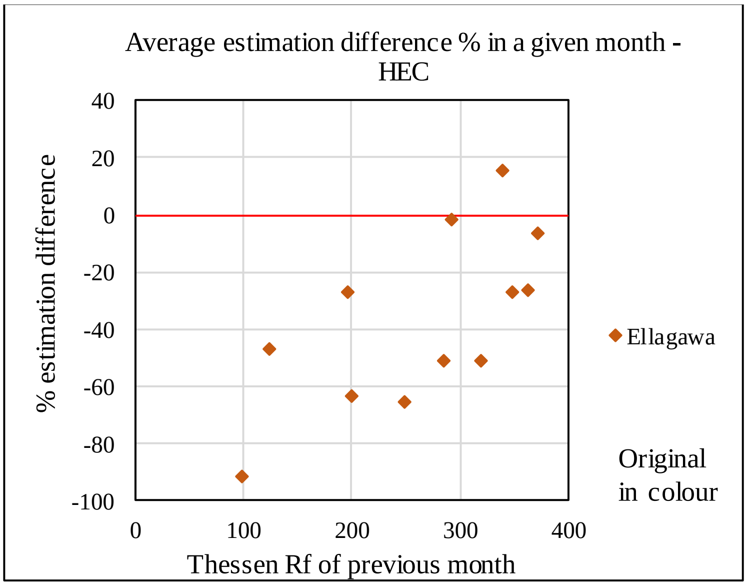


Figure 5-76: Average estimation difference % of yield with RF of previous month – HEC- HMS– Ellagawa basin

5.4.7 Unit Hydrograph Model (UH)- Dunamale Watershed

5.4.7.1 UH Model application

UH model results were analysed using monthly, seasonal and annual temporal resolutions. Monthly variation of UH model streamflow estimation is presented in Figure 5-77, 5-78 and Table 5-53. Results show that throughout the study period model estimates are higher than the observed watershed yield.

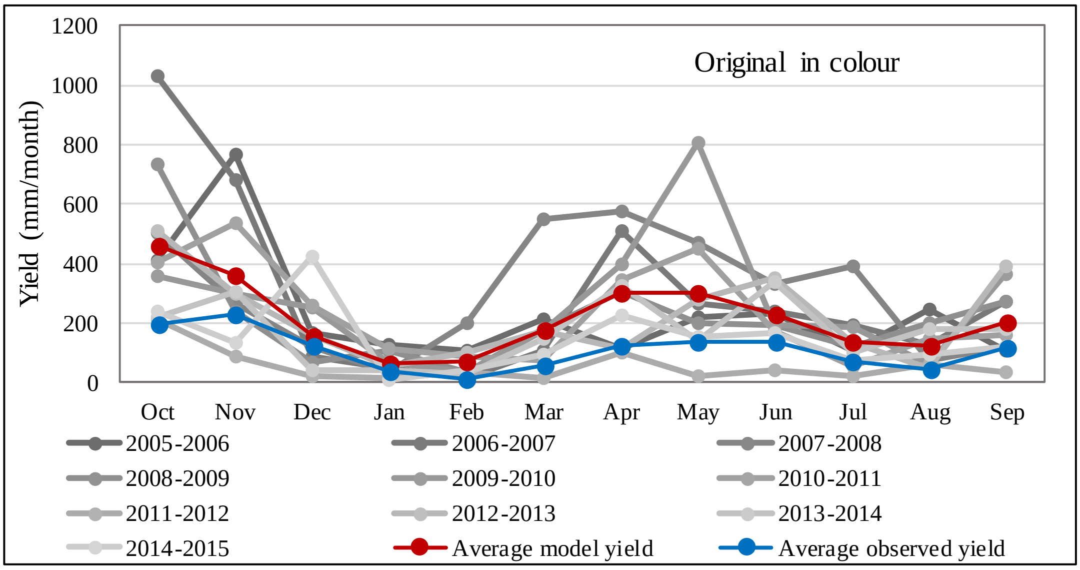


Figure 5-77: Monthly yield variation – UH without thresholds - Dunamale watershed

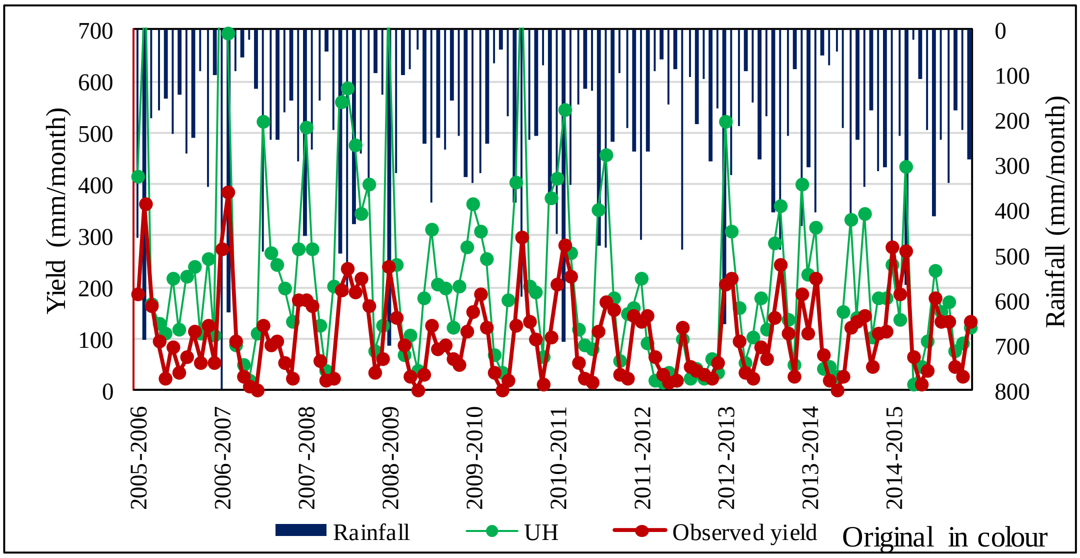


Figure 5-78: Thiessen average rainfall, observed and UH monthly yield for Dunamale watershed

Table 5-53: Monthly, seasonal and annual yield variation (mm) –UH - Dunamale watershed

Year	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Maha**	**Yala**	**annual**
2005-2006	408.2	767.8	165.6	126.8	107.3	214.6	116.7	217.9	235.9	110.3	249.2	104.9	1790.3	1034.9	2825.2
2006-2007	1033.3	680.5	87.9	50.3	18.6	109.3	511.8	263	238.3	195.5	130.3	270.6	1979.9	1609.5	3589.4
2007-2008	500.7	267.8	122.7	38	197.1	549.3	575.4	467.3	334.9	391.3	75.5	123.4	1675.6	1967.8	3643.4
2008-2009	736.7	238.5	66.2	104.8	36.3	177.5	307.8	202.1	192.7	120.9	197.4	271.3	1360.0	1292.2	2652.2
2009-2010	356.8	301.4	249.7	67.3	34.1	172.2	394.7	807	196.4	187.4	62.8	365	1181.5	2013.3	3194.8
2010-2011	403.1	534.7	262.2	115.2	87.3	77.5	342	449.9	175.1	56.8	147.8	159.1	1480.0	1330.7	2810.7
2011-2012	214.8	88.8	19.1	13.8	34.1	17.9	99.4	21.3	43	22.2	59.7	35.8	388.5	281.4	669.9
2012-2013	511.2	301.3	157.9	52.8	101.2	175.3	115.1	280.2	351.6	135.8	50	394	1299.7	1326.7	2626.4
2013-2014	221.8	308.3	39.9	43.7	27.6	149.9	325.7	139.3	338	100.8	177.4	177.6	791.2	1258.8	2050.0
2014-2015	239	135.1	426.1	10.3	44.9	94.3	229.4	151.6	166.6	75.9	91.2	118.5	949.7	833.2	1782.9
average	462.56	362.42	159.73	62.30	68.85	173.78	301.80	299.96	227.25	139.69	124.13	202.02	1289.64	1294.85	2584.49

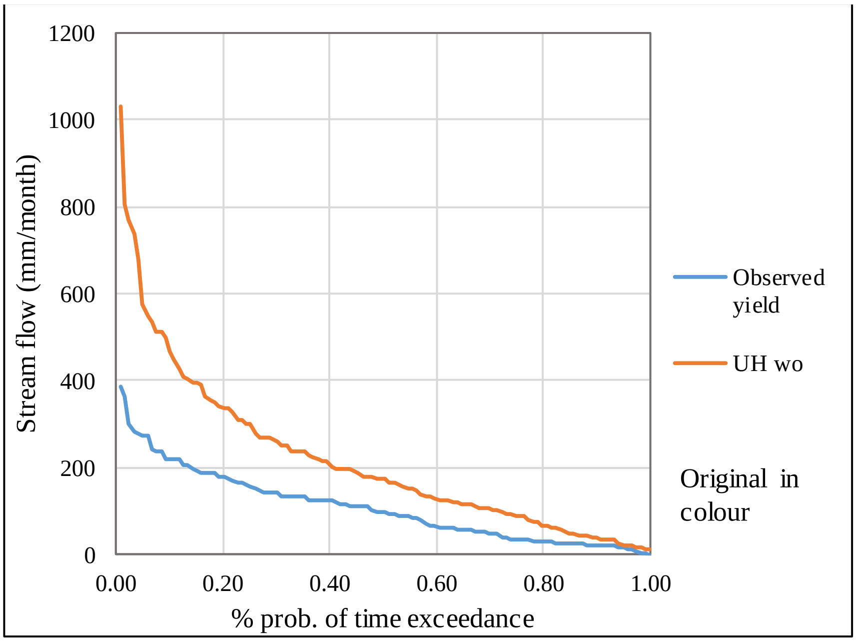


Figure 5-79: Monthly PoR FDC for UH Dunamale Watershed

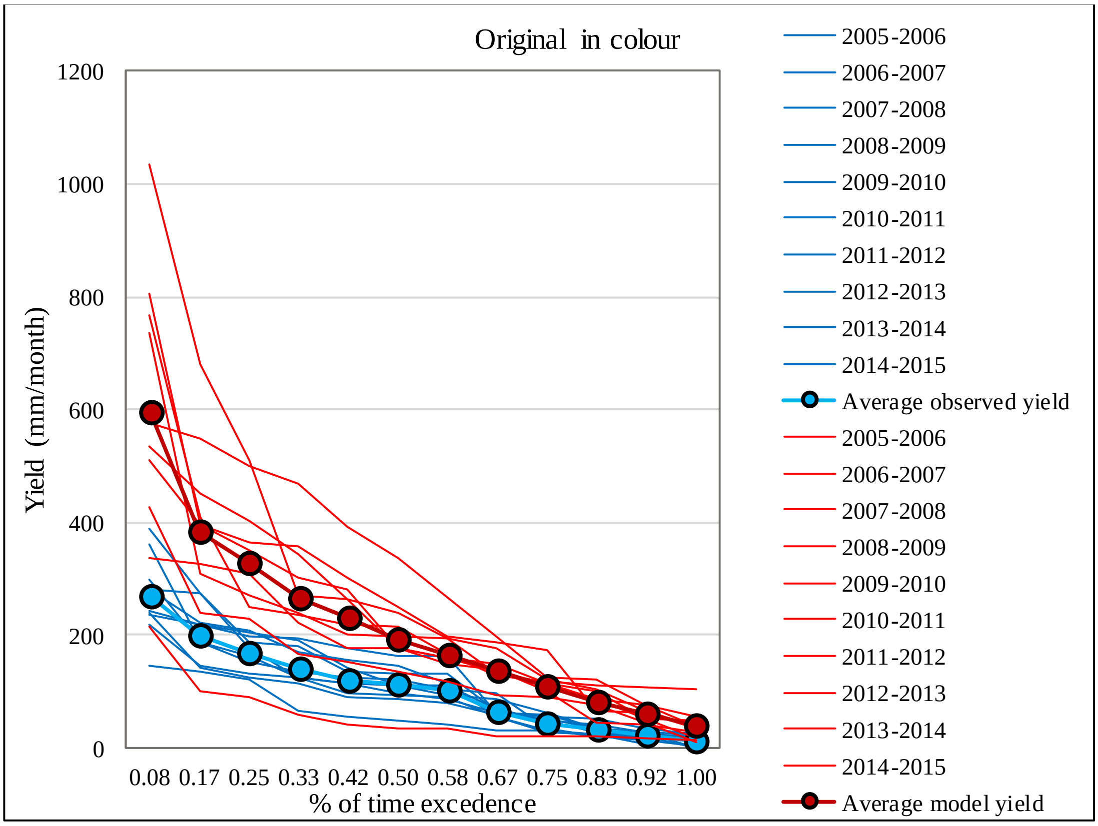


Figure 5-80: Annual FDC of monthly streamflow for UH model- Dunamale Watershed

FDC for PoR and Annual FDC of monthly streamflow are presented in Figure 5-79 and 5-80. Results indicate that UH model yield is higher than observed yield for all high, medium and low flows. The difference between model yield and observed yield is approximately 2.5 times higher for high flows. Figure 5-81 and Table 5-54 represents the seasonal and annual water balance difference for UH model.

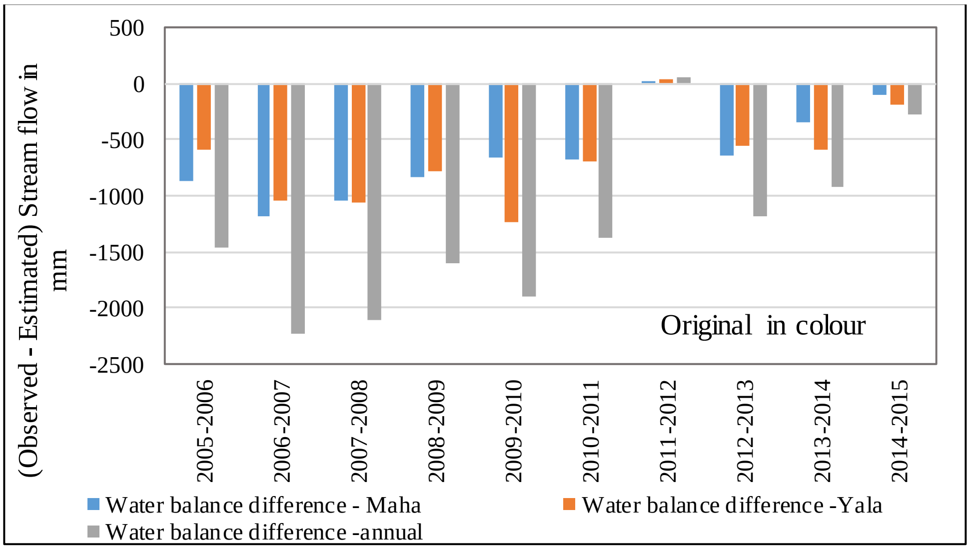


Figure 5-81: Seasonal and Annual Water Balance Difference UH – Dunamale

Table 5-54: Seasonal and Annual Water Balance Difference UH - Dunamale

	water balance in mm		
	Water Balance Difference-Maha	**Water Balance Difference-Yala**	**Water Balance Difference-Annual**
2005-2006	-869.39	-587.79	-1457.18
2006-2007	-1185.91	-1042.63	-2228.54
2007-2008	-1038.01	-1061.91	-2099.92
2008-2009	-829.11	-776.36	-1605.47
2009-2010	-662.55	-1242.13	-1904.68
2010-2011	-675.46	-694.94	-1370.40
2011-2012	22.50	36.17	58.67
2012-2013	-636.85	-550.21	-1187.06
2013-2014	-344.53	-583.02	-927.55
2014-2015	-93.81	-178.96	-272.77
average	204.3	305.9	510.1

5.4.7.1 Comparison of Numerical Indicators

UH model over estimates streamflow except in water year 2011/2012 which is a dry year with data inconsistencies. The results clearly show the need to apply yield thresholds for UH model for design yield estimation. Numerical indicators of estimated streamflow by UH model for Dunamale watershed is in Table 5-55.

Table 5-55: Numerical Indicators of IGM Model Estimations - Dunamale basin

Numerical indicators	**Dunamale Watershed**
Average Annual Water Balance Error (mm)	-1299.49
Average Maha Season Water Balance Error (mm)	-631.31
Average Yala Season Water Balance Error (mm)	-668.18
Percentage error of annual average runoff coefficient	-101.13
MRAE overall hydrograph	2.52
MRAE PoR FDC	2.51
MRAE Annual FDC	2.325

5.4.7.1 Comparison – Dunamale Watershed

Monthly, seasonal and annual variation of UH model yield estimations were compared with the observed rainfall and observed streamflow (Figure 5-83and 5-84). UH model results show significant over estimations when compared with observed yield. In the water year 2011/2012 both estimations are close to each other. Model yield is approximately twice the observed yield. Hence, there is a need to apply thresholds for rational model applications.

5.4.7.1.1 Effect of Yield Thresholds

Figure 5-82, Figure 5-83 and Table 5-56 shows the percentage difference relative to observed yield for UH.

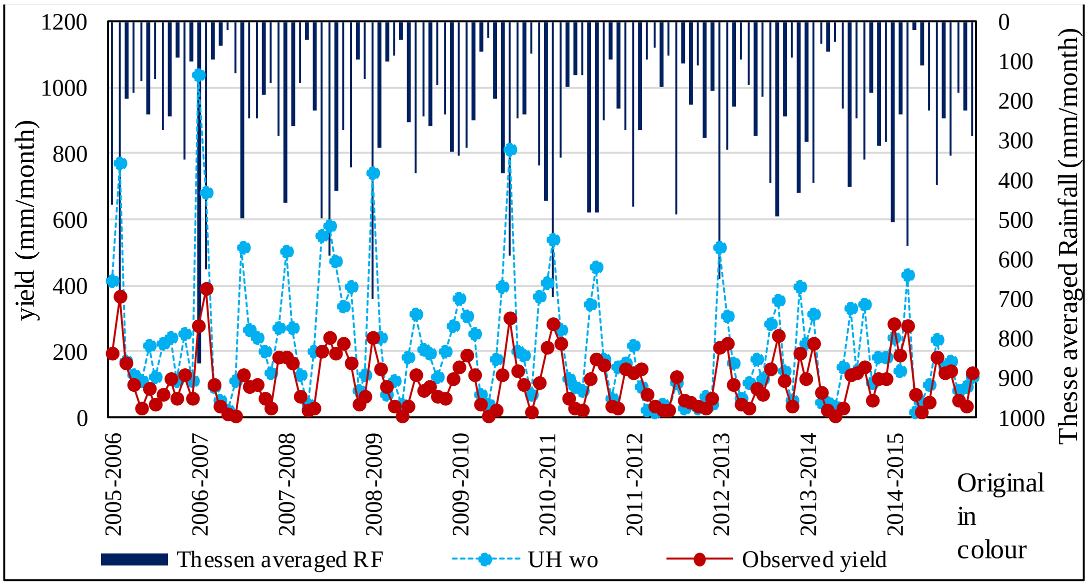


Figure 5-82: Comparison of average monthly observed and modelled yield values with average thiessen rainfall (2005/2006-2014/2015)

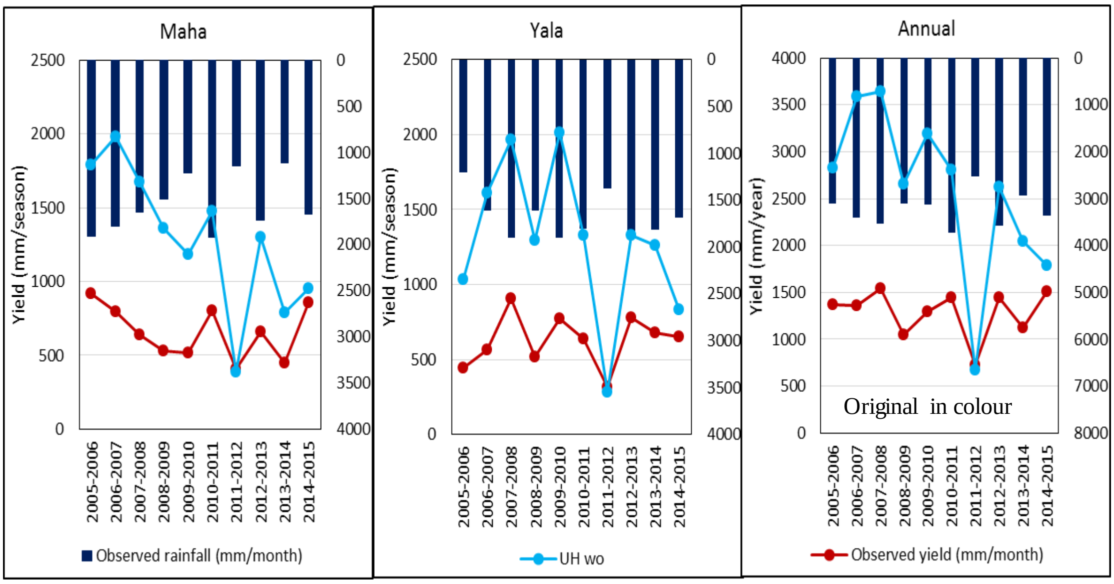
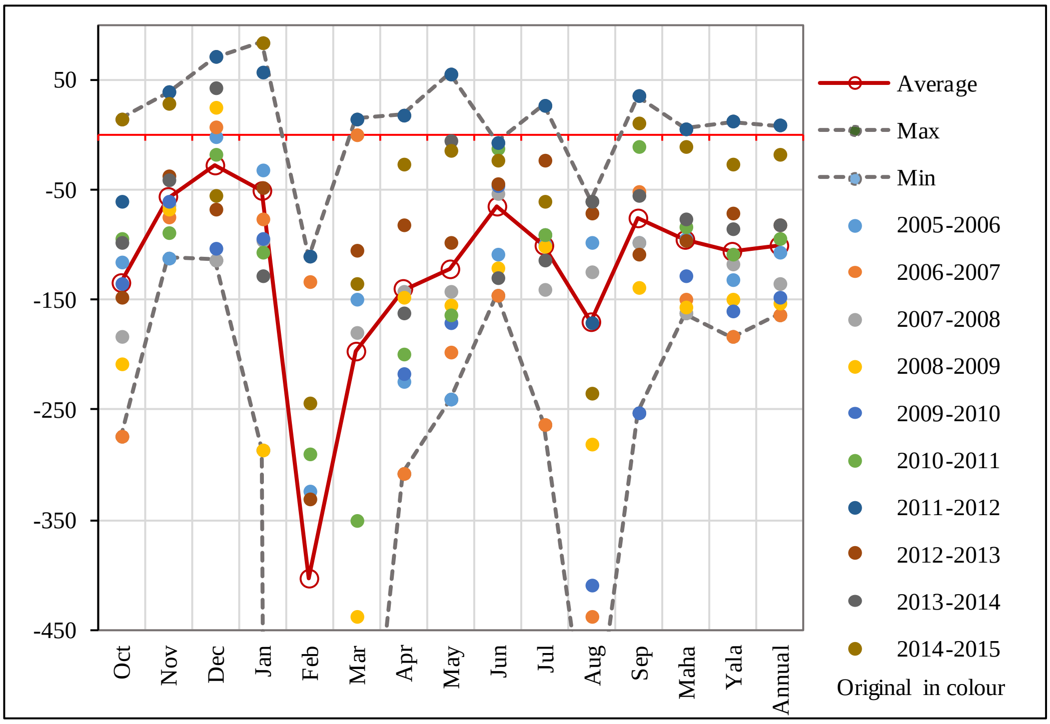


Figure 5-83: Maha, Yala and annual yield comparison- uh model - Dunamale watershed

5.4.7.1.2 Hydrograph Comparison

Monthly, Seasonal and Annual PDSE between UH model estimates and observed yield of UH model (Figure 5-84, Table 5-56) shows that during February and August months, model highly over estimates the streamflow. In all other months model averagely over estimation is comparatively low. Average over estimation of Maha season is 96%, in Yala season the sasme is 107%. Annual average over estimation is very high at 101%.



Original in colour

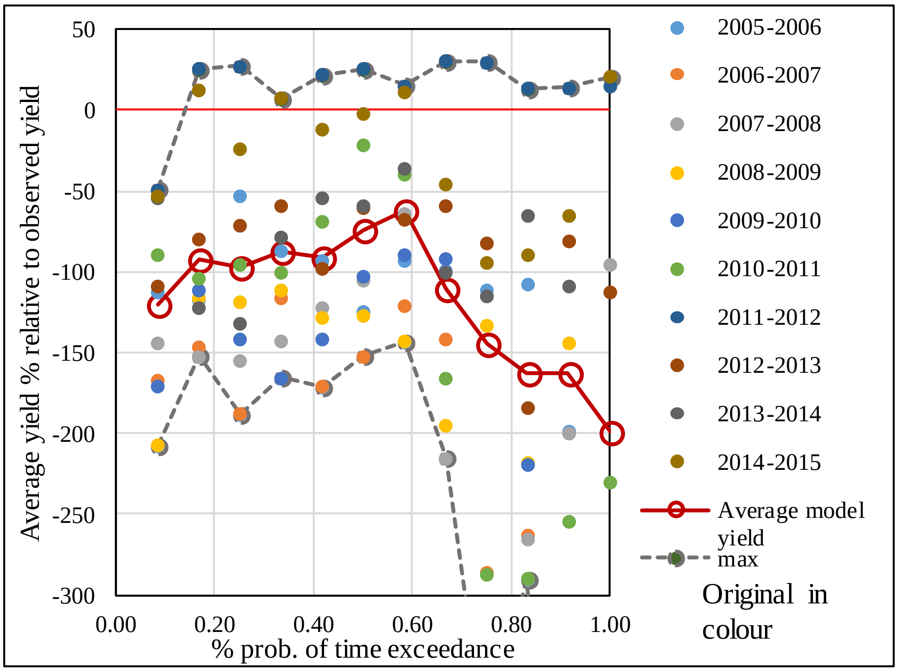
Figure 5-84: Monthly, seasonal, annual PDSE_UH- Dunamale watershed

Table 5-56: Average Monthly, Seasonal and Annual PDSE_UH – Dunamale Watershed

#	**Average yield % relative to observed yield**
Oct	-135.1
Nov	-58.1
Dec	-28.0
Jan	-51.1
Feb	-403.7
Mar	-197.5
Apr	-141.6
May	-122.4
Jun	-65.8
Jul	-101.5
Aug	-170.6
Sep	-76.3
Maha	-95.9
Yala	-106.6
Annual	-101.1

5.4.7.1.3 Duration Curve Comparison

Variation of PDSE_UH values corresponding to the annual flow duration curves are shown by the Figure 5-85 and Table 5-57.



Original in colour

Figure 5-85: PDSE_UH values and % Time of Exceedance – Dunamale Watershed

Table 5-57: Average PDSE_UH values and % Time of Exceedance – Dunamale Watershed

% Probability of time exceedance	**Average model yield % relative to observed yield**
8%	-120.76
17%	-92.04
25%	-96.86
33%	-87.37
42%	-90.78
50%	-74.30
58%	-61.87
67%	-110.51
75%	-144.20
83%	-163.24
92%	-162.64
100%	-198.53

The flow duration curve matching of each year clearly shows that in most of the years the high flow periods corresponding to the time of exceedance values below 60% had varied in between 0 to -120. After 60% graph shows a steep slope and higher over estimation of model yield. The larger minimum values reflected the presence of missing and questionable data.

5.4.7.1.4 Evaluation Summary – Dunamale Watershed

On average, HEC Model estimates in Maha and Yala seasons are 96% and 106% higher than the observed streamflow of Dunamale watershed. However, both monthly averages from hydrograph analysis and duration curve comparisons indicate that low flows are highly over estimated. A comparison of the average yield estimation error in each month with the average Thiessen rainfall of the previous month indicated that an approximate average antecedent rainfall value over estimates the model yield. (Figure 5-86).

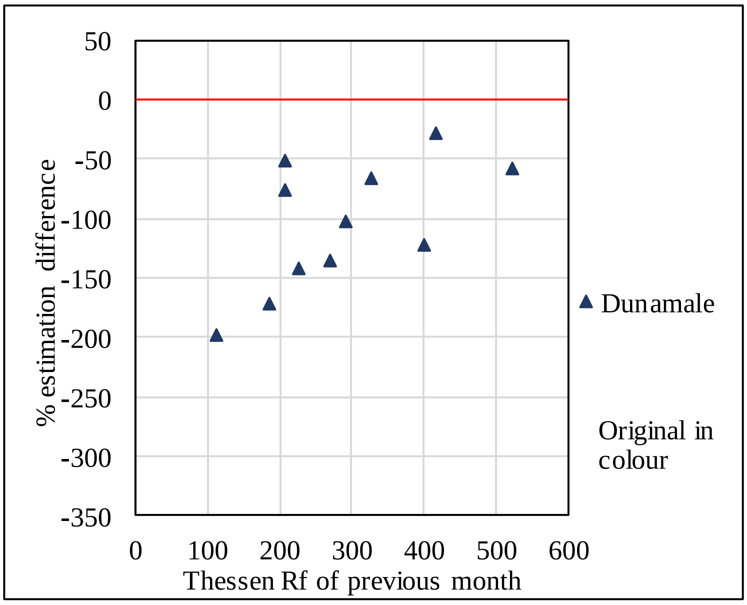


Figure 5-86: Average estimation difference % for AMC conditions - Dunamale watershed

5.4.8 Unit Hydrograph Model (UH) - Ellagawa Watershed

5.4.8.1 UH model application

UH model results were analysed at monthly, seasonal and annual temporal resolutions. Monthly variation of UH model results of Ellagawa watershed is presented in Figure 5-87. 5-88 and Table 5-59. Results show that in almost all years model results are in the same range of the observed yield.

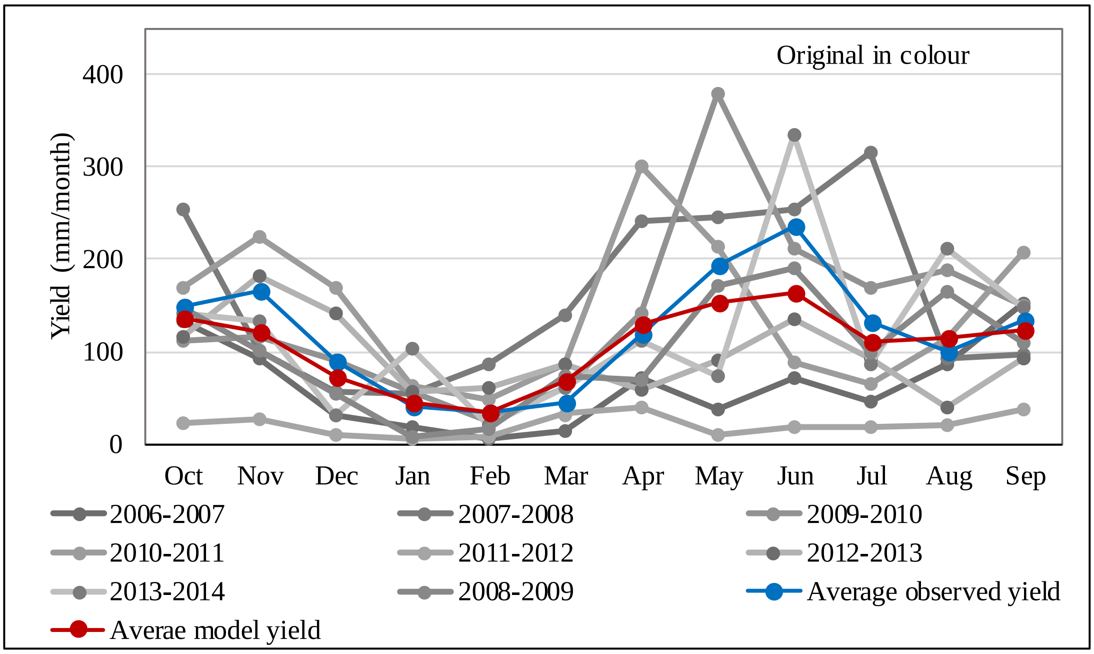


Figure 5-87: Monthly yield variation - Irrigation model - Ellagawa watershed

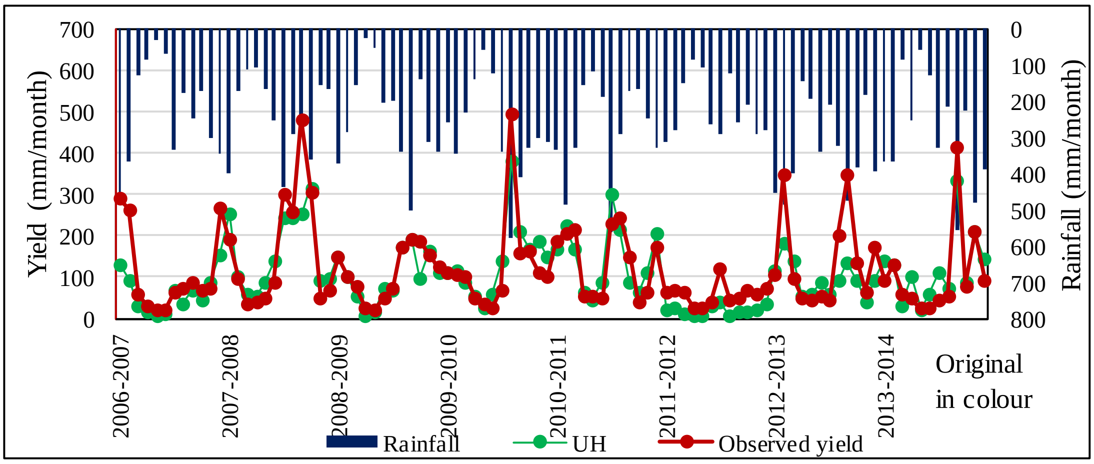


Figure 5-88: Thiessen Average Rainfall, Observed and UH monthly yield for Ellagawa Watershed

Table 5-58: Monthly, seasonal and annual yield variation (mm) – UH – Ellagawa watershed

Year	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Maha**	**Yala**	**annual**
2006-2007	132.7	92.4	31	17.9	6.3	14.6	71.3	37.3	71.2	45.4	86.1	152.8	294.9	464.1	759.0
2007-2008	253.5	101.5	57.6	54.6	86.1	140.3	242.2	245.8	254.7	315.9	92.1	97	693.6	1247.7	1941.3
2008-2009	148.8	100.7	54	8	16.5	73.2	69.5	171.7	191.1	98.7	164.1	110.6	401.2	805.7	1206.9
2009-2010	112.4	116.2	90.4	55.7	25.5	61.7	140.6	379.8	211	169.5	187.3	149.2	461.9	1237.4	1699.3
2010-2011	169.9	223.4	168.8	62.5	47.3	86.2	300.2	214.2	87.8	65.8	114	207.8	758.1	989.8	1747.9
2011-2012	23	27.3	11	6.3	8	32.3	39.1	9.1	19	18.5	21.6	36.6	107.9	143.9	251.8
2012-2013	116	182.3	141	56.8	60.6	86.5	57.9	91.5	135.9	93	40.7	93.6	643.2	512.6	1155.8
2013-2014	140.9	132.6	31.5	104	21	60.1	112.4	72.7	335.3	86	211.7	147	490.1	965.1	1455.2
average	137.2	122.1	73.2	45.7	33.9	69.4	129.2	152.8	163.3	111.6	114.7	124.3	481.4	795.8	1277.2

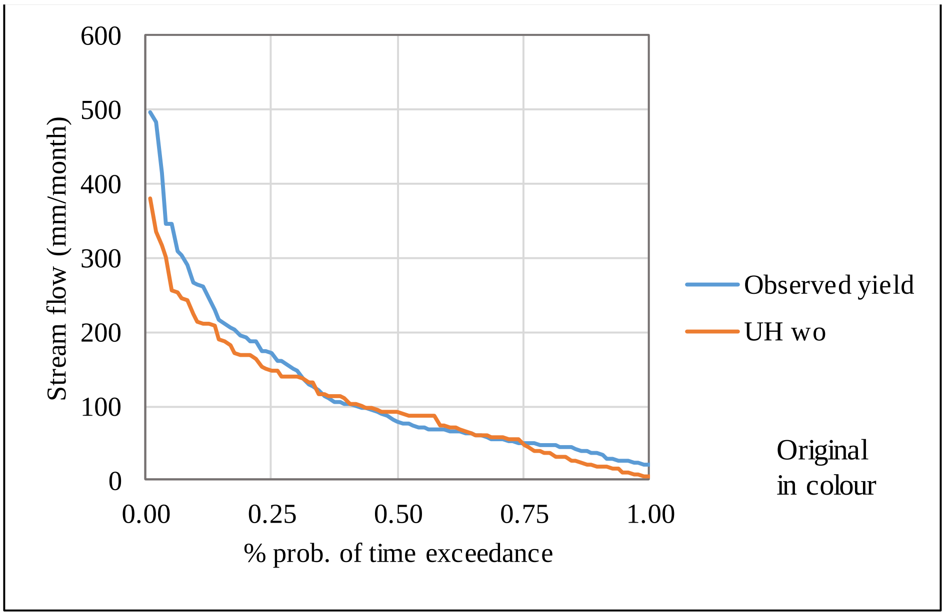


Figure 5-89: Monthly PoR FDC for Ellagawa Watershed UH model

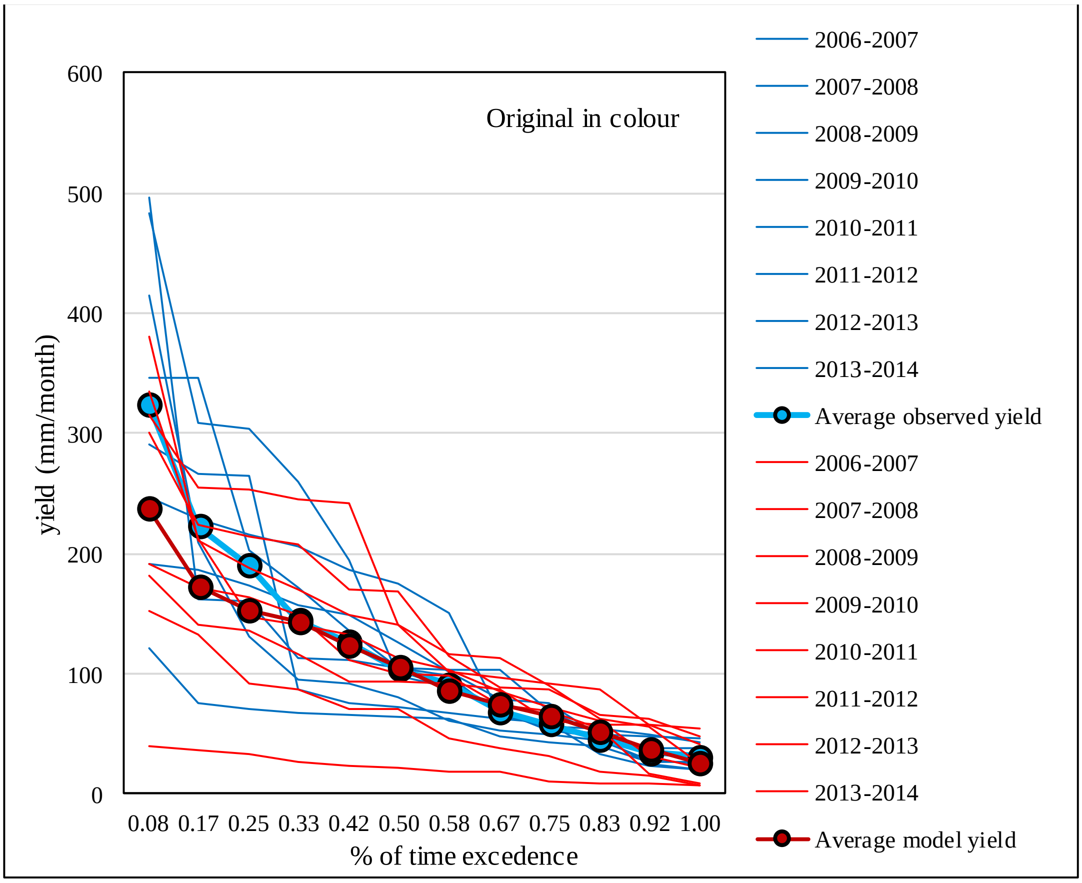


Figure 5-90: Annual FDC of monthly streamflow of UH model - Ellagawa Watershed

PoR FDC and Annual FDC of monthly streamflow are represented in Figure 5-89 and 5-90. Results show that UH model yield and observed yield are with the same order of magnitude for high, medium and low flows.

5.4.8.2 Comparison of Numerical Indicators

Figure 5-91 and Table 5-59 represents the seasonal and annual water balance difference for UH model. 2006/2007, 2008/2009, 2011/2012, 2012/2013 years received underestimated the streamflow values from UH model. In the other years, seasonal or annual over estimations could be observed.

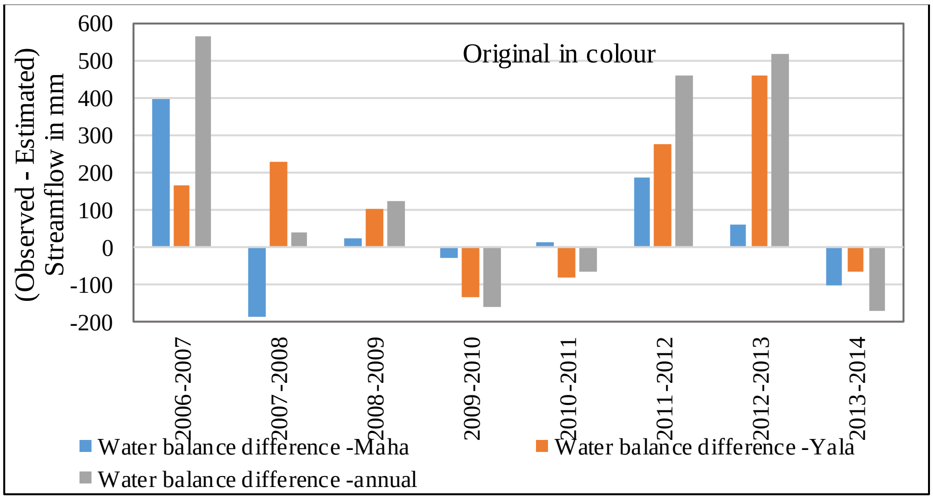


Figure 5-91: Seasonal and Annual Water Balance Difference UH - Ellagawa

Table 5-59: Seasonal and Annual Water Balance Difference UH– Ellagawa

#		Water balance difference in mm	
Year	**Water Balance Difference-Maha**	**Water Balance Difference-Yala**	**Water Balance Difference-Annual**
2006-2007	396.39	167.68	564.07
2007-2008	-187.80	228.87	41.08
2008-2009	20.84	103.67	124.51
2009-2010	-26.69	-133.79	-160.49
2010-2011	11.77	-79.77	-68.00
2011-2012	185.40	273.19	458.59
2012-2013	58.12	457.57	515.69
2013-2014	-103.68	-67.98	-171.66
Average	44.29	118.68	162.97

Table 5-60: Numerical Indicators of UH Model Estimations - Ellagawa basin

	Ellagawa Watershed
Average Annual Water Balance Error (mm)	162.97
Average Maha Season Water Balance Error (mm)	44.29
Average Yala Season Water Balance Error (mm)	118.68
Percentage error of annual average runoff coefficient	11.32
MRAE overall hydrograph	0.4
MRAE PoR FDC	0.39
MRAE Annual FDC	0.32

5.4.8.3 Comparison Ellagawa Watershed

5.4.8.3.1 Effect of Yield Thresholds

Monthly, seasonal and annual hydrograph comparison with UH model results is in Figure 5-92 and Figure 5-93.

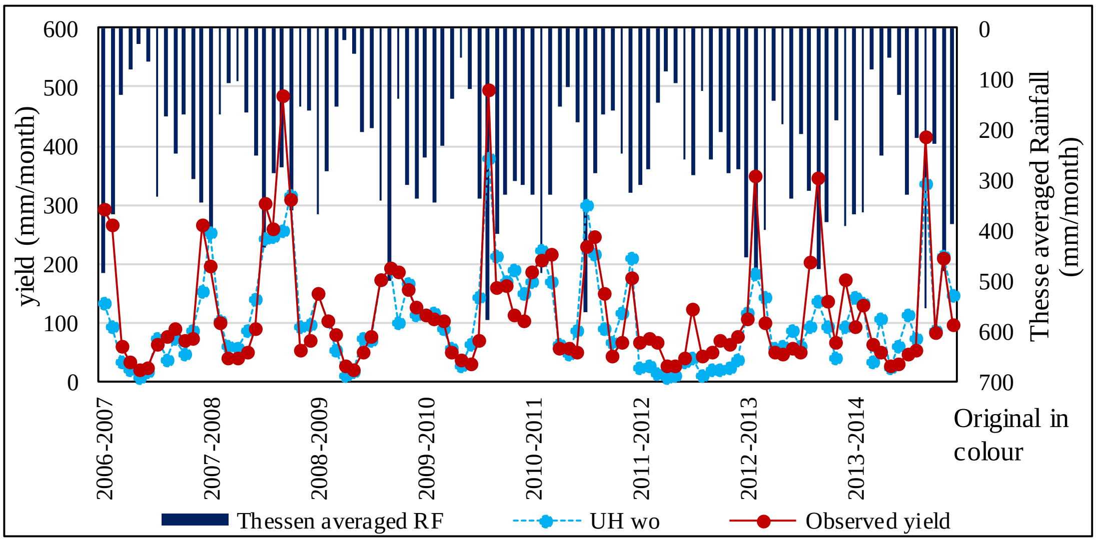
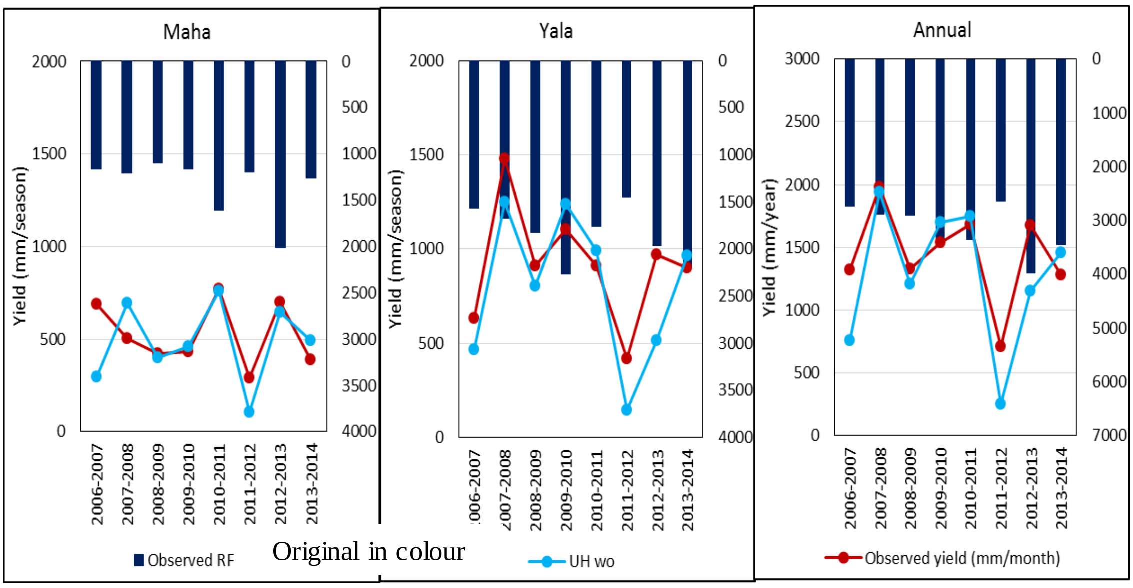


Figure 5-92: Hydrograph comparison with UH model monthly yield– Ellagawa



Original in colour

Figure 5-93: Seasonal and annual hydrograph analysis - UH model - Ellagawa

5.4.8.3.2 Hydrograph Comparison

Figure 5-94 and Table 5-61 show the percentage difference relative to observed yield for UH model.

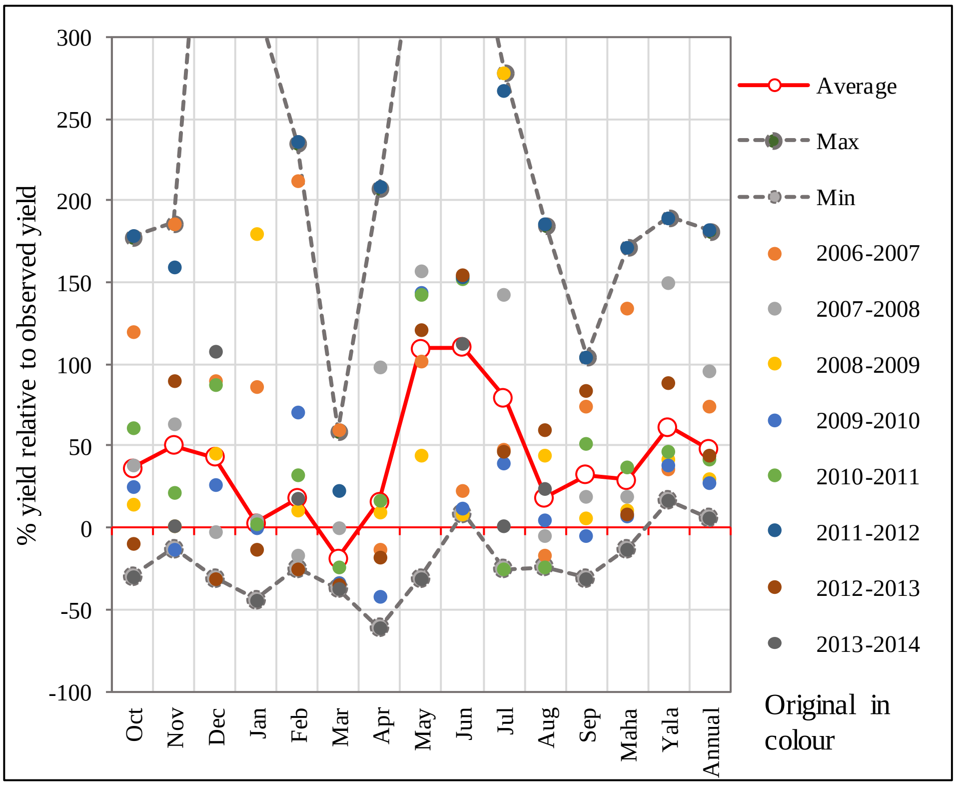


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Figure 5-94: Monthly, seasonal, annual PDSE_UH- Ellagawa watershed

Monthly, seasonal and annual PDSE of UH model show that during January, March, April, and August months the model over estimates the watershed yield, while in other months, flow is under estimated. Maximum values of UH model yield estimates are very much high and this indicates the influence of questionable data.

Table 5-61: Average Monthly, Seasonal and Annual PDSE_UH – Ellagawa watershed

#	**Average yield % relative to observed yield**
Oct	11.1
Nov	39.5
Dec	26.6
Jan	-12.0
Feb	2.1
Mar	-42.7
Apr	-9.7
May	44.3
Jun	64.3
Jul	27.3
Aug	-18.1
Sep	10.6
Maha	10.9
Yala	20.9
Annual	16.7

5.4.8.3.3 Duration Curve Comparison

Variation of PDSE_UH values corresponding to the annual flow duration curves are shown by the Figure 5-95 and Table 5-62. All average model yield values below 60% of the time exceedance are above zero. This indicates that the model under estimate the yield. When the percentage time of exceedance is higher than 60%, model values are over estimated. The average percentage of over estimation is 1.1% and the average percentage of under estimation is 10.42%.

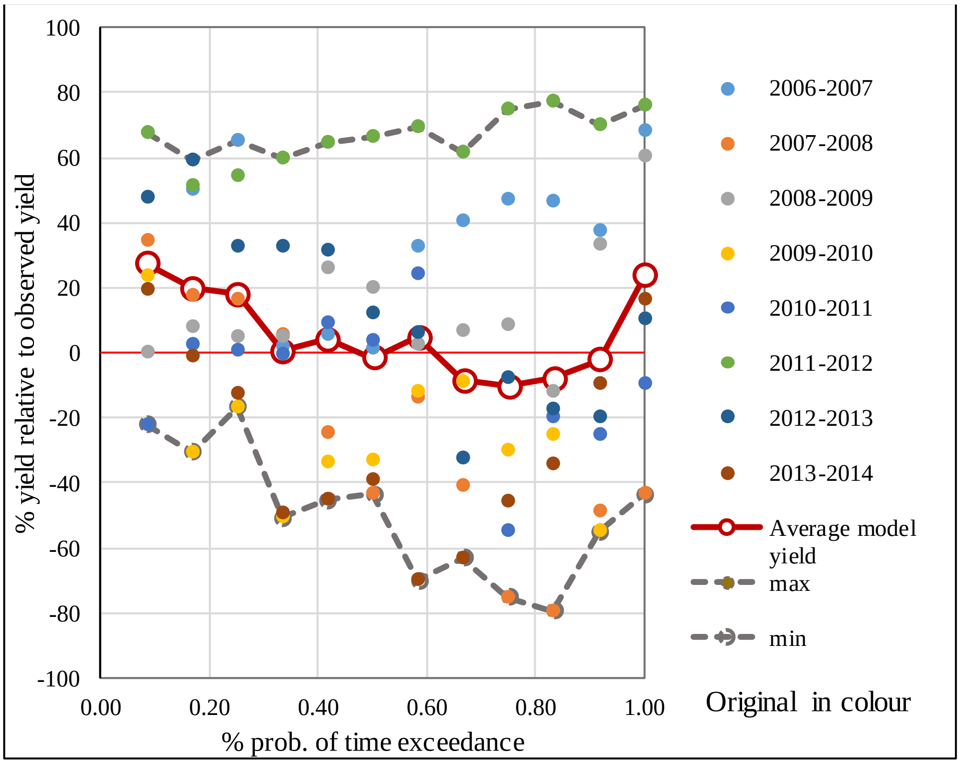

Figure 5-95: PDSE_UH values and % time of exceedance – Ellagawa watershed

Table 5-62: Average PDSE_UH values and % time of exceedance – Ellagawa watershed

% probability of time exceedance	Average % of model yield relative to observed yield
8%	27.27
17%	19.68
25%	18.13
33%	0.54
42%	4.11
50%	-1.62
58%	4.86
67%	-8.67
75%	-10.35
83%	-7.99
92%	-2.18
100%	23.61

5.4.8.3.4 Evaluation summary – Ellagawa watershed

On average, UH Model estimates in Maha and Yala seasons are 10.9% and 20.9% respectively lower than the observed streamflow of Ellagawa watershed. A comparison of the average yield estimation error in each month with the average Thiessen rainfall of the previous month indicated that an approximate average antecedent rainfall value of 270 mm/month, acts as the threshold between under estimation and over estimation (Figure 5-96).

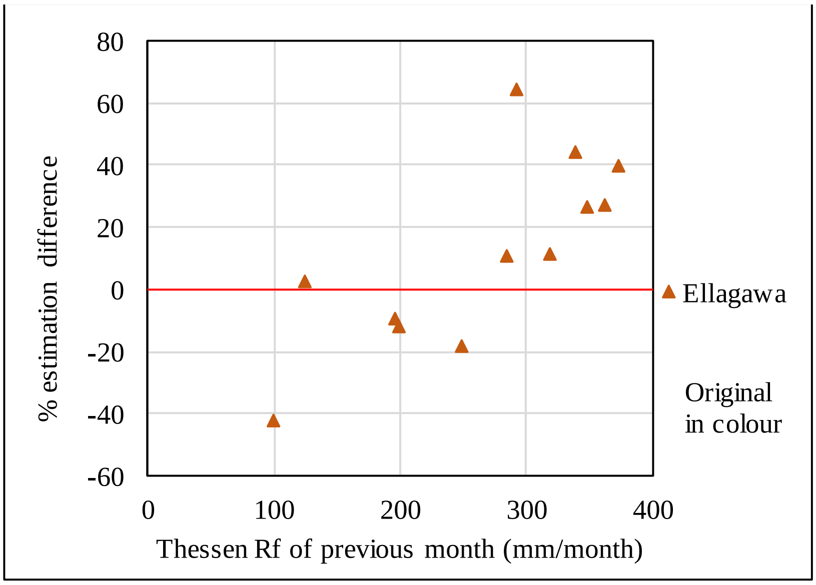

Figure 5-96: Average estimation difference % for AMC conditions - Ellagawa watershed

6 RESULTS SUMMARY

6.1 Comparison of Design Yield

Comparison of monthly yield values of IGM, HEC-HMS and UH models with design rainfall (75% probable rainfall in Irrigation guideline, Sri Lanka) for Dunamale and Ellagawa watersheds are in Figure 6-1.

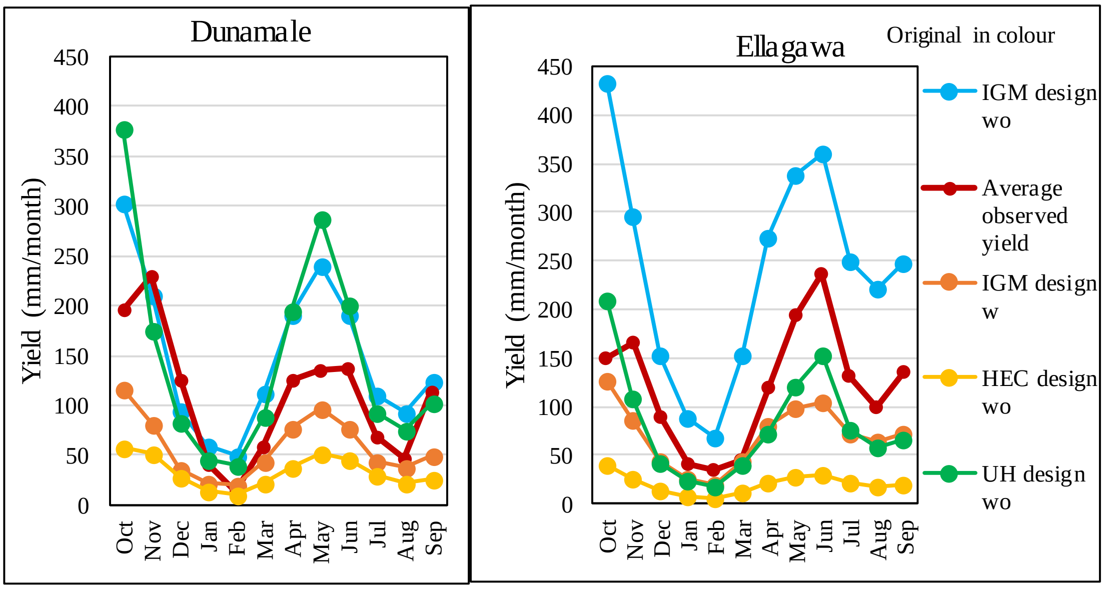

Figure 6-1: Monthly model yield comparison for design rainfall input

In this, observed yield values are the average observed streamflow over the study period, corresponding to each watershed. Comparison shows that the IGM with thresholds should be the values that must be need for designs when adhering to Ponrajah (1984).

The flow duration curves of IGM, HEC-HMS, UH and average observed streamflow are in Figure 6-2.

The MRAE values for the design values with the average observed streamflow corresponding to most recent years are in Table 6-1.

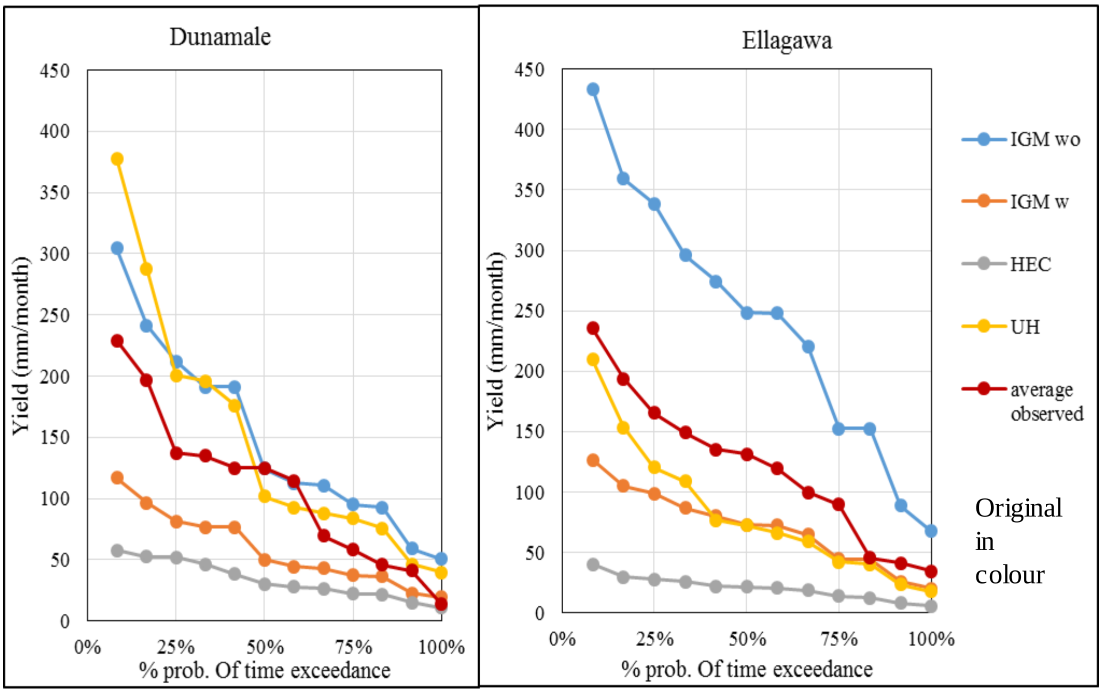

Figure 6-2: Comparison of FDC of monthly yield estimation with observed yield FDC

Table 6-1: MRAE values for the design values corresponding to average observed streamflow

MRAE	Flow type	Dunamale	Ellagawa
IGM with thresholds	overall hydrograph	0.43	0.38
	Overall FDC	0.44	0.39
	Annual FDC	0.44	0.39
	High flow	0.49	0.43
	Low flow	0.36	0.33
HEC-HMS model	overall hydrograph	0.63	0.82
	Overall FDC	0.63	0.82
	Annual FDC	0.63	0.82
	High flow	0.71	0.83
	Low flow	0.52	0.81
UH model	overall hydrograph	0.61	0.4
	Overall FDC	0.52	0.35
	Annual FDC	0.52	0.35
	High flow	0.40	0.31
	Low flow	0.68	0.40

The evaluation of MRAE values indicate tha IGM model has obtained comparatively lower MRAE values than other two models for both Dunamale and Ellagawa watersheds. HEC-HMS model shows comparatively higher MRAE values than other two models for both watersheds.

6.2 Computation of watershed yield

6.2.1 Monthly, seasonal and annual yield

Comparison of watershed yield is the comparison of observed streamflow values with modelled streamflow values with modelled streamflow values computed using observed areal average rainfall during the study period. The comparison of thessen average rainfall and modelled streamflow over the study period for Dunamale and Ellagawa are shown by hydrographs in Fig 6-3, 6-4 and Fig 6-5, 6-6 respectively. Seasonal and annual yield comparisons for Dunamale and Ellagawa are in Figure 6-7, and Fig 6-8 respectively.

Monthly variation of model yield in Dunamale basin clearly shows that HEC model and UH model over estimates the flow, but IGM varies in the same range of observed yield. Considering Ellagawa basin, HEC model shows a time diviation from observed flow, while slightly over estimates the flow. In between 2011-2012, 2013-2014 UH model show deviations from observed yield. IGM monthly variation is in the same range of observed yield.

Seasonal and annual variation of models show that in Dunamale basin, IGM model closely estimates the yield with observed yield, while other two models over estimating. In Ellagawa basin, UH model shows closest variation with observed yield while, IGM underestimates the flow and HEC model overestimates the flow.

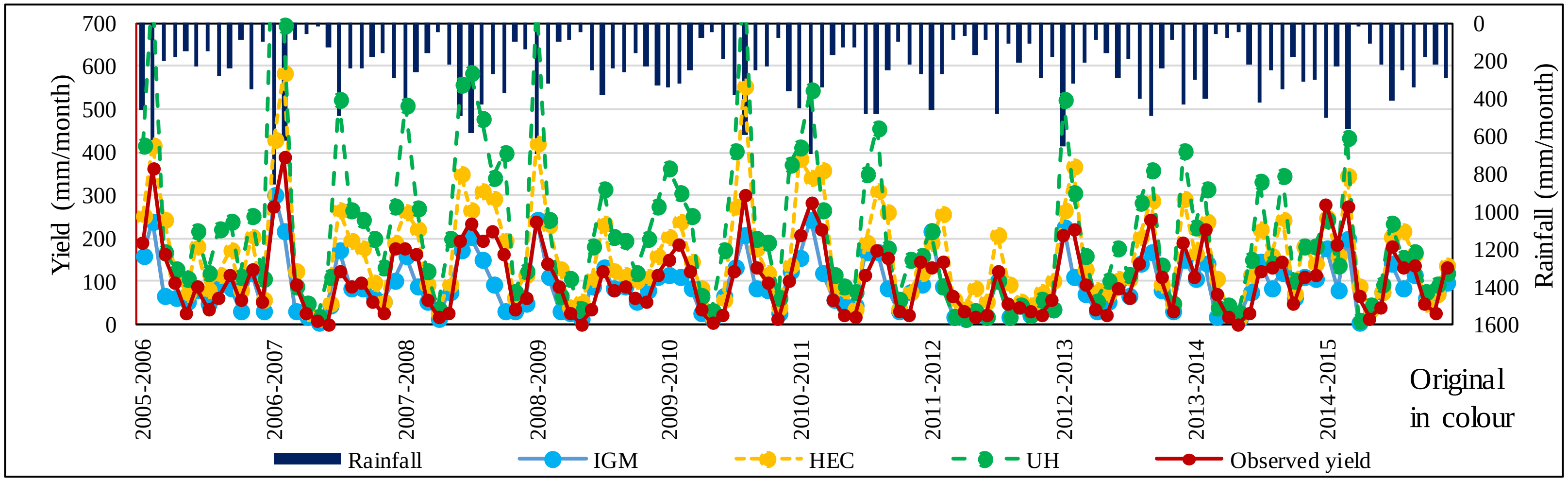

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Figure 6-3: Monthly model yield comparison - Dunamale watershed

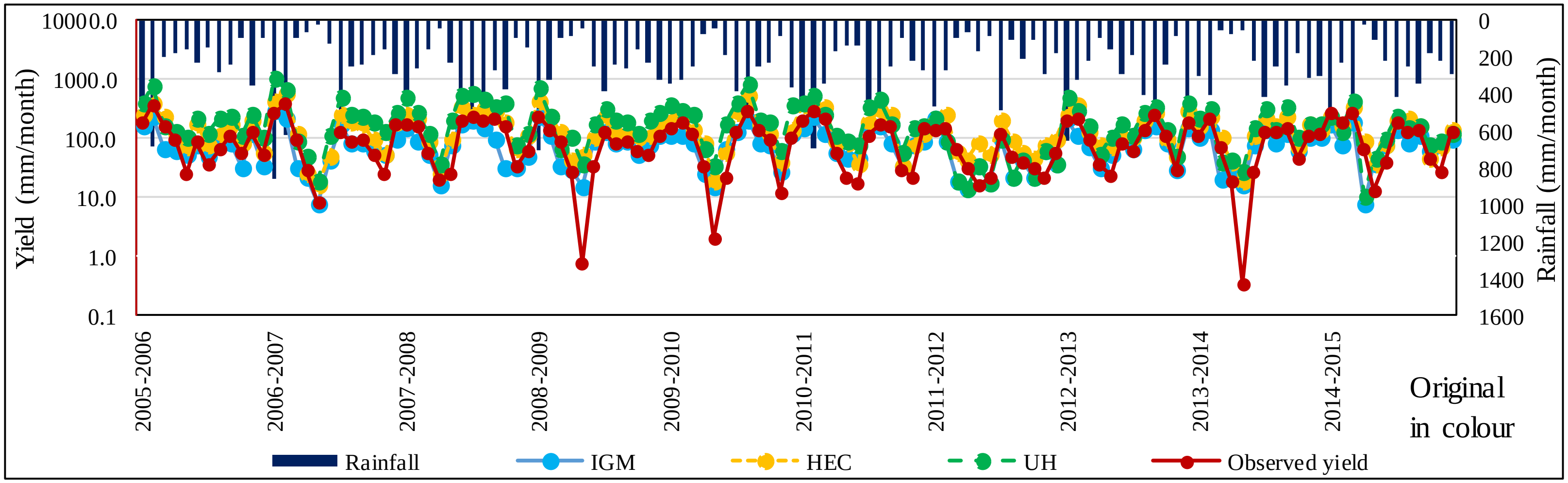

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Figure 6-4: Monthly yield comparison - Log scale - Dunamale

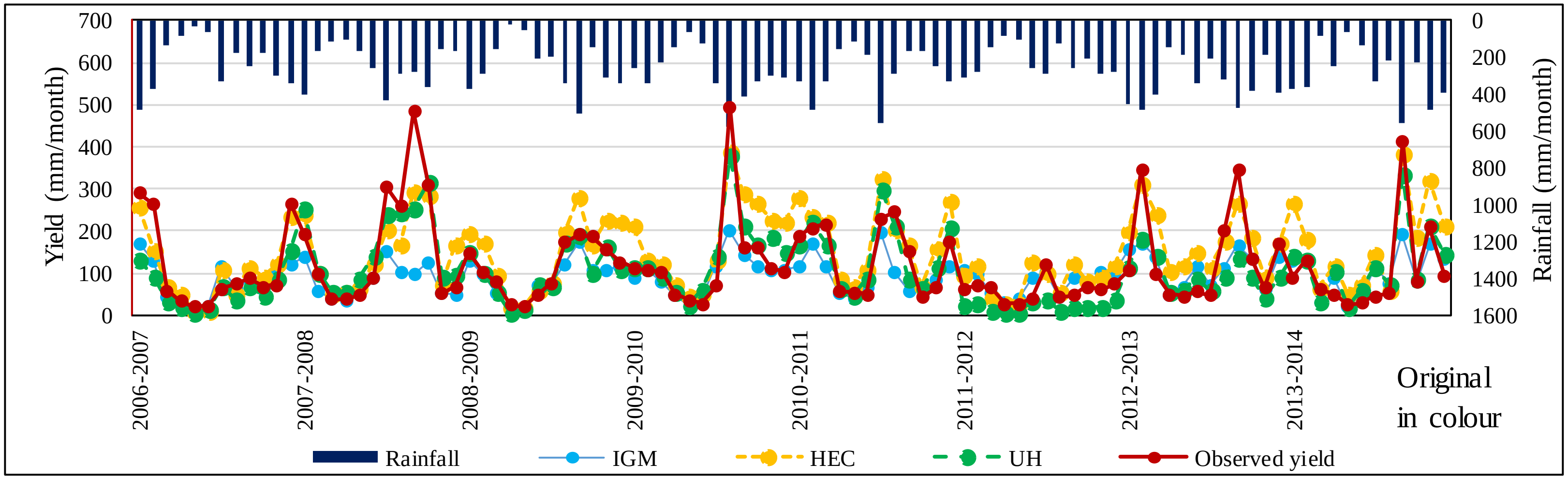

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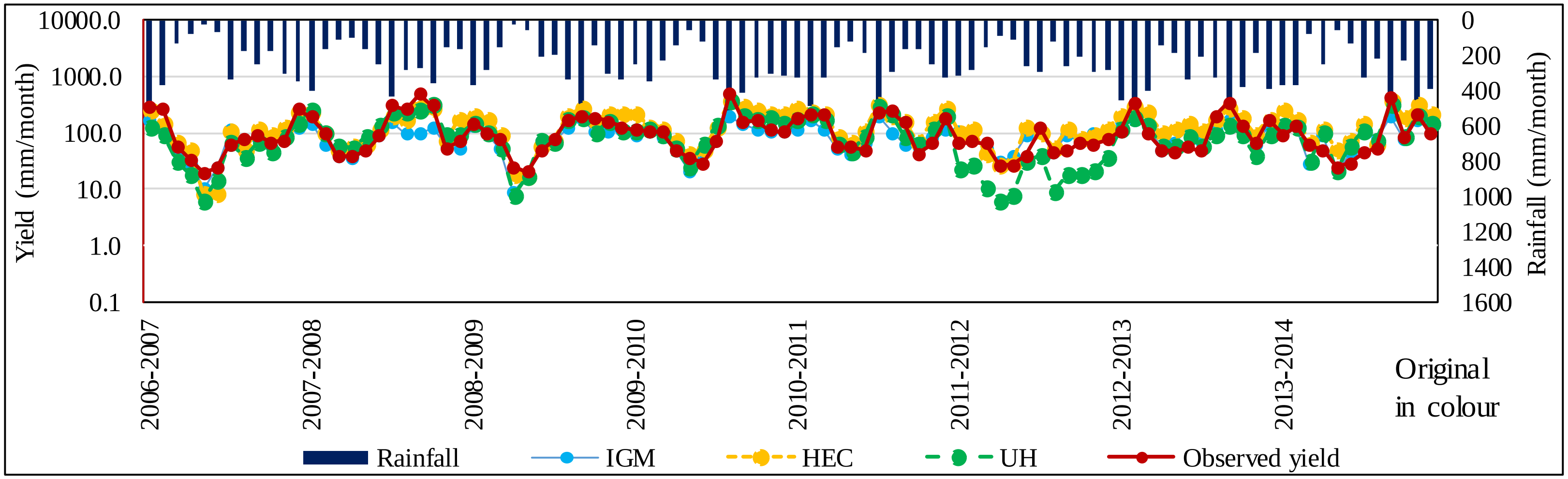
Figure 6-5: Monthly model yield comparison - Ellagawa watershed



Original in colour

Figure 6-6: Monthly yield comparison - Log scale - Ellagawa

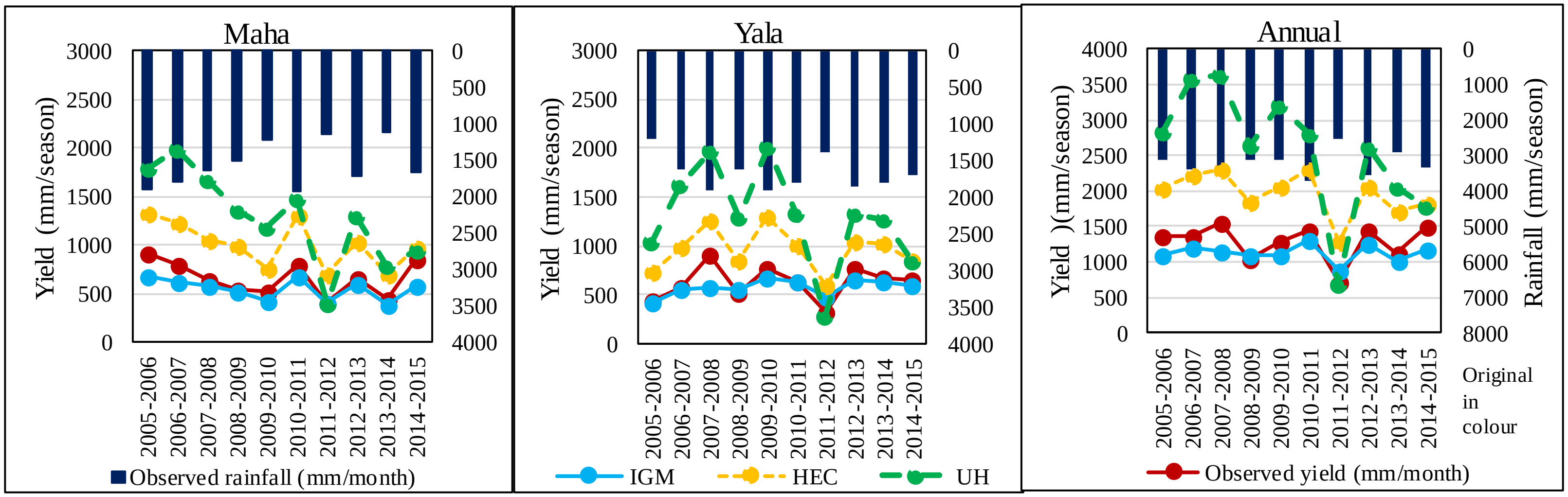


Figure 6-7: Seasonal and annual model yield comparison – Dunamale

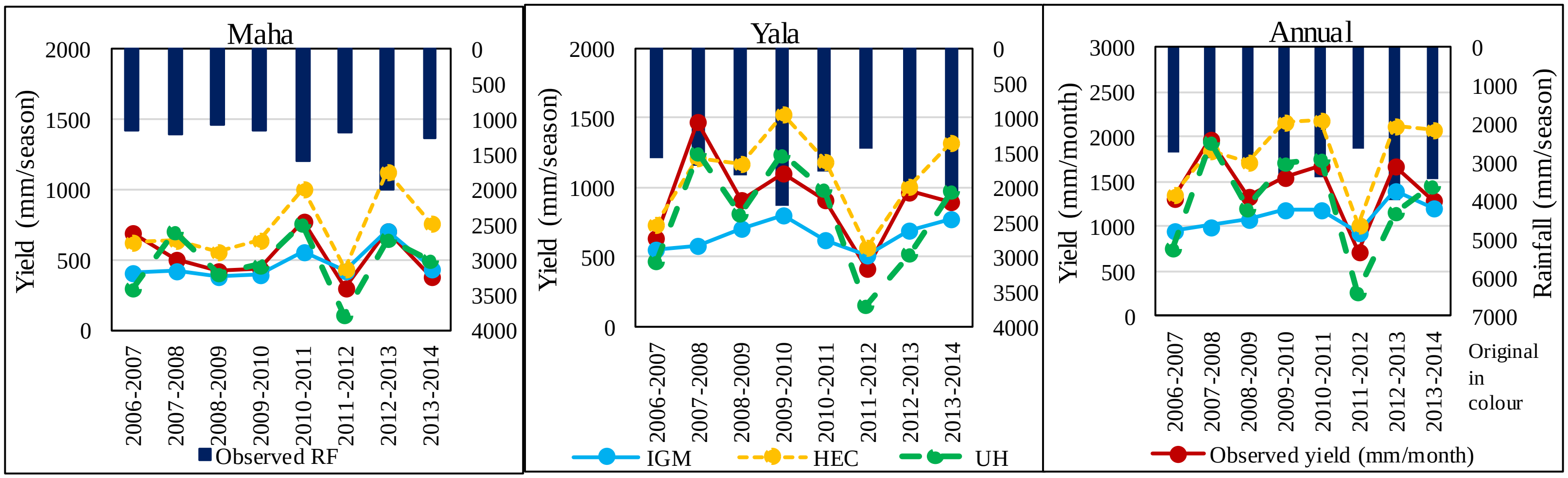


Figure 6-8: Seasonal and annual model yield comparison – Ellagawa

6.2.2 Monthly flow duration curves

Corresponding monthly flow duration curves for the research period are in Figure 6-9. Results indicate deviations of HEC-HMS and UH model results from average observed yield in Dunamale watershed. All three models show lower variations for Ellagawa watershed.

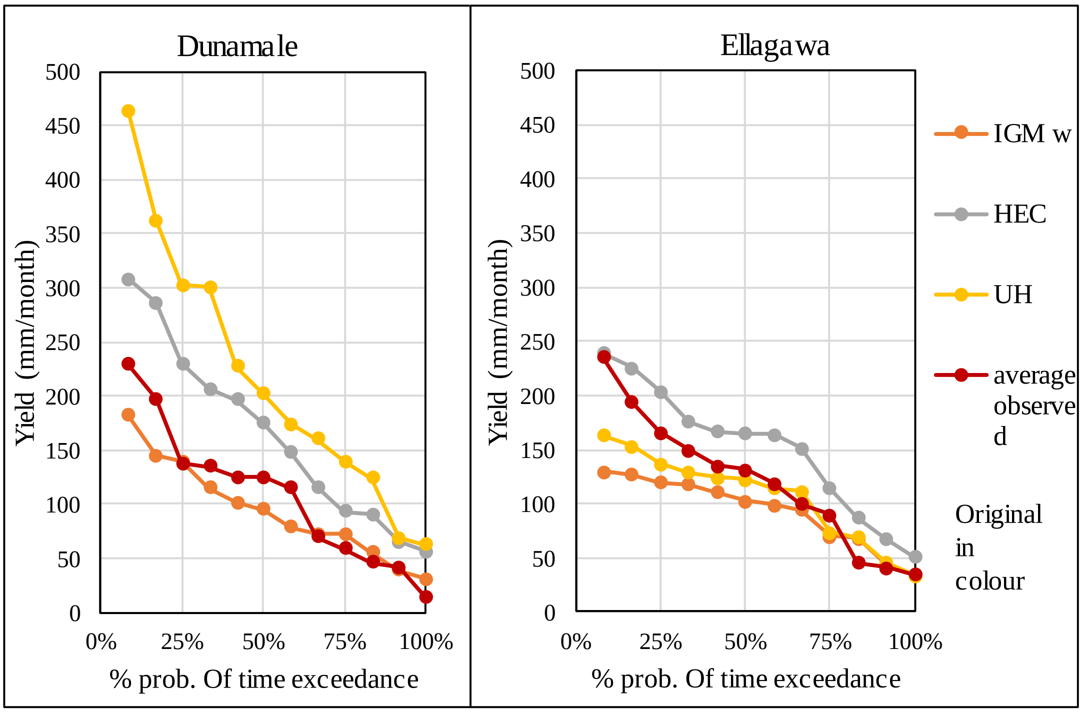


Figure 6-9: Average monthly FDC comparison for observed rainfall input

6.2.3 Numerical indicators

The MRAE values of model estimations are shown in Table 6-2.

By evaluating with the observed yield, It can be seen that the lowest MRAE values are obtained by IGM. IGM slightly under estimates the average seasonal and annual model yield, while other models are over estimating, except UH model in Ellagawa basin. Hence, as the verification with observed yield, IGM can be considered best suitable yield estimation model, among considered models.

In Dunamale basin, HEC model flow over estimation percentage is lower than UH model and, HEC model provides the second lowest MRAE values. In Ellagawa basin, UH model underestimates the flow and shows the second lowest MRAE values. Comparing the number of assumptions and easiness to model application for an ungauged catchment, HEC model gets prioritization than UH model. Considering the percentages of over estimations, it is clear that correction factors need to be applied for both UH and HEC models. Considering Dunamale and Ellagawa basins, each model in Dunamale basin shows higher MRAE values than Ellagawa basin. The effect of catchment size for model estimation results need to be further evaluated.

Table 6-2: MRAE values for model estimations

MRAE	Flow type	Dunamale	Ellagawa
IGM with thresholds	overall hydrograph	1.09	0.35
	Overall FDC	1.09	0.35
	Annual FDC	0.88	0.27
	High flow	0.19	0.22
	Low flow	0.31	0.11
HEC-HMS model	overall hydrograph	1.9	0.58
	Overall FDC	1.9	0.57
	Annual FDC	1.7	0.51
	High flow	0.45	0.31
	Low flow	1.17	0.51
UH model	overall hydrograph	2.52	0.4
	Overall FDC	2.51	0.39
	Annual FDC	2.32	0.32
	High flow	0.89	0.11
	Low flow	1.56	0.12

6.3 Estimations – Magnitude and Percentage of Deviation

Magnitude and percentage deviations in the monthly average model estimates when compared with average observed streamflow are shown in Table 6-3.

The variation of seasonal and annual percentage error show that IGM shows comparatively closer yield estimations for both watersheds and the model yield values are under estimated. HEC model over estimates the yield for both watersheds and UH model show uncertain results.

Table 6-3: Magnitude and percentage deviation of model estimates

#		Dunamale watershed			Ellagawa watershed		
		IGM	**HEC**	**UH**	**IGM**	**HEC**	**UH**
Annual streamflow estimation error	mm per year	160.1	-683.8	-1299.5	322.7	-370.7	163.0
	%	12%	-53%	-101%	22%	-26%	11%
Maha season streamflow estimation error	mm per year	110.4	-346.5	-631.3	59.9	-195.5	44.3
	%	17%	-53%	-96%	11%	-37%	8%
Yala season streamflow estimation error	mm per year	49.7	-337.2	-668.2	262.8	-175.2	118.7
	%	8%	-54%	-107%	29%	-19%	13%
Monthly average streamflow estimation error	mm per year	13.8	-56.5	-107.8	26.9	-30.9	13.6
	%	13%	-61%	-71%	22%	-26%	11%

6.4 Effect of Antecedent Rain

The model estimates showed that over and under estimations are directly correlated with antecedent rainfall. When there is high antecedent rainfall, the models overestimated while the rains followed by dry or relatively dry months indicated streamflow under estimation.

Model output comparisons are compared for each model (Fig 6-10) and they show that the all models irrespective of the magnitude of difference, behave in the same manner. Therefore, it is important to consider the antecedent rainfall effect when decisions are made.

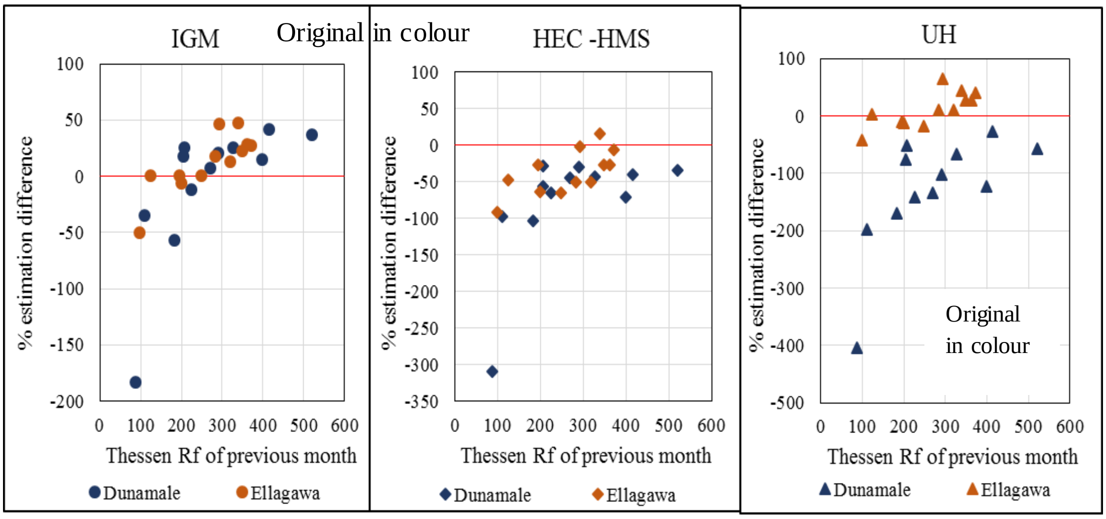


Figure 6-10: Average estimation difference % for rainfall of previous month

6.5 Comparison of Yield Thresholds

Comparison of design yield values of each model was carried out by incorporating Ponrajah (1984), yield thresholds to HEC-HMS and UH models. The monthly variations with average observed streamflow for both watersheds are shown in Figure 6-11.

The flow duration curves in Figure 6-12, evaluation indicators are in Table 6-4.

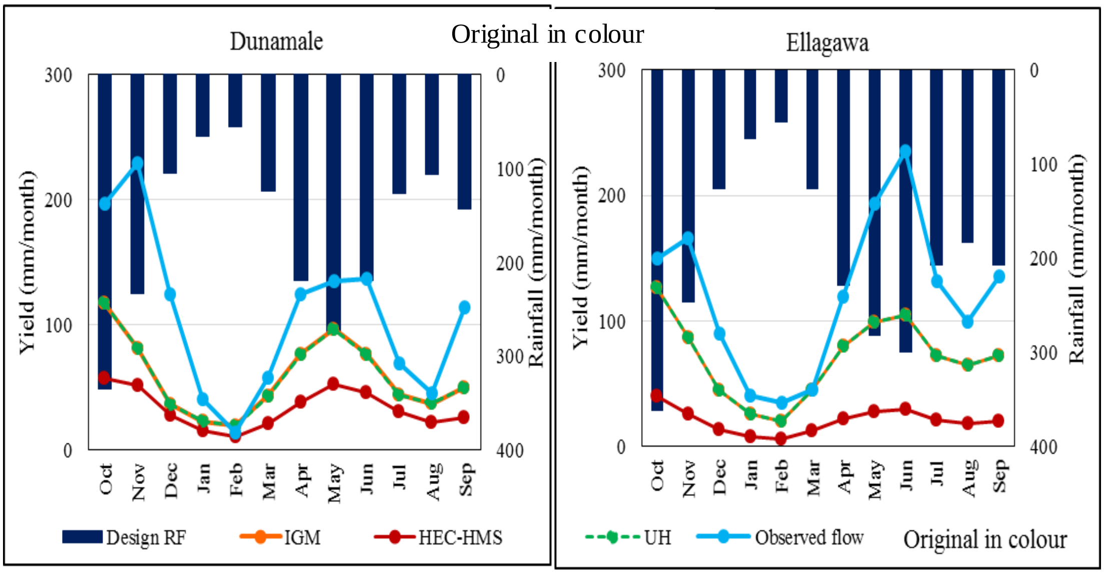


Figure 6-11: Model variation comparison- incorporation of yield thresholds for design rainfall application

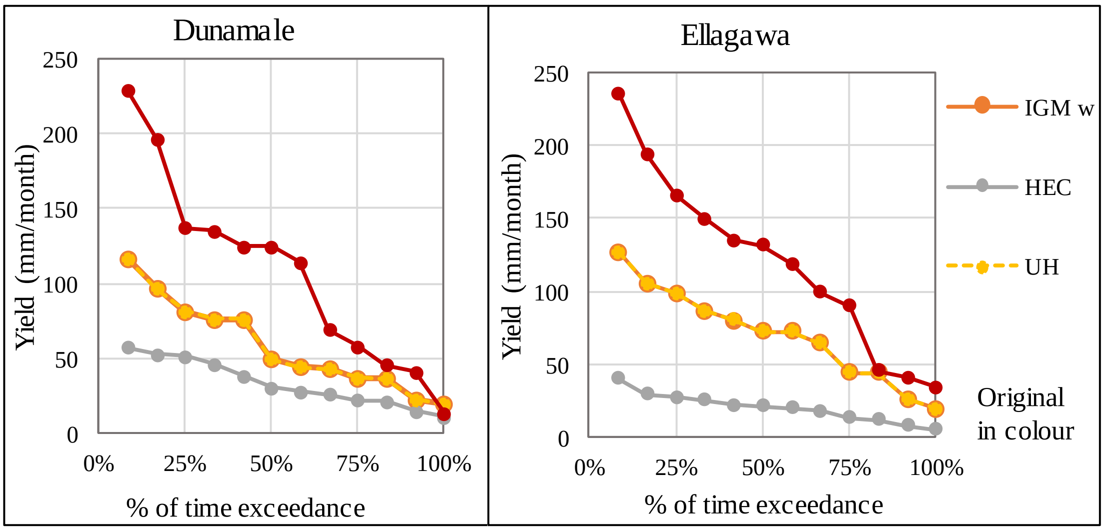


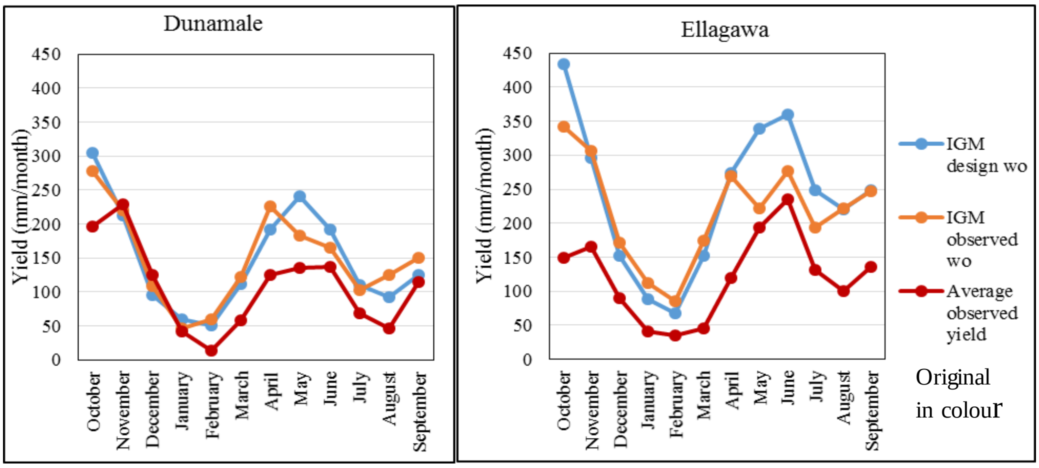
Figure 6-12: FDC for models incorporation of yield thresholds - design rainfall application

Table 6-4: Numerical indicators for yiled threshold comparison for design rainfall application

MRAE	Flow type	Dunamale	Ellagawa
IGM with thresholds	overall hydrograph	0.43	0.38
	Overall FDC	0.44	0.39
	Annual FDC	0.44	0.39
	High flow	0.49	0.43
	Low flow	0.36	0.33
HEC-HMS model	overall hydrograph	0.63	0.82
	Overall FDC	0.63	0.82
	Annual FDC	0.63	0.82
	High flow	0.71	0.83
	Low flow	0.52	0.81
UH model	overall hydrograph	0.43	0.38
	Overall FDC	0.44	0.39
	Annual FDC	0.44	0.39
	High flow	0.49	0.43
	Low flow	0.36	0.33

6.6 Yield Comparison

Comparison of monthly yield value of analysis part 1 and analysis part 2 is presented in Figure 6-6 to Figure 6-9. Results show that IGM without thresholds, over estimates streamflow and the percentage of over estimation is in the same range. After applying yield limitations as a correction factor, variation of IGM model yield comes below the graph of observed yield. IGM design rainfall estimation results slightly reduces from IGM observed rainfall application results.



Original in colour

Figure 6-13: Model yield comparison- IGM wo - Dunamale and Ellagawa watersheds

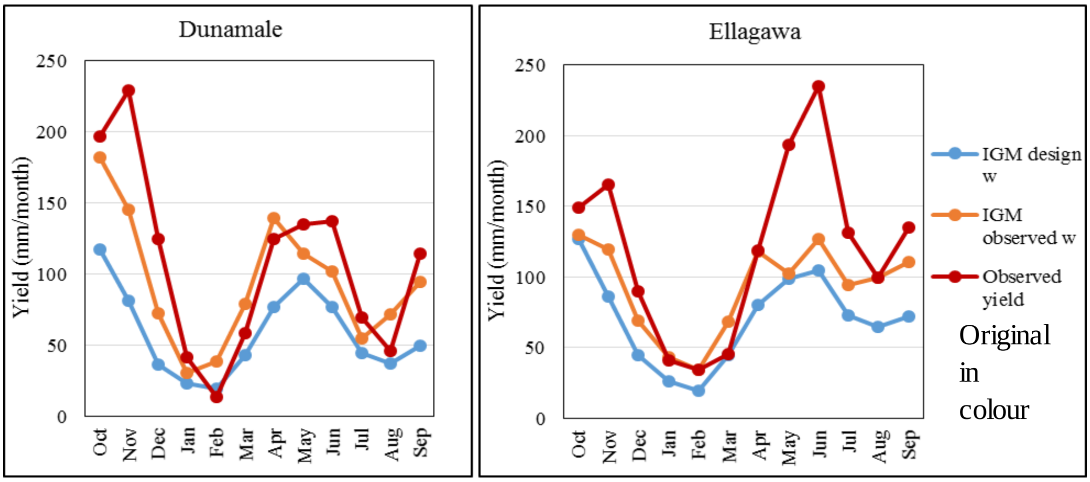


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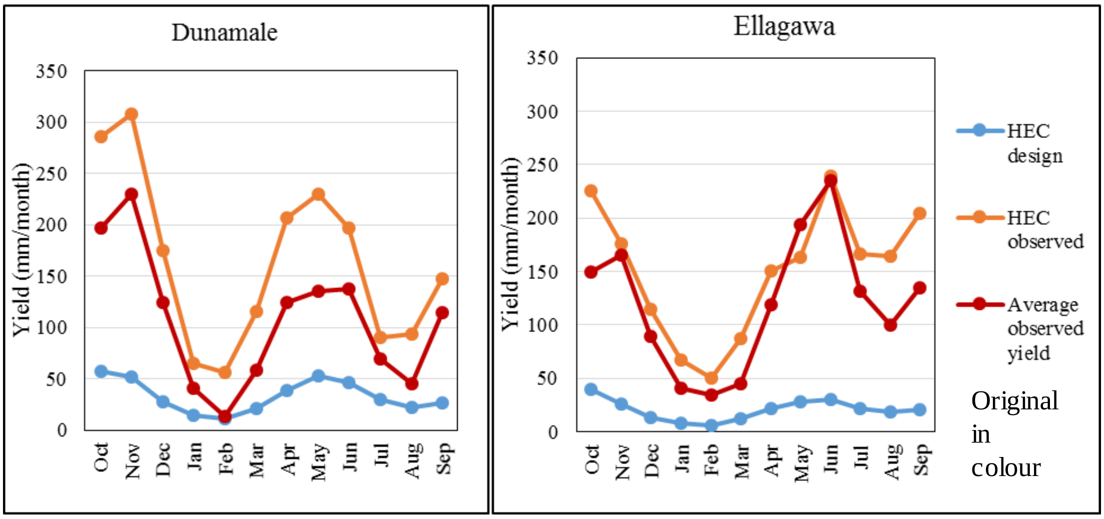
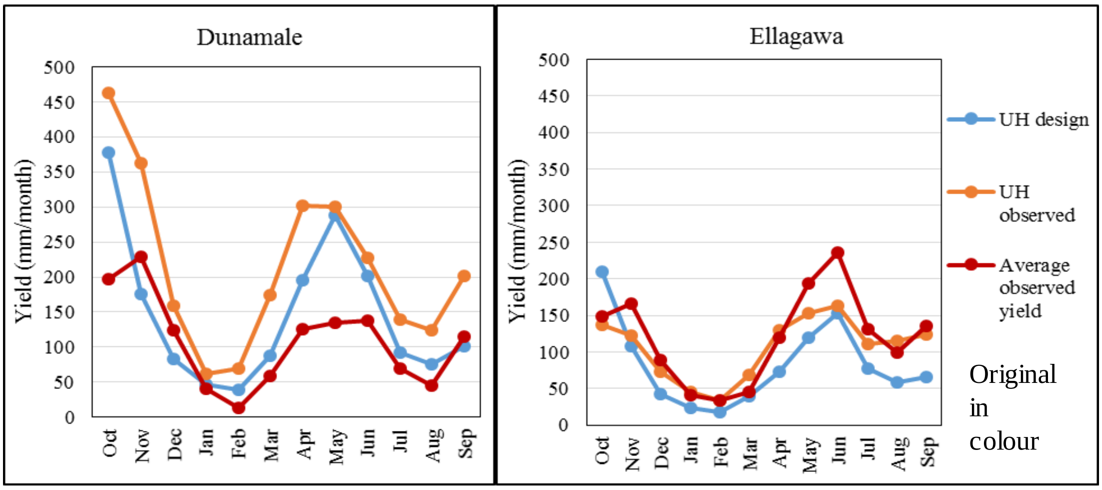
Figure 6-14: Model yield comparisons - IGM w - Dunamale and Ellagawa watersheds



Original in colour

Figure 6-15: Model yield comparisons - HEC - Dunamale and Ellagawa watersheds



Original in colour

Figure 6-16: Model yield comparisons - UH - Dunamale and Ellagawa watersheds

Though UH model variation show a slight change with design rainfall application and observed rainfall application, HEC model shows a considerable variation in between design rainfall application and observed rainfall application in both basins. Observed rainfall application results vary in the range of observed yield, but it is approximately 5 times higher than the design rainfall application for HEC model.

7 DISCUSSION

7.1 Design and Observed Data

Dataset used for computations consisted of design data from Ponrajah (1984) and observed data obtained from collection agencies. Data station adequacy was checked with WMO standards.

Data used in study were relatively consistent but showed deviations in response. This could be either due to areal averaging of rainfall or due to non-representativeness of hydrology in models, or due to errors in measurements. It is very important to perform data checking and maintain the awareness of data issues throughout the modelling effort. In this study, data discrepancies could be clearly observed when the model results were generated.

It is very important to note that the data quality and methods used are the key to realistic modelling. In this study which attempted to compare model types targeted a good quality data set. Therefore, data collection authorities must take steps to “quality flag” the data to move forward with meaningful hydrologic modelling for yield estimations.

It was also noted that the design data of guideline for Sri Lanka requires updating. It is a clear necessity to address spatial distribution of available data for modellers to rationally use in their specific location based case studies.

The models used in the current study required design data such as model parameters. These were limited because of the low number of practical applications meaningfully cited in literature. Therefore more case study research need to be carried out for better design office applications.

7.2 Model Parameters

IGM parameters were based on Ponrajah (1984). This did not contain evidence regarding cited parameters or the model. It is important to support guideline with reviewed publications to ensure sustainable irrigation infrastructure.

This study did not calibrate HEC-HMS or UH model. Instead, selection of model parameters were based on published literature, guidelines and text books. The present study resorted to this method because it is the only available option for a design office practitioner to perform streamflow estimations in ungauged watersheds and even in the case of ungauged sub-watersheds of of a gauged main watershed.

Results show the importance of either carrying out more measurements or performing research with available data specifically targeting the parameter concerns of a practicing engineer.

In case of wet zone watersheds, the present study results confirm that the iso-yield curves must be used with yield thresholds. Therefore this study can be used to the support use of upper and lower thresholds mentioned in Ponrajah (1984)

7.3 Model Components

Irrigation guideline model is a direct yield estimation method and hence the key model components were 1) the extraction of values from spatially coarse seasonal yield curves, 2) Apportioning assumption for monthly yield values. The availability of a guideline and the personal knowledge on many time tested applications in Sri Lanka, supported easy applications demonstrated in the two case studies.

The HEC model and UH model applications were carried out at a daily temporal resolution. This was done with the assumption, that the process based models would reflect better hydrological behaviour when finer resolution data are used to aggregate results to a coarser time interval.

Process sub models of HEC models were selected by resorting to published material and there was a difference in selection when dealing with each case study.

The uncertainty faced by a modeller when selecting sub models can lead to errors in model estimations. Due to the detailed handling of hydrological behaviour in a watershed the HEC model creates ambiguities but produces a result. Hence, the modellers and water managers must carefully evaluate model results.

The UH model is based on many assumptions. However the time tested practice provides significant confidence when model selection is carried out. However the model deals with effective rainfall, direct runoff and it is event based. Therefore, many assumptions must be done in relations to continuous estimations, total runoff conversion, and baseflow computations. Apart from the above a modeller needs to estimate Ct and Cp values to ensure that the unit hydrograph generation process in reasonable. These factors create significant uncertainties when modelling streamflow using UH theory.

All these models demonstrated many model formulation, model development, and modelling uncertainties. Therefore, it is very important for infrastructure designers to incorporating appropriate design safety factors for sustainability of irrigation development works.

7.4 Design Options

Available design options were evaluated by carrying out a comprehensive literature review and a comparative evaluation with design rainfall input. This critical literature evaluation revealed that the IGM is the best available guideline option while HEC-HMS and UH models were the preferred modern hydrological models.

Comparison of model estimates with average observed data indicated that the IGM provided the most representative streamflows but with an over estimation. The over estimations by HEC-HMS and UH models were much higher than that of the IGM.

Therefore, unless further research shows more conclusive results, hence best option of an irrigation infrastructure designer would be to use the time tested IGM. However it is important to note that, even though the rainfall uncertainty may be taken care by the 75% probable values, the modelling uncertainties are present in the model estimations.

7.5 Model Estimations Comparison

Model estimations by analysis part 1 and analysis part 2 were compared separately. Since, there is not any option to compare and evaluate design model yield values, they were analysed with observed yield. Design model results with observed yield and model yield values with observed rainfall application (Analysis part 2) were also compared with observed yield (Appendix G). Order of magnitude of model estimations relative to observed yield were compared for both analysis part 1 and part 2. Results are shown in Table 7-1 and Table 7-2.

Table 7-1: Order of magnitude comparison for Analysis part 1 – Design rainfall application

Duration		**Dunamale**			**Ellagawa**		
		IGM	**HEC**	**UH**	**IGM**	**HEC**	**UH**
Annual	Annual	0.54	0.31	1.37	0.58	0.17	0.69
Seasonal	Maha	0.48	0.28	1.22	0.66	0.20	0.84
	Yala	0.61	0.35	1.52	0.54	0.15	0.60
Seasonal average		0.55	0.31	1.37	0.60	0.18	0.72
monthly	Oct	0.60	0.29	1.92	0.85	0.27	1.40
	Nov	0.36	0.23	0.77	0.52	0.16	0.66
	Dec	0.29	0.22	0.67	0.50	0.15	0.47
	Jan	0.55	0.37	1.13	0.63	0.19	0.57
	Feb	1.42	0.80	2.90	0.57	0.16	0.51
	Mar	0.74	0.37	1.51	0.98	0.27	0.88
	Apr	0.61	0.31	1.57	0.67	0.18	0.61
	May	0.72	0.39	2.13	0.51	0.14	0.62
	Jun	0.56	0.34	1.47	0.45	0.13	0.65
	Jul	0.64	0.44	1.34	0.55	0.16	0.58
	Aug	0.81	0.49	1.65	0.65	0.19	0.59
	Sep	0.44	0.23	0.89	0.54	0.15	0.49
monthly average		0.64	0.37	1.50	0.62	0.18	0.67

According to the results, it is clear that, both HEC-HMS and IGM models under estimate annual and seasonal yield in analysis part 1 while UH model over estimates in Dunamale watershed and underestimates in Ellagawa watershed. In February and August dry months, IGM and UH show over estimation of the monthly yield.

When comparing all the model results, average monthly order of magnitude of IGM in analysis part 1compared with observed yield is 0.64 for Dunamale and 0.62 for Ellagawa watershed. For HEC-HMS, the values 0.37 for Dunamale and 0.18 for Ellagawa watersheds. UH model show comparatively higher values as 1.5 for Dunamale and 0.67 for Ellagawa watersheds.

Comparison of overall order of magnitude values of each model in both watersheds, In analysis part 1 – design rainfall application and comparing with other qualitative criteria as parameter availability, easiness of applicability, number of parameters etc., the ranking for IGM, HEC-HMS and UH models as 1, 2, 3.

The comparison shows the need to suitably identify parameters of each model to closely reproduce watershed streamflows. There after work should be carried out to incorporate safety factors safety factors to embed the uncertainties associated with model conceptualizations.

Table 7-2: Order of magnitude comparison for Analysis part 2 – Observed rainfall application

Duration		**Dunamale**			**Ellagawa**		
		IGM	**HEC**	**UH**	**IGM**	**HEC**	**UH**
Annual	Annual	0.88	1.53	2.01	0.78	1.26	0.89
Seasonal	Maha	0.83	1.53	1.96	0.89	1.37	0.92
	Yala	0.92	1.54	2.07	0.71	1.19	0.87
Seasonal average		0.88	1.53	2.01	0.80	1.28	0.89
monthly	Oct	0.93	1.45	2.35	0.87	1.51	0.92
	Nov	0.63	1.34	1.58	0.72	1.06	0.74
	Dec	0.58	1.40	1.28	0.77	1.27	0.81
	Jan	0.74	1.57	1.51	1.06	1.64	1.12
	Feb	2.84	4.10	5.04	1.00	1.47	0.98
	Mar	1.35	1.98	2.98	1.51	1.92	1.53
	Apr	1.12	1.65	2.42	0.99	1.27	1.08
	May	0.85	1.71	2.22	0.53	0.85	0.79
	Jun	0.74	1.43	1.66	0.54	1.02	0.69
	Jul	0.79	1.30	2.01	0.72	1.26	0.85
	Aug	1.57	2.04	2.71	1.00	1.65	1.15
	Sep	0.82	1.28	1.76	0.82	1.51	0.92
monthly average		1.08	1.77	2.29	0.88	1.37	0.97

Comparison of analysis part 2, observed rainfall application results with observed yield considering the order of magnitude, it is clear that for both watersheds IGM underestimates the seasonal and annual yield approximately by 30%, while HEC model over estimates streamflow for both watersheds. UH model overestimates flow for Dunamale watershed and underestimates flow for Ellagawa watershed.

When comparing all the model results, average monthly order of magnitude of IGM in analysis part 1compared with observed yield is 1.08 for Dunamale and 0.88 for Ellagawa watershed. For HEC-HMS, the values 1.77 for Dunamale and 1.37 for Ellagawa watersheds. UH model show comparatively higher values as 2.29 for Dunamale and 0.97 for Ellagawa watersheds.

Therefore, comparison of overall order of magnitude values of each model in both watersheds, In analysis part 2 – observed rainfall application and comparing with other qualitative criteria as parameter availability, easiness of applicability, number of parameters etc., the ranking for IGM, HEC-HMS and UH models as 1, 2, 3.

Therefore, it can be summarized that hydrological modelers need to do correct modelling and a safety factor need to be used for hydrological uncertainty.

7.6 Model Verification

Model verification was done with observed data. For that purpose, observed Thiesen averaged rainfall was initially applied to the models for runoff generation. Then the model runoff was compared with observed runoff. 75% probable rainfall of observed data was not used in the comparison. Comparison of IGM 75% probable rainfall and average observed thiessen rainfall in both basins is presented in Figure 7-1. Runoff coefficient comparison corresponding to all models is presented in Figure 7-2.

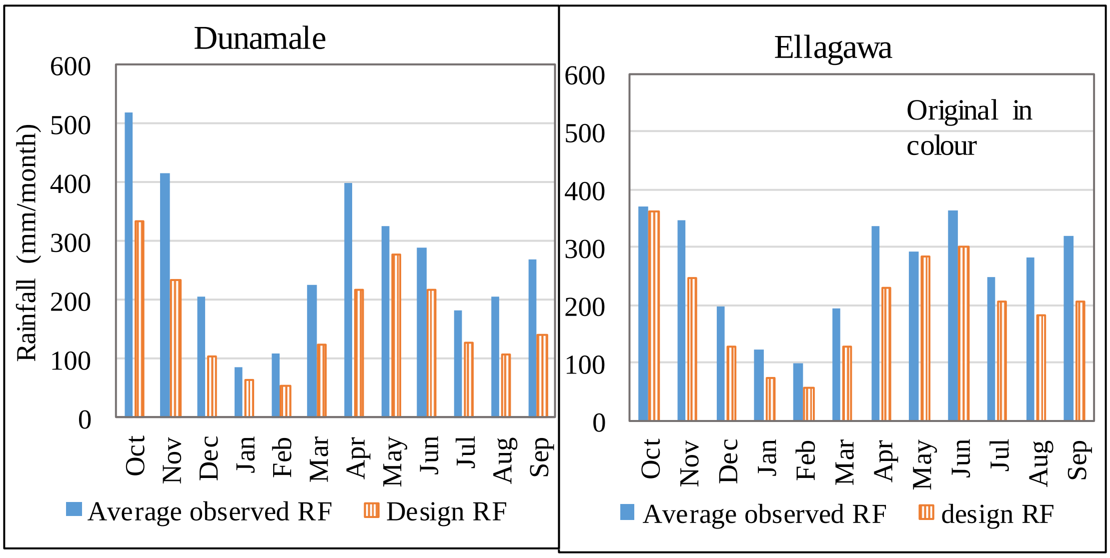


Figure 7-1: Rainfall comparison - Dunamale and Ellagawa watersheds

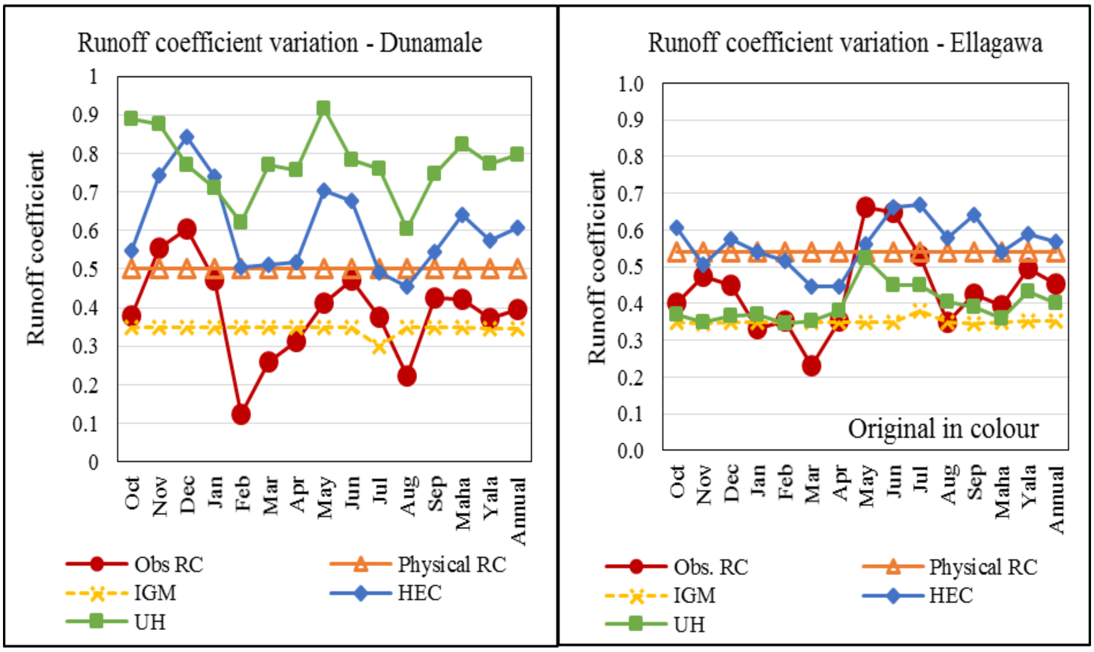


Figure 7-2: Runoff coefficient comparison - Dunamale and Ellagawa watersheds

Figure 7-3: Average runoff coefficients of Ellagawa and Dunamale watersheds

#	**Dunamale**				**Ellagawa**			
	IGM	**HEC**	**UH**	**Observed**	**IGM**	**HEC**	**UH**	**Observed**
Oct	0.35	0.55	0.89	0.38	0.35	0.61	0.37	0.40
Nov	0.35	0.74	0.87	0.55	0.34	0.51	0.35	0.48
Dec	0.35	0.84	0.77	0.60	0.35	0.57	0.37	0.45
Jan	0.35	0.74	0.71	0.47	0.35	0.54	0.37	0.33
Feb	0.35	0.51	0.62	0.12	0.35	0.52	0.35	0.35
Mar	0.35	0.51	0.77	0.26	0.35	0.45	0.35	0.23
Apr	0.35	0.52	0.76	0.31	0.35	0.45	0.38	0.35
May	0.35	0.70	0.92	0.41	0.35	0.56	0.52	0.66
Jun	0.35	0.68	0.78	0.47	0.35	0.66	0.45	0.65
Jul	0.30	0.49	0.76	0.38	0.38	0.67	0.45	0.53
Aug	0.35	0.45	0.60	0.22	0.35	0.58	0.40	0.35
Sep	0.35	0.54	0.75	0.42	0.35	0.64	0.39	0.42
Maha	0.35	0.64	0.82	0.42	0.35	0.54	0.36	0.39
Yala	0.34	0.58	0.77	0.37	0.35	0.59	0.43	0.50
Annual	0.35	0.61	0.80	0.40	0.35	0.57	0.40	0.45
Average	0.35	0.61	0.77	0.39	0.35	0.56	0.40	0.44

In comparison of Dunamale watershed the UH model indicated a significantly higher runoff coefficient than observed. On average IGM showed the runoff coefficients closest to the observed value but was much lower than that estimated using physical characteristics. HEC model with an averaged value of 0.61was also estimated a higher runoff coefficient that the observed value. In the Ellagawa watershed the observed average runoff coefficient was 0.44. The runoff coefficient estimated by IGM, HEC and UH models were 0.35, 0.56 and 0.4 respectively. The UH model estimated runoff coefficient was closer to the observed value but was much lower than the 0.54 value estimated using physical characteristics. The runoff coefficient in both watersheds indicated the over estimation of streamflow that was noted in the previous comparisons.

8 CONCLUSIONS

1. According to the state of art review, Irrigation department yield estimation model (IGM) is the best available watershed yield estimation model.
2. Comparison of three models revealed that IGM is the closest monthly yield estimation model with 12.5% and 22.5% annual difference in estimation for Dunamale and Ellagawa watersheds respectively.
3. HEC model over estimates streamflows by 53.2% and 25.7% in Dunamale and Ellagawa watersheds respectively while the UH model overestimates the streamflow of Ellagawa by 101% and underestimates the streamflow by 16.7% in Dunamale watershed.
4. IGM underestimates the streamflow in rainy months and overestimates during relatively dry months. The threshold time of exceedance is 60% for both Dunamale and Ellagawa watersheds.
5. The use of HEC and UH model results create significant ambiguities when compared with the IGM because of the unreliability associated with the process and parameters.
6. Yield model estimates when compared with the observations show that in all three models the antecedent rainfall acts as a key factor influencing model overestimation and underestimations.
7. IGM, HEC-HMS and UH model development and parameter estimations need better reference material to arrive at accurate watershed yield values. It is therefore important to systematically determine design safety factors to account modelling uncertainties.

9 RECOMMENDATIONS

1. Yield models need to be compared and evaluated for dry and intermediate zone catchments and necessary case studies must be carried out to evaluate the effect of catchment size.
2. Research results in the present work were affected due to problems with process and parameter selection, hence further researches need to be done for selected case study applications.

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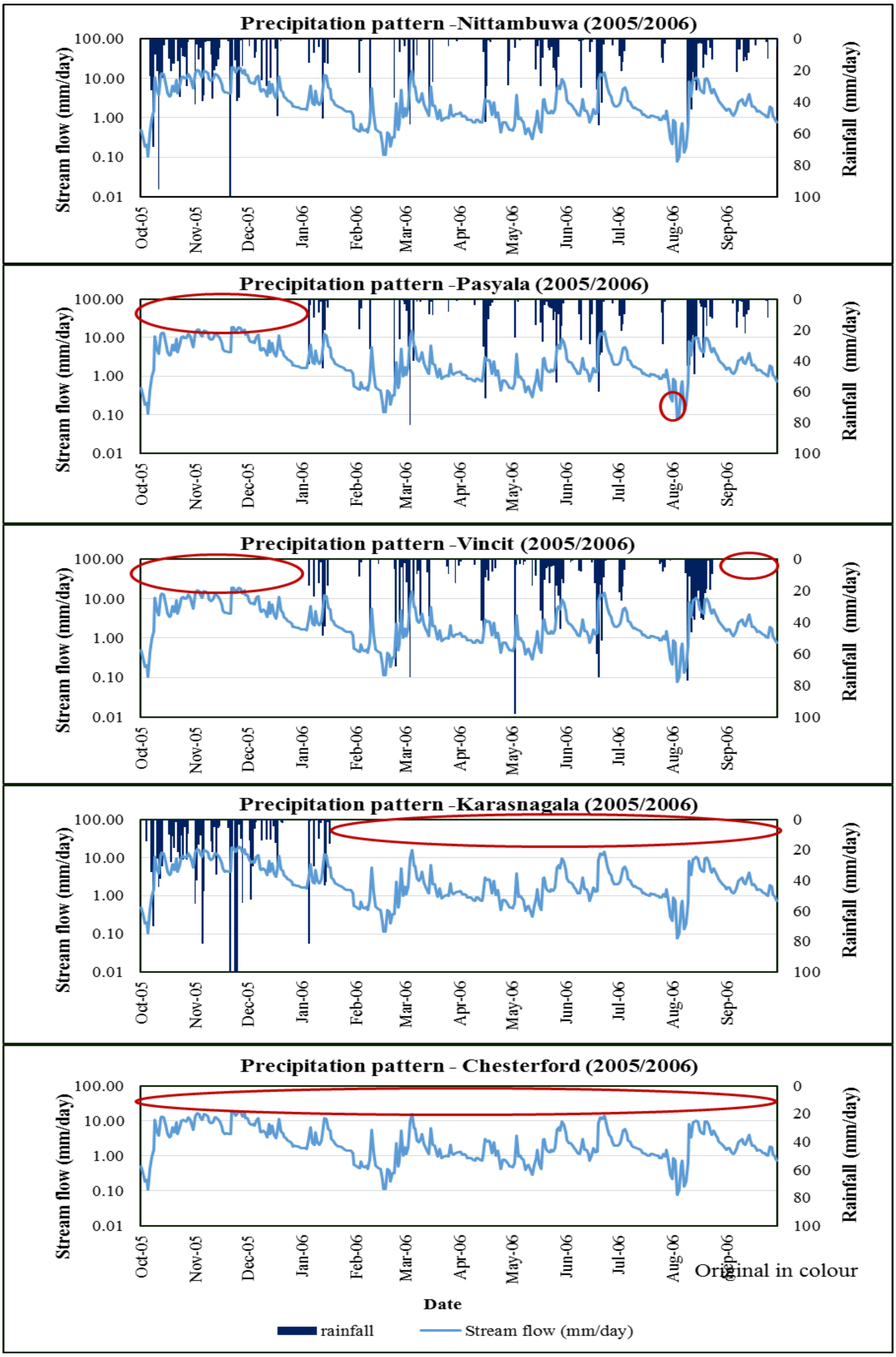
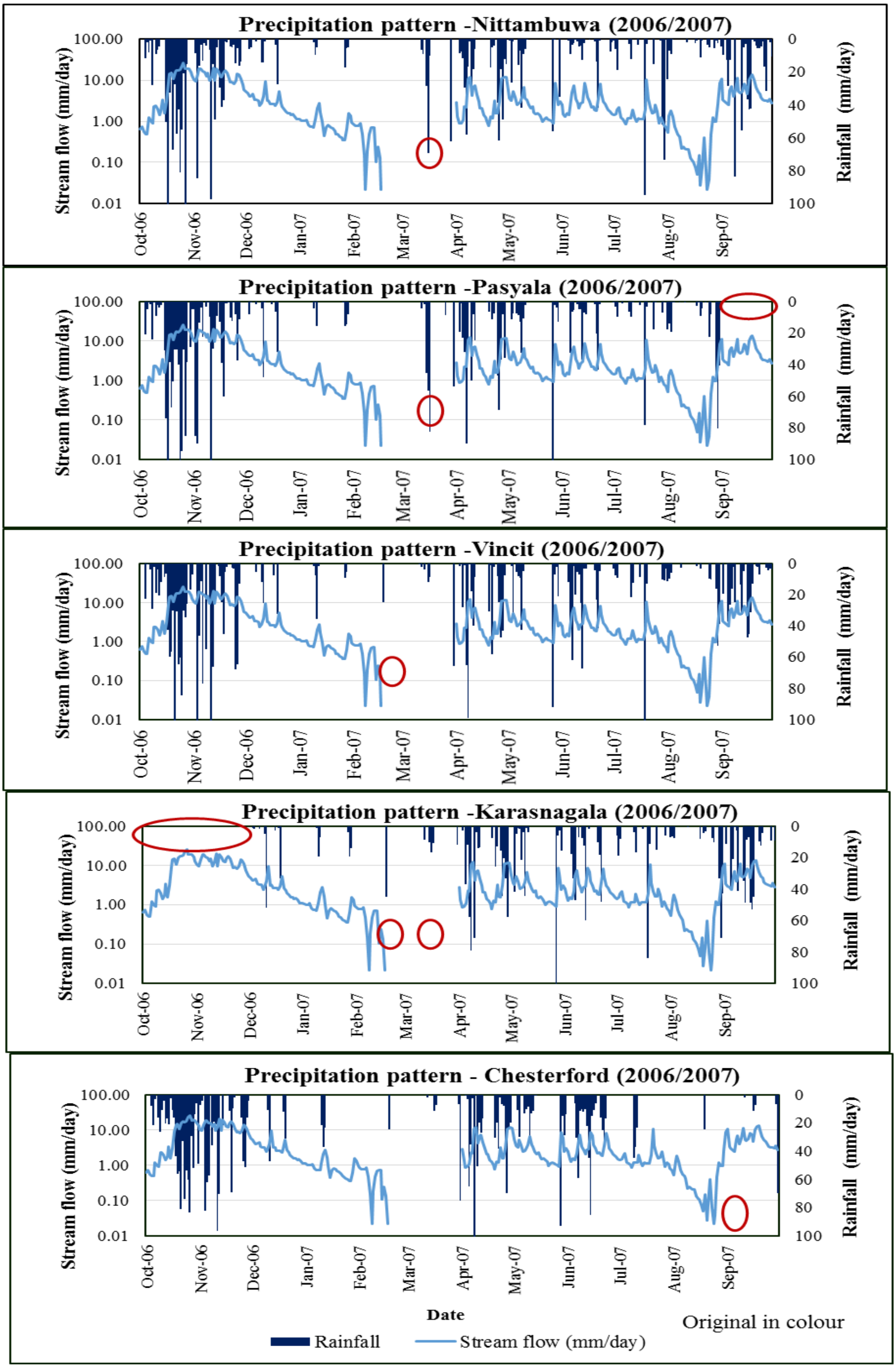
APPENDIX A: Streamflow variation corresponding to rainfall – Dunamale watershed



Original in colour

Figure A- 1: Stream flow response to rainfall – Dunamale watershed - 2005-2006


Precipitation pattern -Nittambuwa (2006/2007)

Precipitation pattern -Pasyala (2006/2007)

Precipitation pattern -Vincit (2006/2007)

Precipitation pattern -Karasnagala (2006/2007)

Precipitation pattern - Chesterford (2006/2007)

Figure A- 2: Stream flow response to rainfall – Dunamale watershed - 2006-2007

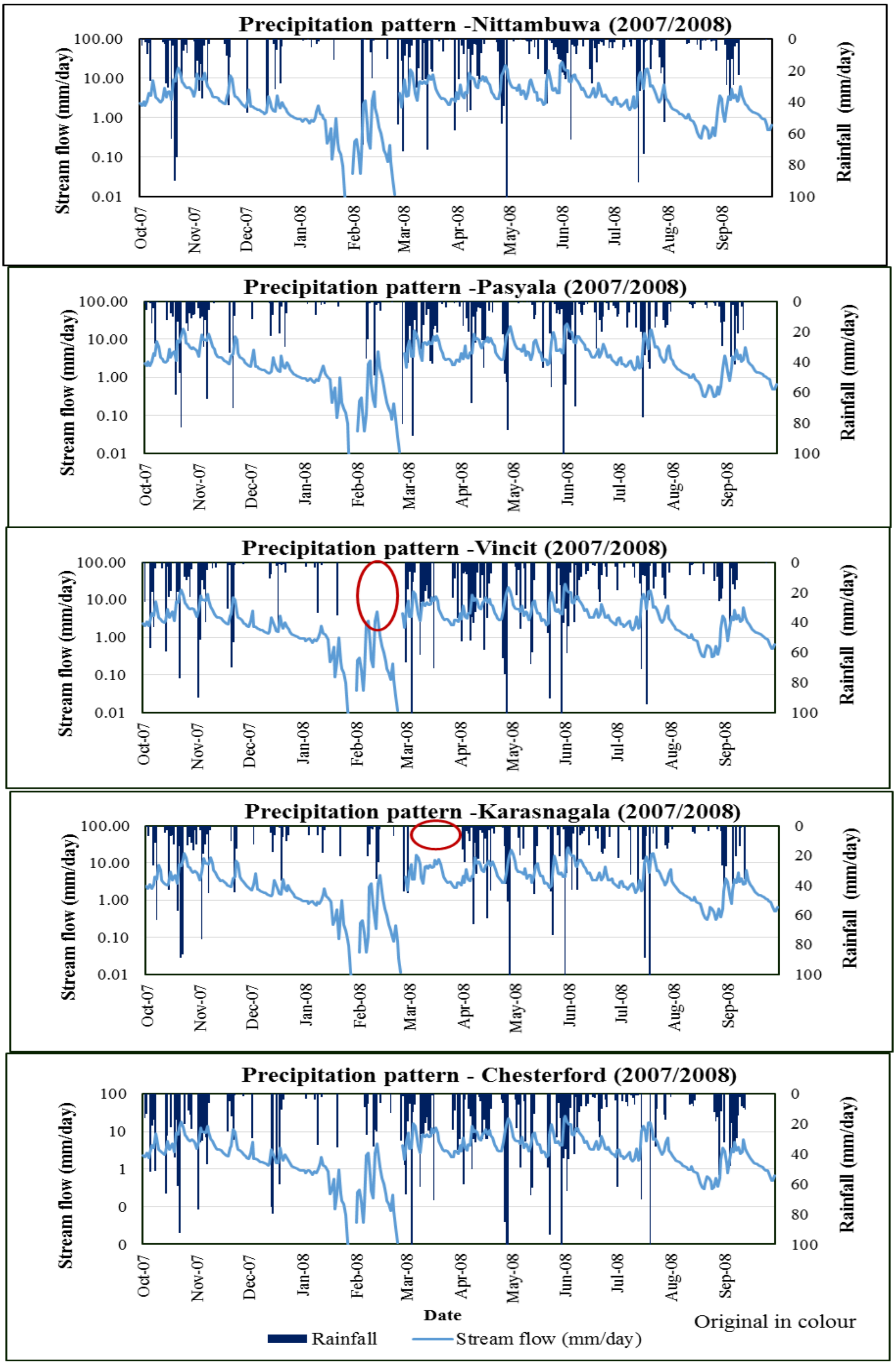
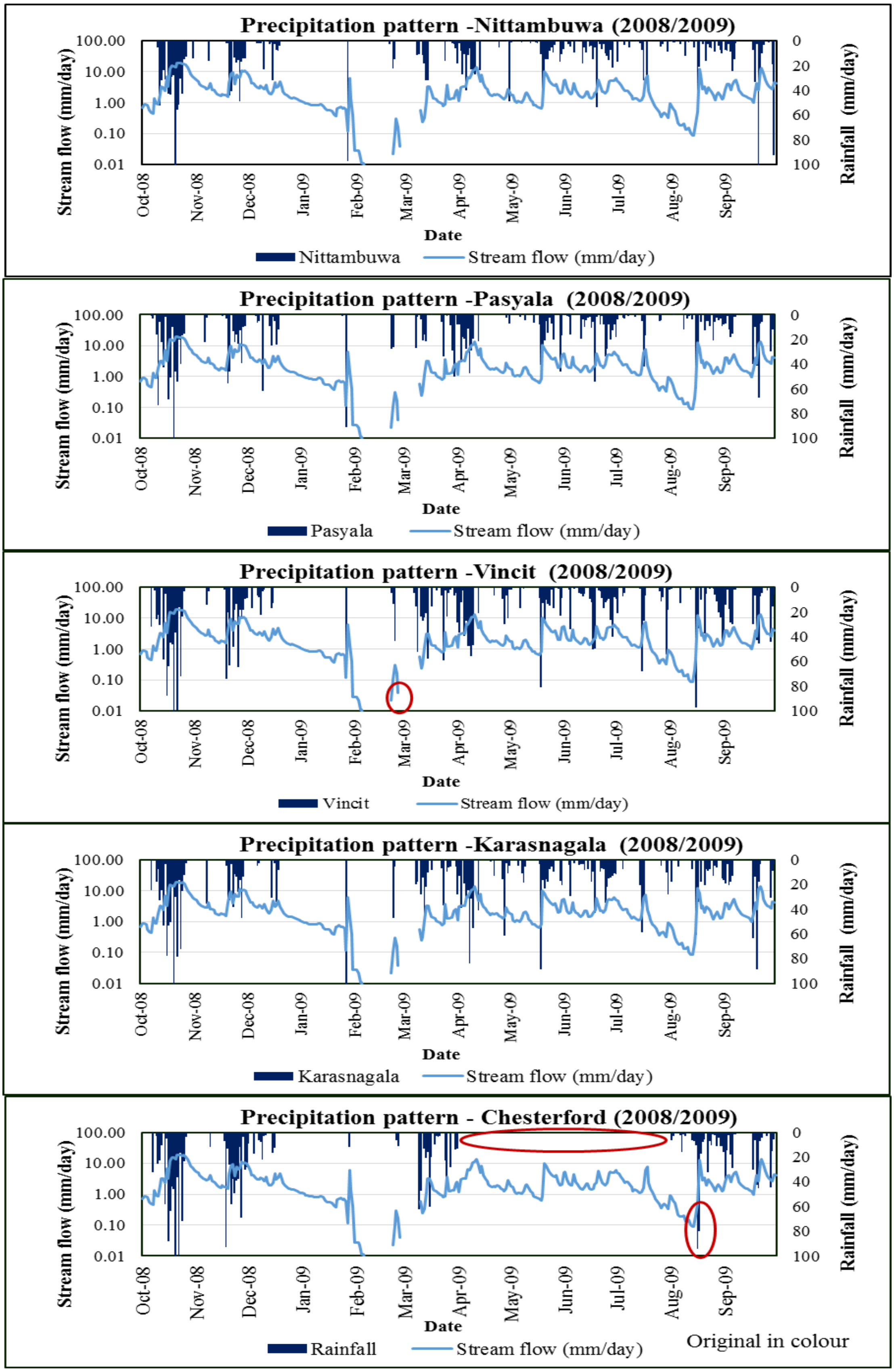


Figure A- 3: Stream flow response to rainfall - Dunamale watershed - 2007-2008



Original in colour

Figure A- 4: Stream flow response to rainfall - Dunamale watershed - 2008-2009

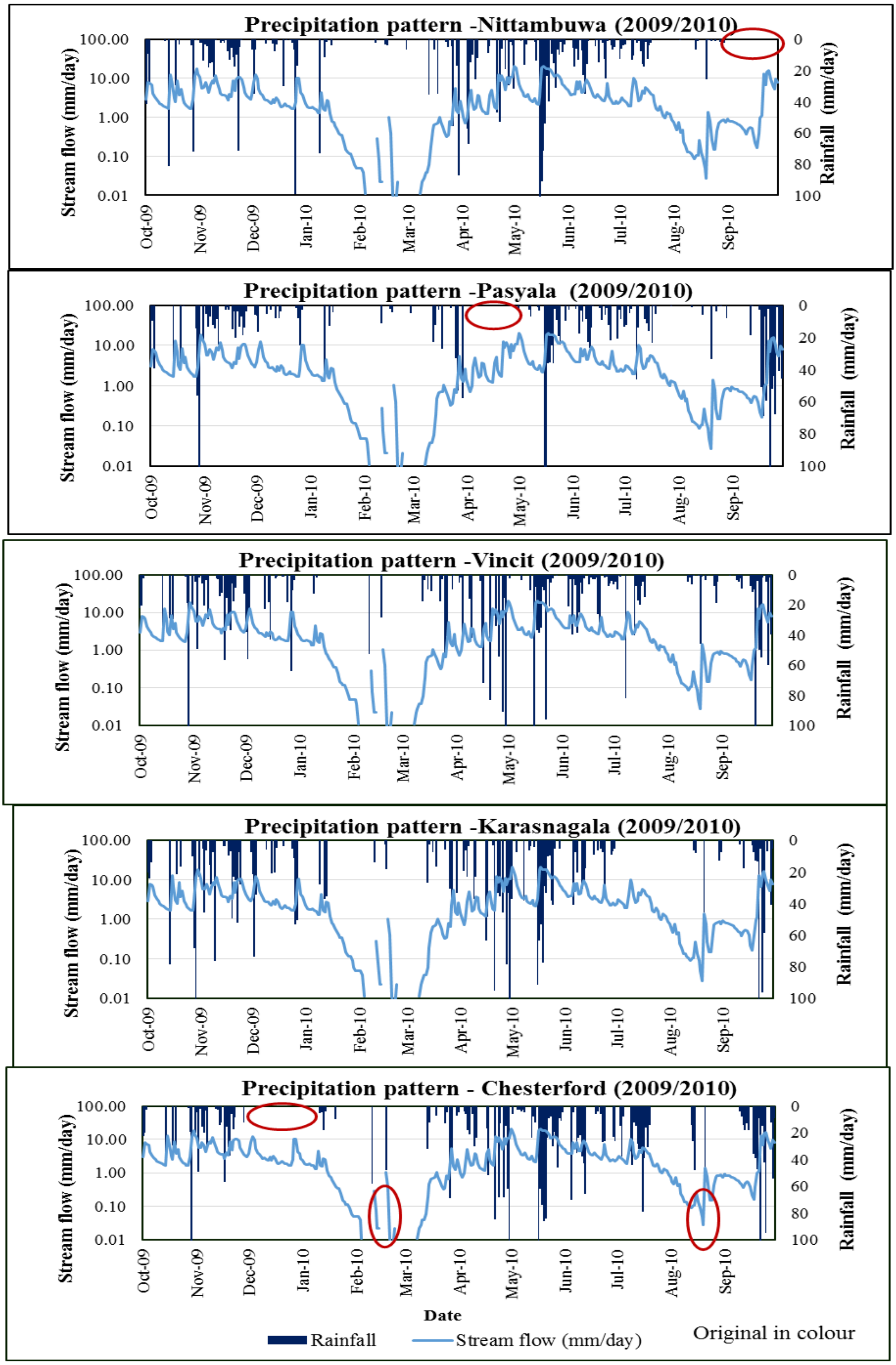
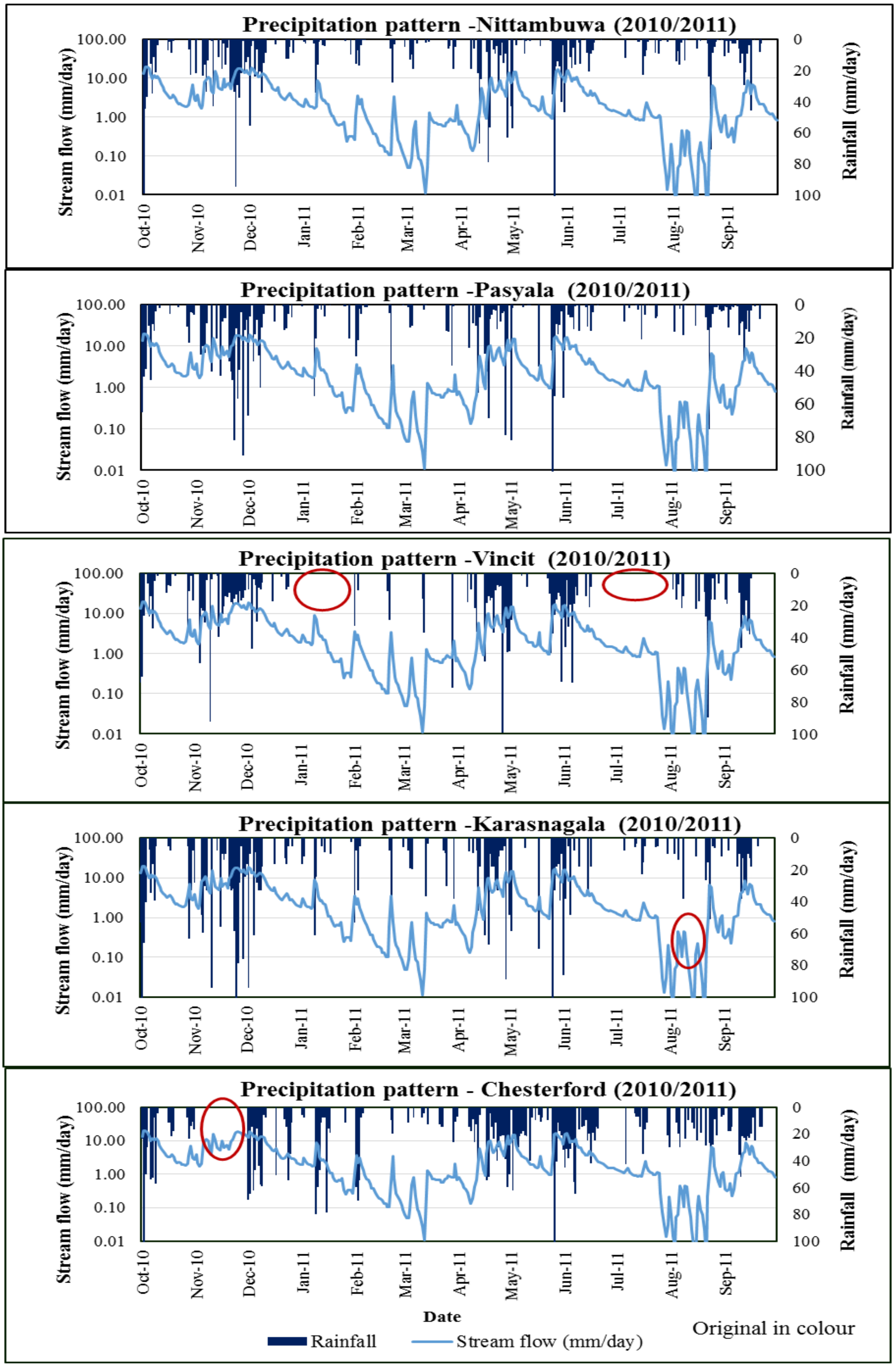


Figure A- 5: Stream flow response to rainfall - Dunamale watershed - 2009-2010



Original in colour

Figure A- 6: Stream flow response to rainfall - Dunamale watershed - 2010-2011

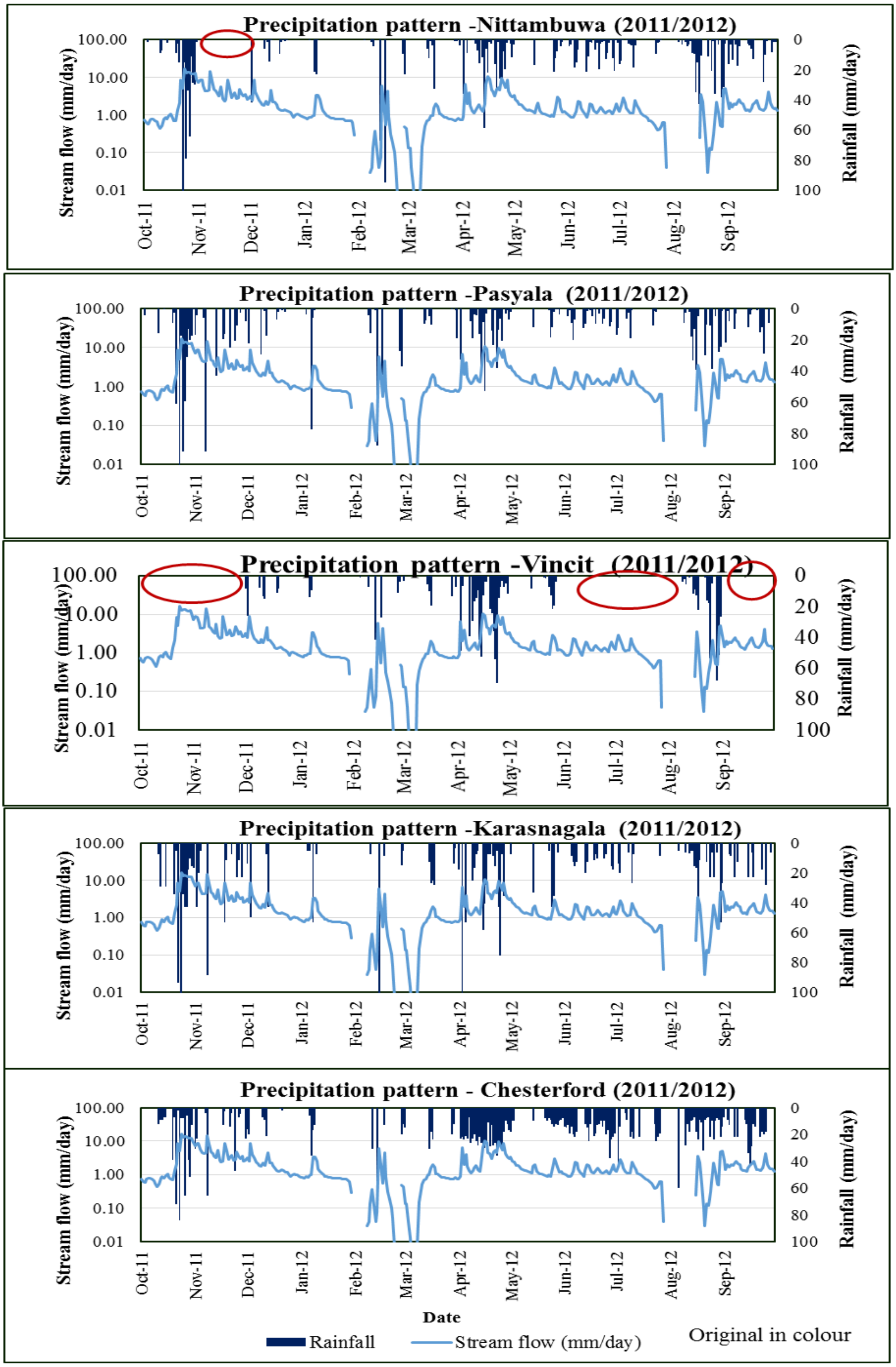
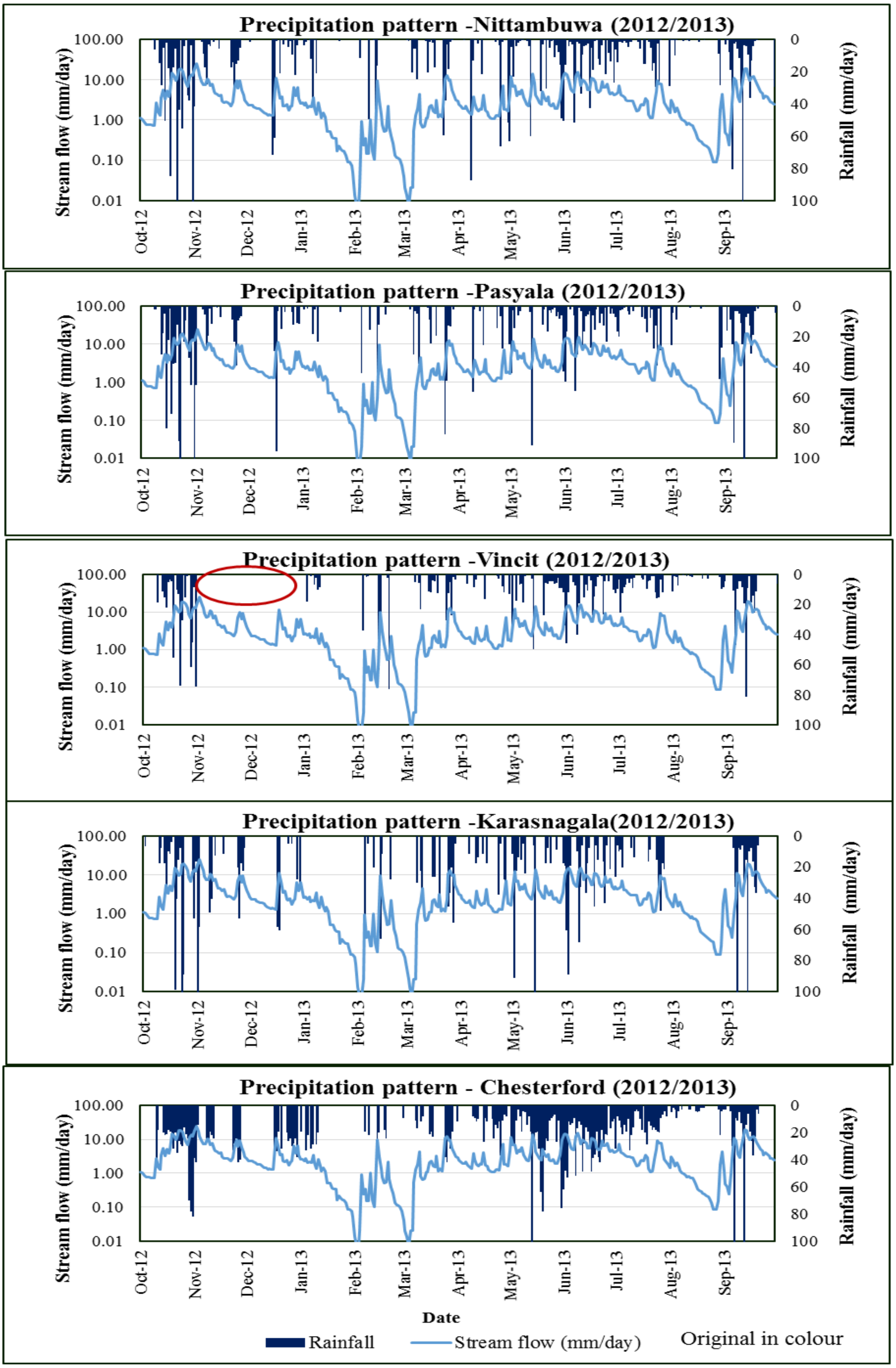


Figure A- 7: Stream flow response to rainfall - Dunamale watershed - 2011-2012



Original in colour

Figure A- 8: Stream flow response to rainfall - Dunamale watershed - 2012-2013

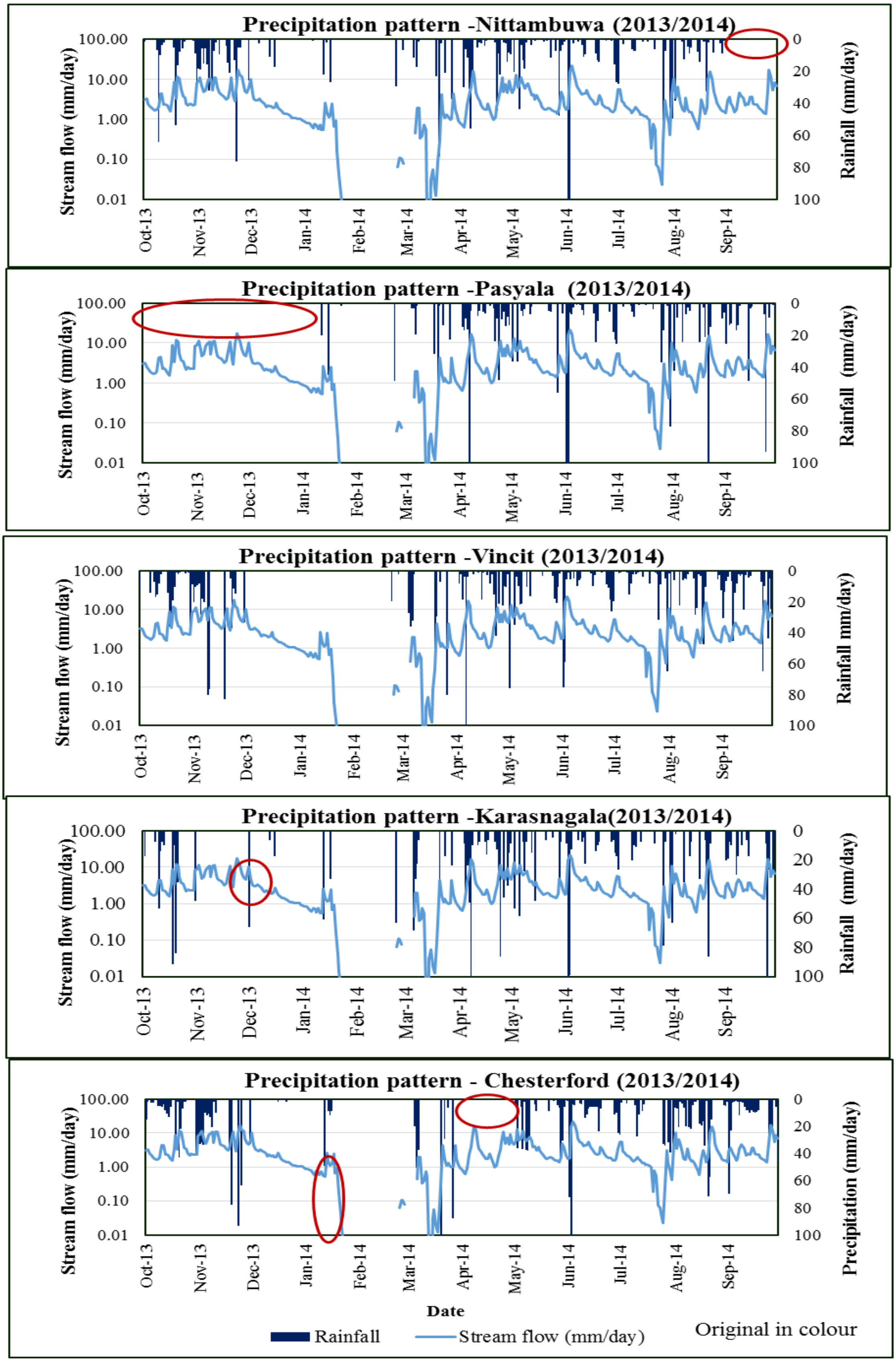
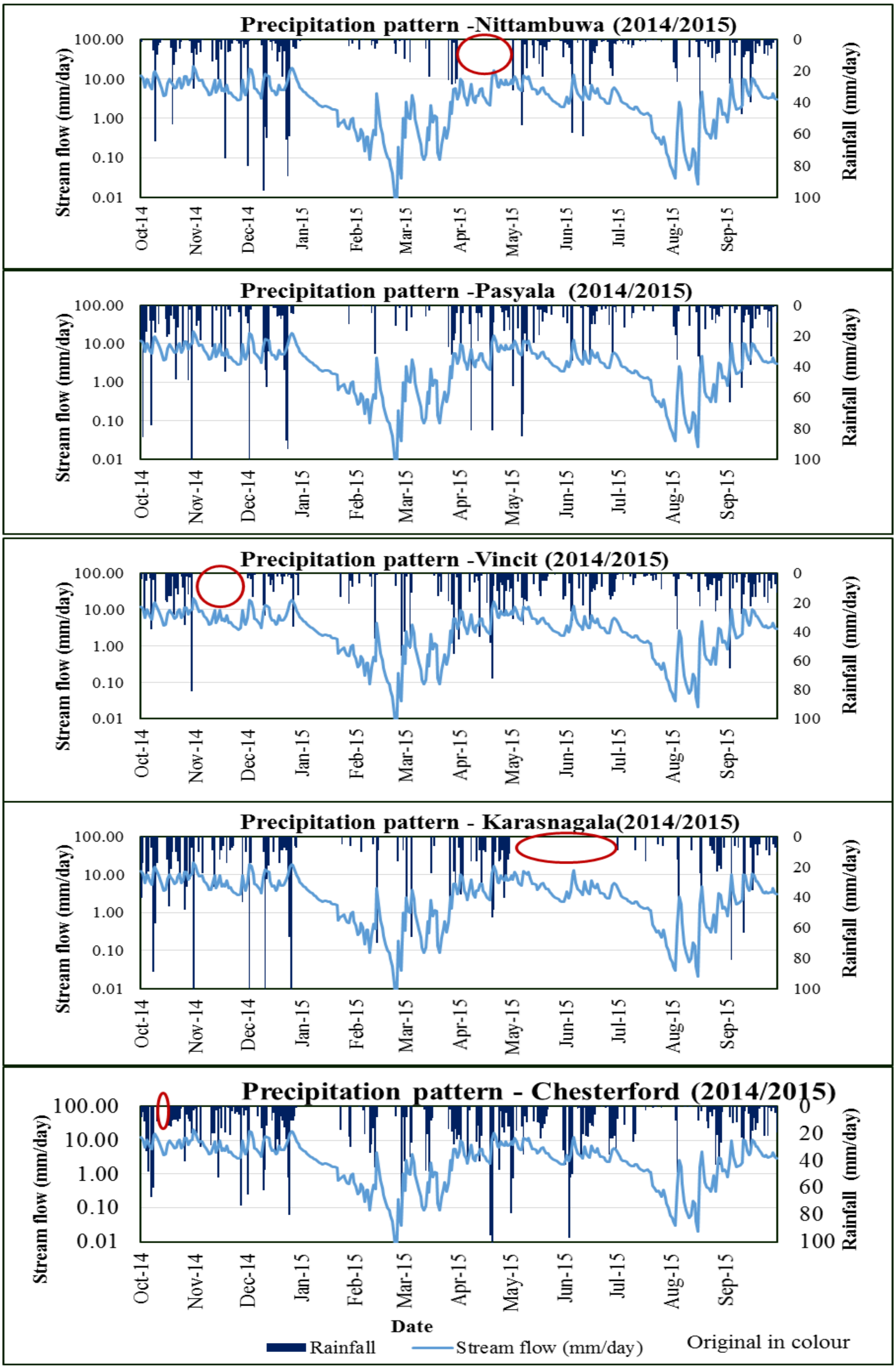


Figure A- 9: Stream flow response to rainfall - Dunamale watershed - 2013-2014



Precipitation pattern -Nittambuwa (2014/2015)

Precipitation pattern -Pasyala (2014/2015)

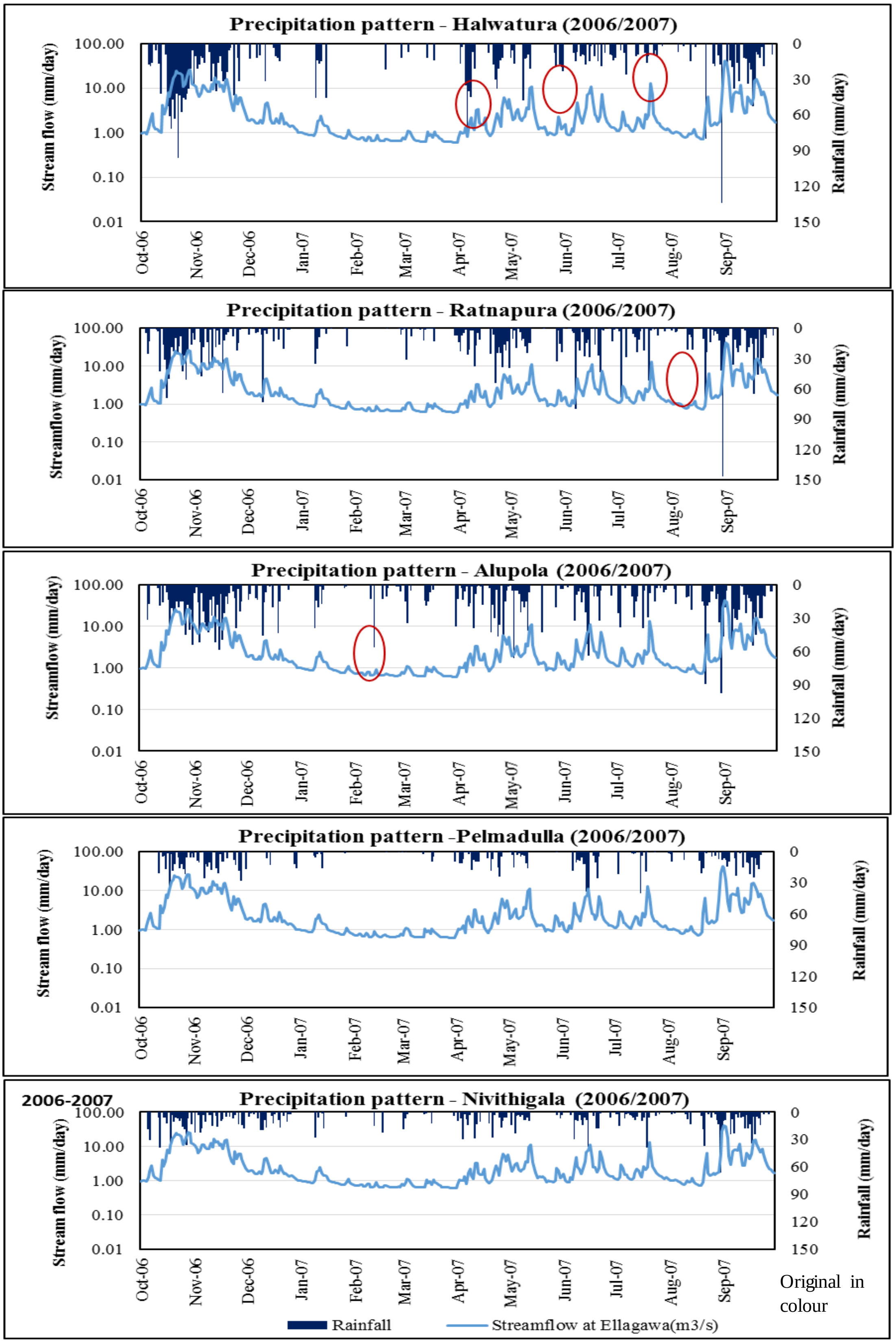
Precipitation pattern -Vincit (2014/2015)

Precipitation pattern - Karasnagala(2014/2015)

Precipitation pattern - Chesterford (2014/2015)

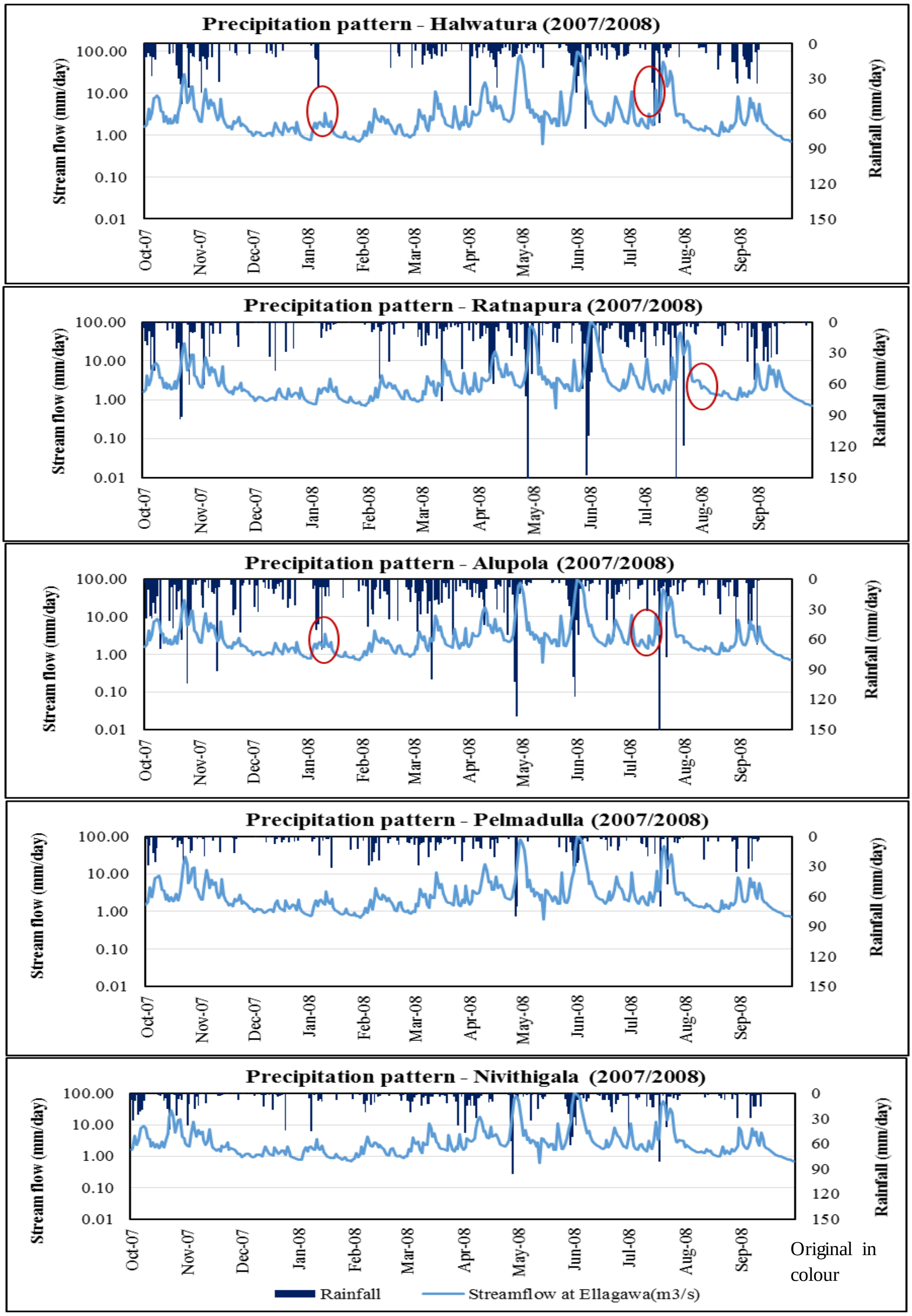
Figure A- 10: Stream flow response to rainfall - Dunamale watershed - 2014-2015

APPENDIX B: Streamflow Variation Corresponding to Rainfall – Ellagawa watershed



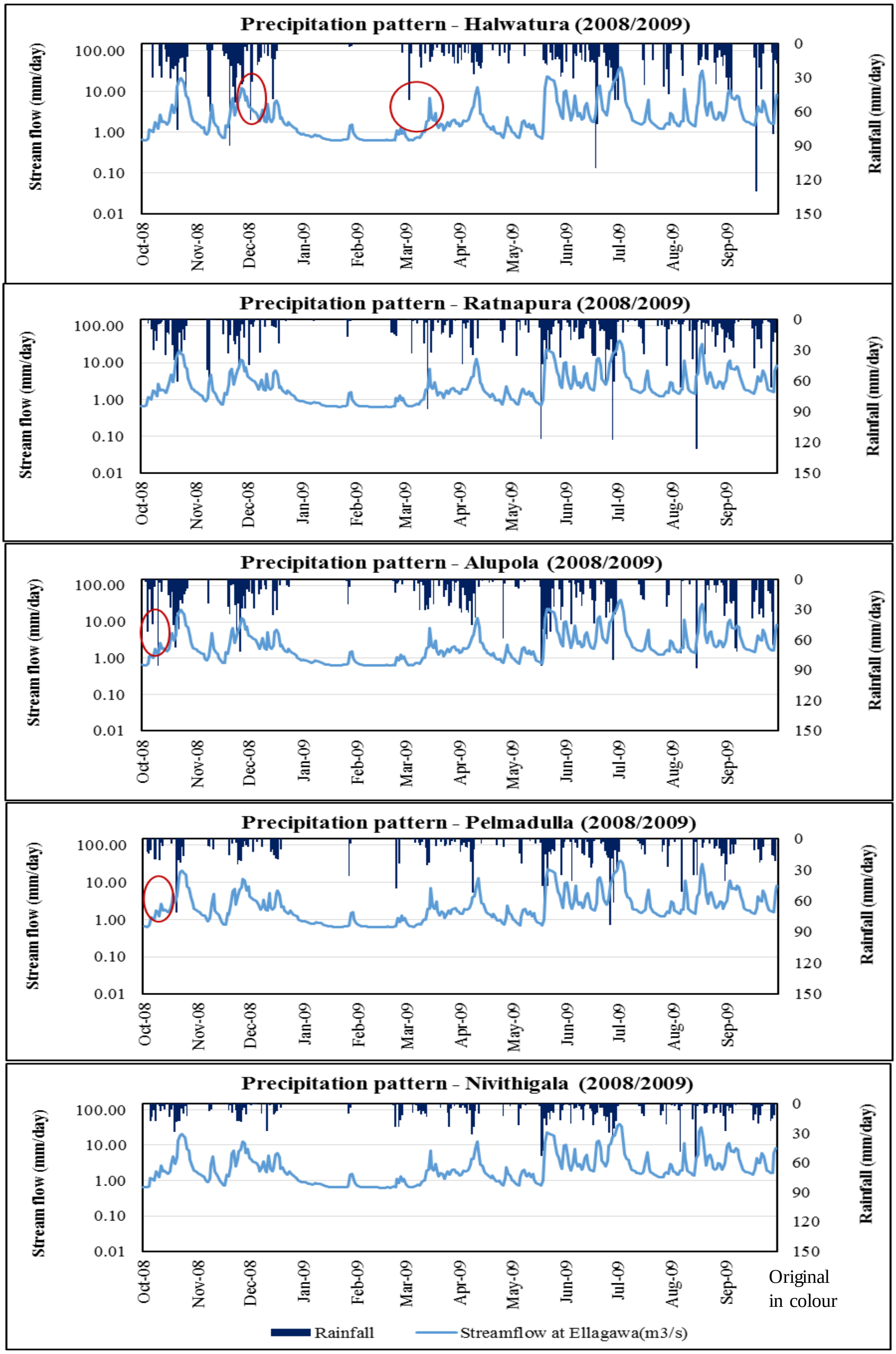
Original in colour

Figure B- 1: Stream flow response to rainfall – Ellagawa watershed - 2006-2007



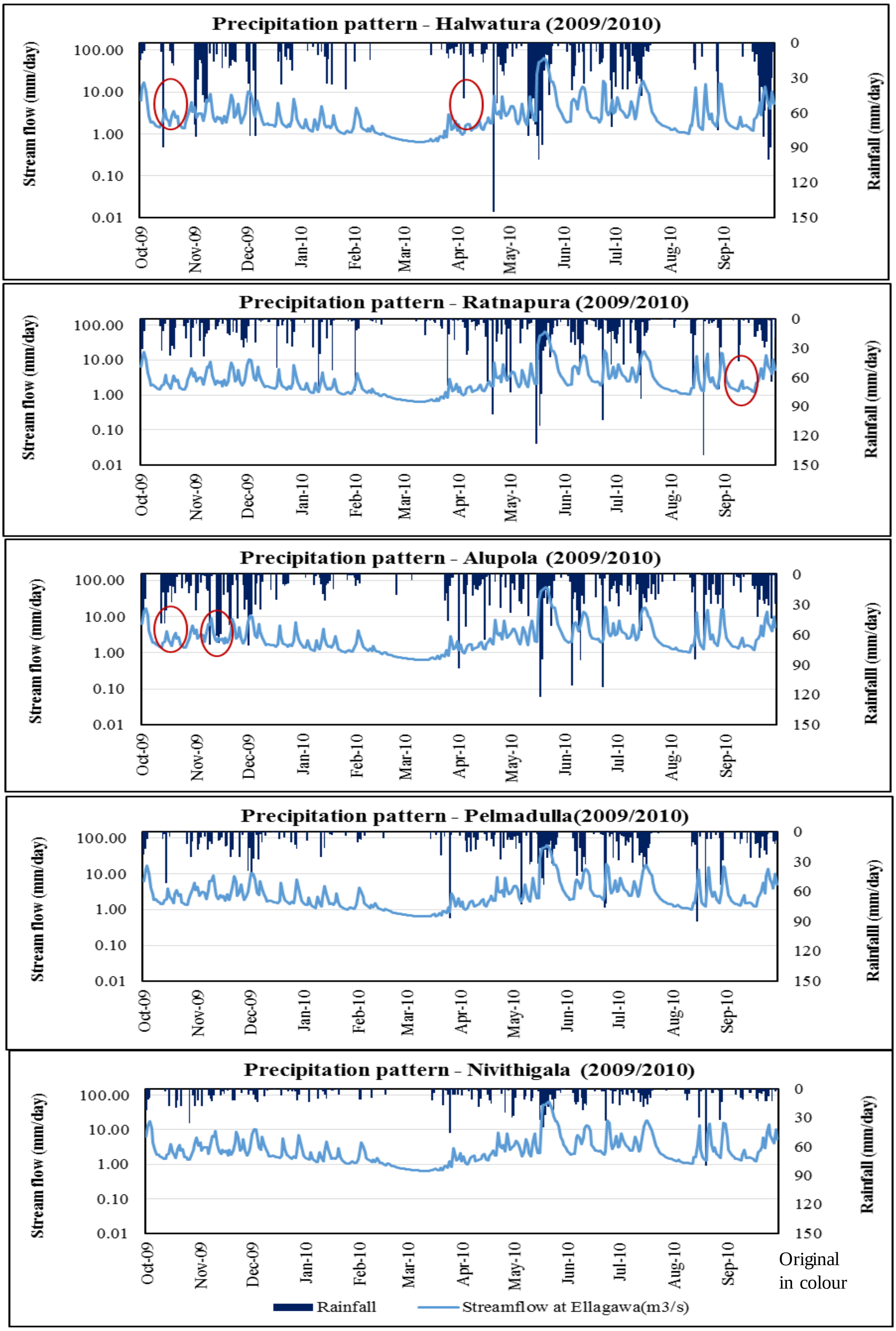
Original in colour

Figure B- 2: Stream flow response to rainfall – Ellagawa watershed - 2007-2008



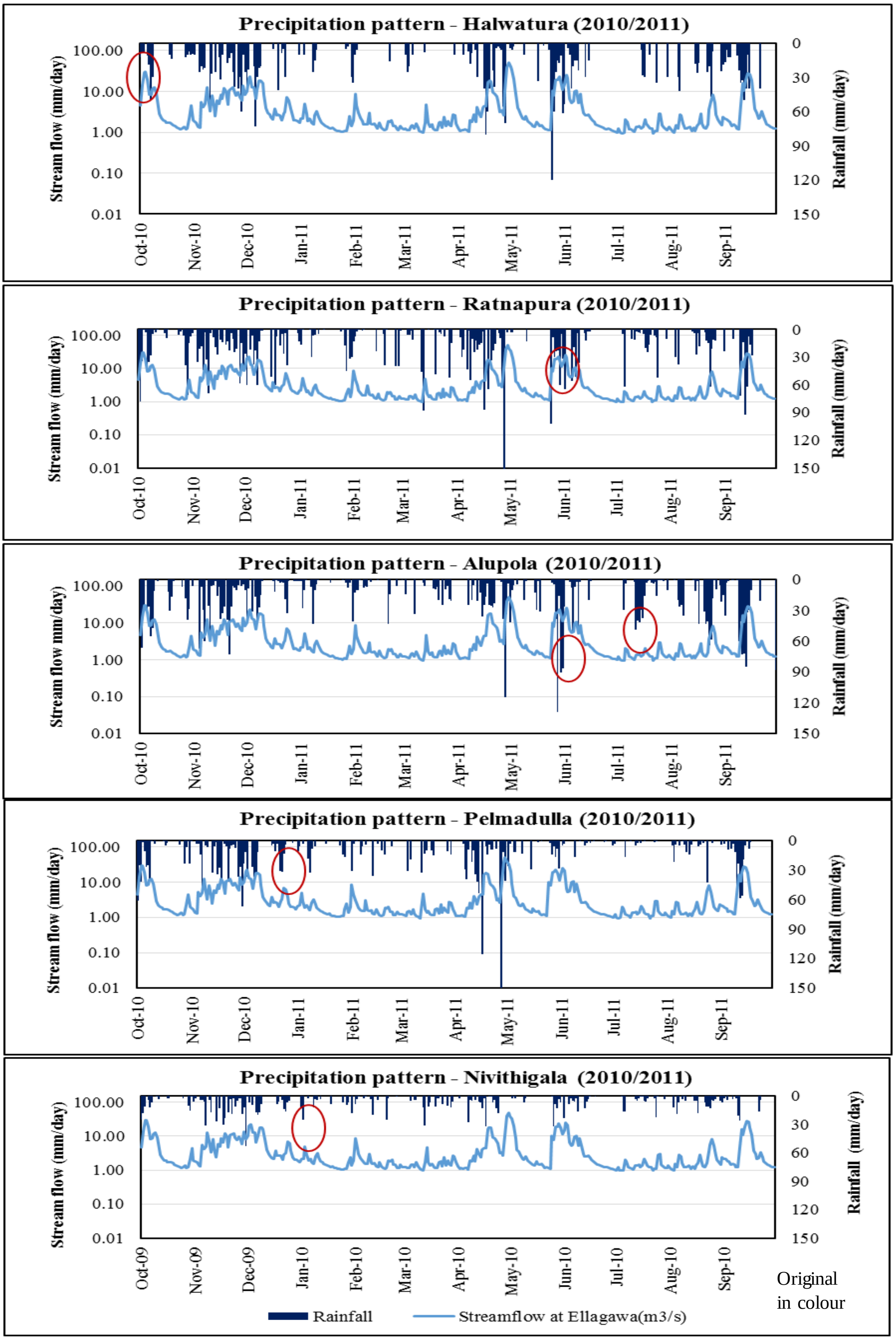
Original in colour

Figure B- 3: Stream flow response to rainfall – Ellagawa watershed- 2008-2009



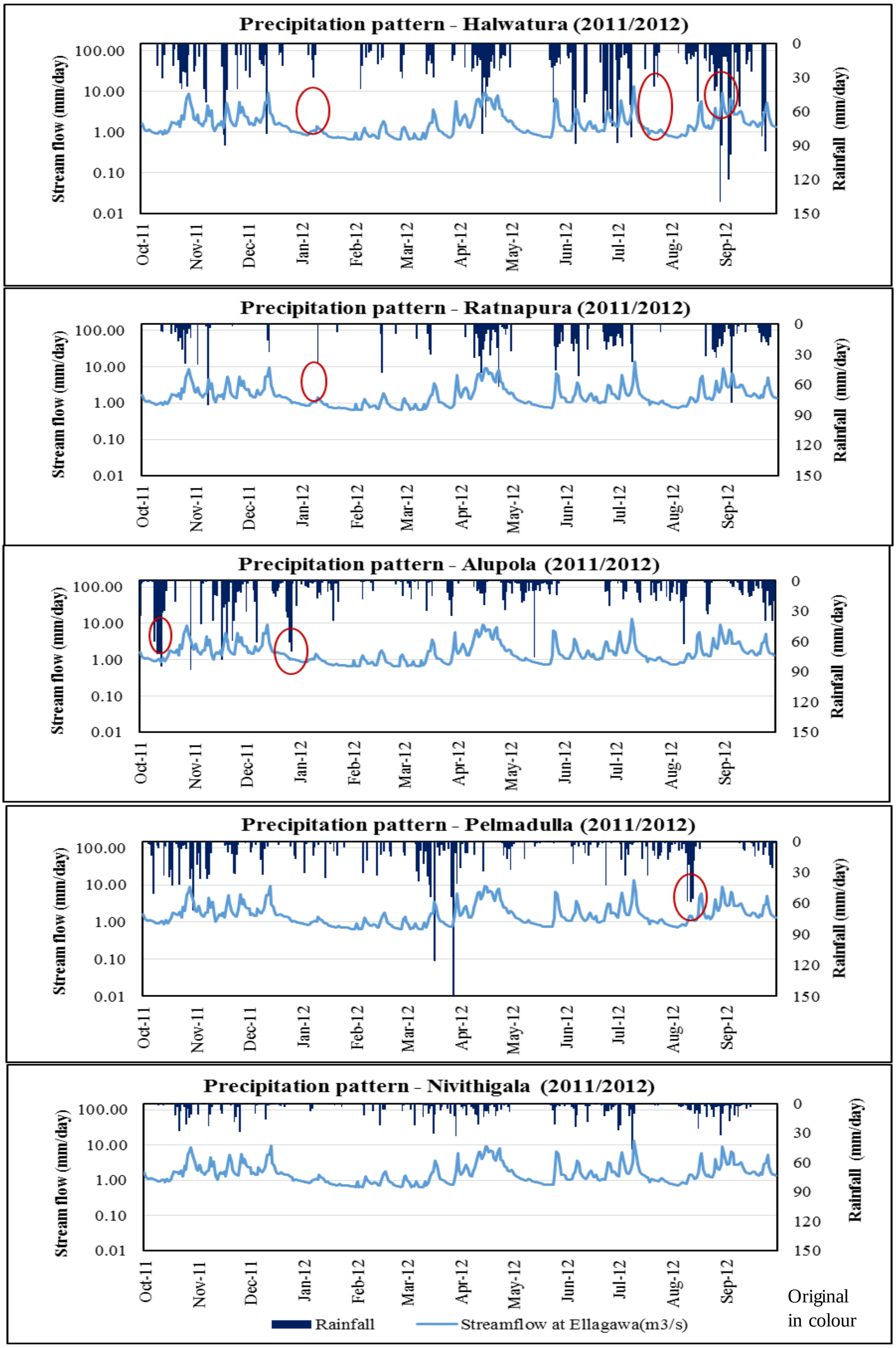
Original in colour

Figure B- 4: Stream flow response to rainfall – Ellagawa watershed- 2009-2010



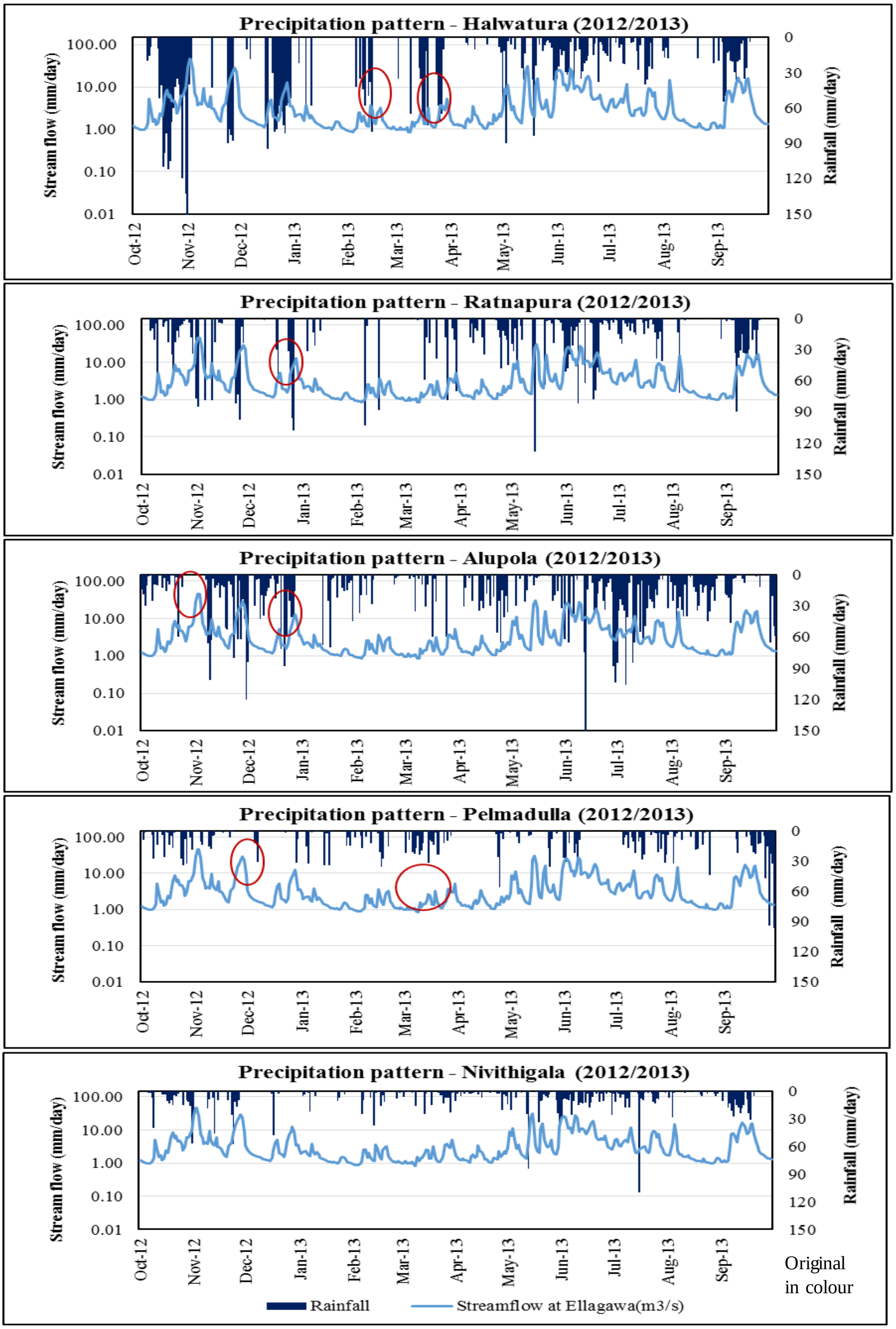
Original in colour

Figure B- 5: Stream flow response to rainfall – Ellagawa watershed - 2010-2011



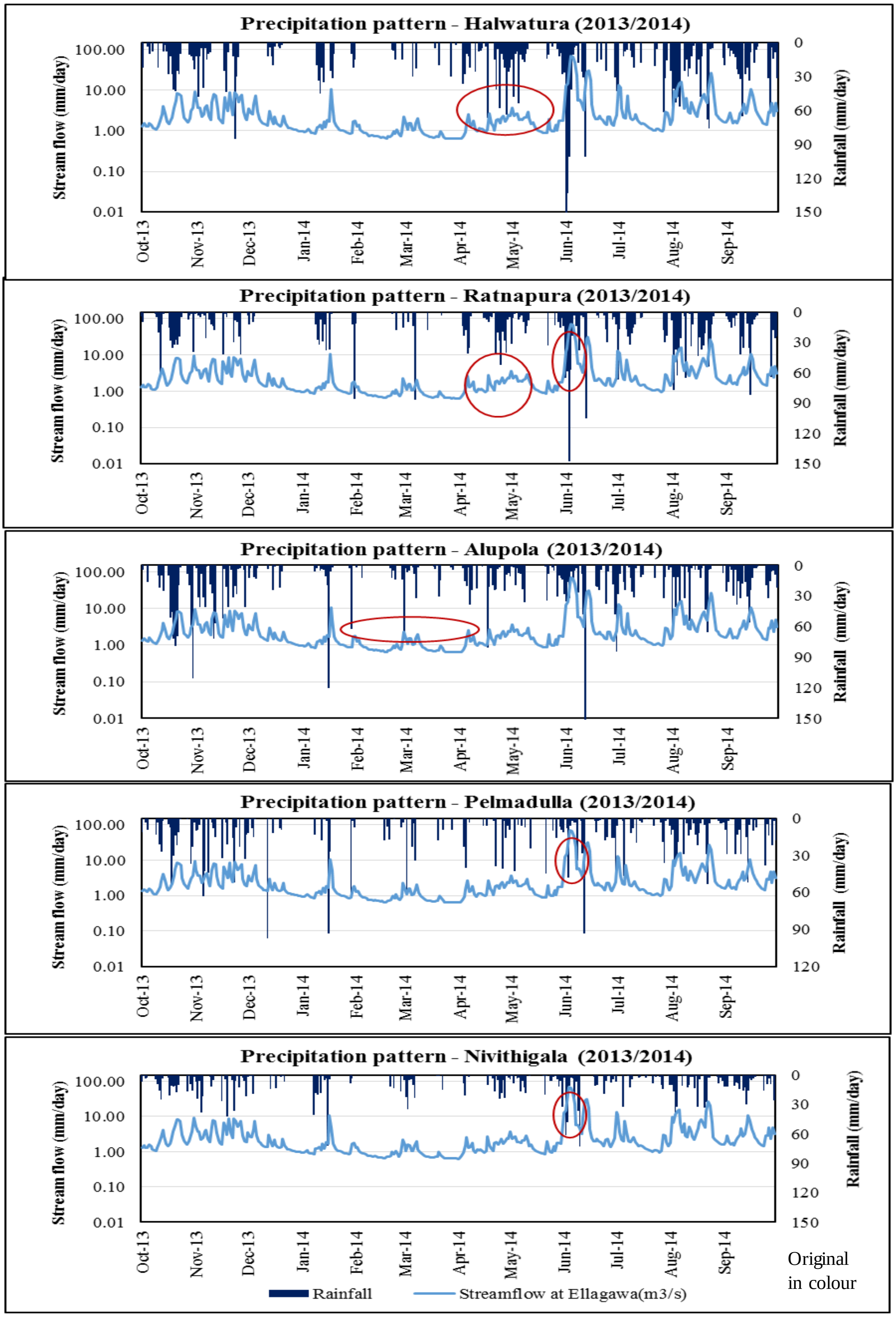
Original in colour

Figure B- 6: Stream flow response to rainfall – Ellagawa watershed - 2011-2012



Original in colour

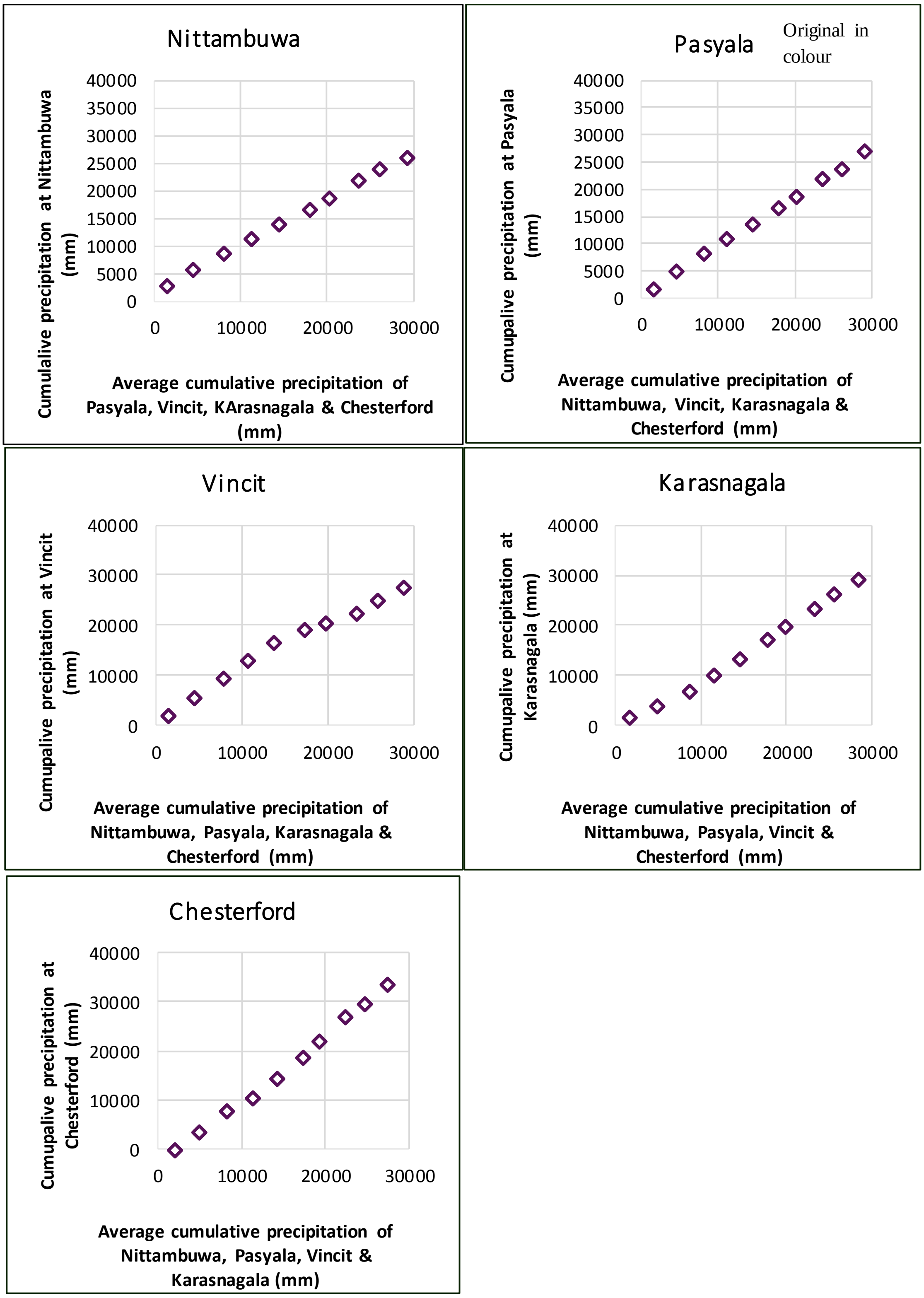
Figure B- 7: Stream flow response to rainfall – Ellagawa watershed - 2012-2013



Original in colour

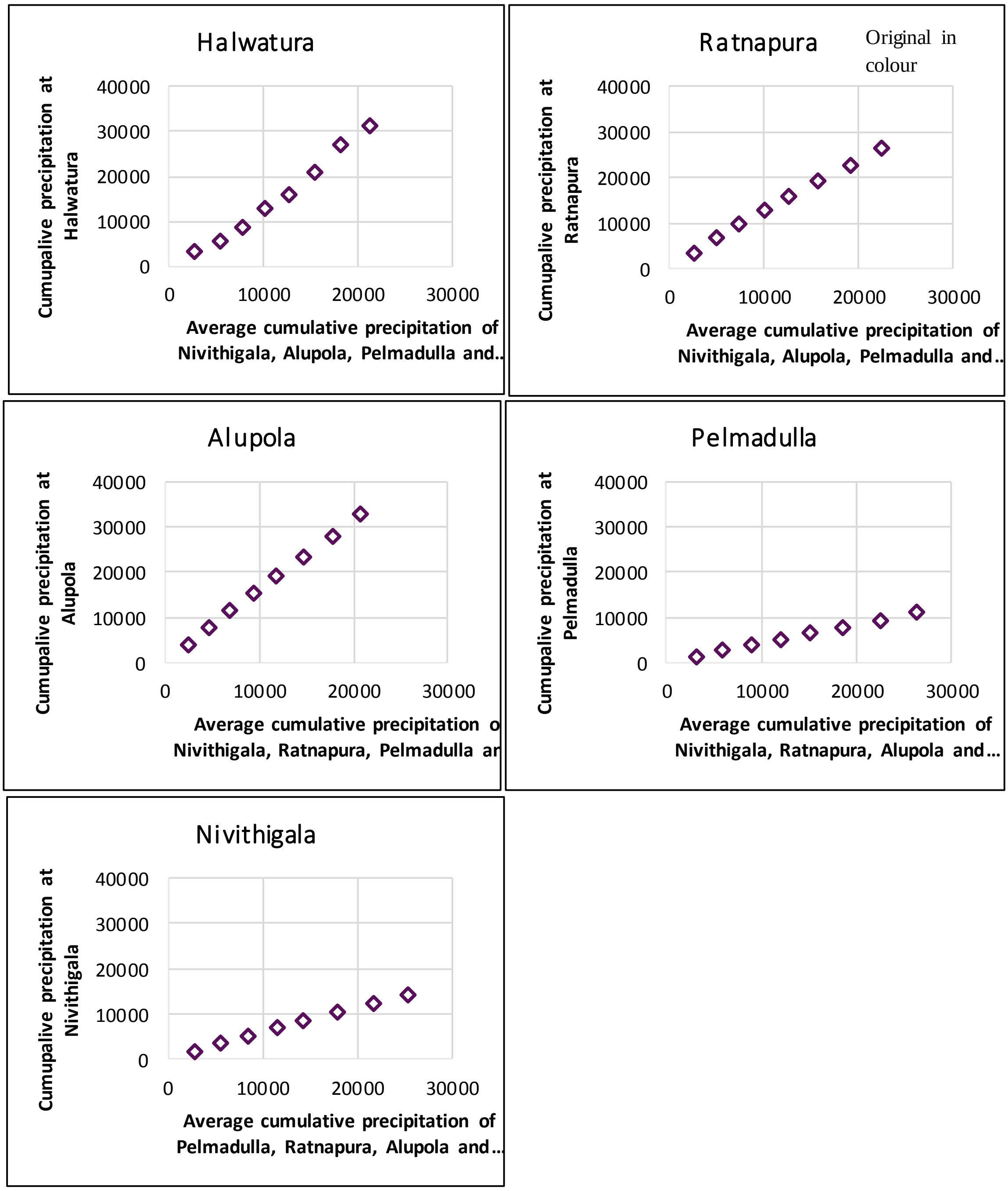
Figure B- 8: Stream flow response to rainfall – Ellagawa watershed - 2013-2014

APPENDIX C: Double mass curve results for Dunamale and Ellagawa watersheds



Original in colour

Figure D- 1: Double mass curve for Dunamale watershed



Original in colour

Figure D- 2: Double mass curve for Ellagawa watershed

APPENDIX D: HEC-HMS daily model results for observed rainfall input for Dunamale and Ellagawa watersheds

Dunamale watershed - Modelled and Observed streamflow

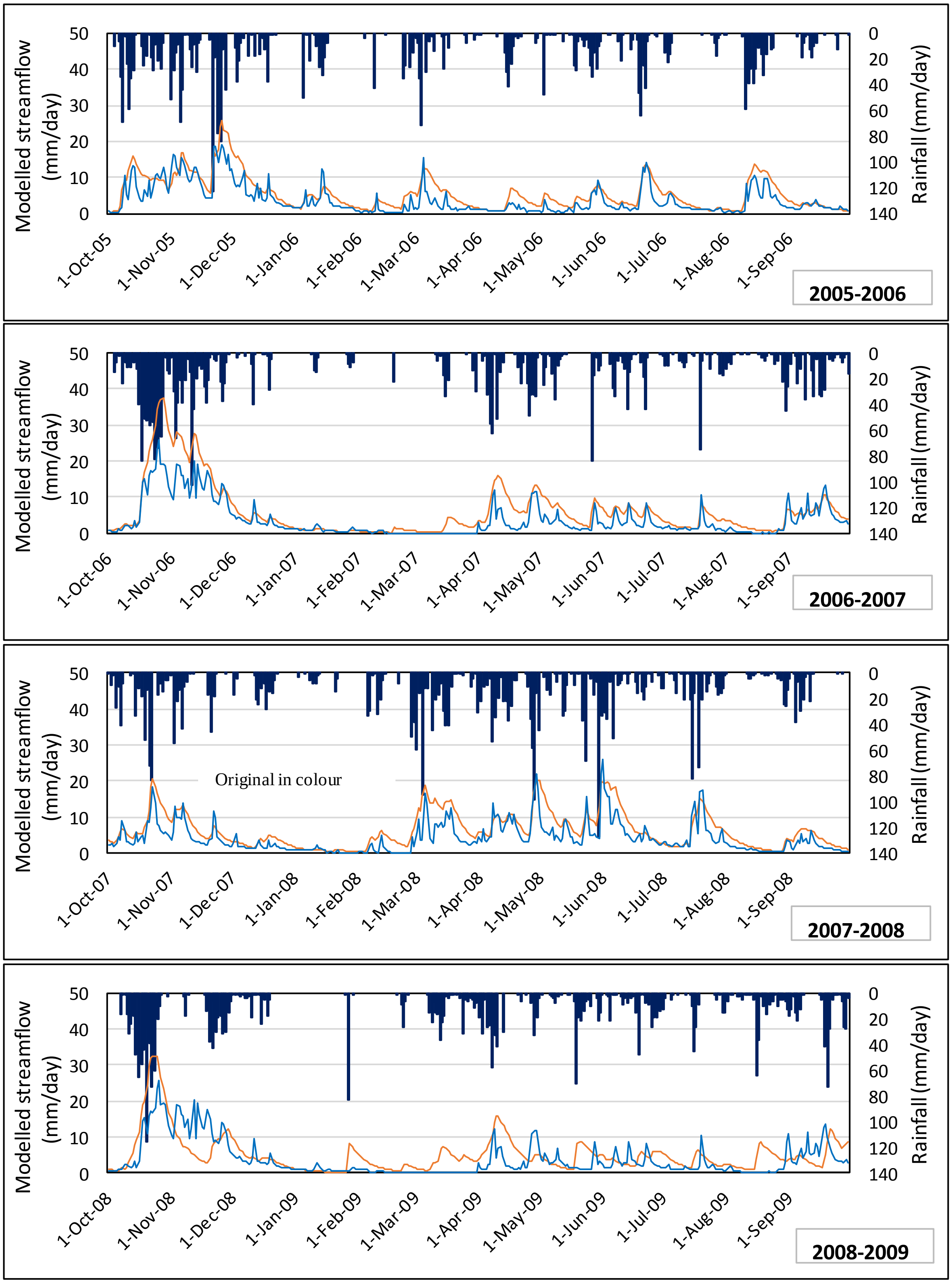
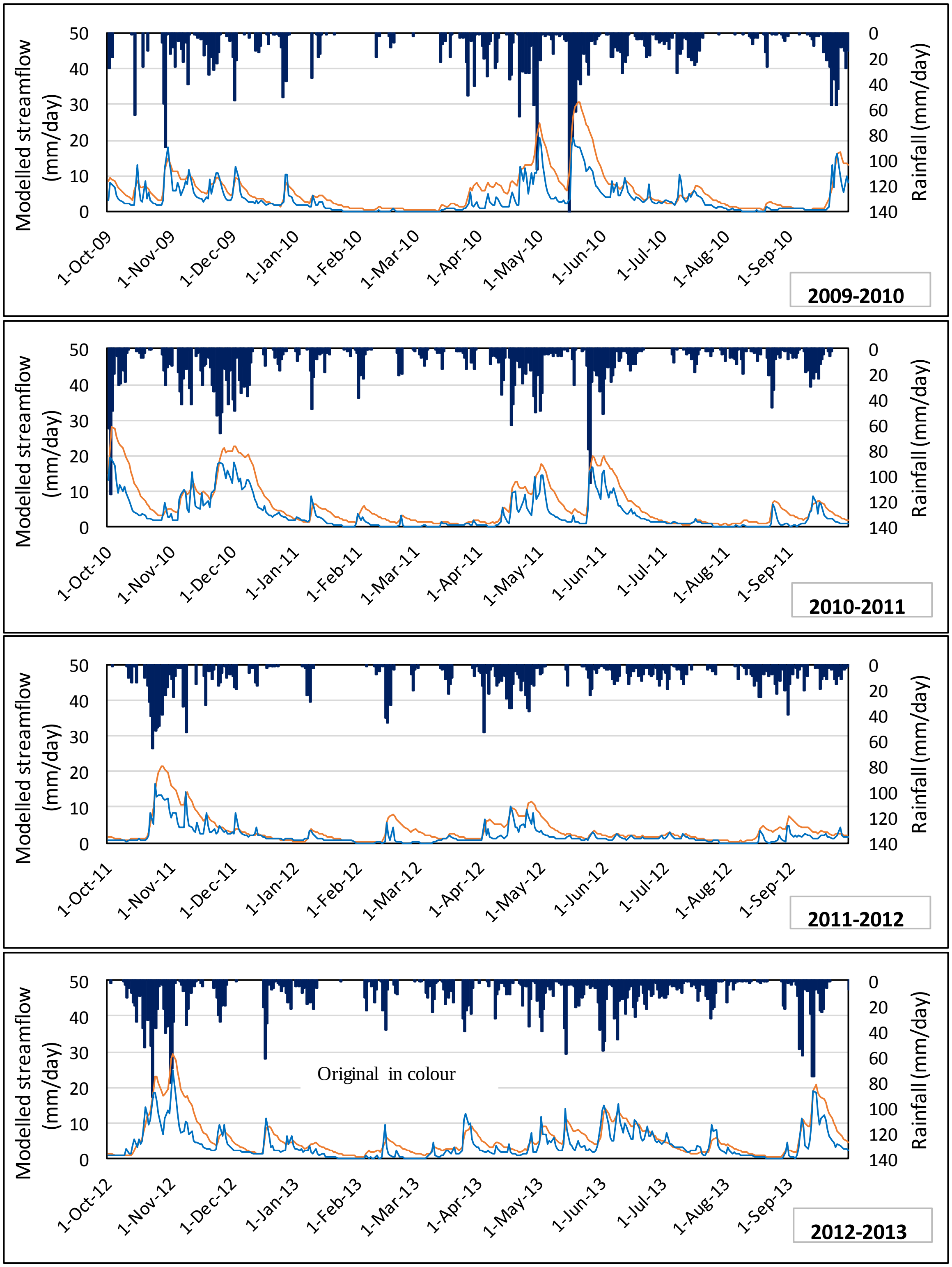


Figure E- 1: Modelled and observed streamflow (2005-2009) - Dunamale watershed



Original in colour

Figure E- 2: Modelled and observed streamflow (2009-2013) - Dunamale watershed

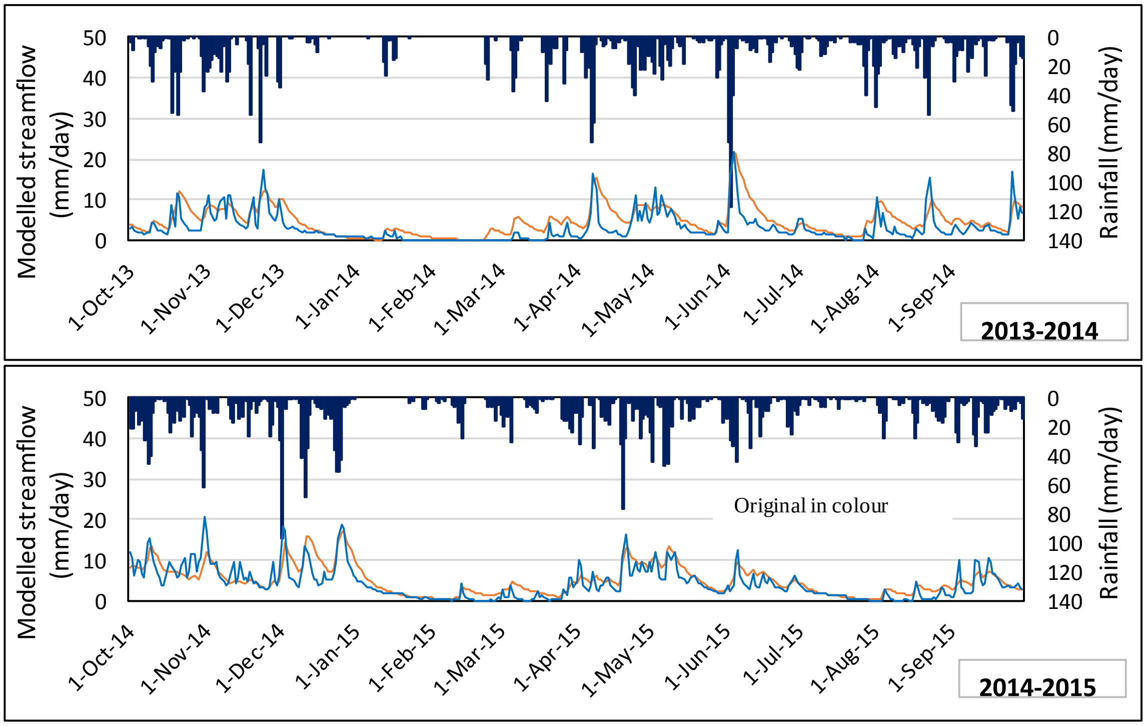


Figure E- 3: Modelled and observed streamflow (2013-2015) - Dunamale watershed

Log scale modelled and observed streamflow

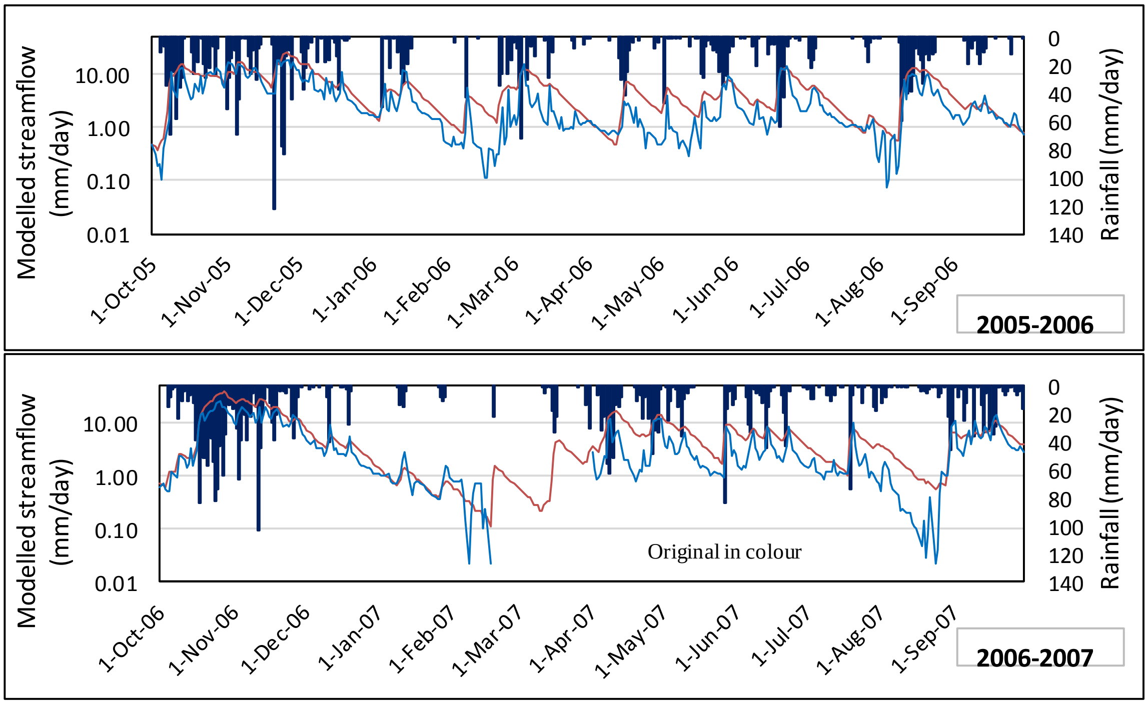


Figure E- 4: Modeled and observed streamflow - (2005-2007)- Dunamale watershed

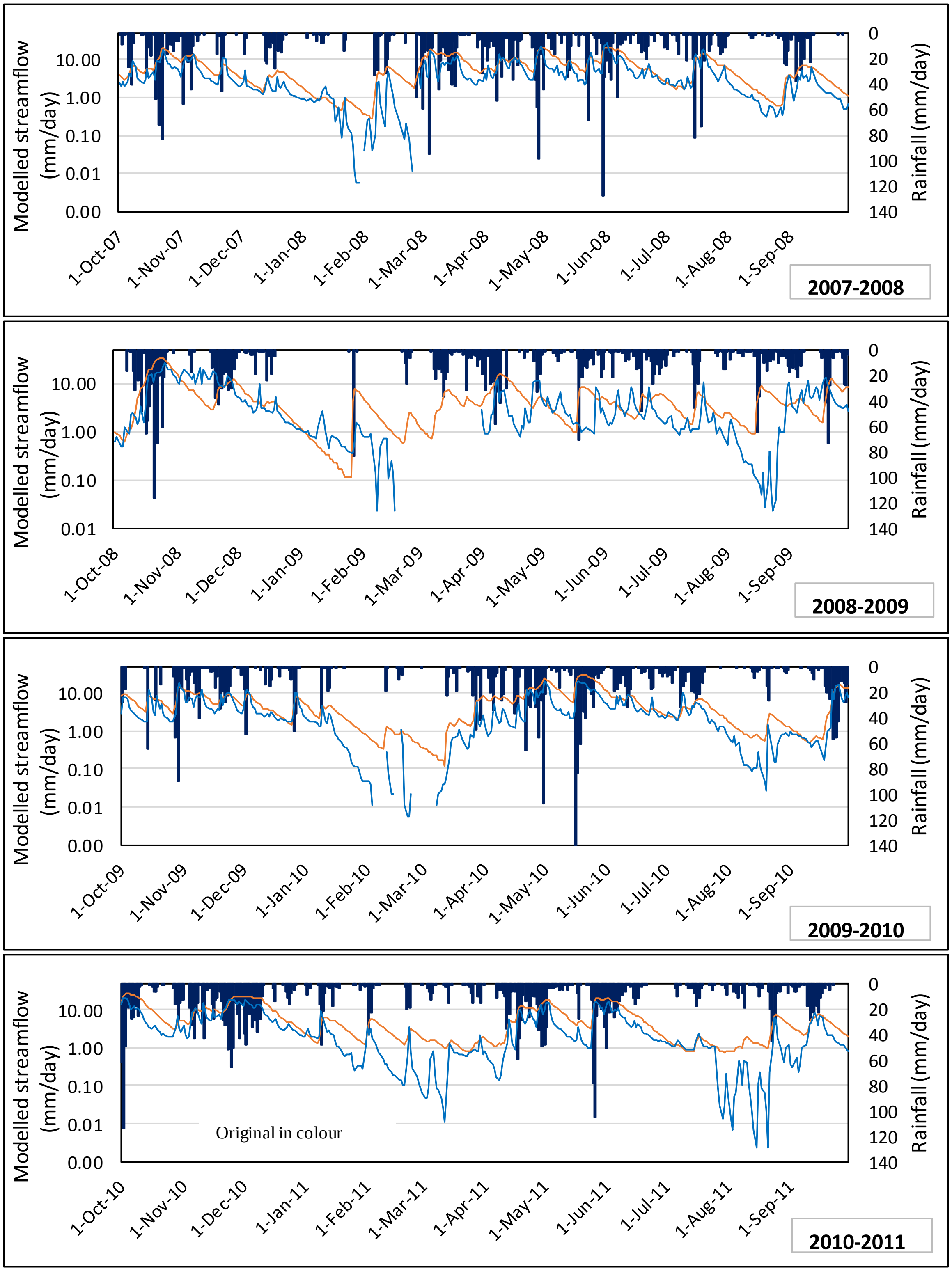


Figure E- 5: Modeled and observed streamflow - (2007-2011)- Dunamale watershed

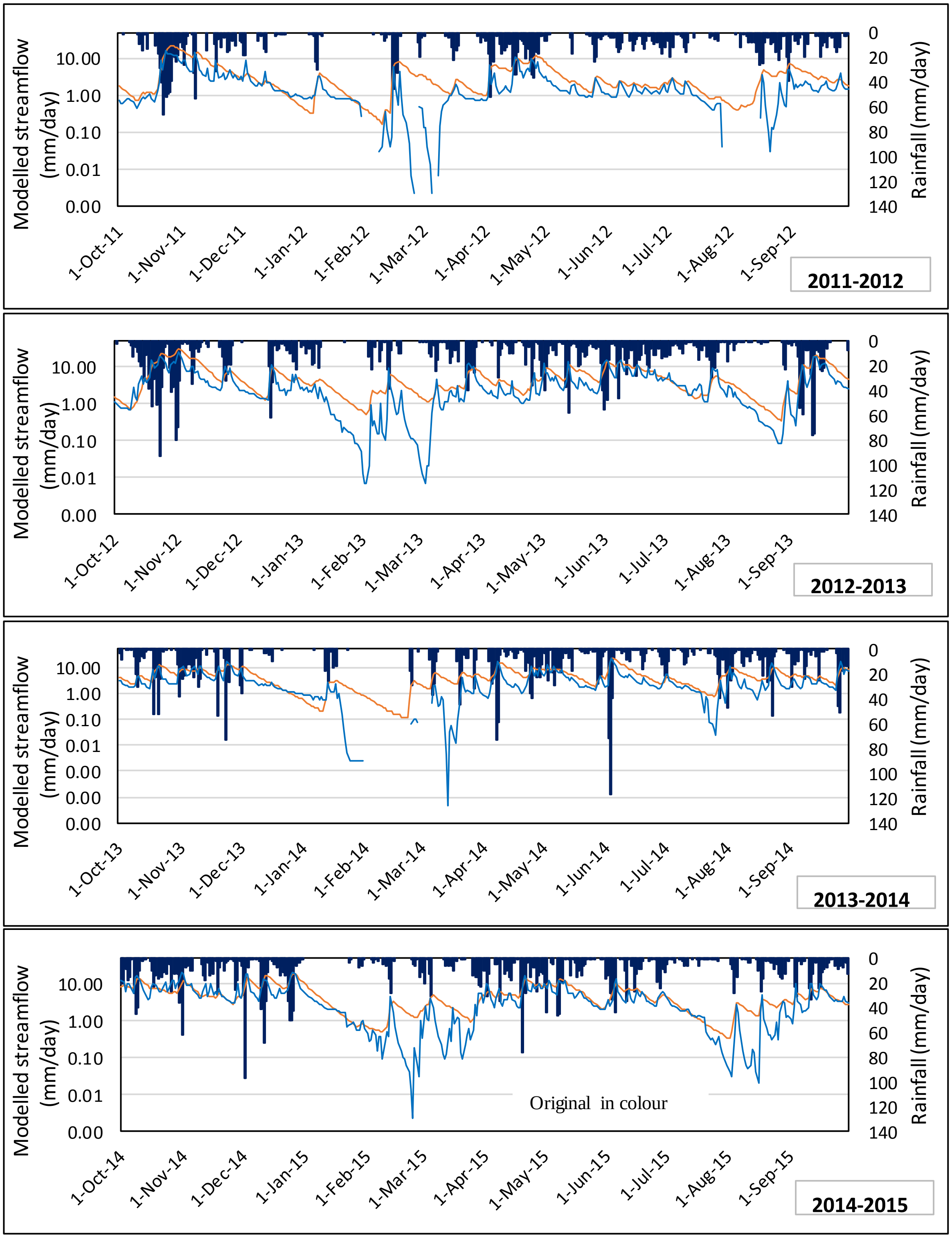


Figure E- 6: Modeled and observed streamflow - (2011-2015)- Dunamale watershed

Ellagawa - Modelled and observed streamflow

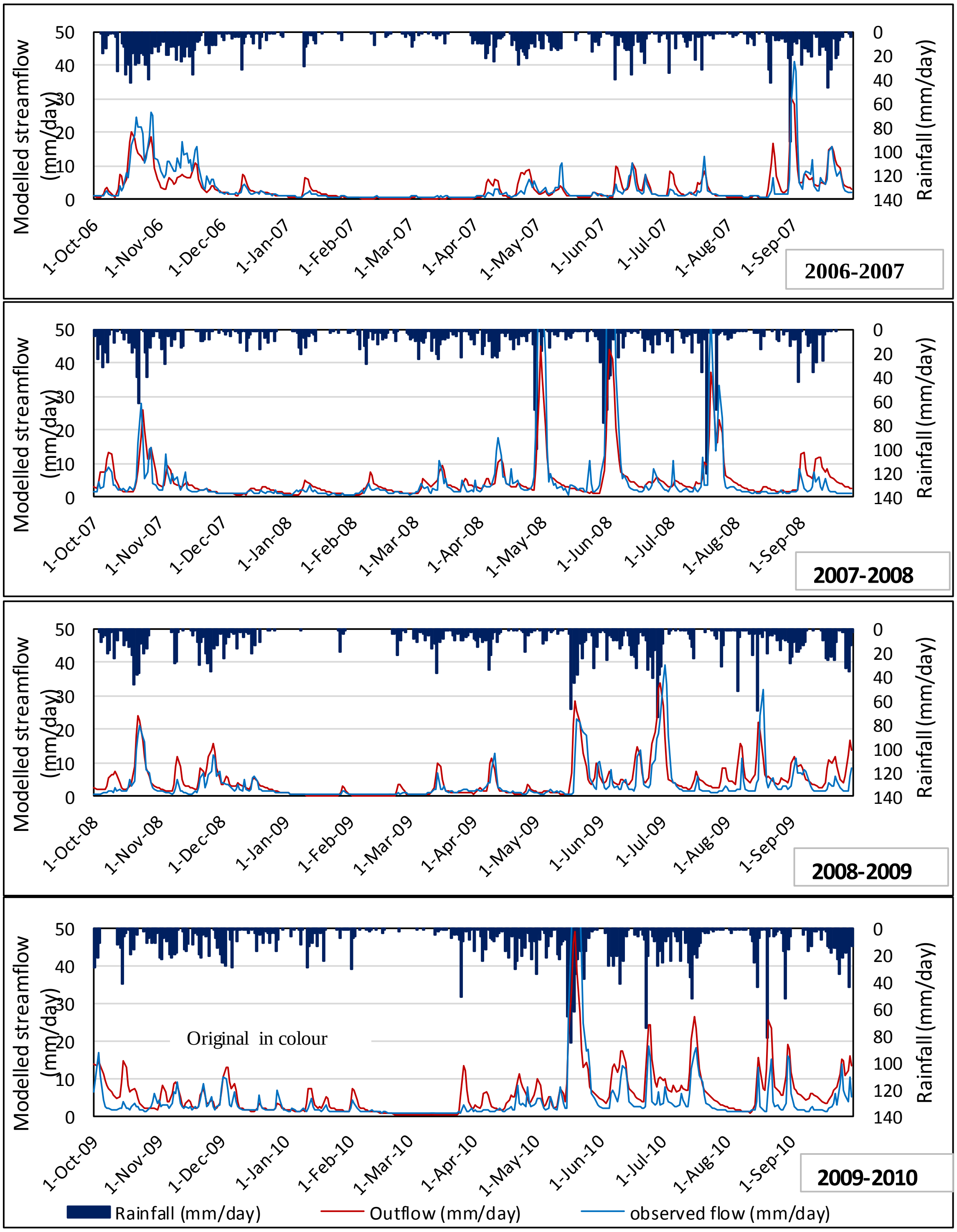


Figure E- 7: Modeled and observed streamflow - Ellagawa - 2006-2010

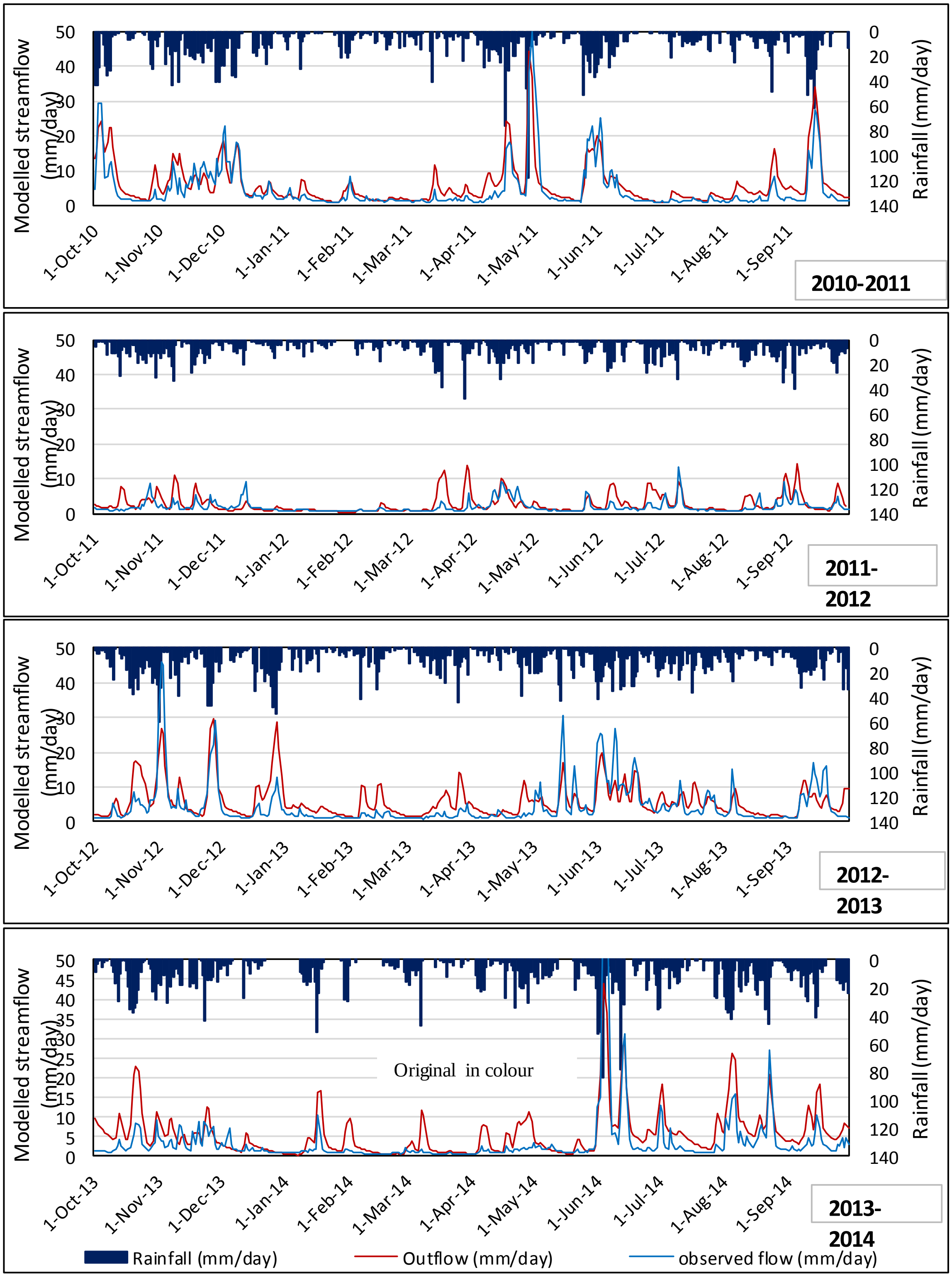
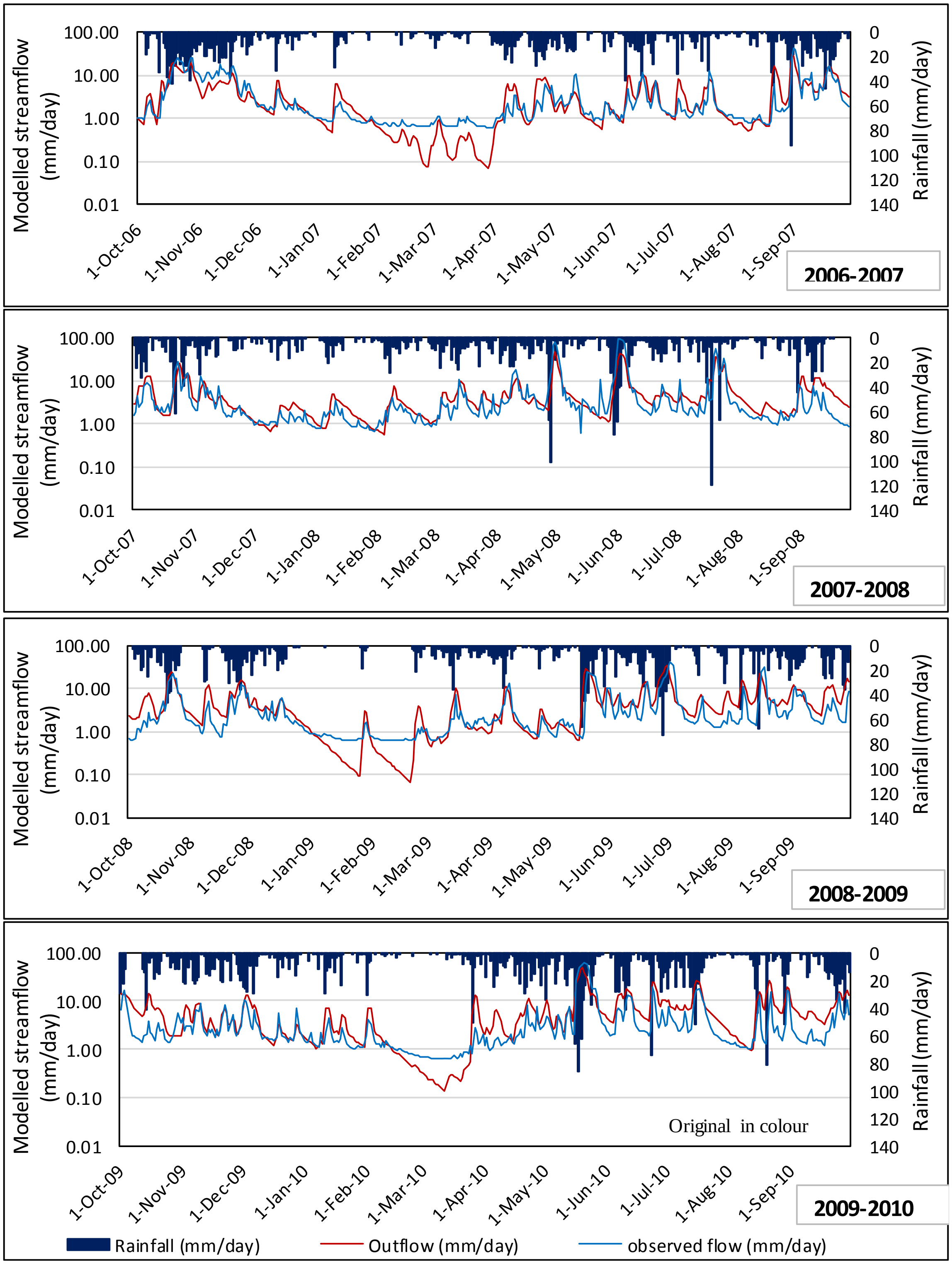


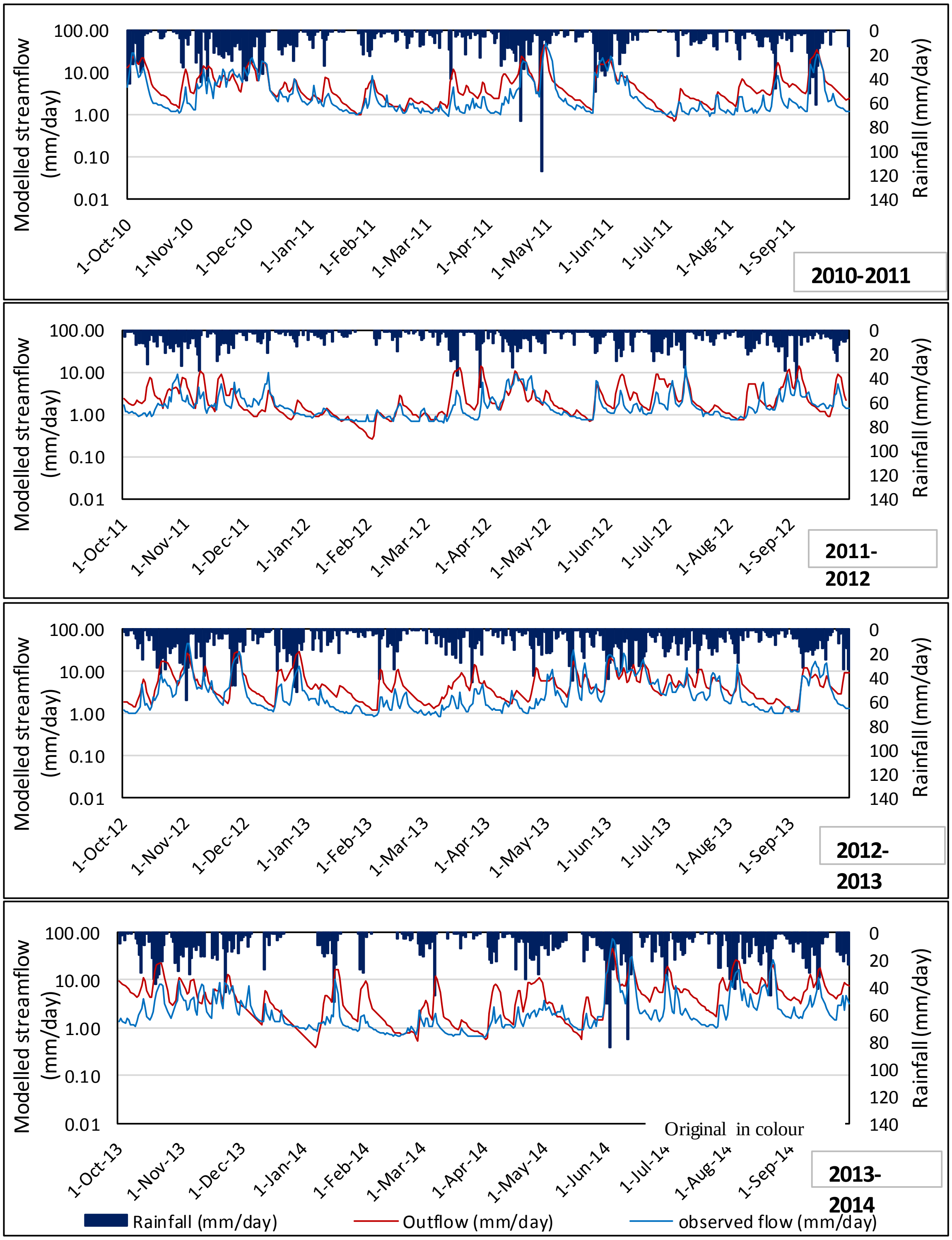
Figure E- 8: Modeled and observed streamflow - Ellagawa - 2010-2014

Semi log scale modelled and observed streamflow



Original in colour

Figure E- 9: Modelled and observed streamflow - Ellagawa - 2006-2010



Original in colour

Figure E- 10: Modeled and observed streamflow - Ellagawa - 2010-2014

APPENDIX E: UH model effective rainfall variation for Dunamale and Ellagawa watersheds

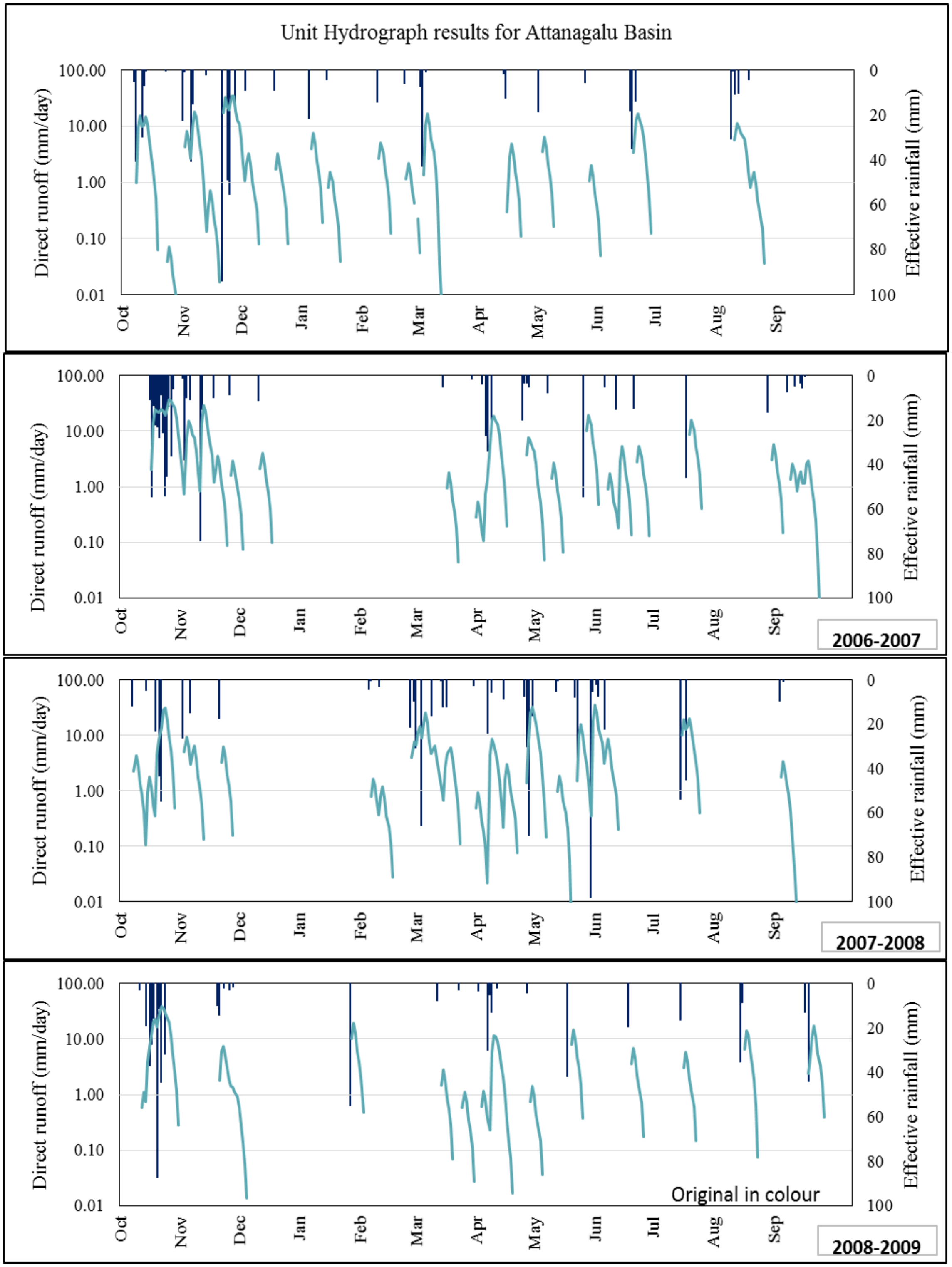


Figure F- 1: Effective rainfall and direct runoff variation (2005-2009) - Dunamale watershed

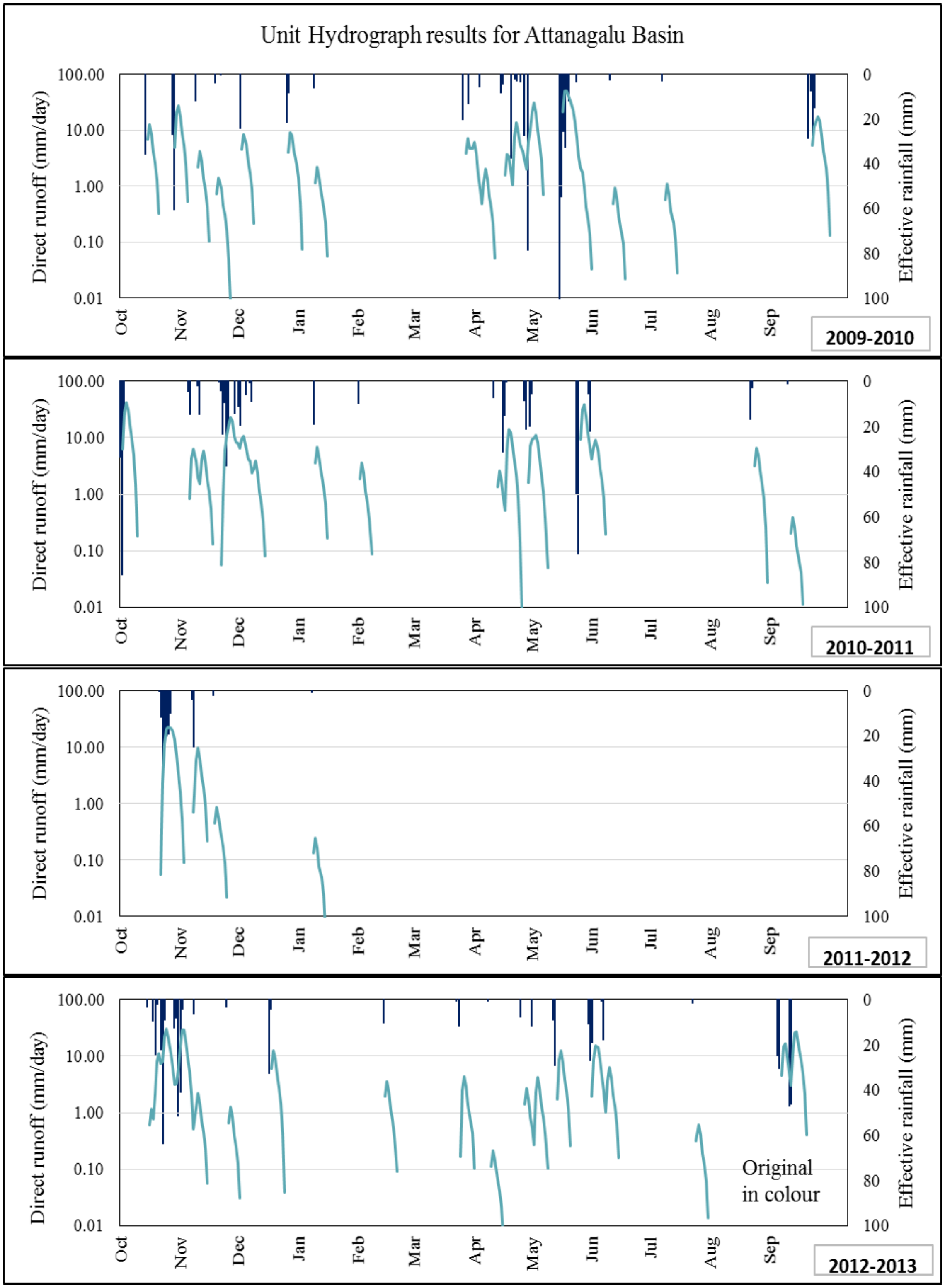


Figure F- 2: Effective rainfall and direct runoff variation (2009-2013) - Dunamale watershed

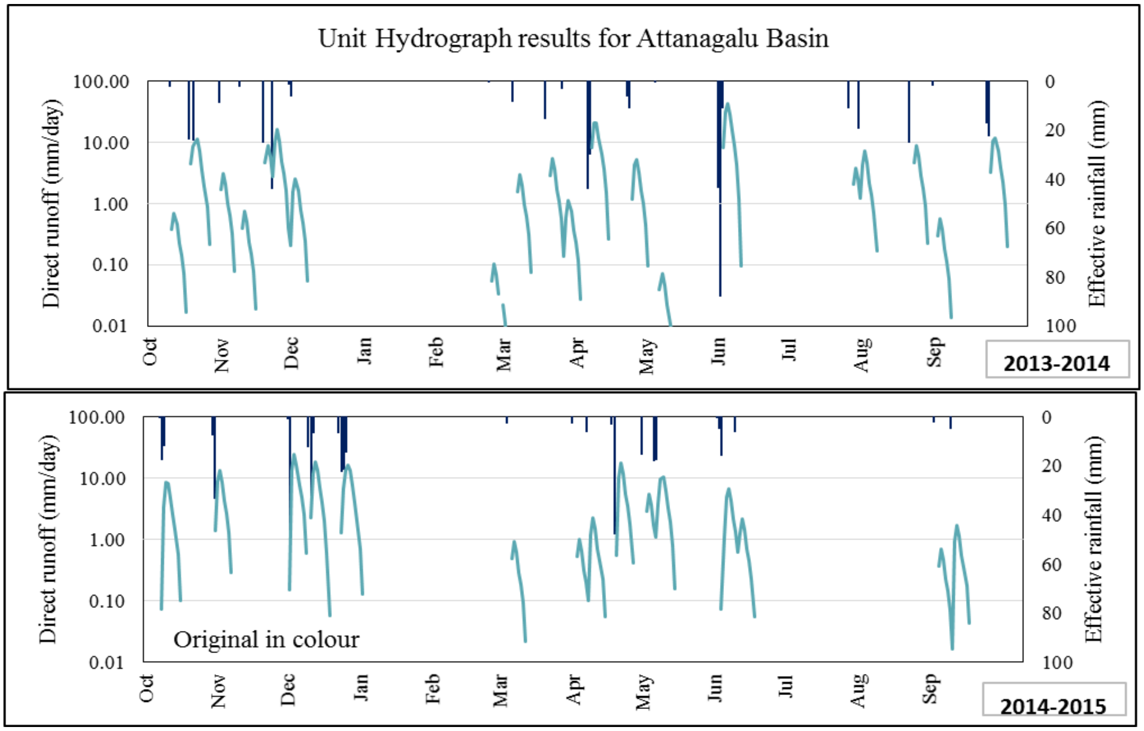
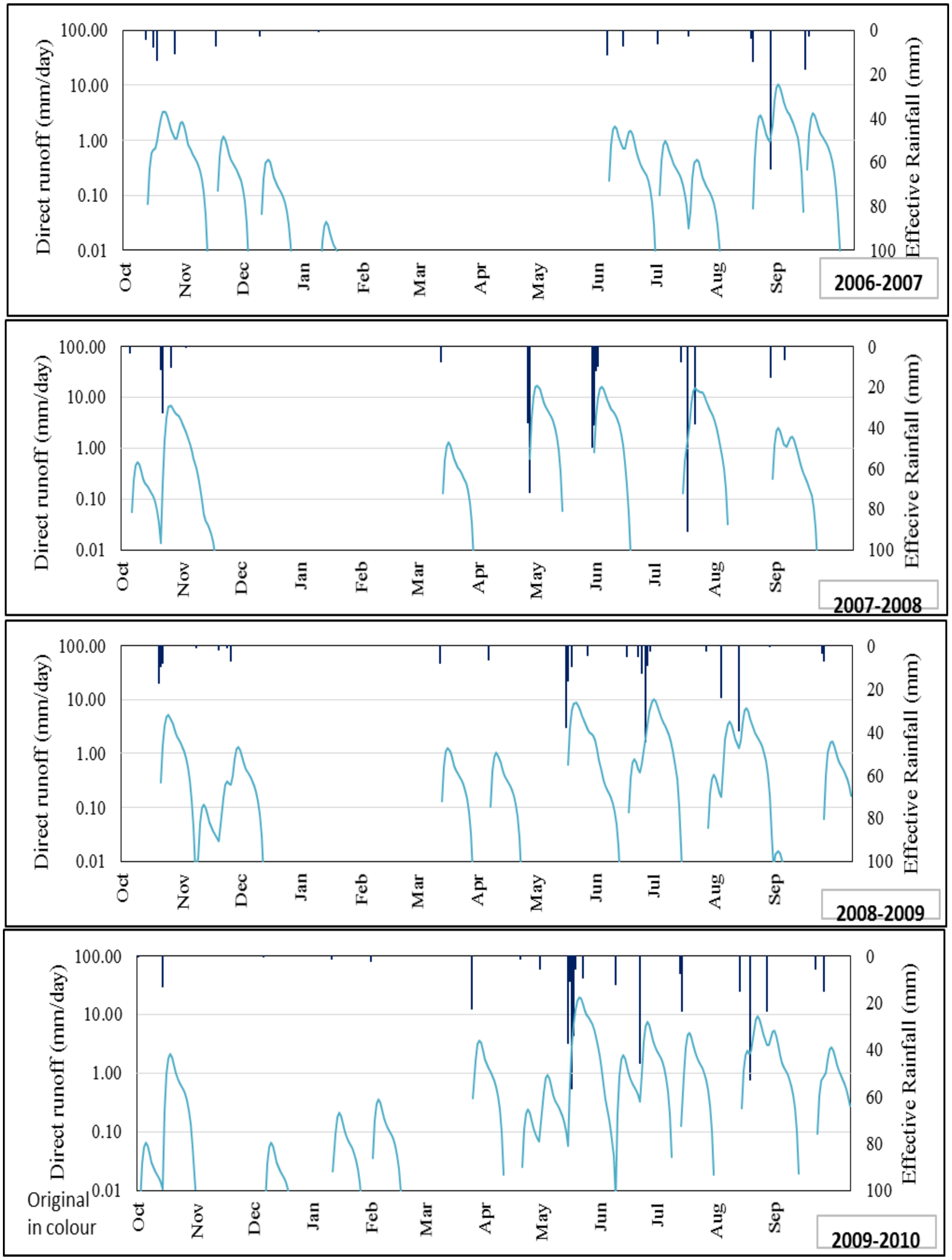


Figure F- 3: Effective rainfall and direct runoff variation (2013-2015) - Dunamale watershed



Original in colour

Figure F- 4: Effective rainfall and direct runoff variation (2006-2010) - Kalu river basin

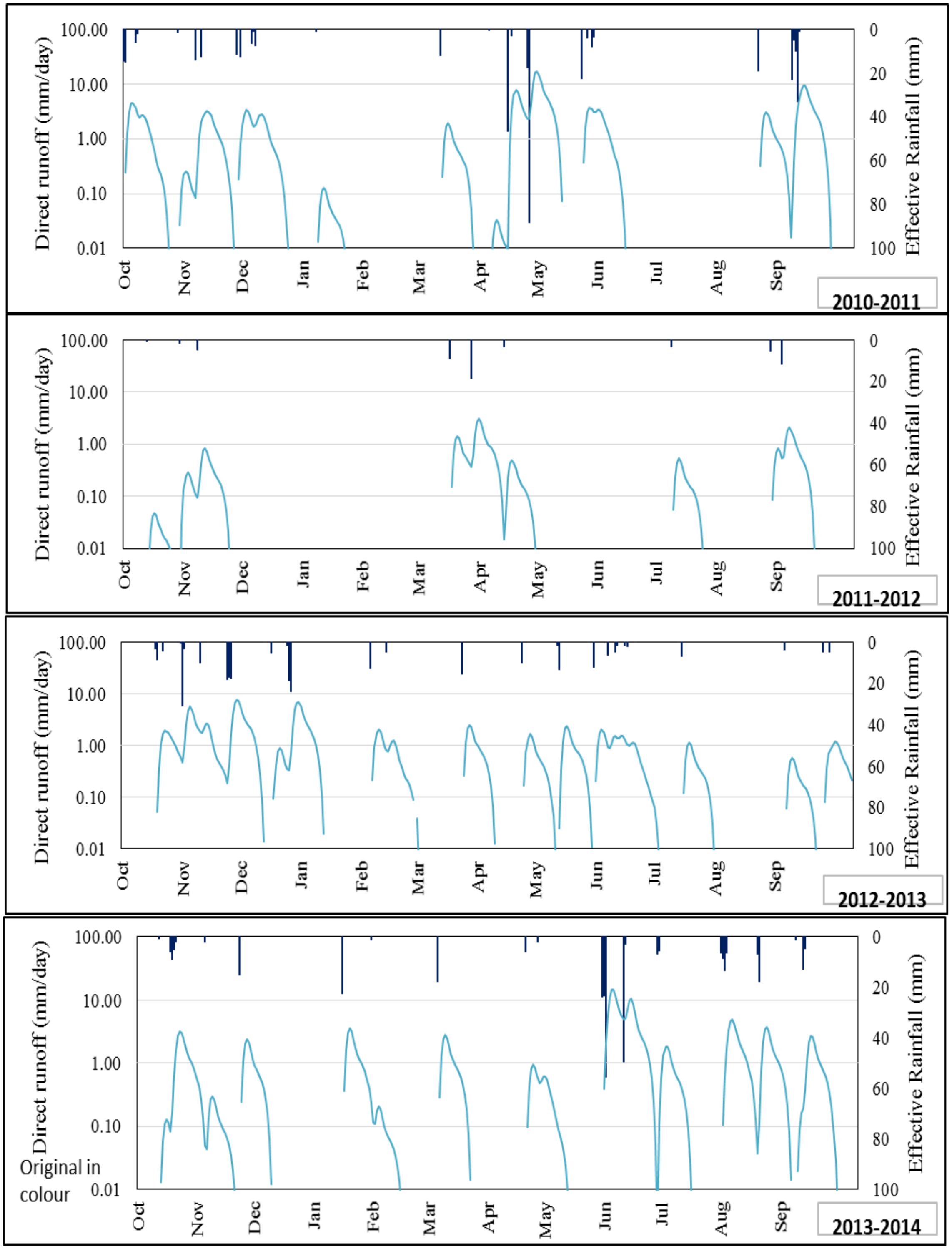
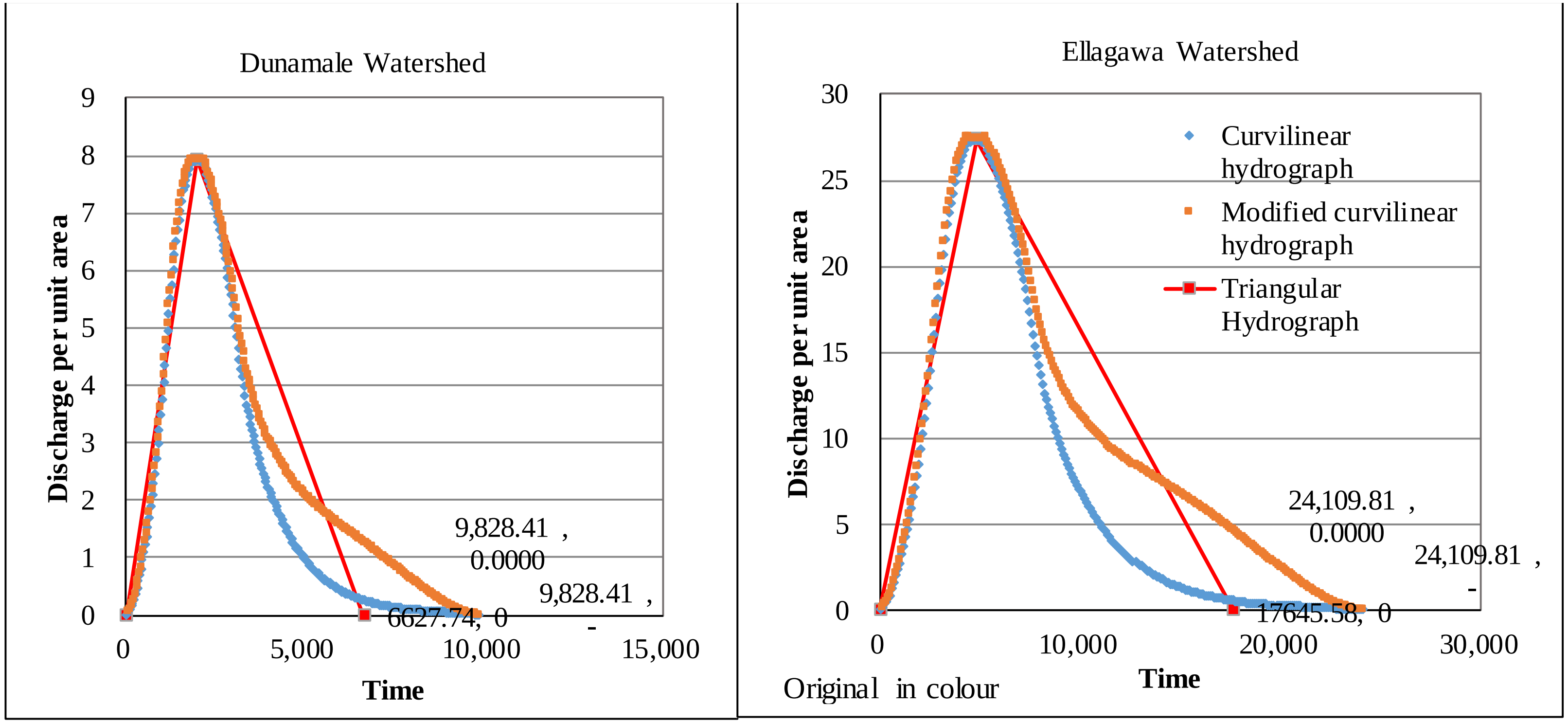


Figure F- 5: Effective rainfall and direct runoff variation (2010-2014) - Kalu river basin

APPENDIX F: UH model derivation and results



Original in colour

Figure F-1: Triangular and curvilinear unit hydrographs for Dunamale and Ellagawa watersheds

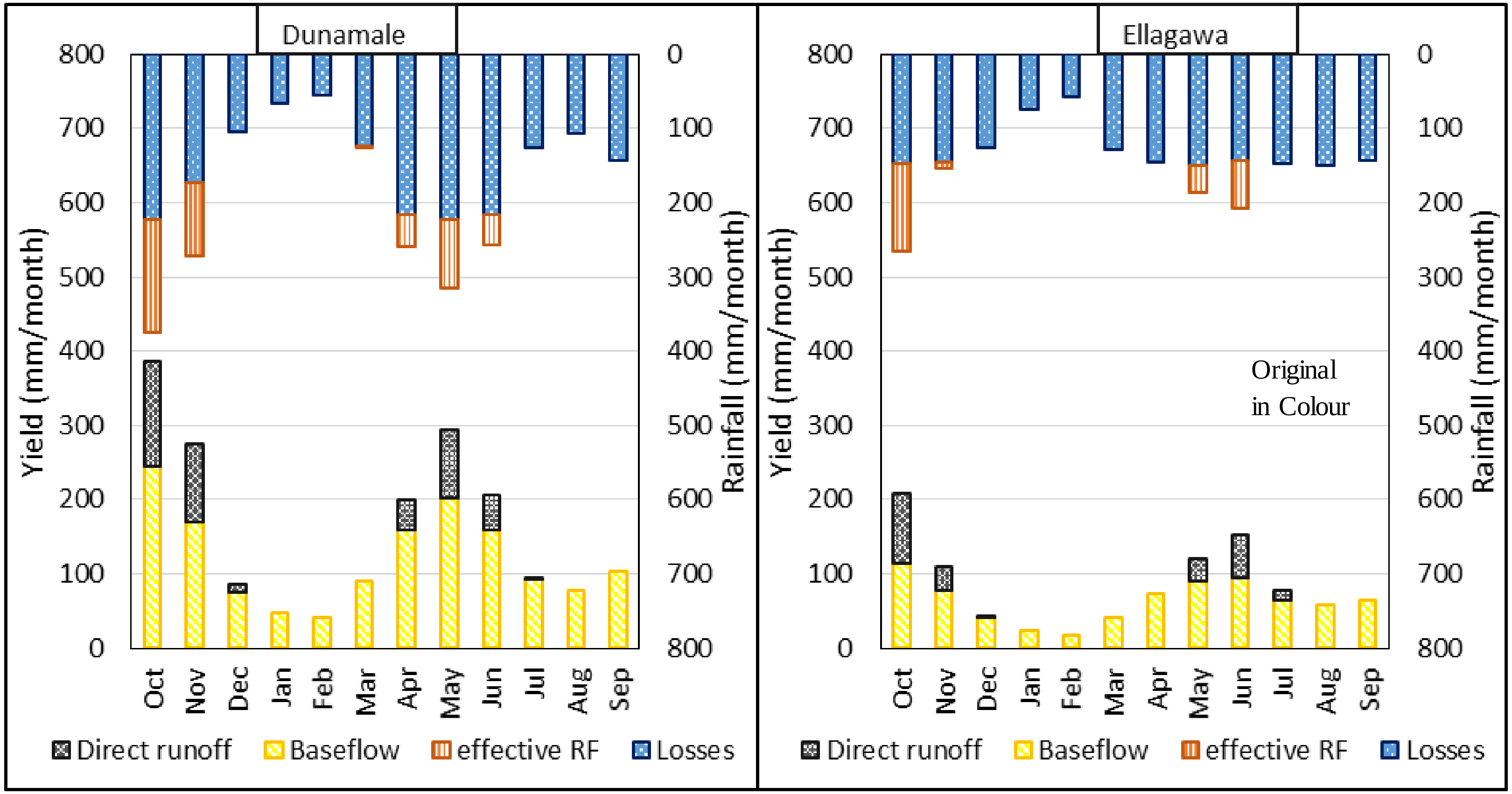


Figure F-2: Design Rainfall and Watershed Yield - Dunamale and Ellagawa Watersheds

APPENDIX G: Yield model comparison results

Table G- 1: Model yield comparison for design rainfall application

Duration		**Dunamale**				**Ellagawa**			
		IGM (w)	**HEC (wo)**	**UH (wo)**	**Observed**	**IGM (w)**	**HEC (wo)**	**UH (wo)**	**Observed**
monthly	Oct	117.1	57.5	377.7	196.8	126.7	40.0	209.5	149.4
	Nov	81.6	51.8	176.3	229.2	86.5	25.7	108.6	165.5
	Dec	36.6	27.9	83.6	124.8	44.5	13.6	42.0	89.8
	Jan	22.8	15.1	46.5	41.2	25.9	7.8	23.3	41.0
	Feb	19.4	11.0	39.6	13.7	19.8	5.6	17.7	34.5
	Mar	43.2	21.6	88.2	58.4	44.6	12.3	40.2	45.5
	Apr	76.6	38.5	195.9	124.9	80.2	22.0	72.4	119.2
	May	96.7	52.6	287.6	134.9	98.9	27.9	120.3	193.7
	Jun	76.6	46.4	200.9	137.0	105.1	29.8	153.3	235.3
	Jul	44.4	30.4	92.9	69.3	72.6	21.4	76.8	131.6
	Aug	37.2	22.4	75.8	45.9	64.5	18.5	58.7	99.5
	Sep	49.9	26.4	101.9	114.6	72.5	20.4	65.9	135.2
Seasonal	Maha	320.7	184.9	811.9	664.2	348.0	105.0	441.3	525.7
	Yala	381.4	216.7	955.1	626.7	493.8	140.0	547.4	914.5
Annual	Annual	702.1	401.6	1766.9	1290.8	841.8	245.0	988.7	1440.1

Table G- 2: Model yield comparison for observed rainfall application

duration		**Dunamale**				**Ellagawa**			
		IGM (w)	**HEC (wo)**	**UH (wo)**	**Observed**	**IGM (w)**	**HEC (wo)**	**UH (wo)**	**Observed**
monthly	Oct	182.14	285.89	462.56	196.78	130.08	225.84	137.15	149.35
	Nov	145.04	307.82	362.42	229.25	119.84	176.04	122.05	165.52
	Dec	72.48	174.78	159.73	124.83	69.57	114.21	73.16	89.81
	Jan	30.62	64.78	62.30	41.23	43.36	67.03	45.73	40.95
	Feb	38.77	56.06	68.85	13.67	34.40	50.81	33.91	34.54
	Mar	78.88	115.54	173.78	58.41	68.46	87.24	69.36	45.48
	Apr	139.59	206.63	301.80	124.94	118.25	151.04	129.15	119.15
	May	114.44	230.04	299.96	134.87	102.28	163.69	152.76	193.69
	Jun	101.61	196.52	227.25	137.04	126.78	239.55	163.25	235.35
	Jul	54.86	90.27	139.69	69.34	94.41	166.44	111.60	131.58
	Aug	71.92	93.45	124.13	45.87	99.33	164.60	114.70	99.49
	Sep	94.50	147.01	202.02	114.62	110.61	204.33	124.33	135.21
Seasonal	Maha	547.94	1004.87	1289.64	658.33	465.72	721.16	481.36	525.66
	Yala	576.92	963.92	1294.85	626.67	651.68	1089.64	795.79	914.47
Annual	Annual	1124.86	1968.79	2584.49	1285.00	1117.40	1810.80	1277.15	1440.12

APPENDIX H: Specimen calculations

Specimen Calculations for Irrigation Model

Dunamale sub-basin - Base Data			
Maha season		Yala season	
Month	Rainfall (inches)	Month	Rainfall (inches)
October	13.17	April	8.62
November	9.18	May	10.87
December	4.12	June	8.62
January	2.56	July	4.99
February	2.18	August	4.18
March	4.86	September	5.62
Total	36.08	Total	42.89

Dunamale sub-basin Speciman calculation

	Maha		Yala	
Total ranfall	36.08	inches	42.89	inches
rainfall volume	36.08 X (640/12)		42.89 X (640/12)	
	1924.17	Ac.ft	2287.59	Ac.ft
specific yield	1750.00	Ac.ft per sq mile	2000.00	Ac.ft per sq mile
Run-off without limitation	(1750/1924.17) x 100		(2000/ 2287.59) X100	
	91%		87%	
Runoff with limitation	35%		35%	
Area of the catchment	157.5	sqkm	157.5	sqkm
Area of the catchment	60.81	sq mile	60.81	sq mile

Without considering yield limitations

Monthly specific yield/ inch of rainfall	1750/36.08		2000.00/42.89	
	48.51	Ac.ft	46.63	Ac.ft
specific yield for October	48.51 X 13.17			
	638.91	Ac.ft		
Yield for October	638.91 X 60.81			
	38852.59	Ac.ft		

Figure D- 3: Double mass curve for Attanagalu basin

Considering yield limitations

specific yield adjustment	1924.17 X 0.35	2287.59 X 0.35
	673.46 Ac. Ft/ sq mile	800.66 Ac. Ft/ sq mile
Monthly specific yield/ inch of rainfall	673.46 / 36.08	800.66 / 42.89
	18.67 Ac.ft	18.67 Ac.ft
specific yield for October	18.67 X 13.17	
	245.87 Ac.ft	
Yield for October	245.87 X 60.81	
	14951.76 Ac.ft	

Specimen Calculations for Unit Hydrograph Model

Base Data

Effective rainfalls	1	cm	C_t	3.78	C_1	0.75
Catchment area	157.5	km^2	C_p	0.38	C_2	2.75
Length of stream	22.55	km			C_3	5.56
Lc	12.67	km				

The standard Unit Hydrograph

t_p = 0.75*Ct*(Lc*L)^0.3

tp = $0.75 \times 3.78 \times (12.67 \times 22.55)^{0.3}$

t_p = 15.46 hr $\boxed{927.86}$ min

t_r = tp / 5.5

t_r = 15.46/ 5.5

t_r = 2.81 hr $\boxed{168.70}$ min

q_p = $(C_2 \times C_p)/T_p$

q_p = (2.75 X 0.38)/ 15.46

q_p = 0.0676 $m^3/s \cdot Km^2 \cdot Cm$

The required Unit Hydrograph

t_R = 24 hr $\boxed{1440.00}$ min

t_{PR} = t_p - (t_r - t_R)/4

t_{PR} = 15.46- (2.81-24)/4

t_{PR} = 20.76 hr $\boxed{1245.45}$ min

q_{pR} = (q_pxt_p)/t_{pR}

q_{pR} = (0.0676x 15.46)/20.76

q_{pR} = 0.0503 m^3/s . Km^2. cm

q_{pR} = 0.0503x157.5

q_{pR} = 7.9276 m^3/s cm

t_b = C_3/ (q_{pR})

t_b = 5.56/(7.9276)

t_b = 110.46 hr $\boxed{6627.74}$ min

T_p = (t_R/2) + t_{PR}

T_p = (24/2)+20.76

T_p = 32.76 hr $\boxed{1965.45}$ min

The required hydrograph was converted to curvilinear hydrograph by multiplying with the values of C/cp, Q/qp.

Sample Calculation for 3 values are given below.

	t/tp	**q/qp**	**t (min)**	**t (min)**	**q before (m^3/s)**	**q before (m^3/s)**	***Dis. Volume (m3)***	***Dis. Volume (m3)***
1	-	-	1965.45 x 0	-	7.926 x 0	-	-	-
2	0.02	0.006	1965.45 x 0.02	39.31	7.926 x 0.006	0.048	((0.048+0)/2)X((39.314-0)X60	56.099
3	0.04	0.012	1965.45 x 0.04	78.62	7.926 x 0.012	0.095	((0.095+0.048)/2)X (78.627-39.314)X60	168.29