IDENTIFICATION OF
MINIMUM DATA DURATION FOR
MONTHLY WATER BALANCE MODEL
CALIBRATION

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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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ABSTRACT

Water scarcity which arose with the growth of population, industrialization, urbanization and climate change, emphasizes the importance of water resources planning and management. Hydrologic modelling for water management in many disciplines has a history dating back to 1940's. Monthly models are commonly used for water resources planning and management because in practice, monthly time step is the choice for planning activities. Water balance models are popular water resources estimation tools which ensure the mass balance in watersheds. Reliability of the model simulations depends upon the nature of the data. Erroneous input can create unrealistic results. Therefore data quality is an important factor to be considered when dealing with data length. Further it is important that the data be representative of the watershed processes. However by using the longest available data, most researchers had attempted to achieve representativeness. In this aspect information contained in the data and careful extraction is important. Literature review shows that the data length selection for monthly water resources models vary between 12 and 780 months and the reasons for selection is mostly individual preference. This lack of a rationale poses a question on model reliability and creates a problem when utilizing public funds for water and associated infrastructure management. The present work is a critical evaluation of appropriate data length for the calibration of a monthly water balance model. In this effort, model calibration and verification has been carried out by considering various data length scenario. Ellagawa watershed in Kalu Ganga river basin of Sri Lanka over the period from 1977 to 2017 was modelled to identify the appropriate data duration for optimization of a two parameter monthly water balance model to contribute towards sustainable water management, planning and design.

Initially a detailed review of available guidelines and research findings to identify the best data duration option available for water managers to calibrate and verify a monthly streamflow estimation model for sustainable water resources management was carried out. Then a two parameter monthly water balance model was used to simulate streamflow of Ellagawa watershed using different data lengths. Considering the total data duration with 42 years of monthly resolution, the model was calibrated over the period from 1983 – 2017 for data duration options 10, 15, 20, 25 and 30 years. Model outputs were verified with the 7 year observed dataset from 1976 to 1983. Using a conceptual multi objective evaluation combining hydrograph, flow duration and water balance difference the observed and computed streamflow were results compared to obtain the most suitable data duration option. Existing literature and guidelines recommend various data durations as data period for modelling. Considering the time of exceedance, the recommended median of less frequent longest length is 24 years, same of less frequent short length is 6 years and the median of most used data length is 10 years for monthly data. Out of 315 case study catchments in literature, which were identified as work on monthly data resolution, 237 catchments were identified as the most used category. In the present work analysis of water balance model calibration and verification results for data durations from 10 to 30 years, identified that consistent results can be achieved with longer data lengths. Multi objective evaluation of the water balance modelling results showed that a threshold data duration of 20 years is the threshold for reliable optimization of a hydrologic model. At this threshold data length the mean values of respective model parameters c and Sc for Ellagawa watershed of Kalu river basin are 0.80 and 605.42. In case of 20 years the average overall Mean Ratio Absolute Error values varied between 0.1643–0.2189 for calibration and 0.2981–0.3039 for verification. This study also concluded that data consistency is important to obtain reliable results and Double Mass Curve with a regression method can be successfully used as a tool for data rectification.

KEYWORDS: Data duration, Parameter Optimization, Monthly Water Balance Model, Data Rectification

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1. Introduction

1.1. Modelling Water Resources

Water has become a very scarce resource because of the effects of population growth, industrialization, urbanization and climate change. Hence the gap between the demand and supply of water keeps widening (Martin-Carrasco, Garrote, Iglesias, & Mediero, 2013; Porkka, Gerten, Schaphoff, Siebert, & Kummu, 2016; G. Wang, Xia, & Che, 2009). The increasing demand for the scarce water resource requires systematic, meaningful and sustainable water resources management and planning. A hydrologic model is the common tool available for water managers to execute this task in a meaningful manner. Hydrologic models vary from simple regression type to detailed physics-based process representations. Irrespective of the type, these models require sufficiently long time series input data such as rainfall and evaporation. Many literature and text book recommendations on the subject of determining model parameters by means of model calibration and verification clearly mention that characteristics and length of data must be evaluated for parameter reliability (Anctil, Perrin, & Andréassian, 2004; Bárdossy, 2007; Das & Bárdossy, 2008; Gan, Dlamini, & Biftu, 1997; Perrin et al., 2007; Wijesekera, 2000; William, 2005; William W-G. Yeh, 1985).

Monthly time scale is the most commonly utilized temporal resolution for practical water resources planning and management (Mouelhi, Michel, Perrin, & Andréassian, 2006; Xiong & Guo, 1999). Therefore, most hydrologic mathematical models attempting to fulfill this purpose, apply monthly input data to calculate monthly outputs. These monthly models vary between regression and physics-based process type representations. Among the popular types are the monthly water balance models which rationalize their model computations by using principle of mass conservation and other relationships which are closer to known physics (Alley, 1984; Boughton, 2007; Klemeš, 1986; Lü et al., 2013; Mouelhi et al., 2006; Vandewiele, Xu, & Ni-Lar-Win, 1992; Xiong & Guo, 1999). Monthly water balance models are popular for water resources management, reservoir simulation, drought assessment, long-term drought forecasting, climate change impact evaluation etc. (Alley, 1984; Mouelhi et al., 2006; Vandewiele et al., 1992; Xiong & Guo, 1999)). According to Xiong & Guo, (1999).

1.2. Data Length and Modelling

Recommendations on data length for monthly water balance model development becomes the first priority of a watershed manager who has completed the model selection. Data length comprises of two sections. One is the calibration data length and the other is the verification data length. Therefore, the total data length is the addition of calibration and verification data lengths. There are research that had been conducted on the methods of splitting the dataset for model calibration and verification (Wu et al., 2013). Zheng (2018) in a related study had considered splitting of the total dataset as 80% for calibration and 20% for verification. Guidelines on mathematical modelling indicate that a comprehensive dataset would include long-term streamflow measurements and rainfall and PET data collected at one or more locations within the catchment along with land use coverage, vegetation cover and impervious area information, including changes over time (Cunderlik, 2003). WMO guideline state that daily or even monthly river flow data may be sufficient for assessing regional water security; multi-decadal records of continuous rainfall are necessary for reliable frequency analysis; and a few years of data may be sufficient to calibrate a groundwater model (Bureau of Meteorology, 2017). Recommendations on hydrologic practices (Shaw, 1994) while indicating the practice of British Meteorological Office for the computation of average annual rainfall that considers a 30 year minimum duration, states that flow records of 20-30 years are required to provide the streamflow pattern representative of the flow regime. For continuous modeling, an observed input containing sufficient events to calibrate all parameters has been recommended (James, 2005). Literature on the selection of data duration for monthly models do not indicate firm recommendations (Gupta, Sorooshian, & Yapo, 1996; Sorooshian, Gupta, & Fulton, 1983; Ye, Bates, Viney, & Sivapalan, 1997). Using a daily mathematical model and variety of data lengths, Gupta & Sorooshian (1985) indicated that a data length of 500 to 1000 points would achieve acceptable precision of optimized parameters and hence a 3-4 years of daily data would be sufficient for model calibration. Interpretation of this result would mean that for monthly modelling a dataset of over 40 years would be required. Subsequently, a study by Yapo, P. O., Gupta, H. V., & Sorooshian, S. (1996), recommends a 8-year dataset for calibration and then state that a the wettest period of the dataset would identify improved parameters. Loucks and van Beek (2017) discussing about sensitivity and uncertainty of model parameters indicate that longer datasets may not lead to better results. This raises the question whether the number of data points or whether the hydrological characteristics of a watershed are important when selecting a dataset for modelling. On the other hand, there are occasions that cite different data periods are suitable to identify different parameters (Wagener, et al. (2001). Data availability and interpolation without sufficient data also creates a significant impact on parameter estimation (Blöschl & Sivapalan (1995).

Dissanayake P.K.M., (2017) emphasis the importance of identifying a model to forecast water availability/ water yield from a watershed of the Planning Manual of National Water Supply and Drainage Board as it is the governing body of water supply in Sri Lanka. A hydrologic model used in four Sri Lankan catchments by Sharifi.M.B., (2016, unpbl), Khandu.D., (2016, unpbl) and Dissanayake P.K.M., (2017, unpbl) is two Parameter Monthly Water Balance Model which was developed by Xiong.L., Guo.S., (1999) appears as a very simple and an easy to use model with monthly time scale inputs and outputs. Based on previous research catchment responses for Sri Lankan catchments, the Two Parameter Monthly Water Balance Model (2PMWBM) is selected in identifying a minimum data duration required for model calibration. Therefore Ellagawa watershed in Kalu River Basin were selected to carryout case study model application.

1.3. Problem Statement

Though there is a desire to use long data lengths, non-availability of data often compels modelers to compromise on the data length in order to fulfill the number of gauging stations required for the model to be realistic. Boughton (2006) in his work cite many other data issues influencing the decision on data length that is used for modelling. It appears that in most modelling work, all available data are used without concerning resource requirements (Anctil, F., Perrin, C., & Andréassian, V. (2004)). The present practice of monthly water balance models also does not demonstrate the use of significantly long datasets for model calibration. There are literature indicating the use of 2-5 years of monthly data for model calibration (Haan, 1972; Hughes, 2004; Qi et al., 2017; Sha, Liu, Wang, Swaney, & Wang, 2013; Szolgay, Hlavčová, Kohnová, & Danihlík, 2003). A comparative study of 203 watersheds by Chang & Chen (2018) had used a 10-year dataset for calibration and verification of monthly watershed models.

In this backdrop, the selection of data length for monthly water resources modelling gives rise to many difficulties. Wide variety of opinion in the available guidance material, constraints due to missing data in datasets, poor quality of data, and constraints due to data accessibility are some of the critical issues faced by practicing watershed managers.

A comprehensive literature review on selecting a data duration for calibration of a monthly water balance model, identifies that there is a clear necessity to carry out a well-designed research to determine a data duration to be used in model calibration.

1.4. Objectives

1.4.1. Overall Objective

To identify the minimum data duration for optimization of a 2Parameter Monthly Water Balance Model for sustainable water management, planning and design.

1.4.2. Specific Objectives

1. Review of the current status of Water Balance Modelling, selection of input data durations, temporal resolution of modelling and selection.
2. Development of two Parameter Monthly Water Balance Model and parameter optimization for Kalu River Basin at Ellagawa in order to evaluate the effect of various input data durations.
3. Comparison of Model Performance for Different input data durations.
4. Give recommendations for Water resources planning Engineering and Management.

1.5. Project Area

The model was tested for the Ellagawa Watershed of the Kaluganga basin in the wet zone of Sri Lanka. The Kaluganga basin is 2690 square kilometers in area. And the length of the river is 129 km starting from the Adams Peak. Kaluganga is considered as the third longest river in Sri Lanka and it carries water through Ratnapura (most upstream) and Kalutara and reach the ocean at Kalutara. Ellagawa streamflow gauging station is located at 80º 13’ 0” E and 6º 43’ 53” N, measuring the streamflow of a watershed area of 1394 square kilometers. Figure 1-*1* is the project area map of Ellagawa Watershed.

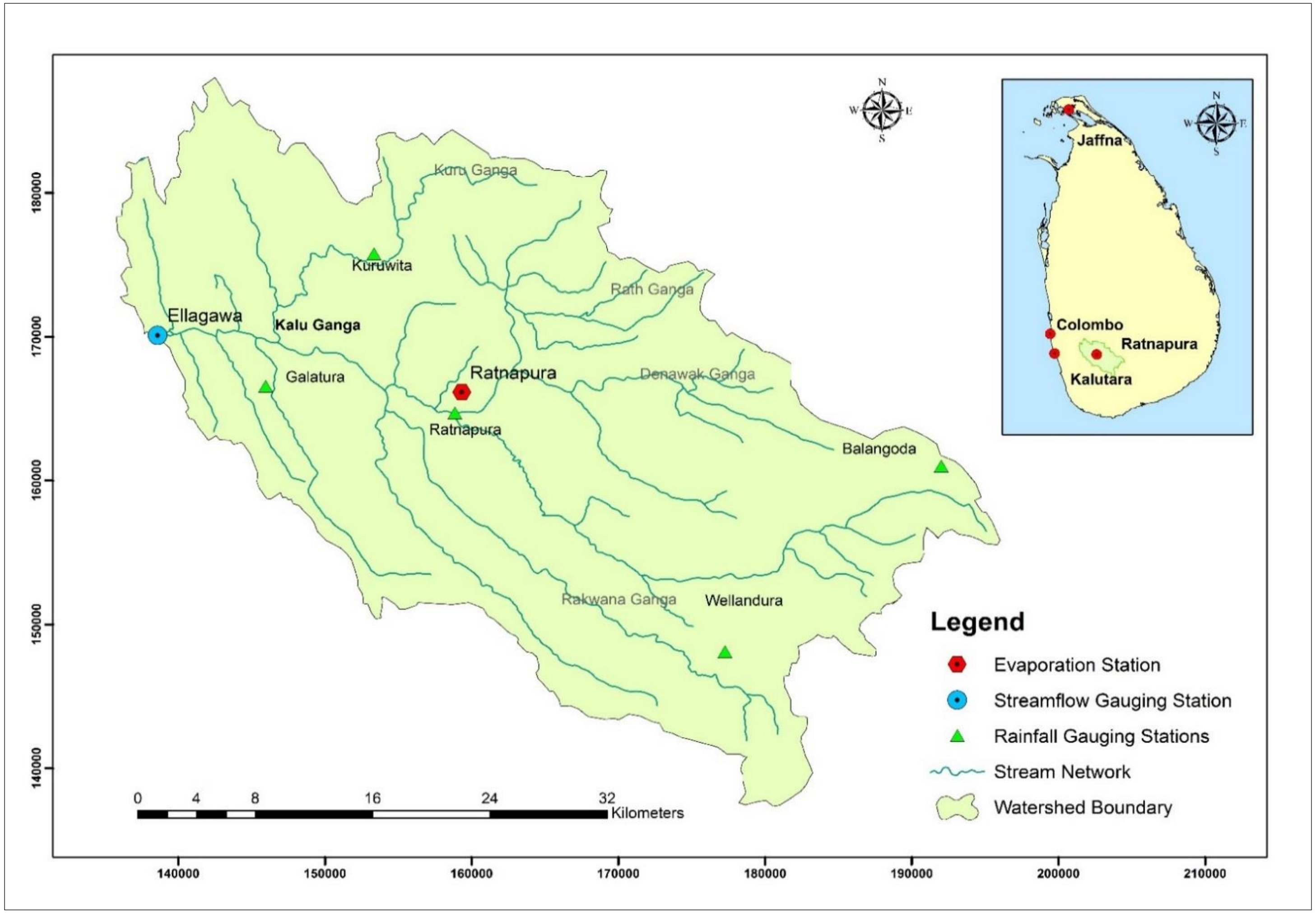

Figure 1-1: Project Area - Ellagawa Watershed

2. Literature Review

The main objective of this Literature Review is to identify and evaluate available guidelines and research findings to identify the state of art data duration options for water managers to calibrate and verify a monthly streamflow estimation model for sustainable water resources management.

2.1. General

A reviewed literature search was conducted to identify the publications available for a practicing water manger to select the appropriate data length for a water resources modelling application. Guidelines and research publications with direct and indirect guidance on data lengths were summarized for a comprehensive review. Direct publications are those which clearly recommended data length for a particular water resource management purpose. Indirect publications are the reported reviewed publications which conveyed the use of a data length for a specific water resources application. The investigation included 63 publications which respectively contained 315 and 138 monthly and daily water management applications providing assistance to select a data length for hydrologic modelling.

2.2. Water Resources Models

Length of a dataset for rational water resources modelling is dependent upon the temporal resolution of data that is used for model computations. Therefore, recommendations on data length depends on the type of model, parameter characteristics and the number of parameters. There are several key factors about models and model parameters that a practitioner need to be aware of when investigating the appropriate model application for a particular application.

Water resources modelling is mostly for planning and management of water as a resource. It is common to carry out these activities using results presented in monthly time scale. This is done in two ways. One is to perform computations and modelling in the daily time scale and then aggregate the results to monthly resolution. The other is to use monthly scale conceptualizations to model and generate monthly and coarser resolution results. This could be noted in the number of literatures that were available for review. Daily and monthly models have their own advantages and disadvantages. In this work the length of data used for monthly and daily applications were evaluated to compare the number of data points used for calibration and verification of each model type. Daily models also provide guidance on parameters to be looked at during applications. The present work concentrated the assessments to capture the data length selection requirements for monthly water resources modelling applications.

The adequacy of monthly streamflow estimations for planning and management of water resources is common knowledge (Mimikou et al., 1991; Vandewiele, Xu and Ni-Lar-Win, 1992; Elizabeth M.Shaw, 1994; WMO 1976). Monthly continuous streamflow models play a major role in watershed management due to many reasons such as, 1) water resources planning and management practice is on monthly or longer time scales, 2) climate change effects on vegetation can be easily specified on a monthly or seasonal scale daily or hourly, 3) large space scale seeking only averages of watershed characteristics can be selected, and 4) monthly hydro-climatological data are most readily available (Mohseni & Stefan 1998). Apart from the above, monthly water balance models have specific advantages such as, simple mathematical representations which are closer to known physics, sufficiency of either precipitation only or precipitation, temperature and evaporation as inputs and having a lesser number of parameters compared to finer time resolution models (Xu & Singh 1998, Douglas P Boyle, Gupta and Sorooshian, 2000a; Vrugt et al., 2003; Bárdossy, 2007).

Monthly water balance models are used to forecast the monthly streamflow or seasonal yield of a catchment. A monthly hydrograph smoothens out the streamflow fluctuations visible at hourly or daily temporal resolutions. The variations in finer resolution measurements are due to variations of watershed resistance to runoff and storage characteristics. Monthly models provide cumulative effects of actual phenomena aggregated over calendar months. Due the aggregation of finer variations the monthly models enable simplifications when handing flow and storage. Therefore monthly models are comparatively simpler and have a smaller number of parameters when compared with daily and hourly models (Xiong and Guo, 1999).

There are many monthly water balance models in use. They are ‘abcd Model’ (Alley, 1984), ‘PE Model’ (Xu & Vandewiele, 1994), ‘Pitman Model and Stanford Model’ (Görgens, 1983), TOPMODEL and Xianjiang Model’ (Chen, Chen, & Xu, 2007), ‘HYDROLOG and HRCYCL’, (Porter & McMahon, 1971), ‘The Catchment Land Surface Model (CLSM)’, (Mahanama, Koster, Reichle, & Zubair, 2008), ‘Tank Model’, (Wijesekera, 2000), ‘Jazim Model’ (Tayefeh Neskili, Zahraie, & Saghafian, 2017), ‘ReNuMa Model’ (Sha, Liu, Wang, Swaney, & Wang, 2013), ‘WatBal’ model (Szolgay, Hlavčová, Kohnová, & Danihlík, 2003) etc.

Monthly water balance models have a long history dating back to 1940s. Thornthwaite and Mather, (1955) developed a two-parameter monthly water balance model (T Model). Palmer, (1965) developed a water balance model (P Model) similar to Thornthwaite and Mather, (1955) and dividing soil moisture in to two layers. A four parameter ABCD water balance model combined with soil moisture storage was developed by Thomas, (1981). Mimikou et al., (1991), Vandewiele et al., (1992) describe several other monthly water balance models developed for Water Resources Planning and Management.

2.3. Parameter Estimation

Parameter estimation is the selection of values for parameters, so that the model will match the watershed system as closely as possible (D. P. Boyle, Gupta and Sorooshian (2000). Model calibration is the process which determines the model parameters based on the available data and prior knowledge (Janssen and Heuberger, 1995). Among many types of models ranging from black box to physics based, there are model parameters which are either physically interpretable or non-interpretable (Vrugt et al., 2003). A desired characteristic of a particular hydrologic model is the capability to simulate its target hydrologic processes under the hydrologic conditions expected to experience by a watershed. Therefore, model parameters estimated should be unique, realistic and independent of the data being used for calibration. Needs and characteristics of model parameters have been discussed by many. It is known that if the models are based on basic principles of physics (mass and energy conservation), then estimation of model parameters is straightforward (Bárdossy, 2007). However, watershed heterogeneity such as non-uniformity of vegetation, slopes, existence of macro pores, together with unresolved spatial and temporal variability of meteorological variables limits the applicability of “known physics”-based models either to laboratories or to well observed small experimental catchments but with limited success.

Therefore, calibration of models with a higher number of parameters, would require to select a suitable data length in order to achieve the desired modelling accuracies and representativeness (Bárdossy, 2007). Practically, calibration is done with a representative dataset and the errors between observed and simulated data are minimized. This is then followed by model verification with an independent dataset in order to ensure the representativeness of the model.

As a result of practical constraints with data, process conceptualization and objective functions, model parameters are inevitably data dependent (Gan, Dlamini and Biftu, 1997). This hints that a search for data lengths required for model applications would require to keep the parameter influence at a low level by selecting a model with a few parameters. In case of data limited situations, a model with a few parameters is usually preferred by hydrologists. This is because higher number of parameters increase the complexity of models and this in turn tend to decrease the model performance (James, (2005). Hence the determination of data length must be linked with the number of parameters associated with the model.

2.4. Selection of Data Length

A practitioner searching for suitable data lengths has two options. They are either to obtain assistance from available guidelines or to evaluate reviewed research publications for acceptable recommendations.

2.4.1. Guideline Suggestions

Guidelines for Rainfall Runoff Modelling by Vaze, J., Jordan, P., Beecham, R., Frost, A., Summerell, (2012) without a specific reference to a data length indicate the importance of long-term streamflow observations for the development of a model that can produce streamflow estimations with an acceptable level of accuracy.

Hydrological Design Data Estimation Techniques issued by Czech Hydro-meteorological Institute (WMO 1993) which state about entry data sets of example studies, indicate the use of 50-year monthly datasets. In case of rainfall analysis for flood forecasting, water security etc., it is important to consider continuous and multi decadal rainfall.

"Good Practice Guidelines – Water Data Management Policy" issued by Bureau of Meteorology of Australia 2017 (WMO) under the water data temporal frequency, states requirement of continuous high frequency rainfall and streamflow data for flood forecasting, and the sufficiency of monthly river flow data to assess regional water security. Also it mentions under water data longevity of measurements that multi-decadal records of continuous rainfall is necessary for reliable rainfall Intensity Duration Frequency (IFD) analysis.

Australian Rainfall and Runoff (ARR) "A Guide to Flood Estimation" Guideline updated in 2016 states that calibration data length should be covering a range different of flood conditions in order to confidently apply a model in data scarce situations. This guideline further states that the parameter uncertainty decreases as the length of the data increases and increases when the length of data decreases. More than a 10-year period is indicated as suitable for flood modelling. In cases where less than 10 years of data is available then regional approaches are recommended as more appropriate for computing base-flow contribution to design flood estimates. ARR goes on to mention that in an ideal situation, more than 10 years of continuous streamflow data is required to perform detailed site-specific analysis. However, ARR guideline before the update required at least 15 years of flood data for flood analysis.

Guideline issued by Department of Water Resources in Rajasthan, India, states that a minimum of 25 years of monthly rainfall data and runoff data of maximum available period is required for yield studies. Guide to Hydrological Practices (WMO-No. 168) (1994) states that at least 30 years of data is required to obtain a representative relationship between rainfall and runoff. WMO/TD - No.554 (WMO 1993) Hydrological Design Data Estimation Techniques document issued by Czech Hydro-meteorological Institute states about entry data sets of example studies done and mention the use of 50 years for monthly data.

Daggupati et al., (2016) mentioning the expensive resource requirements, indicate the need to to use shorter datasets instead of lengthier datasets, Discussing the needs for model development, Razavi and Tolson (2013) recommend the use of one third of a long dataset for calibration while using a longer dataset for model verification. Zheng, (2018) split the data set as 80% data for model calibration and 20% data for model verification based on the common practice e.g. May et al., 2010; Wu et al., 2013]. A modellers guide for rainfall runoff modelling by Kherde (2016) recommend a one year dataset for the warm-up period, a 10 year data set for calibration and a minimum of two years data for validation. If a modeler wish to analyze a situation which occurs once in 10 years, then at least 20 years of data is sufficient. For conceptual rainfall runoff models it is important to include catastrophic events in the observed data for the model to reflect catastrophic events (Kherde, 2016). The variety of guideline statements indicated above, also necessitates a careful review of ongoing research to determine an appropriate data length for water resources model applications.

2.4.2. Research Recommendations

A comparison of reviewed research publications displays the recommendation of data lengths between one year and 30 years for model calibration. A monthly dataset of 60 years enabling 30 years each for model calibration and verification has been recommended as the best modelling option for Nile River (Keshtegar et al., 2016). A comparative monthly water balance modelling effort where 5 non-overlapping 10-year data periods had been evaluated on 5 models and on 10 sites, had reported verification with 40 years of data (Alley, 1984). (Xu and Vandewiele, 1994) working on 91 catchments in Belgium and China having extents between 16 km^2 to 3626 km^2, and using 2, 5, 10, 15, 20 years long monthly data from a 158 year data series, concluded that a 10 year data period is necessary for an adequate model calibration. Selecting 6 events for calibration and 24 events for validation of simple and complex runoff models in semi-arid watersheds, Michaud and Sorooshian, (1994) concluded that a minimum data length of 15 years is required for calibration. GÖrgens (1983) in a research on two hydrologic models for a semi-arid 73.1 km2 catchment with monthly datasets of 3, 6, 10, 15 and 20 years, also concluded that 15 years of monthly data is required for a reliable model optimization. 30 years of data had been identified as the minimum requirement for realistic streamflow estimation to monitor droughts at two Indian catchments (Jain, Jain and Pandey, 2014). After a modelling study of 7 catchments in USA, Haans, (1972) stated that at least one and preferably two or three years of observed monthly flows are required for acceptable parameter estimation.

Burn and Elnur (2002) stated that a minimum of 20 years of data should be available to be included in the reference hydrometric basin network. Kahya and Kalayci (2004) in their work indicated that a 30 year period is long enough to compute a valid mean statistic. Nyunt et al, (2012) carried out a climate change study and utilized 20 years of data for modeling. Similarly for water management purposes data lengths that had been used in research vary from 1 year to 65 years (Haan, 1972; Sorooshian and Gupta, 1983; Alley, 1984; Xu and Vandewiele, 1994a; Vandewiele and Elias, 1995; Gupta, Sorooshian and Yapo, 1996; Xiong and Guo, 1999b; Douglas P Boyle, Gupta and Sorooshian, 2000b; Anctil, Perrin and Andréassian, 2004; Anctil et al., 2006; Perrin et al., 2007b).

Sorooshian and Gupta,(1983) suggests that for any calibration procedure to be successful, the data should be representative of the various natural phenomena experienced by the watershed during a complete seasonal hydrological cycle. He also suggests to choose a wet year for calibration in order to activate all model parameters. James (2005) recommends to collect all rainy and dry events in a dataset to calibrate the parameters thereby ascertaining that the model is sensitive to all events in the watershed. After carrying out a research in Great Usuthu Catchment Gan, Dlamini and Biftu, (1997) suggested that wet years are preferred over dry years as calibration data, because dry years would not contain sufficiently high flows to excite the models.

There are many recommendations in the research carried out for daily water management applications. Perrin et al,(2007) working with 12 catchments varying between 1021 km^2 and 4421 km^2 and using 39 years of daily data stated that 350 days chosen randomly are sufficient to obtain robust estimates for the model. A sample size greater than 500 days has been reported as a threshold to achieve acceptable precision of model parameters V. K. Gupta and Sorooshian, (1985). A comparison of data lengths on a 407 km^2 watershed has highlighted the importance of daily data sets greater than 2-5 years for long term runoff estimation Boughton, (2007). Anctil, Perrin and Andréassian, (2004) in a work for the Serein River Basin in France (1120 km^2) concluded that best model performance was with 3 and 5 year calibration datasets. Sufficiency of at least 8 years of daily data for model calibration has been reported in an application using 55 watersheds having extents between 51- 1891 km^2 by Li et al, (2010) and by Gupta, Sorooshian and Yapo, (1996) in their work for the Leaf river basin (1944km^2), It is noteworthy that Ye et al, (1997) had discussed the inadequacy of a 5 year dataset for the modelling of low yielding watersheds in Australia, Need of at least one hydrologically appropriate year for the activation of model parameters has been highlighted by several research (Sorooshian, Gupta and Fulton, (1983), Refsgaard J.C., (1997), Gan, Dlamini and Biftu, (1997). Choosing a suitable data length for modelling is a balancing the length of dataset and the quality of data (Sorooshian, Gupta and Fulton, 1983). Data length options between shorter periods with high quality data and longer datasets with lesser quality must be appropriately chosen to improve the precision of parameters (V. K. Gupta and Sorooshian, 1985).

2.5. Practical Constraints

2.5.1. Data Length and Quality

Success of model calibration process depends upon the nature of the data used. Erroneous input data causes a significant adverse impact on model calibration (Yen et al., (2014). The dataset used should be representative of the watershed processes. Even though most researchers had tried to achieve the representativeness of data by using longest available data lengths, the information contained in data and the way of extracting these information is considered as more important than the length of data series (Sorooshian, Gupta and Fulton, 1983). Increased data lengths increase the computational burden to obtain the best parameter set and the cost of data acquisition.

Hence the requisite parameter precision, computational constraints and data costs must be optimized to manage the desired quality of data (V. K. Gupta and Sorooshian, 1985). Poor quality of data leading to unsatisfactory of hydrologic modelling is well reflected in the study of 75 Belgian catchments by (Vandewiele and Elias, 1995). Rainfall data must not contain significant errors, and even random errors in a rainfall series significantly affect model performance and parameter values (Oudin et al., 2006). Xu and Vandewiele, (1994) having performed a sensitivity analysis for input data errors in 91 catchments of Belgium and China, concluded that random errors in rainfall data negatively influence model performance and that systematic errors are less important for the estimation of streamflow. However the systematic errors do have a significant influence on model parameter values and consequently on the estimation of other components of water balance. On the other hand, Das and Bárdossy (2008) quoting Chaplot, Saleh and Jaynes (2005) states that models have the capacity to achieve performance criteria by compensating input errors that are within a reasonable range by adjusting their parameters values.

2.5.2. Missing Data Issues

Many research and work in projects use data without missing data periods. The work of Anctil, Perrin and Andréassian, (2004) which focused only on periods without missing data is an example. They go on to mention that in most research, the length of available observation series is rarely addressed. Missing data is often a major issue when attempting to acquire long datasets. This is especially because of the need to have a common dataset for all gauging stations representing the spatial variability of rainfall within a project area. To overcome the issue of non-continuous data in poorly gauged catchments, Perrin et al., (2007a) suggested investigations on model behavior with non-continuous data. Adhering to an appropriate data filling technique has been suggested as a measure to overcome the poor performance of models due to lack of long datasets adequately representing the variations in ground elevation and geography of a project area (Das and Bárdossy, 2008). Though data length requirements are not specifically mentioned, many text books mention methods to fill the missing data in order to ensure common datasets for hydrological computations. There are commonly used data filling methods mentioned in text books. They are 1) Arithmetic Mean

Method 2) Normal Ratio Method 3) Inverse Distance Weighing Method 4) Linear Regression Method 5)Weighted Linear Regression Method 6) Multiple Linear Regression Method 7) Probabilistic Method 8) Nearest Station Method and 9) Areal Precipitation Ratio Method (Chow, Maidment and Mays., (1988); Singh (1994), Allison (2001), Hasan and Croke (2013), Chen and Liu, (2012), Campozano, Sánchez, Avilés, and Samaniego, (2014), De Silva, Dayawansa and Ratnasiri, (2016)).

Filling with the data from nearest available station has been used in a 8 year long daily dataset for a SWAT model application at six watersheds in North Ohio (Bosch et al., (2011). In a case study of 144 sub watersheds in 10 separate watersheds, Liew, Arnold and Garbrecht, (2003) had used the inverse distance weighing method to fill the missing daily data of 31 gauges with the help of four closest gauging stations by constructing a 23 years and 8 years long common dataset. Khandu D., (2015, unpbl) has used a linear interpolation technique to fill missing rainfall data for a 48 year data set for a two parameter monthly water balance model development. Dissanayake (2017, unpbl), Artan et al., (2007) and Gutierrez-Magness and McCuen, (2004) had filled the missing data to carry-out hydrologic modelling, water balance modelling, rainfall runoff modelling by using 8 and 15, 13, and 15 years long datasets.

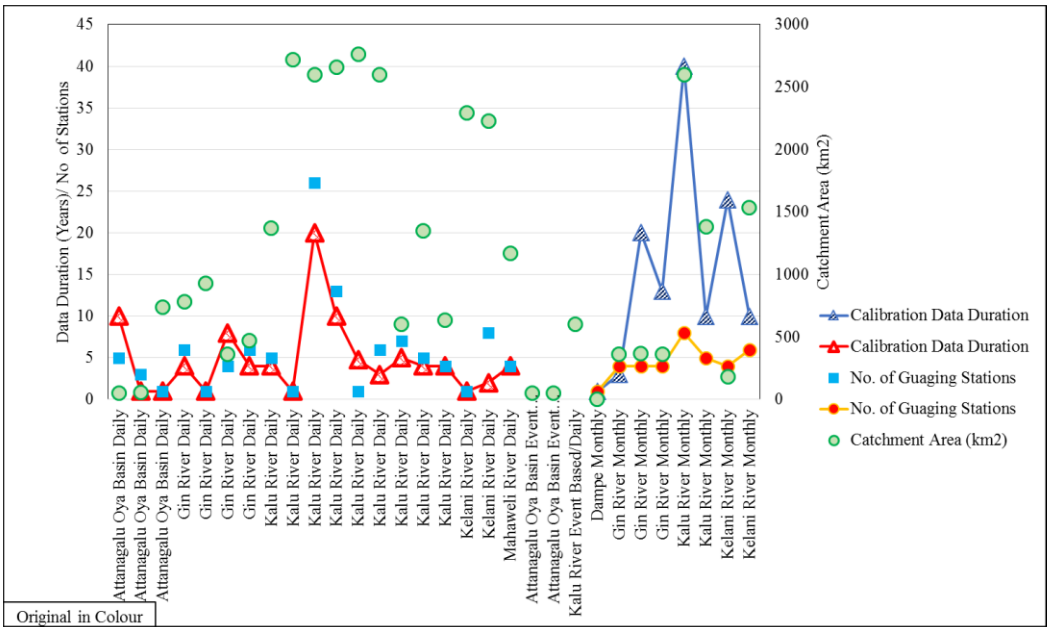

Figure 2-1: Data Length, Station numbers and Resolution of a few Sri Lankan Modelling Studies

2.5.3. Common Data Periods

The data usage for hydrologic modelling vary with the purpose, type of model and model resolution. Occasions where similar studies on the same watershed had utilized different sets of data are shown in the Table 1 of Appendix A. In this summary, the study by Bastiaanssen and Chandrapala, (2003) is an exception because the reported work is based on a remote sensing satellite based evaluation. The choice of gauging stations for the same watershed had varied even with the use of same data resolution and the most likely reason for such differences could be the difficulties to access data. As indicated previously these reasons could be the location preferences, financial limitations, data release constraints, time availability access data, period of interest etc. Figure 2-1 shows that in a particular study area, the gauging stations and data duration have differed thus hinting that the selection of either one of these parameters would influence the other. It also can be noted that the monthly studies have used greater data durations. This could be due to lesser cost of monthly data, and relative easy accessibility pertaining to monthly data.

2.6. Reality of Application

2.6.1. Type of Publications

A summary of reviewed publication was prepared to evaluate. Year of Publication, Watershed Area, Data Resolution, Geography of Usage, Type of model, Number of Parameters, Length of Calibration Data, Length of Verification Data, Length of Total Data Period and Purpose of the Study.

The distribution of Catchment areas, Year of Research Publication and Location of study watersheds reviewed in this work are shown in the Figure 2-2, Figure 2-3 and Figure 2-4. The summary table with key parameters and corresponding references is in Appendix A. Mixture of applications and studies listed in there represent that a wide variety was subjected to the evaluation.

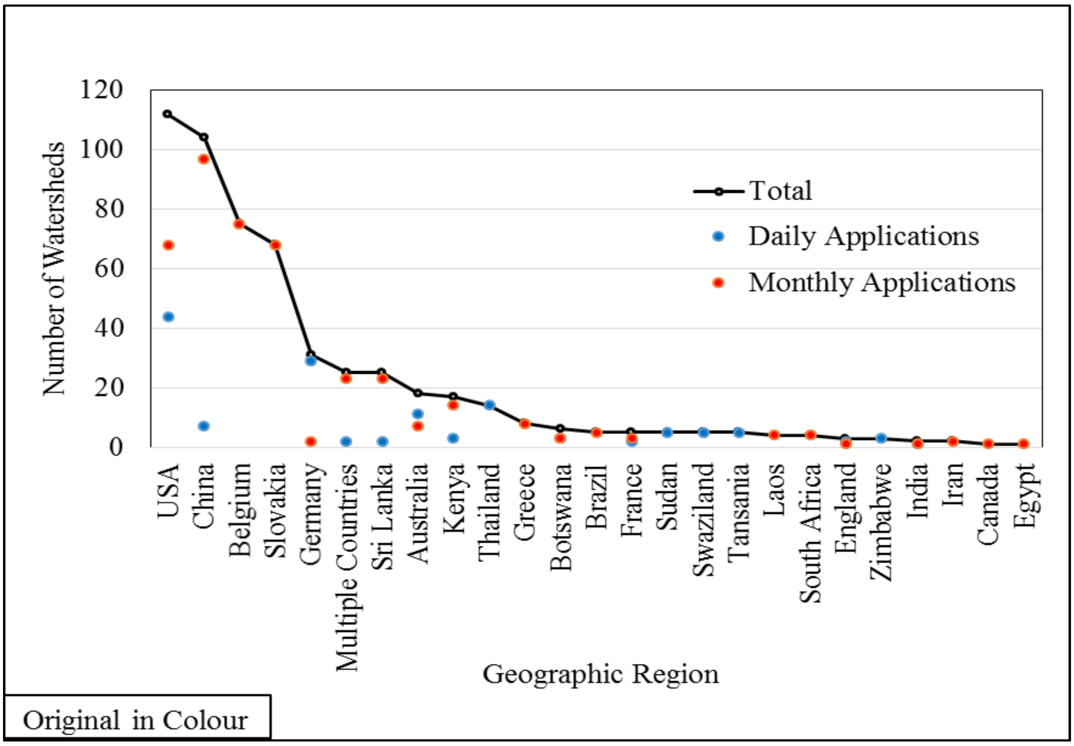

Figure 2-2: Geographical Distribution of Study Watersheds

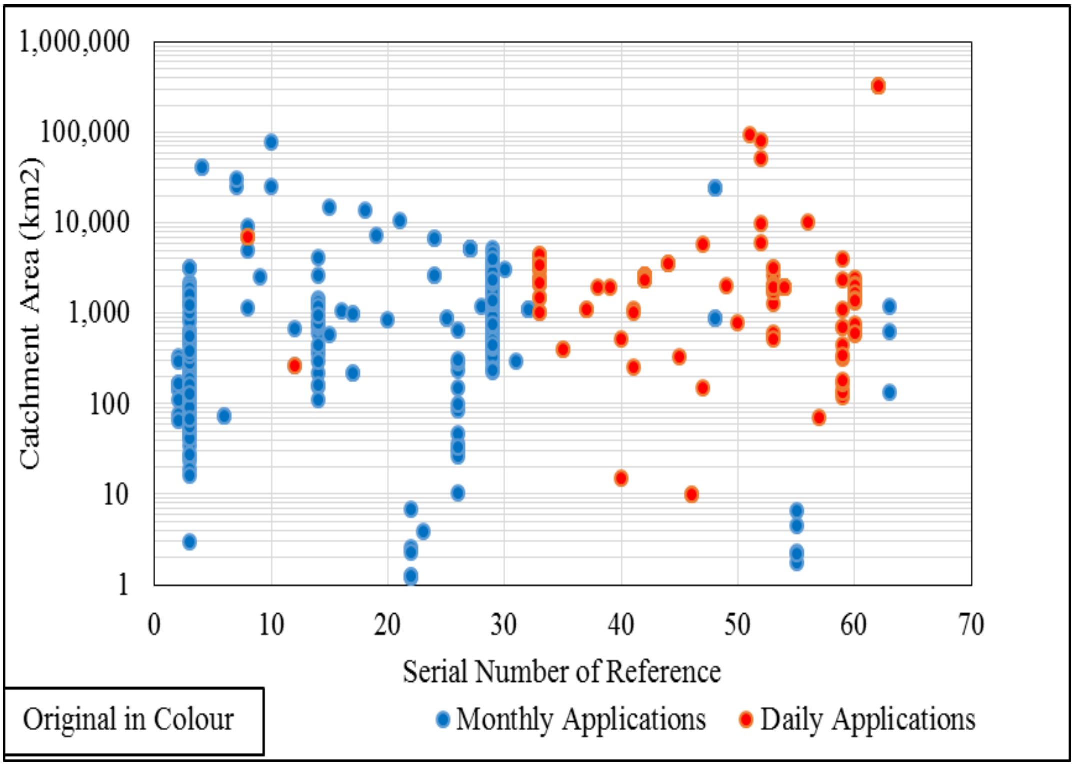

Figure 2-3: Distribution of Catchment Area of Study Watersheds

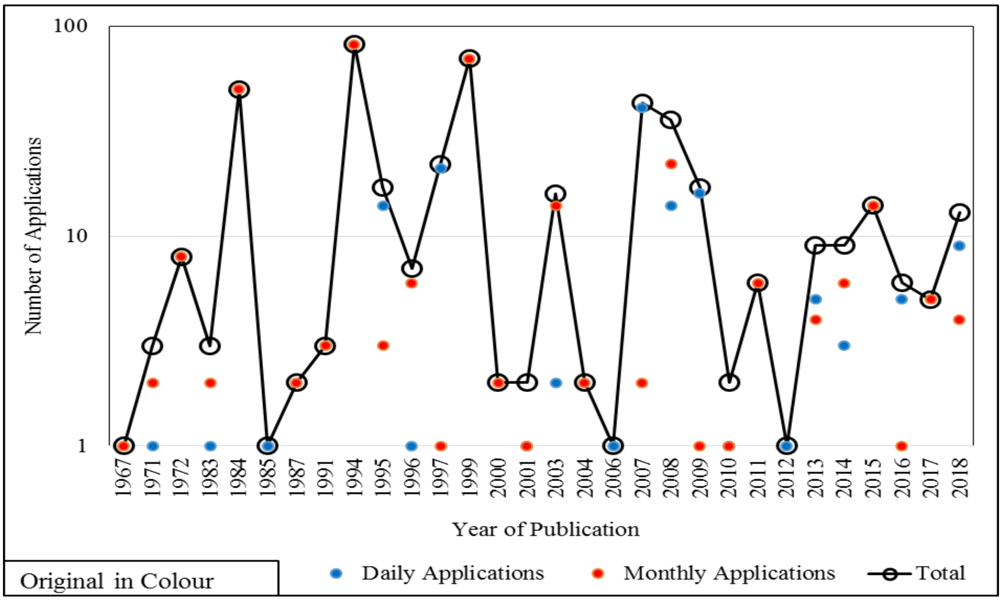

Figure 2-4: Distribution of Applications and Year of Publication

2.6.2. Monthly Water Resources Modelling

The present review identified 48 monthly water resources models of varying complexities. Out of these models, two models had been the center of attraction (Figure 2-5). They are the PE Model (Xu & Vandewiele, 1994) and the 2P Model (Xiong, L., & Guo, S. 1999) which indicated application percentages of 25.7 and 22.2 respectively. A summary of mostly used 10 models for monthly water resources modelling is in Table A.2 of Appendix A and in Figure 2-5.

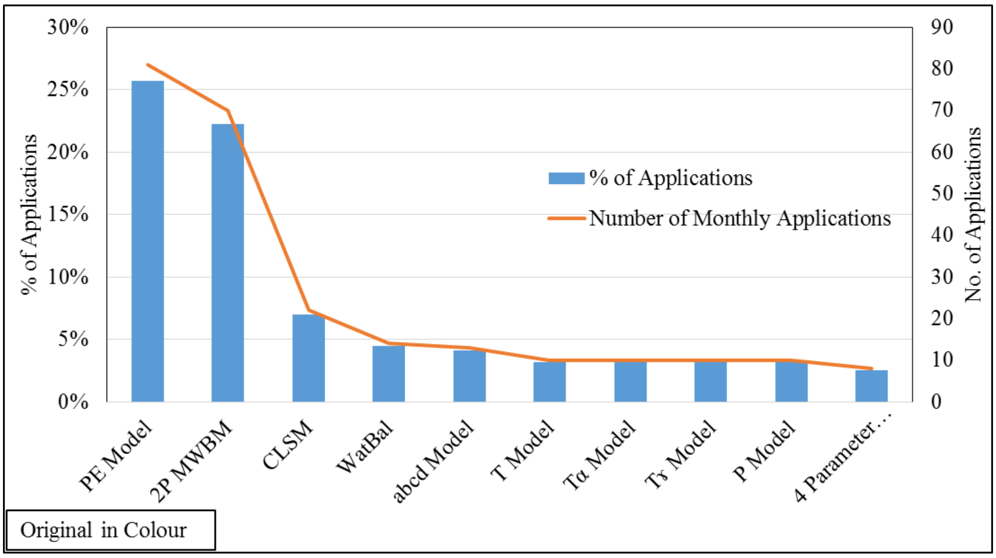

Figure 2-5: Mostly Used Monthly Water Resources Models in Literature

2.6.3. Models and Number of Parameters

Parameter use in daily and monthly water resource management models are shown in the Figure 2-6. Due to model complexities daily models require a greater number of parameters than monthly models and this is clearly shown by this summary of applications. In general the monthly model parameter number varies between 2 and 5. The same for daily models is approximately between 3 and 10. In most models which are commonly used for monthly water resources management applications, the number of parameters vary between 2 and 4. A summary of parameters in the most used 10 models are shown in Figure 2-7 and in Table A.2 in Appendix A.

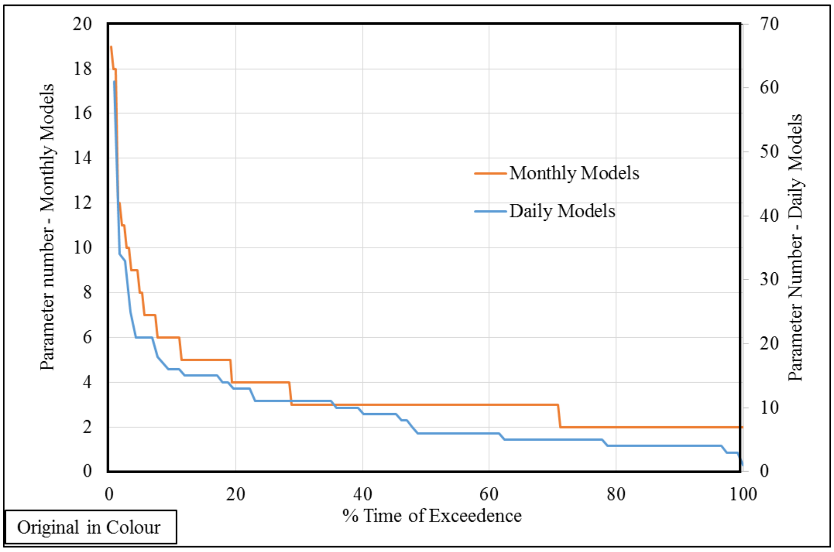

Figure 2-6: Occurrence of Parameter Use in Water Resources Applications

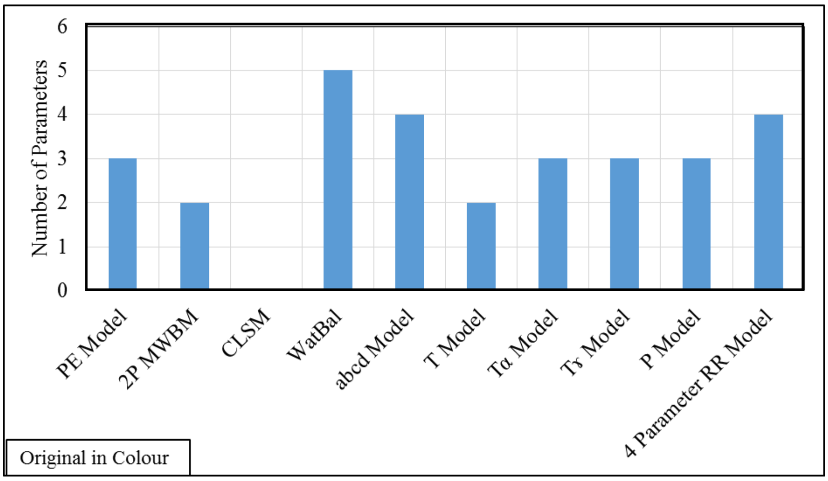

Figure 2-7: Parameters in Mostly Reported Monthly Water Resources Models

2.6.4. Data Length Water Resources Models

2.6.4.1. General

Data length used for model development is important to excite a model during parameter estimation and then to verify the model for its representativeness over hydrologic variability. Though this is amply discussed in literature, many reviewed literatures neglected to explicitly indicate neither the rationale for selection of data length nor the data period used for a particular application. Figure 2-8 and Figure 2-9 shows the use of data length against the time of exceedance of daily and monthly scale watershed applications. The verification data length curve reaches zero data length at an approximate time of exceedance value of 58% and 41% for calibration and verification respectively. This shows a lesser prominence given either to perform model verification or when mentioning the verification period. The summary could also be interpreted that the importance is given to calibration and hence verification had not been carried out. This supports the notion that calibration period is of greater importance when models are developed (Zheng et al. 2018).

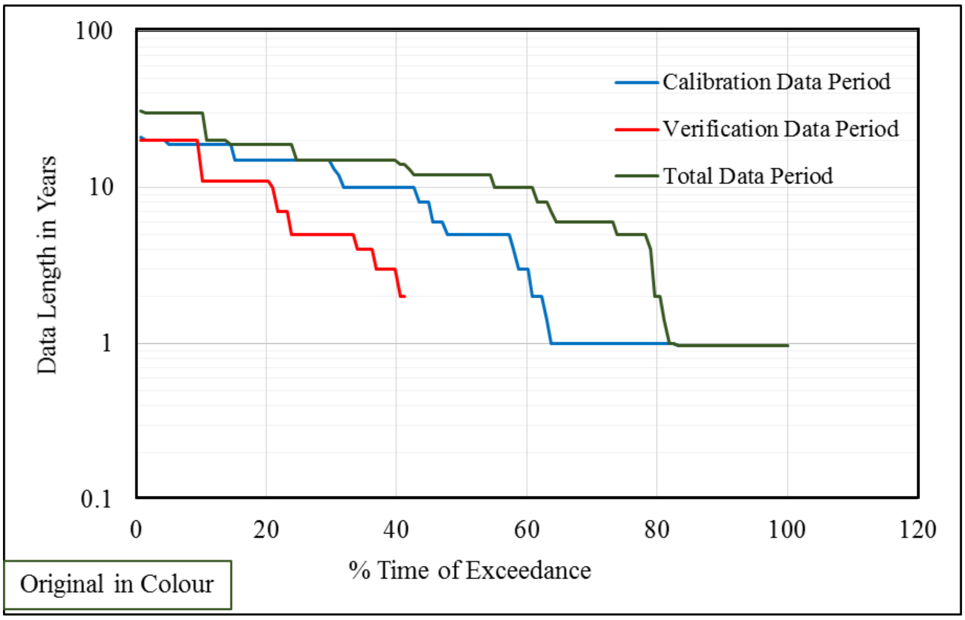

Figure 2-8: Percentage Time of Exceedance of Data Length in all applications (Daily Models)

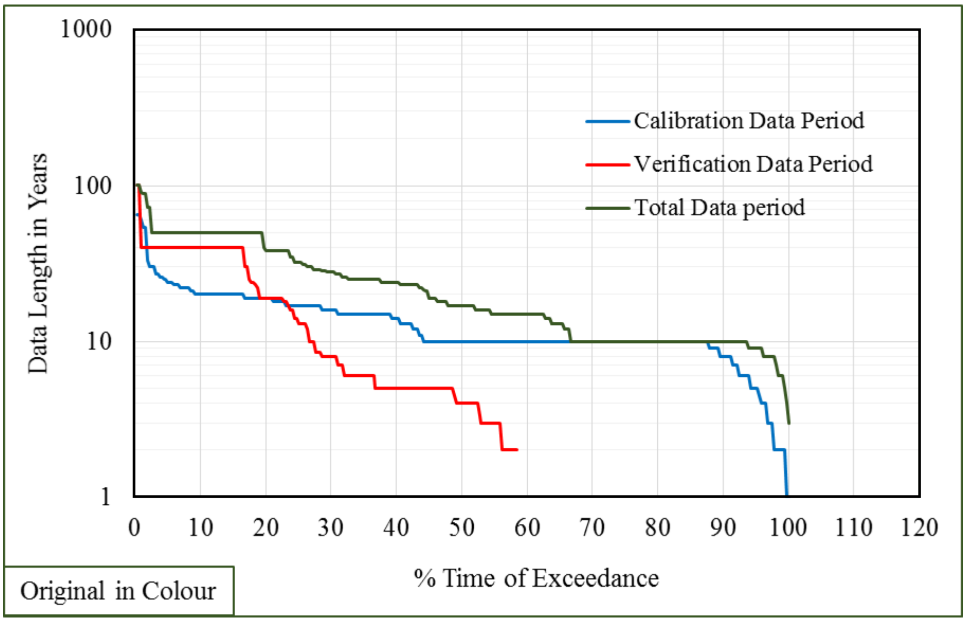

Figure 2-9: Percentage Time of Exceedance of Data Length in all applications (Monthly Models)

2.6.4.2. Calibration Data Length

Individual exceedance curves for calibration and verification cases are in the Figure 11 and Figure 12. Shape of the exceedance curve for calibration data length enables the identification of less frequent data usage. The less frequently used long data lengths shown by highly varying slope of small time of exceedance, are approximately between 0% and 10% time of exceedance for calibration data periods. This segment with highly variable slope over a short % time of exceedance, is followed by a data length range with a shorter bandwidth having milder slopes and spanning over a longer % time of exceedance. This represents the most frequently used data lengths and provides an indication of the percentage usage. Subsequent to this section with a stable slope is another rapidly varying slope which correspond to less frequent short data lengths. The data length ranges that had been used in applications are summarized in the Table 2-1.

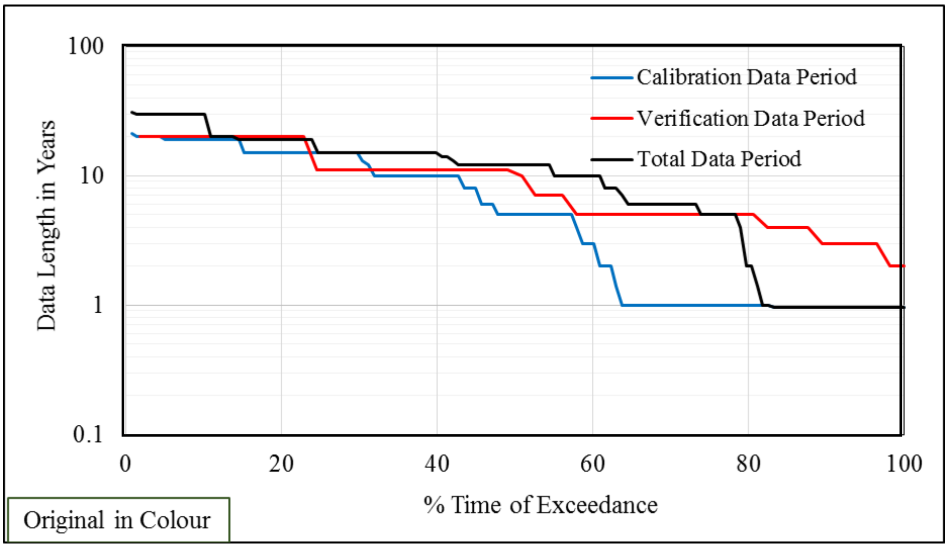

Figure 2-10: Percentage Time of Exceedance of Calibration and Verification Data Period in associated applications (Daily Models)

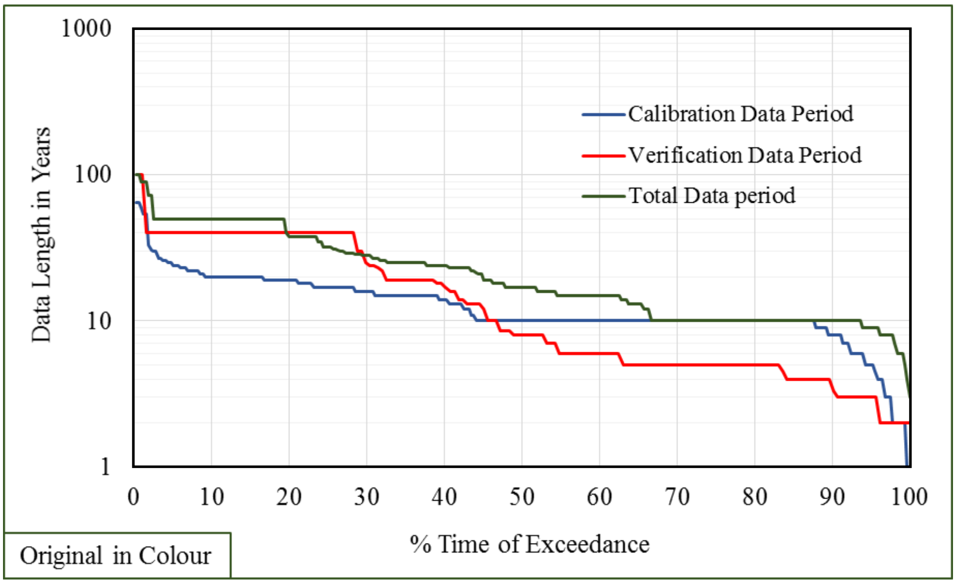

Figure 2-11: Percentage Time of Exceedance of Calibration and Verification Data Period in associated applications (Monthly Models)

Daily models showed that Calibration data duration has respective values of 21, 19 and 19 years as the maximum, minimum and median of the watersheds subjected to the review between 0 to 10% times of exceedance. Similarly the maximum, minimum and median of the reviewed watersheds are 19, 0.96 and 5 years respectively for % time of exceedance between 10 – 85%. Maximum, minimum and median of the reviewed watersheds greater than 85% exceedance is 0.96, 0.96 and 0.96 years.

Monthly models showed that calibration data duration has respective values of 65, 20 and 24.5 years as the maximum, minimum and median of the watersheds subjected to the review between 0 to 10% times of exceedance. Similarly the maximum, minimum and median of the watersheds reviewed are 20, 10 and 10 years respectively for % time of exceedance between 10 – 85%. Maximum, minimum and median of the reviewed watersheds greater than 85% exceedance is 10, 1 and 6 years.

Table 2-1: Data length and Temporal scale (Calibration Period)

	Data Length (Monthly Scale)			**Data Length (Daily Scale)**		
% Time of Exceedance	**Maximum**	**Minimum**	**Median**	**Maximum**	**Minimum**	**Median**
< 10%	65	20	24.5	21	19	19
10% - 85 %	20	10	10	19	0.96	5
> 85 %	10	1	6	0.96	0.96	0.96

2.6.4.3. Verification Data Length

The exceedance curve for verification data lengths shows the long and short less frequent data length usage at either ends. The threshold values interpreted from the curve are shown in Table 2-2.

Table 2-2: Data length and Temporal scale (Verification Period)

	Data Length (Monthly Scale)			**Data Length (Daily Scale)**		
% Time of Exceedance	**Maximum**	**Minimum**	**Median**	**Maximum**	**Minimum**	**Median**
< 28%	101	40	40	20	11	20
28% - 84 %	40	5	6	11	4	6
> 84 %	4	2	3	4	2	3

2.6.4.4. Total Data Length

The exceedance curve for total data lengths shows the long and short less frequent data length usage at either ends. Threshold values interpreted from the curve are shown in Table 2-3.

Table 2-3: Data length and Temporal scale (Total Data Period)

	Data Length (Monthly Scale)			**Data Length (Daily Scale)**		
% Time of Exceedance	**Maximum**	**Minimum**	**Median**	**Maximum**	**Minimum**	**Median**
< 19%	101	50	50	31	19	31
19% - 94 %	40	10	15	19	0.96	19
> 94 %	9	3	8	0.96	0.96	0.96

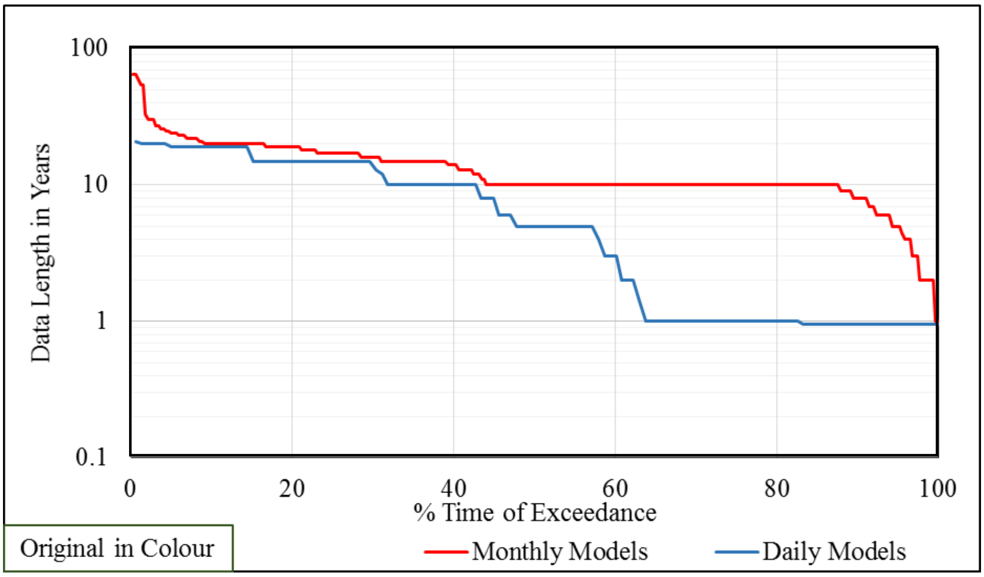

Figure 2-12: Calibration Data Length of Daily and Monthly Temporal Scale

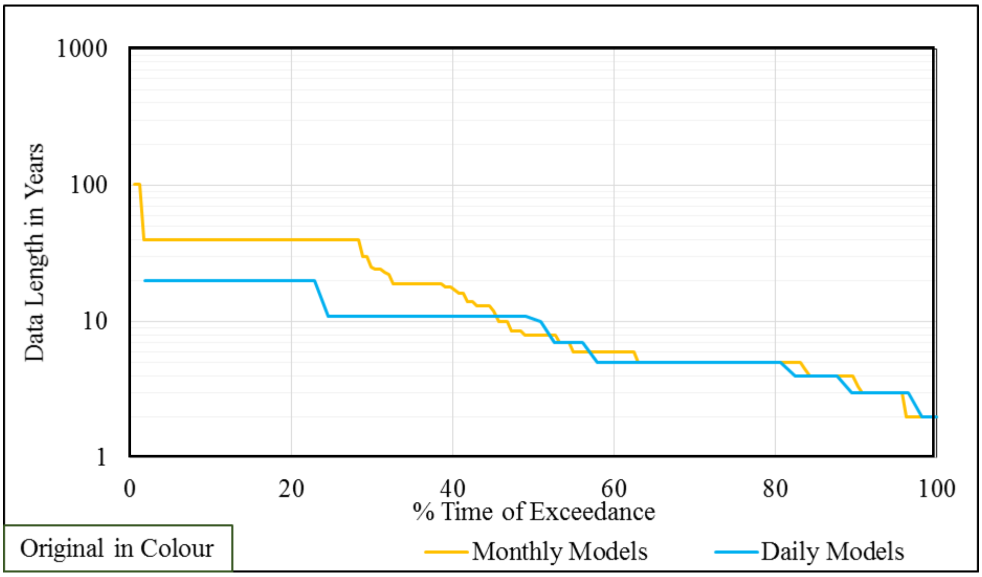

Figure 2-13: Verification Data Length of Daily and Monthly Temporal Scale

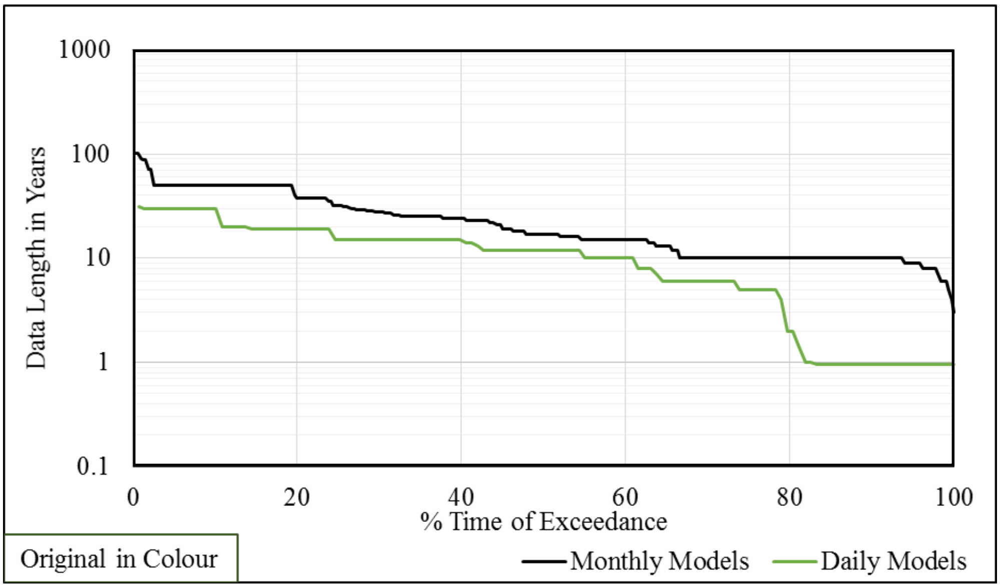

Figure 2-14: Total Data Length of Daily and Monthly Temporal Scale

2.6.5. Catchment Size

All case applications reviewed in the present work were plotted to identify the behavior between the data duration and the size of catchment. Semi logarithmic plots of data length against catchment size indicated a clustering of catchments in Figure 2-15, Appendix A Figure A.1, and Table A.3. Number of applications against the data length is also indicated under each category.

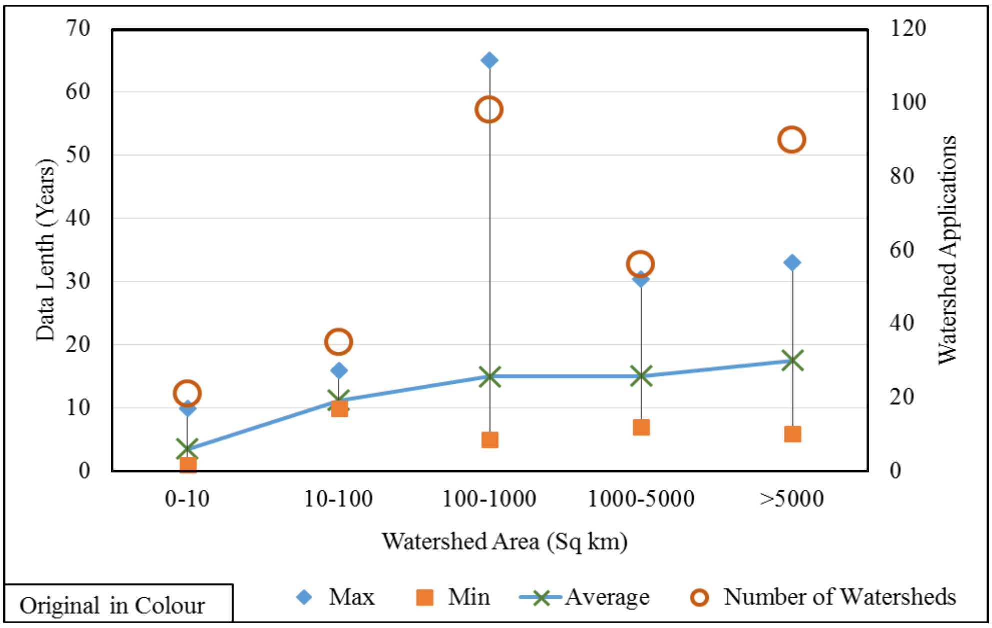

Figure 2-15: Calibration Data Duration Variation According to Watershed Area

Applications with watershed area between 0 – 10 square kilometers has a median of 3 years (Haan, 1972; Xu and Vandewiele, 1994; Allred and Haan, 1996; Bobba et al., 1997). In the range of 10 – 100 km2 the median values is 10 years (GÖrgens, 1983; Alley, 1984; Xu and Vandewiele, 1994; Szolgay et al., 2003). Watershed with sizes from 100 – 1000 km^2 has the highest variation between maximum and minimum catchment area. This is because of a single application with a 65 year data length. In this range, the maximum without this out of ordinary application is 10 years. The median value of data length for 100-1000 watershed is 11 years (Porter and McMahon, 1975; Alley, 1984; Mimikou et al., 1991; Michaud and Sorooshian, 1994; Xu and Vandewiele, 1994; Xiong and Guo, 1999; Szolgay et al., 2003; Mahanama et al., 2008; Sha et al., 2013; Tayefeh Neskili, Zahraie and Saghafian, 2017). Watershed applications between 1000 and 5000 km2 indicated the median data length as 15 years (Mimikou et al., 1991; Xu and Vandewiele, 1994; Hughes, 1995; Xiong and Guo, 1999; Fernandez, Vogel and Sankarsubramanian, 2000; Jothityangkoon, Sivapalan and Farmer, 2001; Mahanama et al., 2008; Martinez and Gupta, 2010; Machado et al., 2011; Qi et al., 2017; dos Santos, de Oliveira and Mauad, 2018). Greater than 5000 km2 study area catchments has a median of 19 years (Hughes, 1995, 2004; Xiong and Guo, 1999b; Chen, Chen and Xu, 2006; Wang, Xia and Che, 2009; Jain, Jain and Pandey, 2013; Bai et al., 2015; Jajarmizadeh et al., 2015; Vilaysane et al., 2015; Qi et al., 2017). A majority of applications in most of the considered watershed range indicated that the median value is between 10 and 19 years. It is felt reasonable to conclude that maximum data length that had been considered by many for monthly applications is in the order of 30 years and that the most common data length could be approximated as 15 years.

2.6.6. Monthly Water Balance Model Review

Monthly water balance models are developed to simulate monthly runoff of a watershed. Monthly water balance models can smooth out unusual variations of rainfall which occurs within few days of a month or a few hours of a day (Xiong & Guo, 1999). Since 1940's, various MWBMs had been developed. Such as, models using monthly rainfall as input, models using rainfall and temperature as input, models using rainfall and evapotranspiration as input and monthly output models using daily input data (Khandu, 2016, Snyder, 1963, Xu & Singh, 1998). Monthly water balance models use spatially, temporally and conceptually lumped data. In spatial lumping means the input parameters such as rainfall and evapotranspiration are spatially averaged. Temporal lumping means that only cumulative inputs or outputs of a long data period such as months. Conceptual lumping means that processes of a basin are not individually considered, but as process sub-models (Mouelhi, Michel, Perrin & Andre´assian, 2005). Advantages of using monthly water balance models are i). availability, ii). low computational costs, iii). reasonable and quick answers, iv). lesser number of parameters (Khandu, 2016,unpbl, Mouelhi et al., 2006 and Wang et al., 2011). A review of water balance models carried out by Xu and Singh, (1998) recognized four types of monthly water balance models based on the type of input. They stated that models using only rainfall data cannot be recommended when other meteorological data besides rainfall data are available and quoted Alley (1984) and Vandewiele et al. (1992), which indicated that the models using precipitation and temperature can be used in reproducing annual and seasonal flows but the state variable simulated by these models may be unrealistic.

2.6.6.1. Selected MWBM Parameters and Applications

Xiong & Guo, (1998) developed and experimented on a two parameter monthly water balance model and concluded that this model can be easily and efficiently incorporated in water resources planning and management. Considering advantages of using monthly water balance models (Khandu, 2016, unpbl, Mouelhi et al., 2006 and Wang et al., 2011) and MWBM review by Xu & Singh, (1998) a model using precipitation and evapotranspiration monthly data can be judged as suitable for more reliable forecasting of streamflow. Therefore the model developed by Xiong & Guo, (1998), which is the Two Parameter Monthly Water balance Model was selected for the present study. The major model inputs required are precipitation (Pt) and Evapotranspiration (EPt) to estimate Streamflow and Soil Moisture level.

2.7. Model Evaluation and Parameter Optimization

Commonly model evaluation is done by using graphical and statistical methods for the comparison of estimated and observed streamflow. Moriasi et al, (2012) stated "The graphical methods used for evaluation include time series plots, scatter plots, cumulative frequency distribution, and contour maps. Some of the statistics used include root mean square error, Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970), index of agreement, percent error, mean absolute error, correlation coefficient, mean error, absolute mean error, relative error, relative bias, standard error of estimate, coefficient of model-fit efficiency, Kolmogorov- Smirnov test, coefficient of determination, mean absolute error, model efficiency, normalized root mean square error, root mean square difference, minimum value of the nonlinear weighted objective function, percent bias, root mean square error to standard deviation ratio, mean error, 95% confidence interval to account for uncertainty, means, and standard deviation". As stated by Johnston. P.R. & Pilgrim D.H., (1976), to obtain parameter values of hydrological models, two broad approaches have been used. 1) Values are estimated from available knowledge of processes or from measurements of physical properties of the watershed where it is assumed that the model realistically represents the measurable physical processes; and 2) Parameter values are found by a systematic optimization technique by achieving the best possible reproduction of the observed runoff in terms of a chosen objective function.

Moriasi et al, (2007) stated that statistical techniques selected for model evaluation should be based on following factors. (1) Robustness in terms of applicability to various constituents, models, and climatic conditions; (2) commonly used, accepted, and recommended in published literature; and (3) identified strengths in model evaluation. Conceptual models with a large number of parameters which cannot be measured directly should be estimated through model calibration i.e. by fitting the modelled outputs to the observed by adjusting model parameters. Objective function or calibration criterion is a measure of fit between simulated outputs to observed outputs. Depending on the objective function, calibration is carried out to minimize or to maximize this measure of fit appropriately (Duan.Q et al., 1994).

Five characteristic difficulties in obtaining a good value for an objective function were identified by Johnston. P.R. & Pilgrim.D.H., (1976). 1) Interdependence of model parameters 2) In difference of the objective function to the value of a parameter 3) Defining the gradient direction 4) Local optima 5) Scaling of parameters. Most common statistical approaches to evaluate outflow hydrographs of a model are Nash & Sutcliffe (1970), Mean Ratio of Absolute Error (MRAE), Relative Error (RE), Ratio of Absolute Error to Mean (RAEM) and Correlation Coefficient (R2) (Xu & Singh, 1998; Xiong & Guo, 1999; Wijesekera, 2000; Mouelhi et al., 2006; Chen et al., 2007; Wang et al., 2011). Xiong and O'Connor (2000) also noted that "the goodness of the estimated optimum parameter set is determined more by the shape of the response surface, which reflects both the rainfall– runoff relation expressed by the data and the structure of the selected model, rather than by the optimization methods used to calibrate the model".

Objective function measures the degree of matching of computed and observed hydrographs. Calibration process estimates model parameters which cannot be estimated directly or which has have no physical meaning. Manual or automated calibration may be performed, and manual calibration relies on user's knowledge of basin physical properties and expertise in hydrologic modeling (Cunderlik and Simonovic, 2004). Green and Stephenson (2009) stated that the method of assessing a model depends on the objective of modeling. For example, modeler may be interested only in peak flows or routing effects, then the area of interest might be different. Authors recommended objective functions such as percent error in peak, percent error in volume and sum of squares / sum of absolute residuals objective functions in single event modeling and to assess the performance of a model over a number of different events the authors had suggested the use of Nash-Sutcliff objective function.

2.7.1. Nash-Sutcliffe Efficiency

Nash and Sutcliffe (1970) defined the efficiency 'E', as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the period under investigation. It is calculated as:

$$E = \frac{F_0 - F}{F_0} \times 100\% \quad (1)$$

$$F_0 = \sum (Qi - Qc)^2 \quad (2)$$

$$F = \sum (Qi - Qi')^2 \quad (3)$$

$$Qc = (\textstyle\sum_{i=1}^{Nc} Qi) / Nc \quad (4)$$

Where Fo is the sum of squared deviations of the observed runoff Qi from the mean value Qc of the observed runoff series in the calibration period, and F is the sum of squared discrepancies of the simulated runoff Qi' from the observed runoff Qi. Nc is the calibration period. The value of E is expected to approach unity for a good simulation of the observed runoff series. A negative modelling efficiency means that the model prediction is worse than using the mean of the observed flows (Krause et al., 2005). Many modelers had used Nash-Sutcliffe coefficient as the objective function during the parameter optimization (Xiong & Guo, 1999; Guo et al., 2002; Zhang & Savenije, 2005; Chen et al., 2007 and Fish, 2011). It has been mentioned that the Nash-Sutcliffe coefficient can be used for evaluating model performance to arrive at a best parameter set for a given watershed (Zhang & Savenije, 2005). Main disadvantage of the Nash-Sutcliffe efficiency is that the differences between the observed and predicted values are calculated as squared values. Therefore larger values in a time series are strongly emphasized whereas lower values getting neglected (Legates & McCabe Jr, 1999, Krause et al., 2005).

2.7.2. Relative Error

The relative error of the volumetric fit between the observed runoff series and the simulated series (Xiong & Guo, 1999) is represented by this indicator.

$$RE = \frac{\sum(Qi - Qi')}{\sum Qi} \times 100\% \quad \ldots\ldots(5)$$

Where Qi is the observed discharge and Qi' is the simulated discharge.

The value of RE is expected to be close to zero for a good simulation of the total volume of the observed runoff series. Xiong & Guo (1999) studied seventy sub-catchments in the Dongjiang, Ganjiang and Hanjiang Basins in the south of China and reported that the RE varies from -0.78 to +0.58 during calibration while the same was -9.0 to +7.22 during validation.

2.7.3. Mean Ratio of Absolute Error

Mean Ratio of Absolute Error objective function is a statistical measure given by the average error in the modelled streamflow by considering the absolute mismatch at each observation point relative to the magnitude of observed streamflow at that particular observation point. Wanniarachchi (2013) computed runoff coefficient by mathematical modelling of Attanagalu Oya watershed (52.6 km^2) for reliable estimations to meet the future challenges of water resources development in Sri Lanka incorporated Mean Ratio of Absolute Error (MRAE) as objective function for calibration and verification. The error value during calibration was 0.3942 while the same during verification was 0.3567. Wijesekera (2000) and Wijesekera & Perera (2010) also used the Mean Ratio of Absolute Error (MRAE) for parameter optimization. The MRAE indicates an average relative error of model output with reference to a given observed streamflow, is defined as follows:

$$MRAE = \frac{1}{n}\left[\sum \frac{|Yobs - Ycal|}{Yobs}\right] \ldots\ldots(6)$$

Where, Yobs, Ycal are the observed and calculated streamflow values while n is the number of data in the time series. This method considers the error of the specific set of observations being matched. Hence it provides a better representation when contrasting observations are present in the observed data set. The research carried out by Wijesekera & Rajapakse (2014) on mathematical modelling of watershed wetland crossings for flood mitigation and groundwater enhancement of Attanagalu Oya watershed of Gampaha District at Karasnagala, have used MRAE as one of the objective function. The model was calibrated and verified and found that the MRAE value varies from 0.62 to 0.84 for calibration and 0.53 to 1.25 for validation. In this work flow duration curves showed good matching with a Mean Ratio of Absolute Error of 0.66 for calibration while the same for validation was 0.70.

2.7.4. Ratio of Absolute Error to Mean

World Meteorological Organization (1974) in its publication recommends Ratio of Absolute Error to Mean (RAEM) as an objective function. RAEM is calculated as given below.

$$A = \frac{\sum|y_c - y_o|}{n\overline{y_o}} \quad \text{.........(7)}$$

$\bar{Y}$, is the mean of the observed discharge.

The general concept is that the differences between the observed and calculated values are normalized by the observed value and optimum parameters are obtained at the minimum value of RAEM. RAEM is an average indicator for the matching of each and every point of the two hydrographs relative to the observed value at that particular time point and it has an advantage of reflecting the matching at each and every point based on the order of magnitude at that point.

2.7.5. Objective Function Evaluation

Objective functions were evaluated by considering their performance during peak flow matching, intermediate flow matching and low flow matching in Table 2-4 . Overall objective function suitability check shows that MRAE and Nash Sutcliffe Coefficient (NSE) performs well for hydrograph and flow duration curve matching. However considering the overall flow matching and intermediate flow matching which is the concern for water resources management in the present work, MRAE objective function is preferred over NSE.

Table 2-4: Objective Function Evaluation

Objective Function	Equation	Peak Flow Matching	Intermediate Flow Matching	Low Flow Matching	Overall Flow Matching	Reference Literature	Overall Objective Function Suitability
MRAE	$MRAE = \frac{1}{n}[\sum \frac{\lvert Yobs - Ycal \rvert}{Yobs}$	Medium	Very Good	Medium	Very Good	Perera & Wijesekera, 2010; Wijesekera, 2000, Wanniarachchi, 2013,	Very Good
Nash Sutcliffe Coefficient (NSE)	$E = 1 - \frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model})^2}{\sum_{i=1}^{n}(X_{obs,i} - \overline{X_{obs}})^2}$	Very Good	Very Good	Medium	Medium	Xiong & Guo, (1999), Guo et al., (2002), Chen et al., 2007; Fish, (2011), Krause et al., (2005), Zhang & Savenije, (2005)	Very Good
RAEM	$A = \frac{\sum \lvert y_c - y_o \rvert}{n\overline{y_o}}$	Poor	Medium	Medium	Medium	Recommended by WMO	Medium
RE	$RE = \frac{\sum(Qi - Qi')}{\sum Qi} \times 100\%$	Poor	Medium	Medium	Medium	Xiong & Guo, (1999) and Guo et al., (2002)	Medium
RMSE	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Xobs,i - Xmodel,i)^2}{n}}$	Medium	Medium	Poor	Medium	Moreda, (1999)	Medium

2.8. Data

Hydrologic modelling requires data such as rainfall, streamflow and evaporation. The problems associated with data such as, quality and missing data were discussed earlier. Longer the dataset it is possible to find inconsistencies, non-homogeneity in the observed data set. Therefore, care must be taken to check the data for errors, because erroneous data will result in unrealistic results. The data errors may occur due to the physical changes in the basin, climate change, and change of location for the gauging station, reading errors or measurement errors (Cheng, He, Cheng, & He, 2016; Gao et al., 2017; Negash, 2014; Searcy & Hardison, 1960; Wakachala, Shilenje, Nguyo, Shaka, & Apondo, 2015).

2.8.1. Data Rectification

Hydrologic data require rectification if they are found to be erroneous or inconsistent. Double Mass Curve method, regression method are some popular data rectification methods (Gao et al., 2017; Searcy & Hardison, 1960).

2.8.1.1. Double Mass Curve Method

Theory of the Double Mass Curve explains that if the data from multiple gauges in a particular setting are consistent, then the cumulative sum of one data set will have a linear relationship with the cumulative sum of other data set within a same time duration. Double mass curve is commonly used for monthly and annual resolution of data only (Dahmen and Hall, 1990). If the data are consistent, then the slope of the line in double mass curve exhibits a constant proportionality of the two data sets. A break in the slope will indicate change in the proportionality between the two datasets. Therefore hydrological data such as rainfall, streamflow, evaporation and sediment transportation can be rectified using double mass curves (Searcy and Hardison, 1960). For rainfall data rectification, cumulative rainfall of one gauging station can be plotted against a set of gauging stations in the area as base data. The ratio of the two slopes identified in the graph at the break point, considered as the correction factor to rectify the data (Subramanya, 2013). Existing literature emphasizes that streamflow rectification cannot be performed against rainfall as base data, because these two rarely have a linear relationship. Streamflow or runoff is depending upon size, shape, slope, surface geology and climate of the watershed other than the rainfall. Therefore it is difficult to identify a linear relationship among them. Therefore Searcy and Hardison, (1960) suggests to use simulated streamflow data from the rainfall as the base data to rectify the observed data. This method is quite ambiguous as there is no guarantee that the observed rainfall data is precise or model performance is reliable. However Wilson, (1969) states that even though the rainfall runoff correlation is not a direct one, an empirical relationship can be established based on annual (water year) rainfall and annual runoff. This author further states that in temperate, tropic and humid climates, a straight-line relationship can be found. Therefore the annual runoff can be obtained from the equation of the regression line. Kohler, (1949) stated that Double Mass Curve can be used to adjust data annually, monthly or seasonally if the dates are known. Nik, (1988) rectified monthly data in his study using statistical regression analysis. Gao et al., (2017) developed a method to rectify streamflow data using the regression line of the double mass curve, which has been used widely afterwards by (Gu, Mu, Gao, Zhao, & Sun, 2019; Murshed & Kaluarachchi, 2018; Shi et al., 2019; Somorowska & Łaszewski, 2019; Y. Wang & Yao, 2019; Yang et al., 2018, 2019; Zhao et al., 2018)

2.9. Summary of Literature Review

The qualitative analysis carried out by using the existing literature which is described in analysis indicate that a total data length above 20-30 years would be the most suitable for a monthly water resources model development. The analysis for the literature review also highlights the need to use a majority of data for model calibration. Therefore, it may be prudent to select at least a 20-year data period for model calibration. Decision alternative selection discussed above was based on the observations made during the review. It is necessary to carry out well designed research to determine design alternatives at finer data range. Data length selection for model development decisions should consider model excitation, data quality, precision of parameters, model complexity and current practice as decision criteria. Considering water resources objectives of the present work, MRAE is the preferred objective function for streamflow matching. Double mass curve and regression method are effective and efficient methods for checking of rainfall, streamflow and other hydro-meteorological data, especially for temperate, tropic and humid climates.

3. Methodology

Methodology flow chart is in Figure 3-1. After identifying the problem addressed in this research, overall and specific objectives were set. Then a literature survey was carried out to identify the current status of water balance modelling, types of models used, number of parameters in a model and their benefits, advantages of using Two Parameter Monthly Water Balance Model (2PMWBM) and benefits of using various objective functions. Kalu River Basin at Ellagawa streamflow gauging station was used as the watershed for case studies. Rainfall, streamflow and evaporation data were collected for the Ellagawa watershed. Data checking was carried out using methods such as visual, water balance and consistency.

Two data sets for calibration and verification were then identified. The calibration data set was then divided in to subsets of different data lengths. Verification data set was kept constant for all calibration data lengths. Then the 2PMWBM was developed based on literature. Initial soil moisture content was an important factor in developing the model. Therefore initial soil moisture content was obtained by using a warm up period of five years. Then model was calibrated with 75 calibration datasets selected from 1983 to 2017 and optimizing model parameters c and SC. The calibration datasets were of 10, 15, 20, 25, and 30 years length. With each of the optimized c and Sc, the model was verified. A common verification data period of 07 years (1976 – 1983) was used. Then the model performance for different input data durations were compared and recommendations are made.

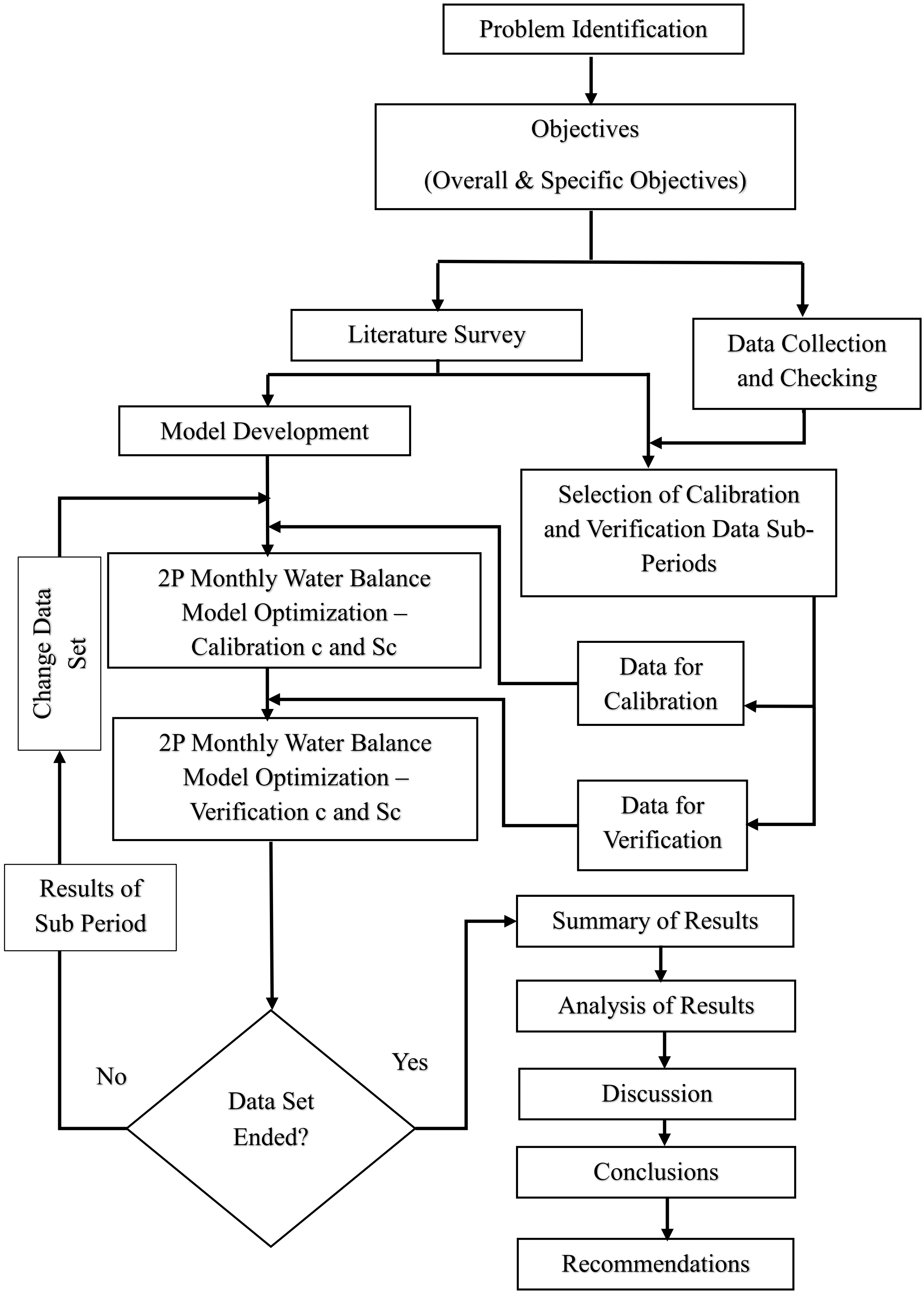

Figure 3-1: Methodology Flow Chart

4. Data and Data Checking

4.1. Description of the Watershed

Ellagawa Watershed in Kalu River basin was selected for this study due to the availability of monthly data. Ellagawa watershed has five rain gauging stations which were considered to calculate Thiessen average rainfall. They are Galatura estate, Balangoda Post office, Wellandura estate, Ratnapura and Keragala. Rathnapura was selected as the evaporation station for this study as shown in Figure 4-2 and Table 4-2 and Table 4-3.

4.1.1. Land Use

Major land use of the watershed extracted from 1:50000 maps is shown in Table 4-1 and Figure 4-1.

Table 4-1: Land Use Distribution of Ellagawa Watershed

Land Use Type	Area (km^2)	Percentage of Area
Forest Area (Forest, Rubber, Coconut, Tea, Other Cultivation)	720.8	51.7%
Built-up Area (Built-Up Area, Homestead)	247.0	17.7%
Marshy Area (Marsh, Paddy)	114.4	8.2%
Grassland (Chena, Grassland, Scrub)	306.3	22.0%
Rock	5.2	0.4%
Total	1393.6	100%

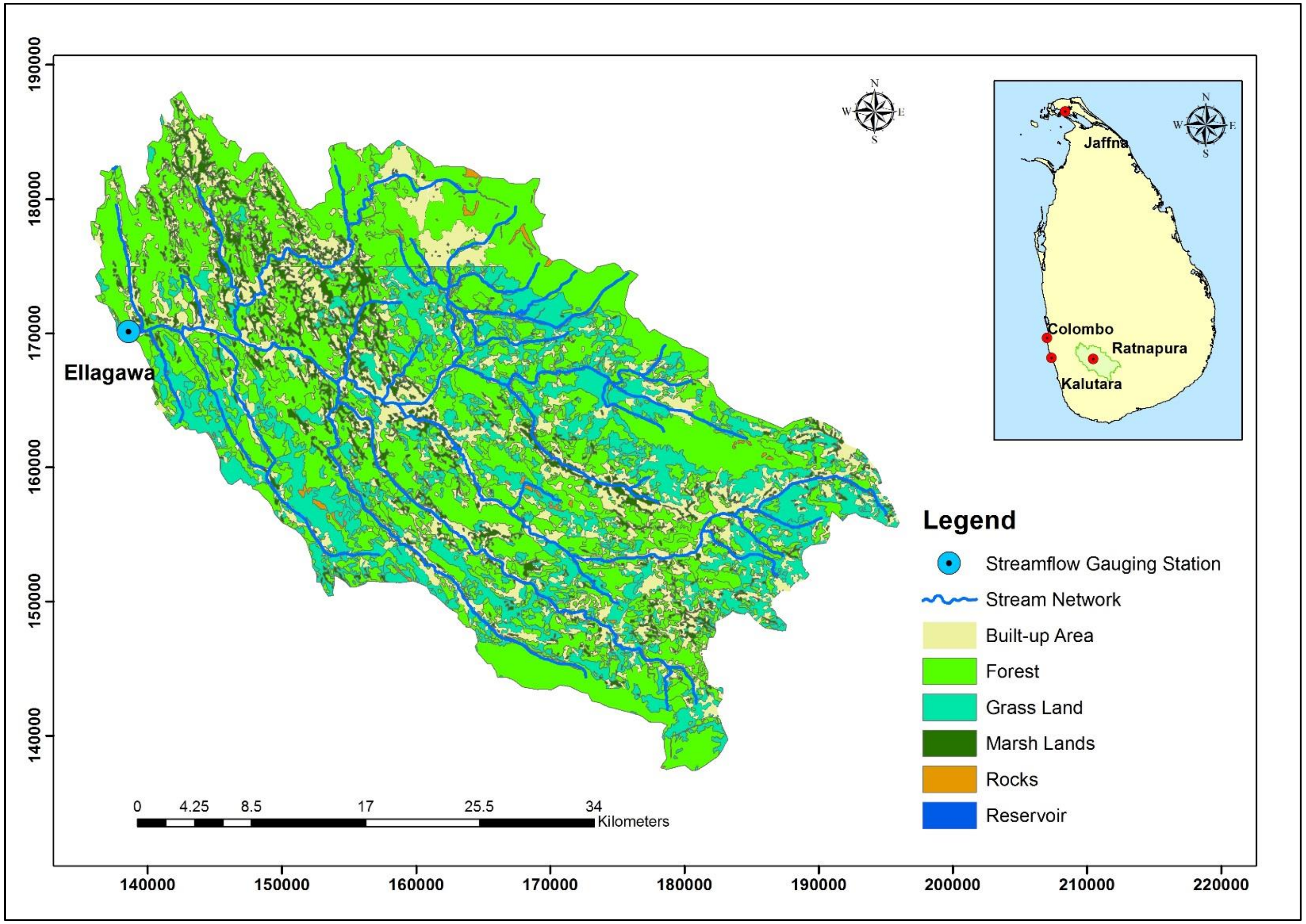

Figure 4-1: Land Use Map - Ellagawa Watershed

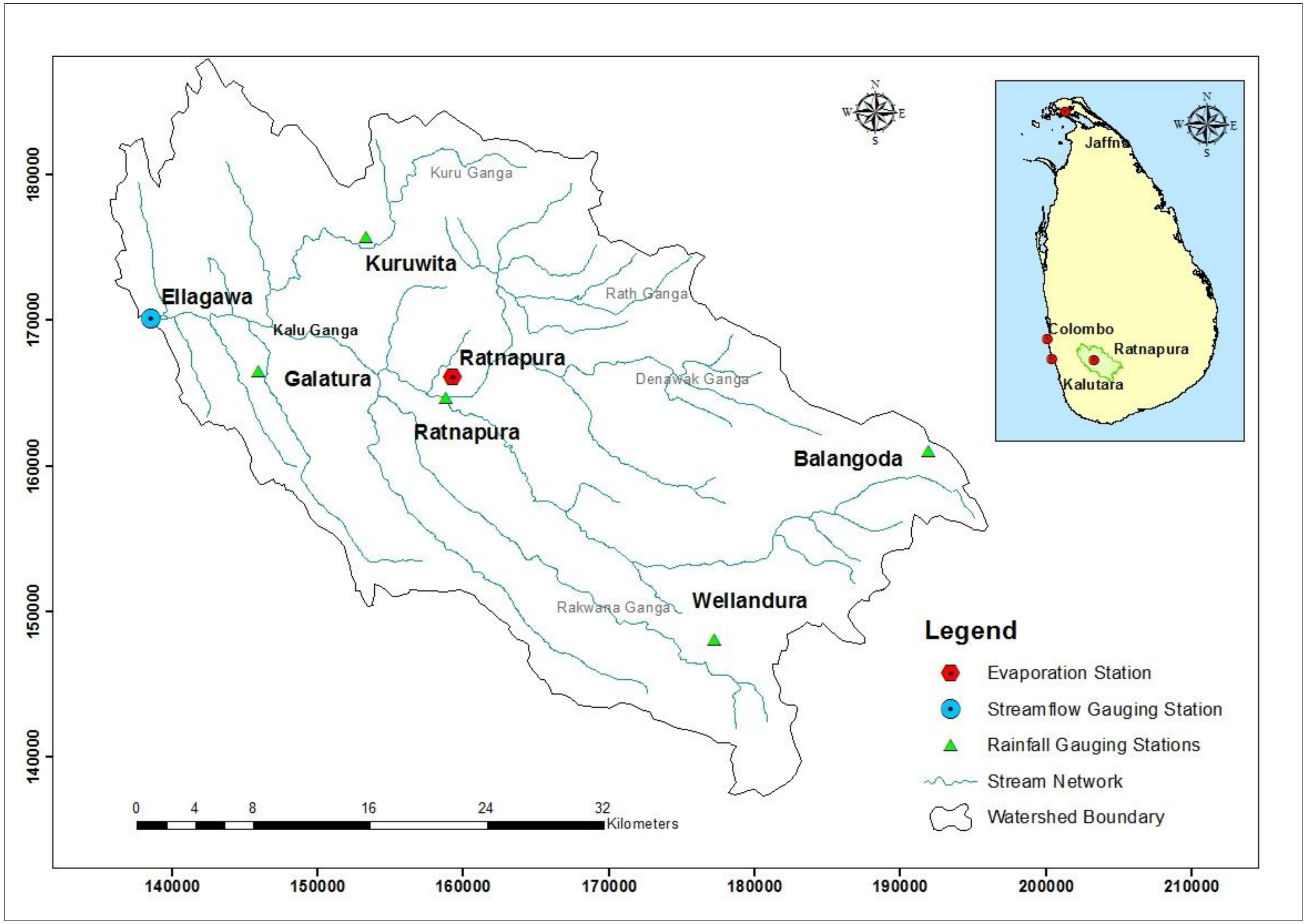

Figure 4-2: Gauging Station Distribution at Ellagawa Watershed

4.2. Rainfall, Evaporation and Streamflow

4.2.1. General

Two parameter monthly water balance model requires precipitation, pan evaporation and streamflow data at Ellagawa streamflow gauging stations as input data. Data of 1983/1984 to 2012/2017 (35 Years) were used for model calibration. Data from 1976/1977 to 1982/1983 (7 years) were used for verification. Rainfall, streamflow and evapotranspiration data were collected from Survey Department, Department of Irrigation and Department of Meteorology as shown in Table 4-2. Further details were obtained from Electricity Master Plan. (1987). Summary of resolution, stations, duration and source of each data collected for model studies is shown in Table 4-2. Location details of the gauging stations given in the Table 4-3.

Table 4-2: Results Summary

Data Type	Data Resolution	Station	Data Duration	Source
Rainfall	Monthly	Galatura Keragala Ratnapura Balangoda Wellandura	1983 -2017	Department of Meteorology
Streamflow	Monthly	Ellagawa	1983 - 2017	Department of Irrigation
Potential Evapotranspiration	Monthly	Ratnapura	1983 - 2017	Department of Meteorology
Topographic Maps	1:50000		Updated 2003	Survey Department

Table 4-3: Gauging Station Location Details

Gauging Station	Location details	
	Latitude	Longitude
Ellagawa	6.9 N	8.44 E
Galatura	6.70 N	80.28 E
Balangoda	6.65 N	80.70 E
Wellandura	6.53 N	80.57 E
Ratnapura	6.68 N	80.40 E

4.2.2. Missing Data

Missing rainfall and evaporation data summaries are shown in Table 4-4 and Table 4-5 respectively.

Table 4-4: Missing Rainfall Data Summary

Station	Missing Months
Galatura Station	1985 - April
	1999 - October
	2007 - September
Keragala Station	1992 - September
	1995 - May, July, August, October, December
	1998 - November, December
	1999 - December
	2000 - December
	2011 - July
Balangoda Station	1994 - December
	1995 - July
	1997 - September
	2012 - January
Wellandura Station	1984 - January
	1990 - October
	1997 - August
	2002 - May, July, September, October, November, December
	2006 - September
	2007 - February, March, September, October, November, December
	2008 - October, November
	2010 - April
	2011 - May, July, November
	2011 - January, December

Table 4-5: Missing Data Summary of Evaporation

Year	Missing Months
1988	May, June
1992	June
2008	April, May, June
2012	November
2013	April, May, June

4.2.2.1. Data Filling

Caldera, et al, (2016) stated that it is not possible to state or recommend a particular method for data filling. However data can be filled based on the number of neighboring gauging stations and their co-relation with that particular station for which the data are filled. Presti, et al (2009) concluded that out of the missing data filling mechanisms tested in their research, which is the simple substitution method may be acceptable. However Presti, et al (2009) quoted, Neter et al. (1996) stating that simple substitution is a well-known and easily available data filling technique available in the literature. In the present study in case of data filling, the missing rainfall data were filled with data from the nearest gauging station.

4.3. Data Checking

4.3.1. General

According to the World Meteorological Organization standards (WMO, 1975), spatial distribution of rainfall and streamflow gauging stations were checked and compared. The station density/spatial distribution used for this study satisfied the WMO standards as shown in Table 4-6.

Table 4-6: Spatial Distribution of Gauging Stations

Gauging Stations	**No. of Stations**	**Station Density (km^2/station)**	**WMO Standard (km^2/station)**
Rainfall	5	278.8	575
Streamflow	1	1393.6	1875

Main types of data used in this study are monthly rainfall, monthly streamflow and monthly pan evaporation. Prior to use these data in the model, data checking was carried out.

4.3.2. Checking for Outliers

Visual checking of data was done to identify the outliers in the dataset. Streamflow and rainfall responses were plotted for the water years from 1983 – 2017 (Figure 4-3). The purple colour circles are where streamflow appears as non-responsive for the rainfall. At Ratnapura station, in year 2001 streamflow does not respond to the high rainfall that had occurred. In Kuruwita station, streamflow has not responded to a high rainfall in year 1986 and year 2016. Similarly for Galutara in year 1999, streamflow has not responded to rainfall. In year 1996 and 2014 Balangoda station shows a comparatively high streamflow for low rainfall and a low streamflow value for high rainfall. Wellandura station in year 2011 shows a low streamflow compared to the rainfall received. However for each rainfall gauging station, streamflow shows a reduction after year 2000.

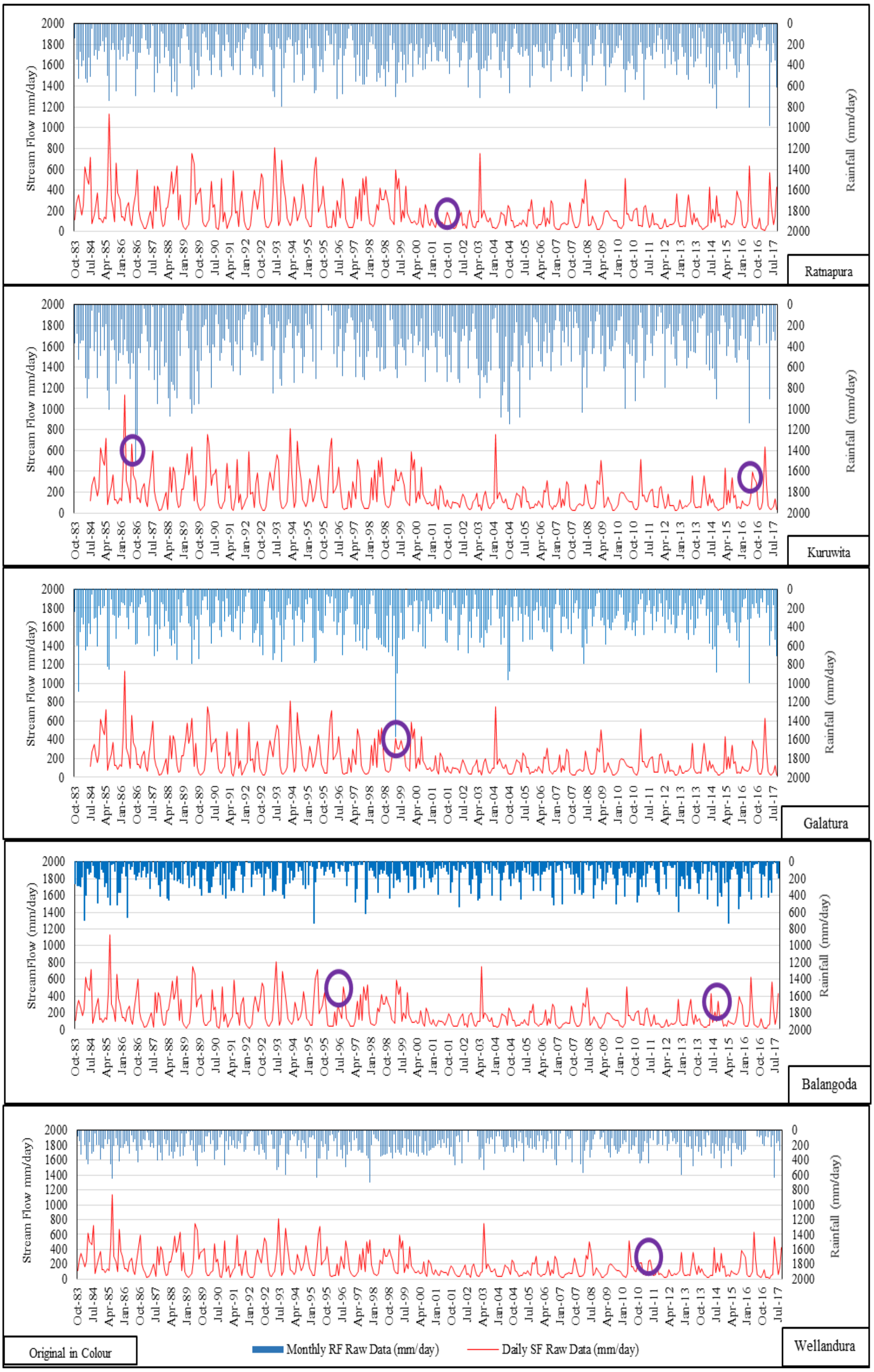

Figure 4-3: Ellagawa Streamflow Response with Rainfall Received at Gauging Stations (1983/84 – 2016/17)

4.3.3. Monthly Data

4.3.3.1. Rainfall

Thiessen weights and the thiessen polygons are shown in Table 4-7 and Figure 4-4 respectively. The monthly maximum, minimum and mean thiessen rainfall values was plotted as shown in Appendix C Figure C.1.

Table 4-7: Thiessen Weights of Rainfall Stations in Ellagawa Watershed

Rainfall Station	Area (km^2)	Thiessen Weight
Balangoda	135.8	0.10
Galatura	194.4	0.14
Kuruwita	294.6	0.21
Ratnapura	448.4	0.32
Wellandura	320.9	0.23

Monthly rainfall pattern over the period of study is shown in Appendix C Figure C.28 to C.32. Mean monthly rainfall pattern over the period Appendix C Figure C.1 reflects the expected two peak monsoonal behavior. However Maximum and Minimum rainfall pattern moves away from the two peak behavior in January and May with a depression in maximum rainfall and increase in Minimum rainfall in January and a depression in minimum rainfall in May. The two-peak behavior resembles the North-East Monsoon in October to February and South-West Monsoon during March to September.

4.3.3.2. Streamflow

Monthly high, medium, low streamflow at Ellagawa is shown in Appendix C Figure C.2. Two peak behavior in October and June is visible in the figure. Lowest streamflow is expected in March. Streamflow variation with respect rainfall at each gauging station is shown in Appendix C Figure C.4 to C.28.

4.3.3.3. Evaporation

High, medium and low flow variation of evaporation at Ratnapura station is shown in Appendix C Figure C.3. The maximum evaporation can be expected in March, which tallies with the lowest rainfall and streamflow occurrence in March as shown in Figure C.1 and C.2.

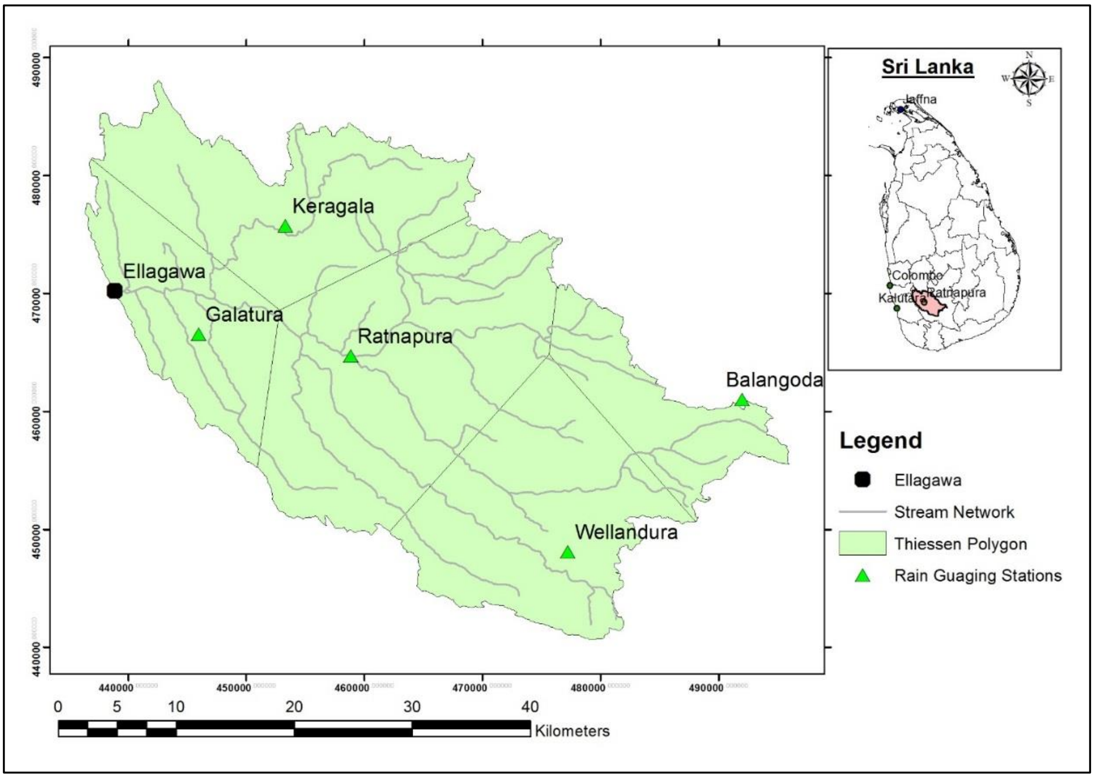

Figure 4-4: Thiessen Polygons for Ellagawa Watershed

4.3.4. Annual Water Balance

Annual water balance is an important data check to compare the rainfall, streamflow, evaporation and annual runoff coefficients of the Ellagawa watershed. Annual water balance is shown in Appendix C Table C.1. A pan coefficient of 0.8 was used to compare the annual water balance with the approximate evapotranspiration value computed using pan evaporation data.

Annual water balance variation indicates a drastic increase in annual water balance difference from year 1999/2000 water year onwards according to Appendix C Figure C.34. Similarly the annual runoff coefficient values are inconsistent over the years. Appendix C Table C.1 with highlighted cells shows the unrealistic values obtained for annual water balance and runoff coefficient.

4.3.5. Consistency Checking

Consistency check for the hydrological datasets was performed by plotting Double Mass Curves (DMC). This check enabled the identification of whether gauging stations had undergone significant changes over the years of data record due to anthropogenic activities, climate changes, human errors, land use changes, flow diversions or change in location or disturbance to the location of the gauging station which might cause inconsistencies and non-homogeneity of the data sets (Dahmen and Hall, 1990; Gao et al., 2017, Subramanya., 2013). A break in the slope of the graph, indicates an inconsistency which should be corrected either using double mass curve method or regression line. Double mass curve is also useful to identify arithmetic errors which may have occurred during data transfer. Longer data sets which are used in hydrologic modelling often consist of inconsistencies. However the application of this method is limited for monthly and daily analysis. The best feature of this method is, it preserves the mean of the data set. Therefore the different slopes obtained in the data series, indicates the change of the mean in two data sets (Dahmen and Hall, 1990). Gao et al., 2017 develops the regression line method which can be used to produce reliable results on the basis of widely available precipitation data.

The annual Double Mass Curves plotted for the rain gauging stations, are given in Figure 4-5. DMC plotted for rain gauging stations shows a good consistency in the data without major deviations. Figure 4-6 is DMC plotted for cumulative streamflow against cumulative rainfall. A break of the slope can be identified in the graph indicating the sudden drop noted in the visual checking. The regression line technique (Gao et al., 2017) was used to rectify the streamflow data. Double Mass Curve plotted for pan evaporation against rainfall is shown in Figure 4-7. A break of the slope can be seen in the graph. The evaluation data also pointed to the need to rectify the data inconsistencies in streamflow and evaporation prior to carryout modelling the watershed.

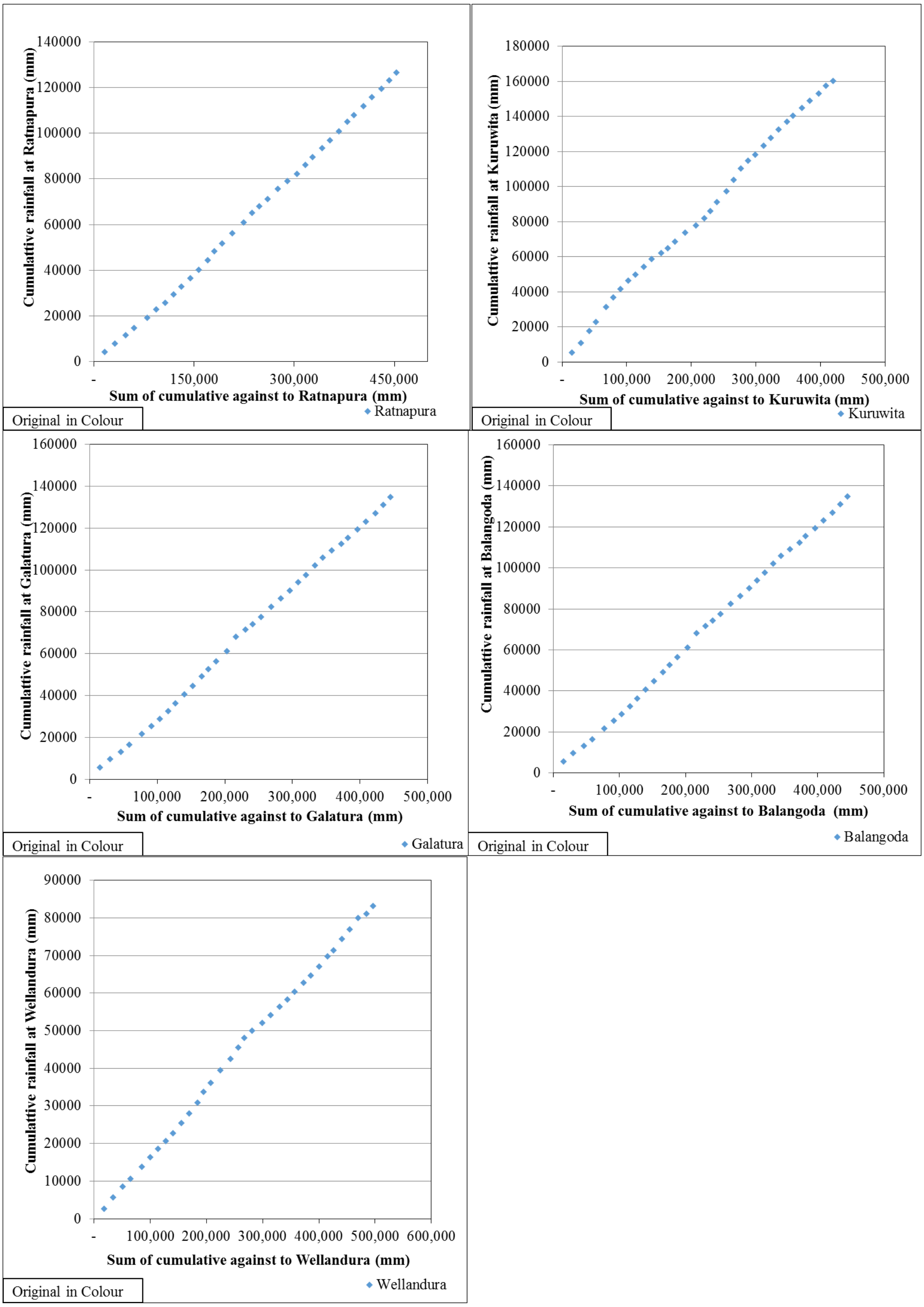

Figure 4-5: Double Mass Curves for Rainfall at Ellagawa Watershed

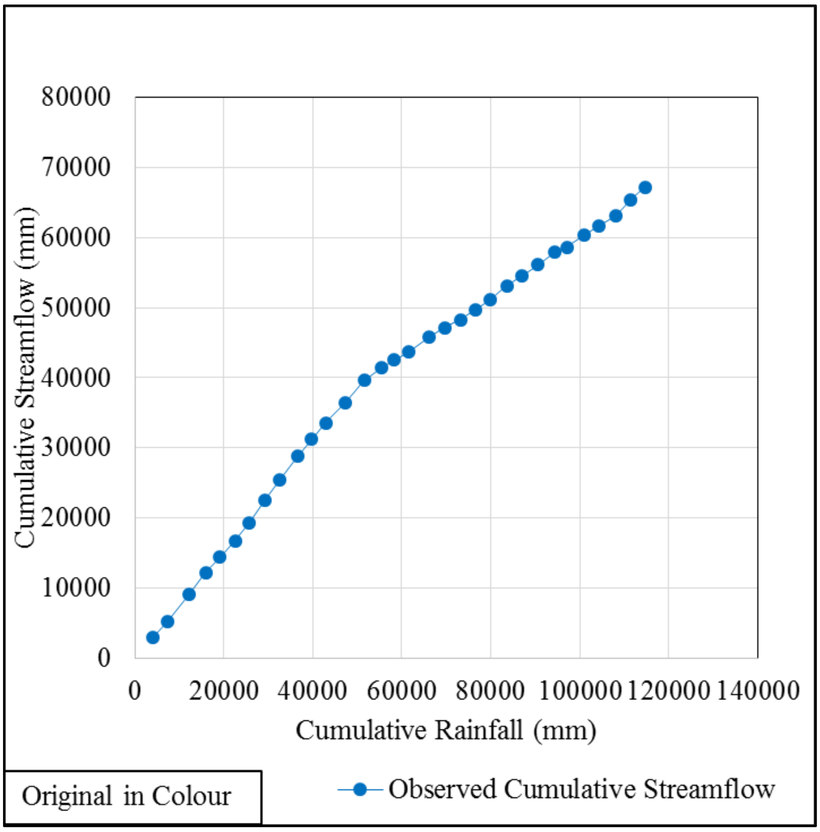

Figure 4-6: Double Mass Curve for Streamflow against Rainfall

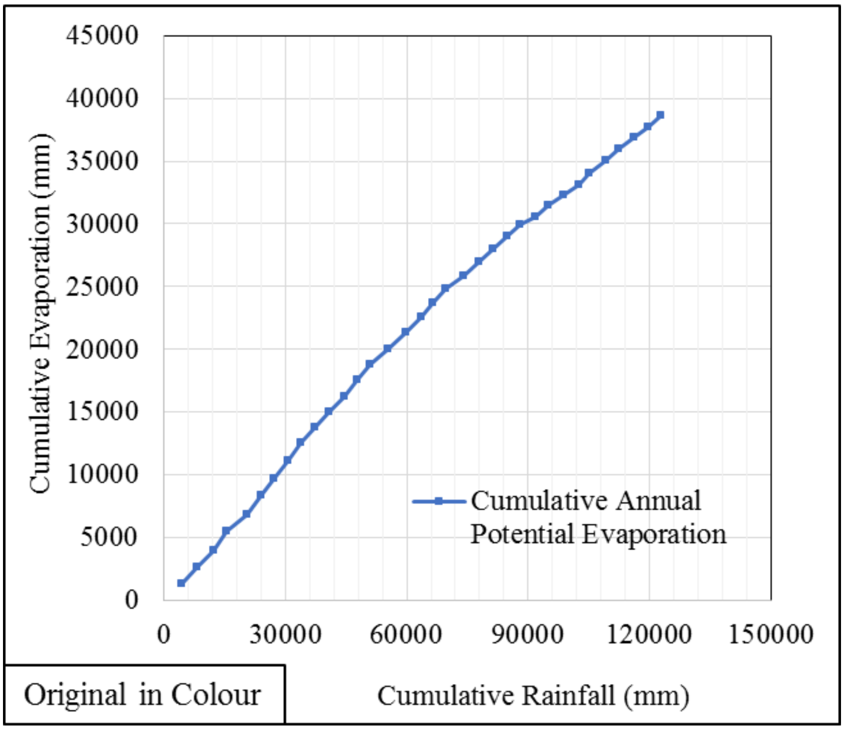

Figure 4-7: Double Mass Curve for Pan Evaporation

4.3.6. Data Rectification

There is a challenge to identify a continuous data set for the comparative evaluation in the present study. An investigation of Annual Consistency rectification was carried out with the entire data set. The rectification regression was then compared with Double Mass Curve (DMC) drawn for each month (Figure C.35 to Figure C.46 in Appendix C). Comparison of regressions of each month with annual regression indicated that the annual regression is quite satisfactory for rectification of monthly data. These results were used to support the rectification of data inconsistencies when carrying out the rectification, at first the dataset was scrutinized to identify a set of years with rational water balance and runoff coefficients.

The water years which showed realistic annual water balance values and annual runoff coefficient values, were selected as base data for data rectification regression computation. Accordingly, 1985/1986, 1986/1987, 1987/1988, 1989/1990, 1990/1991, 1995/1996 and 1996/1997 was selected as base data. Since the base data for rectification commenced from 1985/86 water year, the rectification exercise initially removed the 1983/84 and 1984/85 data for regression identification. Subsequent to drawing DMC and determining regression, the 1983/84 and 1984/85 data were also rectified.

DMC were computed for both monthly and annual scales. The annual DMC and monthly DMC are shown in Appendix C, Figure C.48 and Figure C.49 to Figure C.60 together with the regression equations. These were carried out by assuming that annual rectification is valid for monthly time scale. Figure 4-8 shows the matching of rectification regressions for annual and monthly DMC for streamflow. The annual water balance comparison after rectification is shown in Figure 4-9 and Figure 4-10. Values are in Table 4-8. The observed streamflow and the rectified streamflow variation with the rainfall was compared and is in Figure 4-12. The comparisons indicate a realistic and an acceptable monthly streamflow data series for the present work. Pan evaporation data (Figure 4-7) were also required rectification because of the unrealistic water balance values noted even after streamflow rectification. The pan evaporation rectification regression is in Figure 4-11.

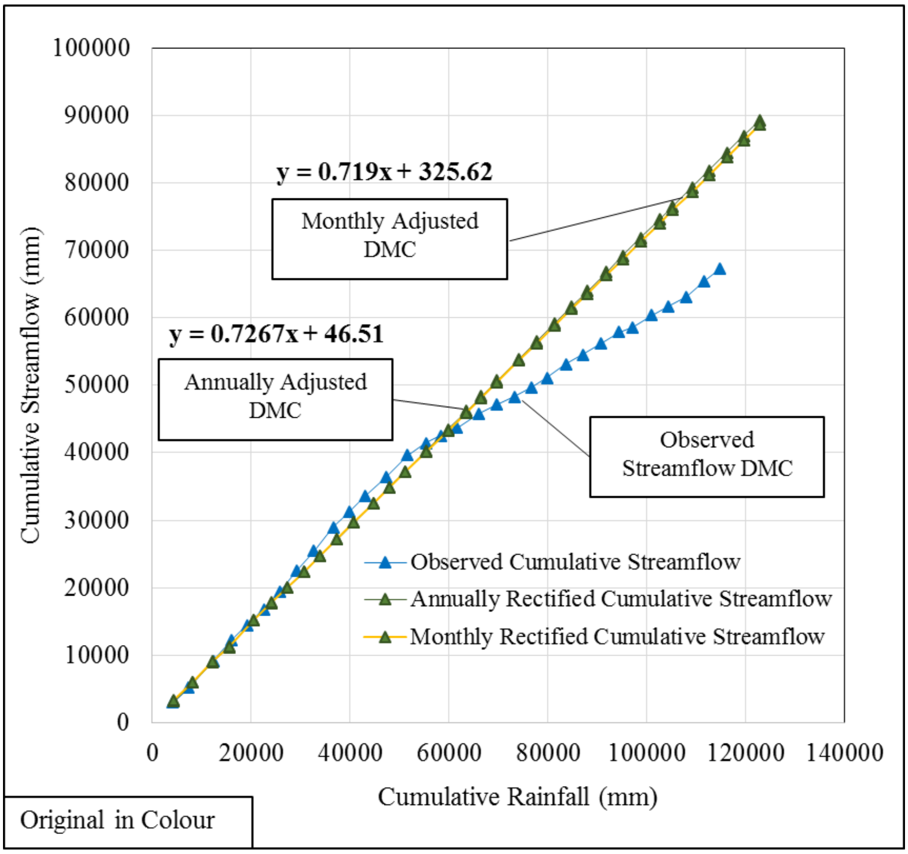

Figure 4-8: Annual Streamflow Rectification and Monthly Streamflow Rectification Using Double Mass Curve

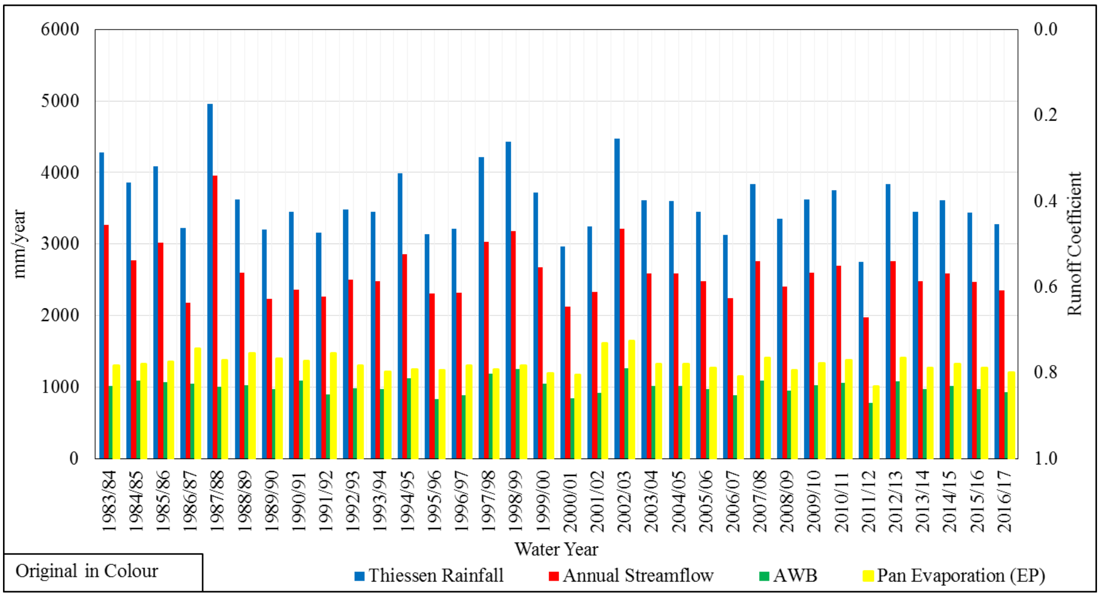

Figure 4-9: Annual Water Balance Comparison after Data Rectification

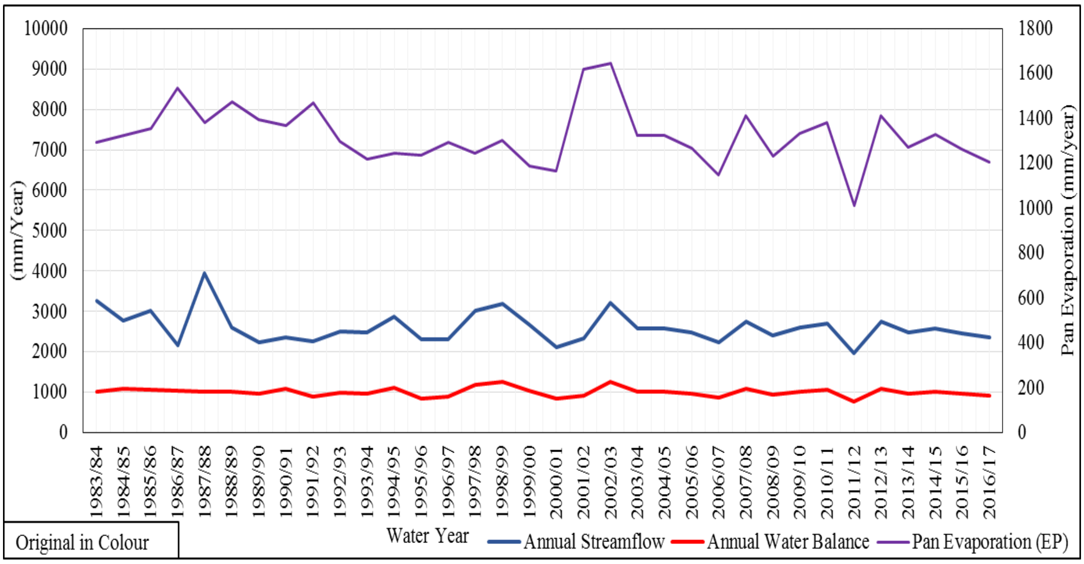

Figure 4-10: Variation of Annual Streamflow Water Balance and Pan Evaporation after Rectification

Table 4-8: Annual Water Balance Comparison after Rectification

Water Year	Thiessen Rainfall (mm)	Annual Streamflow (mm)	Annual Water Balance (mm)	Pan Evaporation (EP) (mm)	AWB/EP	Runoff Coefficient
1983/84	4284.65	3271	1014	1295.17	0.78	0.76
1984/85	3864.03	2774	1090	1324.98	0.82	0.72
1985/86	4090.04	3021	1069	1354.35	0.79	0.74
1986/87	3219.57	2174	1046	1536.65	0.68	0.68
1987/88	4957.27	3952	1005	1379.36	0.73	0.80
1988/89	3621.82	2600	1022	1472.07	0.69	0.72
1989/90	3197.08	2232	965	1393.24	0.69	0.70
1990/91	3447.19	2359	1088	1368.48	0.79	0.68
1991/92	3161.34	2269	892	1467.23	0.61	0.72
1992/93	3479.12	2497	982	1296.62	0.76	0.72
1993/94	3448.13	2475	973	1218.11	0.80	0.72
1994/95	3985.13	2861	1125	1243.15	0.90	0.72
1995/96	3140.35	2306	834	1235.48	0.68	0.73
1996/97	3207.91	2323	885	1294.88	0.68	0.72
1997/98	4217.05	3027	1190	1244.13	0.96	0.72
1998/99	4433.43	3182	1251	1301.87	0.96	0.72
1999/00	3722.34	2672	1050	1186.61	0.89	0.72
2000/01	2962.31	2126	836	1165.20	0.72	0.72
2001/02	3239.88	2326	914	1616.37	0.57	0.72
2002/03	4471.15	3209	1262	1643.15	0.77	0.72

Table 4-8. Annual Water Balance Comparison after Rectification (continued)

Water Year	Thiessen Rainfall (mm)	Annual Streamflow (mm)	Annual Water Balance (mm)	Pan Evaporation (EP) (mm)	AWB/EP	Runoff Coefficient
2003/04	3607.66	2590	1018	1325.82	0.77	0.72
2004/05	3604.74	2587	1017	1324.74	0.77	0.72
2005/06	3449.70	2476	974	1267.77	0.77	0.72
2006/07	3122.05	2241	881	1147.35	0.77	0.72
2007/08	3843.06	2759	1085	1412.32	0.77	0.72
2008/09	3350.44	2405	945	1231.29	0.77	0.72
2009/10	3625.83	2603	1023	1332.49	0.77	0.72
2010/11	3752.90	2694	1059	1379.19	0.77	0.72
2011/12	2746.94	1972	775	1009.50	0.77	0.72
2012/13	3837.94	2755	1083	1410.44	0.77	0.72
2013/14	3453.51	2479	975	1269.16	0.77	0.72
2014/15	3608.21	2590	1018	1326.02	0.77	0.72
2015/16	3435.96	2466	970	1262.72	0.77	0.72
2016/17	3276.78	2352	925	1204.22	0.77	0.72

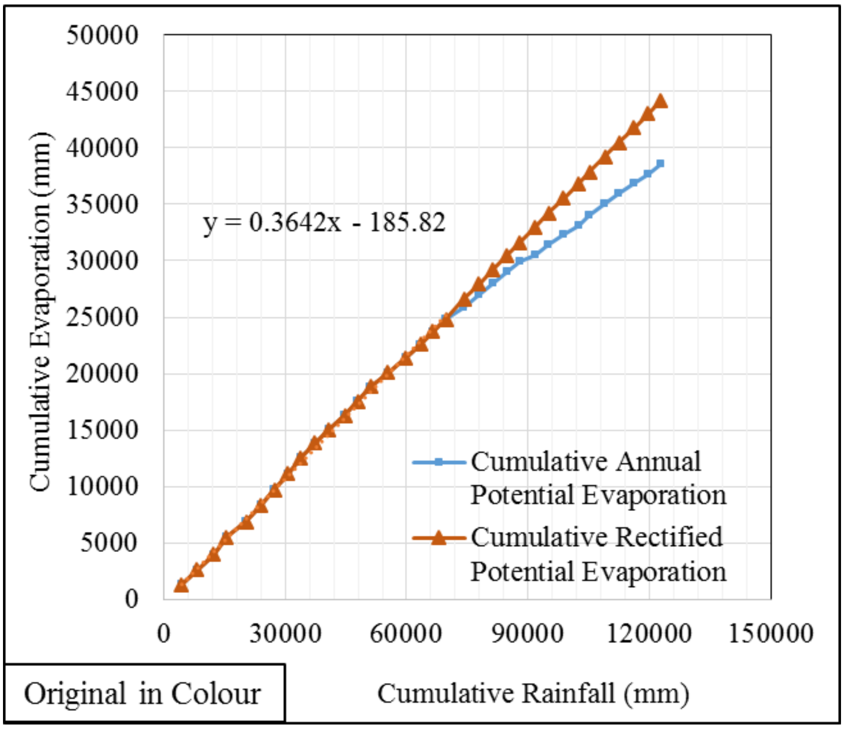

Figure 4-11: Potential Evaporation Rectification using Double Mass Curve

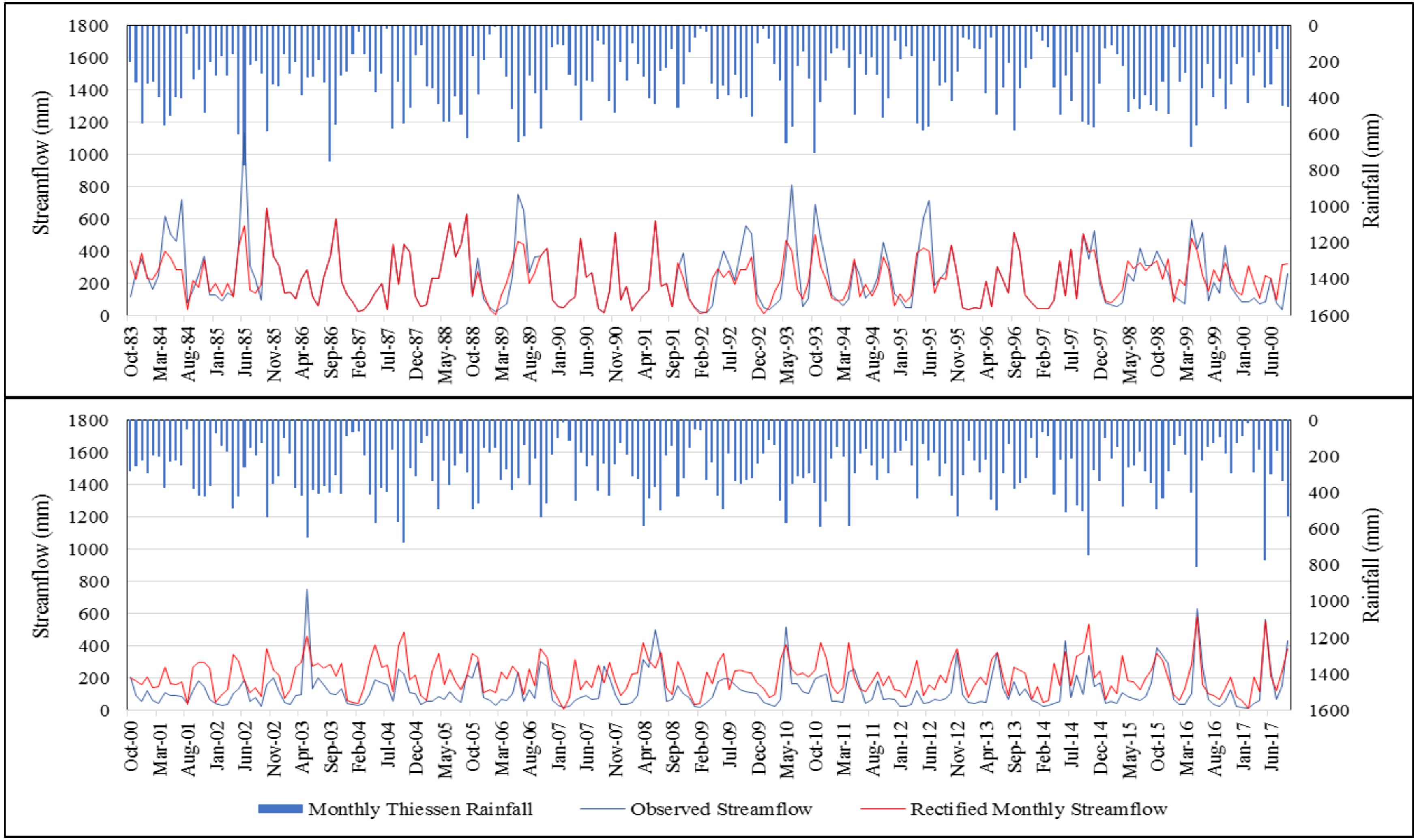

Figure 4-12a – b: Observed and Rectified Streamflow Variation with Thiessen Rainfall (1983/84 - 2016/2017)

5. Analysis and Results

5.1. State of Art Evaluation

The present review revealed that there is a clear deficiency of supporting material for the selection of an appropriate data length to carry out a monthly water resources model development. Available documentation pointed to the criteria that lead to making a rational decision. The following discussion presents the reasoning associated with the selection of criteria while facilitating the determination of available data length alternatives.

5.1.1. Model Excitation

Hydrological models require the calibration datasets to representatively include both wet and dry periods to achieve the precision of model parameters. In case of daily models, even a single representative year has been found as adequate. Models require data not only for model excitation but also to carry out the fitting of mathematical equations representing the watershed hydrology. Reviewed literature did not point to a minimum data length for the excitation of monthly models. One year of daily data contains 365 data points. Therefore, the minimum number of data points to calibrate a model can be considered similar to a daily model. On the other hand, a single water year in daily scale may contain sufficient hydrological variations. In case of monthly data, 360 points cover 30 years and it is felt that this would be more than sufficient to represent the hydrologic variation in monthly scale. Therefore it is felt that even a 20-30 year period containing over 240 data points could be safely considered as a highly favourable data length when considering the model excitation requirements. Using a similar rationalization, a data length period between 10-20 years taken as moderately favourable while data lengths less than 10 years were considered as least favourable.

5.1.2. Data Quality

Literature recognizes the need of good quality data for successful model development. In this context, the quality represents both the quality of measurements and the quality of hydrological representativeness. Hydrological representativeness is important for the model excitation. Quality of measurements are important for the representation of the reality. Missing data is a huge challenge when attempting to preserve these characteristics. Modelers who target the acquisition of a common data period for several rainfall, streamflow, evaporation and other climate data are often faced with the missing data obstacle. It is a very much easier task to capture shorter common data periods without missing data. Therefore, shorter the desired data length the higher is the chance of successfully developing a watershed model. Hence in the present study, identification of data length selection options was based on the allocation of a lower preference rank to longer datasets. This in other words considers that the increase of data length is inversely proportionate to the quality of input data.

5.1.3. Precision of Parameters

Precision of parameters depends on the model calibration and verification. The review identified that many research works around the globe recommend a lengthy dataset for calibration. In certain occasions there had been recommendations to split the entire data set to allocate 80% for calibration and 20% for verification. Therefore, in case of calibration not only longer data length classes lead to better model development but also exercise a higher weight on better model development. Even though the priority is low relative to calibration, longer model verification data leads to better model development. The evaluation of the present practice indicated that for shorter data lengths, verification had a much lower weightage compared to calibration. Selection of mid-range data lengths showed that calibration had received greater priority over verification. In the longer datasets it was noted that equal status had been granted for both calibration and verification. Therefore in the present evaluation of data length options for model development, the calibration data length options were assigned a one-step higher weightage than the verification data length options.

5.1.4. Model Complexity

Complexity of a hydrologic model increases with the advances in improving mathematical descriptions of hydrological processes. Improved mathematical representations for the numerous physical processes observed in the real world inevitably increases the number of model parameters. Optimization of an increased number of model parameters require lengthier datasets which possess better chances of reflecting the variety of process characteristics embedded in the model. The number of parameters and data length relationship in monthly water resources model applications reveal an increasing trend in the data length when the number of parameters increase.

5.2. Analysis Criteria

The literature review exhibits the possibility of executing a qualitative evaluation using five key criteria. At the outset it is important to identify the available decision alternatives. Data length use in research and guidelines indicate that 20 to 40 yearlong datasets are the most favoured for monthly model applications. In order to meaningfully determine the best data length, it is necessary to evaluate the merits and demerits of various data lengths by dividing the options in to shorter ranges. Therefore, the data length selection options were divided into five smaller Likert scale ranges to represent the responses as, “most preferred”, “preferred”, “acceptable”, “low preference” and “very low preference”. The five data range options which in turn form the decision alternatives are, <10, 10-20, 20-30, 30-40 and >40 years respectively. Decision criteria, alternatives, responses and a summary of the rationalization used to assign responses are given in Table 5-1.

5.3. Literature Options

Responses for each criterion were coded numerically by assigning values to measure the preferences as, 9=“most preferred”, 7=“preferred”, 5=“acceptable”, 3=“low preference” and 1=“very low preference”. Table 5-2 presents the numerical values and the normalized indicator for each decision alternative. The data ranges greater than 10-20 years were found as acceptable. The most preferred options were to use a data range greater than 30-40 years. Normalized ranks show that a water resources modeler making attempts to decide on the data length for a water resources management modelling application should at least select a data length between 20-30 years.

Table 5-1: Decision Criteria, Alternatives and Associated Preferences

	Decision Alternatives Data Length Selection Options (number of Years)					Remarks / Rationalization
Criteria *	<10	10-20	20-30	30-40	>40	
Model Excitation	Very Low Preference	Low Preference	Acceptable	Preferred	Most Preferred	30 years with 360 data points would be sufficient to fulfill statistical requirements if any. 30 yeas would adequately represent the desired hydrological characteristics.
Data Quality	Most Preferred	Preferred	Acceptable	Low Preference	Very Low Preference	Shorter data sets have a higher likelihood to possess high quality
Precision of Parameters Calibration	Very Low Preference	Low Preference	Acceptable	Preferred	Most Preferred	Quality of parameter estimation enhances with the length of data used for calibration
Precision of Parameters Verification	Low Preference	Acceptable	Preferred	Most Preferred	Most Preferred	Verification data length has a lower priority according to data splitting recommendations and also as noted in the practice
Model Complexity	Very Low Preference	Low Preference	Acceptable	Preferred	Most Preferred	Models representing reality prefer better representations with lengthier datasets.
Practice amidst Constraints	Very Low Preference	Most Preferred	Preferred	Preferred	Very Low Preference	Use of clusters noted by the change of slope in percentage exceedance curves

* The Likert scale: Most Preferred, Preferred, Acceptable, Low Preference and Very Low Preference are assigned 9,7,5,3,and 1 to reflect the difference in the normalized rank between each data length option

Table 5-2: Normalized Rank and Decision Alternatives for Data Length Selection

	Decision Alternatives Data Length Selection Options (number of Years)				
Criteria*	<10	10-20	20-30	30-40	>40
Model Excitation	1	3	5	7	9
Data Quality	9	7	5	3	1
Precision of Parameters Calibration	1	3	5	7	9
Precision of Parameters Verification	3	5	7	9	9
Model Complexity	1	3	5	7	9
Practice amidst Constraints	1	9	7	7	1
Normalized Rank for Decision	2.67	5	5.67	6.67	6.33

* The Likert scale: Most Preferred, Preferred, Acceptable, Low Preference and Very Low Preference are assigned 9,7,5,3, and 1 to reflect the difference in the normalised rank between each data length option

5.4. Model Calibration and Verification

5.4.1. Data Length Selection

Previous research carried out with similar objectives had identified that data durations less than 10 years would not provide reliable optimization of monthly hydrologic models. Therefore data durations starting from 10 year length were selected for model calibration. 10, 15, 20, 25 and 30 water years are the data durations selected for calibration. Sample datasets were obtained with a one year at a time sliding window. Therefore 75 samples were used for the comparative analysis.

Initial calibrations were carried out for each dataset and results obtained for each data length during calibration and verification were evaluated using performance indicators such as Mean Ratio of Absolute Error (MRAE) of hydrograph, MRAE of flow duration Curves, MRAE for high flows, intermediate flows and low flows and Annual average water balance difference for observed streamflow and simulated streamflow. The high flow, intermediate flow and the low flow was identified as less than 20%, between 20% and 60% and greater than 60% respectively according to Wijesekera, (2018) for Kaluganga Basin.

Table 5-3: Datasets used for model calibration

Data Duration	Sample Datasets used for Calibration	No. of Datasets
10 Years	1983 – 1993, 1984 – 1994, 1985 – 1995, 1986 – 1996, 1987 – 1997, 1988 – 1998, 1989 – 1999, 1990 – 2000, 1991 – 2001, 1992 – 2002, 1993 – 2003, 1994 – 2004, 1995 – 2005, 1996 – 2006, 1997 – 2007, 1998 – 2008, 1999 – 2009, 2000 – 2010, 2001 – 2011, 2002 – 2012, 2003 – 2013, 2004 – 2014, 2005 – 2015, 2006- 2016, 2007 - 2017	25
15 Years	1983 – 1998, 1984 – 1999, 1985 – 2000, 1986 – 2001, 1987 – 2002, 1988 – 2003, 1989 – 2004, 1990 – 2005, 1991 – 2006, 1992 – 2007, 1993 – 2008, 1994 – 2009, 1995 – 2010, 1996 – 2011, 1997 – 2012, 1998 – 2013, 1999 – 2014, 2000 – 2015, 2001 – 2016, 2002 - 2017	20
20 Years	1983 – 2003, 1984 – 2004, 1985 – 2005, 1986 – 2006, 1987 – 2007, 1988 – 2008, 1989 – 2009, 1990 – 2010, 1991 – 2011, 1992 – 2012, 1993 – 2013, 1994 – 2014, 1995 – 2015, 1996 – 2016, 1997 - 2017	15
25 Years	1983 – 2008, 1984 – 2009, 1985 – 2010, 1986 – 2011, 1987 – 2012, 1988 -2013, 1989 – 2014, 1990 – 2015, 1991 – 2016, 1992 - 2017	10
30 Years	1983 – 2013, 1984 – 2014, 1985 – 2015, 1986 – 2016, 1987 - 2017	5
Total		75

Total data period used for the study is 42 years and model calibration used a 35 year data period (October 1983 to September 2017). Approximately 80% of the dataset was used for model calibration. Verification data duration was seven years from October 1976 to September 1983. This independent verification dataset with a period of 7 years is about 20% of the entire dataset. There were options to select the verification dataset either from the beginning of the data set or from the end. Since the data after 1999/2000 appeared questionable, seven year period was selected from the beginning of the dataset.

5.4.2. Model Development and Checking

5.4.2.1. Model Development

A two parameter monthly water balance model development was carried out using concepts given in Xiong & Guo, (1999). Following three concepts were used in developing this model.

$E(t)/ EP(t) = C \times \text{Tanh} [P(t)/ EP(t)]$ ……………………………………….(1)

$Q(t) = S(t-1) + \text{Tanh}\{(S(t-1)+P(t)-E(t)/Sc)\}$………………………………...(2)

$S(t) = S(t-1)+P(t)-E(t)-Q(t)$………………………………………………….(3)

Where,

E(t) – Evaporation Estimation of Model, EP(t) – Pan Evaporation, P(t) – Rainfall, C – Monthly evaporation coefficient, Q(t) – Runoff discharge, S(t-1) – Soil water content at the end of (t-1) month, S(t) - Soil water content at the end of (t) month

5.4.2.2. Warm-up Period

Initial soil water content value, S(t-1) affects monthly runoff in the early months. In this study of Kalu Ganga at Ellagawa watershed, the initial value of soil water content was determined after five complete model runs over the calibration data as the warm-up period. During the warm-up period, the model computations demonstrated the influence of initial soil water content. At the beginning of the cycles the initial soil moisture content S(0) was kept as zero. After 1 to 2 model runs of each data duration soil moisture value at the beginning of the year stabilized and this value was taken as the initial soil moisture content (Figure 5-1) for model calibration.

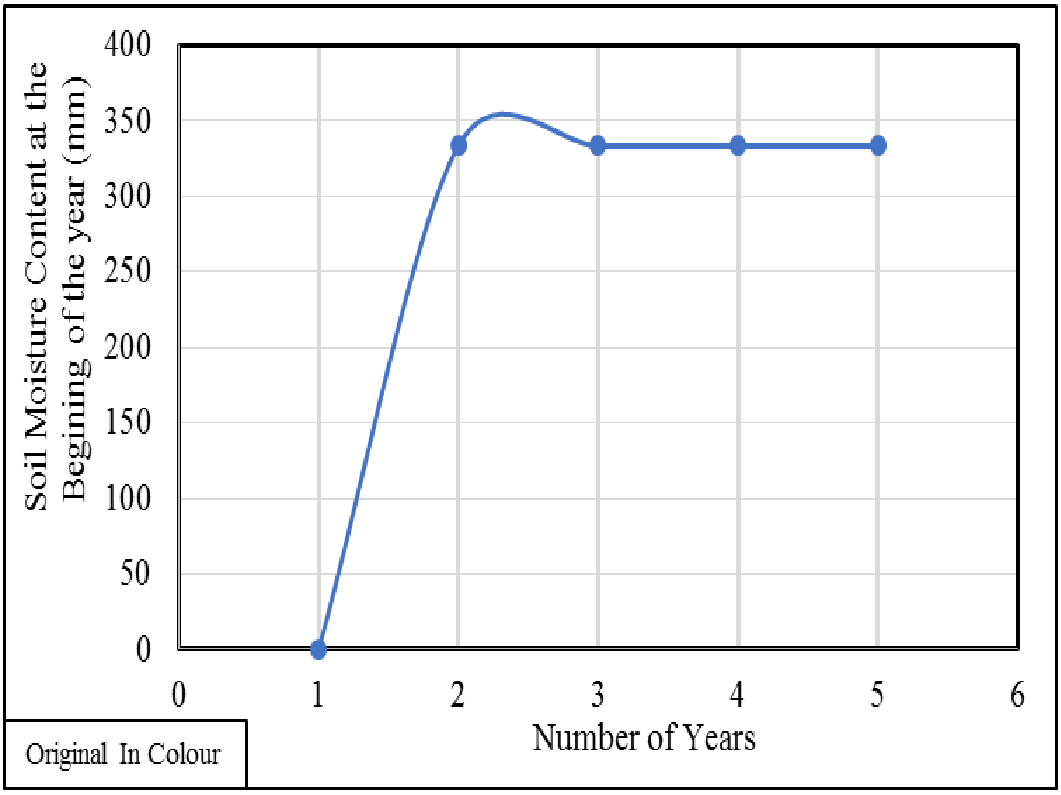

Figure 5-1: Initial Soil Moisture Content Variation in Warm up Period

5.4.2.3. Global Minimum Determination

The parameter optimization was carried out by using a MS Excel spreadsheet model and its built in tool 'Solver'. The initial parameter values were systematically changed to ascertain that the tool avoided the 'local minima' to arrive at the 'Global minimum'. Initially a coarse range of c and Sc values were used to obtain a local minimum values which were then explored with finer c and Sc input values to capture the values at the global minimum of MRAE.

The case of 10 year data length corresponding to the 2000/01 – 2009/10 is shown in Figure 5-2 as an example. The arrows indicate several of the initial parameter values reaching a minimum MRAE during optimization of c and Sc parameters.

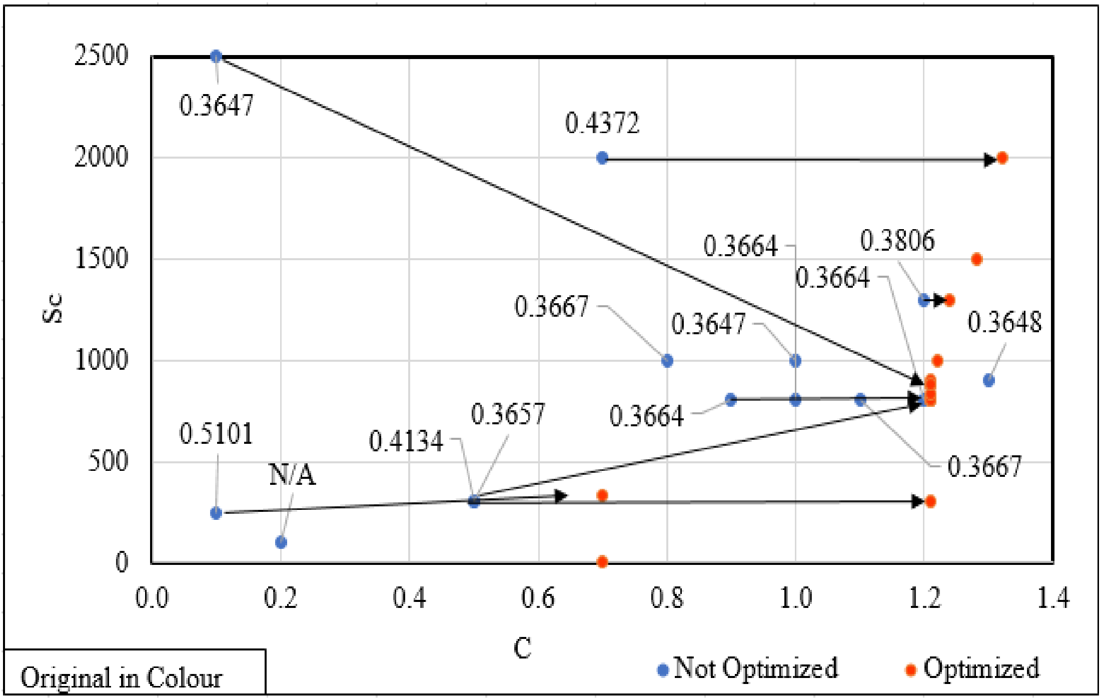

Figure 5-2: Example of Global Minimum Determination (2000/2001 – 2009/2010)

5.4.3. Model Calibration and Verification

5.4.3.1. General

This section illustrates the analysis method used in the calibrations of all datasets in Table 5-3. Thiessen average rainfall and pan evaporation values were used as the model inputs.

Model calibrations for each individual data length used a warm up period of 5 years for the determination of initial soil moisture content. Many combinations of initial values for c and Sc were used to arrive at the global minimum MRAE.

The monthly streamflow hydrographs, flow duration curves, soil moisture level variation and annual water balance corresponding to observed and model estimated streamflow were evaluated.

5.4.3.2. Comparison of a 10 year Model

Comparisons for the 10 year data set from 1983/83 – 19992/93 are shown by Figure 5-3 (monthly hydrographs), Figure 5-5 (monthly period of record FDC), Figure 5-10 (Annual Water Balance), and Figure 5-7 (soil moisture level variation). The MRAE of each flow region of FDC curve clearly shows the relative error value comparison reflected by this objective function. Thus the MRAE justifies its selection for water resources assessments.

Soil moisture content plotting during calibration and verification also showed a rational variation of moisture levels along with the rainfall received at the watershed (Figure 5-7 and Figure 5-8). Scatter plots of observed and model estimated streamflow during calibration and verification in Figure 5-9 also show the goodness of model and its parameters.

5.4.3.3. Calibration and Verification Summary

Model calibration and verification results for each data length are shown in Table 5-7, Table 5-8 (10 year datasets) and Appendix D.6, Table D-1, D-2 (15 year datasets), Table D-3, D-4 (20 year datasets), Table D-5, D-6 (25 year datasets) and Table D-7, D-8 (30 year datasets).

Comparison of calibration results corresponding to streamflow hydrograph (Appendix D.1), flow duration curve (Appendix D.2), water balance (Appendix D.3), soil moisture levels (Appendix D.4) and scatter plots (Appendix D.5) clearly show the degree of good of fit. Model Verification results are in Appendix E. Table 5-4 gives a summary of evaluation indicators.

Table 5-4: Results of Ellagawa 2P Model Calibration and Verification for 10 year period from 1983/84 – 1992/93

Model Performance	Calibration	Verification
C	0.99	0.99
SC	600.00	600.00
MRAE – Overall Hydrograph	0.3055	0.2923
Soil Moisture Content - Beginning of Period	165.44	153.16
Soil Moisture Content – End of Period	165.44	153.16
Maximum Soil Moisture Content (mm)	167.08	167.07
Minimum Soil Moisture Content (mm)	79.12	90.00
Average Annual Water Balance Difference (mm)	(186.83)	(334.19)
Data Period	1983/1984 – 1992/1993	1976/1977 – 1982/1983
Maximum Flow (mm/Month)	731.32	744.19
Minimum Flow (mm/month)	14.48	19.91
FDC MRAE - Overall	0.1392	0.1845
FDC MRAE – High flow	0.0454	0.1465
FDC MRAE – Intermediate flow	0.1284	0.1605
FDC MRAE – Low flow	0.1951	0.2292

Optimized parameter values of c and Sc were 0.99 and 600 respectively. The Overall MRAE value has reduced in the verification period. i.e. The MRAE value during calibration was 0.3055 and the same was 0.2923 during verification. Similarly the MRAE values for Overall FDC, High, Intermediate and Low flows of the flow duration curves (FDC) were 0.1392, 0.0454, 0.1284 and 0.1951 respectively. The Average Annual Water Balance error was (186.83) mm.

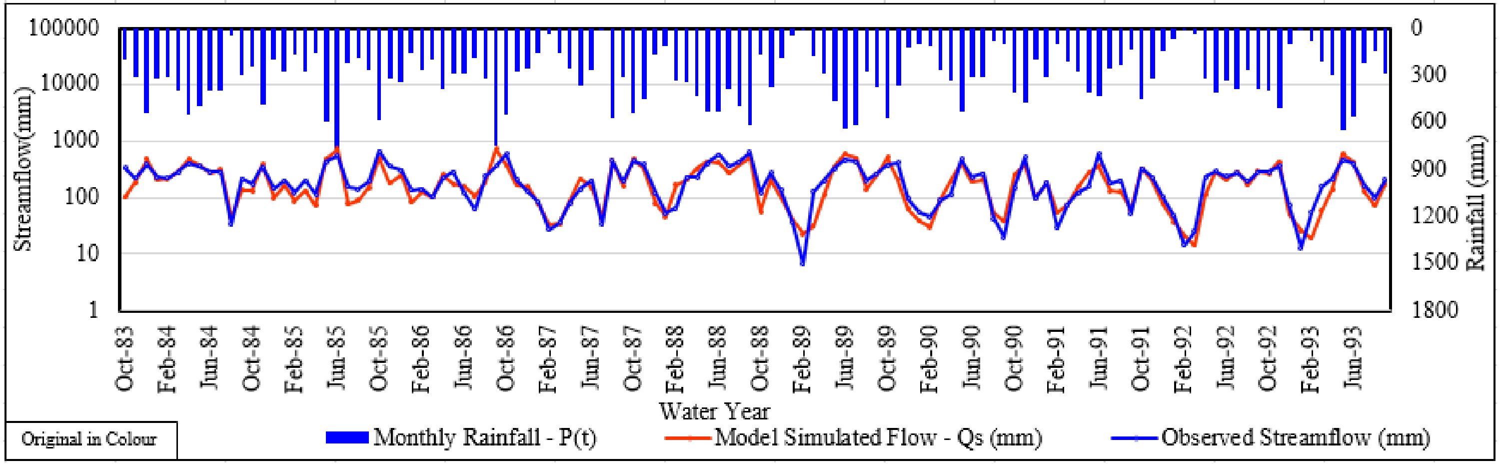

Figure 5-3: Hydrograph Observed Streamflow and Modeled Streamflow Variation with Rainfall 1983 – 1993 (Calibration)

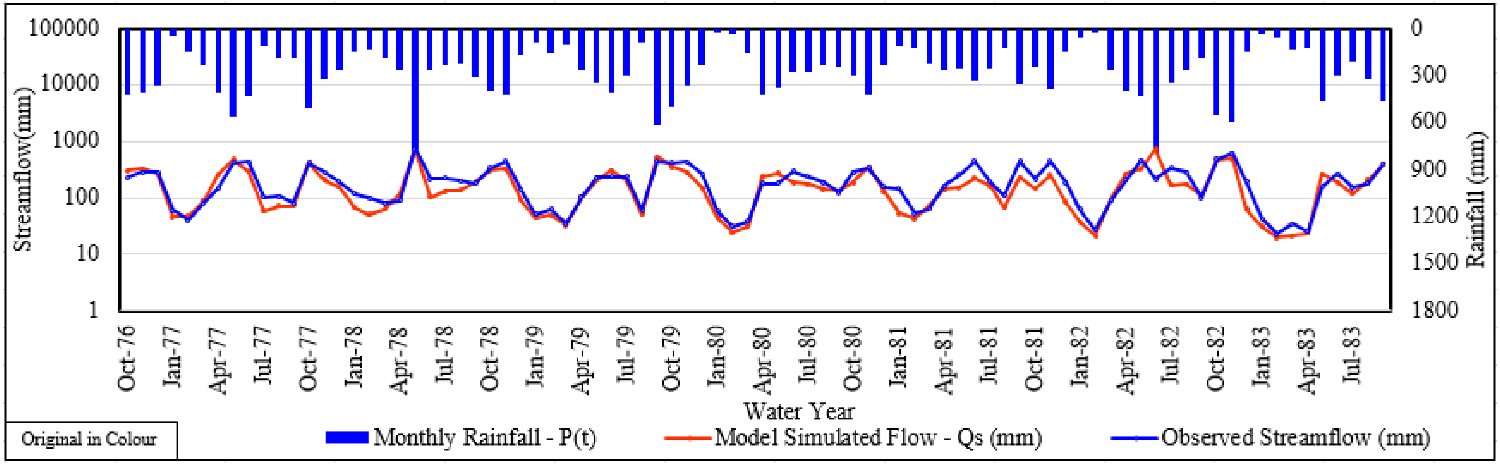

Figure 5-4: Hydrograph Observed Streamflow and Modeled Streamflow Variation with Rainfall 1976 - 1983 (Verification)

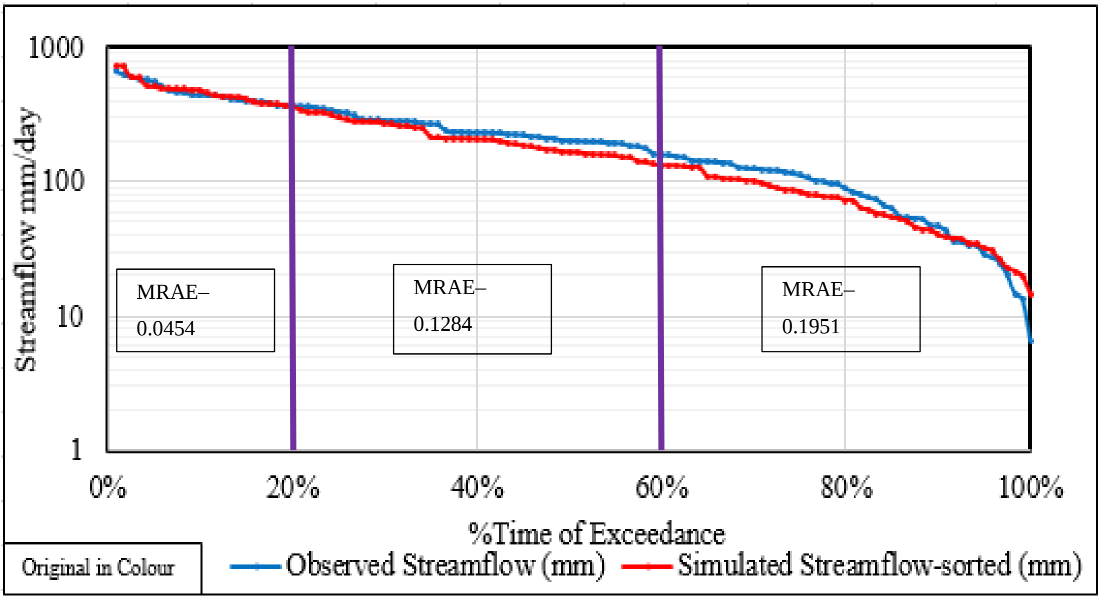

Figure 5-5: Flow Duration Curve of Calibration – 10 year Dataset 1983/84 – 1992/93

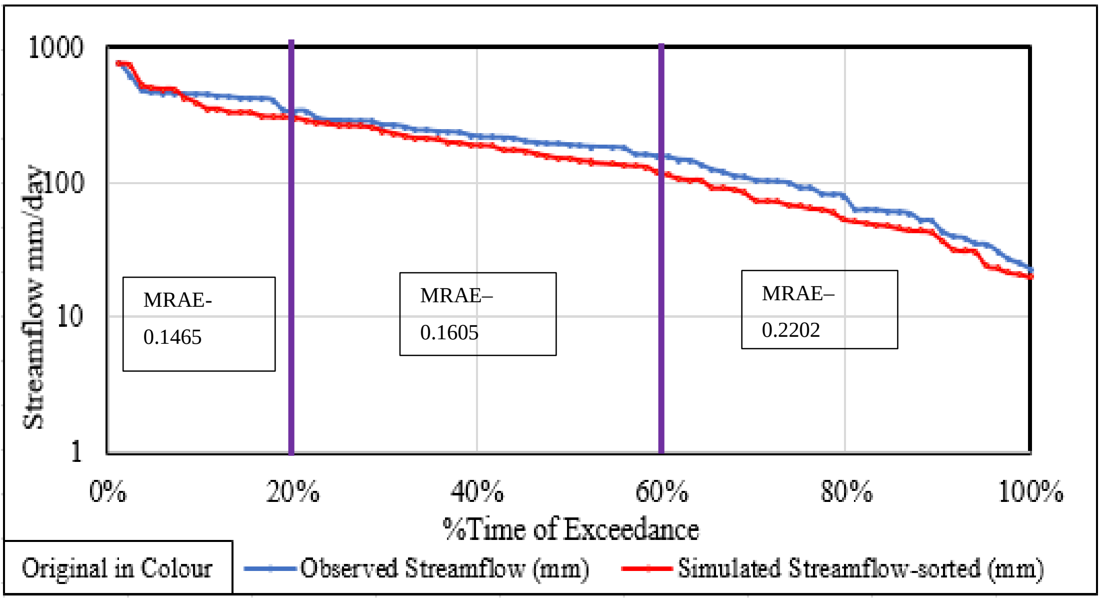

Figure 5-6: Flow Duration Curve of Verification – 7 year Data set 1976/77 – 1982/83

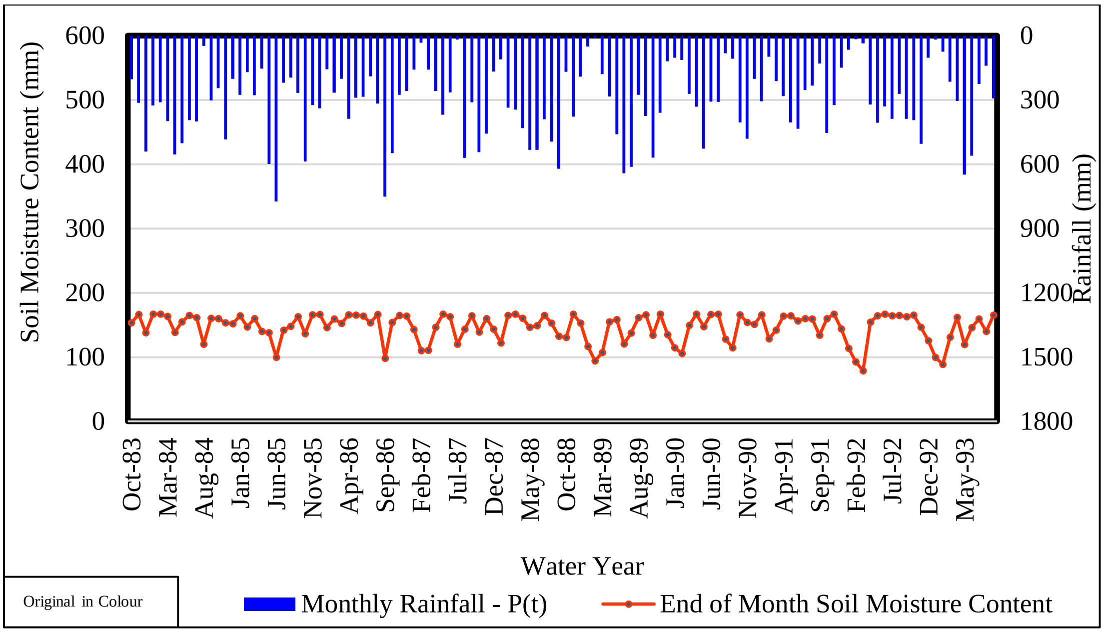

Figure 5-7: Variation of Soil Moisture Content 10 year Dataset (1983/84 – 1992/93)

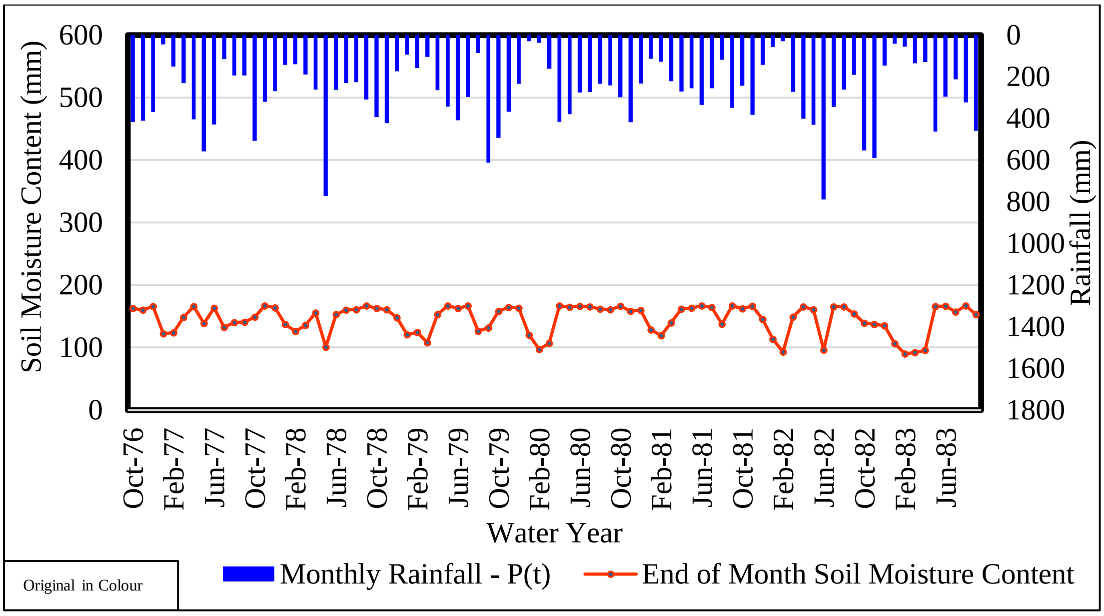

Figure 5-8: Variation of Soil Moisture Content for 7 year Dataset (1976/77 – 1982/83)

Soil Moisture Content follows the same pattern as rainfall for calibration and verification data periods as seen in Figure 5-7, Figure 5-8.

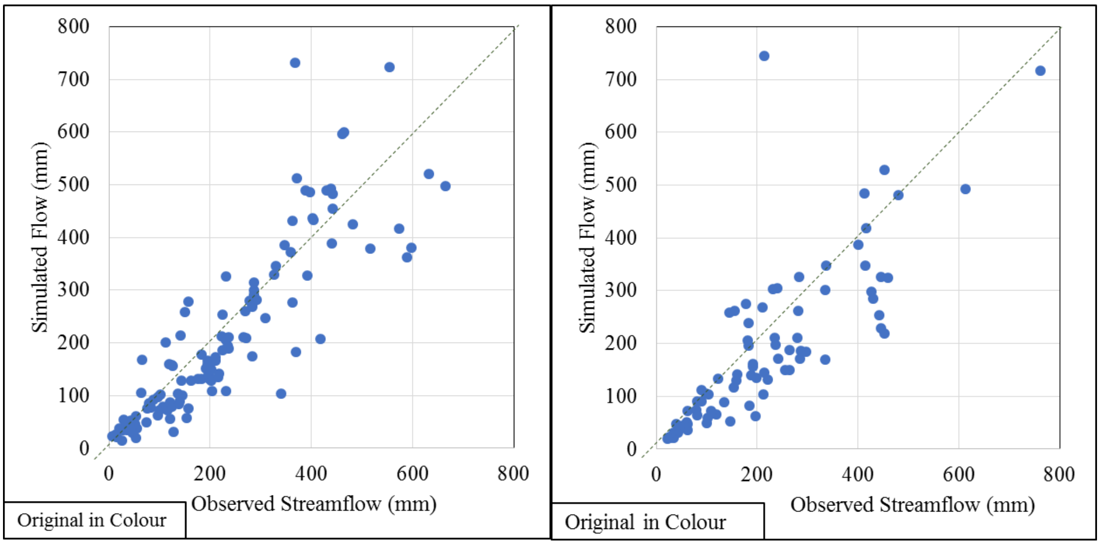

Figure 5-9: Observed and Simulated Streamflow Variation during Calibration and Verification

Table 5-5: Annual Water Balance of Calibration – 10 year dataset (1983/84 – 1992/93)

Water Year	Thiessen Average Rainfall (mm)	Observed Streamflow (mm)	Simulated Streamflow (mm)	Observed Water Balance (mm)	Simulated Water Balance (mm)	Annual Water Balance Difference (mm)	AWB % Difference
1983/84	4286.62	3271.14	3112.96	1015.48	1173.66	(158.18)	(15.58)
1984/85	3857.82	2773.60	2601.16	1084.21	1256.66	(172.45)	(15.91)
1985/86	4090.04	3020.57	2853.03	1069.47	1237.01	(167.53)	(15.67)
1986/87	3219.57	2173.90	1959.05	1045.67	1260.52	(214.85)	(20.55)
1987/88	4957.27	3951.87	3678.91	1005.40	1278.36	(272.96)	(27.15)
1988/89	3621.82	2599.75	2406.53	1022.08	1215.30	(193.22)	(18.90)
1989/90	3197.08	2231.77	2065.59	965.31	1131.49	(166.18)	(17.21)
1990/91	3434.14	2359.29	2162.60	1074.85	1271.54	(196.69)	(18.30)
1991/92	3145.51	2269.21	2035.28	876.30	1110.23	(233.94)	(26.70)
1992/93	3479.12	2497.31	2405.00	981.81	1074.12	(92.31)	(9.40)

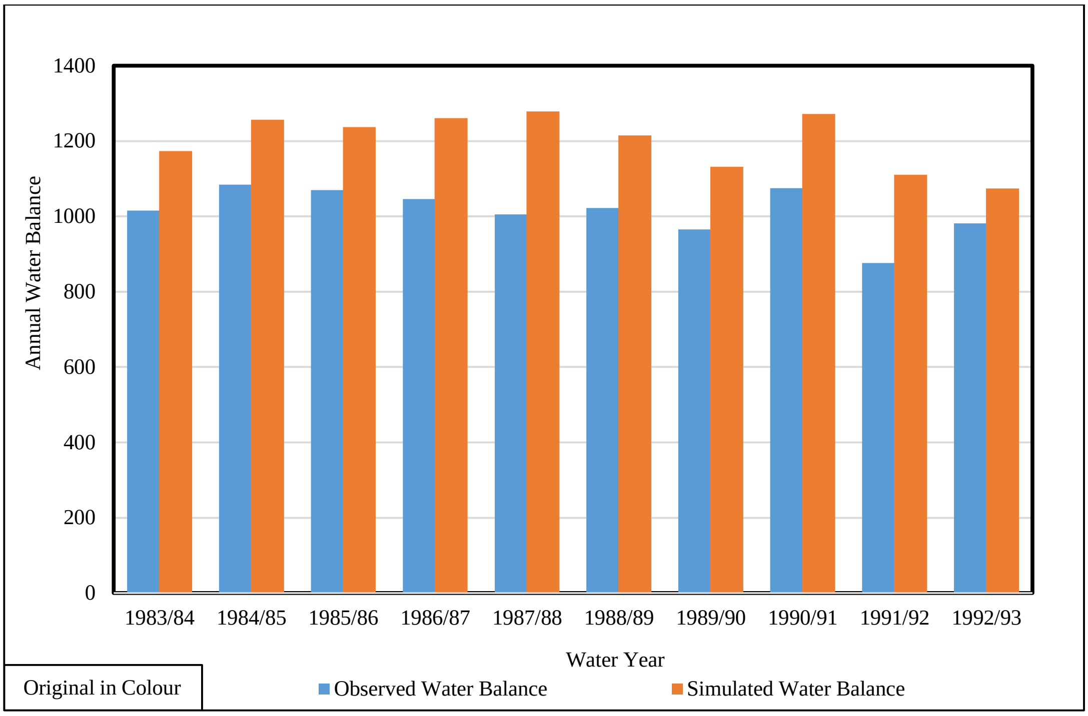

Figure 5-10: Annual Water Balance of the Calibration- 10 year Data Period (1983/84 -1992/93)

Table 5-6: Annual Water Balance of Verification 7 year dataset (1976/77 – 1982/83)

Water Year	Thiessen Average Rainfall (mm)	Observed Streamflow	Simulated Streamflow	Observed Water Balance	Simulated Water Balance	Annual Water Balance Difference	Annual Water Balance % Difference
1976/77	3517.97	2250.30	2321.50	1267.67	1196.47	71.20	5.62
1977/78	3632.36	2856.14	2361.72	776.22	1270.63	(494.42)	(63.70)
1978/79	3357.61	2391.50	2237.27	966.11	1120.34	(154.23)	(15.96)
1979/80	3141.01	2447.42	2025.29	693.59	1115.72	(422.13)	(60.86)
1980/81	2994.38	2658.90	1801.26	335.48	1193.11	(857.63)	(255.64)
1981/82	3544.22	2622.10	2415.55	922.12	1128.66	(206.55)	(22.40)
1982/83	3401.96	2568.83	2293.26	833.13	1108.70	(275.57)	(33.08)

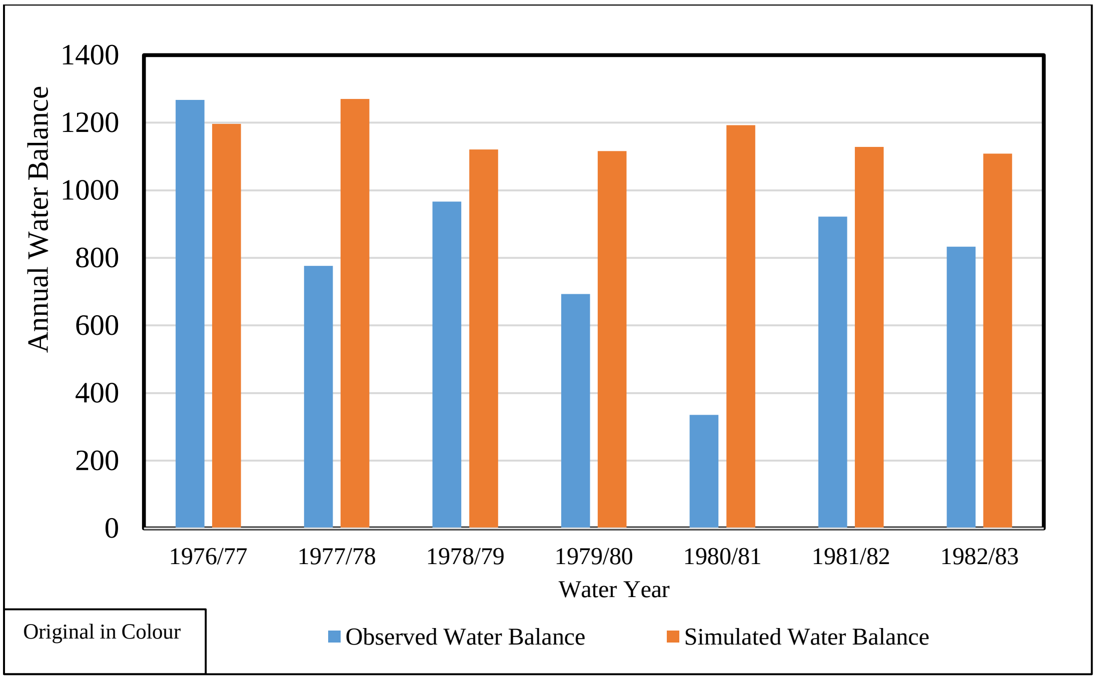

Figure 5-11: Annual Water Balance of Verification – 7 year dataset (1976/77 – 1982/83)

Summary of Results for 10 year data duration for calibration and verification, is given in Table 5-7 and Table 5-8. Corresponding hydrographs, annual water balance comparison and flow durations curves are given in Appendix D.

Table 5-7: Comparison of Calibration outputs and Indicators for 10 Year Datasets

	Data Period	**MRAE - Overall**	**FDC MRAE - Overall**	**FDC MRAE - High**	**FDC MRAE - Intermediate**	**FDC MRAE - Low**	**Soil Moisture Content - Beginning**	**Soil Moisture Content - End**	**Maximum Storage**	**Minimum Storage**	**Average Annual Water Balance Difference**	**Maximum Flow**	**Minimum Flow**	**C**	**SC**
C10-1	1983/1984 –1992/1993	0.31	0.14	0.05	0.13	0.20	165.44	165.44	167.08	79.12	(186.83)	731.32	14.48	0.99	600.00
C10-2	1984/1985 –1993/1994	0.31	0.14	0.04	0.12	0.21	198.76	198.76	206.38	95.62	(194.54)	724.95	16.98	0.99	741.13
C10-3	1985/1986 –1994/1995	0.30	0.13	0.02	0.10	0.22	190.58	190.58	191.30	89.10	(179.58)	718.67	15.93	0.99	686.99
C10-4	1986/1987 –1995/1996	0.28	0.12	0.02	0.09	0.21	159.67	159.67	183.23	85.76	(168.59)	651.02	15.44	0.99	657.99
C10-5	1987/1988 –1996/1997	0.28	0.11	0.02	0.08	0.19	187.06	187.06	199.43	93.43	(155.70)	643.53	16.85	0.98	716.18
C10-6	1988/1989 –1997/1998	0.28	0.12	0.03	0.08	0.21	195.22	195.22	199.81	96.62	(109.30)	602.83	18.23	0.92	717.54
C10-7	1989/1990 –1998/1999	0.24	0.09	0.04	0.06	0.15	218.18	218.18	223.17	104.54	(82.92)	631.86	18.85	0.96	801.43
C10-8	1990/1991 –1999/2000	0.21	0.09	0.05	0.05	0.15	216.40	216.40	219.93	105.45	(19.21)	640.01	19.65	0.92	789.81
C10-9	1991/1992 –2000/2001	0.18	0.10	0.11	0.05	0.15	213.91	213.91	214.53	107.13	61.89	654.32	21.17	0.84	770.46
C10-10	1992/1993 –2001/2002	0.18	0.10	0.14	0.04	0.13	171.78	171.78	200.21	118.96	111.21	671.21	30.72	0.77	718.99
C10-11	1993/1994 –2002/2003	0.15	0.07	0.12	0.03	0.10	194.15	194.15	194.93	126.13	96.96	676.47	37.63	0.77	700.00
C10-12	1994/1995 –2003/2004	0.15	0.07	0.10	0.03	0.09	176.12	176.12	187.73	122.07	81.63	632.25	36.73	0.77	674.15
C10-13	1995/1996 –2004/2005	0.14	0.06	0.09	0.04	0.07	170.75	170.75	171.01	113.67	66.82	642.29	35.57	0.77	614.13
C10-14	1996/1997 –2005/2006	0.12	0.05	0.10	0.03	0.05	170.09	170.09	176.40	117.30	76.93	641.50	36.73	0.75	633.47
C10-15	1997/1998 –2006/2007	0.13	0.09	0.14	0.03	0.14	152.39	152.39	152.62	91.98	86.31	654.25	38.77	0.74	548.10
C10-16	1998/1999 –2007/2008	0.11	0.08	0.10	0.02	0.13	141.99	141.99	150.54	89.22	52.11	654.72	38.46	0.74	540.63
C10-17	1999/2000 –2008/2009	0.10	0.08	0.06	0.03	0.15	120.66	120.66	126.33	83.68	(19.26)	495.28	34.68	0.78	453.66
C10-18	2000/2001 –2009/2010	0.09	0.07	0.04	0.03	0.14	119.20	119.20	121.24	77.19	(37.98)	494.42	33.90	0.78	435.44
C10-19	2001/2002 –2010/2011	0.12	0.10	0.03	0.04	0.19	208.30	208.30	209.47	141.68	(24.01)	499.50	45.77	0.77	752.22
C10-20	2002/2003 –2011/2012	0.09	0.07	0.03	0.03	0.12	129.19	129.19	129.23	87.61	(32.49)	494.52	35.08	0.78	464.09
C10-21	2003/2004 –2012/2013	0.09	0.07	0.03	0.03	0.12	122.11	122.11	129.23	87.64	(30.33)	494.36	35.08	0.78	464.11
C10-22	2004/2005 –2013/2014	0.09	0.06	0.03	0.03	0.11	111.00	111.00	130.18	86.55	(27.24)	508.48	35.24	0.78	467.51
C10-23	2005/2006 –2014/2015	0.09	0.06	0.03	0.03	0.11	124.93	124.93	129.96	76.99	(27.58)	565.41	35.20	0.78	466.71
C10-24	2006/2007 –2015/2016	0.09	0.07	0.03	0.04	0.12	114.42	114.42	127.00	67.40	(37.86)	602.56	34.71	0.79	456.06
C10-25	2007/2008 –2016/2017	0.08	0.06	0.03	0.05	0.08	105.57	105.57	124.90	63.78	(47.04)	609.26	35.17	0.79	448.54

Table 5-8: Comparison of Verification Indicators for 10 Year Datasets

	Data Period	MRAE - Overall	FDC MRAE - Overall	FDC MRAE - High	FDC MRAE - Intermediate	FDC MRAE - Low	Average Annual Water Balance Difference	Soil Moisture Content - Beginning	Soil Moisture Content - End	Maximum Storage	Minimum Storage	Maximum Flow	Minimum Flow	C	SC
V10-1	1976/1977–1982/1983	0.2923	0.1845	0.1465	0.1605	0.2292	(334.19)	153.16	153.16	167.07	90.00	744.19	19.91	0.99	600.00
V10-2	1976/1977–1982/1983	0.2582	0.1553	0.1440	0.1629	0.1538	(342.17)	200.99	200.99	206.37	109.29	734.89	23.57	0.99	741.13
V10-3	1976/1977–1982/1983	0.2709	0.1685	0.1454	0.1652	0.1843	(344.44)	183.18	183.18	191.30	102.23	738.58	22.34	0.99	686.99
V10-4	1976/1977–1982/1983	0.2779	0.1741	0.1458	0.1646	0.1990	(341.80)	173.36	173.36	183.18	98.21	740.65	21.56	0.99	657.99
V10-5	1976/1977–1982/1983	0.2603	0.1522	0.1429	0.1560	0.1534	(325.25)	192.70	192.70	199.43	107.59	738.56	23.86	0.98	716.18
V10-6	1976/1977–1982/1983	0.2578	0.1213	0.1363	0.1255	0.1090	(256.21)	192.51	192.51	199.81	111.09	745.68	25.81	0.92	717.54
V10-7	1976/1977–1982/1983	0.2472	0.1325	0.1389	0.1439	0.1178	(302.58)	219.90	219.90	223.17	120.59	734.12	26.81	0.96	801.43
V10-8	1976/1977–1982/1983	0.2504	0.1176	0.1342	0.1218	0.1044	(251.78)	215.88	215.88	219.91	121.91	740.58	28.18	0.92	789.81
V10-9	1976/1977–1982/1983	0.2641	0.1008	0.1256	0.0812	0.1069	(158.18)	208.96	208.96	214.54	123.31	752.09	30.18	0.84	770.46
V10-10	1976/1977–1982/1983	0.2859	0.0911	0.1198	0.0519	0.1146	(80.69)	191.33	191.33	200.19	118.65	763.77	30.51	0.77	718.99
V10-11	1976/1977–1982/1983	0.2884	0.0895	0.1202	0.0530	0.1091	(78.00)	184.91	184.91	194.91	116.00	765.20	30.03	0.77	700.00
V10-12	1976/1977–1982/1983	0.2898	0.0874	0.1213	0.0574	0.0990	(84.77)	176.17	176.17	187.73	112.03	765.93	29.14	0.77	674.15
V10-13	1976/1977–1982/1983	0.3018	0.0864	0.1212	0.0614	0.0924	(75.39)	155.15	155.15	171.01	97.28	769.37	27.59	0.77	614.13
V10-14	1976/1977–1982/1983	0.3032	0.0852	0.1192	0.0553	0.0967	(58.11)	161.76	161.76	176.40	104.02	770.42	28.54	0.75	633.47
V10-15	1976/1977–1982/1983	0.3232	0.0827	0.1216	0.0607	0.0834	(46.83)	131.08	131.08	152.62	73.70	773.19	26.20	0.74	548.10
V10-16	1976/1977–1982/1983	0.3241	0.0832	0.1222	0.0624	0.0827	(50.65)	128.40	128.40	150.54	71.22	772.80	25.89	0.74	540.63
V10-17	1976/1977–1982/1983	0.3389	0.1047	0.1256	0.0794	0.1186	(92.08)	96.80	96.80	126.26	44.14	767.20	22.23	0.78	453.66
V10-18	1976/1977–1982/1983	0.3447	0.1108	0.1254	0.0813	0.1323	(93.59)	90.05	90.05	121.25	38.79	767.44	21.61	0.78	435.44
V10-19	1976/1977–1982/1983	0.2843	0.0940	0.1187	0.0496	0.1249	(80.91)	202.36	202.36	209.45	123.41	761.53	31.43	0.77	752.22
V10-20	1976/1977–1982/1983	0.3348	0.1054	0.1262	0.0796	0.1172	(97.15)	100.74	100.74	129.21	47.39	766.34	22.43	0.78	464.09
V10-21	1976/1977–1982/1983	0.3346	0.1047	0.1262	0.0798	0.1178	(97.91)	100.76	100.76	129.21	47.41	766.28	22.41	0.78	464.11
V10-22	1976/1977–1982/1983	0.3339	0.1026	0.1260	0.0789	0.1134	(95.08)	101.99	101.99	130.17	48.39	766.71	22.60	0.78	467.51
V10-23	1976/1977–1982/1983	0.3342	0.1029	0.1260	0.0790	0.1142	(95.40)	101.69	101.69	129.94	48.15	766.64	22.57	0.78	466.71
V10-24	1976/1977–1982/1983	0.3367	0.1085	0.1264	0.0814	0.1259	(102.01)	97.82	97.82	126.94	45.00	765.98	22.03	0.79	456.06
V10-25	1976/1977–1982/1983	0.3385	0.1124	0.1267	0.0830	0.1340	(106.45)	95.08	95.08	124.85	42.79	765.73	21.66	0.79	448.54

5.5. Estimating the Effect of Data Length

Summary of indicators used for the comparative study of monthly streamflow estimation accuracy are presented in the forthcoming figures from Figure 5-12 to Figure 5-39.

5.5.1. Model Parameter Variation

Optimized model parameter variation showed a high variation of values with shorter data lengths while the variation gradually declined as the data length used for model calibration increased from 10 years to 30 years. It is noteworthy that the number of datasets in each group also declined with the selection of longer periods. However there is a clear convergence of parameter values when the calibration data length is greater than 25 years (Figure 5-12, Figure 5-13). Both parameters converged to a less than 10 % margin (c: 6.3%, Sc: 4%) beyond a threshold data length of 25 years (Figure 5-14, Figure 5-15, Table 5-9)

The average values of c parameter for the 25 year data lengths was 0.78 while the same for 30 year data lengths was 0.79. Average values of Sc parameter for the 25 year and 30 year data lengths was approximately 578. Percentage Relative variation of an indicator was calculated as given below.

$$\text{Percentage Relative Variation} = \frac{(\text{Maximum Value} - \text{Minimum Value}) * 100\%}{\text{Minimum Value}} \quad \ldots\ldots (1)$$

Table 5-9: Response of Model Parameters to Calibration Data Length

Data Length (Years)	Parameter C				Parameter Sc			
	Max	Min	Mean	% Variation	Max	Min	Mean	% Variation
10	0.99	0.74	0.84	34.0%	801.43	435.44	612.77	84.0%
15	0.996	0.75	0.82	32.4%	750.00	434.56	602.41	72.6%
20	0.89	0.76	0.80	17.4%	775.25	522.63	605.42	48.3%
25	0.82	0.77	0.78	6.3%	590.73	568.13	578.73	4.0%
30	0.79	0.78	0.79	1.3%	583.42	571.49	578.84	2.1%

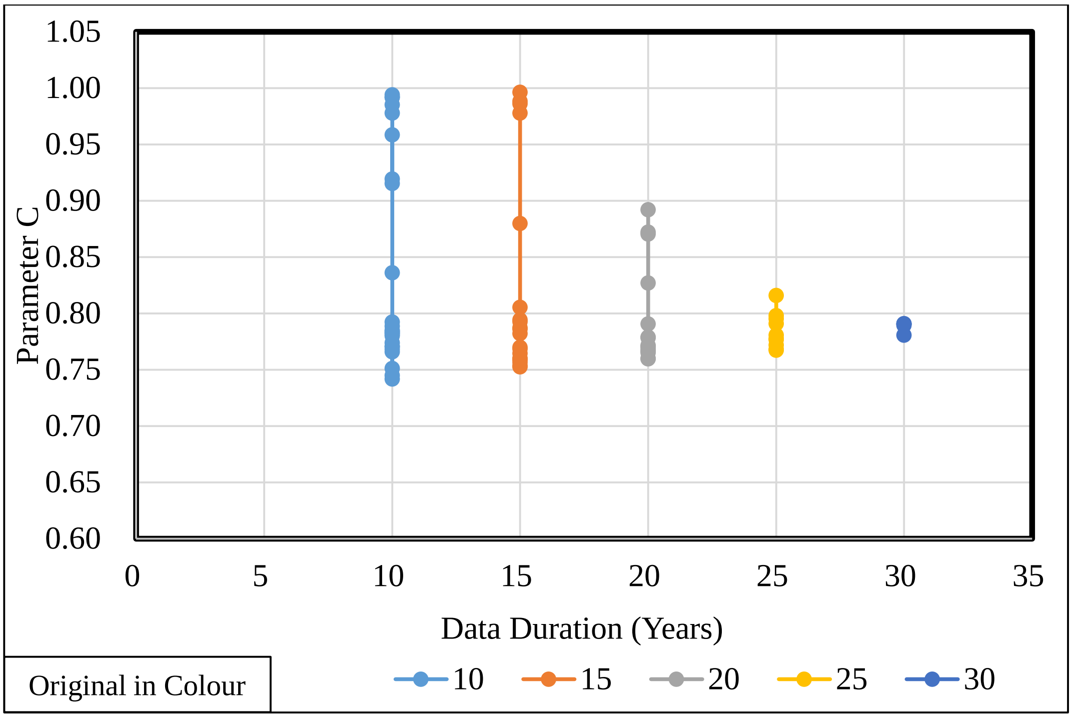

Figure 5-12: Parameter c Variation with Data Length

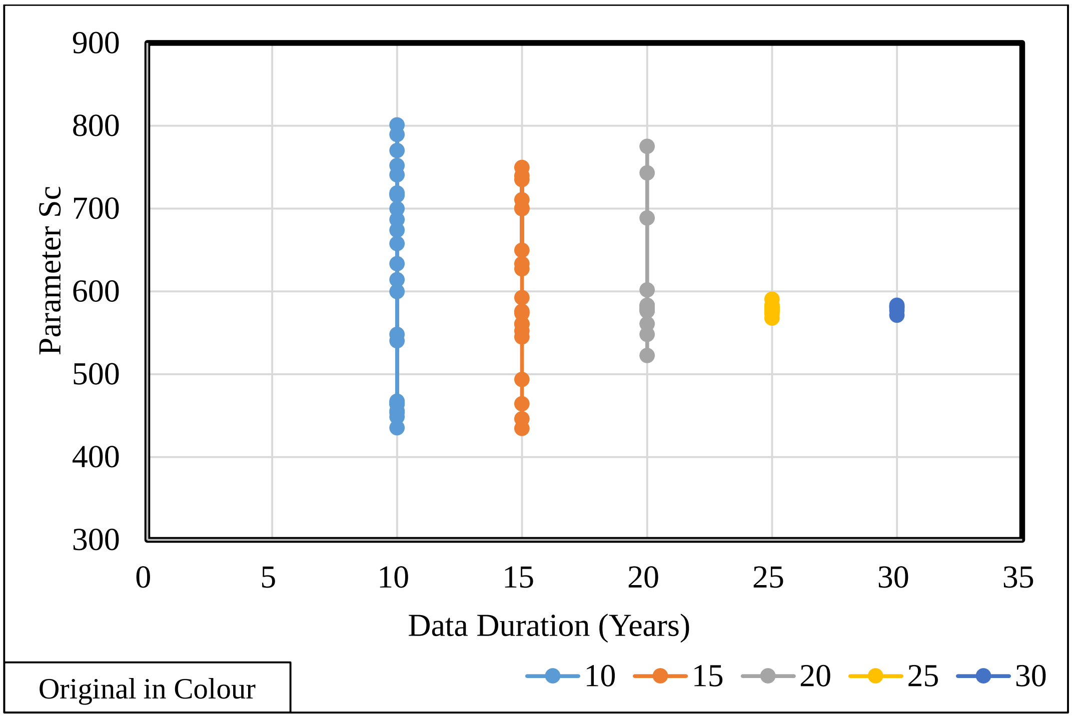

Figure 5-13: Parameter Sc Variation with Data Length

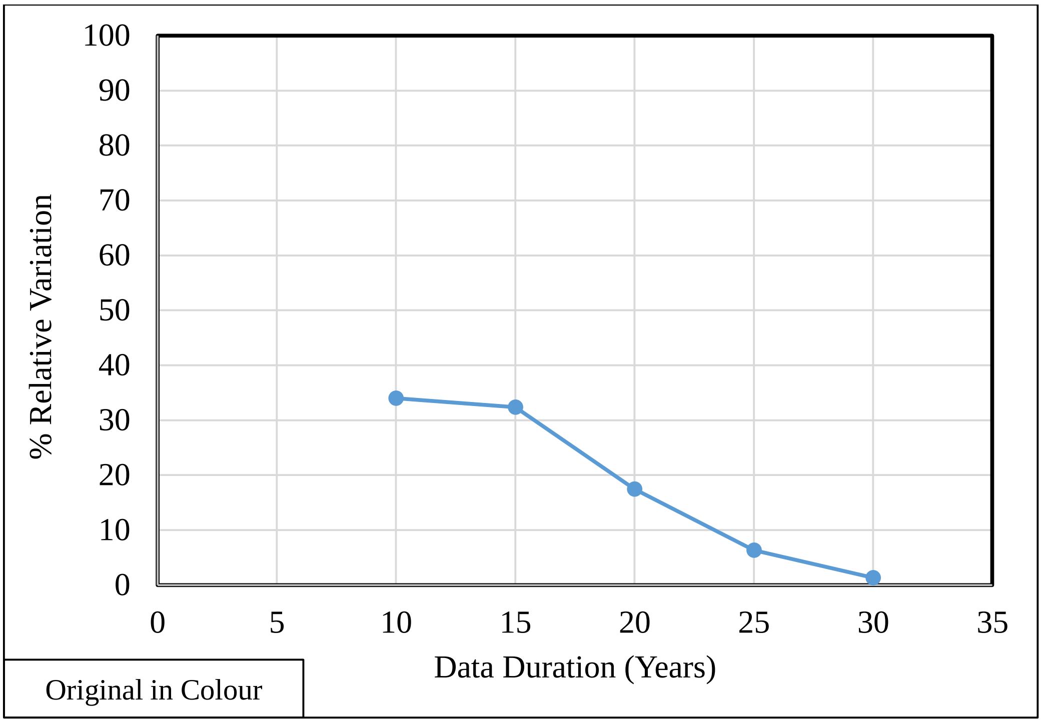

Figure 5-14: Parameter C Variation Relative to the Minimum optimized Value for each Data Length

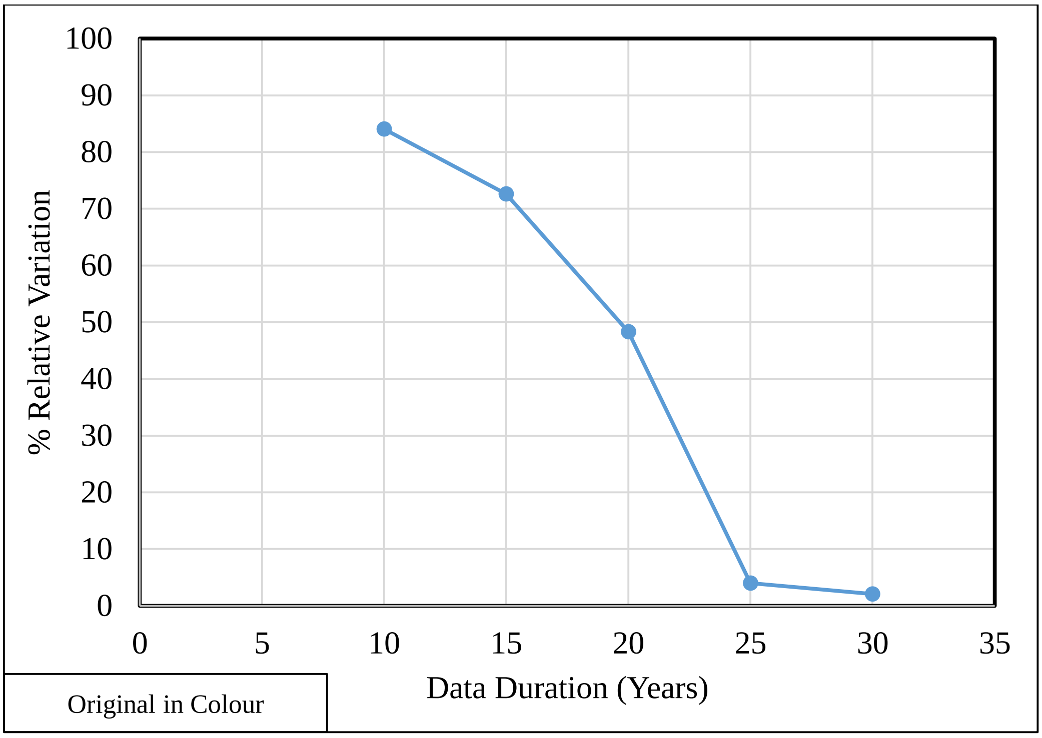

Figure 5-15: Parameter Sc Variation Relative to the Minimum optimized Value for each Data Length

5.5.2. Overall Hydrograph Evaluation

Minimum MRAE values of model calibration corresponding to each data length are in Figure 5-16 and in Table 5-10. These values show a wide variation with shorter data lengths but as the data length increases, the fitting of hydrographs become consistent. Results indicate that the worst fitting of overall hydrographs was with a 10 year data length having a MRAE value of 0.3057. The best fitting MRAE was 0.0818 obtained for a 10 year data length. The most consistent values of optimum showed a maximum of 16% variation between each data length option. The overall hydrograph matching with 30 year data lengths indicated an average MRAE of 0.2189 while the best MRAE was 0.0818. This shows that about 28% of 10 year data length cases, and about 30% of 15 year data length options resulted in poorer hydrograph matching than the average of the 30 year data length cases. MRAE variation with data length options during verification is shown in Figure 5-17 and in Table 5-10. The results show the best MRAE of overall hydrograph matching was obtained 0.2472 at 10 year data length. The average overall MRAE of 30 year data length is 0.3025 during verification. Figure 5-18 and Figure 5-19 shows the % relative variation of MRAE value with data length options during calibration and verification.

Table 5-10: MRAE Variation with Data Length during Calibration and Verification

Data Length (Years)	Calibration				Verification			
	Minimum	Maximum	Mean	% Variation	Minimum	Maximum	Mean	% Variation
10	0.0818	0.3057	0.1675	273.71	0.2472	0.3447	0.2991	39.46
15	0.0828	0.2696	0.1643	225.83	0.2555	0.3428	0.3000	34.18
20	0.1055	0.2387	0.1693	126.18	0.2545	0.3227	0.2981	26.84
25	0.1296	0.2187	0.1762	68.74	0.2935	0.3108	0.3039	5.92
30	0.2006	0.2328	0.2189	16.05	0.3008	0.3049	0.3025	1.36

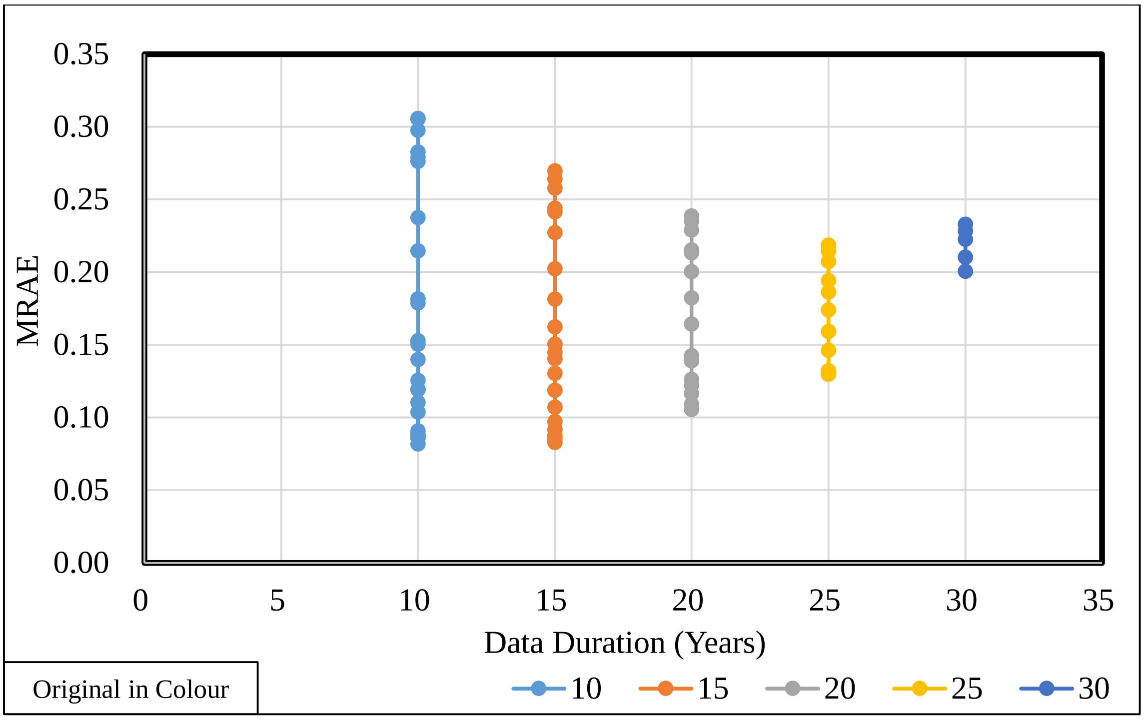

Figure 5-16: Variation of MRAE for Overall Hydrograph Matching - Calibration

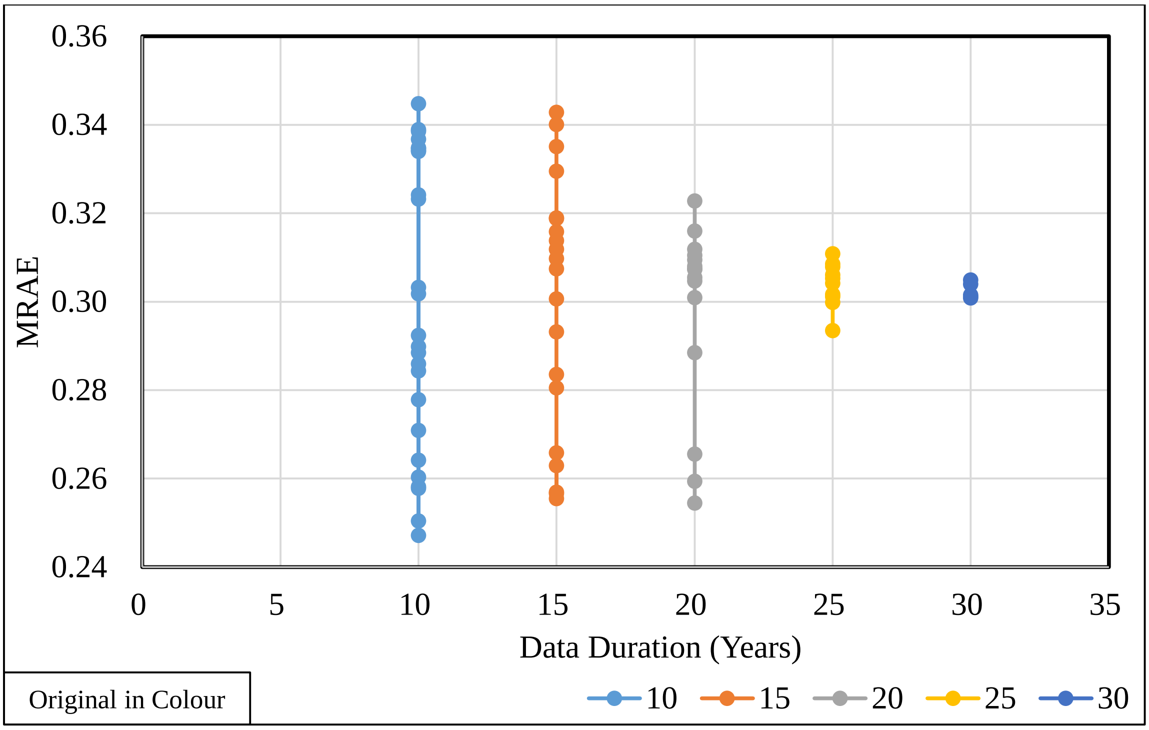

Figure 5-17: Variation of MRAE for Overall Hydrograph Matching – Verification

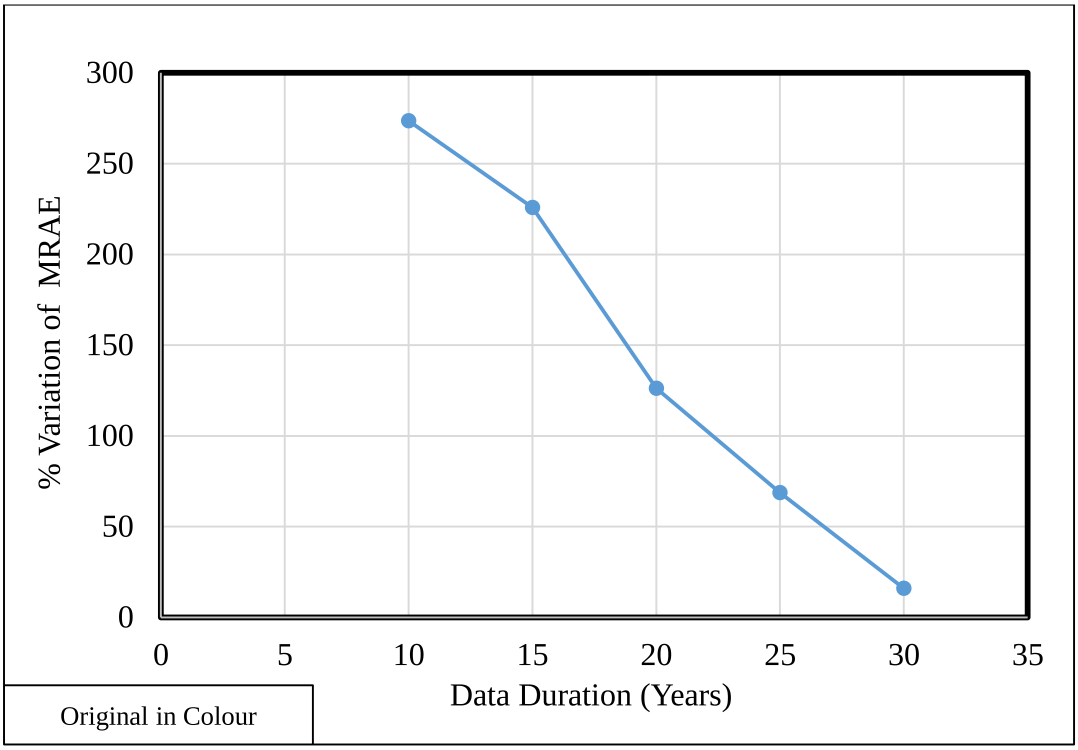

Figure 5-18: Variation of Overall MRAE – Calibration

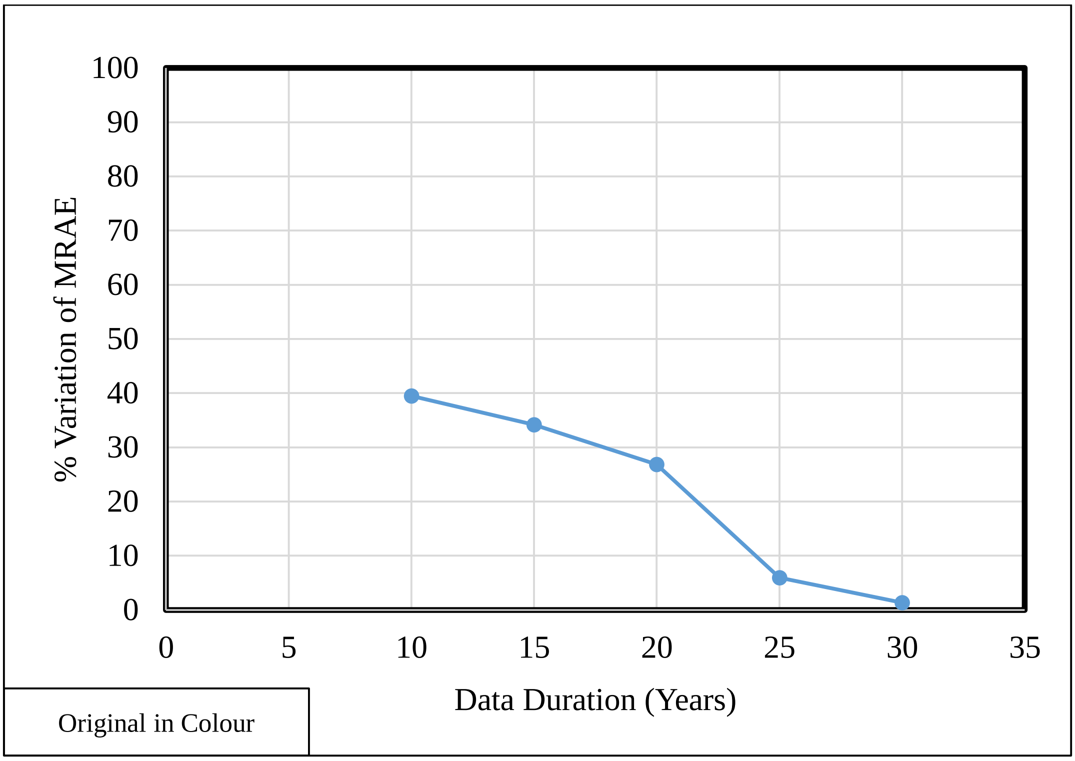

Figure 5-19: Variation of Overall MRAE – Verification

5.5.3. Evaluation of Flow Duration Curve

MRAE values of the overall FDC converges with the increase in data duration. During calibration the MRAE variation is less than 20% at 30 year data period and at the same time less than 5% for verification data period. The worst MRAE value was 0.1413 obtained at 10 year data period. Best MRAE was also obtained at 10 year data period. Figure 5-22, Figure 5-23 and Table 5-11 indicates the variation of MRAE of overall FDC with data duration.

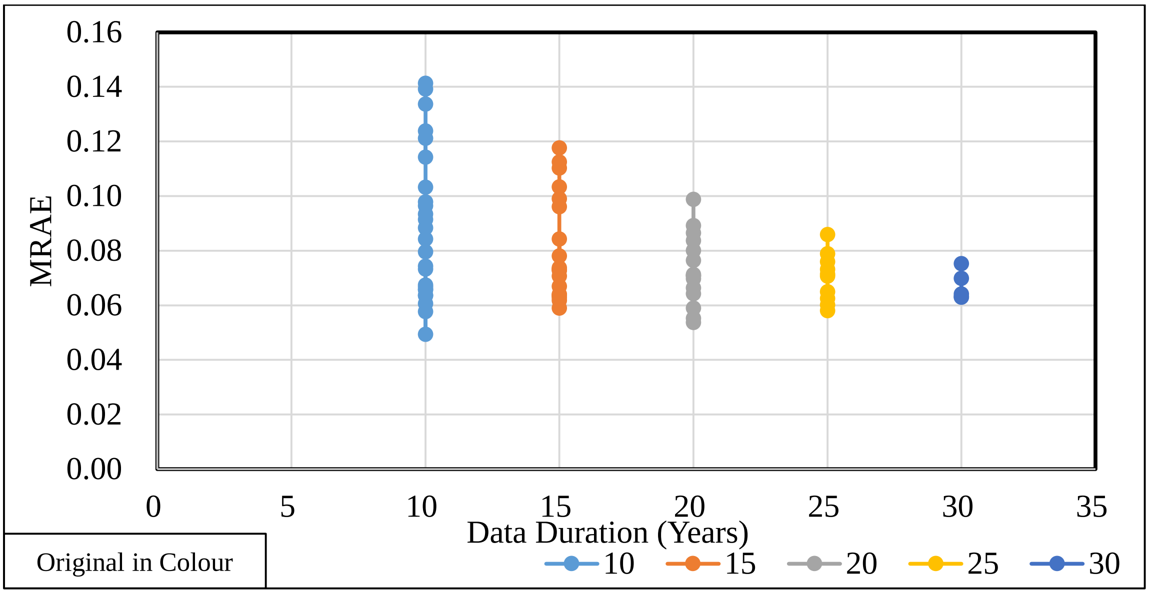

Figure 5-20: Flow Duration Curve MRAE Variation with Data Durations – Calibration

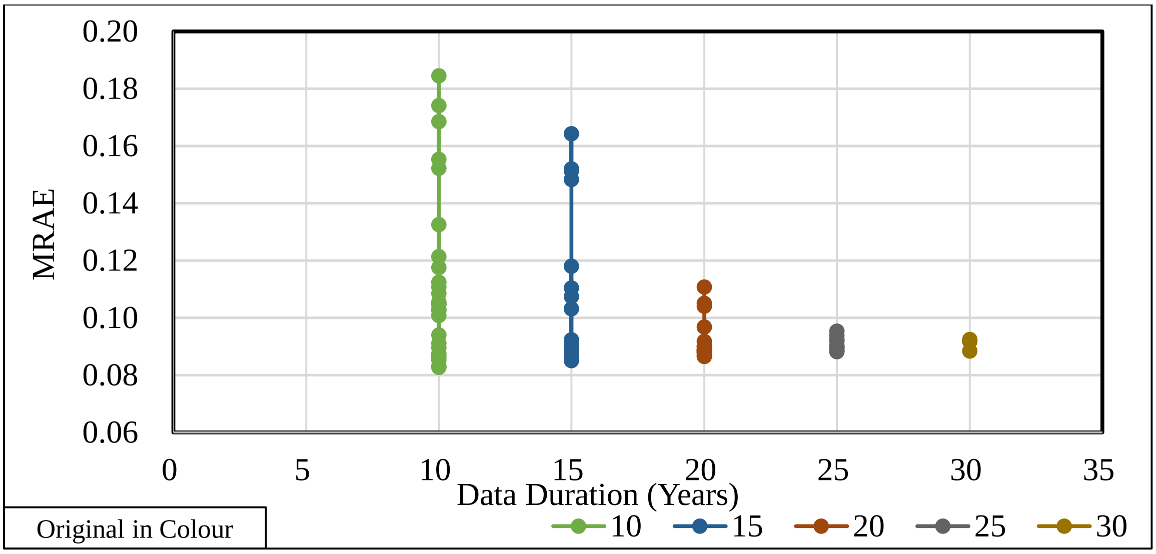

Figure 5-21: Flow Duration Curve MRAE Variation with Data Durations - Verification

Table 5-11: FDC MRAE Variation with Data Length during Calibration and Verification

Data Length (Years)	Calibration				Verification			
	Minimum	Maximum	Mean	% Variation	Minimum	Maximum	Mean	% Variation
10	0.0494	0.1413	0.0887	186.34	0.0827	0.1845	0.1143	123.13
15	0.0590	0.1177	0.0804	99.49	0.0850	0.1643	0.1053	93.21
20	0.0537	0.0988	0.0731	84.09	0.0865	0.1107	0.0928	27.95
25	0.0580	0.0860	0.0702	48.11	0.0882	0.0954	0.0909	8.16
30	0.0630	0.0753	0.0671	19.61	0.0884	0.0924	0.0913	4.54

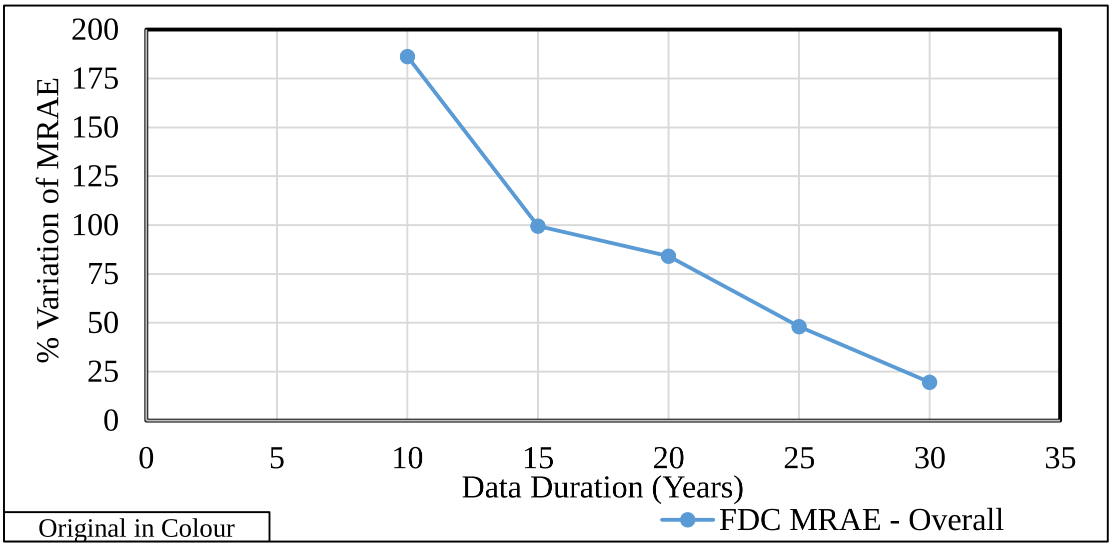

Figure 5-22: % Variation of MRAE with Data Duration (Calibration)

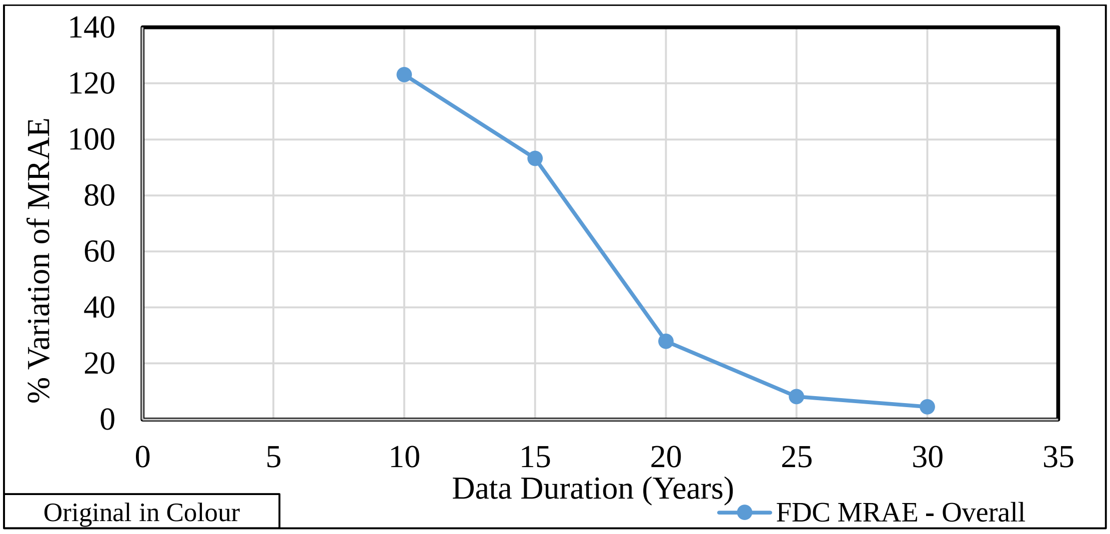

Figure 5-23: % Variation of MRAE with Data Duration (Verification)

5.5.4. Evaluation of High flows

Minimum MRAE values of model calibration corresponding to each data length are in Figure 5-24 and in Table 5-12. The high flow matching was very good irrespective of data length. The worst and best matching MRAE values were 0.1358 (10 year data length) and 0.0178 (15 year data length) respectively. The consistency of MRAE values increased with the selected data length. The % relative MRAE variation is approximately 40% at 25 year data duration. MRAE variation of High flow during verification is shown in Figure 5-25 and Table 5-12. The graphs of relative variation during calibration and verification are in Figure 5-26 and Figure 5-27.

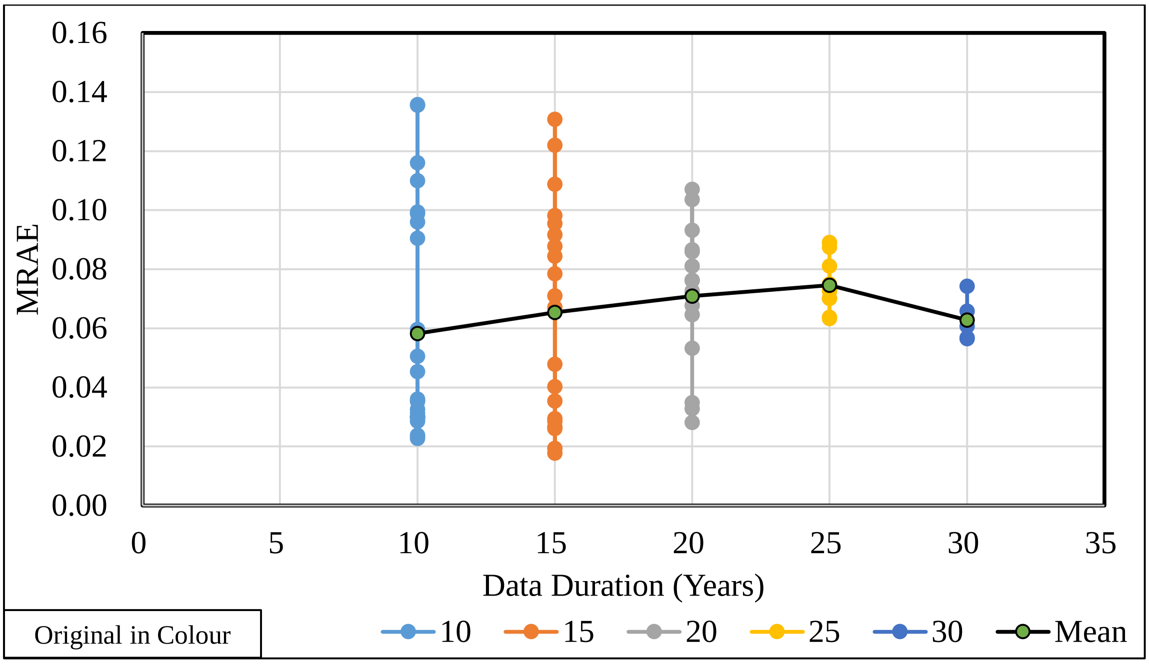

Figure 5-24: High Flow MRAE Variation with Data Length - Calibration

Table 5-12: High flow MRAE Variation with Data Length during Calibration and Verification

Data Length (Years)	Calibration				Verification			
	Minimum	Maximum	Mean	% Variation	Minimum	Maximum	Mean	% Variation
10	0.0228	0.1358	0.0583	495.68	0.1187	0.1465	0.1293	23.47
15	0.0178	0.1308	0.0654	636.85	0.1199	0.1451	0.1279	21.08
20	0.0281	0.1071	0.0709	280.90	0.1218	0.1319	0.1252	8.22
25	0.0633	0.0891	0.0746	40.80	0.1228	0.1266	0.1242	3.03
30	0.0566	0.0742	0.0629	31.23	0.1229	0.1250	0.1244	1.70

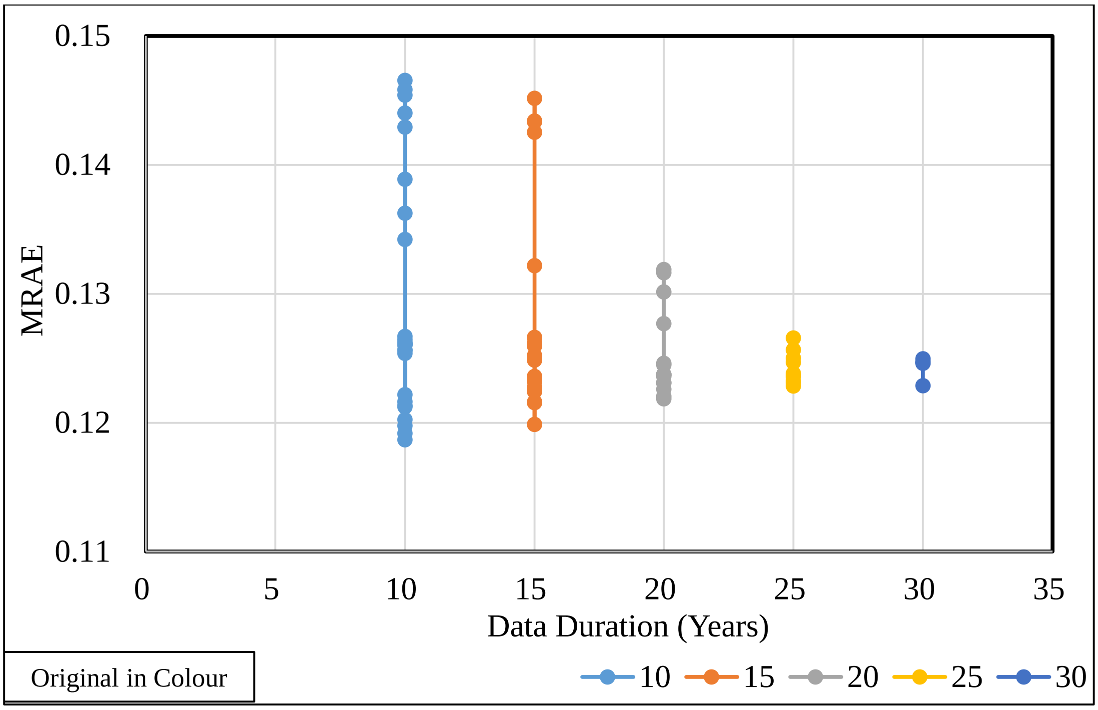

Figure 5-25: High Flow MRAE Variation with Data Length – Verification

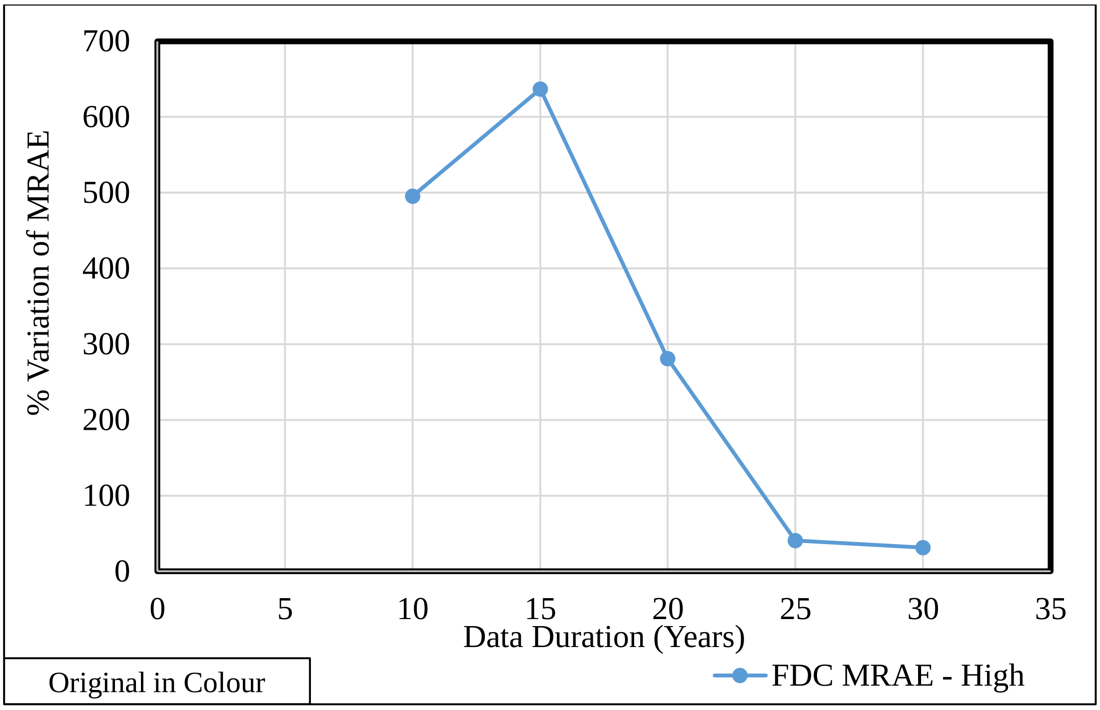

Figure 5-26: Relative Variation of Calibration High Flow MRAE

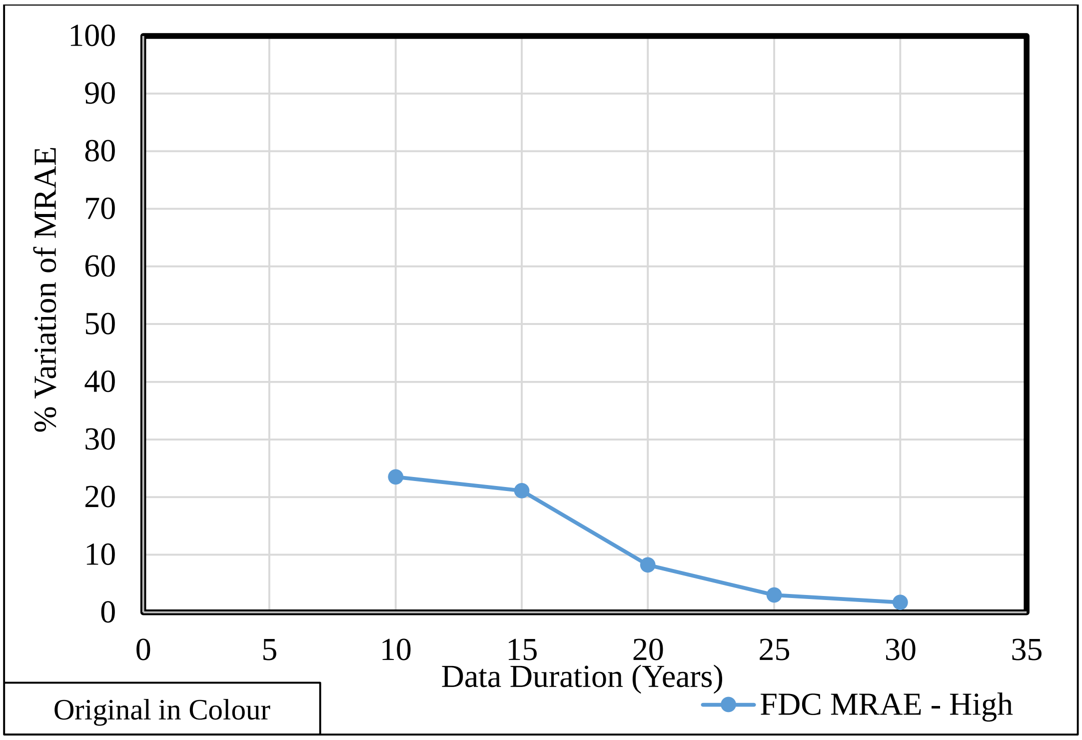

Figure 5-27: Relative Variation of Verification High Flow MRAE

5.5.5. Evaluation of Intermediate Flows

Minimum MRAE values for intermediate flow of FDC of model calibration are in Table 5-13 and Figure 5-28. The intermediate flow matching is very good in each data length. The worst MRAE was 0.1284 obtained for a 10 year dataset. The Mean MRAE as seen in Figure 5-28 reduced with the increase in data length. Data sets of 10 year and 15 year shows high variation relative to the minimum of the MRAE. However at 30 year data length, % variation of MRAE becomes a reasonable value. However the MRAE values obtained still shows good matching of the FDC. Verification MRAE variation is 8.8% at 30 year data duration. The Intermediate flow MRAE values variation with the data duration is shown in Figure 5-29. % Variation of MRAE relative to minimum of MRAE is shown in Figure 5-31 for Calibration and Verification.

Table 5-13: Intermediate flow MRAE Variation with Data Length during Calibration and Verification

Data Length (Years)	Calibration				Verification			
	Minimum	Maximum	Mean	% Variation	Minimum	Maximum	Mean	% Variation
10	0.0206	0.1284	0.0512	524.66	0.0496	0.1652	0.0950	233.27
15	0.0186	0.1048	0.0427	462.82	0.0574	0.1658	0.0884	188.88
20	0.0209	0.0708	0.0336	239.39	0.0625	0.1100	0.0752	75.82
25	0.0217	0.0429	0.0274	97.22	0.0655	0.0790	0.0700	20.51
30	0.0236	0.0337	0.0278	42.42	0.0663	0.0721	0.0706	8.80

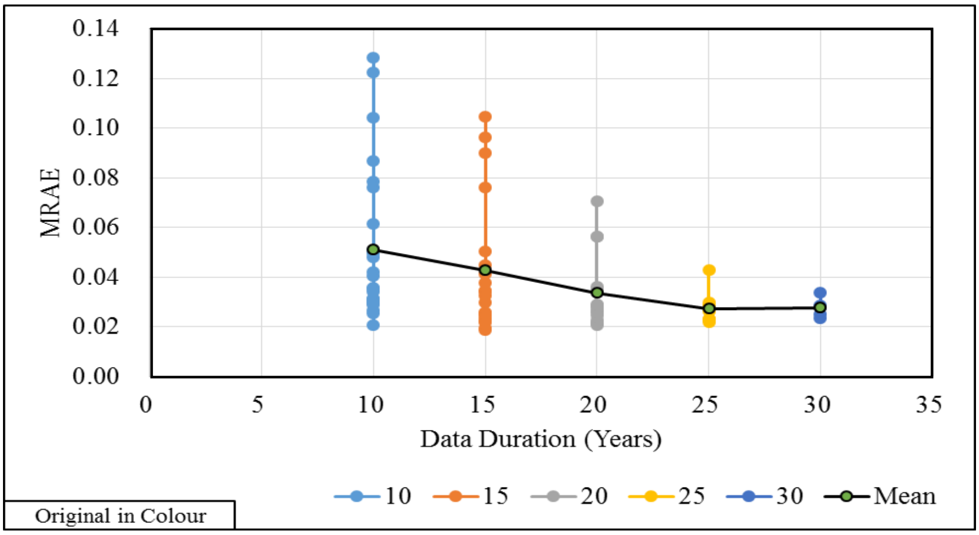

Figure 5-28: Intermediate Flow MRAE Variation with Data Length – Calibration

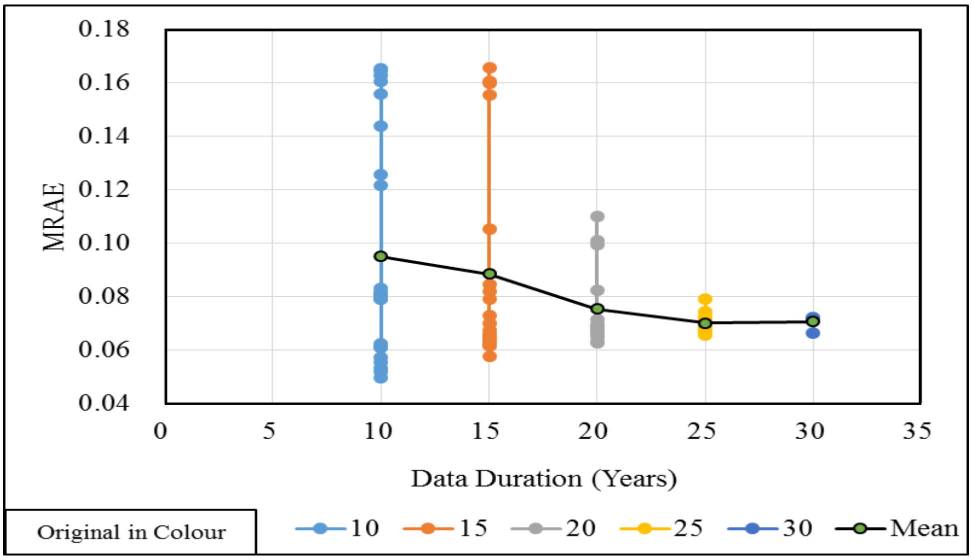

Figure 5-29: Intermediate Flow MRAE Variation with Data Length – Verification

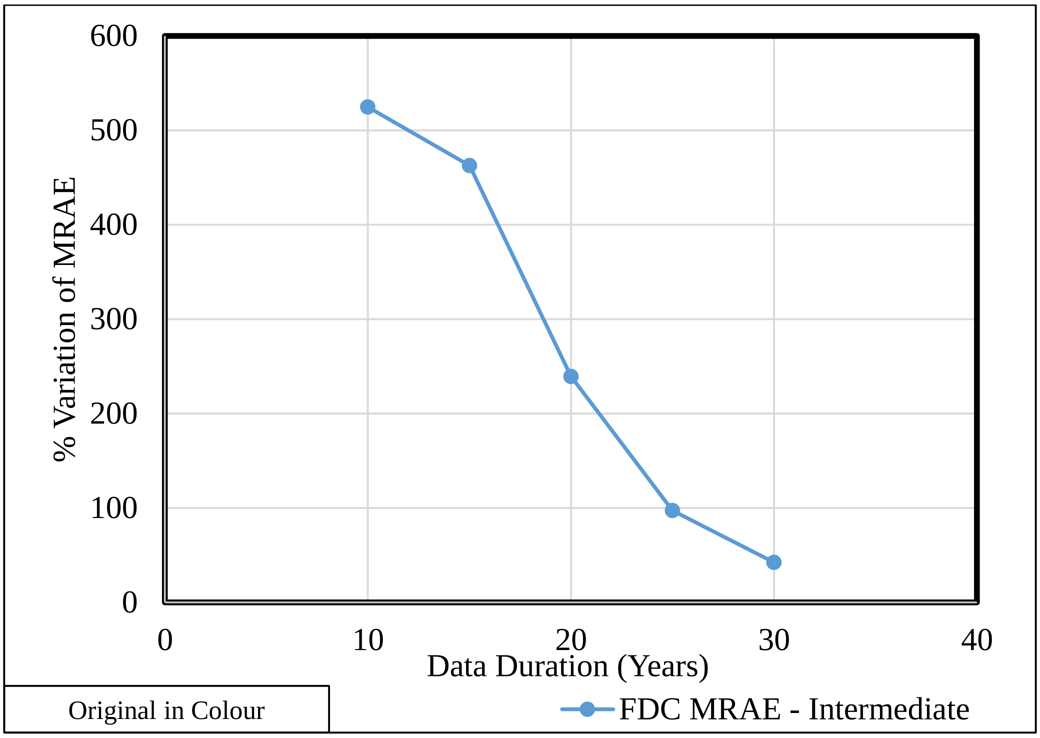

Figure 5-30: % Variation of MRAE during Calibration

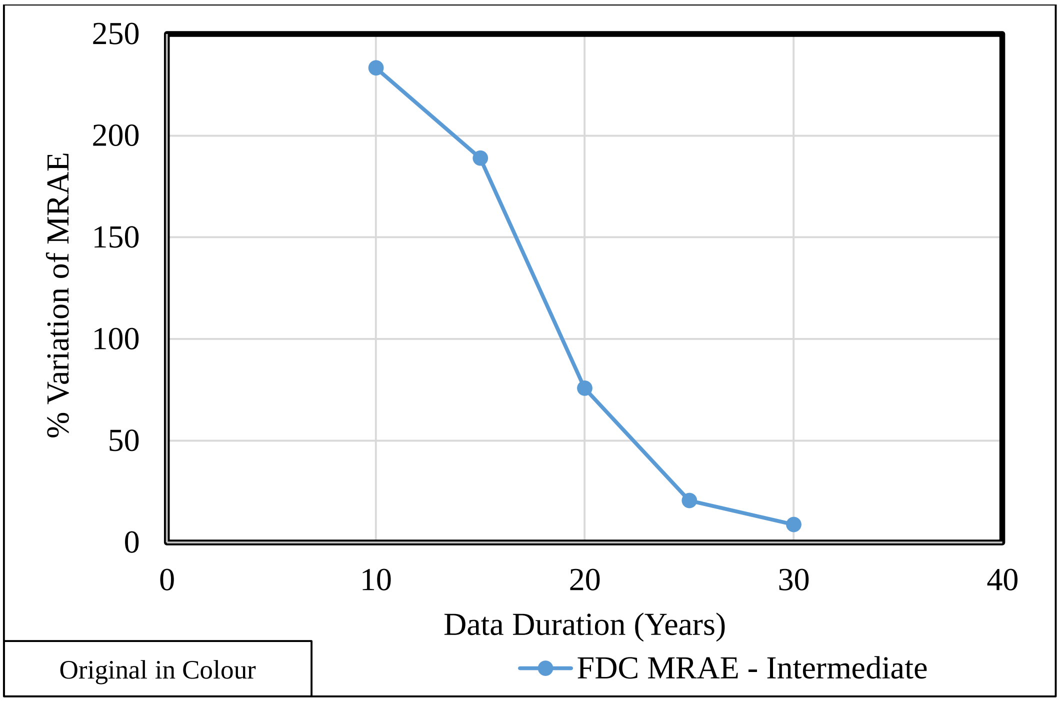

Figure 5-31: % Variation of MRAE during Calibration and Verification

5.5.6. Evaluation of Low Flows

The low flow MRAE value variation with the data length is shown in Figure 5-32 and Table 5-14. The worst MRAE value of 0.2168 was obtained at 10 year data length. Best MRAE was 0.0502 which was also obtained at 10 year data period. The % variation of calibration and verification data sets at 30 year data length is approximately 16% and 3.5% respectively. Figure 5-33 shows the MRAE variation with data length for verification. Figure 5-34 and Figure 5-35 shows the % MRAE variation with the minimum of the dataset for calibration and verification.

Table 5-14: Low flow MRAE Variation with Data Length during Calibration and Verification

Data Length (years)	Calibration				Verification			
	Minimum	Maximum	Mean	% Variation	Minimum	Maximum	Mean	% Variation
10	0.0502	0.2168	0.1415	331.71	0.0827	0.2292	0.1254	177.26
15	0.0859	0.1762	0.1255	105.23	0.0862	0.1731	0.1099	100.90
20	0.0726	0.1602	0.1141	120.67	0.0872	0.0999	0.0927	14.59
25	0.0831	0.1356	0.1108	63.23	0.0916	0.0958	0.0935	4.57
30	0.1013	0.1174	0.1086	15.88	0.0917	0.0949	0.0939	3.52

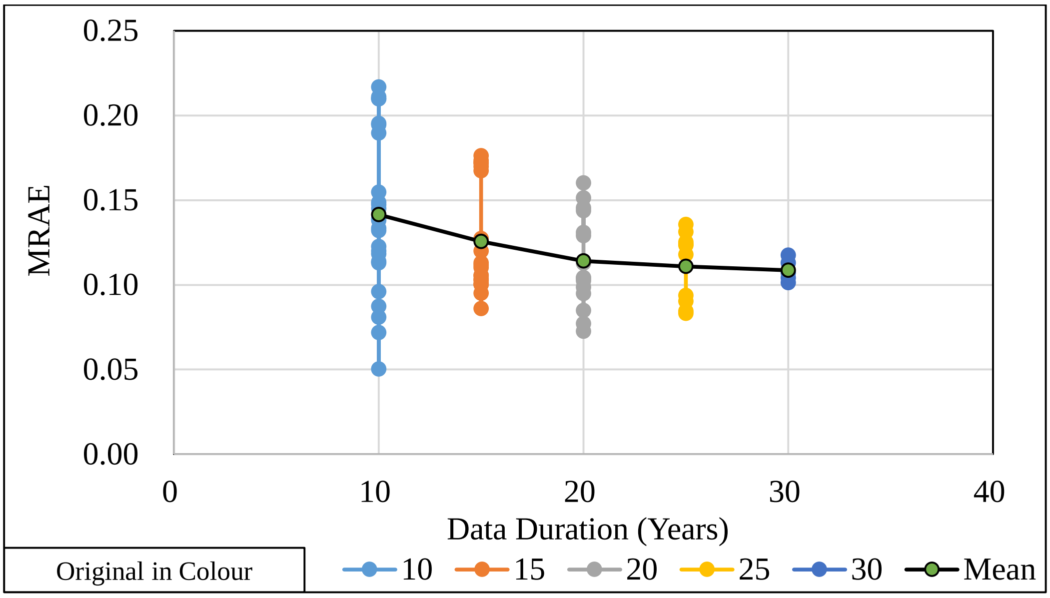

Figure 5-32: Low flow MRAE Variation with Data Length – Calibration

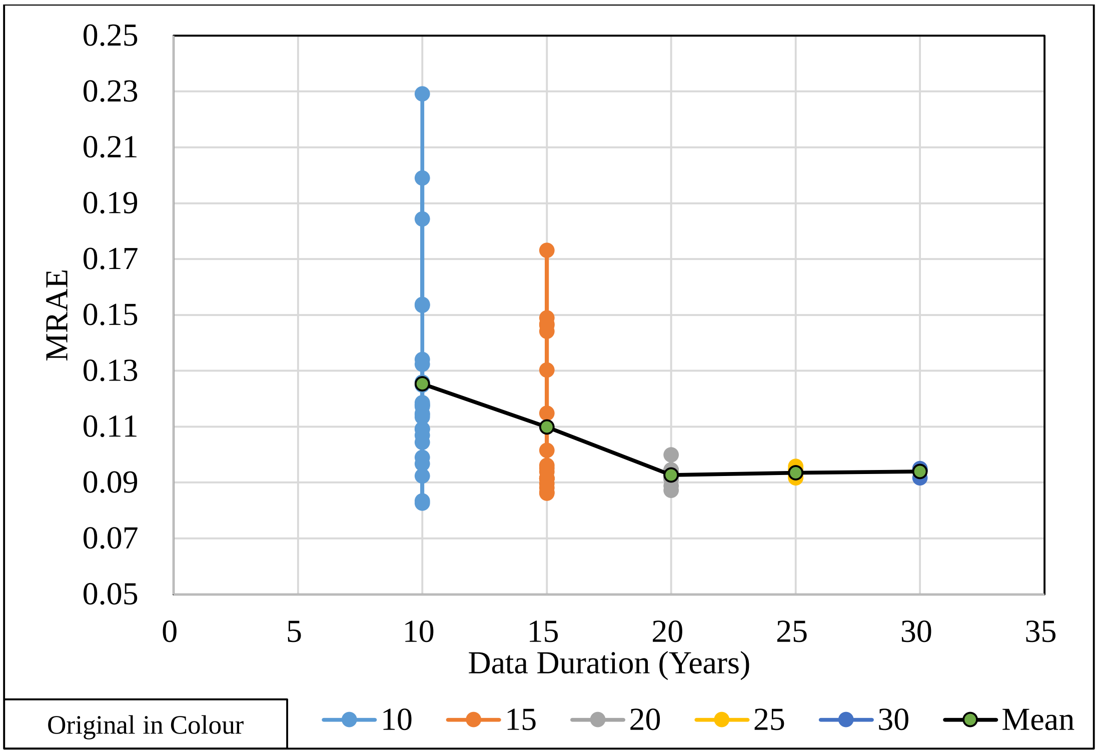

Figure 5-33: Low flow MRAE Variation with Data Length – Verification

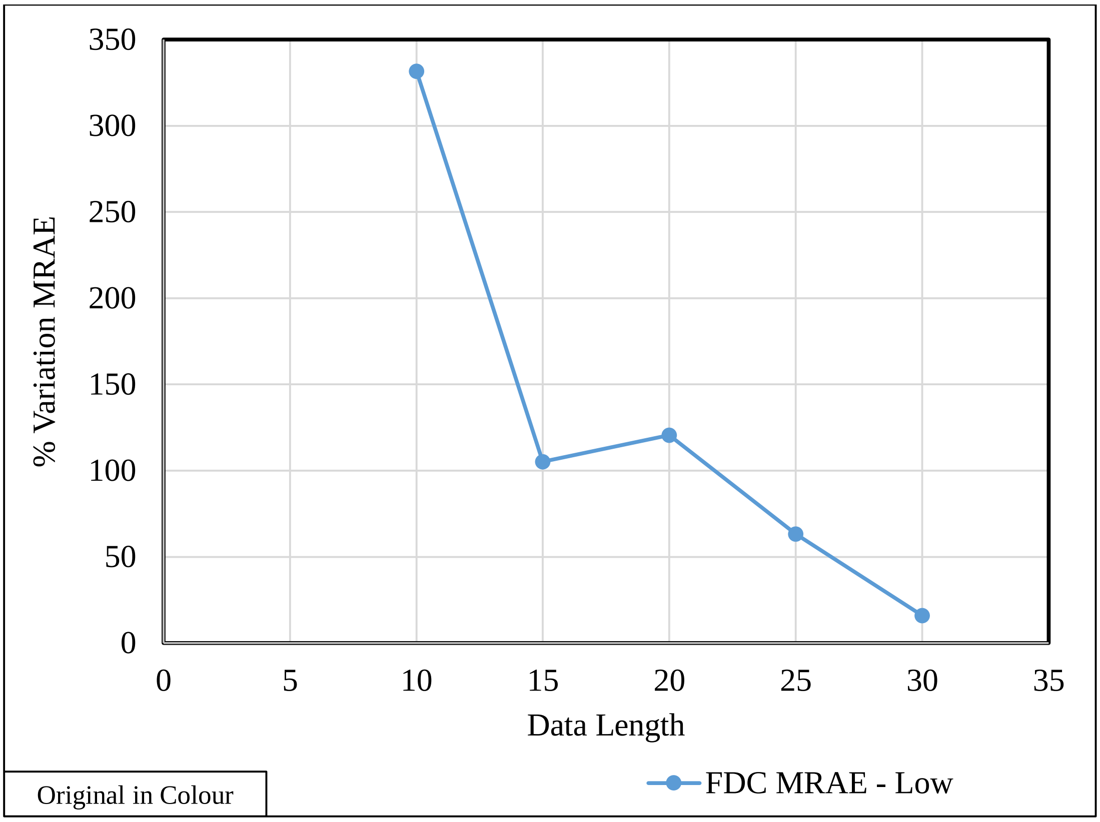

Figure 5-34: % Variation of MRAE with Data Length for Calibration

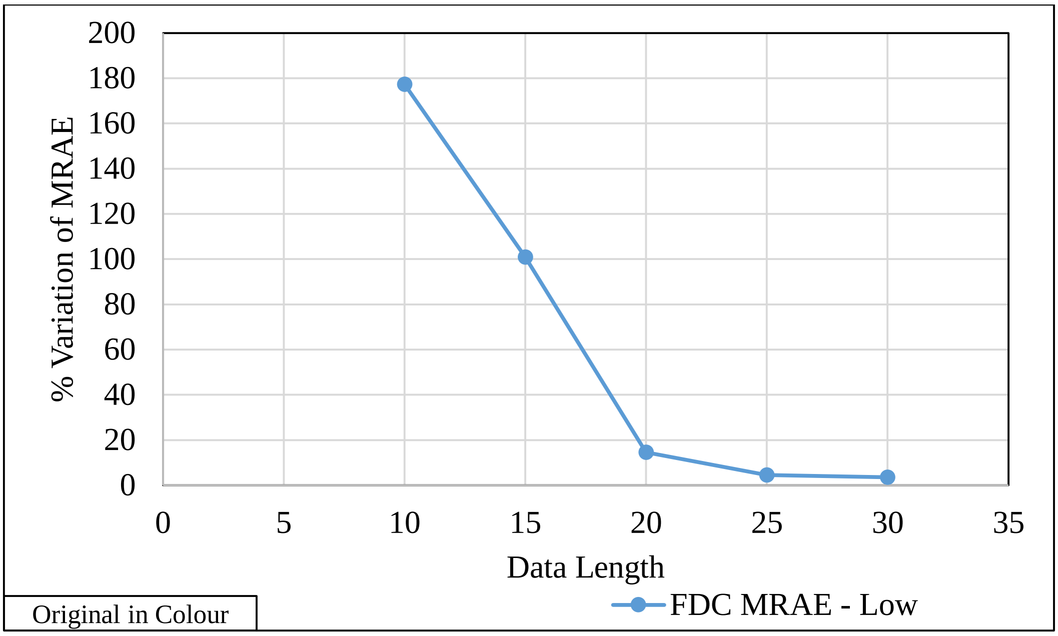

Figure 5-35: % Variation of MRAE with Data Length for Verification

5.5.7. Evaluation of Average Annual Water Balance

Annual Water Balance (AWB) variation with data length is shown in Figure 5-36 and Table 5-15. The verification of AWB variation is shown in Figure 5-37 and % relative variation of AWB for calibration and verification is shown in Figure 5-38 and Figure 5-39.

Table 5-15: Annual Water Balance Variation with Data Length during Calibration and Verification

Data Length (years)	Calibration				Verification			
	Minimum	Maximum	Mean	% Variation	Minimum	Maximum	Mean	% Variation
10	(194.54)	111.21	(29.86)	157.17	(344.44)	(46.83)	(159.67)	86.41
15	(154.75)	95.32	(5.51)	161.60	(347.18)	(59.65)	(140.37)	82.82
20	(62.99)	69.57	23.17	210.44	(224.00)	(67.84)	(110.87)	69.71
25	12.01	42.33	34.61	252.52	(134.44)	(77.12)	(96.99)	42.64
30	19.44	27.47	23.52	41.32	(104.97)	(92.90)	(102.06)	11.49

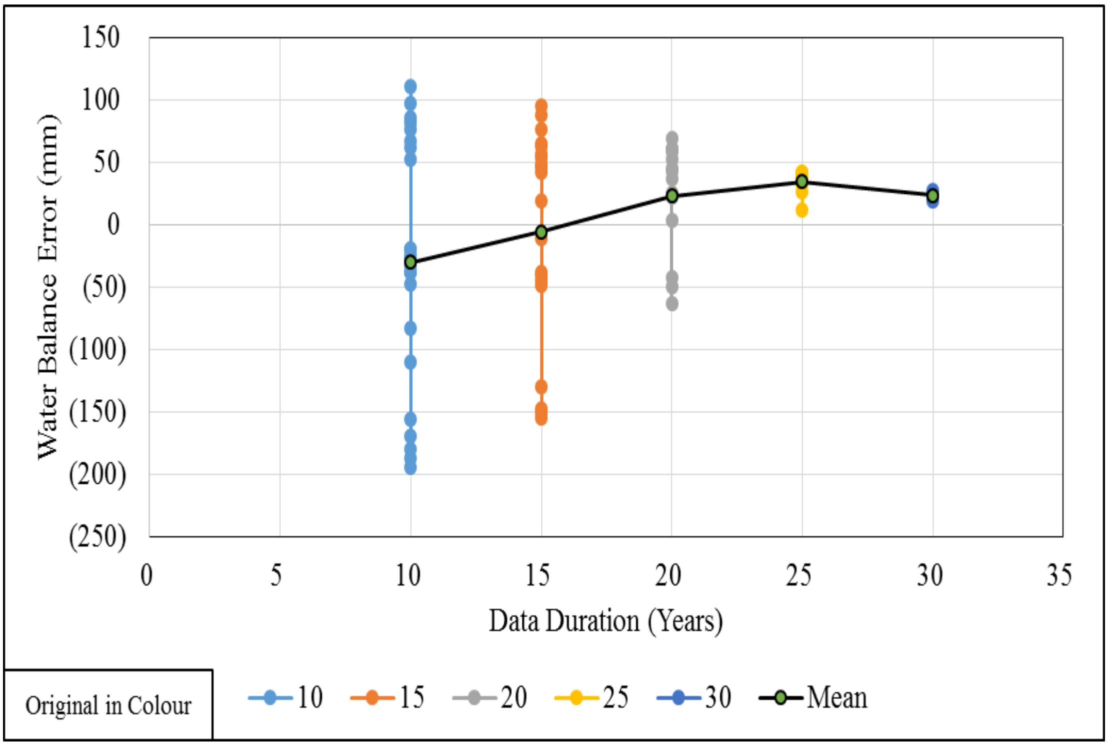

Figure 5-36: Annual Water Balance Variation with Data Length - Calibration

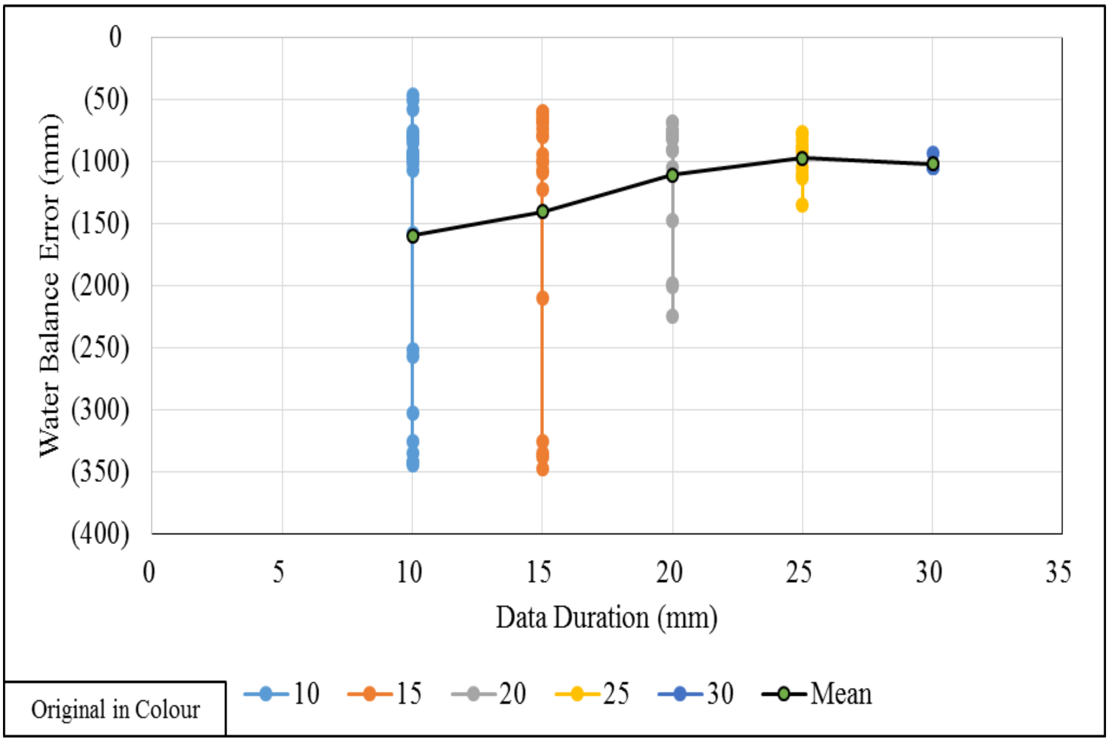

Figure 5-37: Annual Water Balance Variation with Data Length – Verification

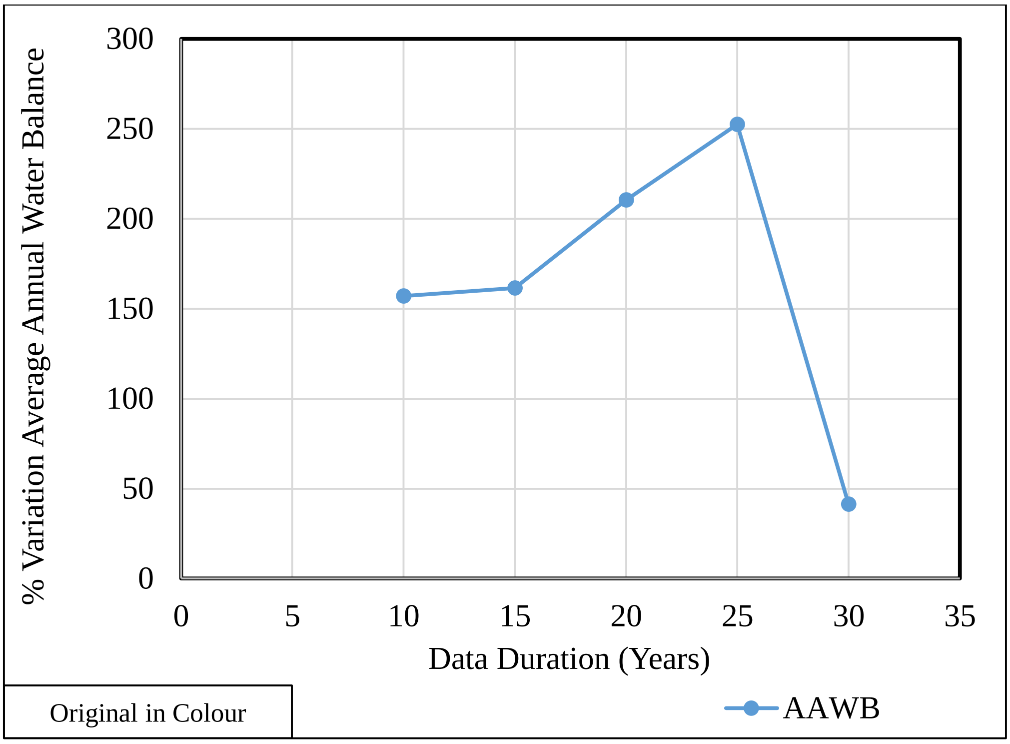

Figure 5-38: % Variation of AWB Difference Calibration

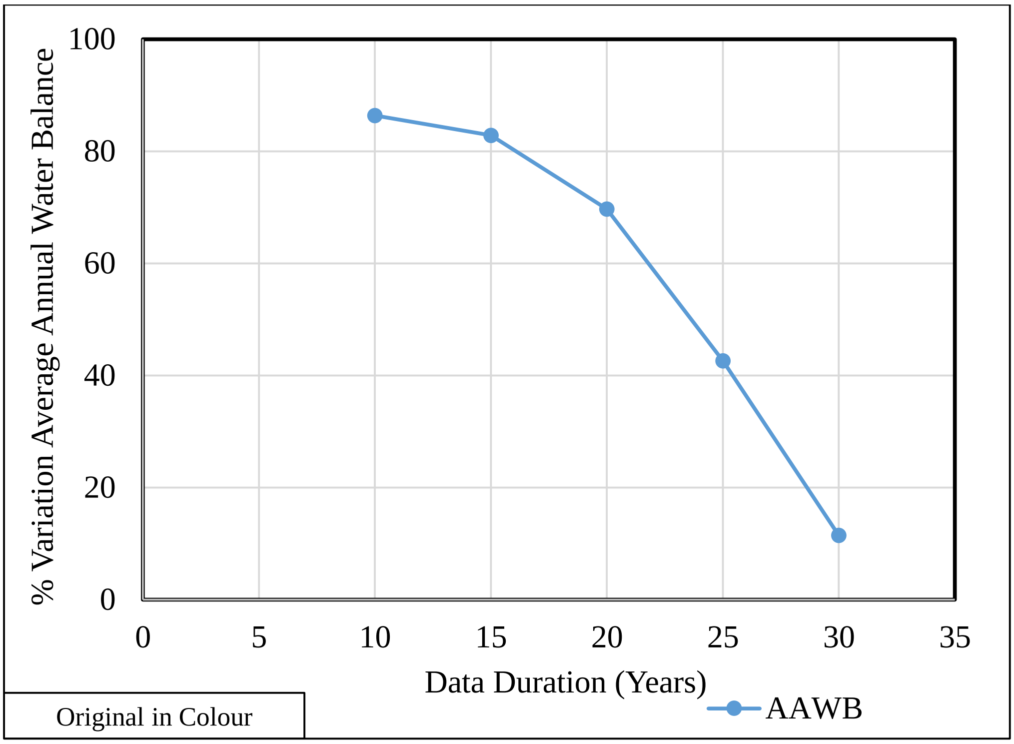

Figure 5-39: % Variation of AWB Difference Verification

5.5.8. Evaluation of Options

5.5.8.1. Factors

In the present work data length options for monthly water balance model development is evaluated. The overall hydrograph matching, flow duration curve matching and the water balance are the key factors that require careful consideration. The modelling results with a range of data lengths indicated that there are two major aspects that require attention. They are, 1) The goodness of fit between observed and computed outputs and 2) the consistency of goodness of fit for any data length from a longer time series data length.

5.5.8.2. Conceptualization

A qualitative conceptual evaluation model was used to select the most suitable data length (Figure 5-40). In this model overall hydrograph matching, flow duration curve matching (Overall, High, Intermediate and Low flow) and the water balance matching were assigned equal weightage on a 1 to 5 likert scale. In case of magnitude, each data length option was evaluated based on the maximum error that resulted in the concerned data series. The consistency was ranked based on the % relative variation. Assigning of scores from 5 – 1 were for respective MRAE ranges < 0.1, between 0.1 and 0.35, between 0.35 and 0.45, between 0.45 and 0.55 and greater than 0.55. The data length range with lowest to highest % relative error were assigned scores from 1 to 5. All flow duration curves magnitude scores (Overall, High, Medium, Low flow) were averaged to get the composite magnitude score of flow duration curve. Performance during calibration and verification was given equal weightage. The final overall scores are in the Table 5-16 and the error values prior to assigning scores are in the Table 5-17.

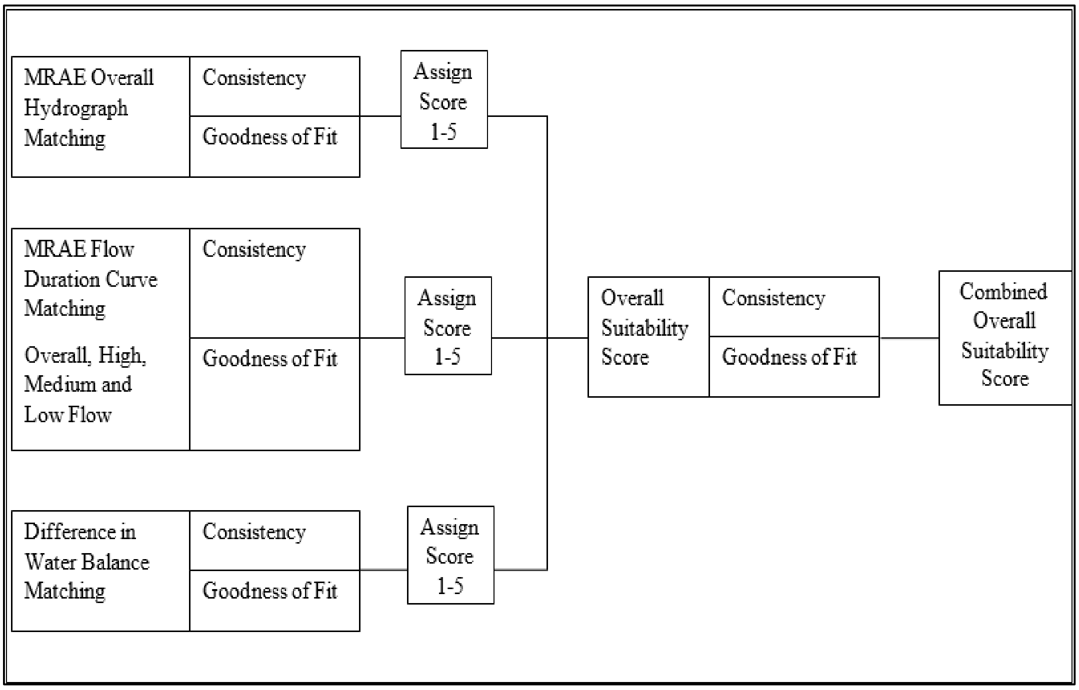

Figure 5-40: Model for Evaluation of Overall Suitability

Table 5-16: Overall Scores from Evaluation

Description of Score Allocation		10 Years	15 Years	20 Years	25 Years	30 Years
MRAE Hydrograph Matching	Magnitude	4.0	4.0	4.0	4.0	4.0
	Consistency	1.0	2.0	3.0	4.5	4.5
MRAE Flow Duration Curve Matching	Magnitude	4.0	4.0	4.4	4.8	4.8
	Consistency	1.1	1.9	3.0	4.0	5.0
Average Annual Water Balance Relative Error	Magnitude	2.5	2.5	3.0	4.0	4.0
	Consistency	2.0	2.0	2.0	4.0	5.0
Overall Evaluation		2.4	2.7	3.2	4.2	4.5

Table 5-17: Error Values for Assigning Scores

Indicator			Calibration					Verification				
			10 Years	15 Years	20 Years	25 Years	30 Years	10 Years	15 Years	20 Years	25 Years	30 Years
MRAE Hydrograph Matching	Magnitude	Maximum MRAE	0.3057	0.2696	0.2387	0.2187	0.2328	0.3447	0.3428	0.3227	0.3108	0.3049
	Consistency	Rank	5	4	3	1	2	5	4	3	2	1
MRAE Flow Duration Curve Matching	Magnitude	Maximum MRAE	0.1413	0.1177	0.0988	0.0860	0.0753	0.1845	0.1643	0.1107	0.0954	0.0924
	Consistency	Rank	5	4	3	2	1	5	4	3	2	1
MRAE High flow	Magnitude	Maximum MRAE	0.1358	0.1308	0.1071	0.0891	0.0742	0.1465	0.1451	0.1319	0.1266	0.1250
	Consistency	Rank	5	4	3	2	1	5	4	3	2	1
MRAE Intermediate flow	Magnitude	Maximum MRAE	0.1284	0.1048	0.0708	0.0429	0.0337	0.1652	0.1658	0.1100	0.0790	0.0721
	Consistency	Rank	5	4	3	2	1	4	5	3	2	1
MRAE Low Flow	Magnitude	Maximum MRAE	0.2168	0.1762	0.1602	0.1356	0.1174	0.2292	0.1731	0.0999	0.0958	0.0949
	Consistency	Rank	5	4	3	2	1	5	4	3	2	1
Average Annual Water Balance Difference	Magnitude	Maximum Error	0.194	0.162	0.238	0.083	0.077	0.670	0.675	0.531	0.430	0.407
	Consistency	Rank	4	3	5	2	1	4	5	3	2	1

6. Discussion

6.1. Model Selection

Out of the models in use for hydrologic modelling, the Two Parameter Monthly Water Balance Model (2PMWBM) developed by Xiong & Guo, 1998 was used in this research because, this model is easy to handle and has only two parameters. Also the model performance is good, it takes less time for operation and required base data were available for the selected catchment. Moreover, since the present research is on data length, it is vital for model complexities to be avoided for the emphasis on data length.

6.2. Model Evaluation and Objective Function

A literature review carried out for various objective functions such as Nash-Sutcliffe Efficiency, Correlation Coefficient, and Ratio of Absolute Error to Mean (RAEM), Relative Error and Mean Ratio of Absolute Error (MRAE), MRAE was selected as the objective function for model evaluation as its performance when capturing intermediate flows is high. When planning for water resources management, intermediate flows of a flow duration curve is of great concern because of the potential to harness for productive uses. During model optimization it could be noted that MRAE emphasizes on intermediate flow.

6.3. Data Duration Options

The literature survey carried out to identify a minimum data duration required for reliable optimization of a hydrologic model identified that data durations less than 10 years will not provide reliable optimization for a monthly water balance model. Models which use daily data performed well in shorter data durations such as 1, 2, 3, 5 and 8 years. For models which use monthly data needed longer data durations such as 15, 25 or 33 years to stabilize the model. Hence, the minimum data duration used for comparative model calibration in the present work was 10 years. Therefore data durations 10, 15, 20, 25 and 30 years were used for model calibration in order to compare model performance.

6.4. Data

For the selected watershed at Ellagawa, monthly data was available for rainfall, evaporation and streamflow. Therefore the data was collected from 1976/1977 to 2016/2017. Then data checking was carried out to identify outliers and inconsistencies. During annual water balance checking, a reduction in streamflow was identified after the water year 1999/2000. Thiessen average rainfall and evaporation was indicating the same order of magnitude throughout the entire dataset. The streamflow data was originally collected from the Department of Irrigation, Sri Lanka. Further checking was done to assess the reliability of the measure and it was informed that the data sources is reliable. However annual water balance check was unrealistic and identified inconsistency in the dataset. Therefore using double mass curve and regression method, streamflow data was rectified. Furthermore, reliable base data were selected considering the rational performance with respect to water balance and runoff coefficients. This study revealed the importance of correct base data. It also contributes to the strengthening of prevailing knowledge on rectifying inconsistent monthly data.

6.5. 2P Model Evaluation

Two Parameter Monthly Water Balance Model evaluation was done by using hydrograph matching, Flow Duration Curve (FDC) matching, High, Intermediate and Low streamflow matching and matching of Water Balance. In case of high, intermediate and low flow matching the FDC was based on a research monograph (Wijesekera, 2018) on Kalu River Basin.

Graphical methods and indicator values enabled the realization of optimum models for each data length case used in the study. The MS Excel spreadsheet and the Solver tool was versatile when optimizing the parameters and identifying the global minimum with a reasonable number of trials.

6.6. Evaluation of Data Length

The suitable data length for model development was evaluated by matching the capability of a dataset to develop a model to repeat the watershed hydrology. In this evaluation a multiple objective evaluation method was used by combining overall hydrograph, flow duration curve and water balance comparison. A conceptual model using a simple averaging method was the tool that combine the objectives, in the assigning of scores, the MRAE classification was based on the performance noted during optimization. This may be improved in future by carrying out research on more watersheds in different climates and with a variety of land uses and watershed sizes.

6.7. Model Parameter Variation with Data Duration Options

Model parameters of the 2PMWBM are C and Sc. Parameter C is the time conversion factor from annual to monthly scale. Parameter Sc denotes the field capacity. The model parameters are responsible for the efficiency of the model. The parameter C and Sc varies with the data duration options. As seen in Figure 5-12 and Figure 5-13, parameters converge with the increase in data duration. The variation between maximum and minimum value of the parameters in Figure 5-12 and Figure 5-13 shows the numerical difference between maximum and minimum values of the model parameters and Figure 5-14 and Figure 5-15 shows the percentage variation with respect to the minimum of the data set. Variation is less after 20 years of data length. Model parameter values C and Sc converged to respective values of 0.79 and 578.73.

7. Conclusions

1. State of the art data length option for the calibration of a monthly hydrologic model which is between 20 – 30 years, could be successfully captured with a qualitative conceptual model used in the literature review of present study.
2. The multi objective evaluation of a two parameter monthly water balance model using 75 datasets with data lengths varying between 10 and 30 in steps of 5 revealed that the threshold data length for Ellagawa watershed is 20 years.
3. Evaluations showed that when the data length is longer than 20 years the multi objective score is well above the median of the scale. Therefore the 20 year period can be recommended as the threshold data length for a reliable monthly water balance model development.
4. Data length of 10, 15, 20, 25 and 30 years developed the best 2PMWB Models having maximum MRAE values 0.3057, 0.2697, 0.2387, 0.2187 and 0.2329 respectively.
5. The 2PMWB Model optimization with a data length of 20 years converged to optimized c and Sc parameter values 0.80 and 605.42 respectively.
6. Data quality is very important for satisfactory hydrologic modelling of watersheds. The inconsistent monthly streamflow data of Ellagawa watershed could be satisfactorily rectified using double mass curves with a regression analysis.

8. Recommendations

More case studies on input data length options must be carried out to develop guidelines for reliable watershed model development in various climates and at watersheds with different land uses, topography and catchment areas.

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APPENDIX A – Analysis of Literature

Table A.1: Summary of Data Associated with Modelling Studies

Reference	River Basin	Gauging Station	Data Resolution	No. of Gauging Stations	Calibration Data Duration	Catchment Area (km^2)
Perera, K. R. J., & Wijesekera, N. T. S. (2012)	Attanagalu Oya Basin	Karasnagala	Daily	5	10	53
Wijesekera & Rajapakse, 2013	Attanagalu Oya Basin	Karasnagala	Daily	3	1	54
Bastiaanssen and Chandrapala, 2003	Attanagalu Oya Basin	Negombo Lagoon	Daily	1	1	736
Wickramaarachchi, Ishidaira and Wijayaratna,(2013)	Gin River	Agaliya	Daily	6	4	780
Bastiaanssen and Chandrapala, 2003	Gin River	Galle	Daily	1	1	932
Dissanayake, 2017	Gin River	Thawalama	Daily	4	8	364
Wickramaarachchi, Ishidaira and Wijayaratna, (2013)	Gin River	Thawalama	Daily	6	4	470
Dissanayake, 2017	Kalu River	Ellagawa	Daily	5	4	1372
Bastiaanssen and Chandrapala, 2003	Kalu River	Kalutara	Daily	1	1	2719
Nyunt et al., 2012	Kalu River	Putupaula	Daily	26	20	2598

Table A.1: Summary of Data Associated with Modelling Studies (Continued)

Reference	River Basin	Gauging Station	Data Resolution	No. of Gauging Stations	Calibration Data Duration	Catchment Area (km^2)
Samarasinghe, S. M. J. S., Nandalal, H. K., Weliwitiya, D. P., Fowze, J. S. M., Hazarika, M. K., & Samarakoon, L. (2010)	Kalu River	Putupaula	Daily	13	10	2658
Schulz and Kingston, 2017	Kalu River	Putupaula	Daily	1	4.75	2765
Wijesekera & Musiake, 1990b	Kalu River	Putupaula	Daily	6	3	2598
Kanchanamala, Herath and Nandalal, 2016	Kalu River	Ratnapura	Daily	7	5	603
Jayadeera, 2016	Kalu River	Ellagawa	Daily	5	4	1350
Jayadeera, 2016	Kalu River	Ratnapura	Daily	4	4	635.1
Bastiaanssen and Chandrapala, 2003	Kelani River	Colombo	Daily	1	1	2292
De Silva, Weerakoon and Herath, 2014	Kelani River	Hanwella	Daily	8	2	2230
Wijesekera & Musiake, 1990a	Mahaweli River	Peradeniya	Daily	4	4	1167

Table A.1: Summary of Data Associated with Modelling Studies (Continued)

Reference	River Basin	Gauging Station	Data Resolution	No. of Gauging Stations	Calibration Data Duration	Catchment Area (km^2)
Wijesinghe and Wijesekera, 2012	Attanagalu Oya Basin	Karasnagala	Event Based/Daily	1	30 events	52.8
Thapa and Wijesekera, 2017	Attanagalu Oya Basin	Karasnagala	Event Based/Daily	2	30 events	52.58
Nandalal and Ratnayake, 2009	Kalu River	Ratnapura	Event Based/Daily	1	4 Events	604
Dahanayake and Wijesekera, 2017	Dampe	Ratmalana	Monthly	1	1	0.62
Wijesekera, 2000	Gin River	Thawalama	Monthly	4	3	361
Khandu, 2015	Gin River	Thawalama	Monthly	4	20	368.75
Gunasekara, 2019	Gin River	Thawalama	Monthly	4	13	360
Ampitiyawatta and Guo, 2010	Kalu River	Putupaula	Monthly	8	40	2598
Gunasekara, 2018	Kalu River	Ellagawa	Monthly	5	10	1383
Khandu, 2015	Kelani River	Deraniyagala	Monthly	4	24	182.54
Perera, K. R. J., & Wijesekera, N. T. S. (2012)	Kelani River	Glencourse	Monthly	6	10	1537

Table A.2: Summary of Mostly used Monthly Water Resources Models

No.	Name of Model	Model Reference	Number of Parameters	Number of Monthly Applications	% of Applications
1	PE Model	Xu, C. Y., & Vandewiele, G. L. (1994)	3	81	25.7%
2	2P MWBM	Xiong, L., & Guo, S. (1999)	2	70	22.2%
3	The Catchment Land Surface Model (CLSM)	Mahanama, S. P., Koster, R. D., Reichle, R. H., & Zubair, L. (2008)	**	22	7.0%
4	WatBal	Szolgay, J., Hlavčová, K., Kohnová, S., & Danihlík, R. (2003)	5	14	4.4%
5	abcd Model	Alley, W. M. (1984), Bai, P., Liu, X., Liang, K., & Liu, C. (2015)	4	13	4.1%
6	T Model	Alley, W. M. (1984)	2	10	3.2%
7	Tα Model	Alley, W. M. (1984)	3	10	3.2%
8	Tɤ Model	Alley, W. M. (1984)	3	10	3.2%
9	P Model	Alley, W. M. (1984)	3	10	3.2%
10	4 Parameter RR Model	Kirchner, J. W. (2009), Haan, C. T. (1972)	4	8	2.5%

** Number of Parameters were unspecified

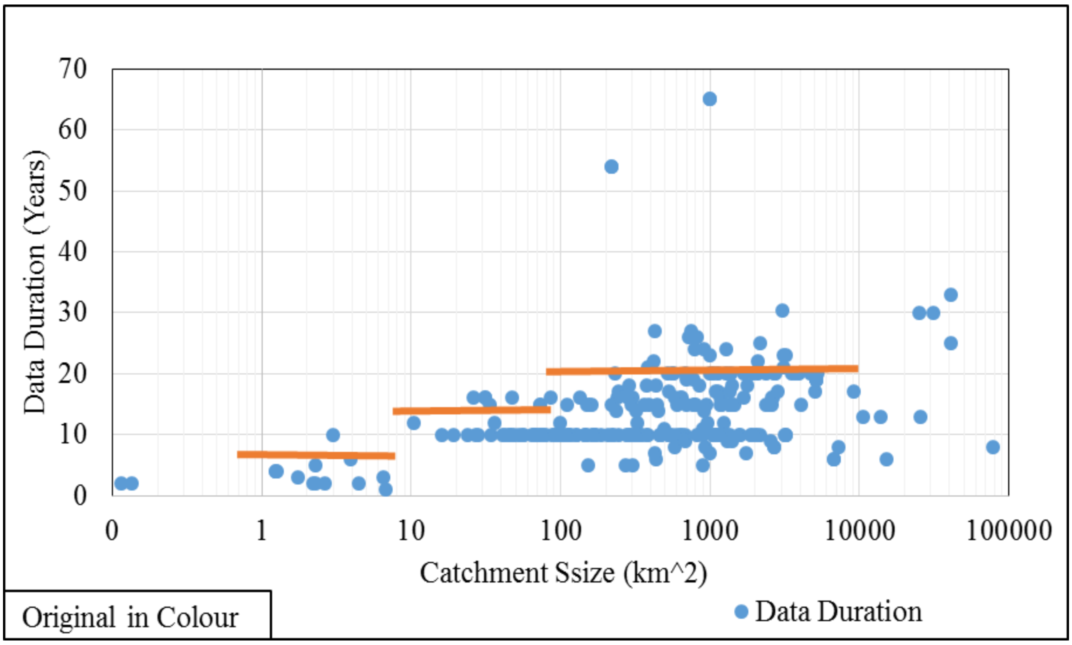


Figure A.1: Distribution of Calibration Data Duration According to Size of Watershed

Table A.3: Calibration Data Duration Variation According to Watershed Area

Range	**0-10**	**10-100**	**100-1000**	**1000-5000**	**>5000**
Max	10	16	65	30.4	33
Min	1	10	5	7	6
Average	3	11	15	15	18
Median	3	10	11	15	19

APPENDIX B - Data

Table B.1: Thiessen Average Rainfall Data - Ellagawa Watershed

Year	Monthly Rainfall (mm/Month)			Annual Rainfall (mm/Year)
	Maximum	Mean	Minimum	
1983/1984	522.35	338.87	70.74	4066.43
1984/1985	667.13	320.18	178.19	3842.21
1985/1986	707.54	348.77	142.67	4185.24
1986/1987	542.31	275.24	40.41	3302.92
1987/1988	567.76	397.31	117.90	4767.77
1988/1989	631.19	309.75	91.97	3717.05
1989/1990	507.20	275.09	111.15	3301.12
1990/1991	391.05	282.45	152.60	3389.46
1991/1992	448.20	262.16	67.86	3145.88
1992/1993	570.01	281.82	80.48	3381.78
1993/1994	564.72	300.67	141.81	3608.03
1994/1995	518.07	314.78	75.45	3777.42
1995/1996	482.85	270.01	78.29	3240.09
1996/1997	513.18	270.96	55.65	3251.55
1997/1998	479.06	351.49	142.39	4217.93
1998/1999	673.98	369.63	140.38	4435.57
1999/2000	457.12	308.22	154.90	3698.65
2000/2001	354.95	255.00	83.41	3060.01
2001/2002	435.76	276.05	109.11	3312.56
2002/2003	559.93	353.71	131.13	4244.49
2003/2004	542.68	314.54	122.72	3774.50
2004/2005	610.92	296.95	147.74	3563.40
2005/2006	472.64	291.35	156.83	3496.20
2006/2007	479.58	262.57	62.63	3150.78
2007/2008	574.71	294.38	127.42	3532.61
2008/2009	430.37	278.64	67.76	3343.70
2009/2010	545.45	299.38	151.33	3592.58
2010/2011	526.31	314.83	186.89	3777.95
2011/2012	434.09	222.65	113.87	2671.82
2012/2013	532.36	319.35	114.63	3832.21
2013/2014	496.72	286.14	98.33	3433.64
2014/2015	743.80	300.68	97.44	3608.21
2015/2016	786.08	282.26	87.55	3387.08
2016/2017	773.16	270.55	21.29	3246.56

Table B.2: Evaporation Data - Ratnapura Station

Year	Evaporation (mm/Month)			Annual Evaporation (mm/Year)
	Maximum	Mean	Minimum	
1983/1984	131.76	107.93	81.31	1295.17
1984/1985	138.84	110.41	89.57	1324.98
1985/1986	132.11	112.86	88.35	1354.35
1986/1987	172.22	128.05	93.93	1536.65
1987/1988	137.61	100.87	30.00	1210.42
1988/1989	178.27	122.67	85.28	1472.07
1989/1990	142.54	116.10	88.86	1393.24
1990/1991	135.72	114.04	81.03	1368.48
1991/1992	186.45	114.83	30.00	1377.94
1992/1993	137.17	108.05	85.43	1296.62
1993/1994	124.46	101.51	81.45	1218.11
1994/1995	145.92	103.60	82.43	1243.15
1995/1996	153.16	102.96	84.96	1235.48
1996/1997	136.12	107.91	84.53	1294.88
1997/1998	146.72	103.68	82.06	1244.13
1998/1999	137.52	108.49	85.10	1301.87
1999/2000	124.48	98.88	65.82	1186.61
2000/2001	134.09	97.10	72.07	1165.20
2001/2002	111.26	90.90	69.96	1090.86
2002/2003	111.18	87.85	64.12	1054.20
2003/2004	106.35	88.21	62.51	1058.56
2004/2005	110.41	90.65	70.46	1087.77
2005/2006	87.62	80.41	70.72	964.89
2006/2007	105.78	77.46	51.27	929.53
2007/2008	83.87	48.46	29.30	581.51
2008/2009	108.61	75.20	55.70	902.41
2009/2010	95.90	72.99	41.74	875.92
2010/2011	91.67	65.35	43.96	784.17
2011/2012	106.13	77.91	55.64	934.97
2012/2013	122.18	65.35	30.00	784.17
2013/2014	107.14	72.87	46.36	874.42
2014/2015	96.41	75.69	52.80	908.24
2015/2016	96.10	72.07	51.15	864.84
2016/2017	92.10	74.97	58.80	899.59

Table B.3: Streamflow Data - Ellagawa Watershed

Year	Streamflow (mm/Month)			Annual Streamflow (mm/Year)
	Maximum	Mean	Minimum	
1983/1984	718.92	327.29	77.28	3927.46
1984/1985	1134.59	286.27	88.19	3435.18
1985/1986	664.19	251.71	63.09	3020.57
1986/1987	597.90	181.16	27.04	2173.90
1987/1988	632.62	329.32	52.34	3951.87
1988/1989	750.02	254.10	21.27	3049.15
1989/1990	481.30	185.98	19.96	2231.77
1990/1991	588.81	196.61	28.98	2359.29
1991/1992	397.96	211.45	20.77	2537.42
1992/1993	810.49	264.87	38.51	3178.48
1993/1994	688.90	246.36	61.71	2956.35
1994/1995	715.12	288.29	48.47	3459.44
1995/1996	512.25	192.17	37.15	2306.07
1996/1997	508.57	193.55	39.35	2322.57
1997/1998	529.59	237.11	52.19	2845.38
1998/1999	591.95	268.80	71.23	3225.57
1999/2000	437.11	148.50	37.02	1782.02
2000/2001	209.87	95.51	43.42	1146.13
2001/2002	192.84	93.52	27.76	1122.29
2002/2003	751.48	177.36	41.31	2128.38
2003/2004	256.97	109.96	33.87	1319.53
2004/2005	224.19	100.13	40.08	1201.50
2005/2006	306.96	117.97	35.00	1415.60
2006/2007	302.40	114.36	20.42	1372.33
2007/2008	501.46	171.35	39.46	2056.18
2008/2009	198.58	115.08	20.95	1380.98
2009/2010	515.07	133.01	29.55	1596.11
2010/2011	255.29	145.33	44.79	1743.94
2011/2012	125.10	61.40	27.55	736.84
2012/2013	359.88	144.48	47.19	1733.72
2013/2014	430.24	110.98	26.02	1331.76
2014/2015	351.47	117.38	40.25	1408.53
2015/2016	631.21	167.65	29.70	1676.51
2016/2017	566.71	153.11	14.82	1837.34

APPENDIX C – Data Checking

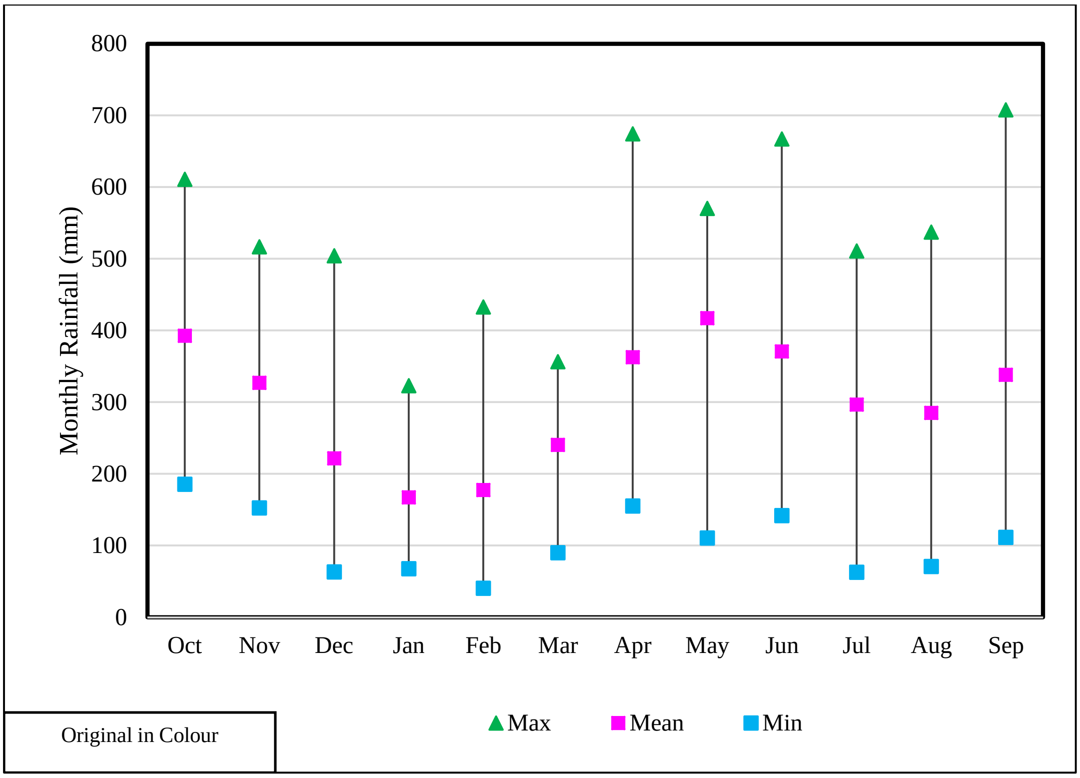


Figure C.1: Maximum, Mean and Minimum Variation of Thiessen Average Rainfall (1983/84-2016/17)

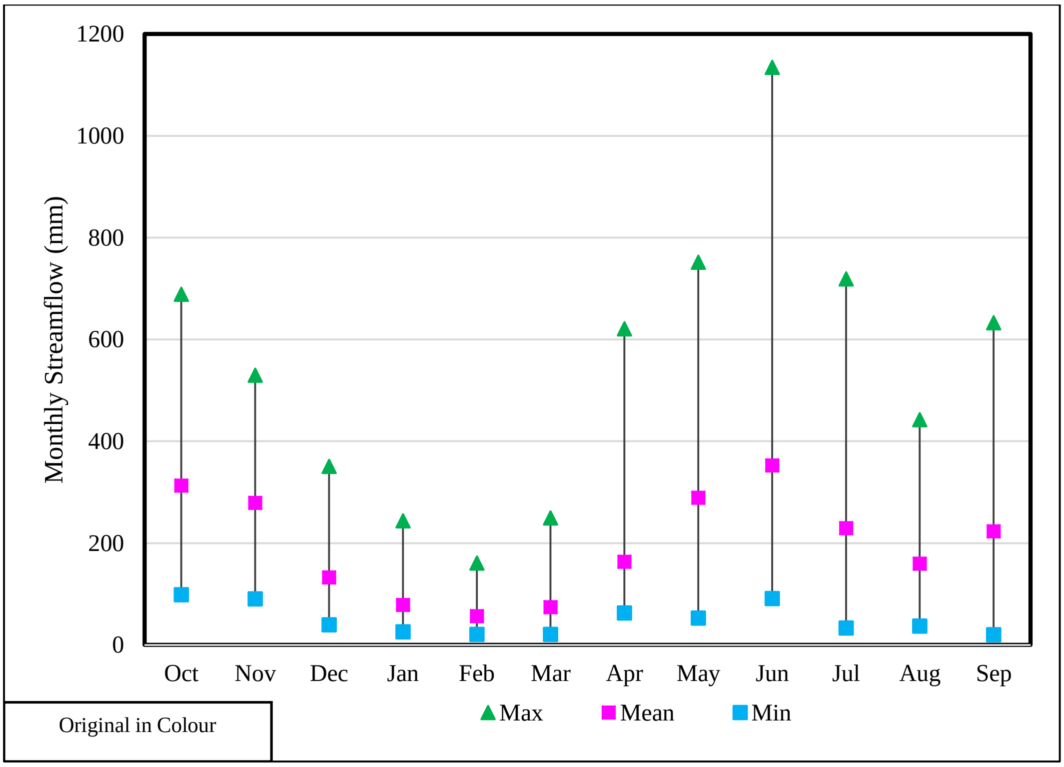


Figure C.2: Maximum, Mean and Minimum Variation of Thiessen Average Streamflow (1983/84-2016/17)

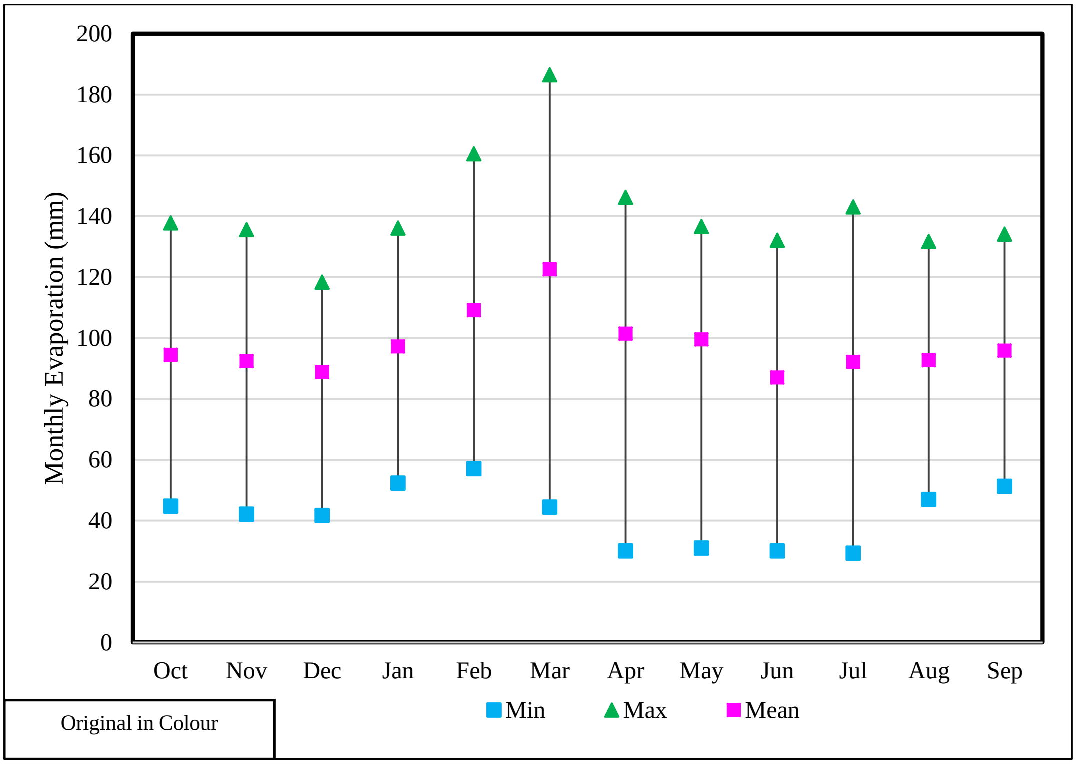


Figure C-3: Maximum, Mean and Minimum Variation of Evaporation (1983/84-2016/17)

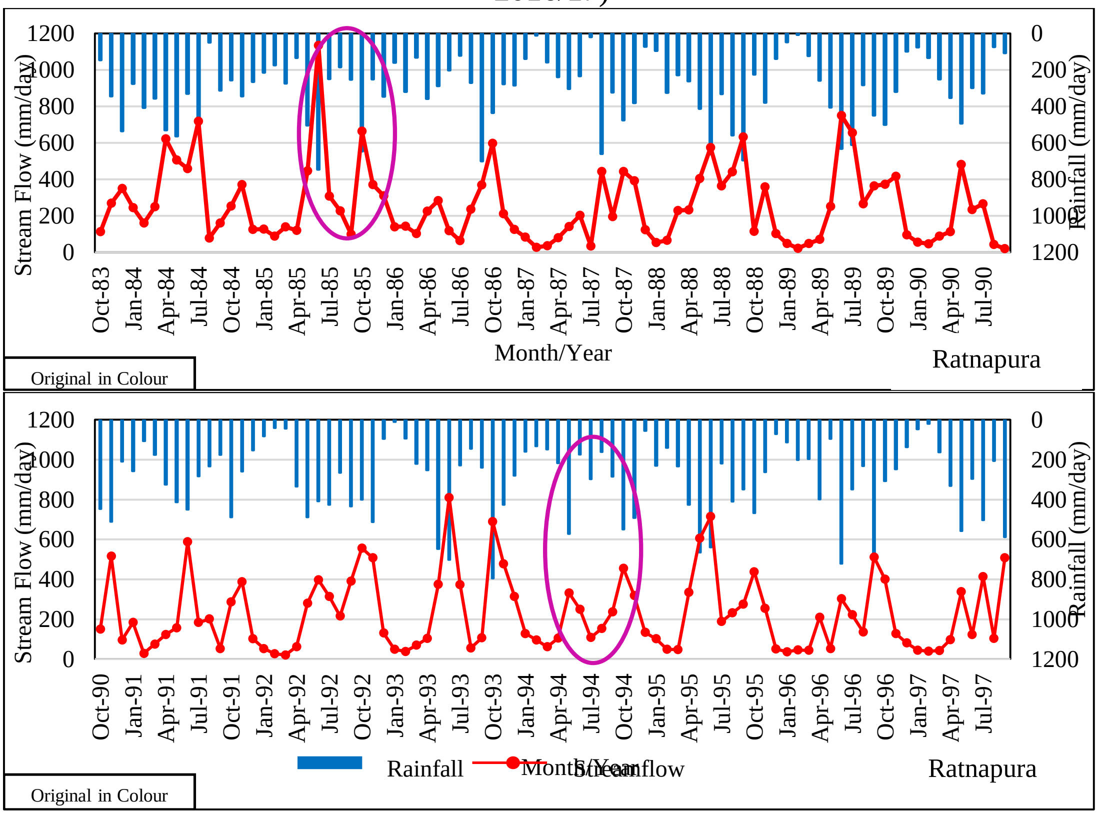


Figure C.4-C.5: Ellagawa monthly streamflow response with Ratnapura Rainfall Station monthly data (1983/1984 – 1996/1997)

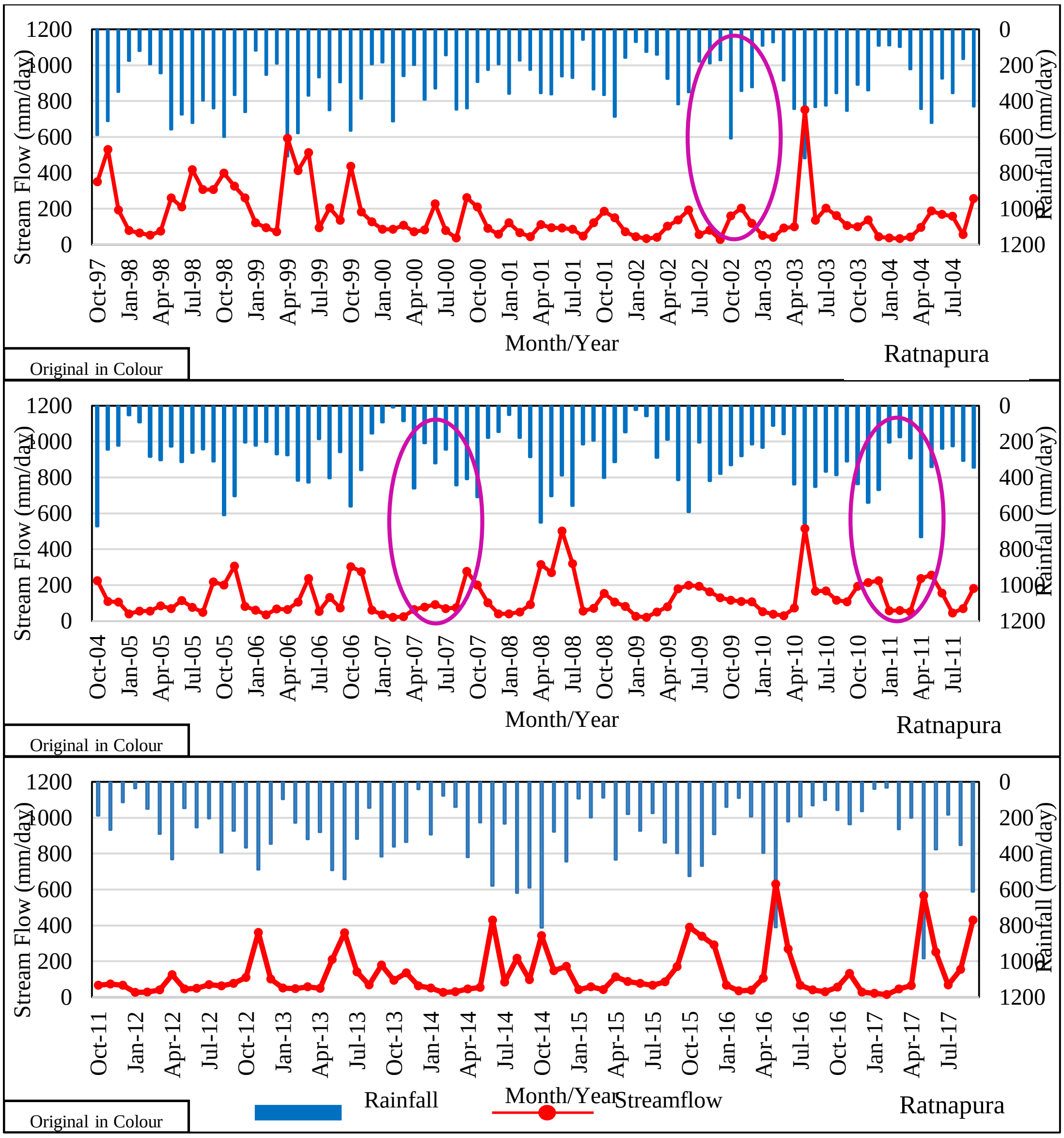


Figure C.6-C.8: Ellagawa monthly streamflow response with Ratnapura Rainfall Station monthly data (1997/1998 – 2016/2017)

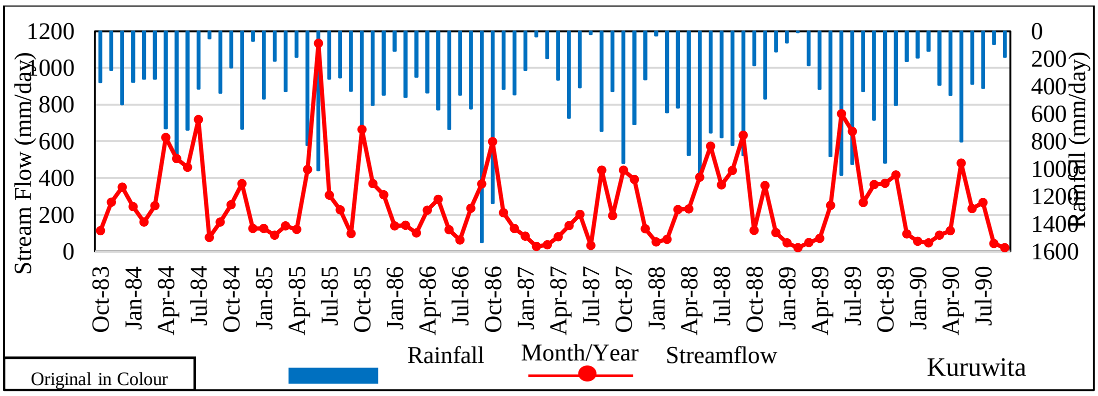


Figure C.9: Ellagawa monthly streamflow response with Kuruwita Rainfall Station monthly data (1983/1984 – 1989/1990)

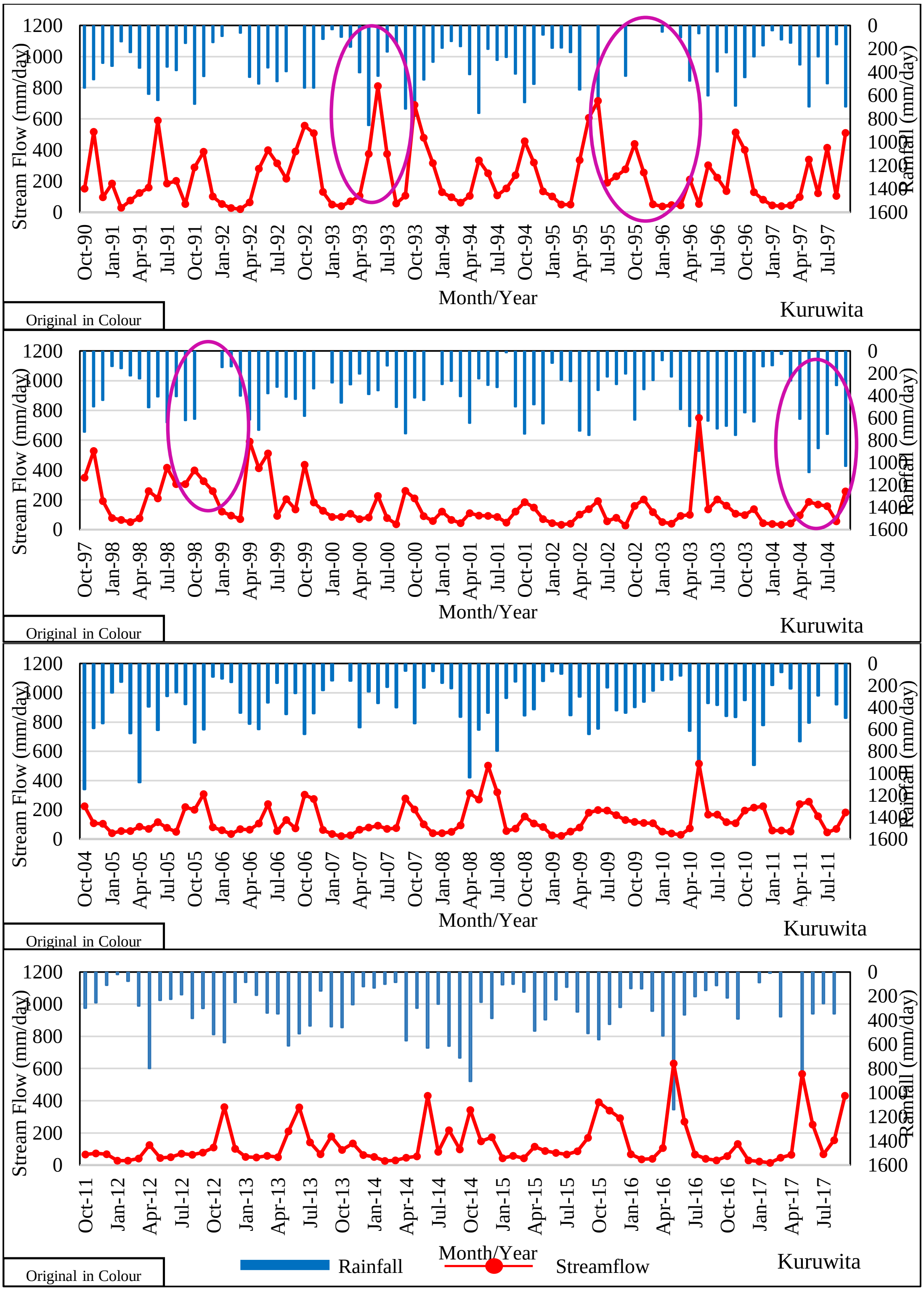


Figure C.10-C.13: Ellagawa monthly streamflow response with Kuruwita Rainfall Station monthly data (1990/1991 – 2016/2017)

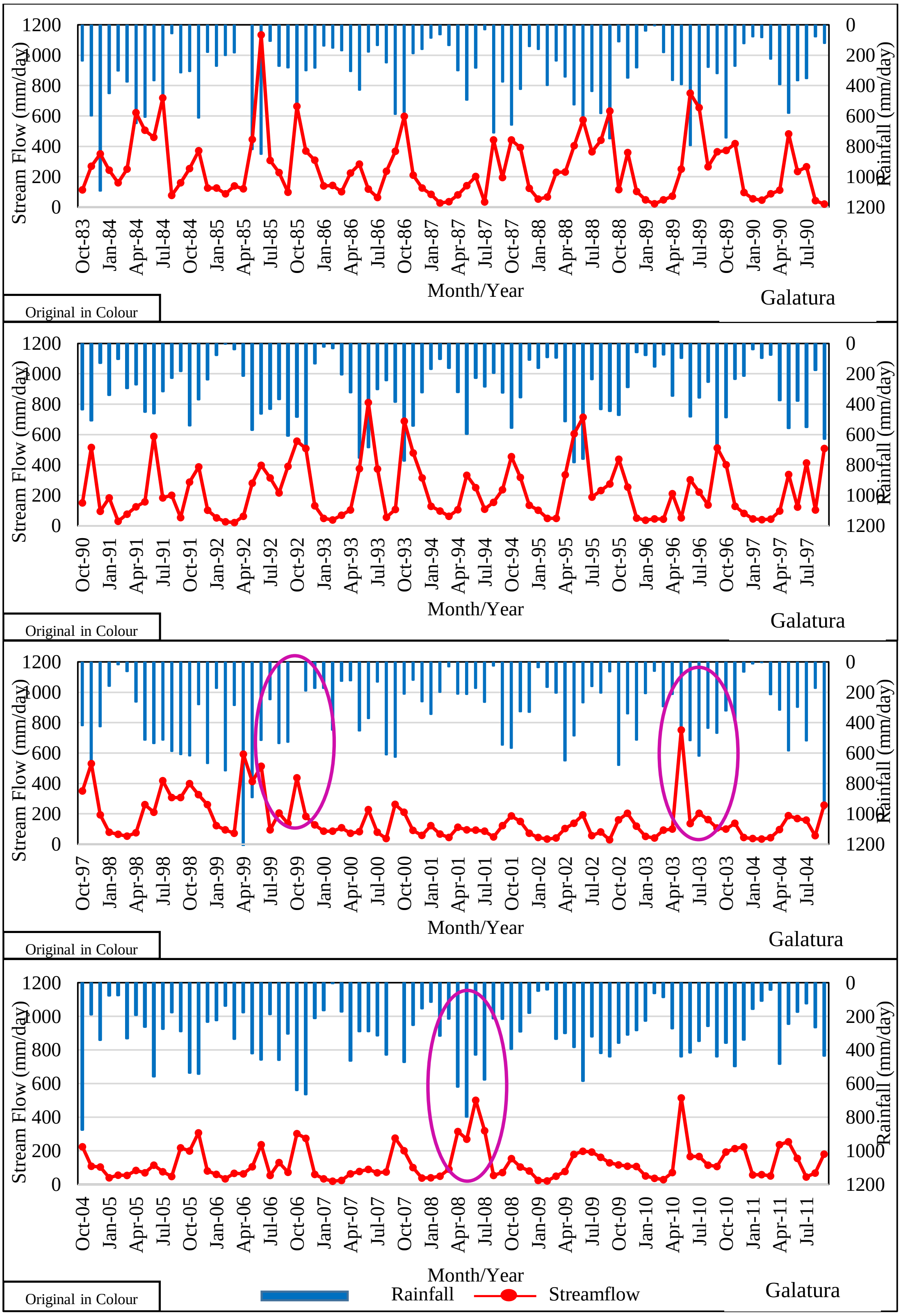


Figure C.14-C.17: Ellagawa monthly streamflow response with Galatura Rainfall Station monthly data (1983/1984 – 2010/2011)

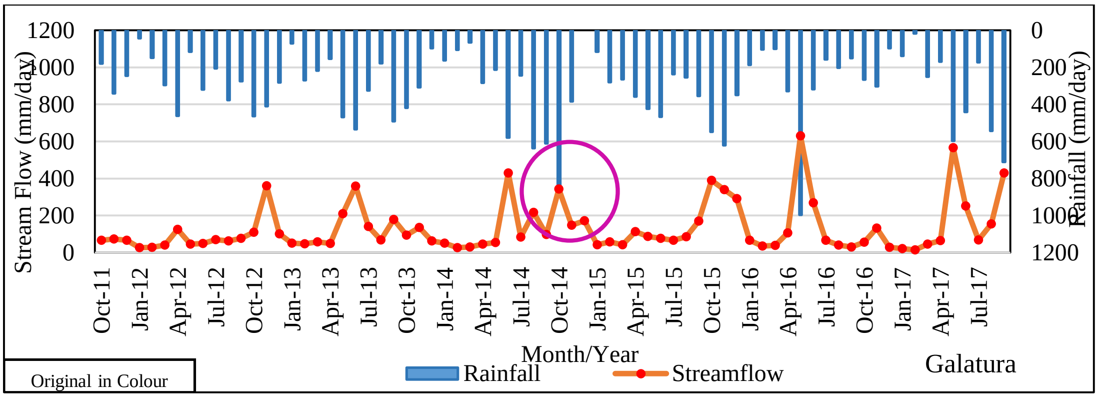


Figure C.18: Ellagawa monthly streamflow response with Galatura Rainfall Station monthly data (2011/2012 – 2016/2017)

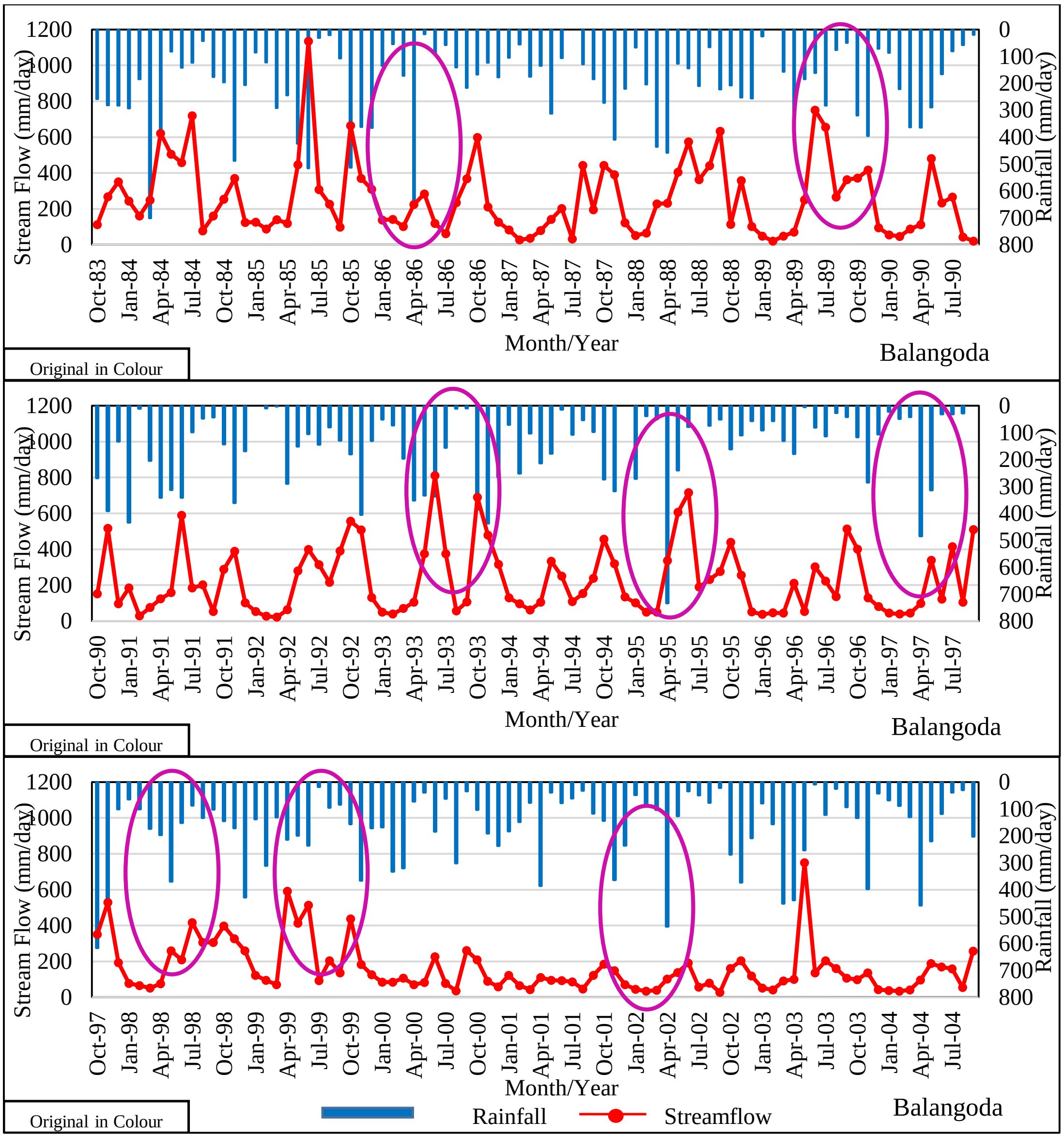


Figure C.19-C.21: Ellagawa monthly streamflow response with Balangoda Rainfall Station monthly data (1983/1984 – 2003/2004)

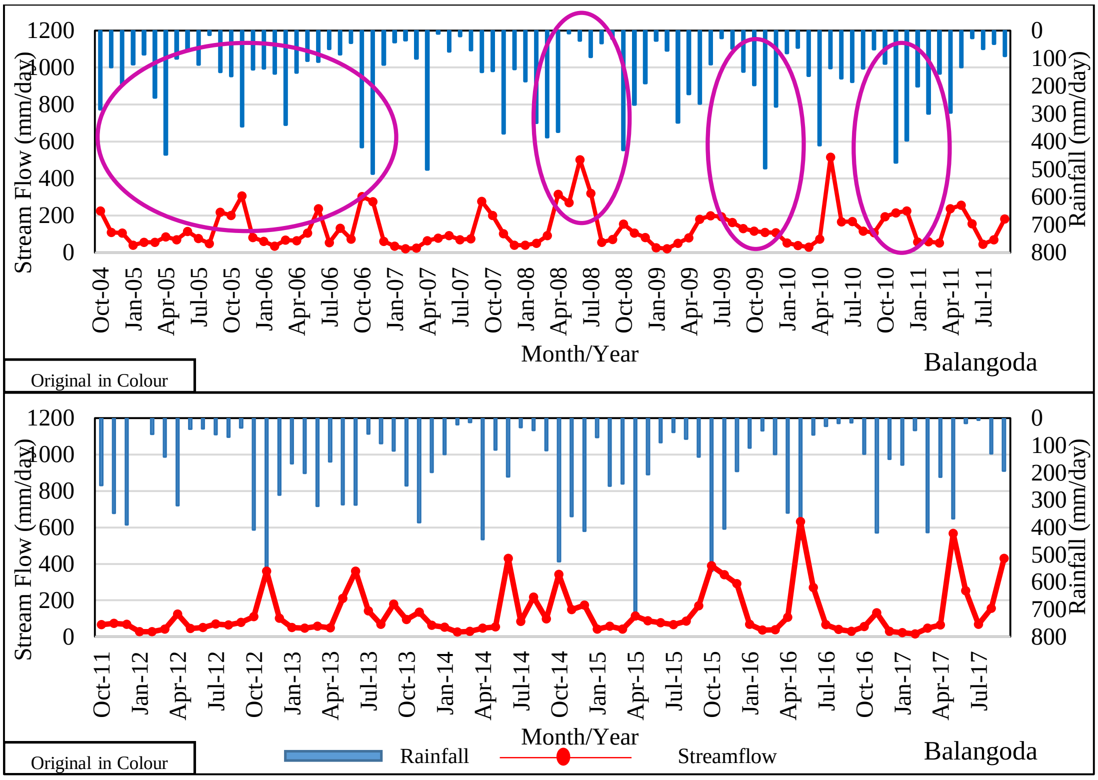


Figure C.22-C.23: Ellagawa monthly streamflow response with Balangoda Rainfall Station monthly data (2004/2005 – 2016/2017)

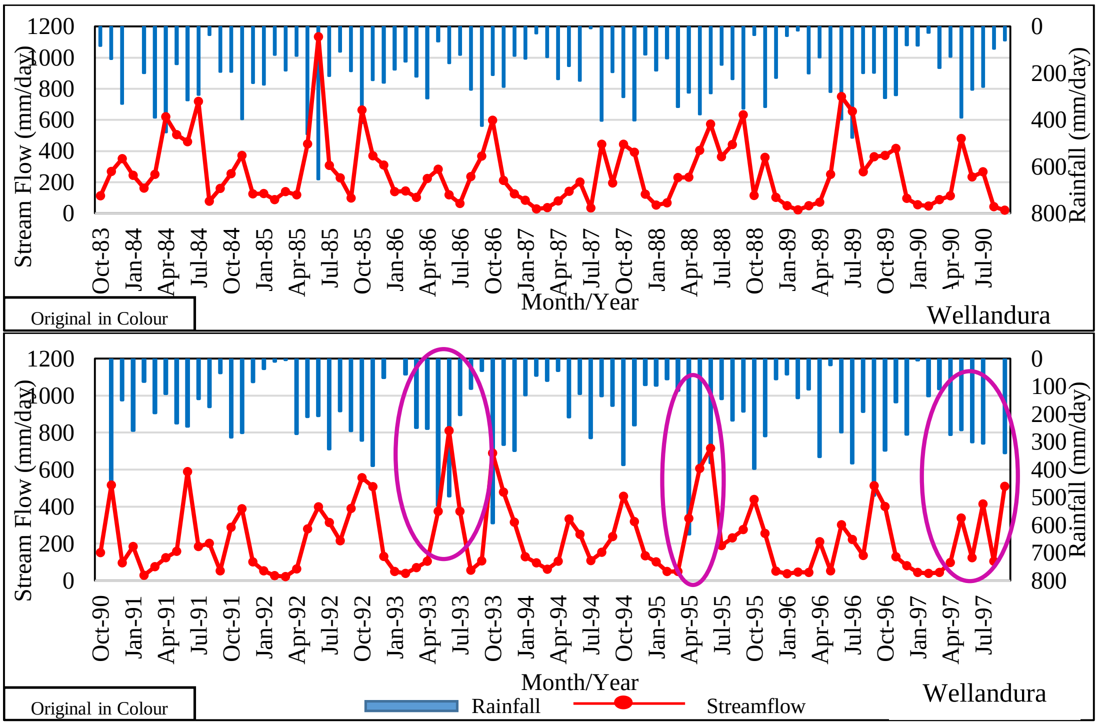


Figure C.24-C.25: Ellagawa monthly streamflow response with Wellandura Rainfall Station monthly data (1983/1984 – 1996/1997)

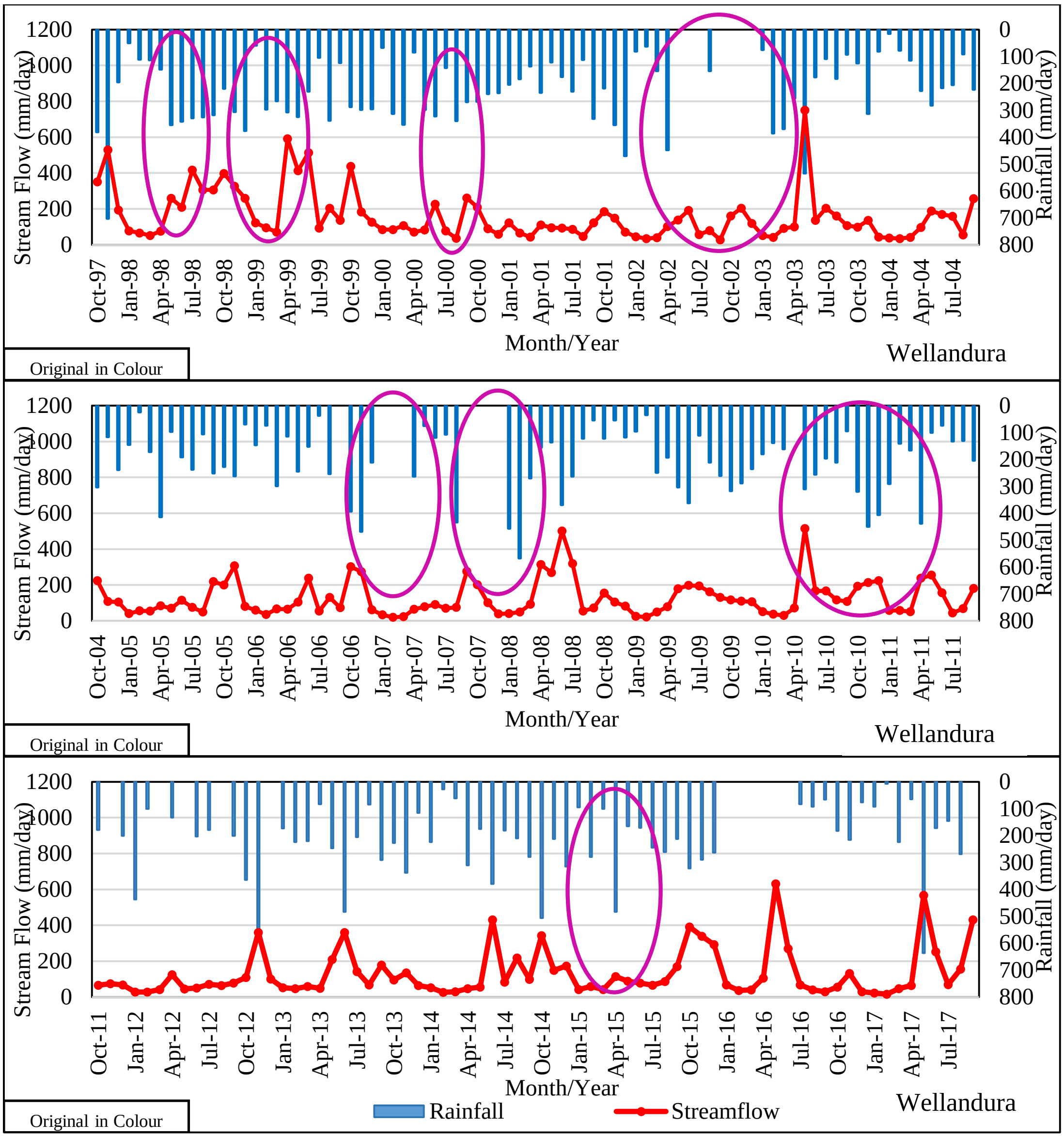


Figure C.26-C.28: Ellagawa monthly streamflow response with Wellandura Rainfall Station monthly data (1997/1998 – 2016/2017)

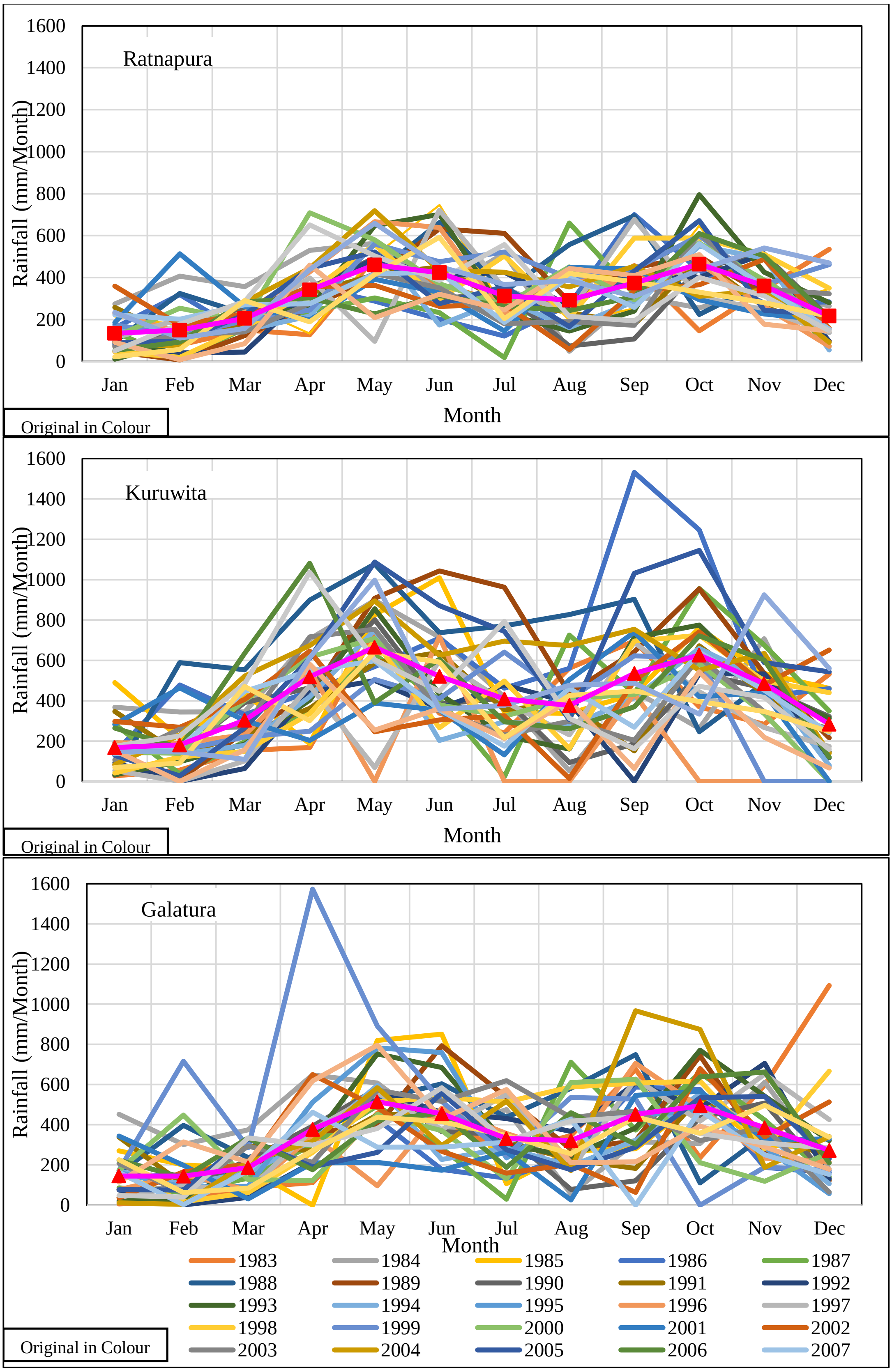


Figure C.29-C.31-: Monthly Rainfall Comparison – Ellagawa Watershed

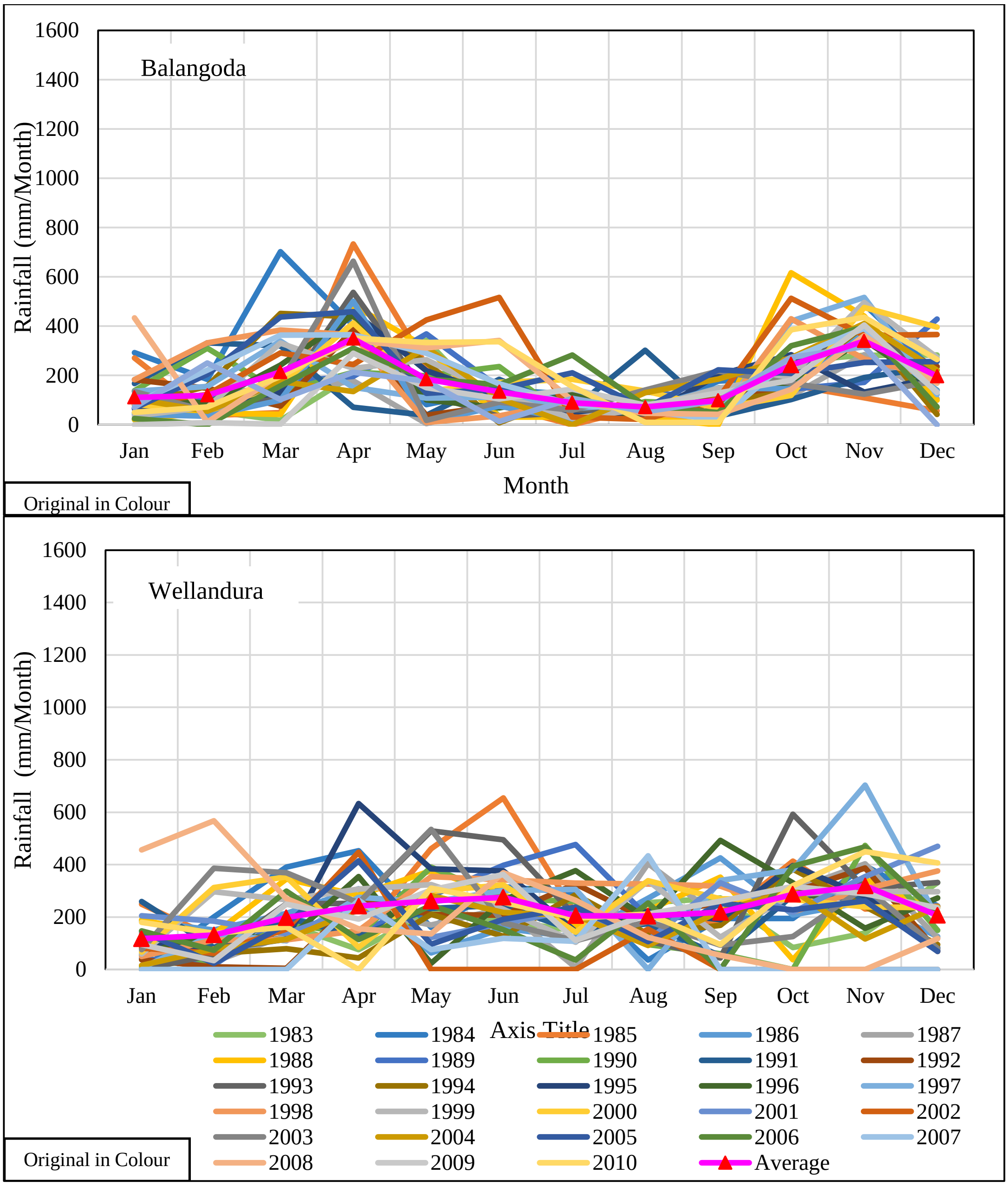


Figure C.32-C.33-: Monthly Rainfall Comparison – Ellagawa Watershed

Table C.1: Annual Water Balance - Ellagawa Watershed

Water Year	Thiessen Annual Average Rainfall (mm)	Streamflow (mm)	Annual Water Balance (AWB) (mm)	Pan Evaporation (EP) (mm)	Evapotranspiration (mm) (k*EP)	AWB/EP	ET/EP	Runoff Coefficient
1983/84	4284.65	3927.46	357	1295.17	1036.1	0.3	0.8	0.92
1984/85	3864.03	3435.18	429	1324.98	1060.0	0.3	0.8	0.89
1985/86	4090.04	3020.57	1069	1354.35	1083.5	0.8	0.8	0.74
1986/87	3219.57	2173.90	1046	1536.65	1229.3	0.7	0.8	0.68
1987/88	4957.27	3951.87	1005	1379.36	1103.5	0.7	0.8	0.80
1988/89	3621.82	3049.15	573	1472.07	1177.7	0.4	0.8	0.84
1989/90	3197.08	2231.77	965	1393.24	1114.6	0.7	0.8	0.70
1990/91	3447.19	2359.29	1088	1368.48	1094.8	0.8	0.8	0.68
1991/92	3161.34	2537.42	624	1467.23	1173.8	0.4	0.8	0.80
1992/93	3479.12	3178.48	301	1296.62	1037.3	0.2	0.8	0.91
1993/94	3448.13	2956.35	492	1218.11	974.5	0.4	0.8	0.86
1994/95	3985.13	3459.44	526	1243.15	994.5	0.4	0.8	0.87
1995/96	3140.35	2306.07	834	1235.48	988.4	0.7	0.8	0.73
1996/97	3207.91	2322.57	885	1294.88	1035.9	0.7	0.8	0.72
1997/98	4217.05	2845.38	1372	1244.13	995.3	1.1	0.8	0.67

Table C.1: Annual Water Balance - Ellagawa Watershed (Continued)

Water Year	Thiessen Annual Average Rainfall (mm)	Streamflow (mm)	Annual Water Balance (AWB) (mm)	Pan Evaporation (EP) (mm)	Evapotranspiration (mm) (k*EP)	AWB/EP	ET/EP	Runoff Coefficient
1998/99	4433.43	3225.57	1208	1301.87	1041.5	0.9	0.8	0.73
1999/00	3722.34	1782.02	1940	1186.61	949.3	1.6	0.8	0.48
2000/01	2962.31	1146.13	1816	1165.20	932.2	1.6	0.8	0.39
2001/02	3239.88	1122.29	2118	1090.86	872.7	1.9	0.8	0.35
2002/03	4471.15	2128.38	2343	1054.20	843.4	2.2	0.8	0.48
2003/04	3607.66	1319.53	2288	1058.56	846.8	2.2	0.8	0.37
2004/05	3604.74	1201.50	2403	1087.77	870.2	2.2	0.8	0.33
2005/06	3449.70	1415.60	2034	964.89	771.9	2.1	0.8	0.41
2006/07	3122.05	1372.33	1750	929.53	743.6	1.9	0.8	0.44
2007/08	3843.06	2056.18	1787	791.02	632.8	2.3	0.8	0.54
2008/09	3350.44	1380.98	1969	902.41	721.9	2.2	0.8	0.41
2009/10	3625.83	1596.11	2030	875.92	700.7	2.3	0.8	0.44
2010/11	3752.90	1743.94	2009	784.17	627.3	2.6	0.8	0.46
2011/12	2746.94	736.84	2010	934.97	748.0	2.1	0.8	0.27
2012/13	3837.94	1733.72	2104	1022.84	818.3	2.1	0.8	0.45

Table C.1: Annual Water Balance - Ellagawa Watershed (Continued)

Water Year	Thiessen Annual Average Rainfall (mm)	Streamflow (mm)	Annual Water Balance (AWB) (mm)	Pan Evaporation (EP) (mm)	Evapotranspiration (mm) (k*EP)	AWB/EP	ET/EP	Runoff Coefficient
2013/14	3453.51	1331.33	2122	874.42	699.5	2.4	0.8	0.39
2014/15	3608.21	1407.51	2201	908.24	726.6	2.4	0.8	0.39
2015/16	3435.96	2307.21	1129	864.84	691.9	1.3	0.8	0.67
2016/17	3276.78	1837.34	1439	899.59	719.7	1.6	0.8	0.56

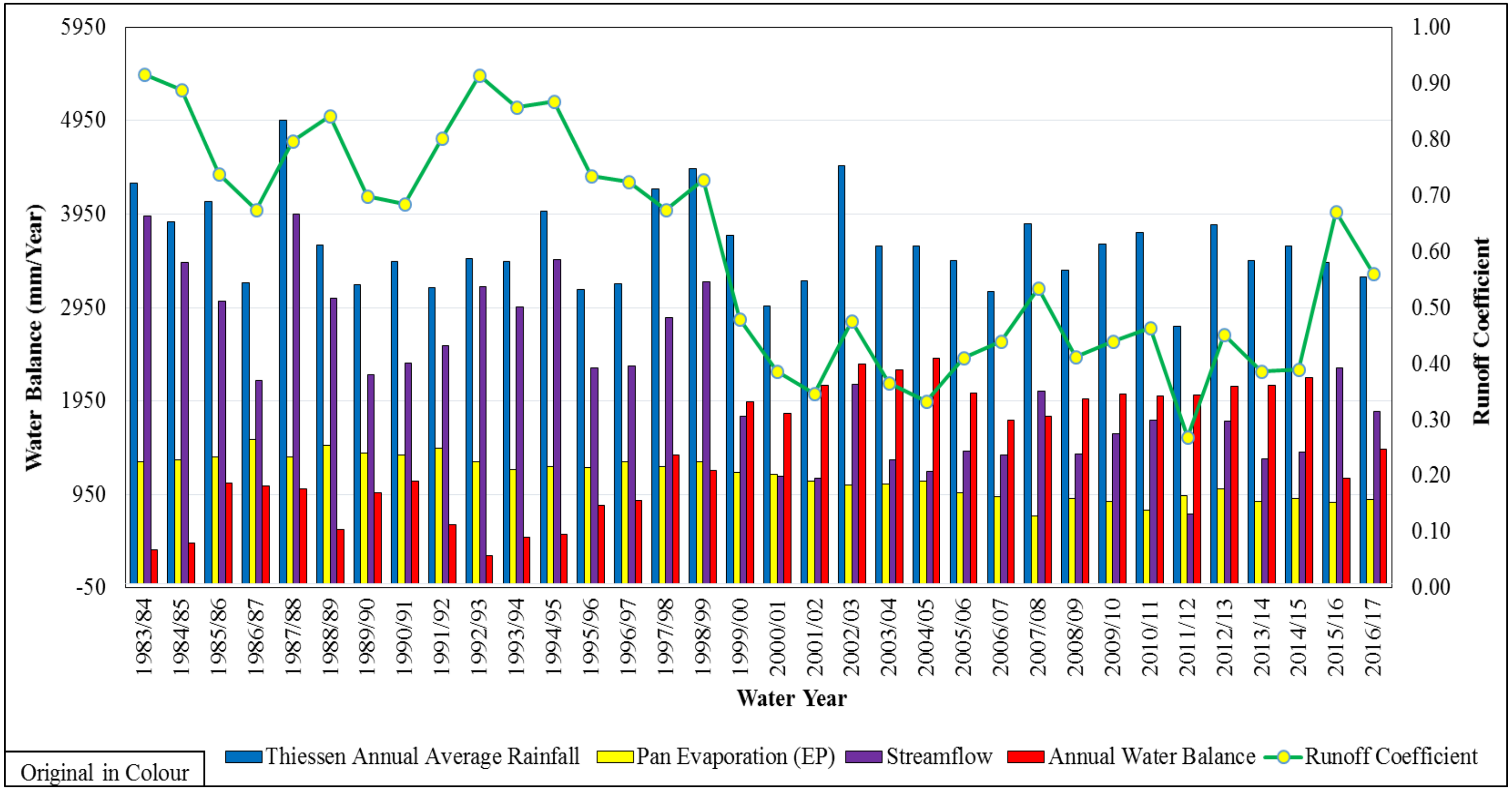


Figure C.34: Annual Water Balance of Ellagawa Watershed

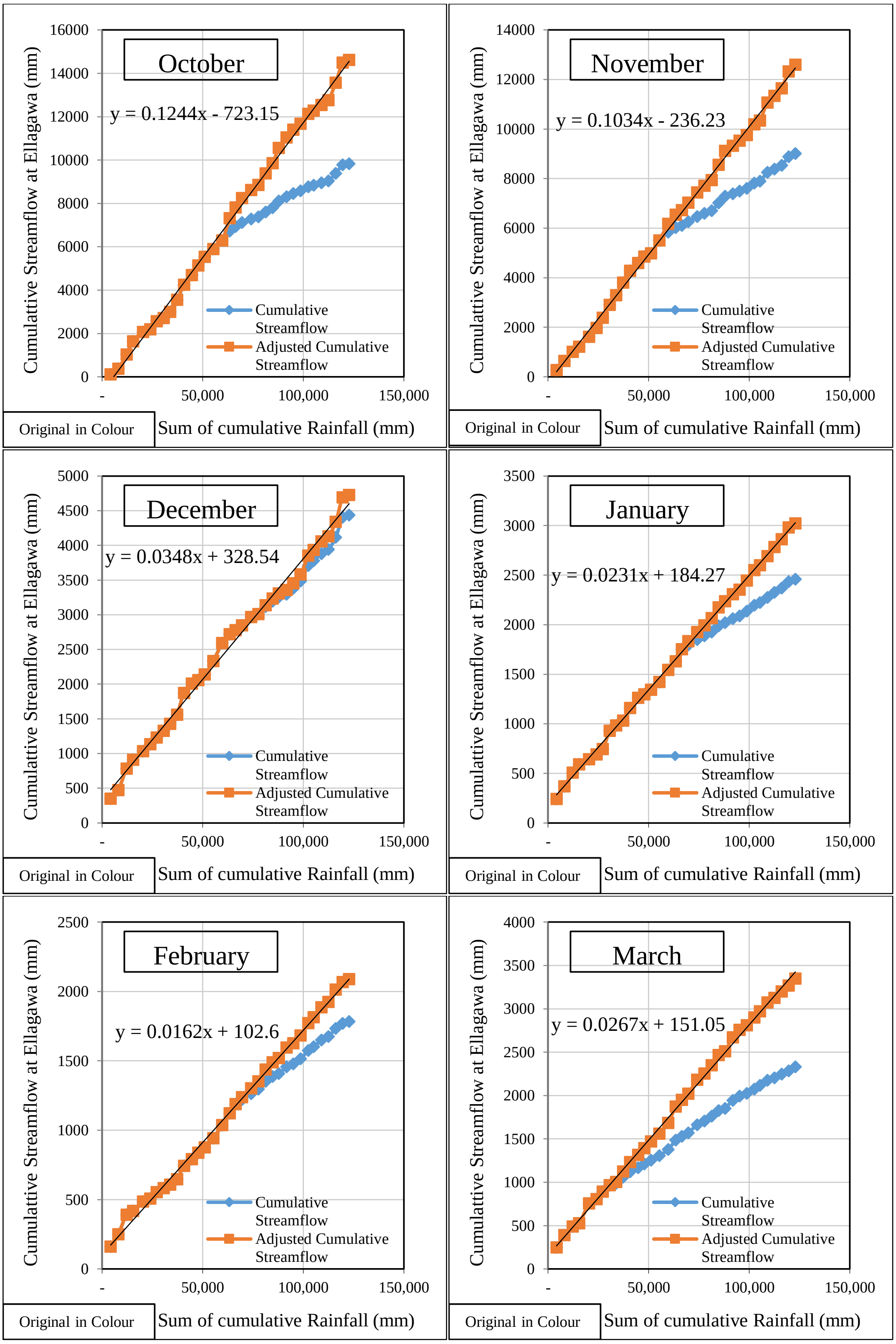


Figure C.35-C.40: Monthly Double Mass Rectification Regression Curves with entire Dataset (October–March)

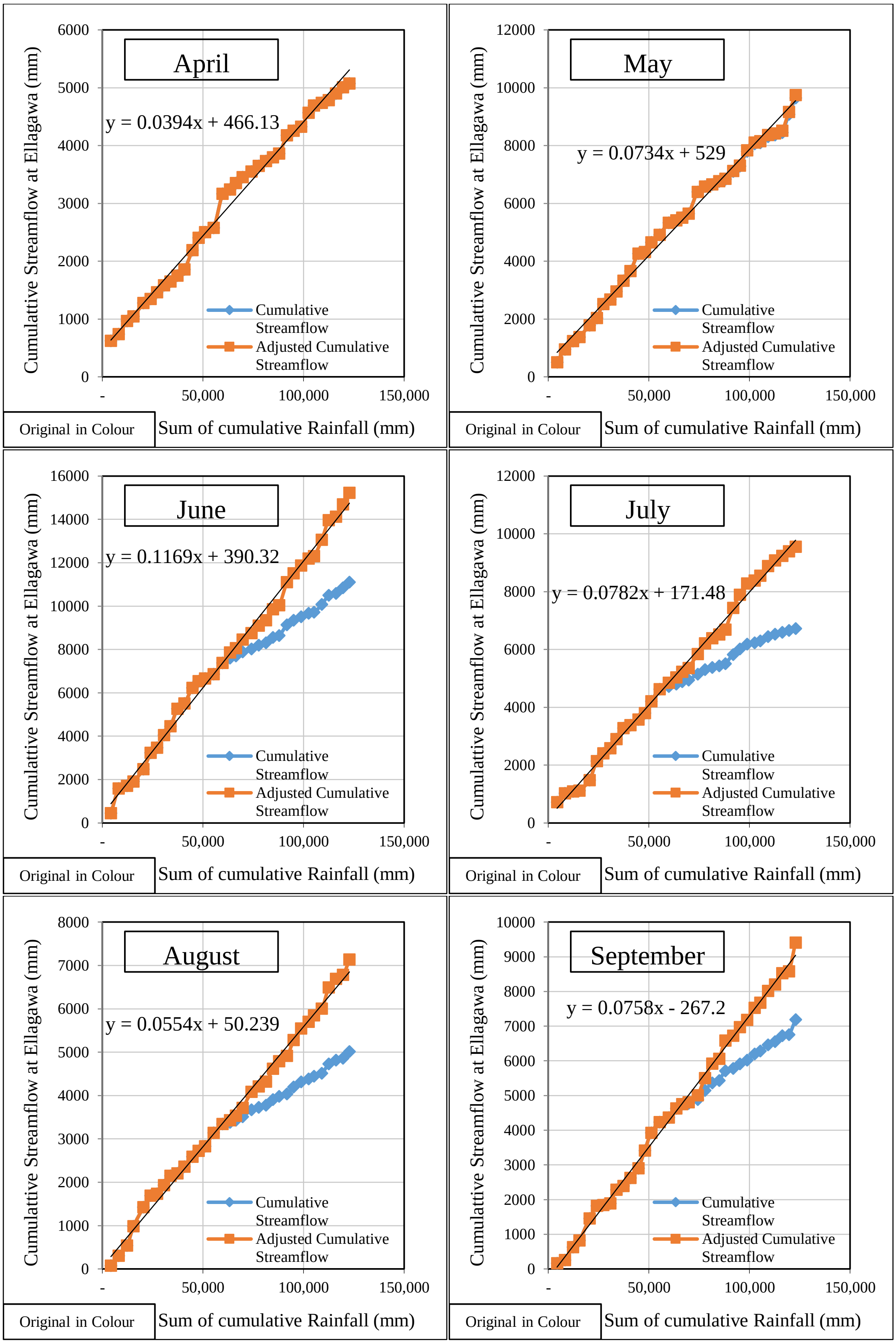


Figure C.41-C.46: Monthly Double Mass Rectification Regression Curves with entire Dataset (April–September)

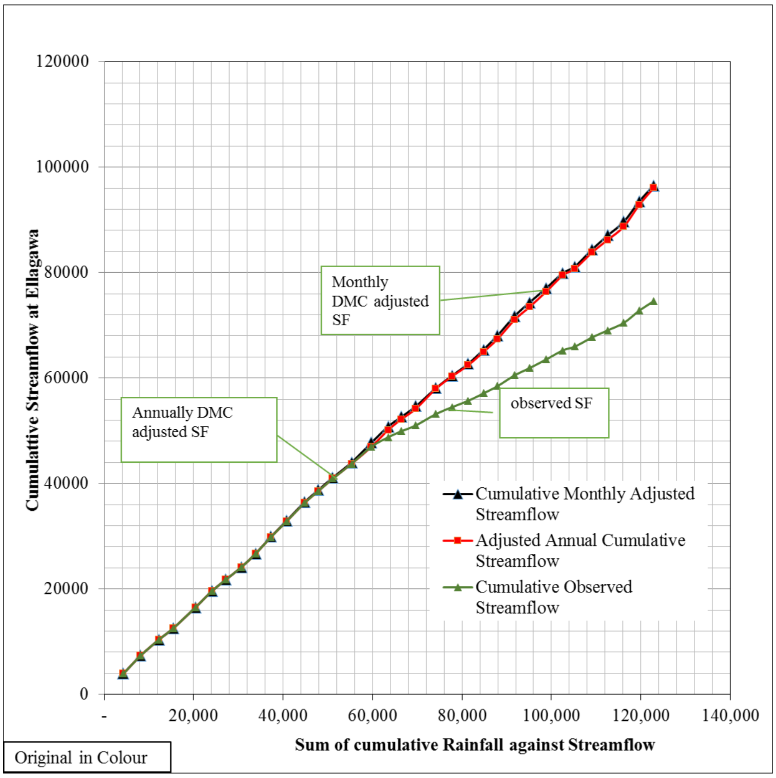


Figure C.47: Comparison of Annual and Monthly Data rectification with the entire dataset

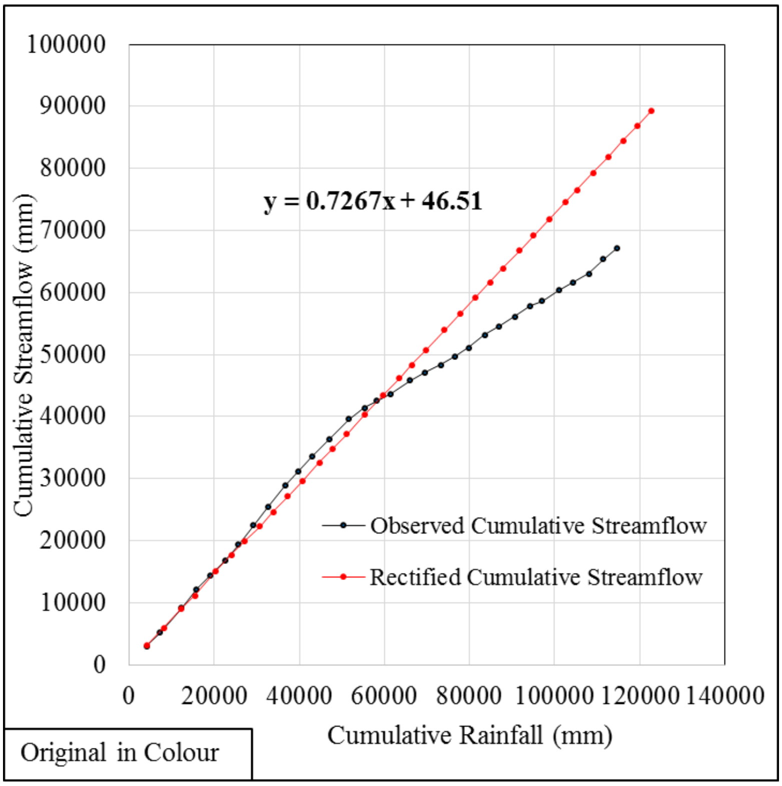


Figure C.48: Double Mass Curve for Observed Streamflow Data (Annual)

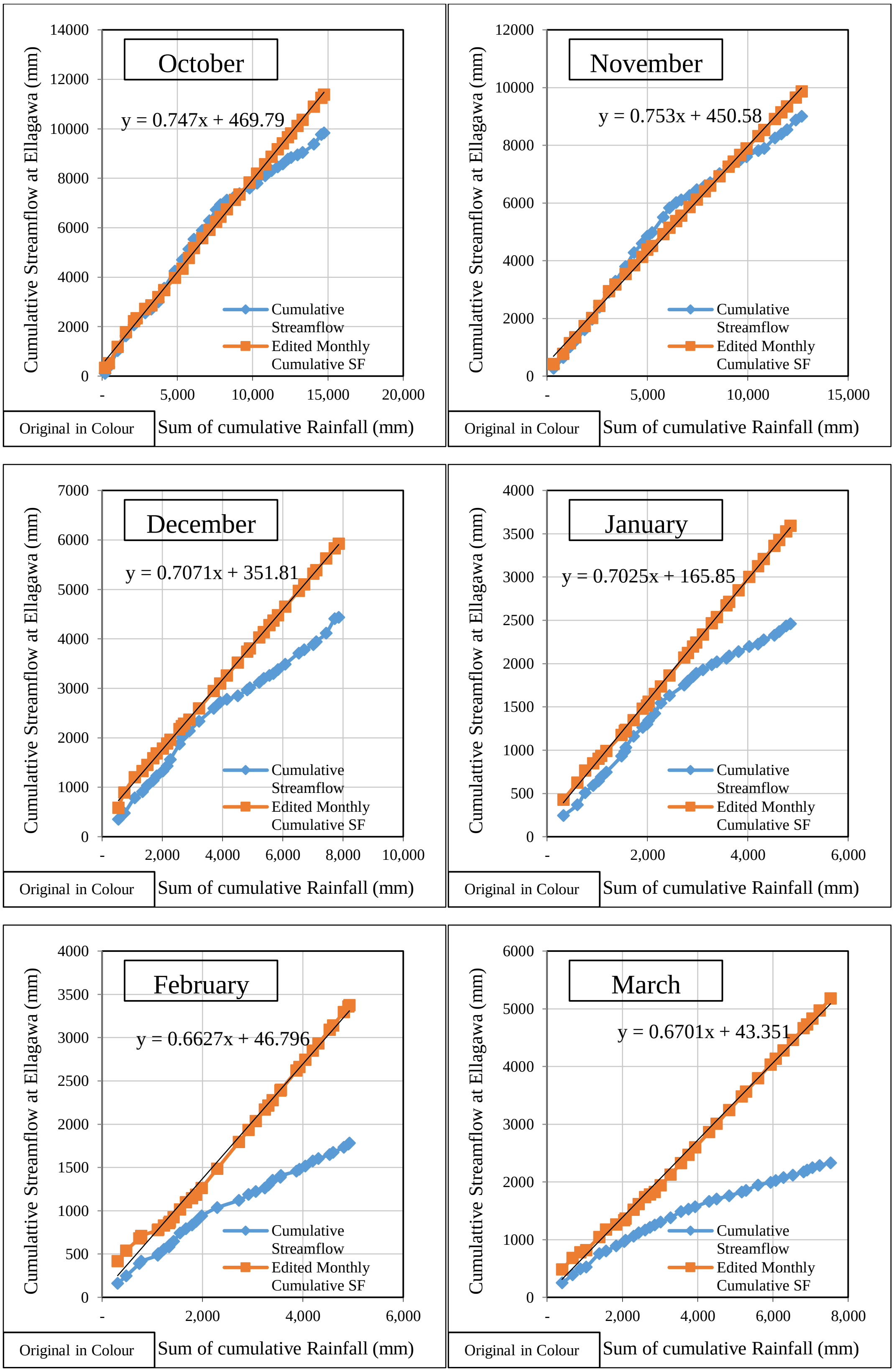


Figure C.49-C.54: Monthly Double Mass Rectification Regression Curves with selected Base dataset (October–March)

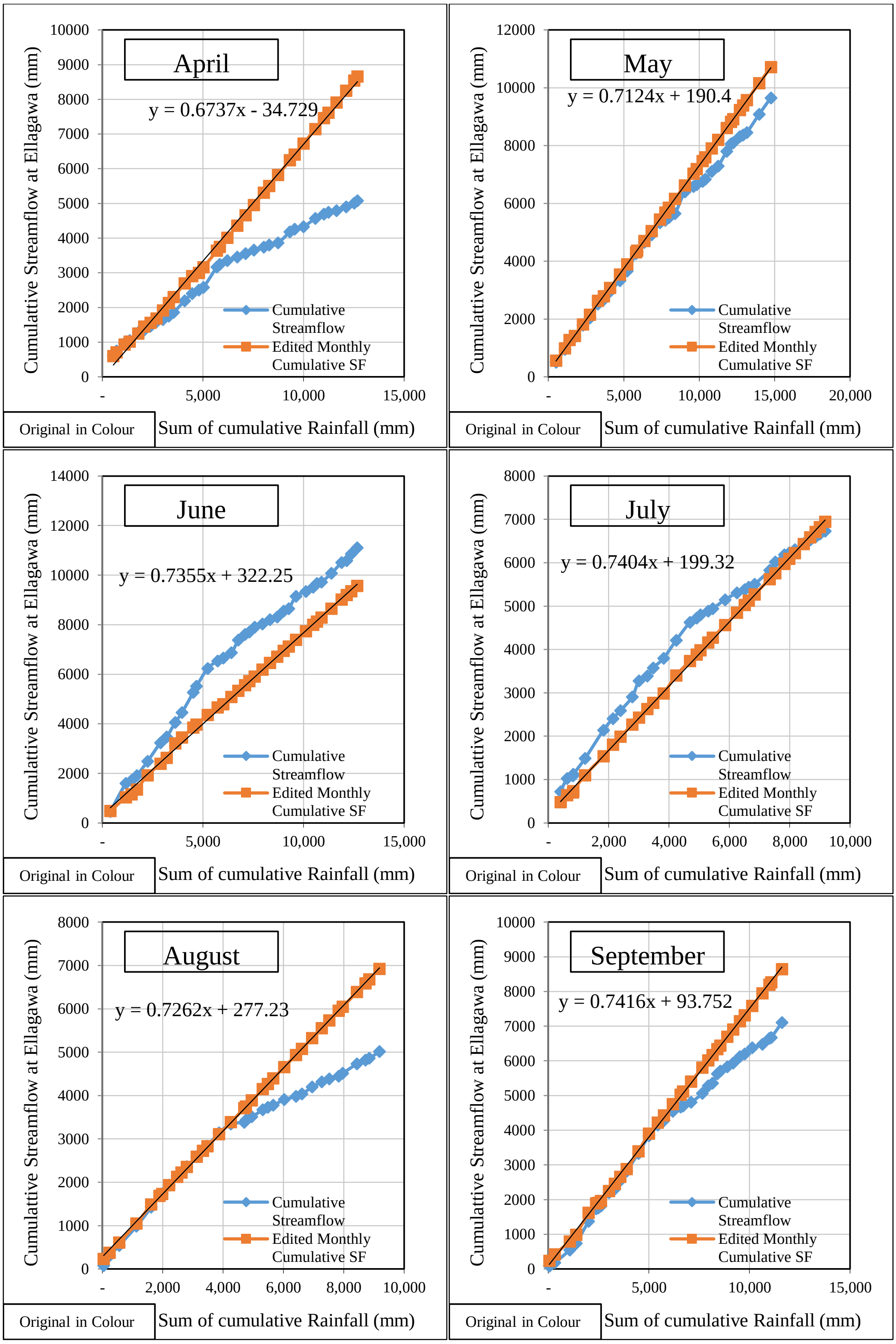


Figure C.55-C.60: Monthly Double Mass Rectification Regression Curves with selected Base dataset (April–September)

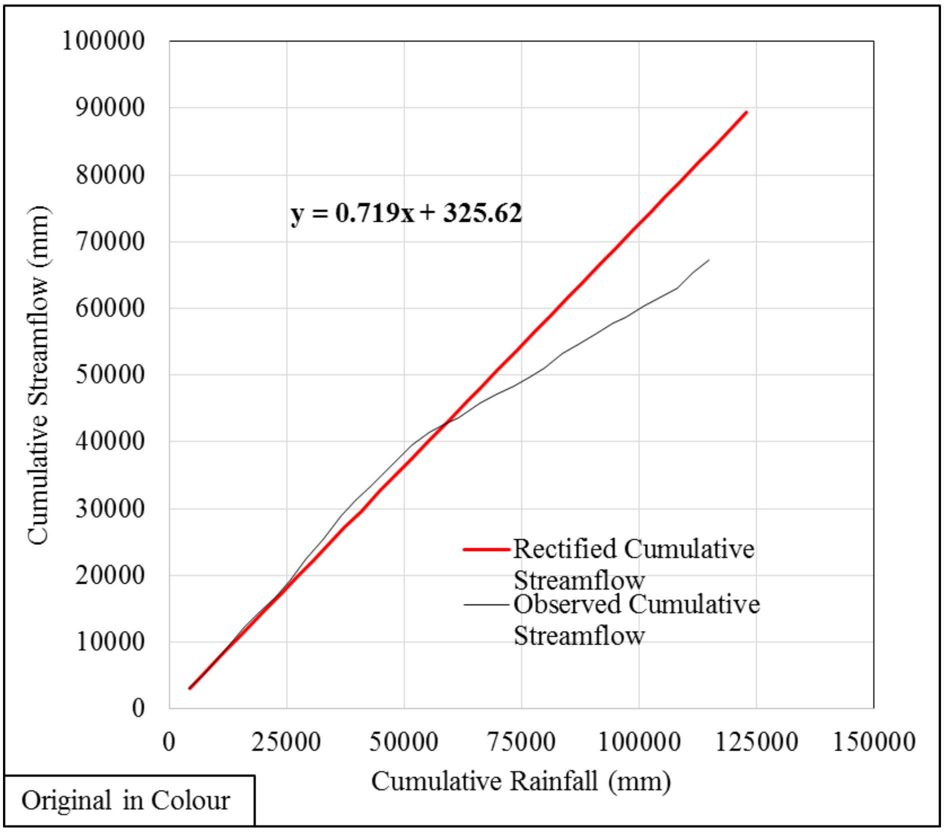


Figure C.61: Double Mass Curve for Observed Streamflow Data (Monthly)

APPENDIX D.1 – Hydrograph Comparison

Hydrograph Comparison – 10 Year Datasets – Calibration (Set 1 – 4)

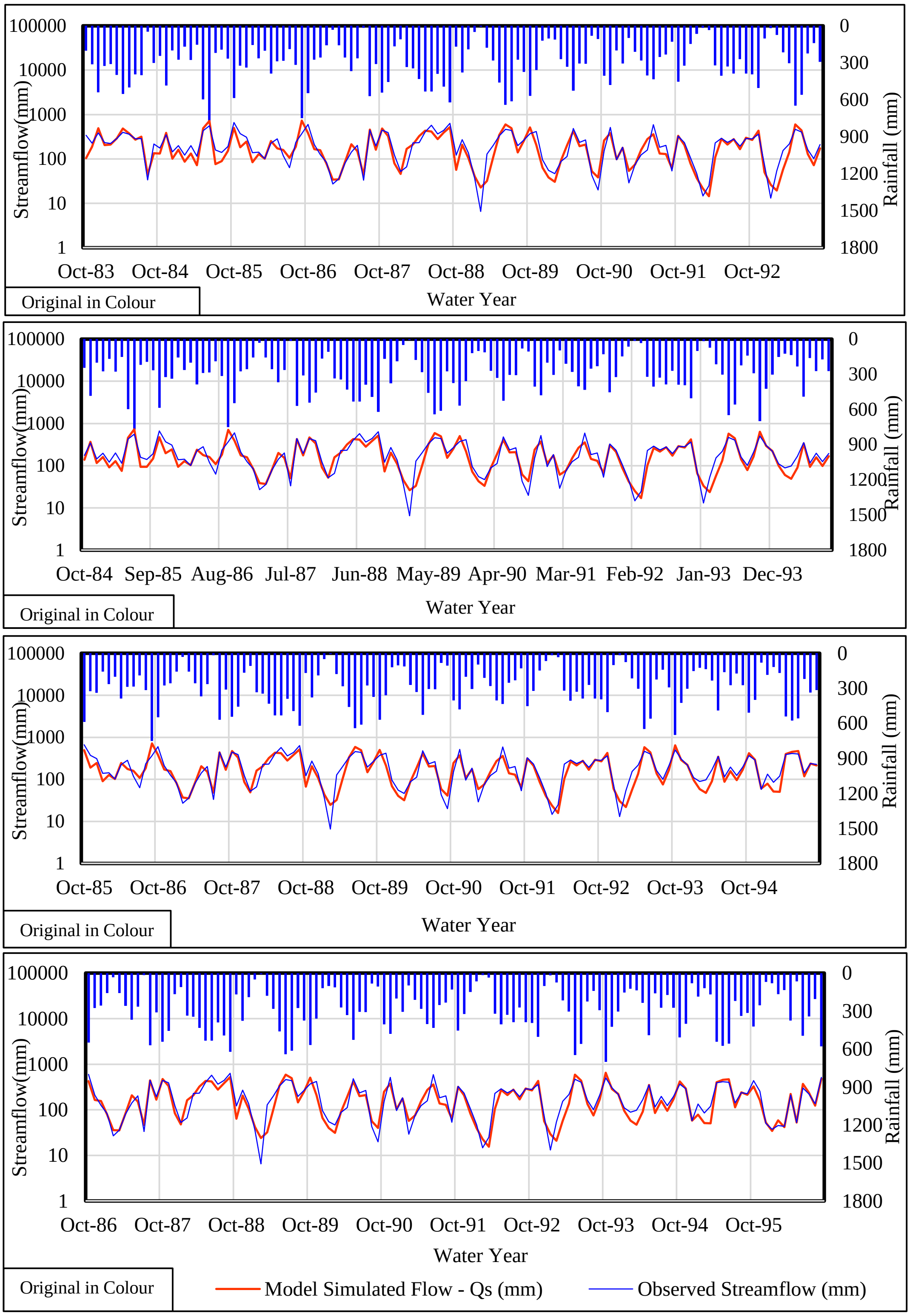


Figure D.1-D.4: Hydrographs of Observed and Simulated Flow Hydrographs of 10 year Datasets (1983/84-1992/93 to 1986/87-1996/97)

Hydrograph Comparison – 10 Year Datasets – Calibration (Set 5 – 8)

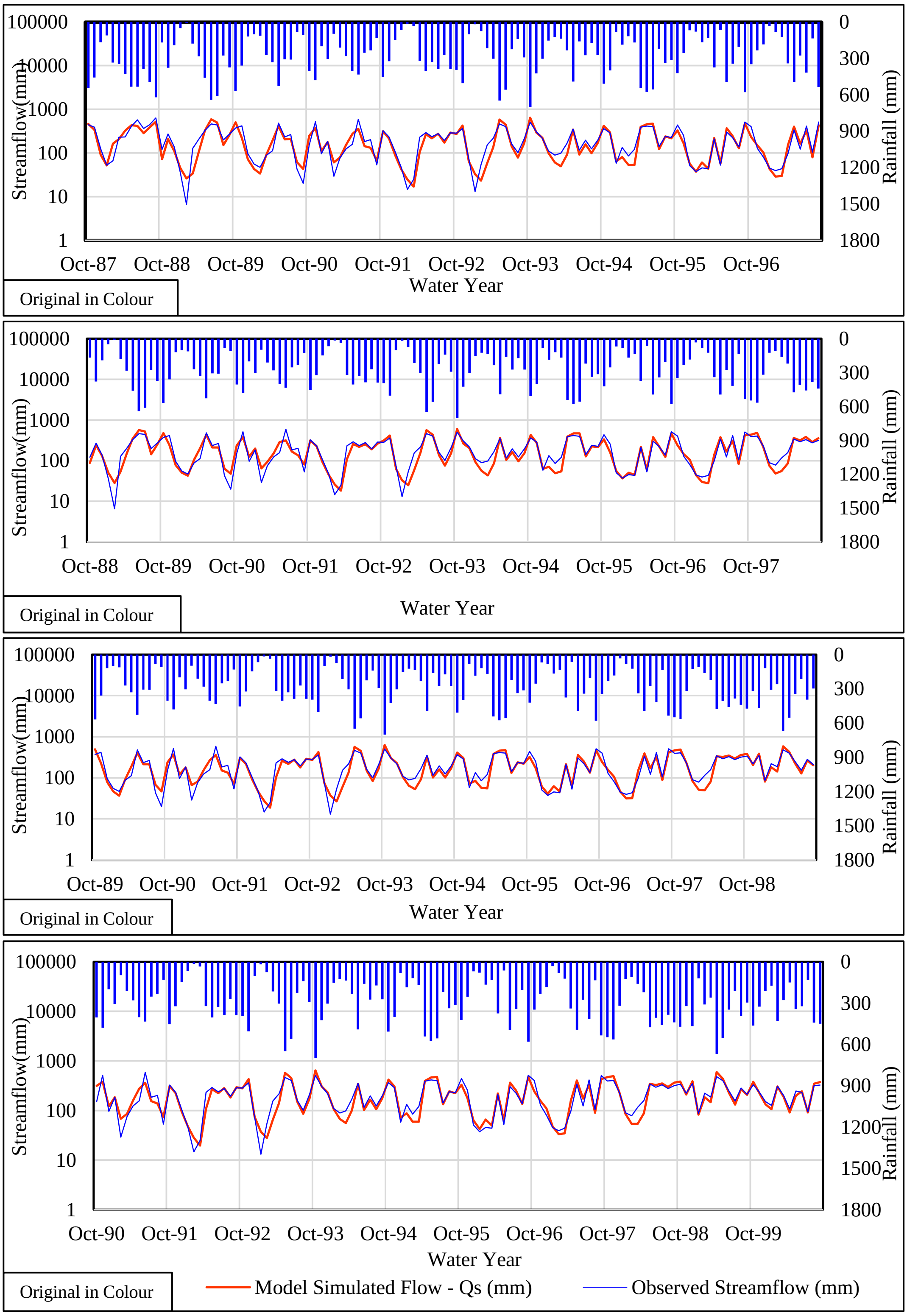


Figure D.5-D.8: Hydrographs of Observed and Simulated Flow Hydrographs of 10 Year Datasets (1987/88-1997/98 to 1990/91-1999/2000)

Hydrograph Comparison – 10 Year Datasets – Calibration (Set 9 – 12)

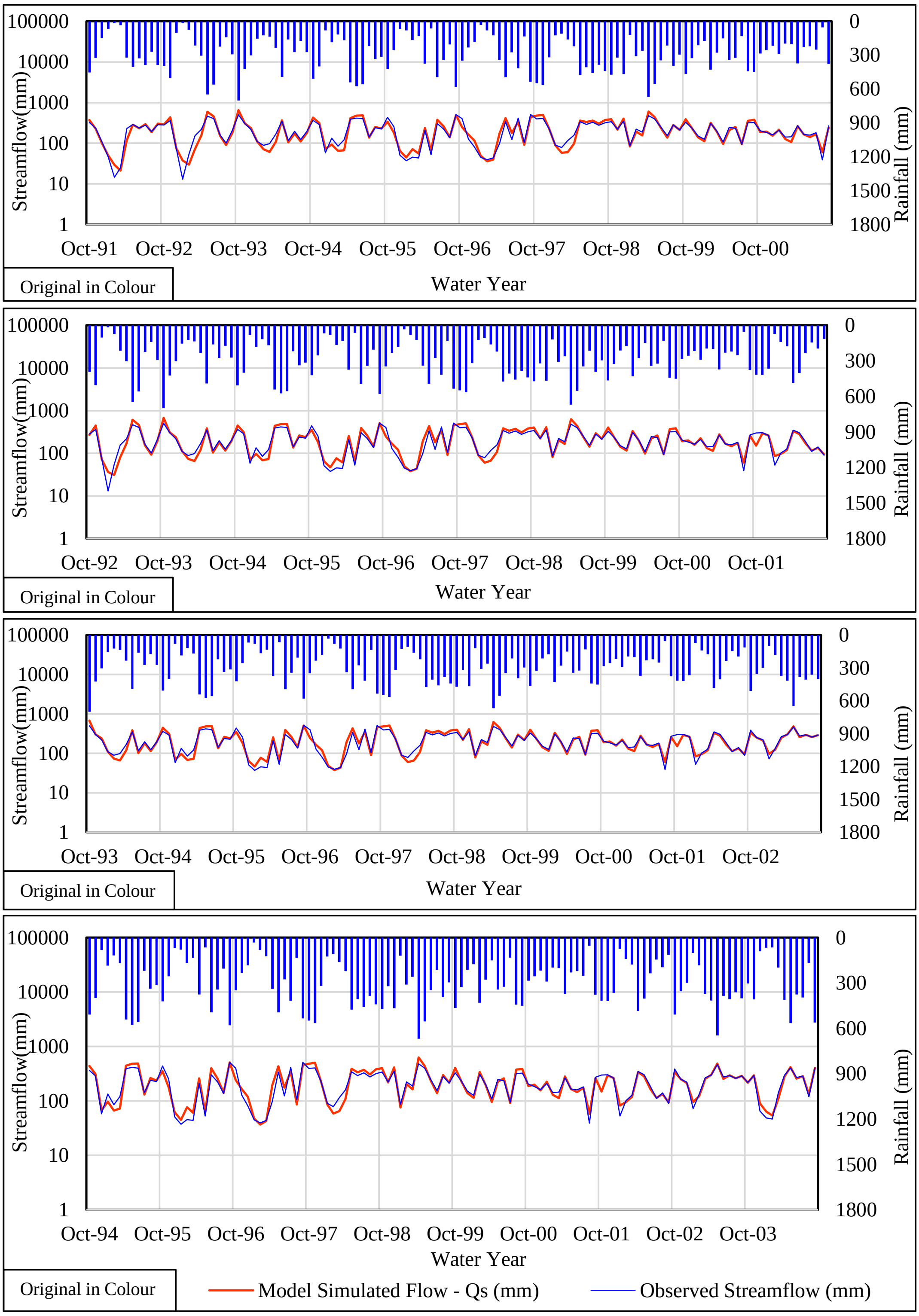


Figure D.9-D.12: Hydrographs of Observed and Simulated Flow Hydrographs of 10 Year Datasets (1991/92-2000/01 to 1994/95-2003/04)

Hydrograph Comparison – 10 Year Datasets – Calibration (Set 13 – 16)

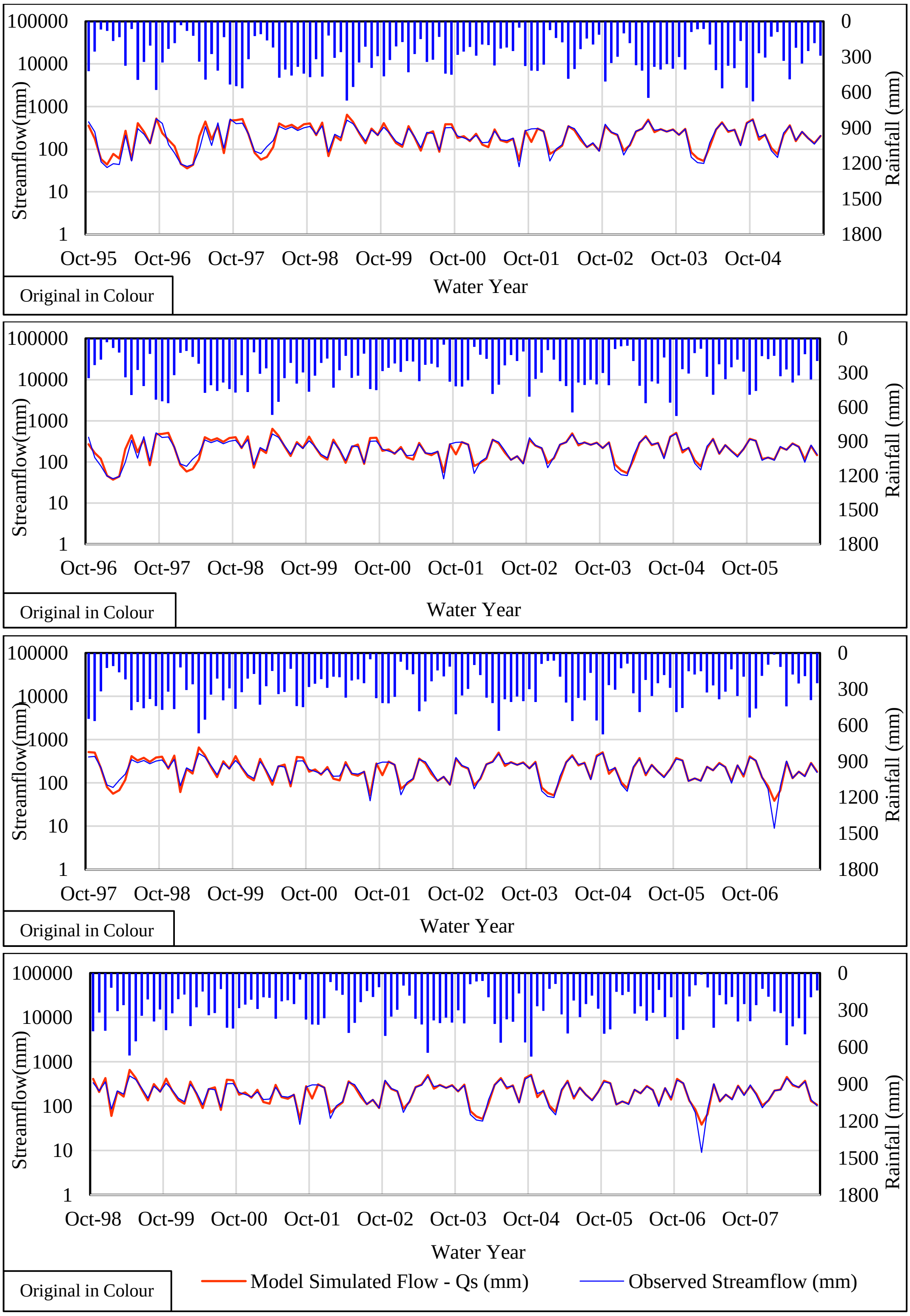


Figure D.13-D.16: Hydrographs of Observed and Simulated Flow Hydrographs of 10 Year Datasets (1995/96-2004/05 to 1998/99-2007/08)

Hydrograph Comparison – 10 Year Datasets – Calibration (Set 17 – 20)

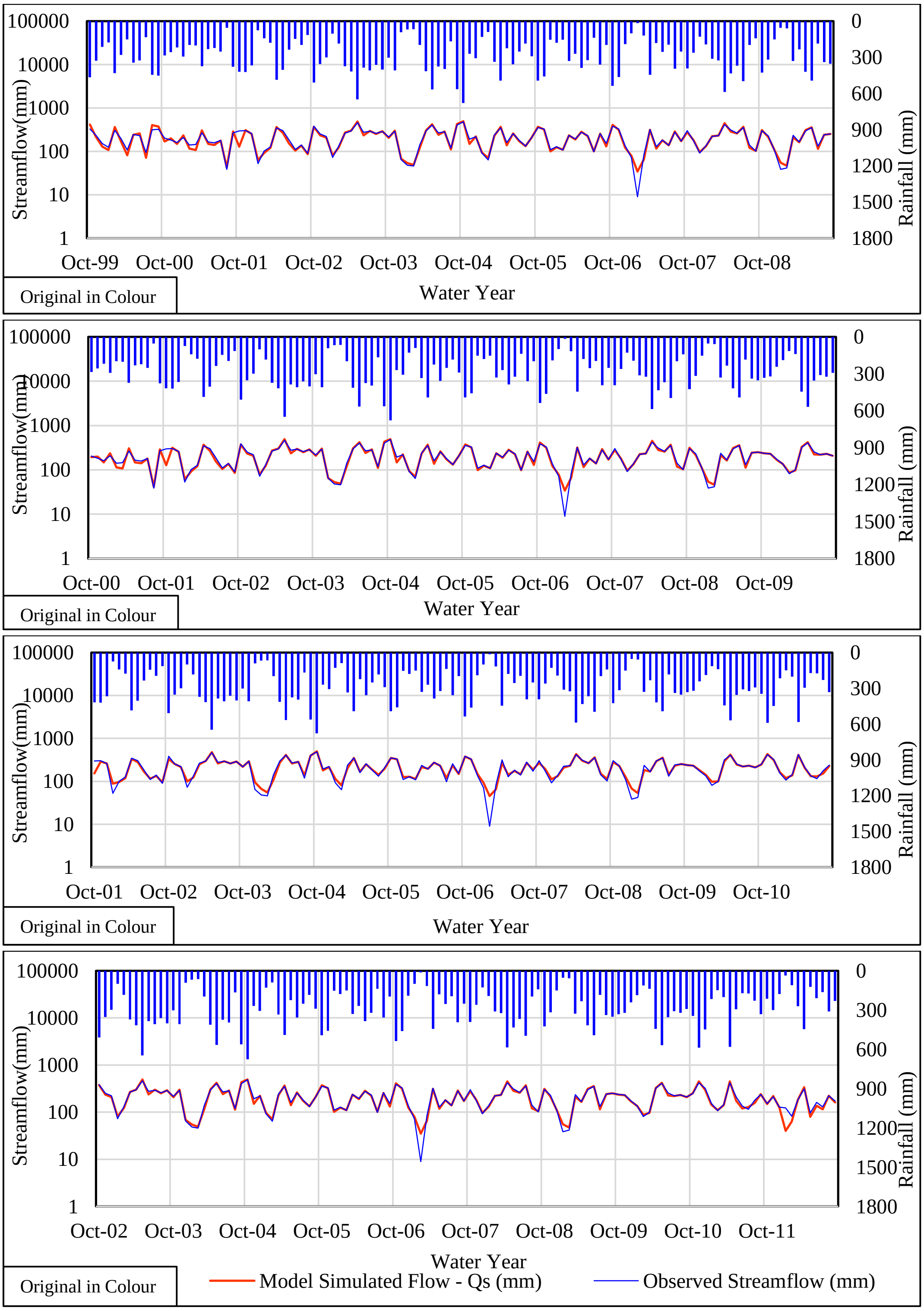


Figure D.17-D.20: Hydrographs of Observed and Simulated Flow Hydrographs of 10 Year Datasets (1999/2000-2008/09 to 2002/03-2011/12)

Hydrograph Comparison – 10 Year Datasets – Calibration (Set 21 – 24)

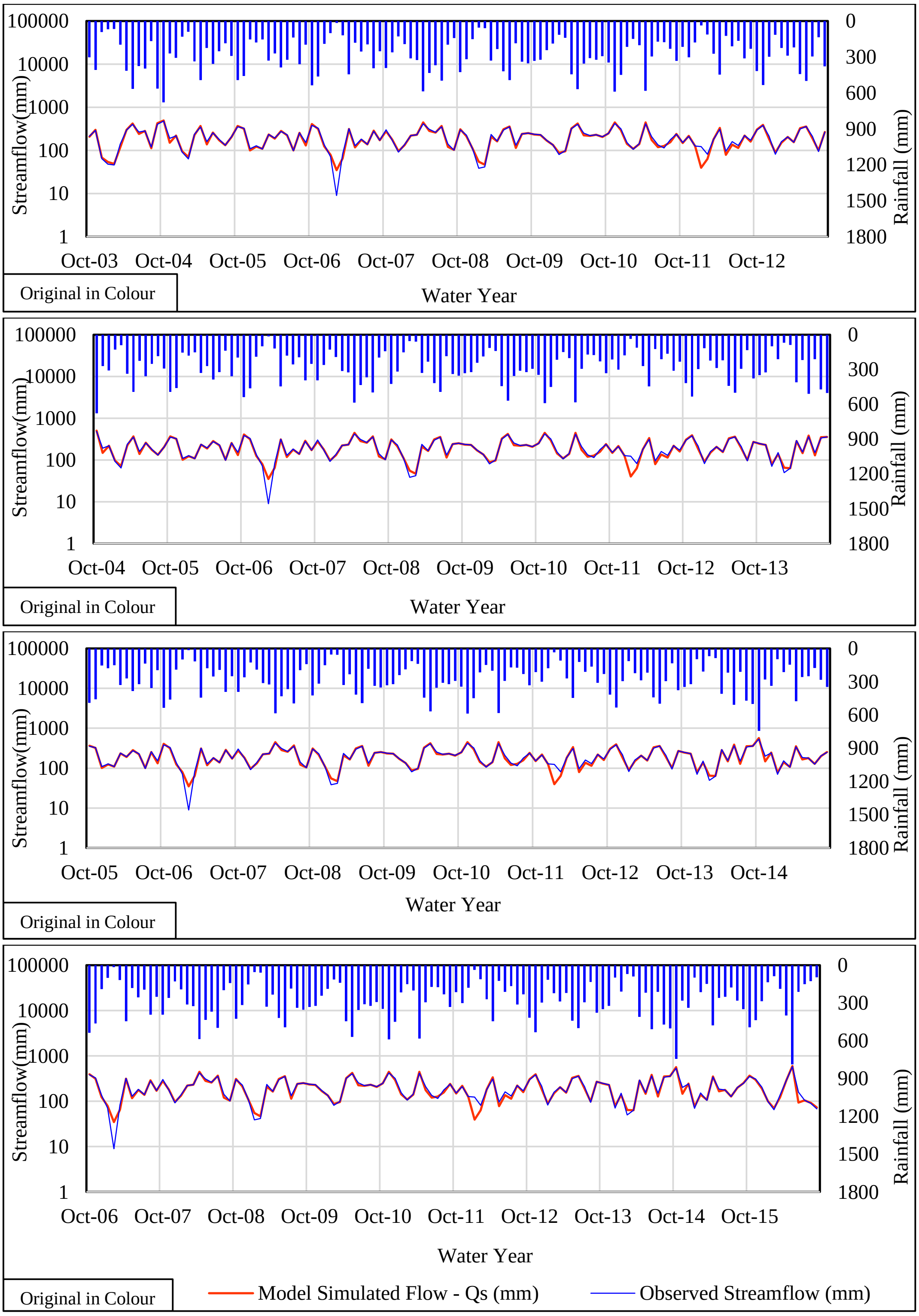


Figure D.21-D.24: Hydrographs of Observed and Simulated Flow Hydrographs of 10 Year Datasets (2003/04-2012/13 to 2006/07-2015/16)

Hydrograph Comparison – 10 Year Datasets – Calibration (Set 25)

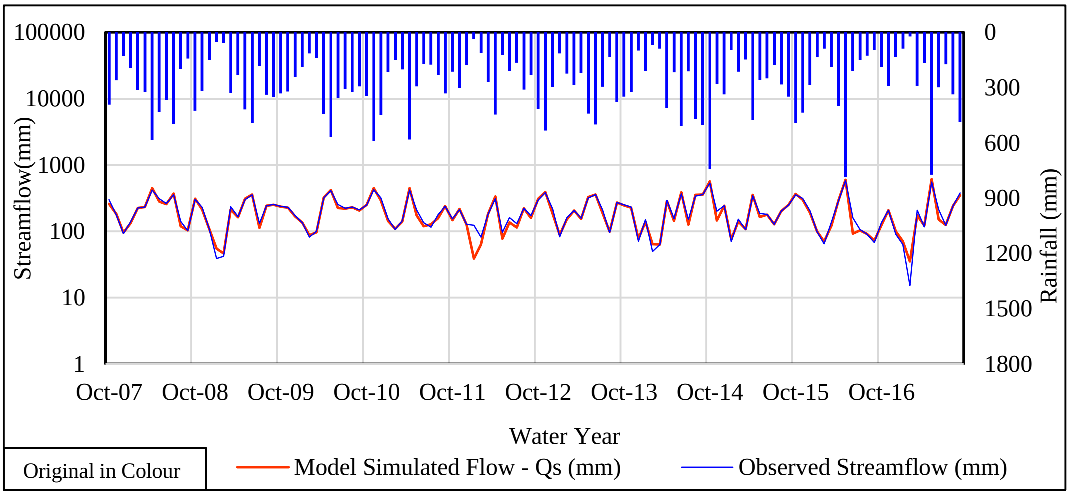


Figure D.25: Hydrographs of Observed and Simulated Flow Hydrographs of 10 Year Datasets (2007/08-2016/17)

Hydrograph Comparison – 15 Year Datasets – Calibration (Set 1 – 4)

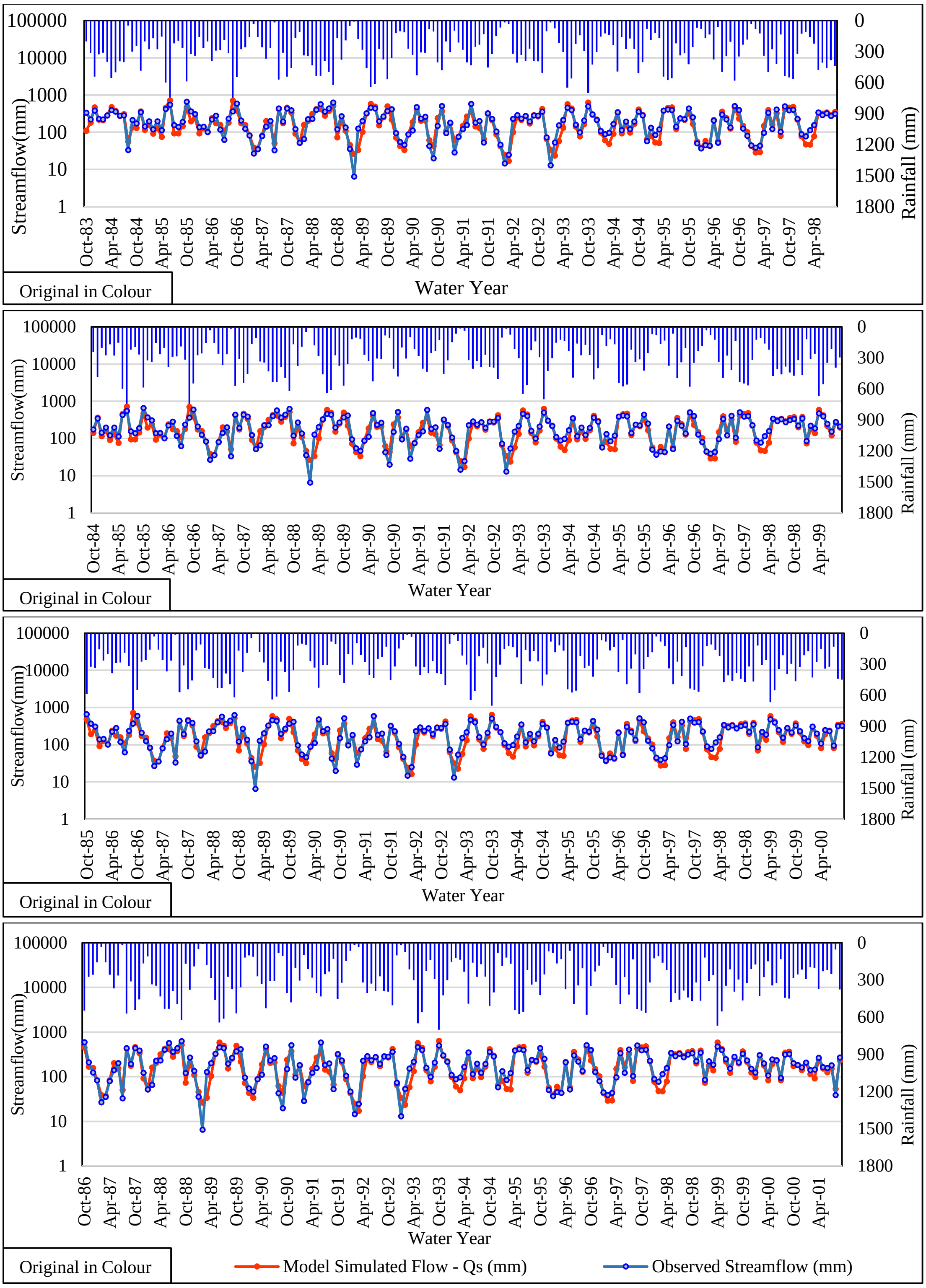
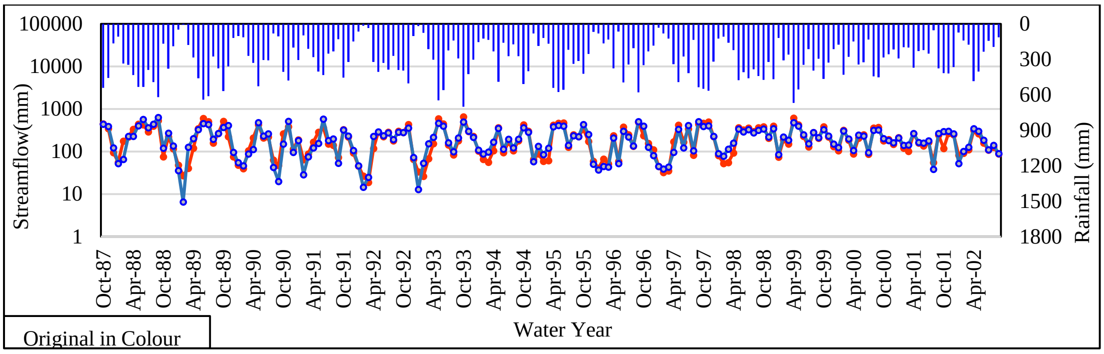
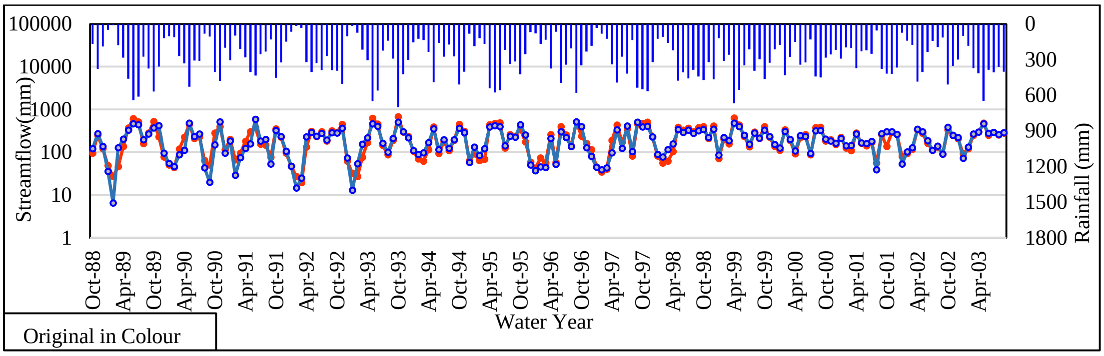
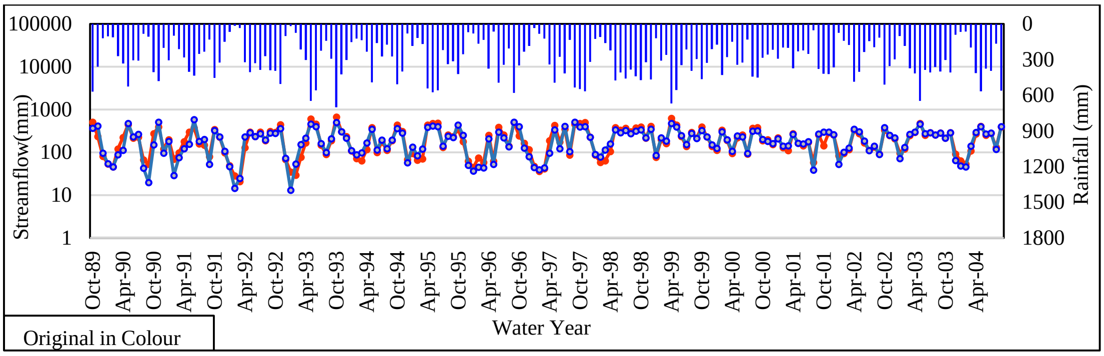


Figure D.26 – D.29: Hydrographs of Observed and Simulated Flow Hydrographs of 15 Year Datasets (1983/84-1997/98 to 1986/87-2000/01)

Hydrograph Comparison – 15 Year Datasets – Calibration (Set 5 – 8)







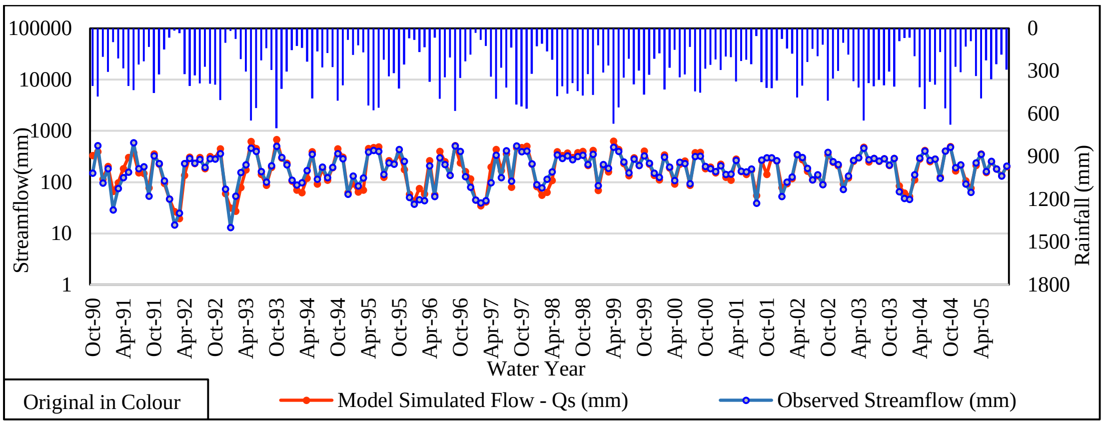
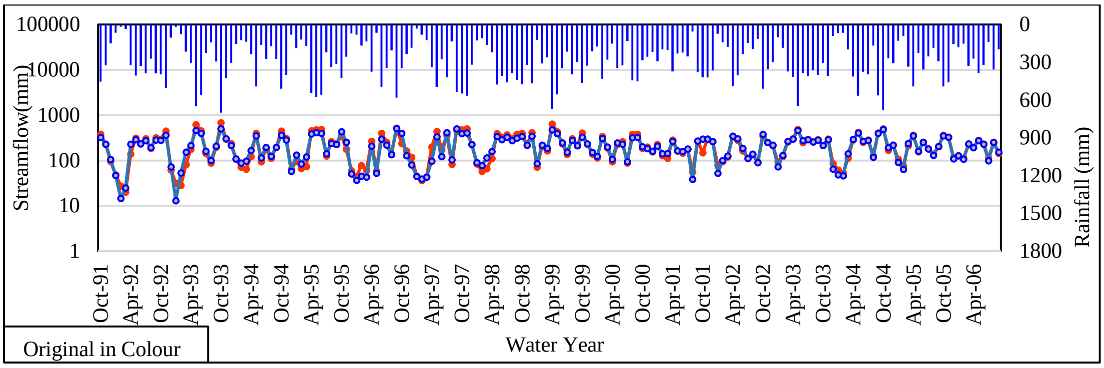
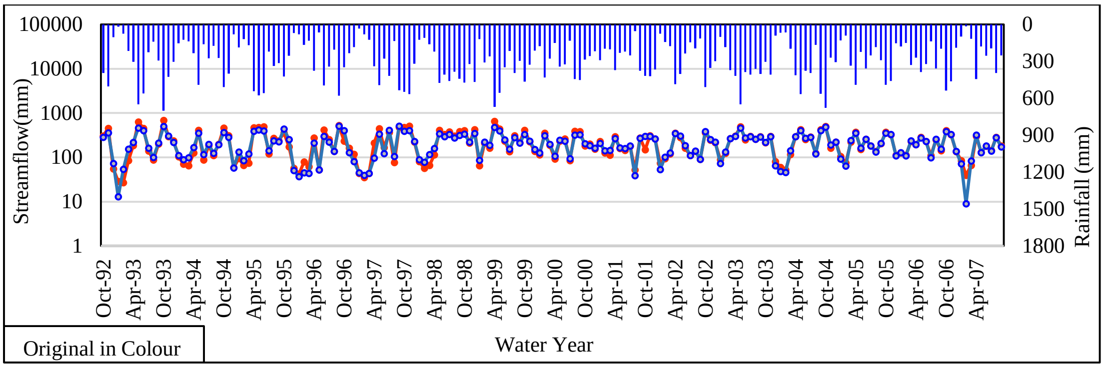
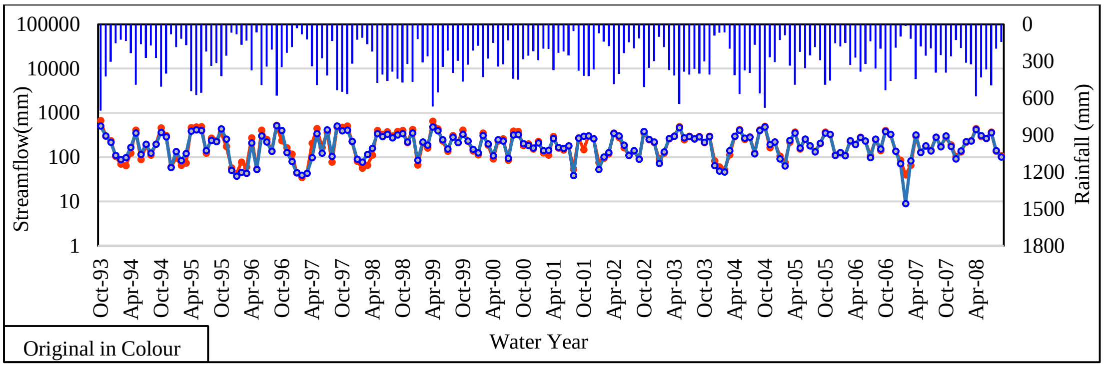


Figure D.30 – D.33: Hydrographs of Observed and Simulated Flow Hydrographs of 15 Year Datasets (1987/88-1997/98 to 1990/91-2004/05)

Hydrograph Comparison – 15 Year Datasets – Calibration (Set 9 – 12)







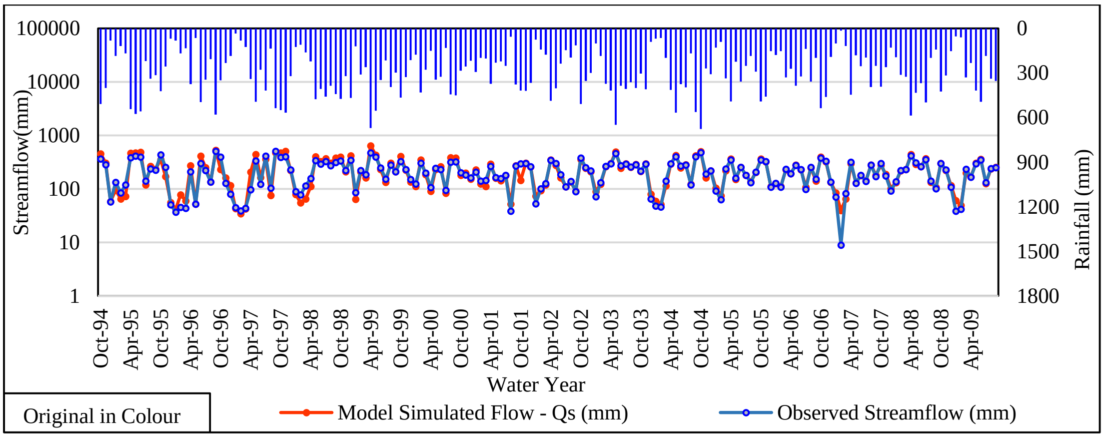


Figure D.34 – D.37: Hydrographs of Observed and Simulated Flow Hydrographs of 15 Year Datasets (1991/92-2005/06 to 1994/95-2008/09)

Hydrograph Comparison – 15 Year Datasets – Calibration (Set 13 – 16)

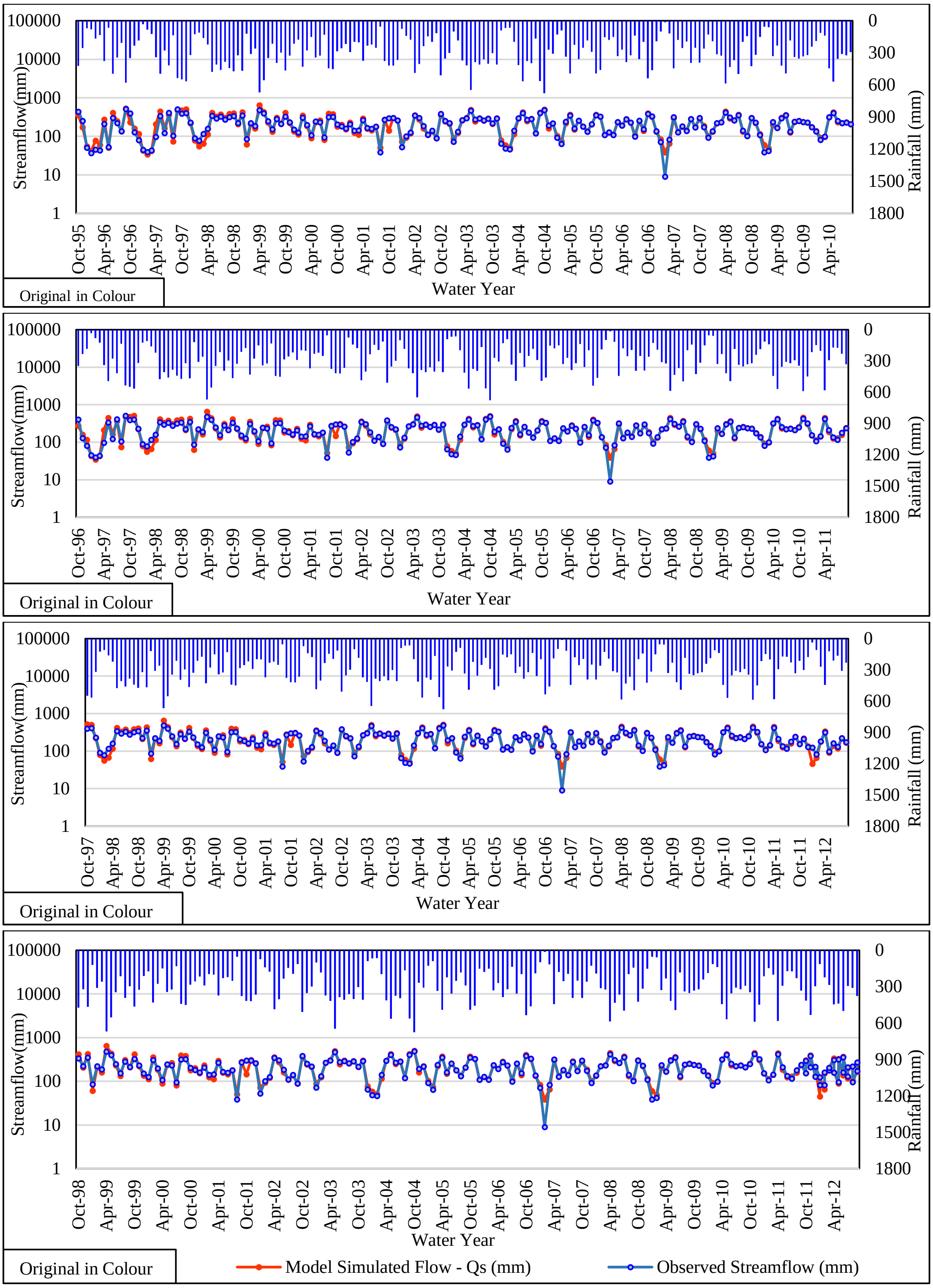


Figure D.38 – D.41: Hydrographs of Observed and Simulated Flow Hydrographs of 15 Year Datasets (1995/96-2009/10 to 1998/99-2012/13)

Hydrograph Comparison – 15 Year Datasets – Calibration (Set 17 – 20)

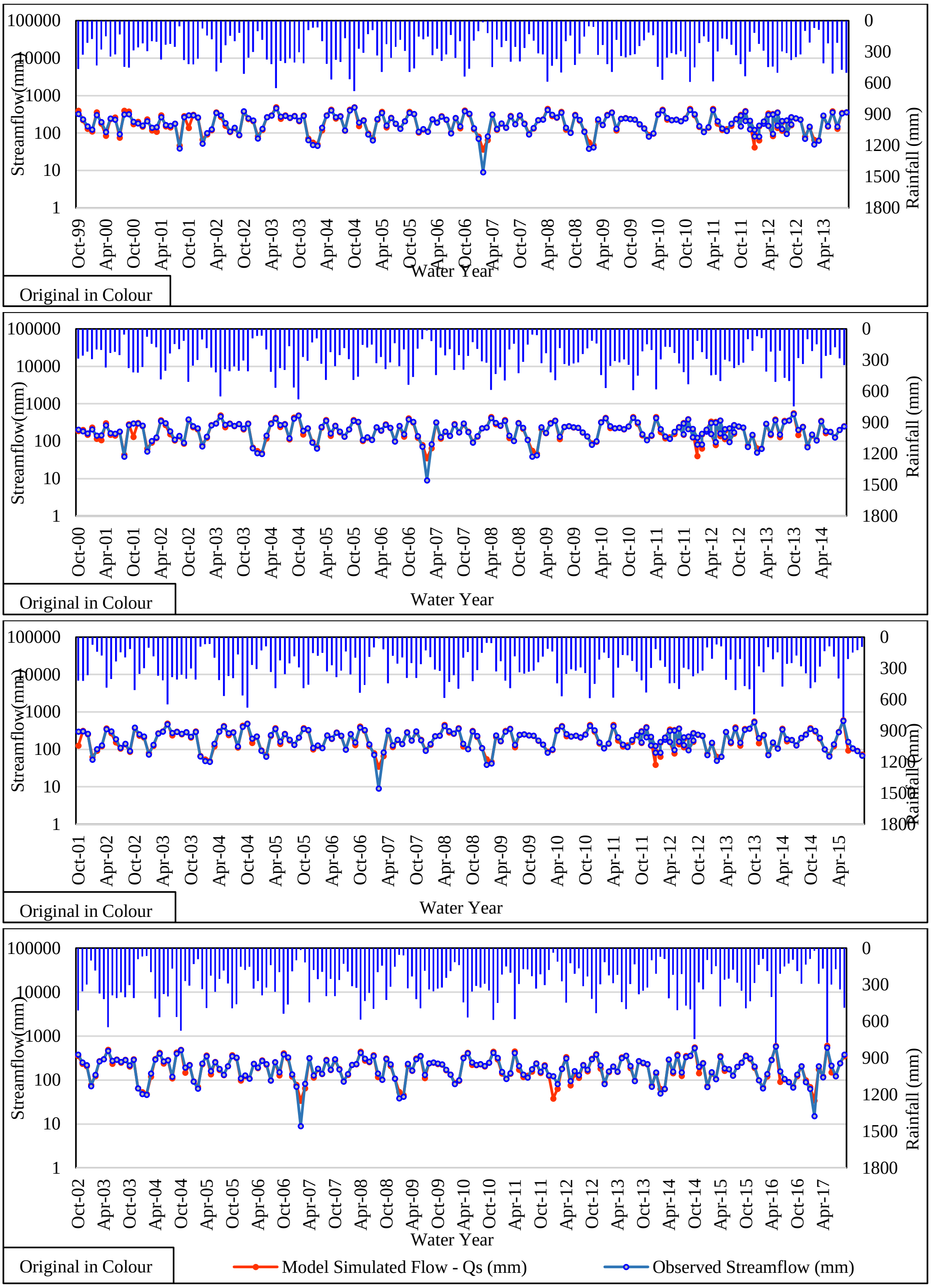


Figure D.42 – D.45: Hydrographs of Observed and Simulated Flow Hydrographs of 15 Year Datasets (1999/2000-2013/14 to 2002/13-2016/17)

Hydrograph Comparison – 20 Year Datasets – Calibration (Set 1 – 2)

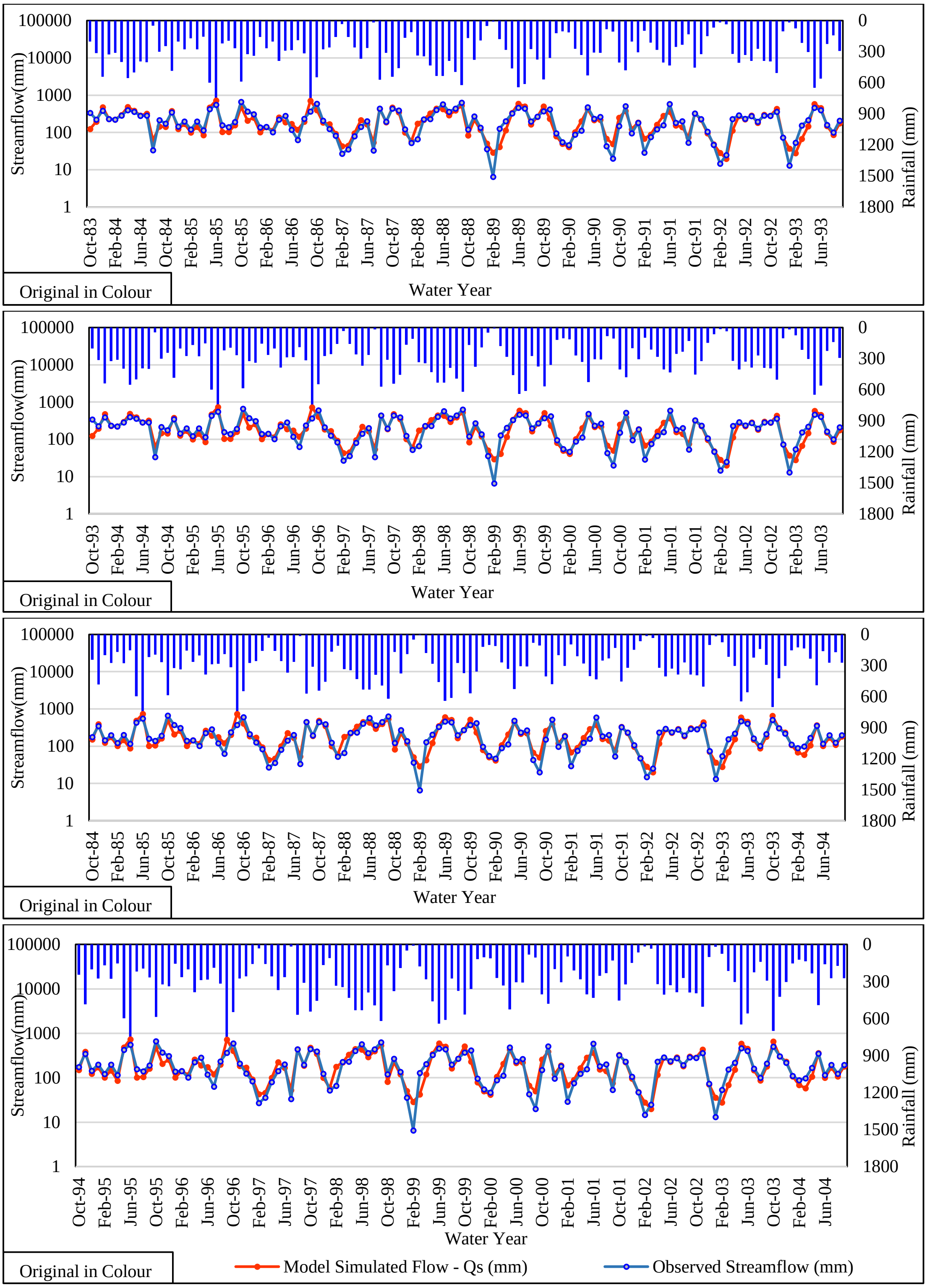
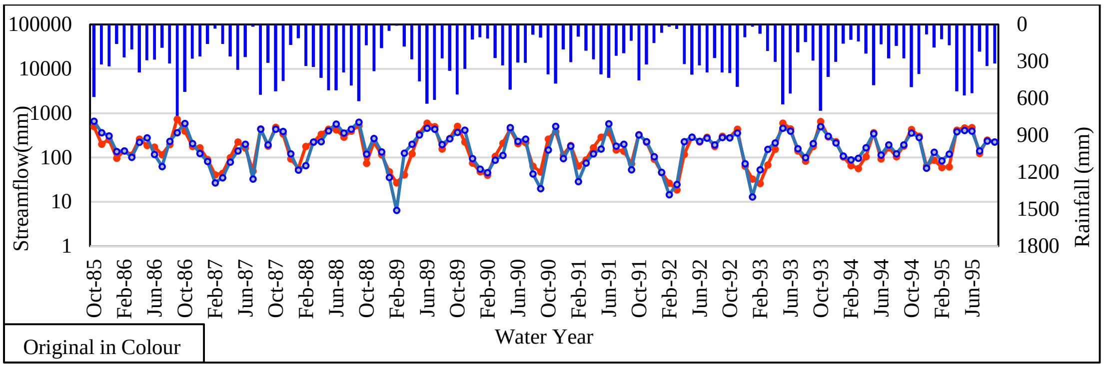
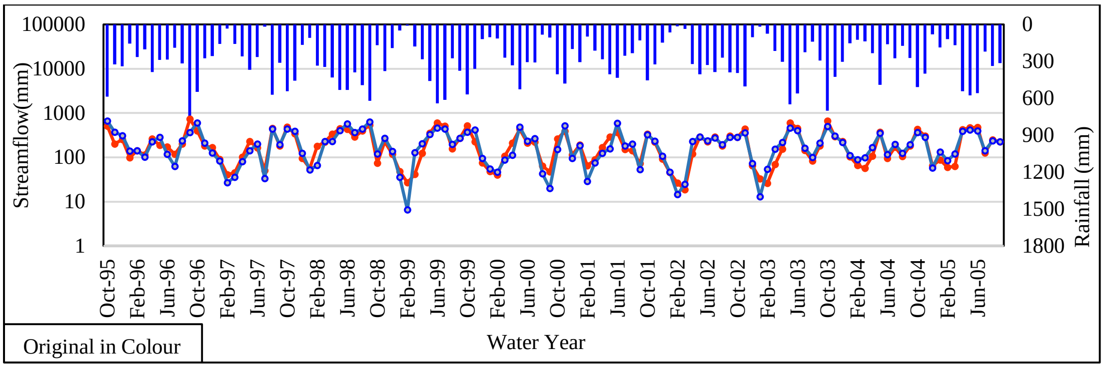
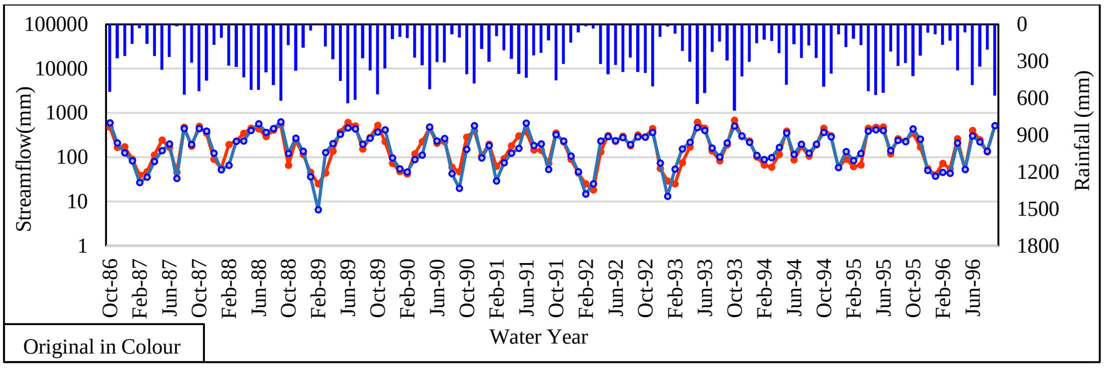


Figure D.46 – D.49: Hydrographs of Observed and Simulated Flow Hydrographs of 20 Year Datasets (1983/1984-2002/03 to 1984/85-2003/04)

Hydrograph Comparison – 20 Year Datasets – Calibration (Set 3 – 4)







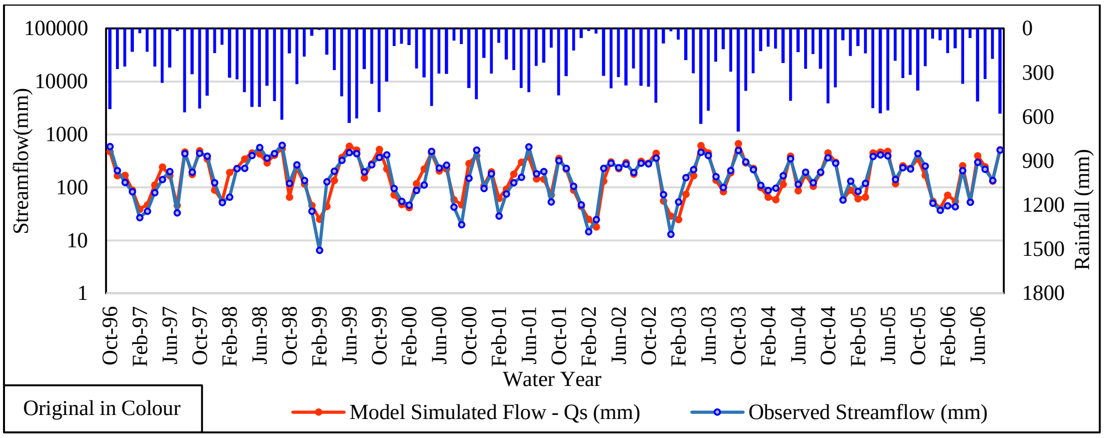


Figure D.50 – D.53: Hydrographs of Observed and Simulated Flow Hydrographs of 20 Year Datasets (1985/1986-2004/05 to 1986/87-2005/06)

Hydrograph Comparison – 20 Year Datasets – Calibration (Set 5 – 6)

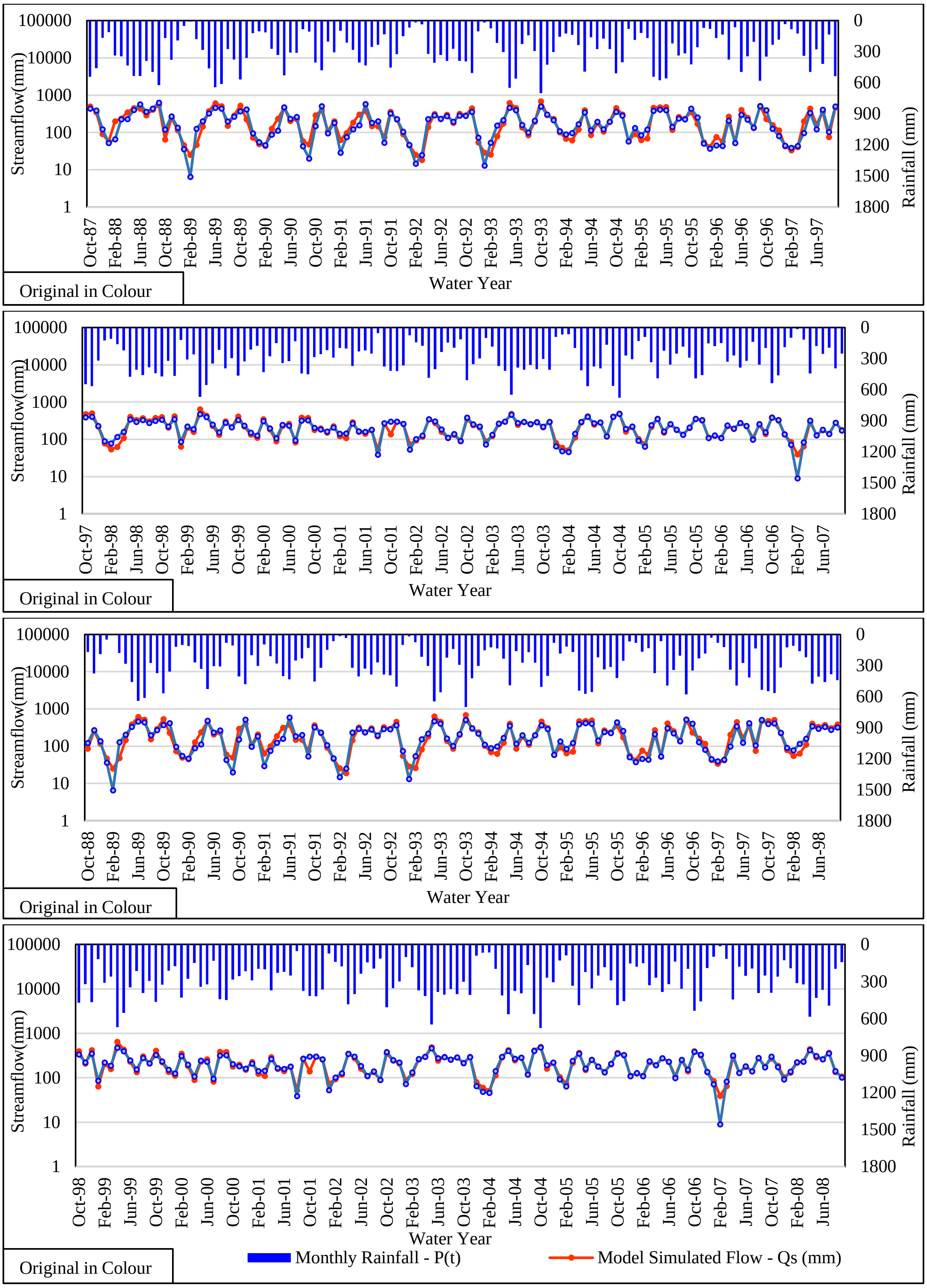


Figure D.54 – D.57: Hydrographs of Observed and Simulated Flow Hydrographs of 20 Year Datasets (1987/1988-2006/07 to 1988/89-2007/08)

Hydrograph Comparison – 20 Year Datasets – Calibration (Set 7 – 8)

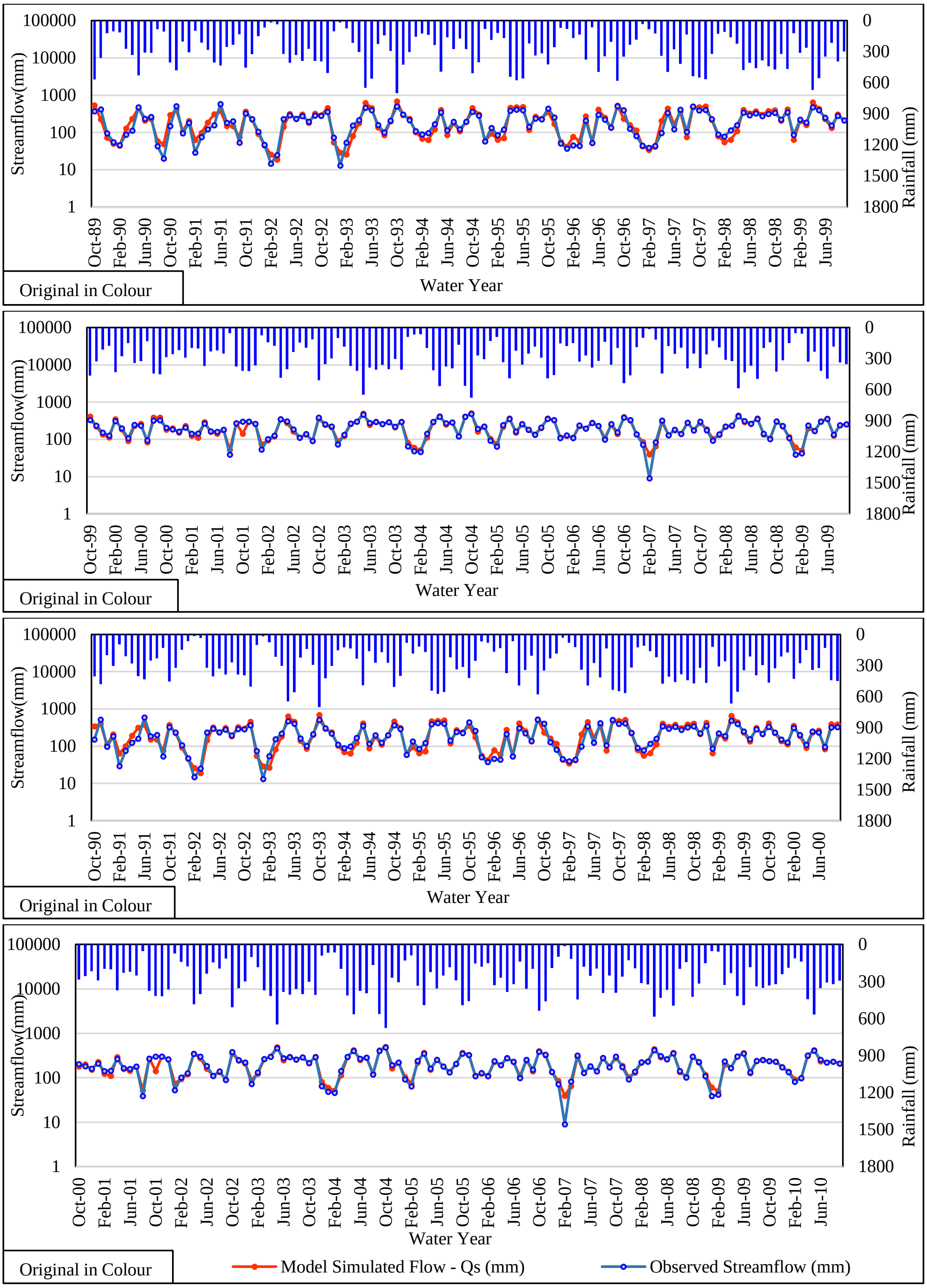


Figure D.58 – D.61: Hydrographs of Observed and Simulated Flow Hydrographs of 20 Year Datasets (1989/1990-2008/09 to 1990/91-2009/10)

Hydrograph Comparison – 20 Year Datasets – Calibration (Set 9 – 10)

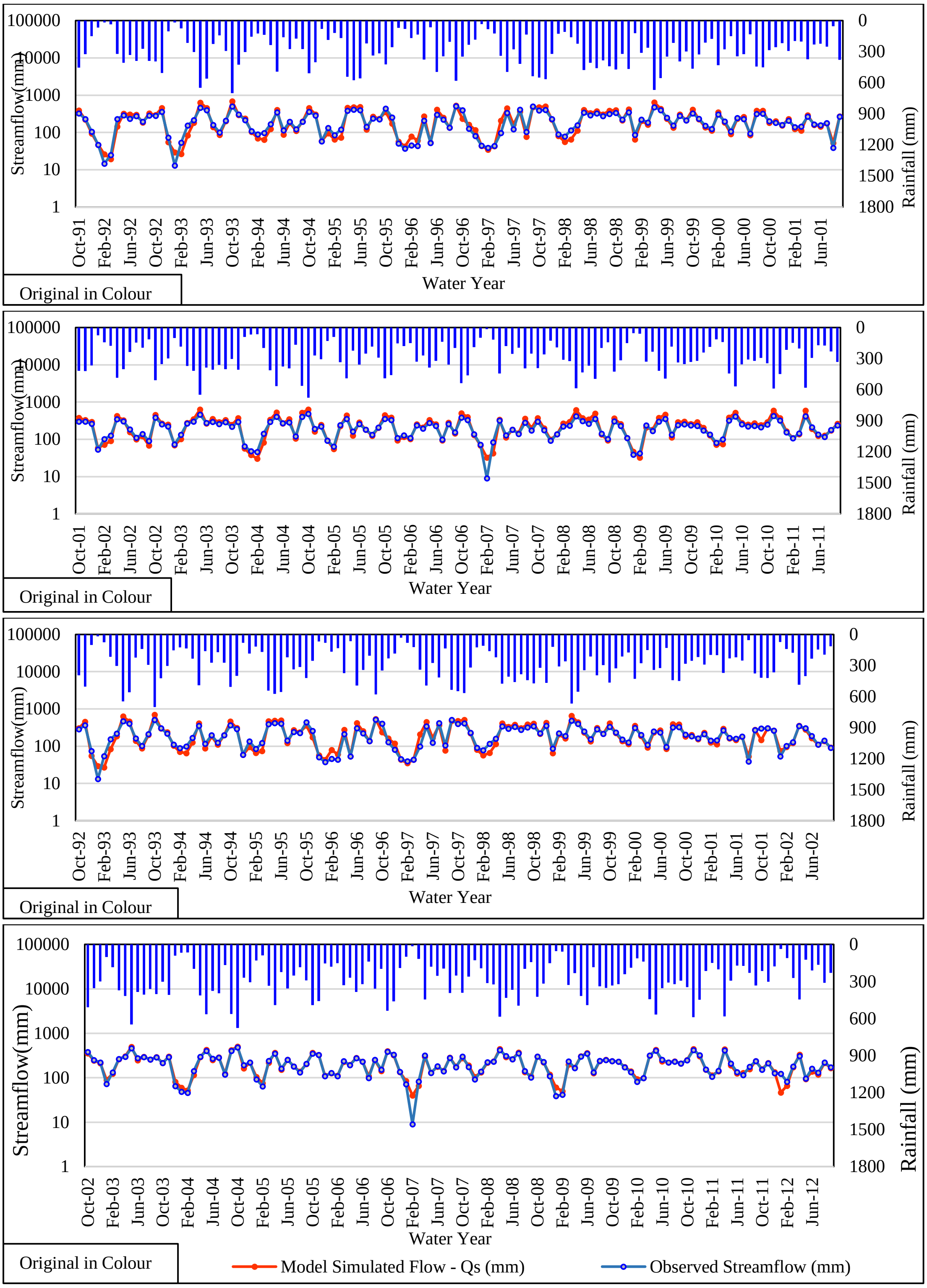


Figure D.62 – D.65: Hydrographs of Observed and Simulated Flow Hydrographs of 20 Year Datasets (1991/1992-2010/11 to 1992/93-2011/12)

Hydrograph Comparison – 20 Year Datasets – Calibration (Set 11 – 12)

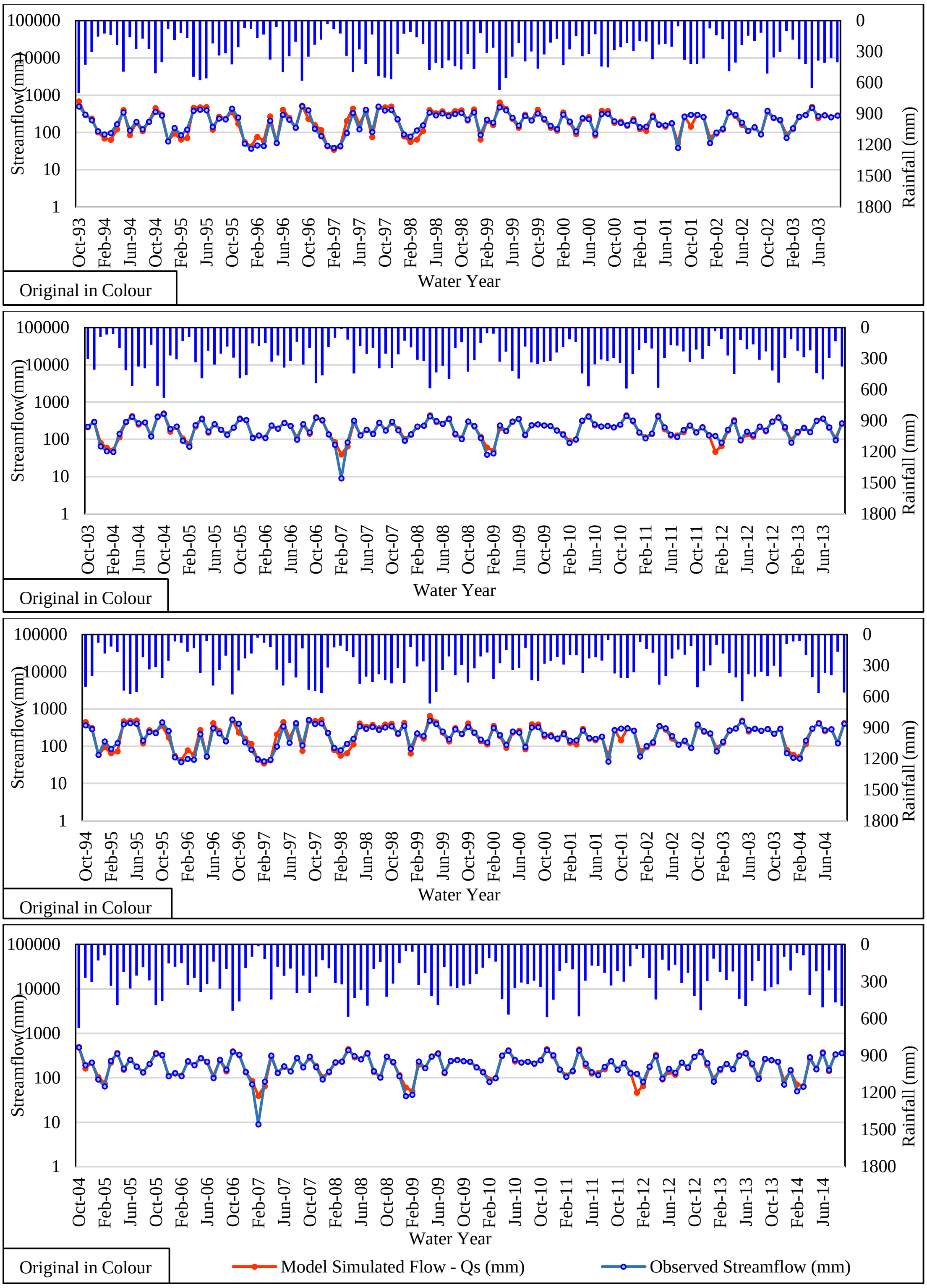


Figure D.66 – D.69: Hydrographs of Observed and Simulated Flow Hydrographs of 20 Year Datasets (1993/1994-2012/13 to 1994/95-2013/14)

Hydrograph Comparison – 20 Year Datasets – Calibration (Set 13 – 14)

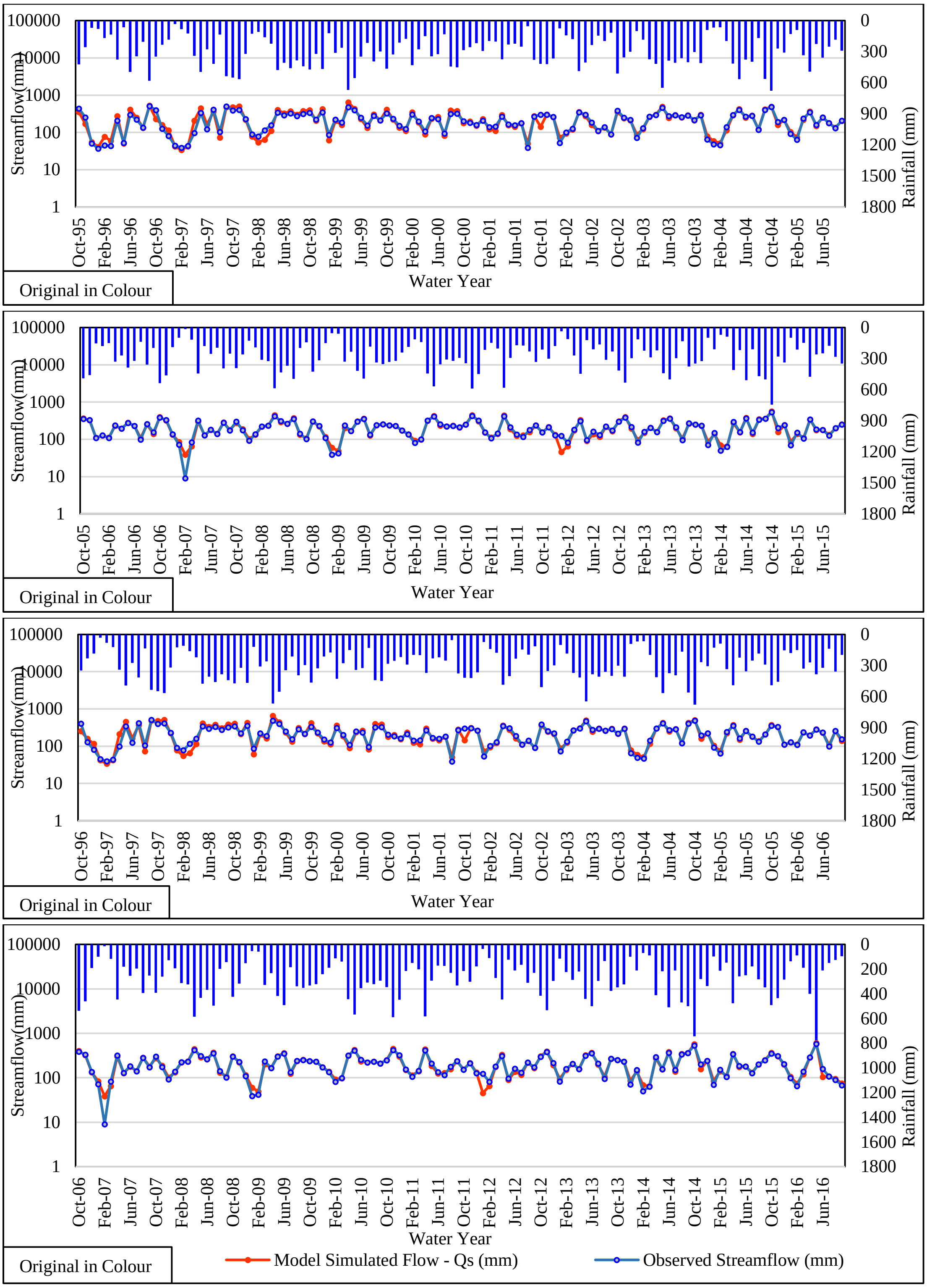
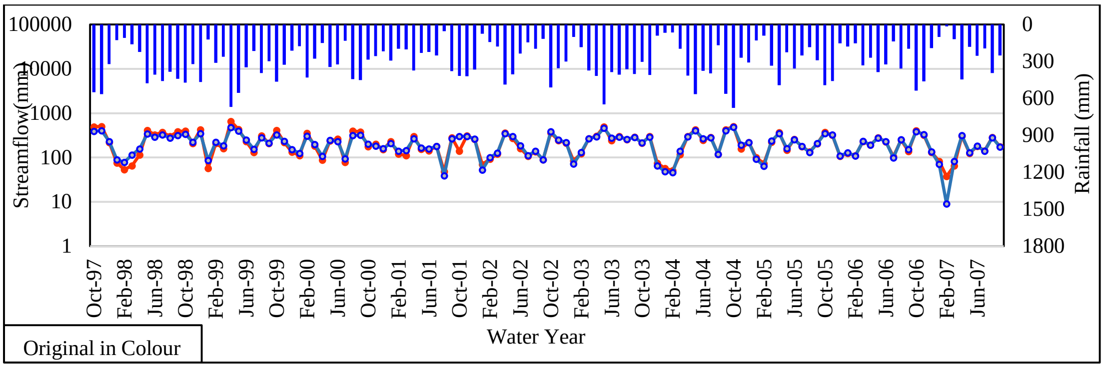


Figure D.70 – D.73: Hydrographs of Observed and Simulated Flow Hydrographs of 20 Year Datasets (1995/1996-2014/15 to 1996/97-2015/16)

Hydrograph Comparison – 20 Year Datasets – Calibration (Set 15)



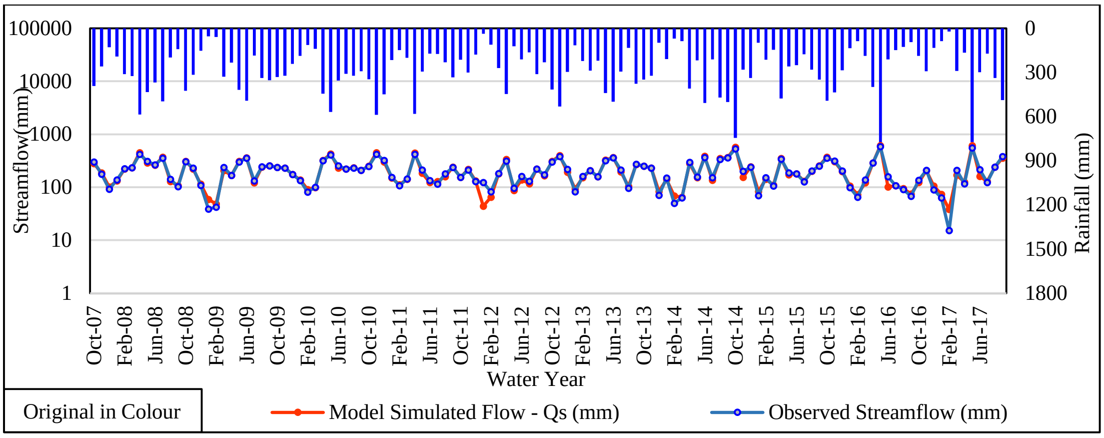


Figure D.74 – D.75: Hydrographs of Observed and Simulated Flow Hydrographs of 20 Year Datasets (1997/1998-2016/17)

Hydrograph Comparison – 25 Year Datasets – Calibration (Set 1 – 2)

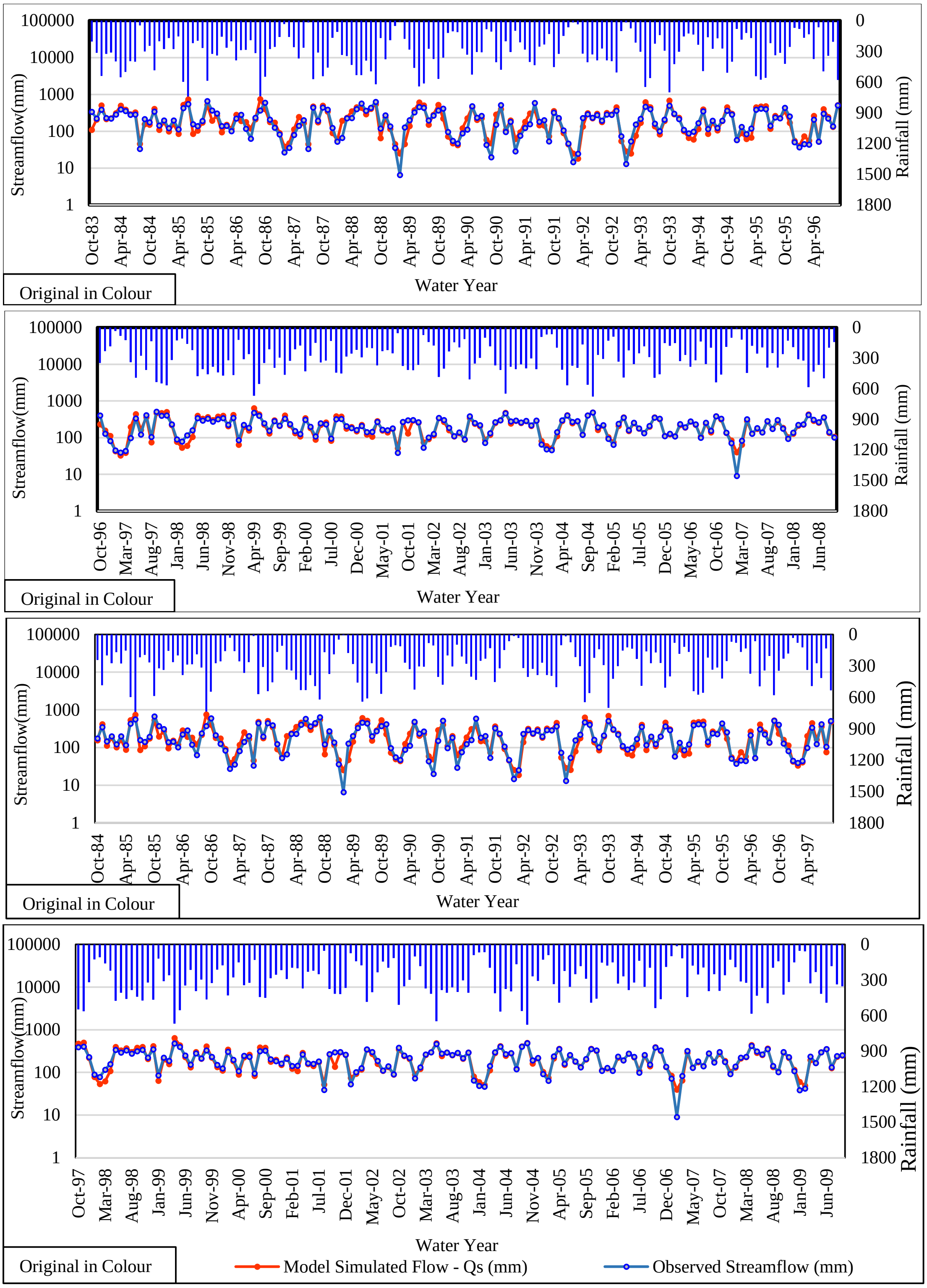


Figure D.76 – D.79: Hydrographs of Observed and Simulated Flow Hydrographs of 25 Year Datasets (1983/1984-2007/08 to 1984/85-2008/09)

Hydrograph Comparison – 25 Year Datasets – Calibration (Set 3 – 4)

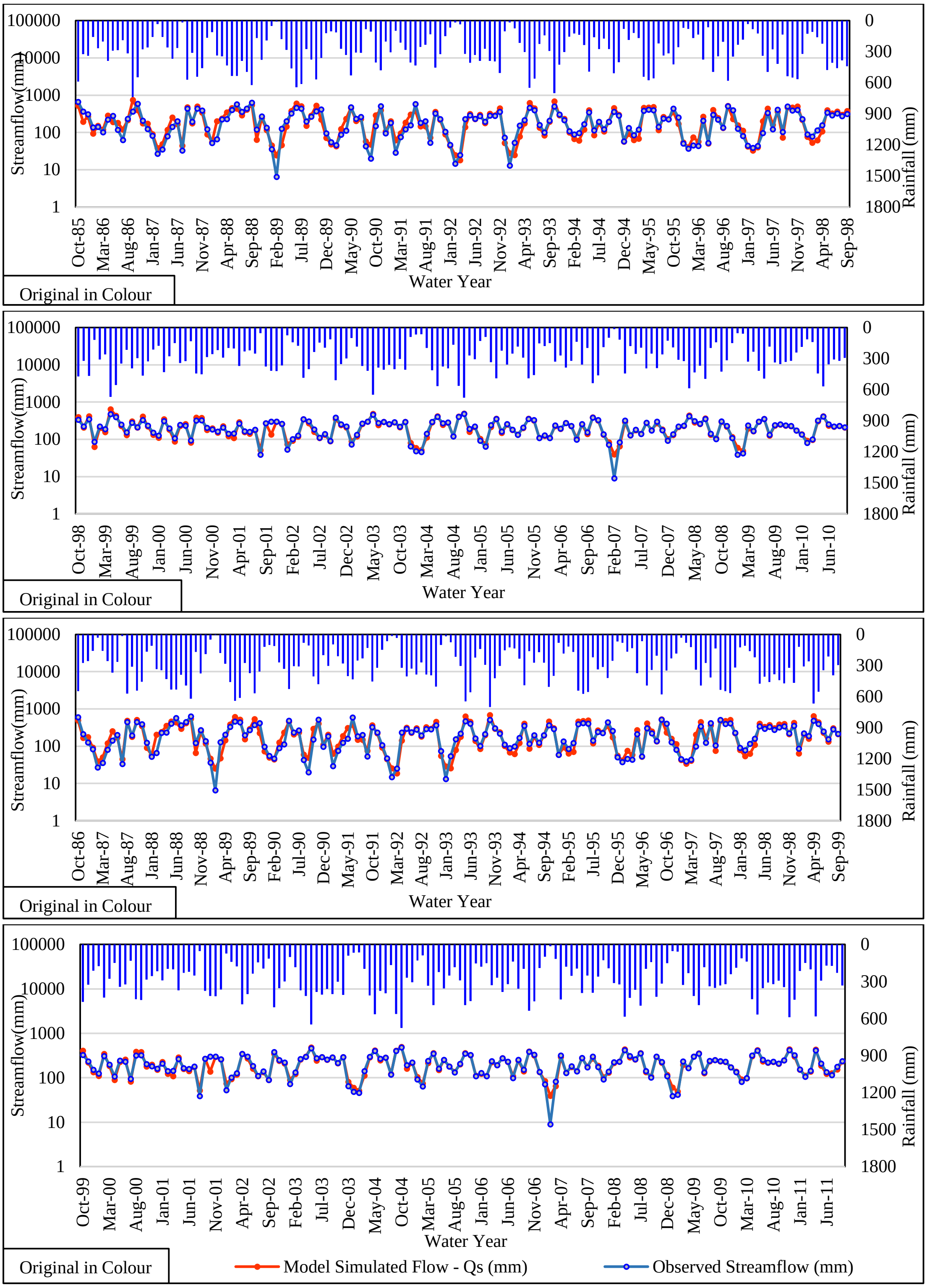
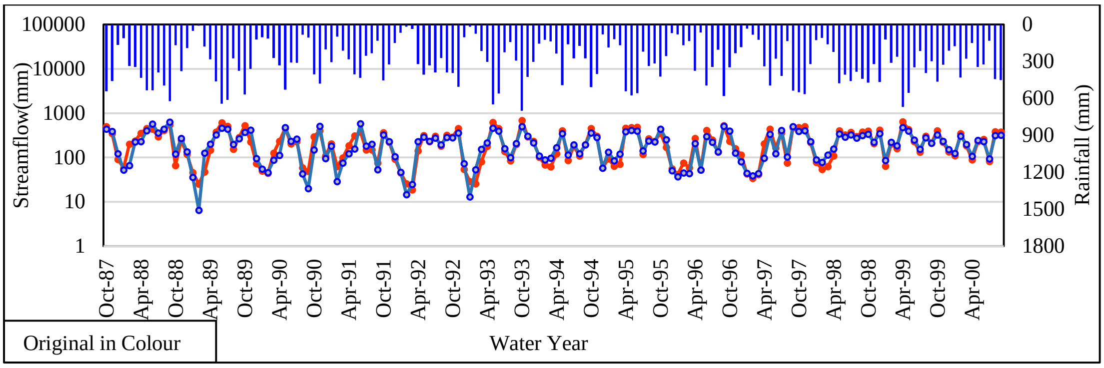
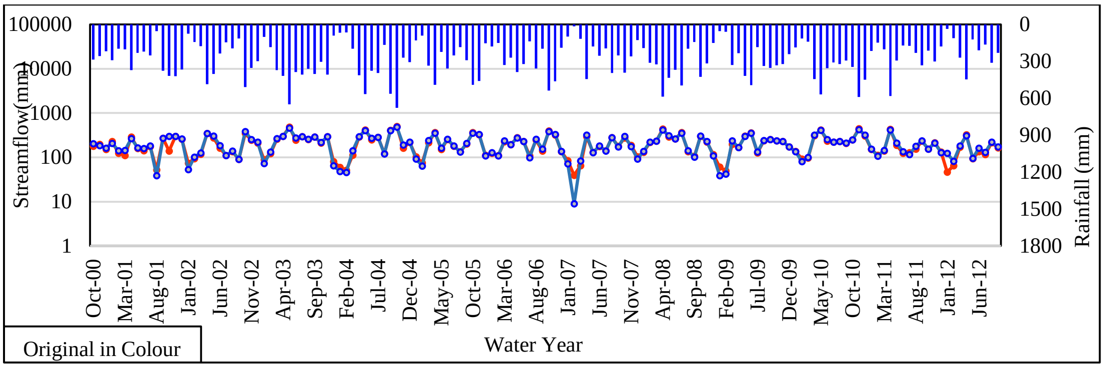
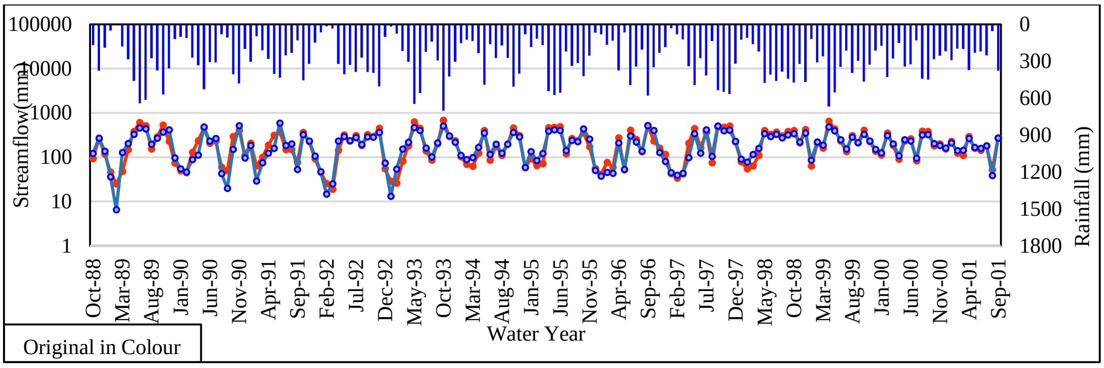


Figure D.80 – D.83: Hydrographs of Observed and Simulated Flow Hydrographs of 25 Year Datasets (1985/1986-2009/10 to 1986/87-2010/11)

Hydrograph Comparison – 25 Year Datasets – Calibration (Set 5 – 6)







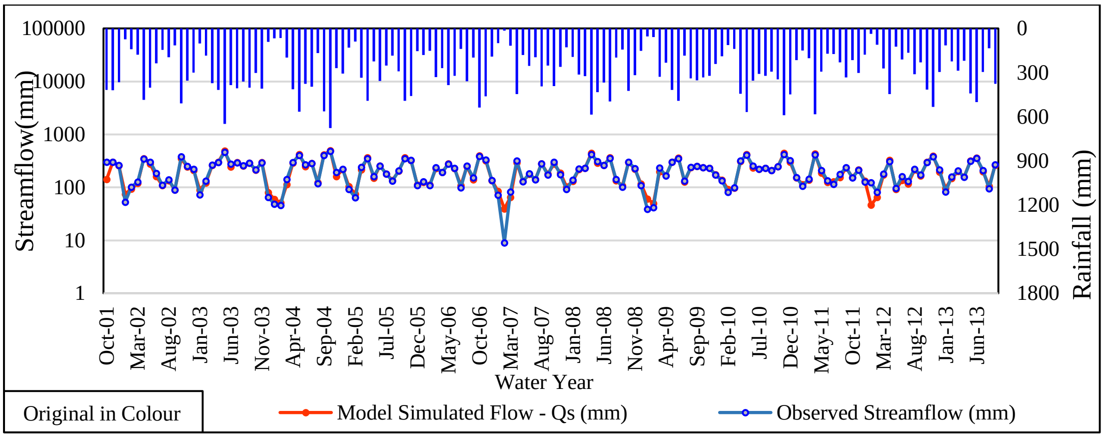


Figure D.84 – D.87: Hydrographs of Observed and Simulated Flow Hydrographs of 25 Year Datasets (1987/1988-2011/12 to 1988/89-2012/13)

Hydrograph Comparison – 25 Year Datasets – Calibration (Set 7 – 8)

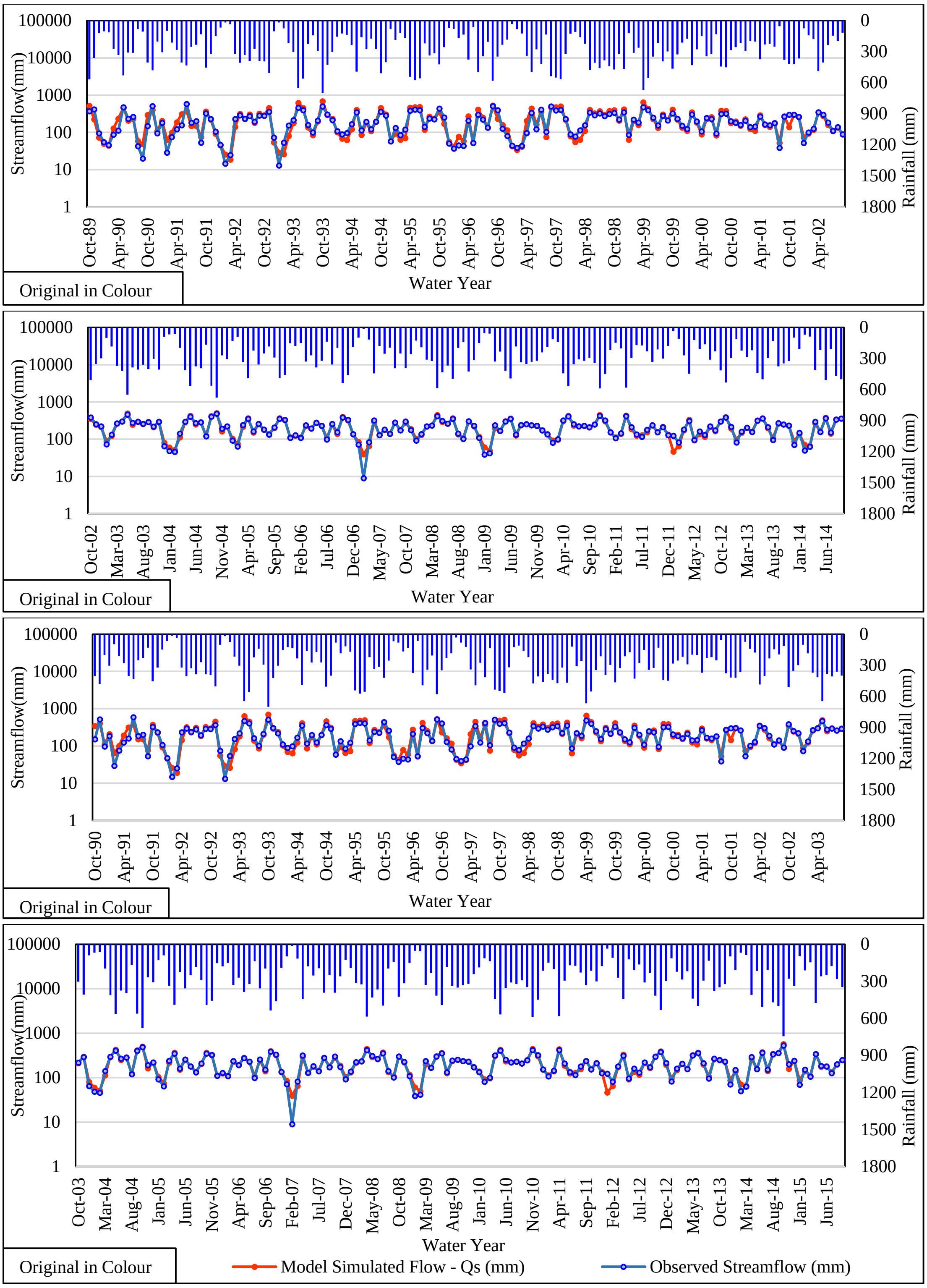


Figure D.88 – D.91: Hydrographs of Observed and Simulated Flow Hydrographs of 25 Year Datasets (1989/1990-2013/14 to 1990/91-2014/15)

Hydrograph Comparison – 25 Year Datasets – Calibration (Set 9 – 10)

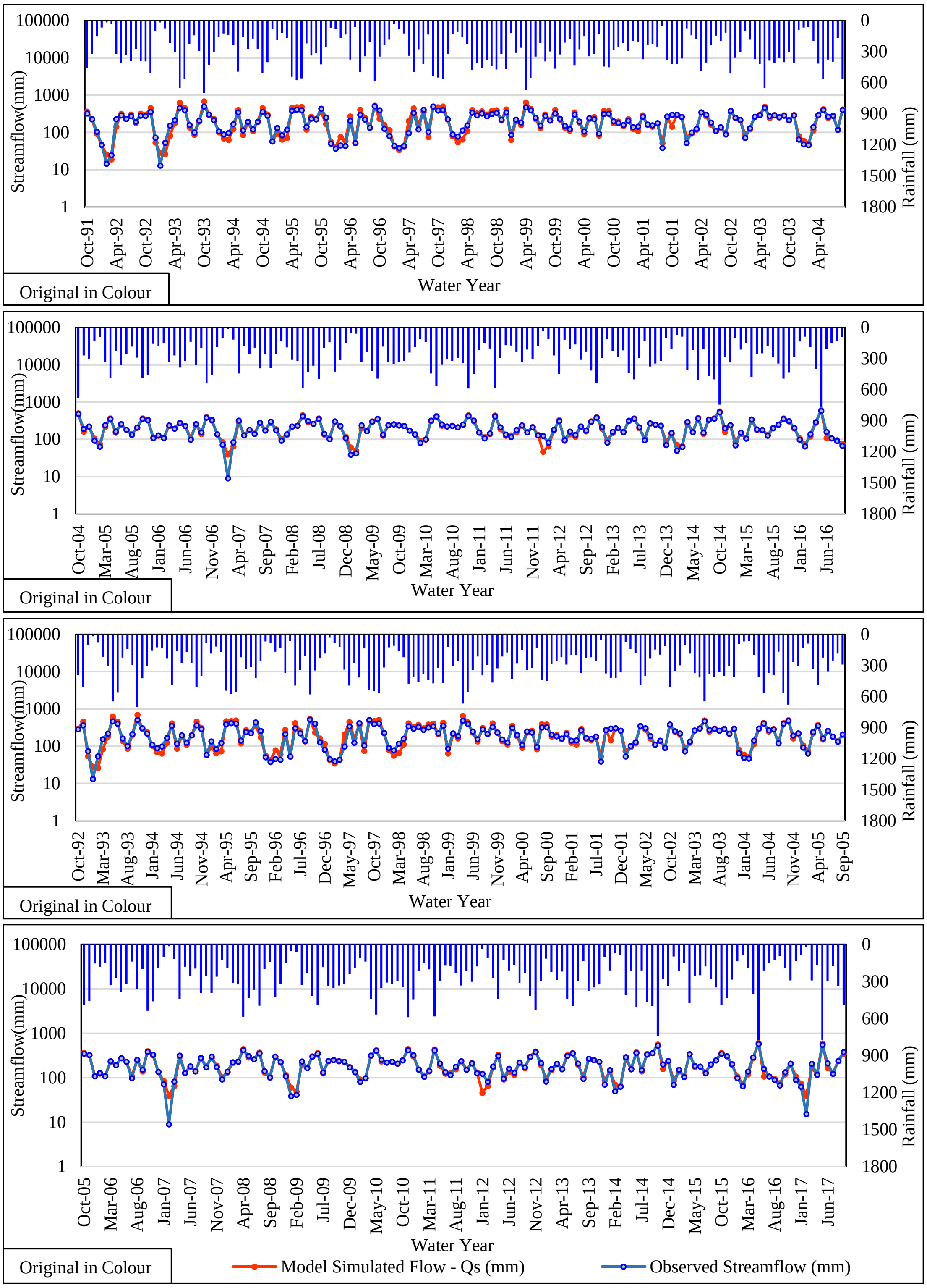
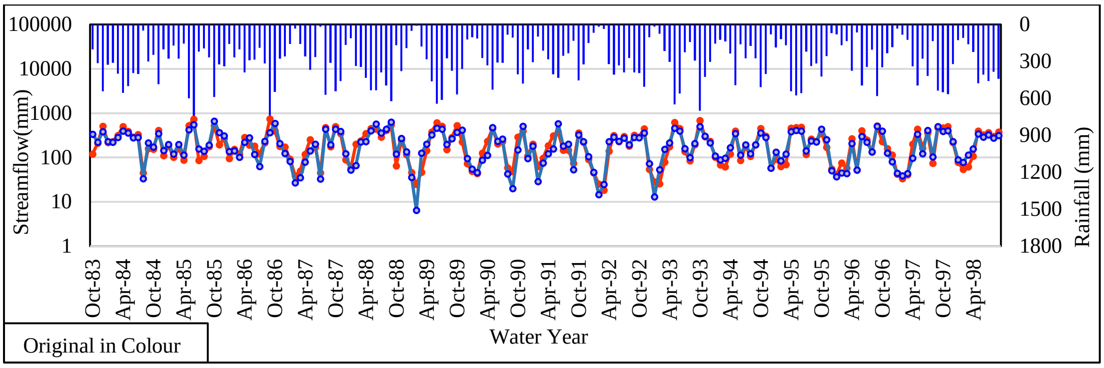
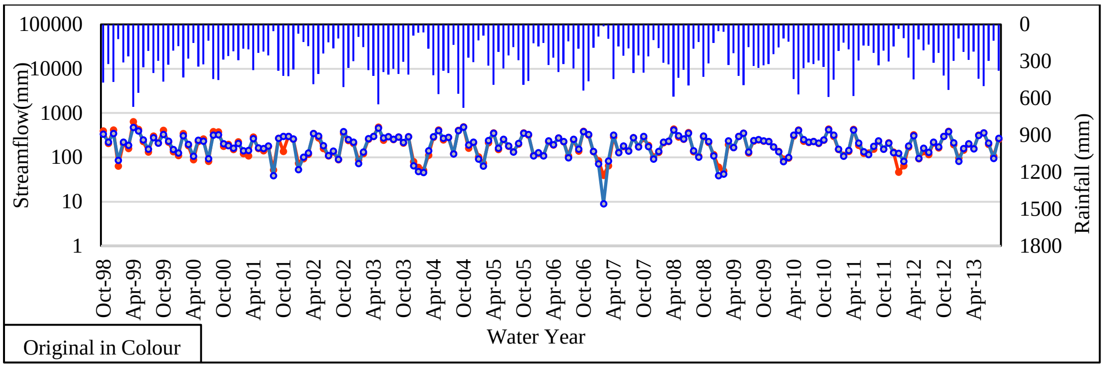
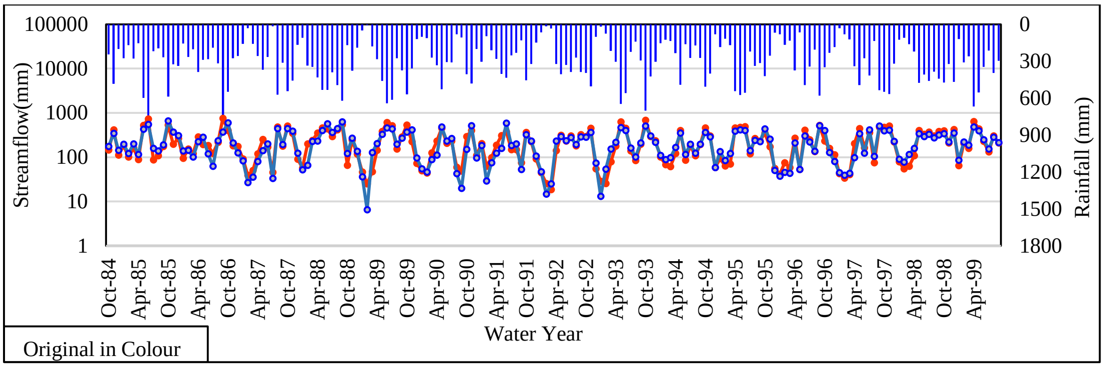


Figure D.92 – D.95: Hydrographs of Observed and Simulated Flow Hydrographs of 25 Year Datasets (1991/1992-2015/16 to 1992/93-2016/17)

Hydrograph Comparison – 30 Year Datasets – Calibration (Set 1 – 2)







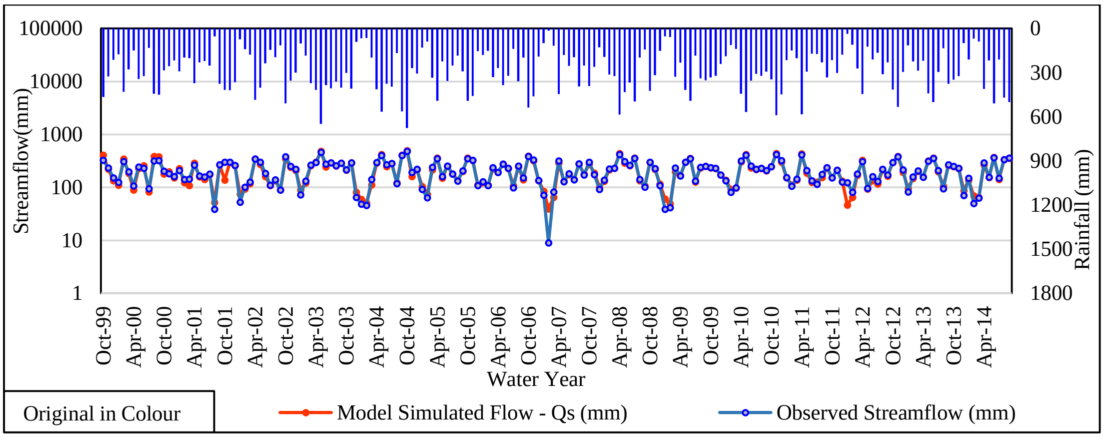
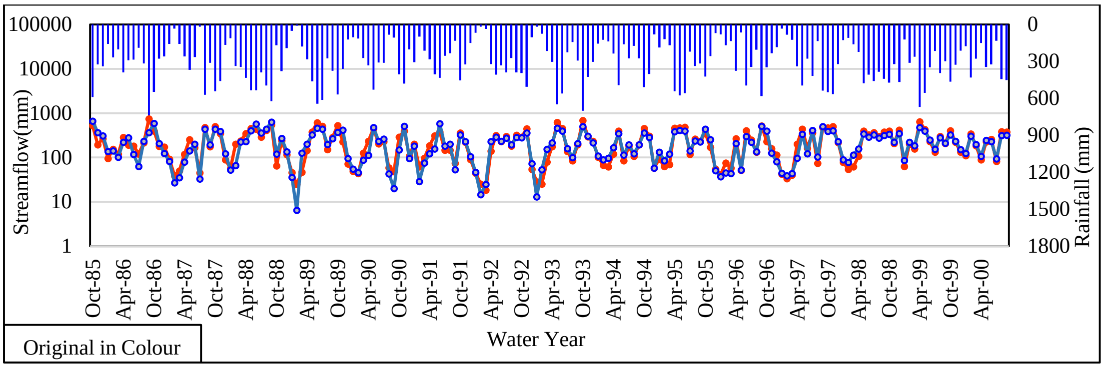
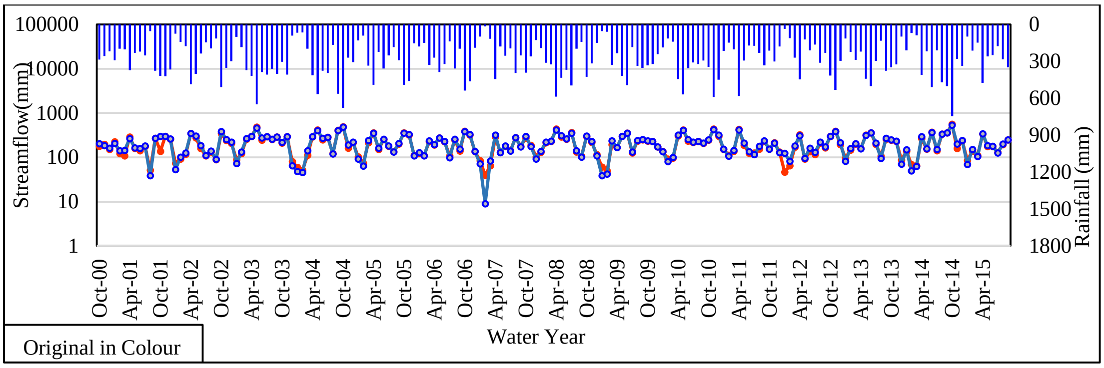
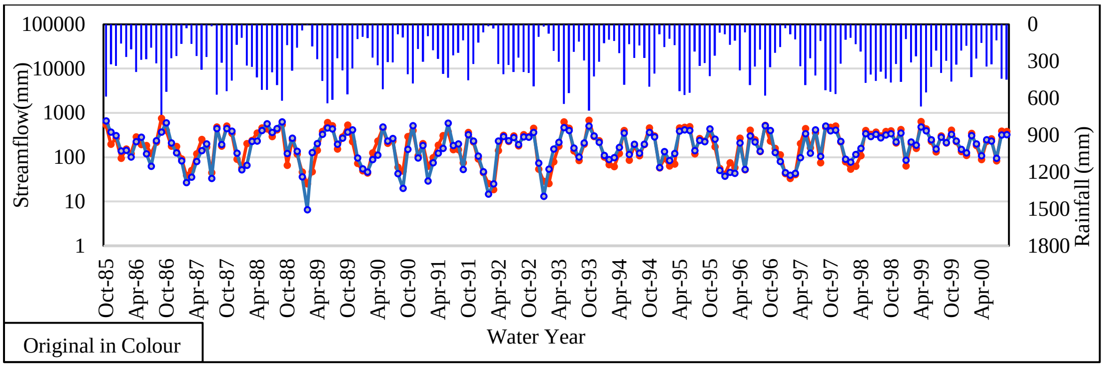


Figure D.96 – D.99: Hydrographs of Observed and Simulated Flow Hydrographs of 30 Year Datasets (1983/1984-2012/13 to 1984/85-2013/14)

Hydrograph Comparison – 30 Year Datasets – Calibration (Set 3 – 4)







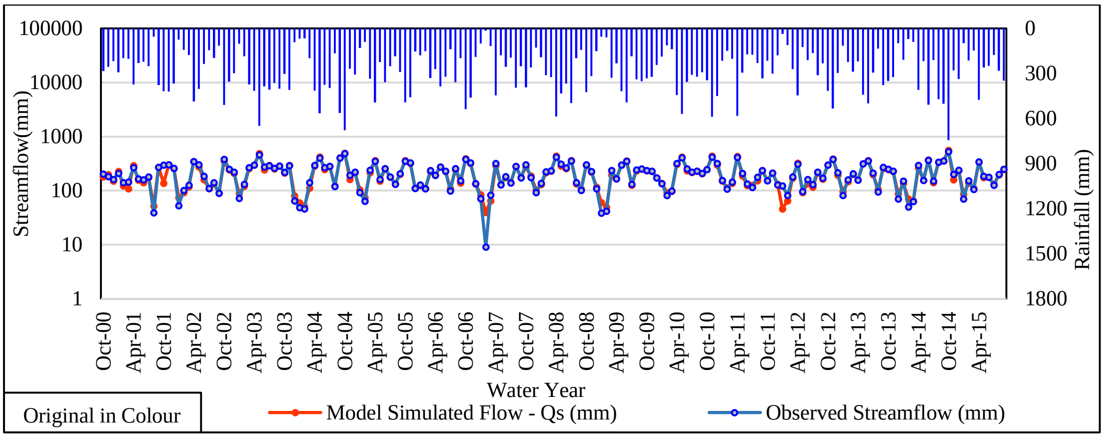
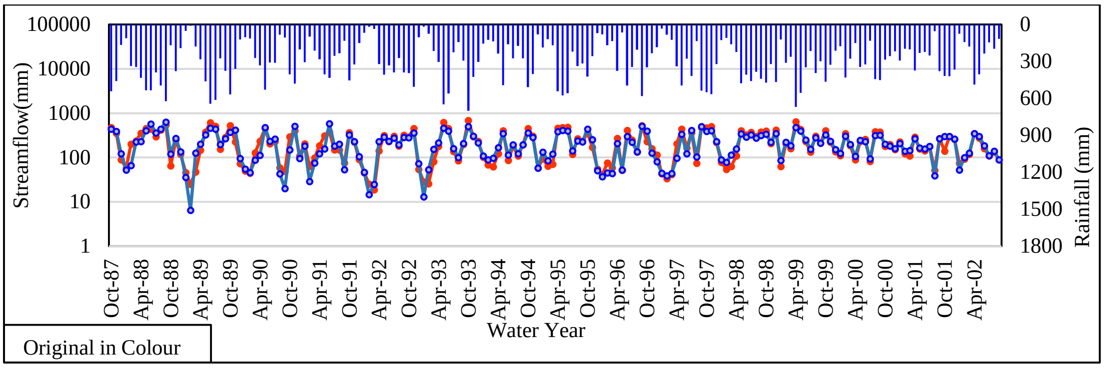


Figure D.100 – D.103: Hydrographs of Observed and Simulated Flow Hydrographs of 30 Year Datasets (1985/1986-2014/15 to 1986/87-2015/16)

Hydrograph Comparison – 30 Year Datasets – Calibration (Set 5)



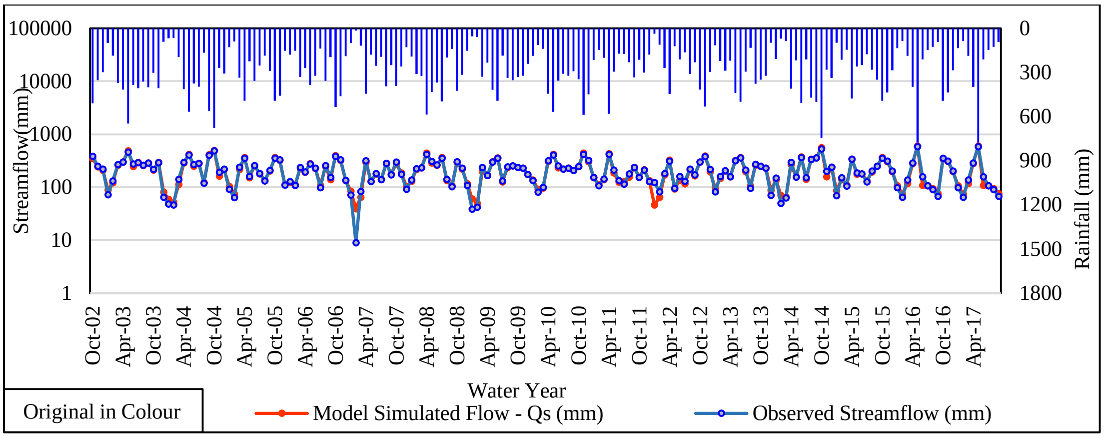


Figure D.104 – D.105: Hydrographs of Observed and Simulated Flow Hydrographs of 30 Year Datasets (1987/1988-2016/17)

APPENDIX D.2 – Flow Duration Curve Comparison

Flow Duration Curve Comparison – 10 Year Datasets – Calibration (Set 1 – 6)

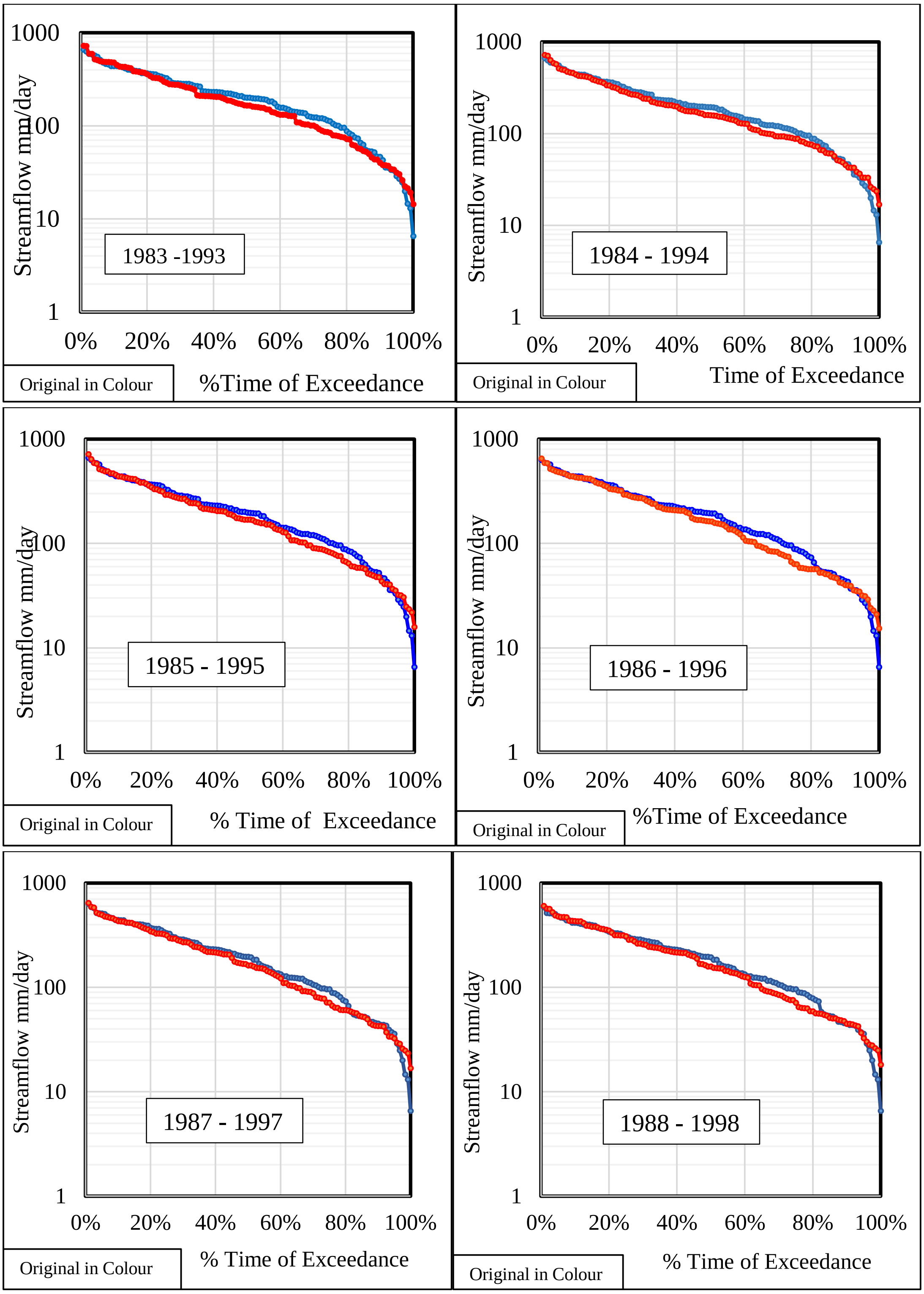


Figure D.106 – D.111 – Flow Duration Curve Comparison – 10 Year Datasets – Calibration

Flow Duration Curve Comparison – 10 Year Datasets – Calibration (Set 7 – 12)

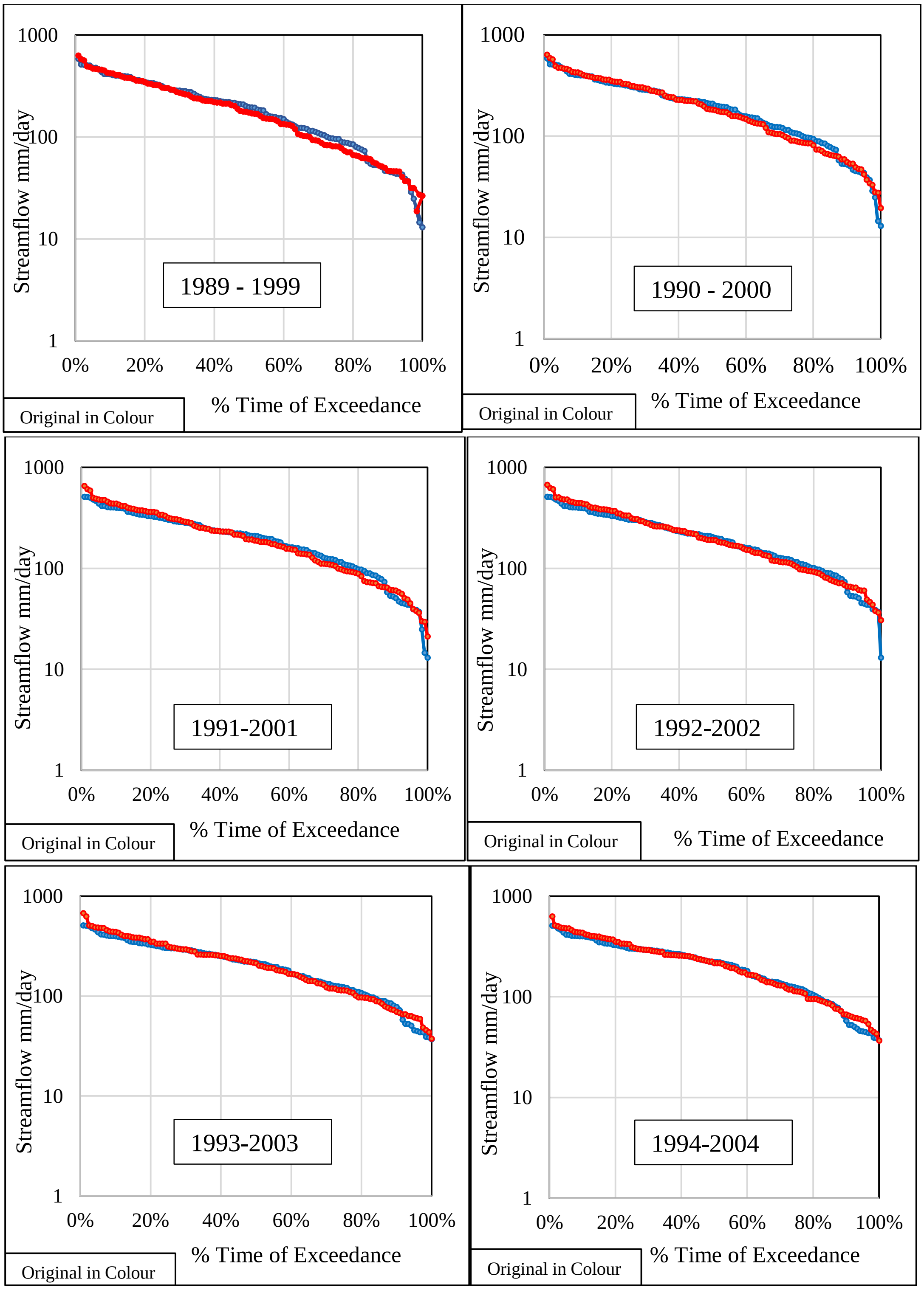


Figure D.112 – D.117 – Flow Duration Curve Comparison – 10 Year Datasets – Calibration

Flow Duration Curve Comparison – 10 Year Datasets – Calibration (Set 13-18)

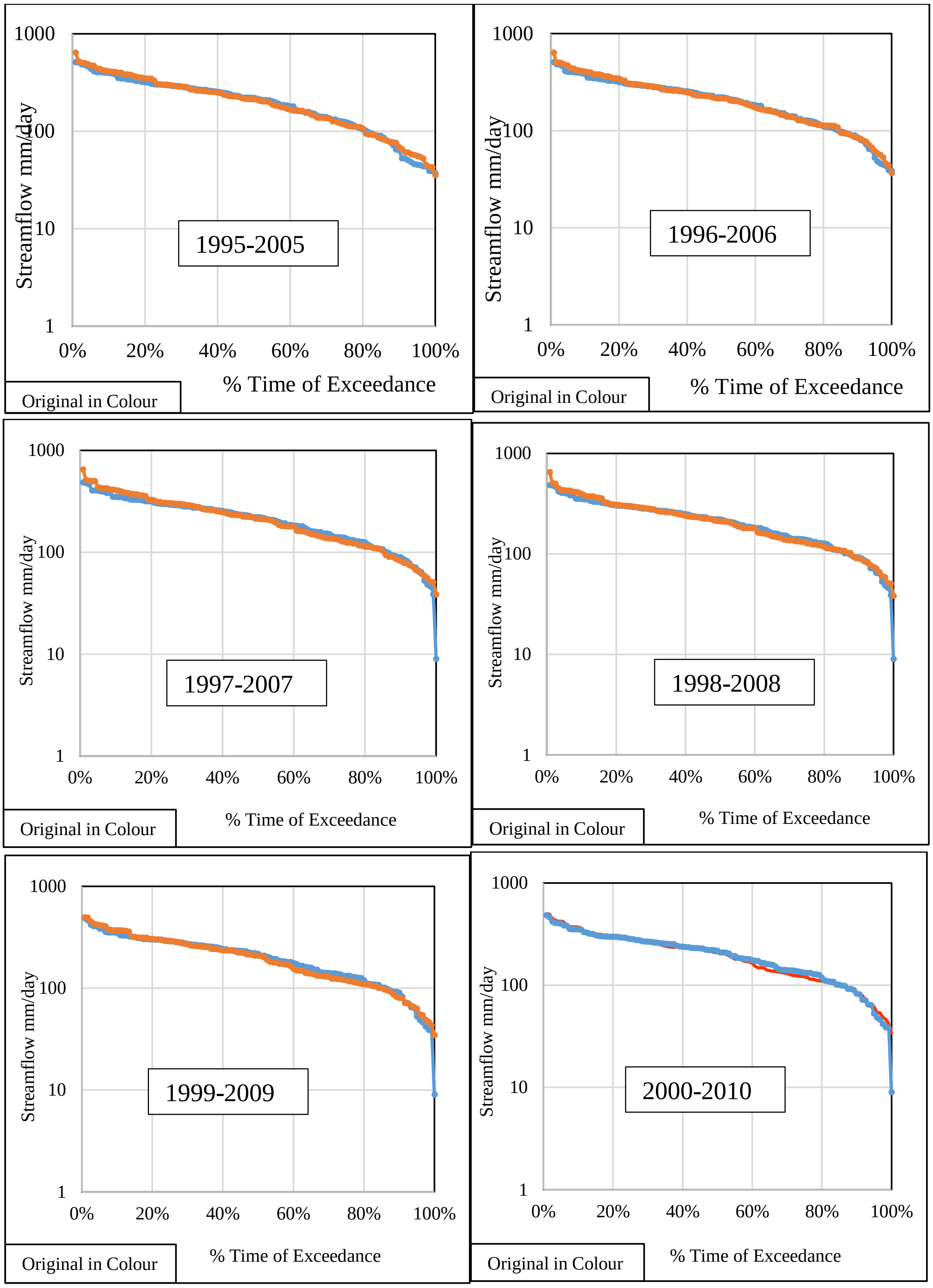


Figure D.118 – D.123 – Flow Duration Curve Comparison – 10 Year Datasets – Calibration

Flow Duration Curve Comparison – 10 Year Datasets – Calibration (Set 19-24)

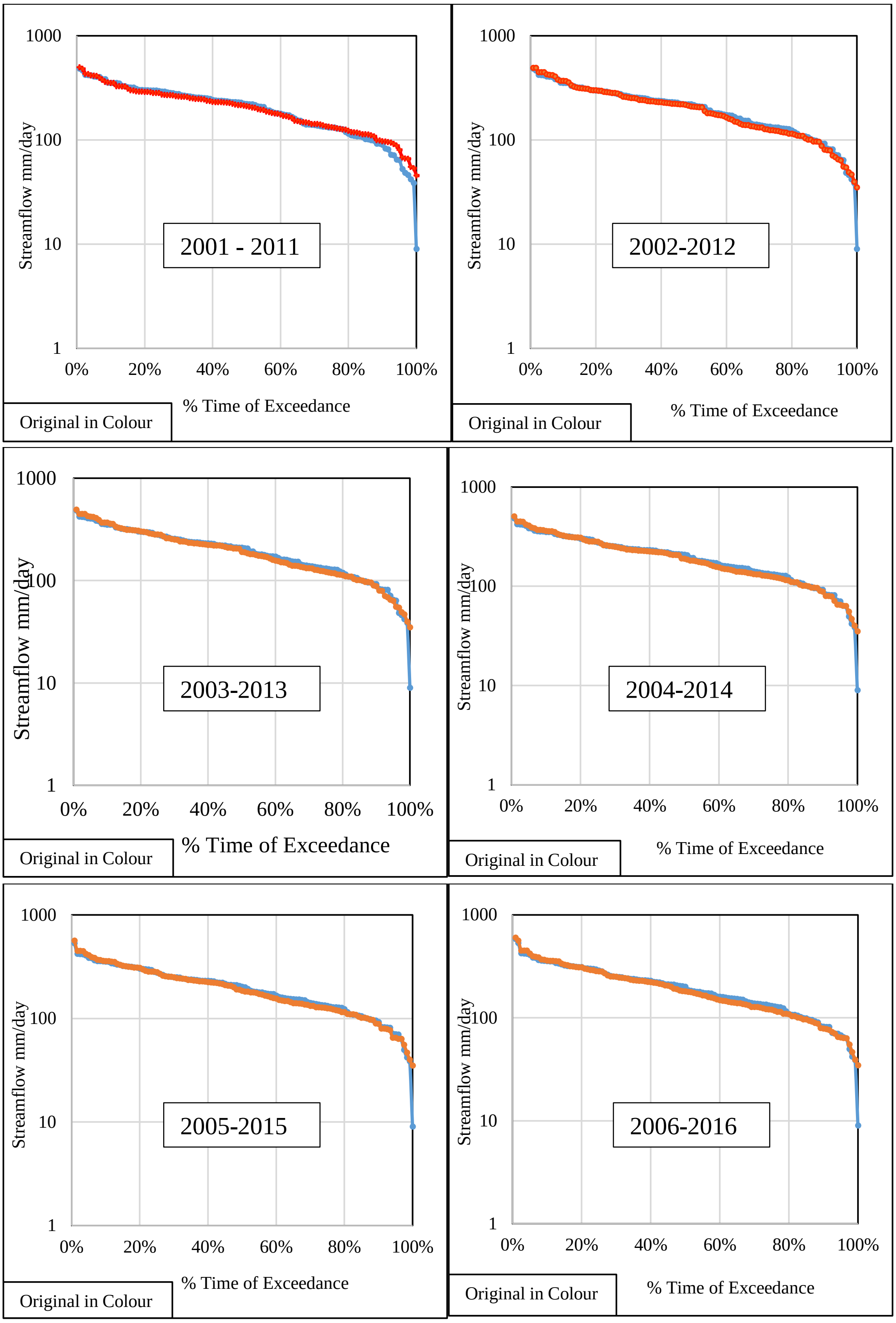


Figure D.124 – D.129 – Flow Duration Curve Comparison – 10 Year Datasets – Calibration

Flow Duration Curve Comparison – 10 Year Datasets – Calibration (Set 25)

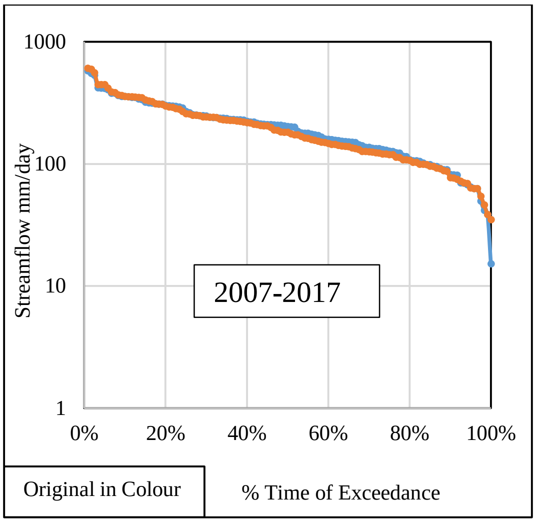


Figure D.130 – Flow Duration Curve Comparison – 10 Year Datasets – Calibration

Flow Duration Curve Comparison – 15 Year Datasets – Calibration (Set 1 – 6)

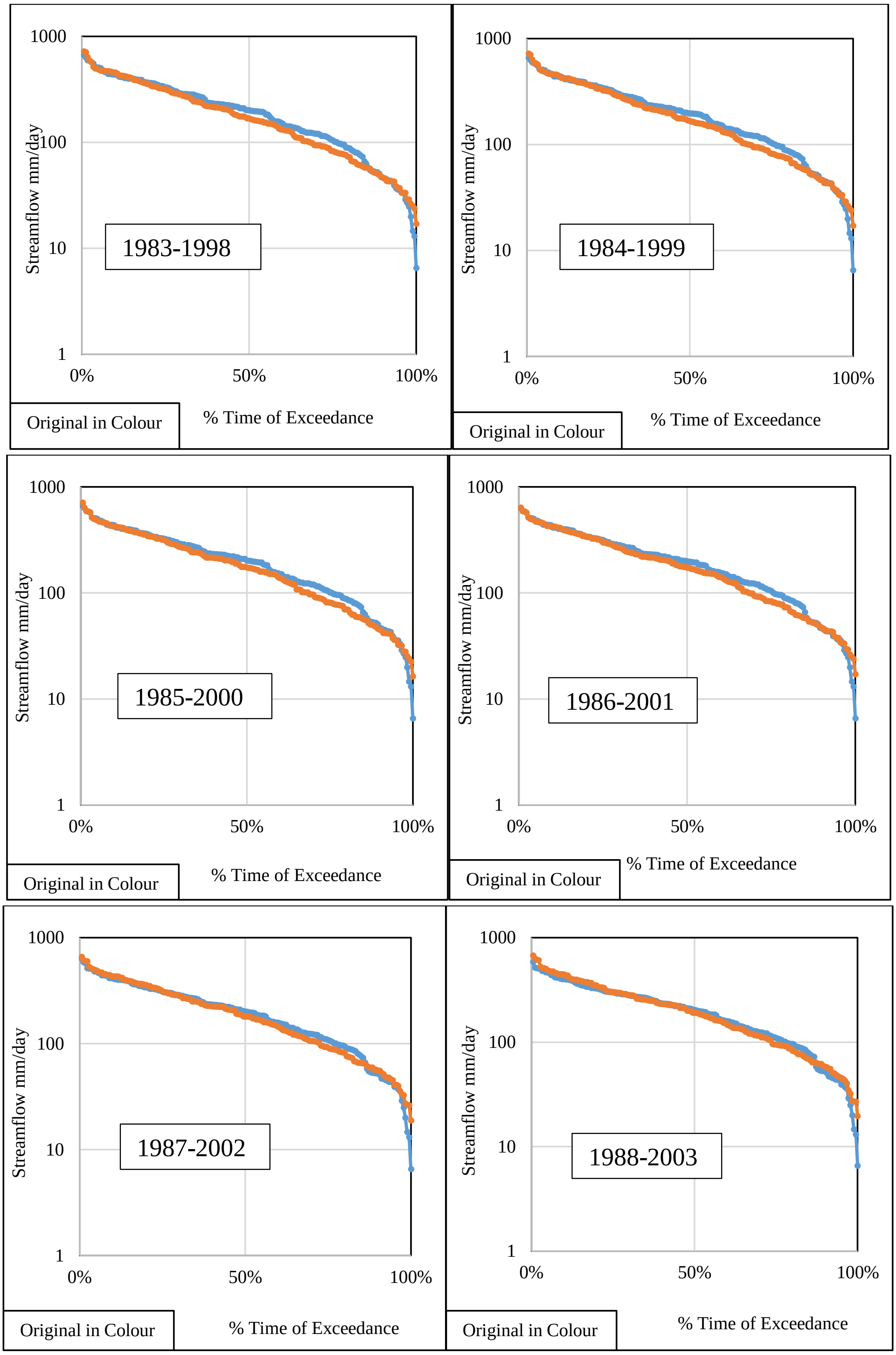


Figure D.131-D136 – Flow Duration Curve Comparison – 15 Year Datasets – Calibration

Flow Duration Curve Comparison – 15 Year Datasets – Calibration (Set 7 – 12)

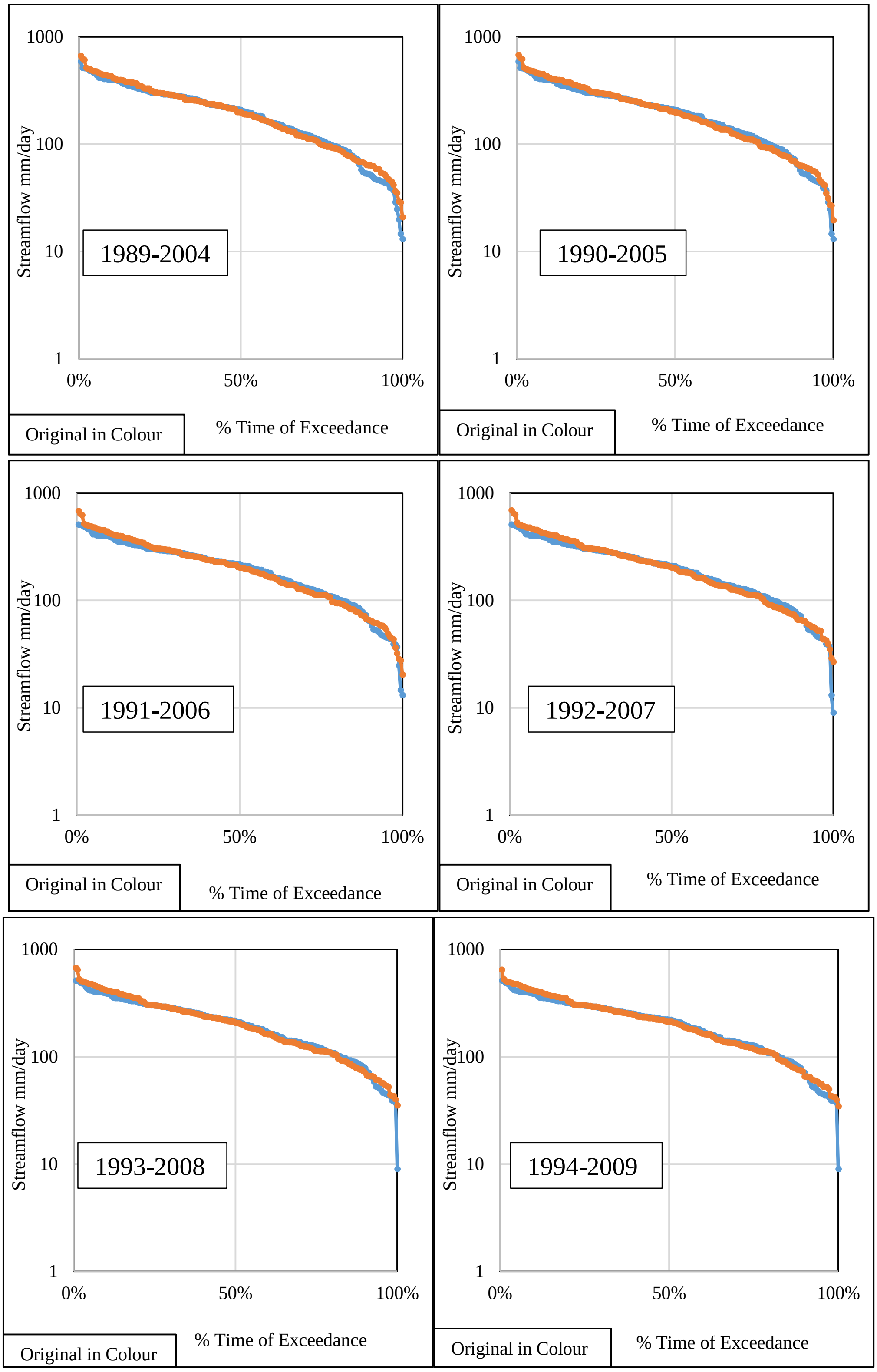


Figure D.137-D.142 – Flow Duration Curve Comparison – 15 Year Datasets – Calibration

Flow Duration Curve Comparison – 15 Year Datasets – Calibration (Set 13–18)

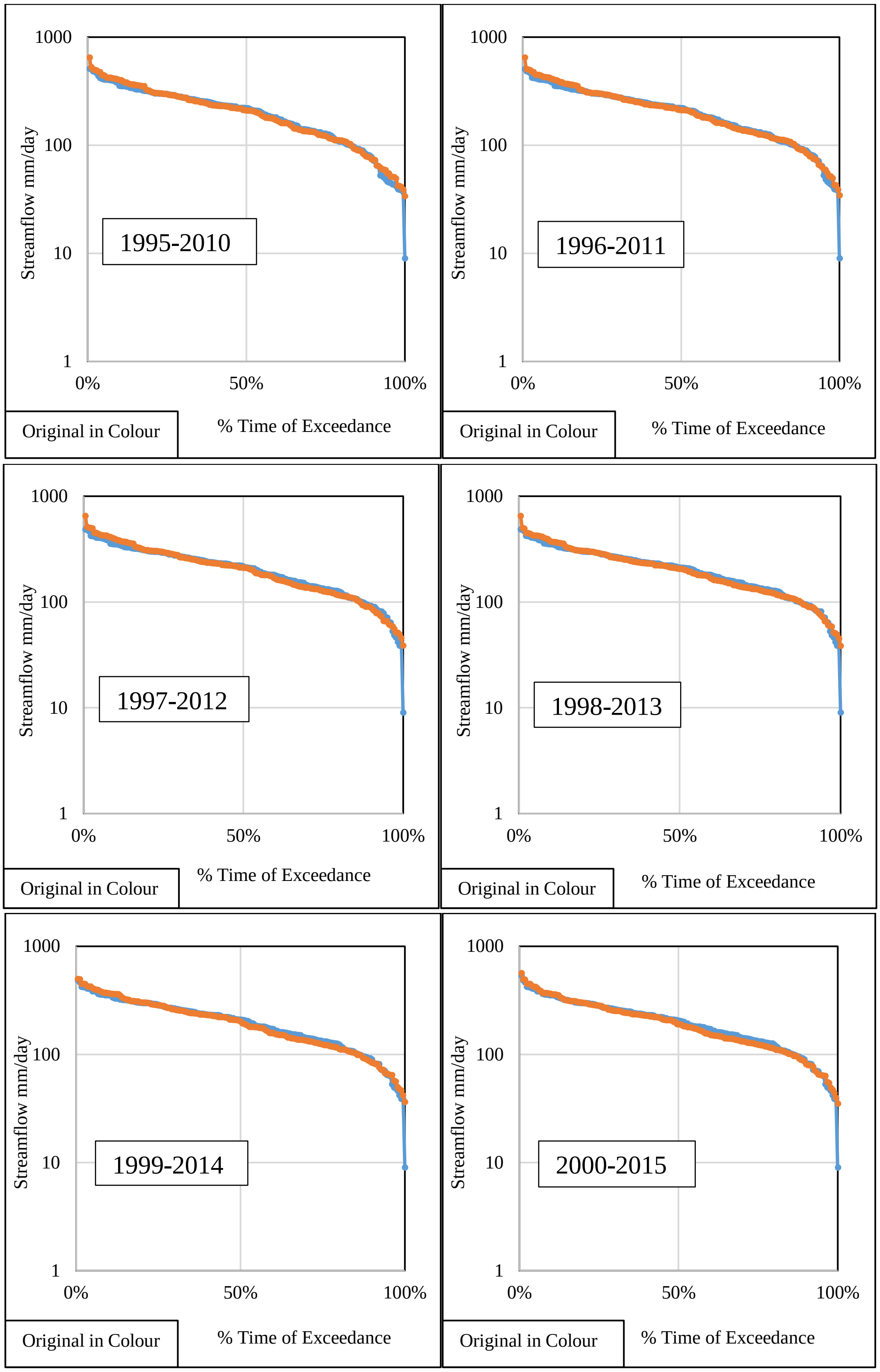


Figure D.143-D.148 – Flow Duration Curve Comparison – 15 Year Datasets – Calibration

Flow Duration Curve Comparison – 15 Year Datasets – Calibration (Set 19–20)

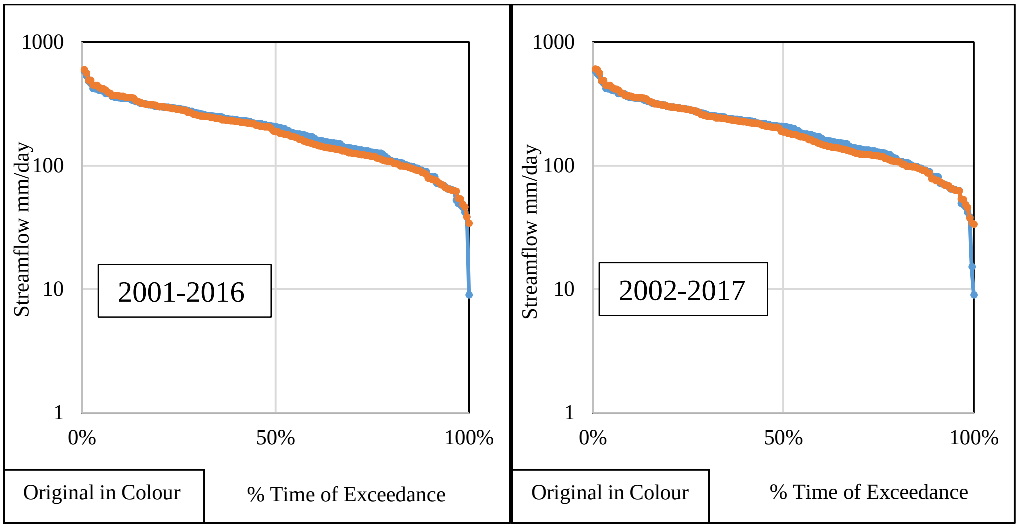


Figure D.149-D.150 – Flow Duration Curve Comparison – 15 Year Datasets – Calibration

Flow Duration Curve Comparison – 20 Year Datasets – Calibration (Set 1 – 6)

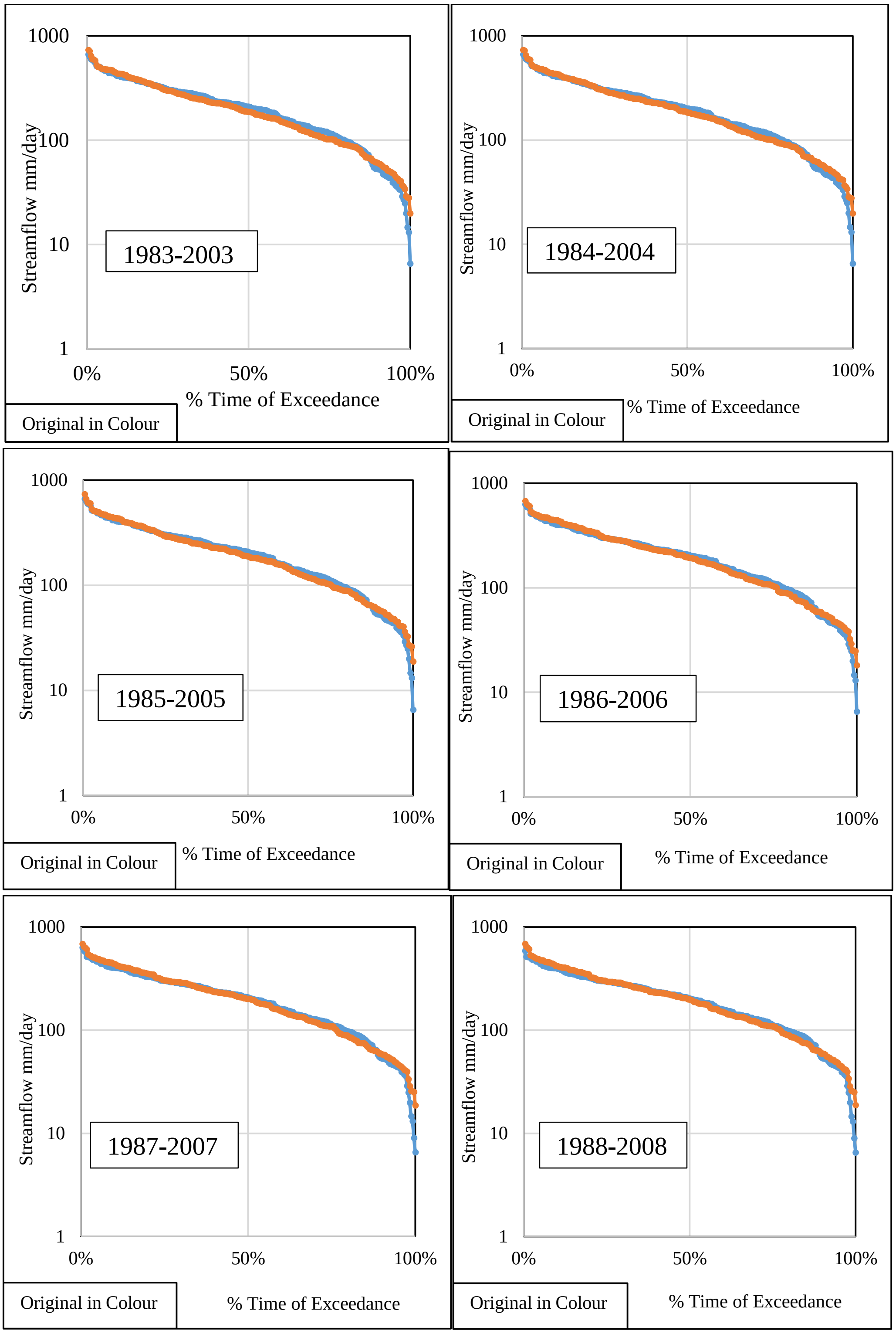


Figure D.151-D.156 – Flow Duration Curve Comparison – 20 Year Datasets – Calibration

Flow Duration Curve Comparison – 20 Year Datasets – Calibration (Set 7 – 12)

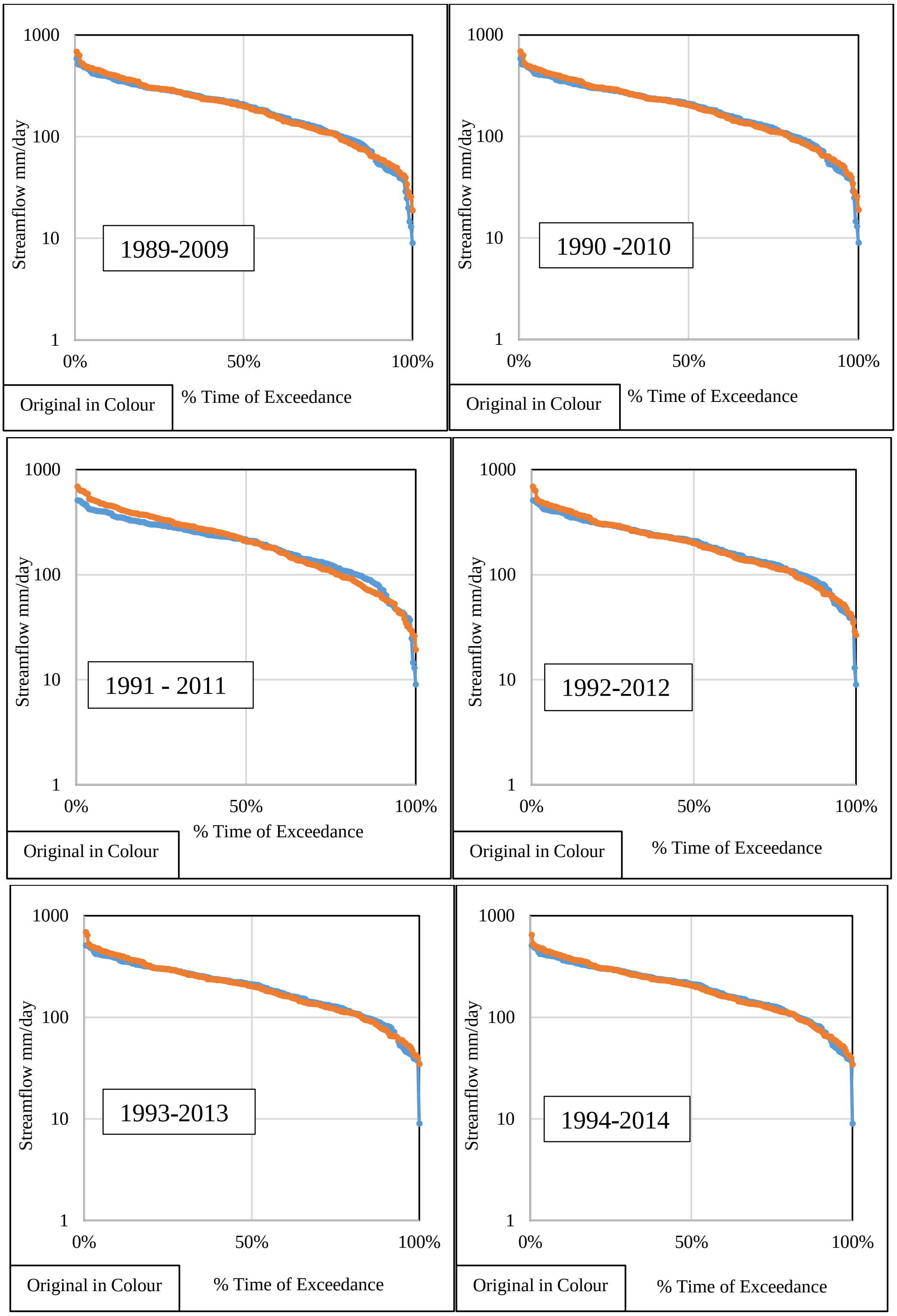


Figure D.157-D.162 – Flow Duration Curve Comparison – 20 Year Datasets – Calibration

Flow Duration Curve Comparison – 20 Year Datasets – Calibration (Set 13–15)

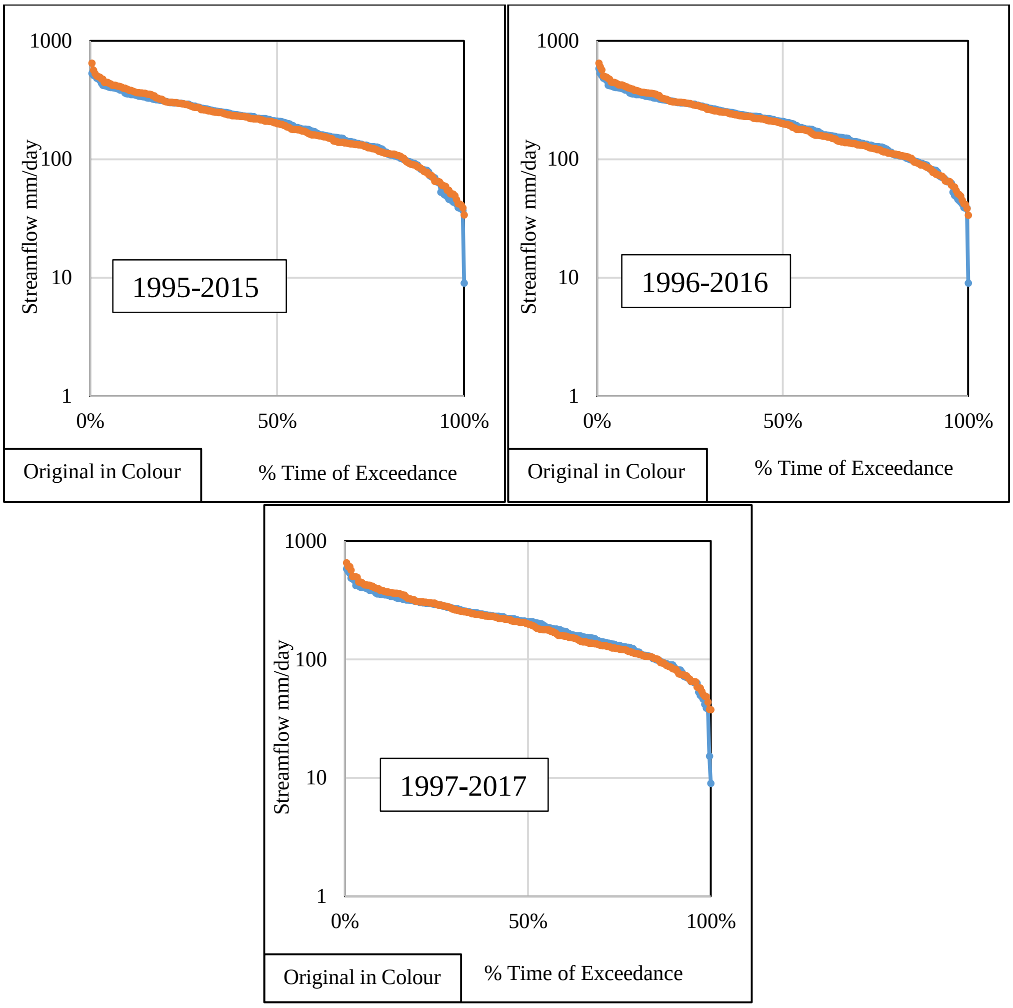


Figure D.163-D.165 – Flow Duration Curve Comparison – 20 Year Datasets – Calibration

Flow Duration Curve Comparison – 25 Year Datasets – Calibration (Set 1 – 6)

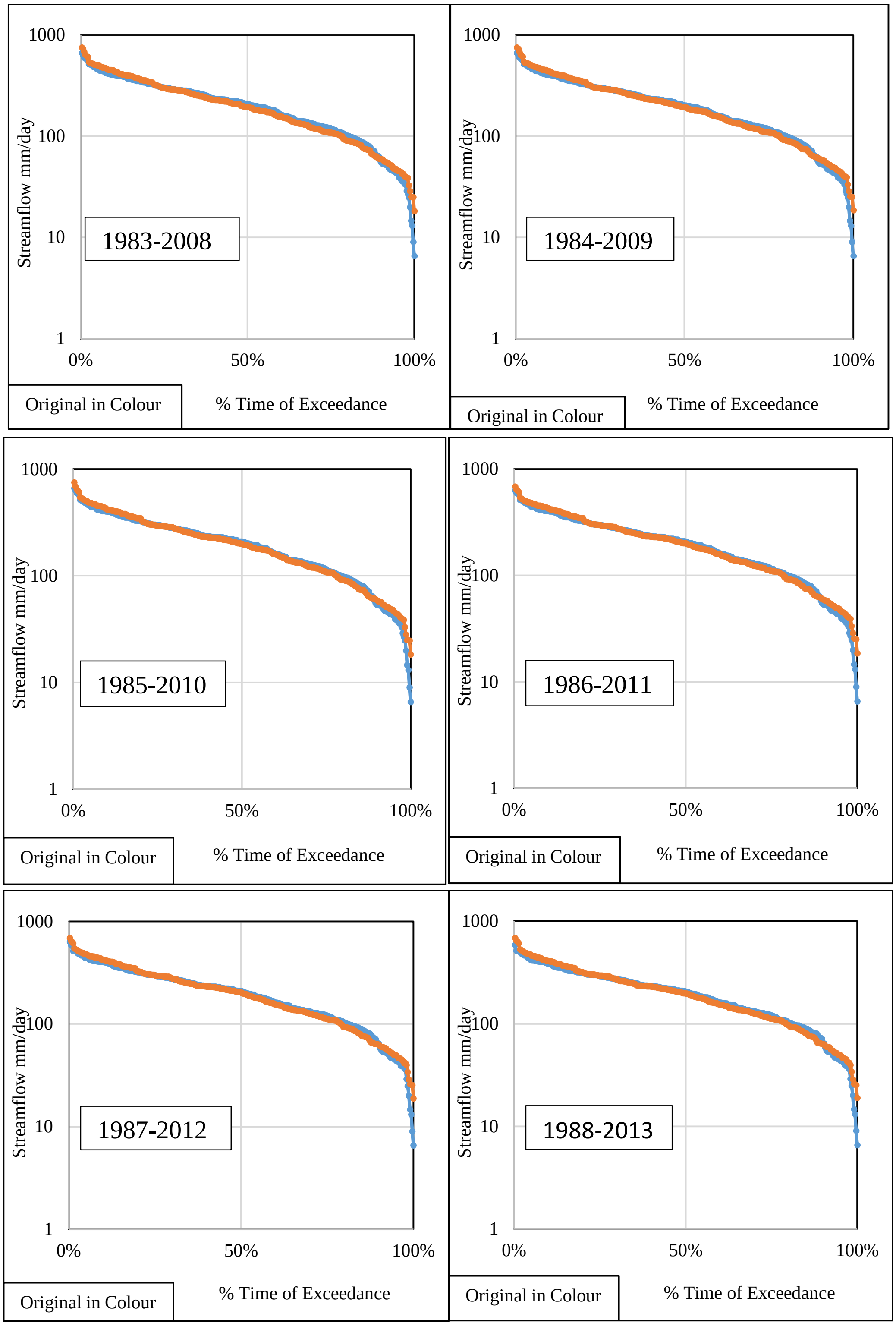


Figure D.166-D.171 – Flow Duration Curve Comparison – 25 Year Datasets – Calibration

Flow Duration Curve Comparison – 25 Year Datasets – Calibration (Set 7 – 10)

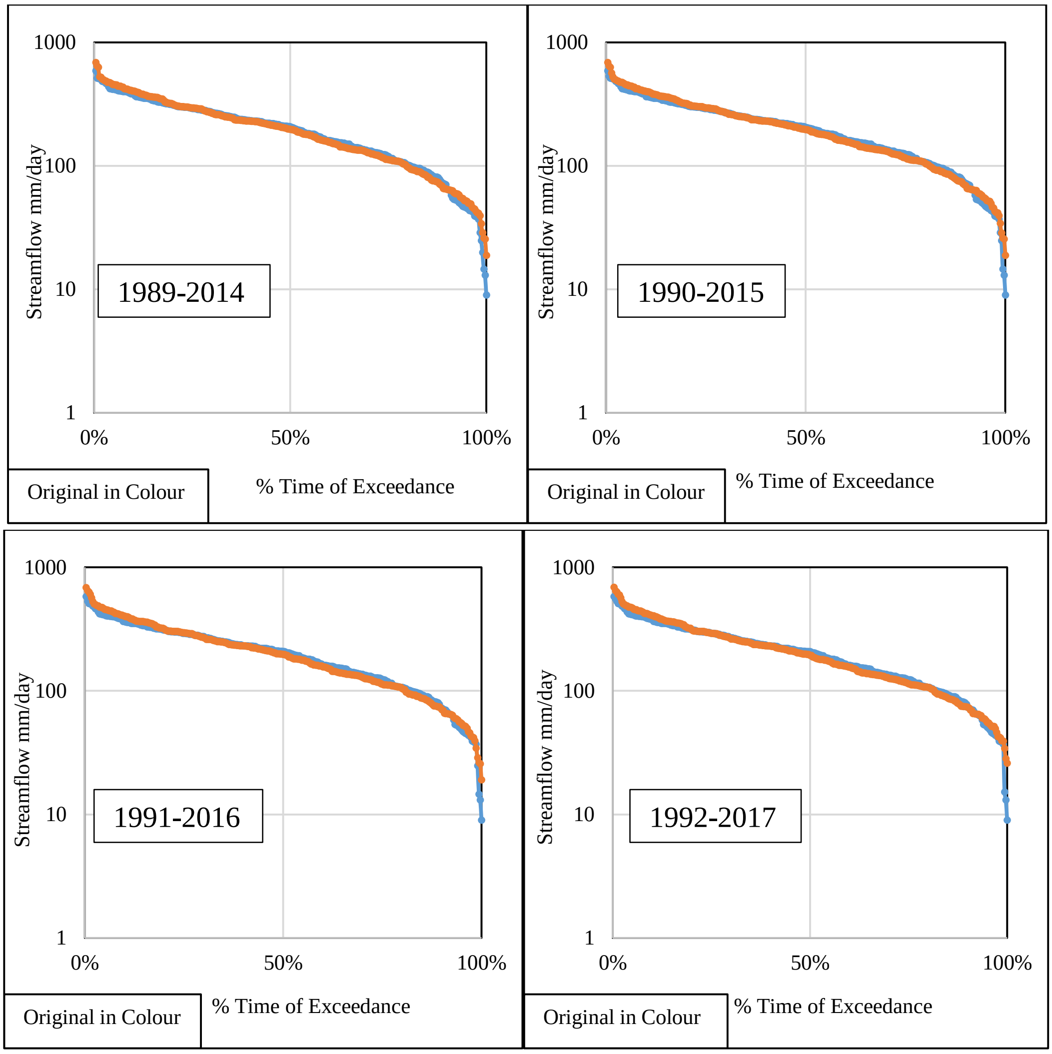


Figure D.172-D.175 – Flow Duration Curve Comparison – 25 Year Datasets – Calibration

Flow Duration Curve Comparison – 30 Year Datasets – Calibration (Set 1 – 5)

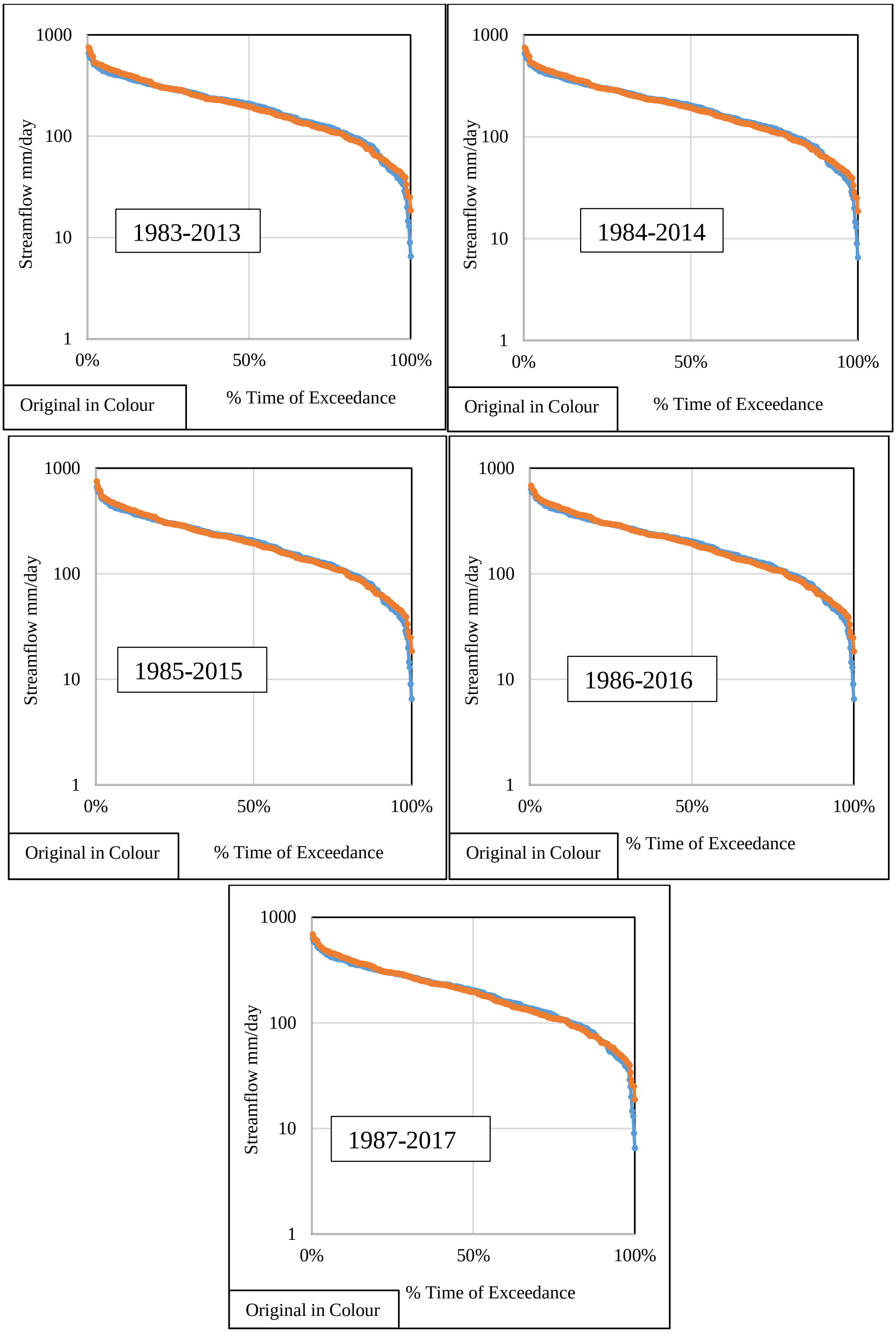


Figure D.176-D.179 – Flow Duration Curve Comparison – 30 Year Datasets – Calibration

APPENDIX D.3 – Annual Water Balance Comparison

Annual Water Balance Comparison – 10 Year Datasets – Calibration (Set 1 – 4)

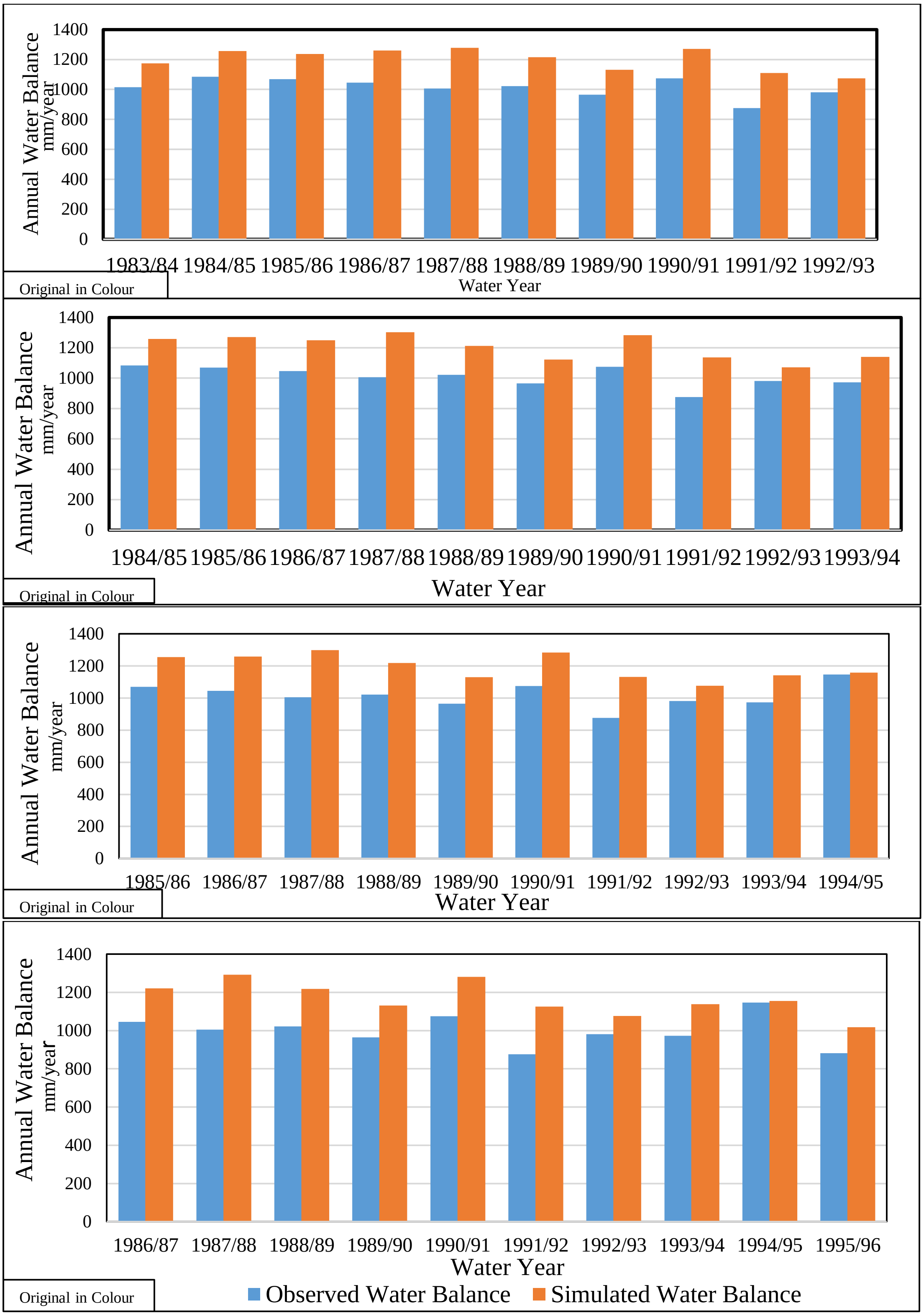


Figure D.169- D.172: Annual Observed and Simulated Water Balance Comparison - 10 year Datasets – Calibration

Annual Water Balance Comparison – 10 Year Datasets – Calibration (Set 5 – 8)

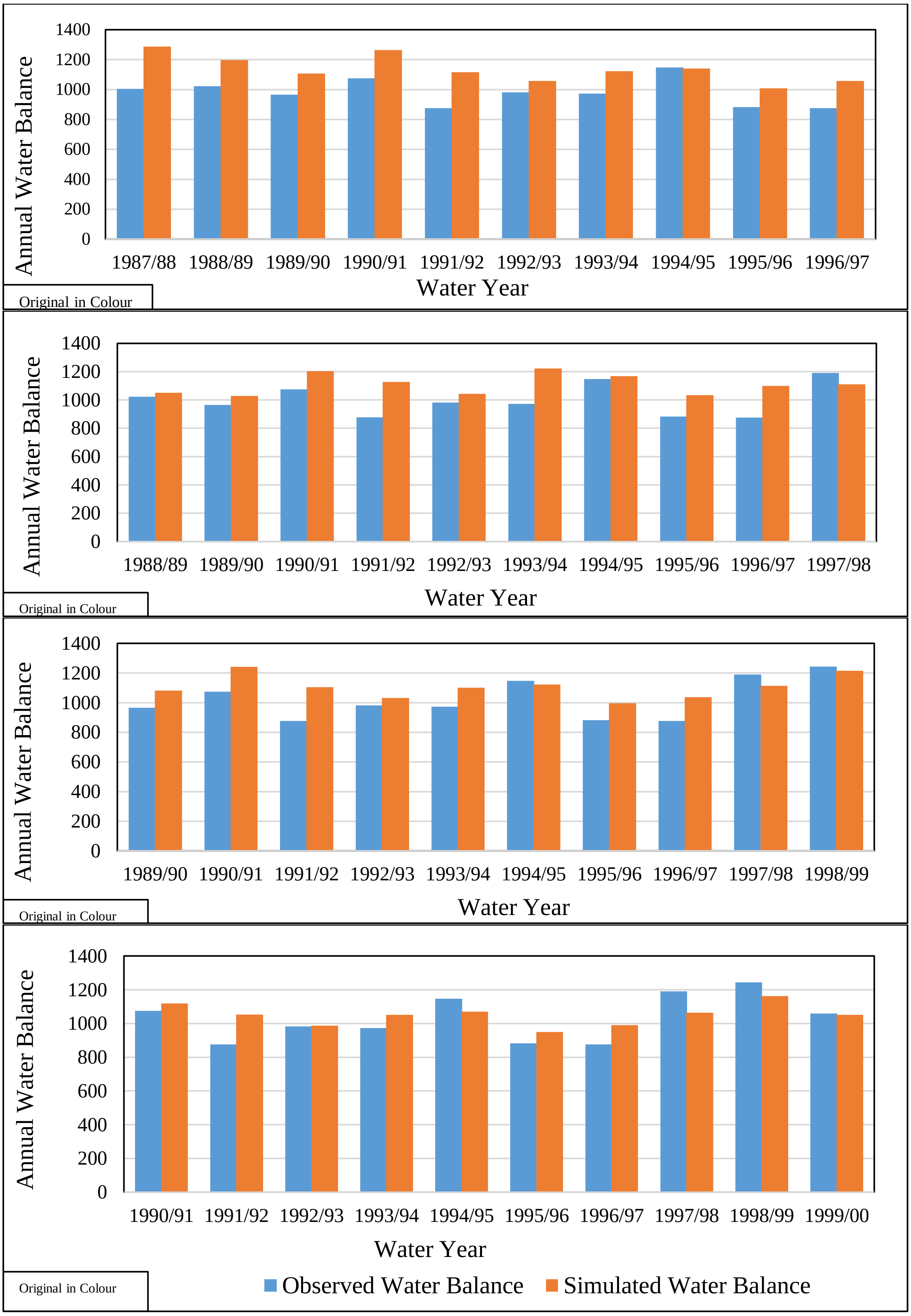


Figure D.173- D.176: Annual Observed and Simulated Water Balance Comparison - 10 year Datasets – Calibration

Annual Water Balance Comparison – 10 Year Datasets – Calibration (Set 9–12)

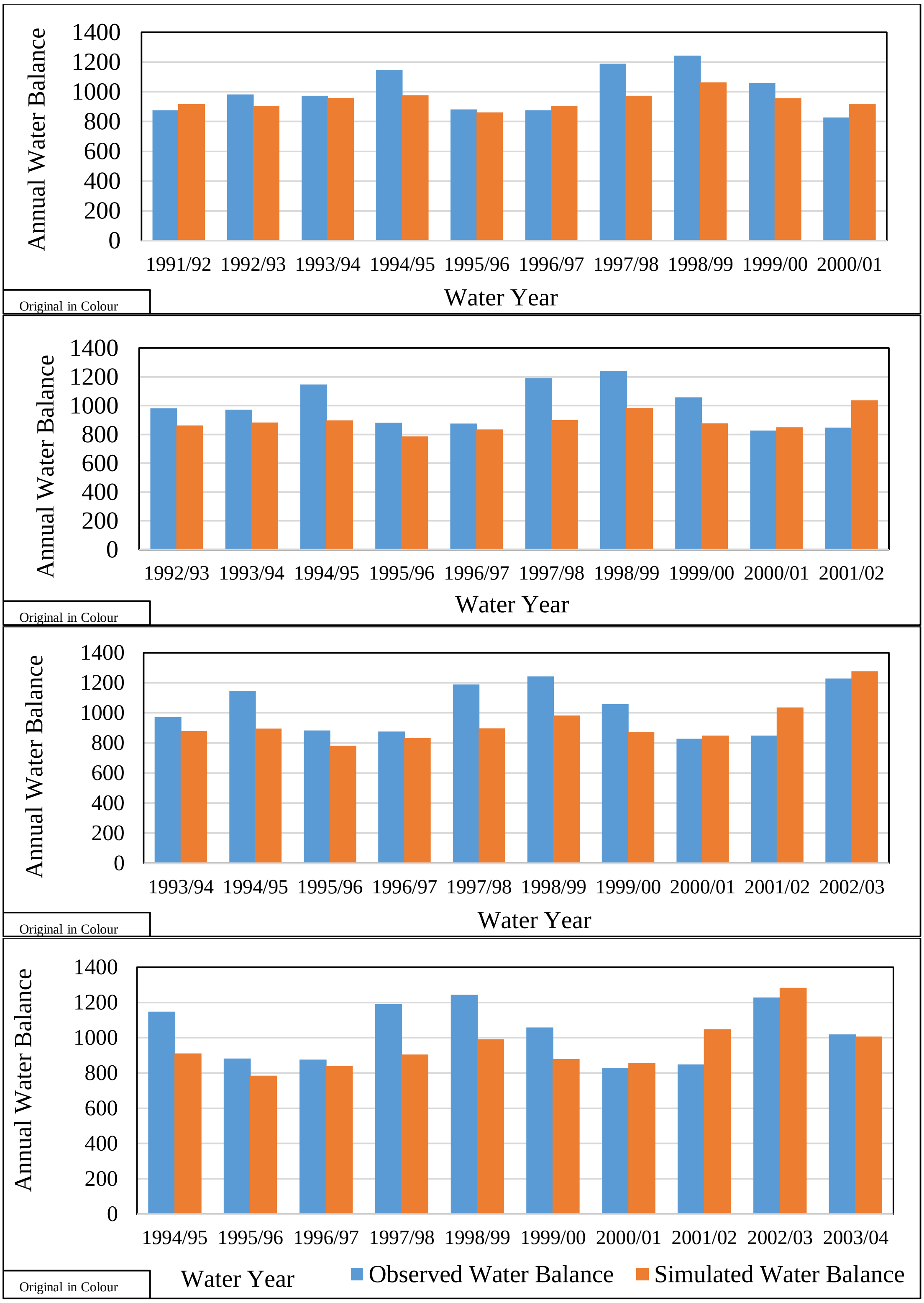


Figure D.177- D.180: Annual Observed and Simulated Water Balance Comparison - 10 year Datasets – Calibration

Annual Water Balance Comparison – 10 Year Datasets –Calibration (Set 13–16)

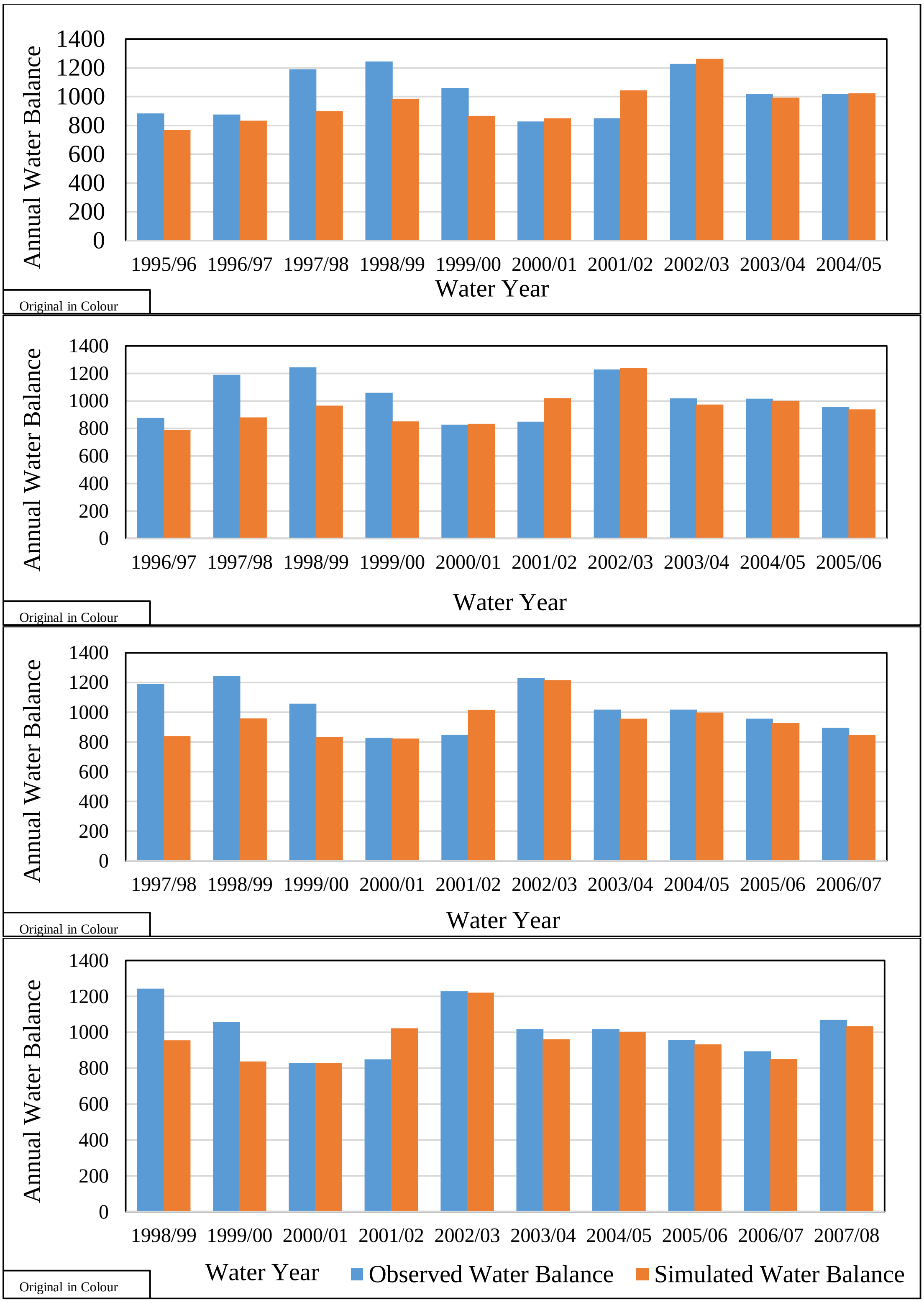
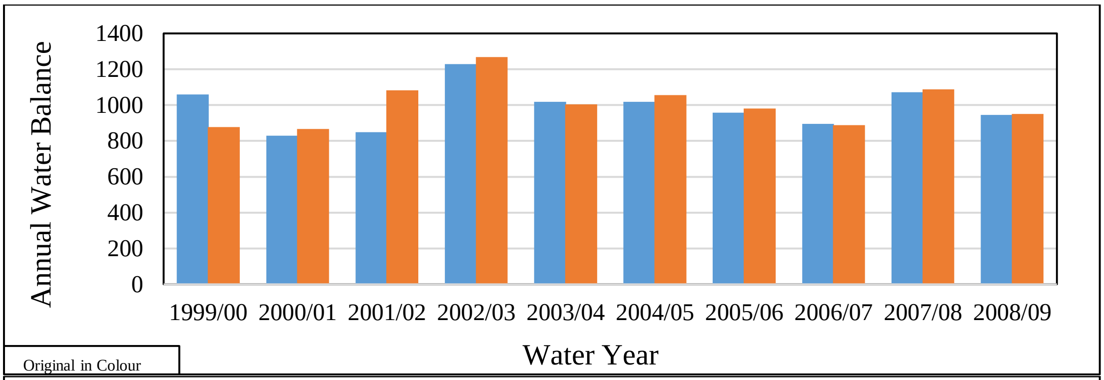
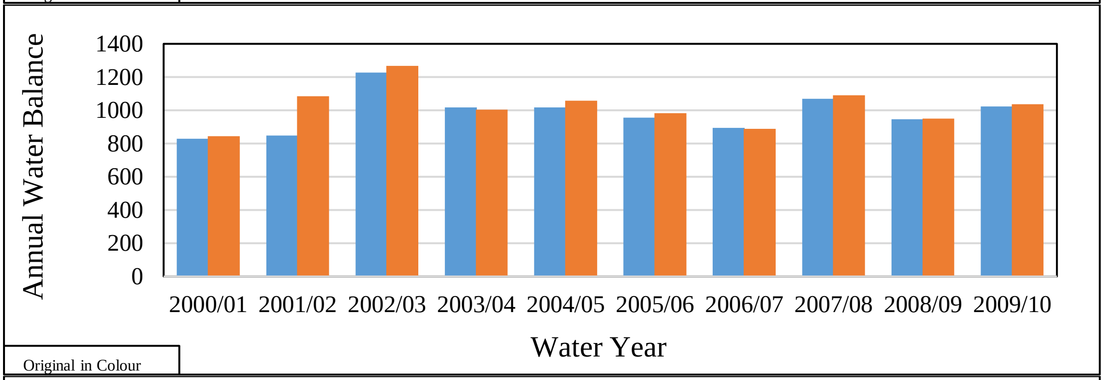
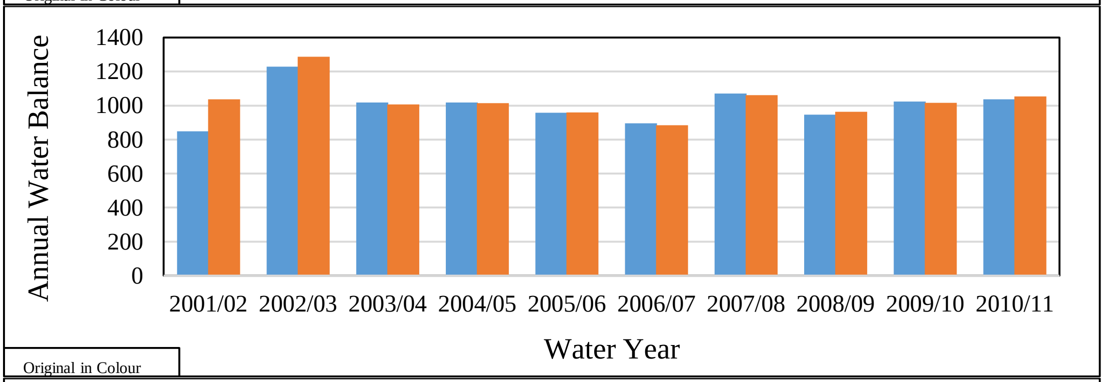


Figure D.181- D.184: Annual Observed and Simulated Water Balance Comparison - 10 year Datasets – Calibration

Annual Water Balance Comparison – 10 Year Datasets –Calibration (Set 17–20)







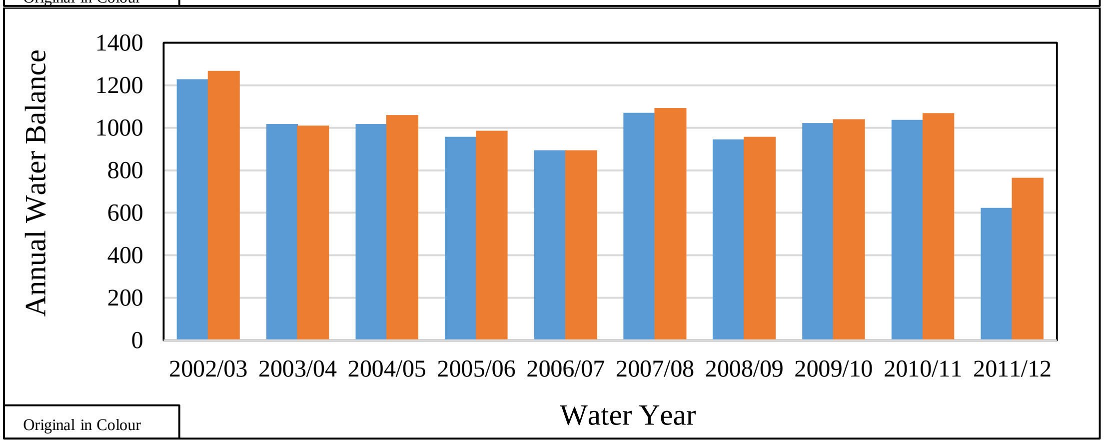


Figure D.185- D.188: Annual Observed and Simulated Water Balance Comparison - 10 year Datasets – Calibration

Annual Water Balance Comparison – 10 Year Datasets –Calibration (Set 21–24)

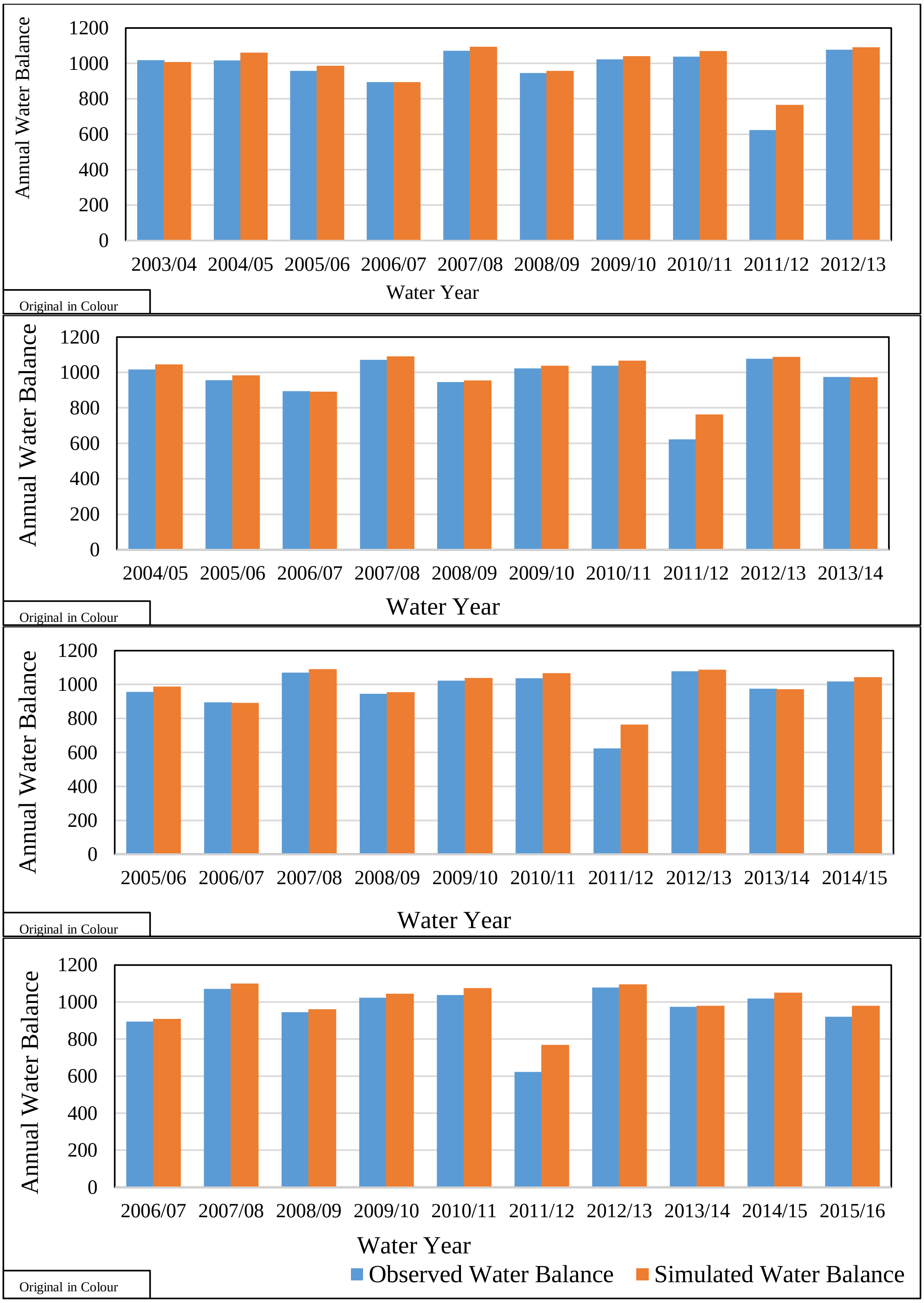


Figure D.185- D.188: Annual Observed and Simulated Water Balance Comparison - 10 year Datasets – Calibration

Annual Water Balance Comparison – 10 Year Datasets –Calibration (Set 25)

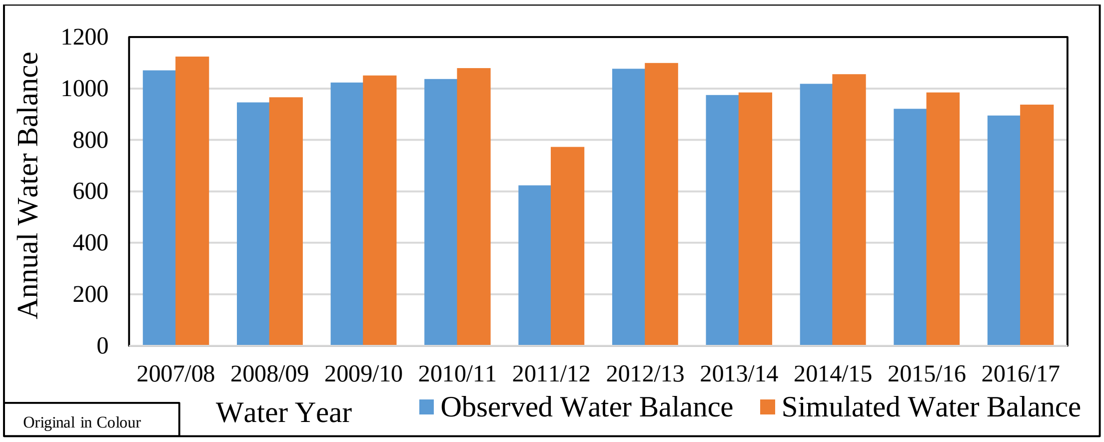


Figure D.189: Annual Observed and Simulated Water Balance Comparison - 10 year Datasets – Calibration

Annual Water Balance Comparison – 15 Year Datasets – Calibration (Set 1 – 4)

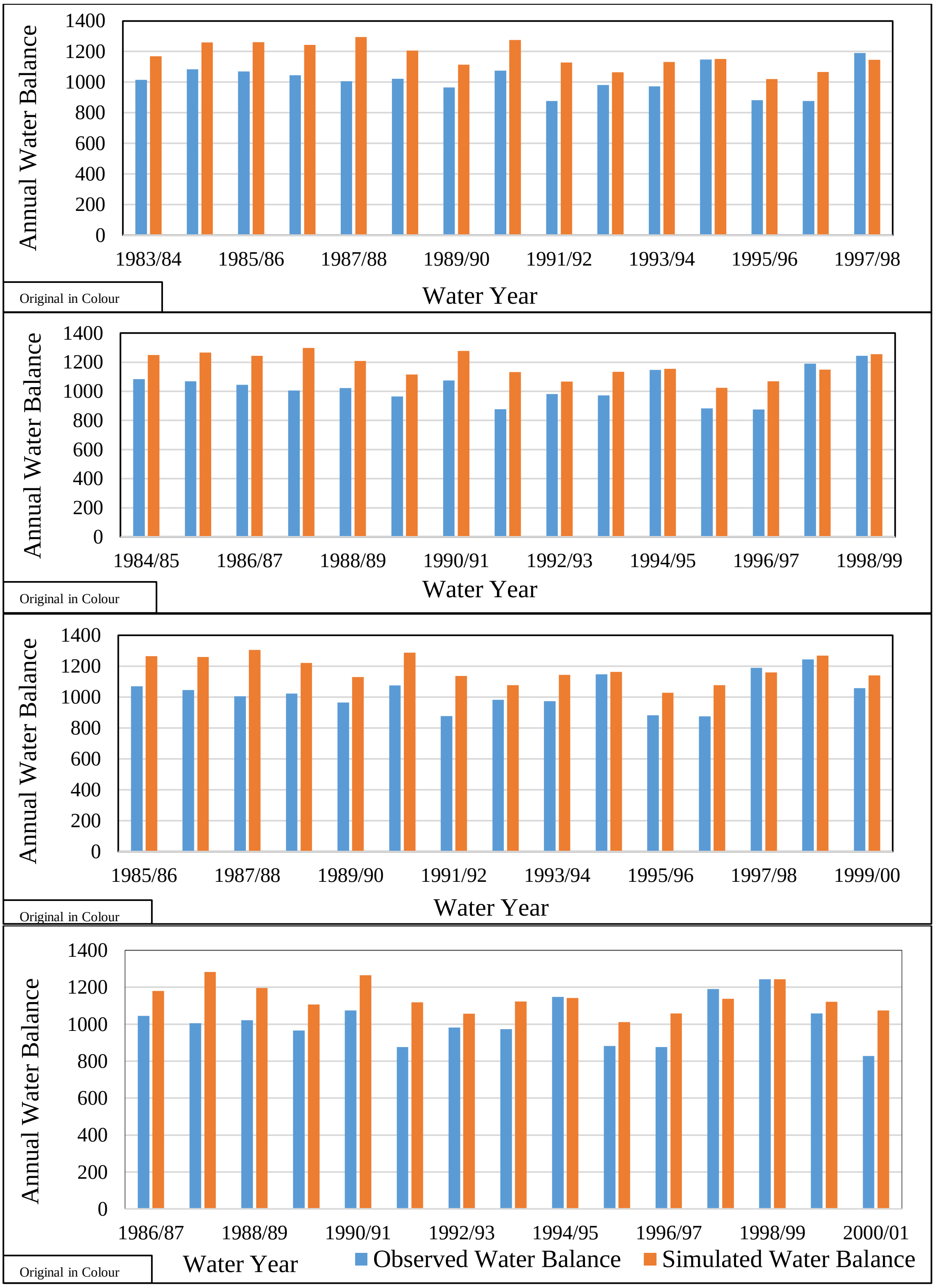
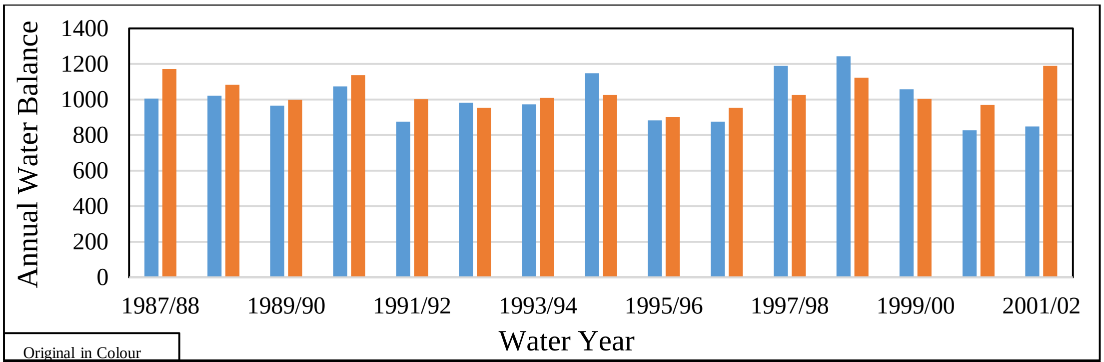
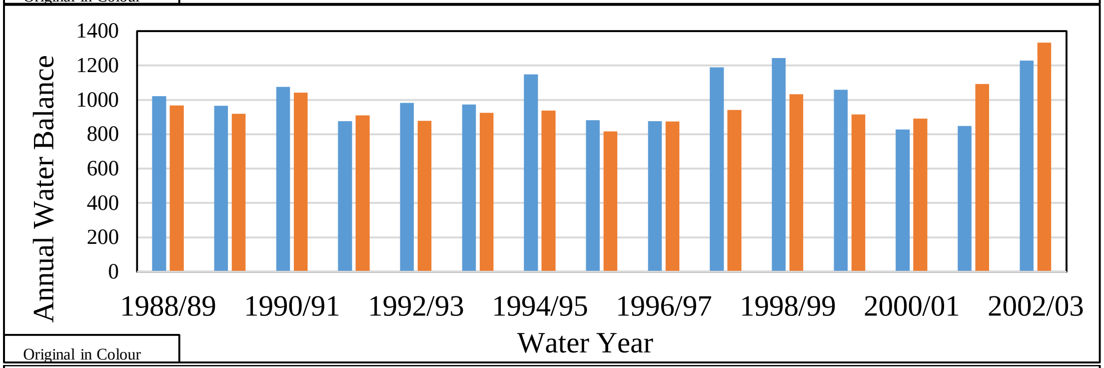
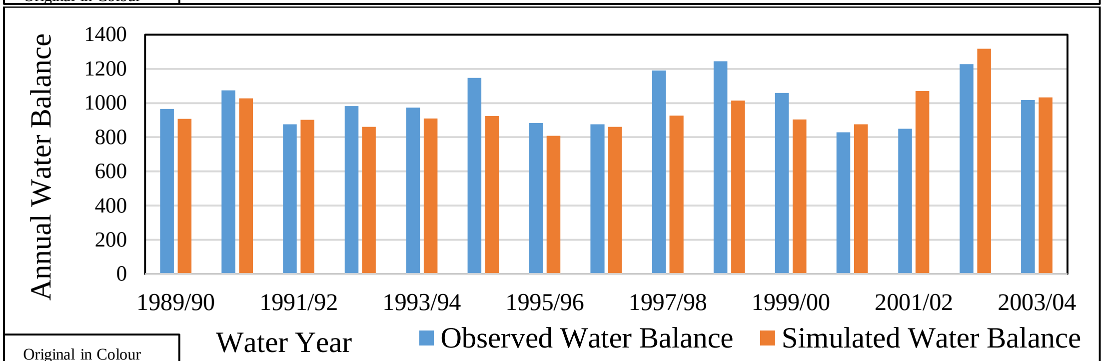


Figure D.190-D.193: Annual Observed and Simulated Water Balance Comparison - 10 year Datasets – Calibration

Annual Water Balance Comparison – 15 Year Datasets – Calibration (Set 5 – 8)







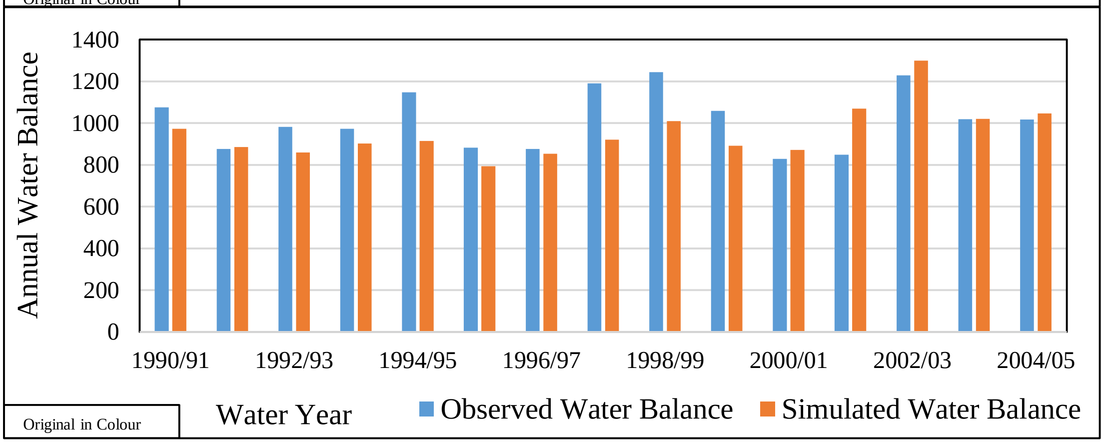


Figure D.194-D.197: Annual Observed and Simulated Water Balance Comparison - 15 year Datasets – Calibration

Annual Water Balance Comparison – 15 Year Datasets – Calibration (Set 9–12)

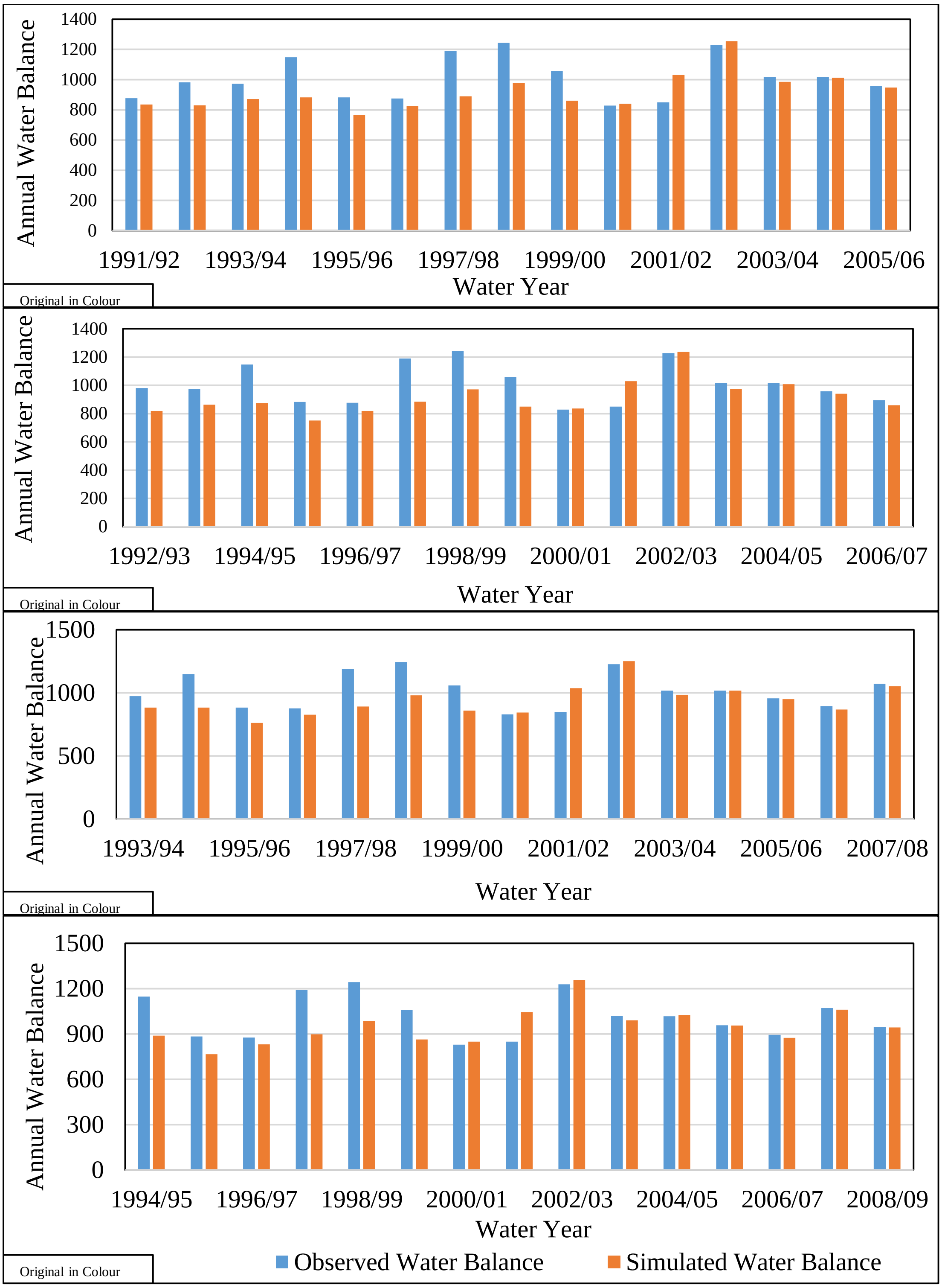


Figure D.198-D.201: Annual Observed and Simulated Water Balance Comparison - 15 year Datasets – Calibration

Annual Water Balance Comparison – 15 Year Datasets–Calibration (Set 13-16)

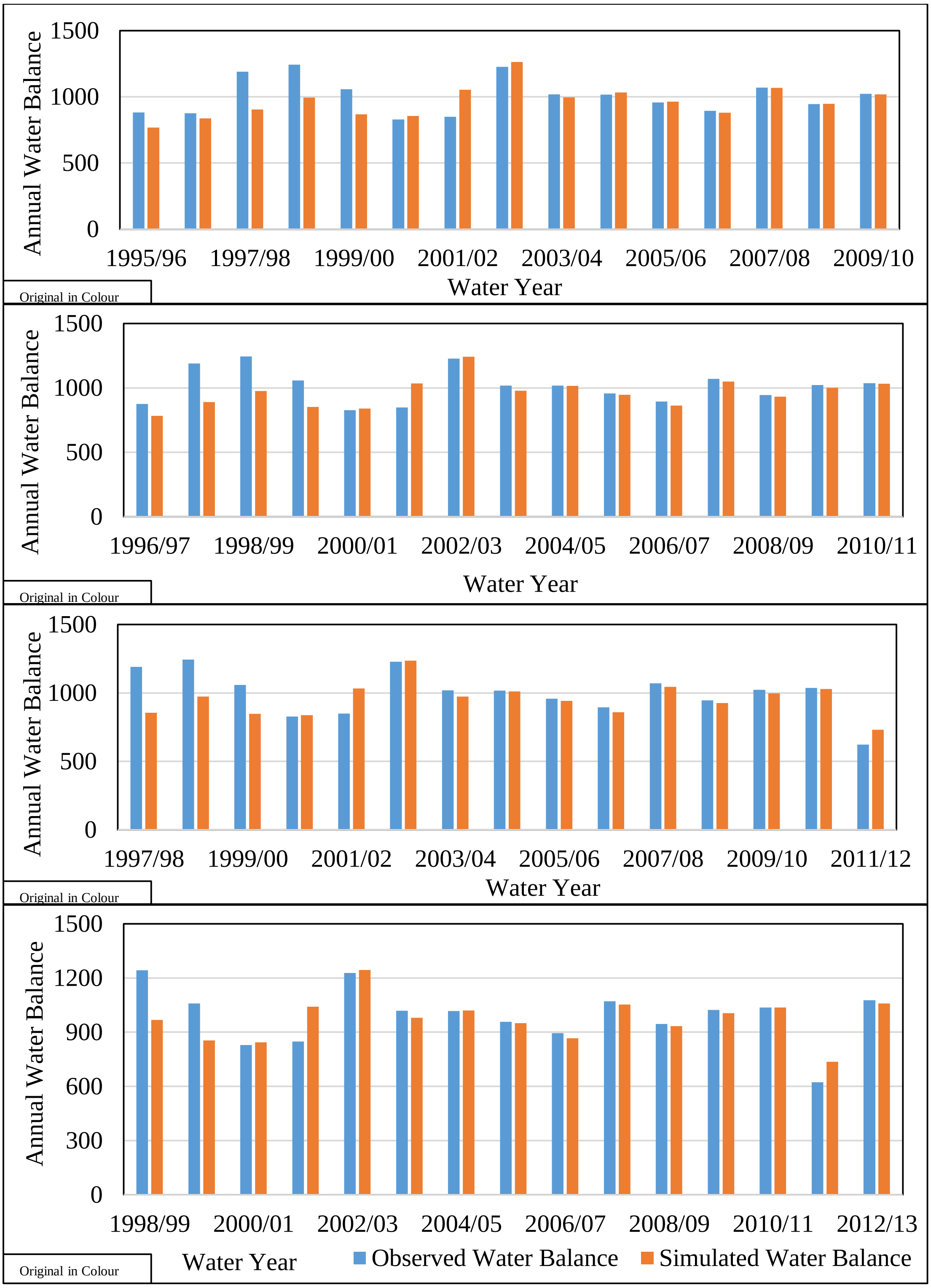


Figure D.202-D.205: Annual Observed and Simulated Water Balance Comparison - 15 year Datasets – Calibration

Annual Water Balance Comparison – 15 Year Datasets–Calibration (Set 17-20)

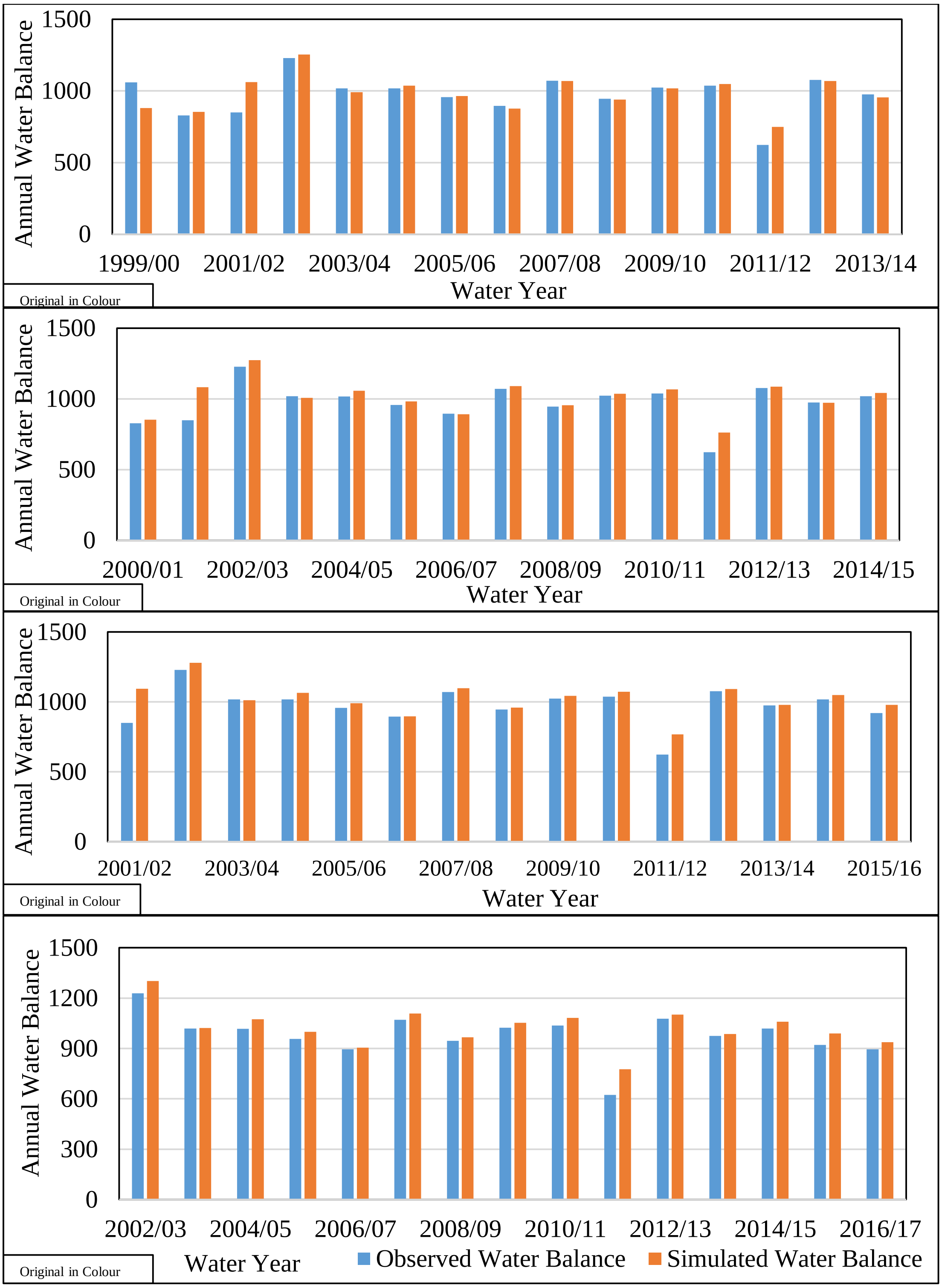


Figure D.206-D.209: Annual Observed and Simulated Water Balance Comparison - 15 year Datasets – Calibration

Annual Water Balance Comparison – 20 Year Datasets – Calibration (Set 1 – 4)

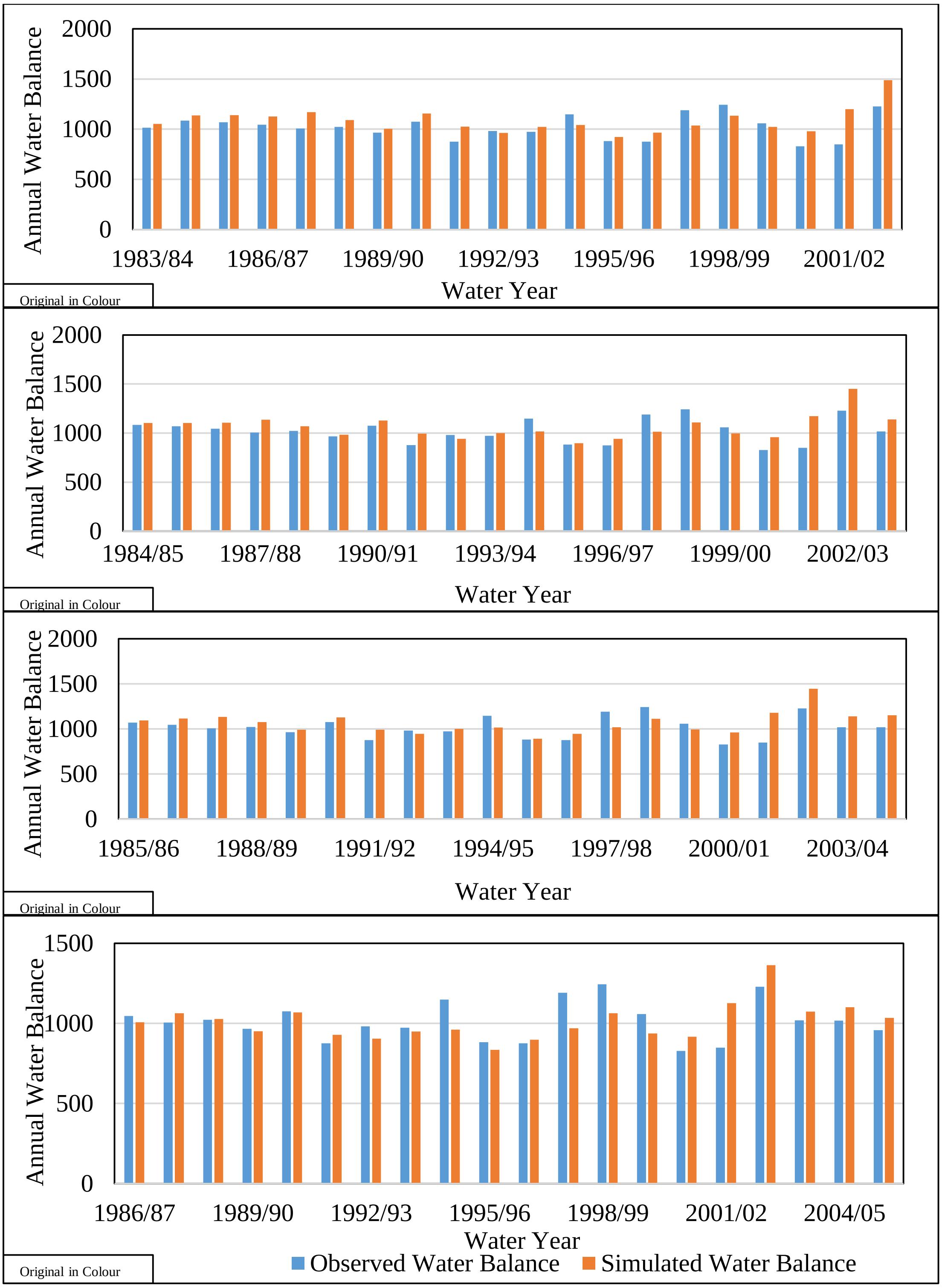


Figure D.210-D.213: Annual Observed and Simulated Water Balance Comparison - 20 year Datasets – Calibration

Annual Water Balance Comparison – 20 Year Datasets – Calibration (Set 5 – 8)

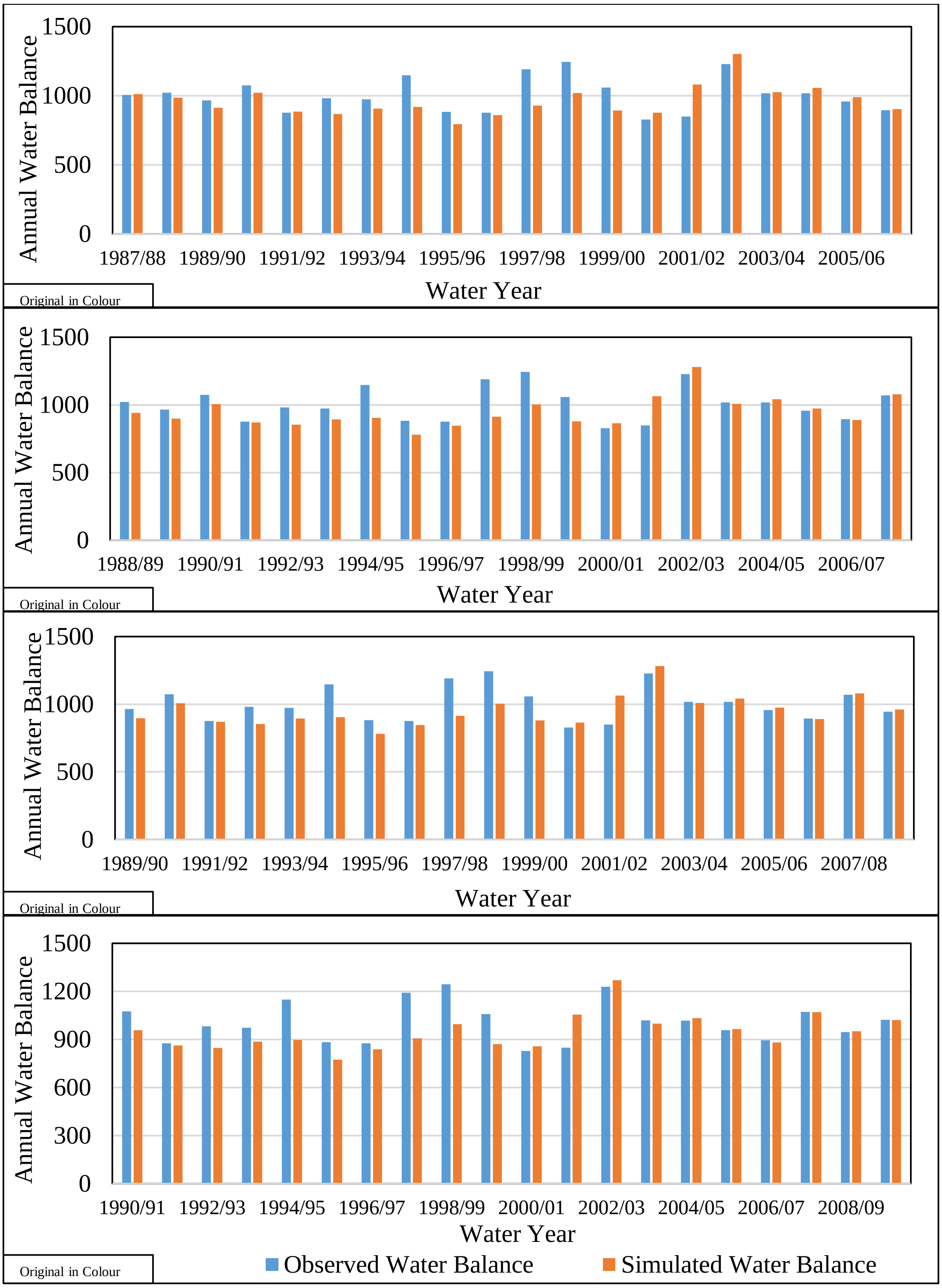


Figure D.214-D.217: Annual Observed and Simulated Water Balance Comparison - 20 year Datasets – Calibration

Annual Water Balance Comparison – 20 Year Datasets – Calibration (Set 9–12)

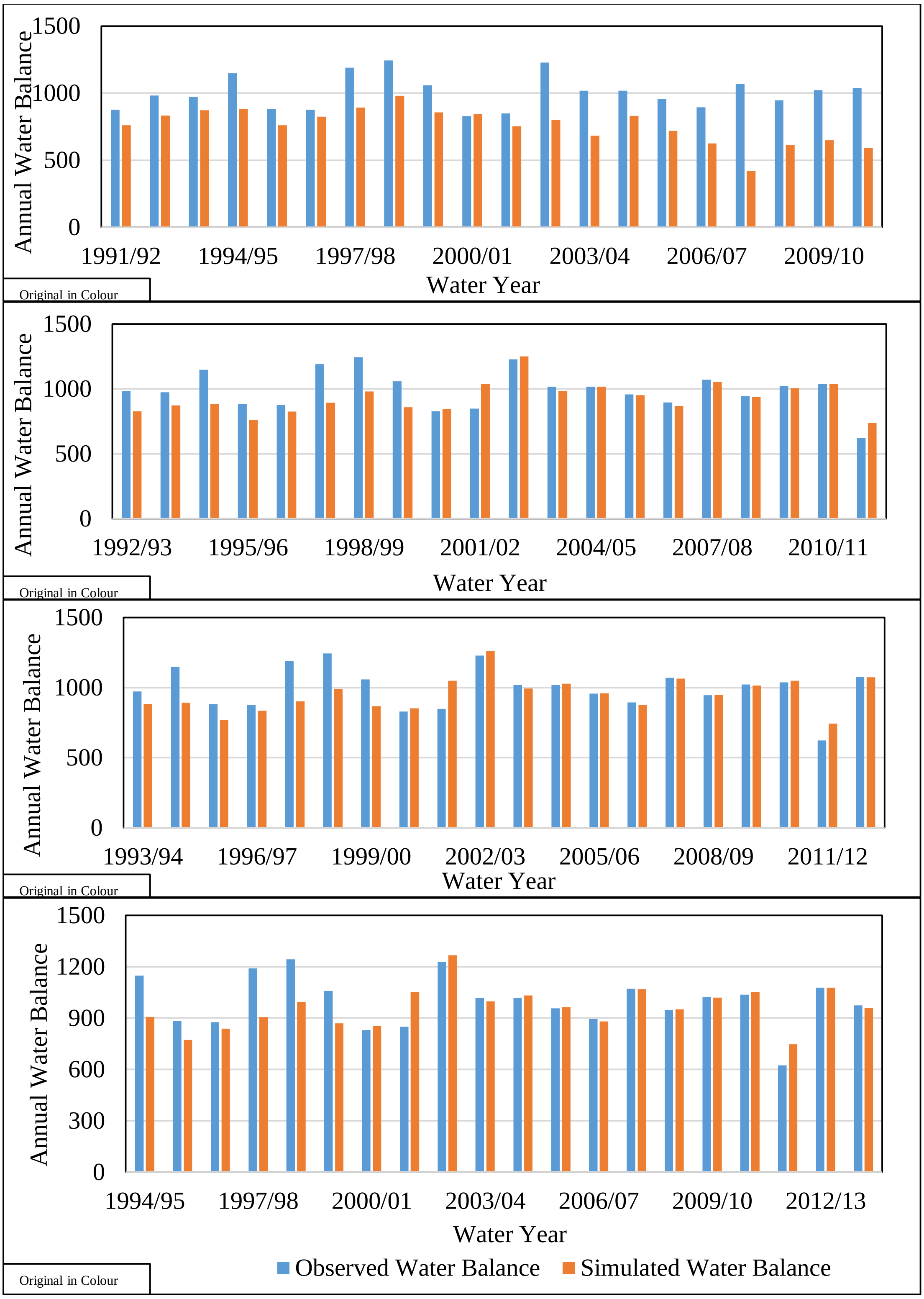


Figure D.218-D.221: Annual Observed and Simulated Water Balance Comparison - 20 year Datasets – Calibration

Annual Water Balance Comparison – 20 Year Datasets–Calibration (Set 13–15)

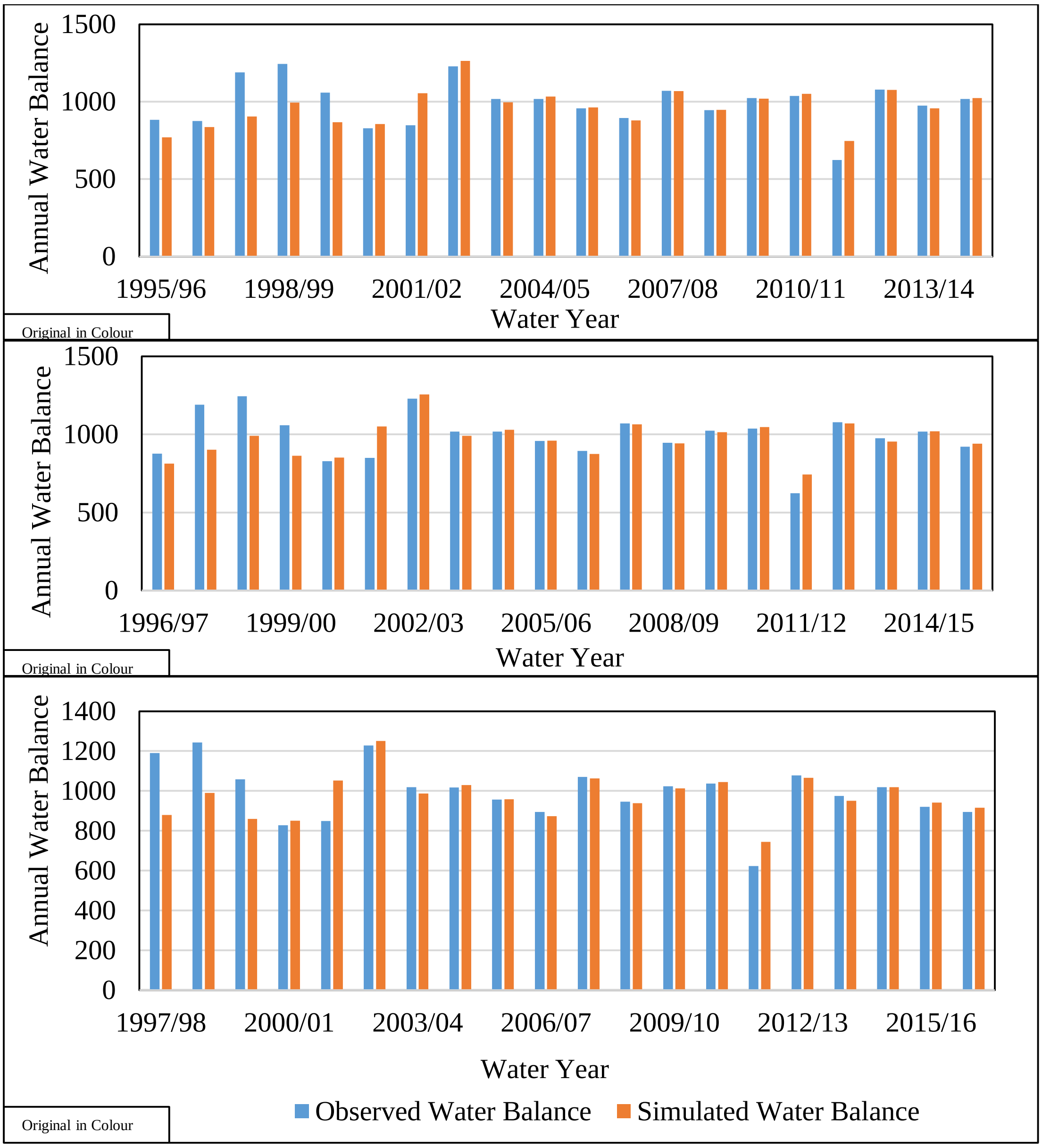
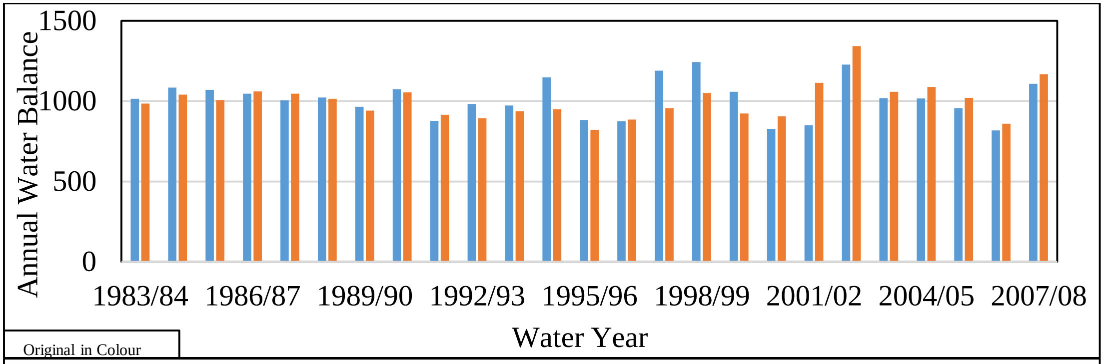
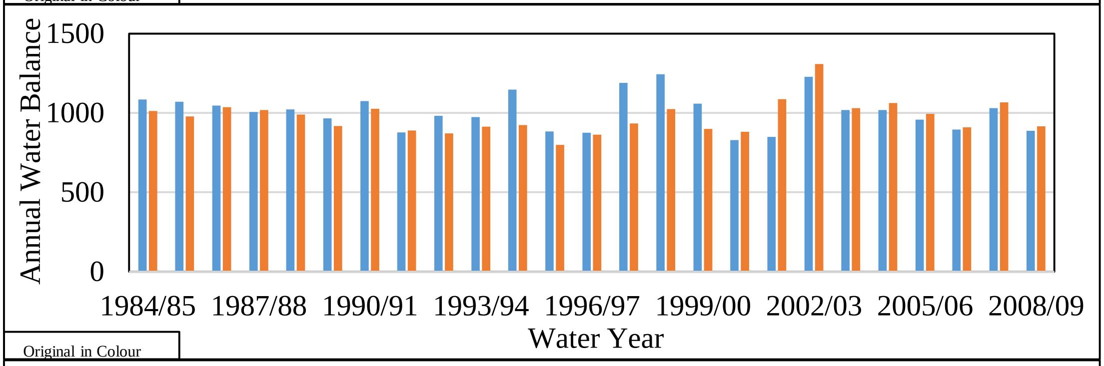
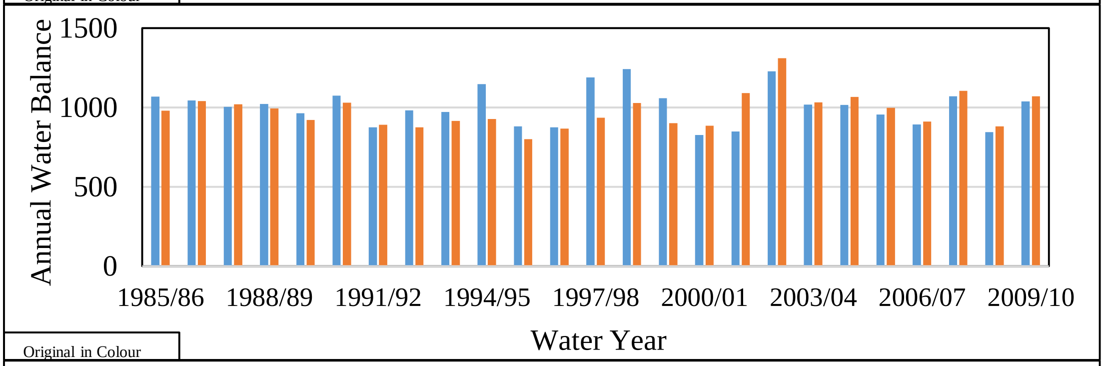


Figure D.222-D.224: Annual Observed and Simulated Water Balance Comparison - 20 year Datasets – Calibration

Annual Water Balance Comparison – 25 Year Datasets – Calibration (Set 1 – 4)







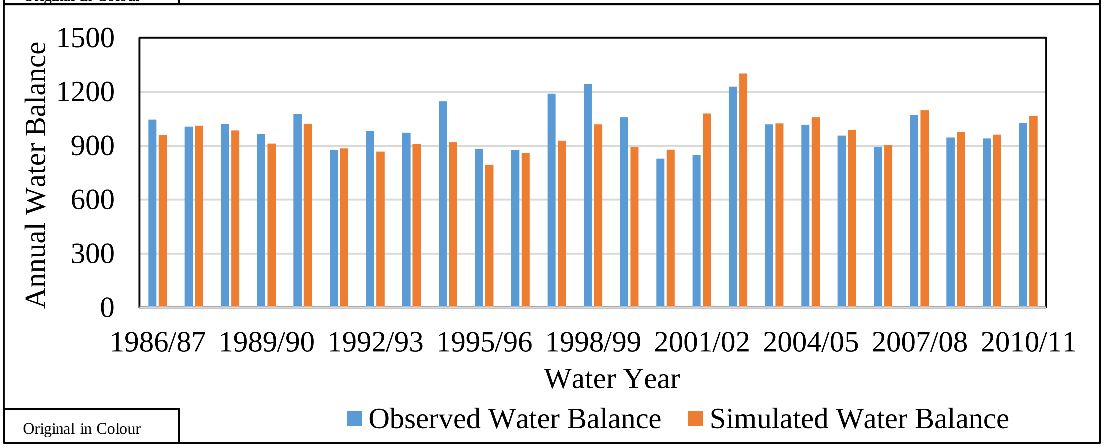
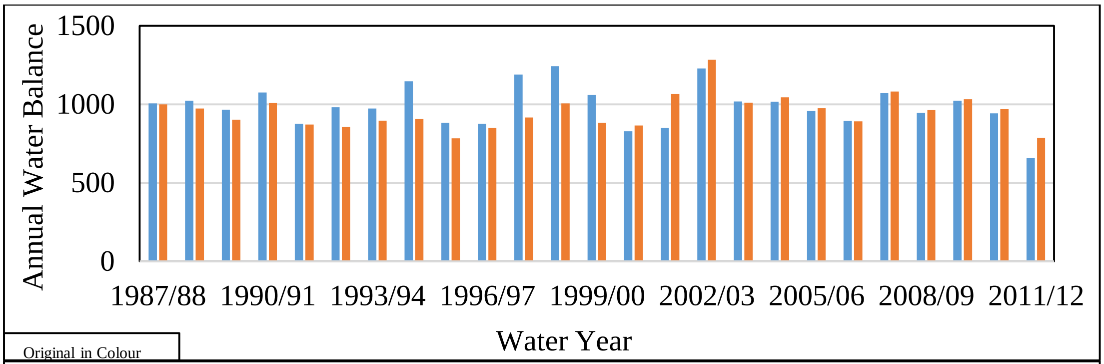
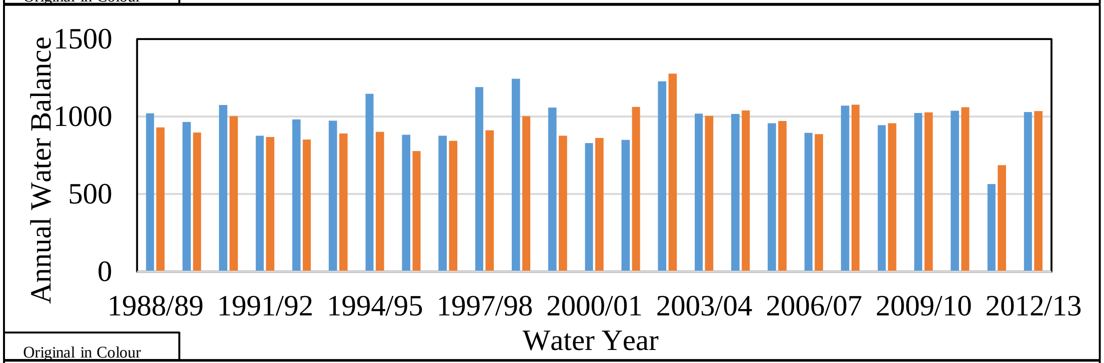
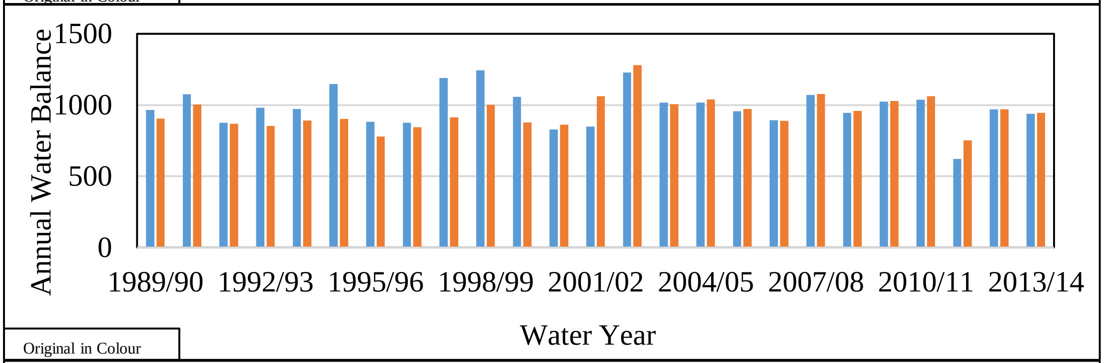


Figure D.225-D.228: Annual Observed and Simulated Water Balance Comparison - 25 year Datasets – Calibration

Annual Water Balance Comparison – 25 Year Datasets – Calibration (Set 5 – 8)







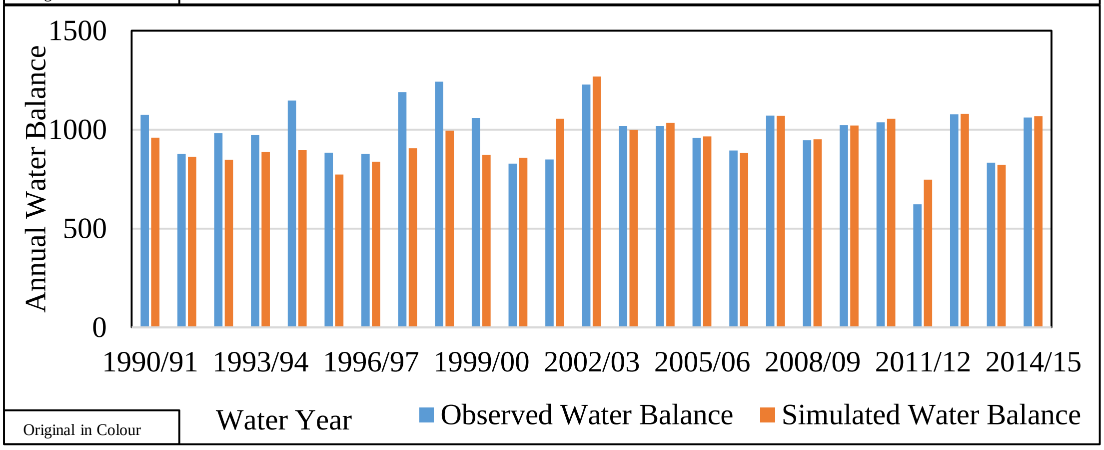


Figure D.229-D.232: Annual Observed and Simulated Water Balance Comparison - 25 year Datasets – Calibration

Annual Water Balance Comparison – 25 Year Datasets – Calibration (Set 9-10)

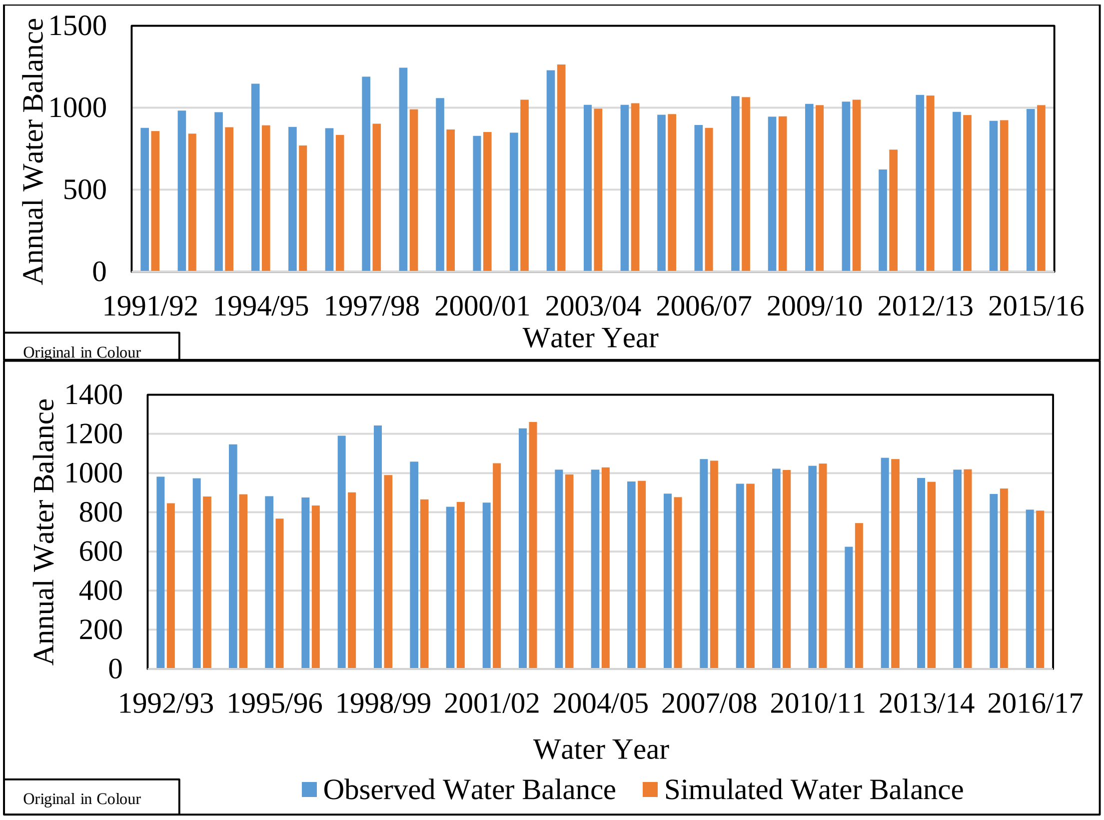


Figure D.233-D.234: Annual Observed and Simulated Water Balance Comparison - 25 year Datasets – Calibration

Annual Water Balance Comparison – 30 Year Datasets – Calibration (Set 1 – 4)

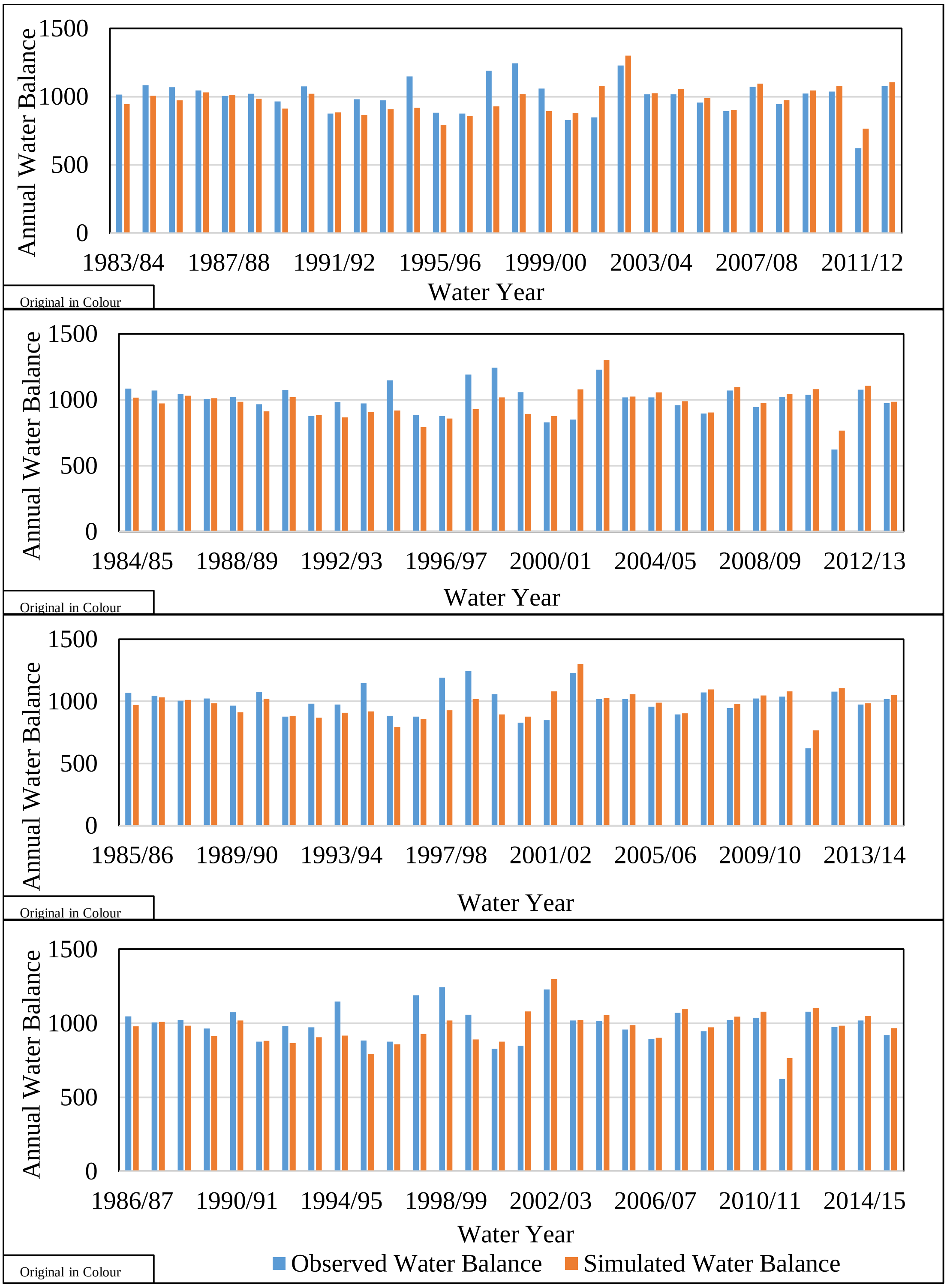


Figure D.235-D.238: Annual Observed and Simulated Water Balance Comparison - 30 year Datasets – Calibration

Annual Water Balance Comparison – 30 Year Datasets – Calibration (Set 5)

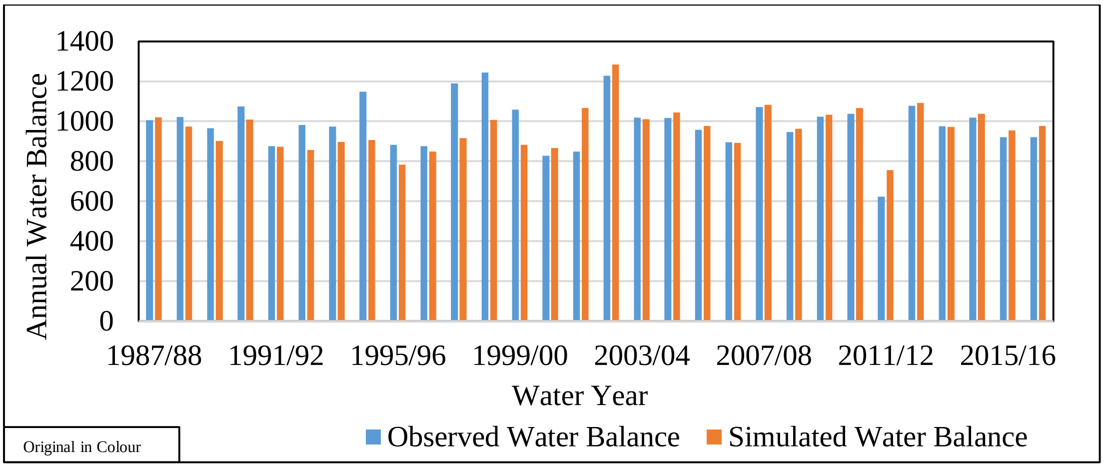


Figure D.239: Annual Observed and Simulated Water Balance Comparison - 30 year Datasets – Calibration

APPENDIX D.4 – Soil Moisture Comparison

Soil Moisture Comparison – 10 Year Datasets – Calibration (Set 1 – 4)

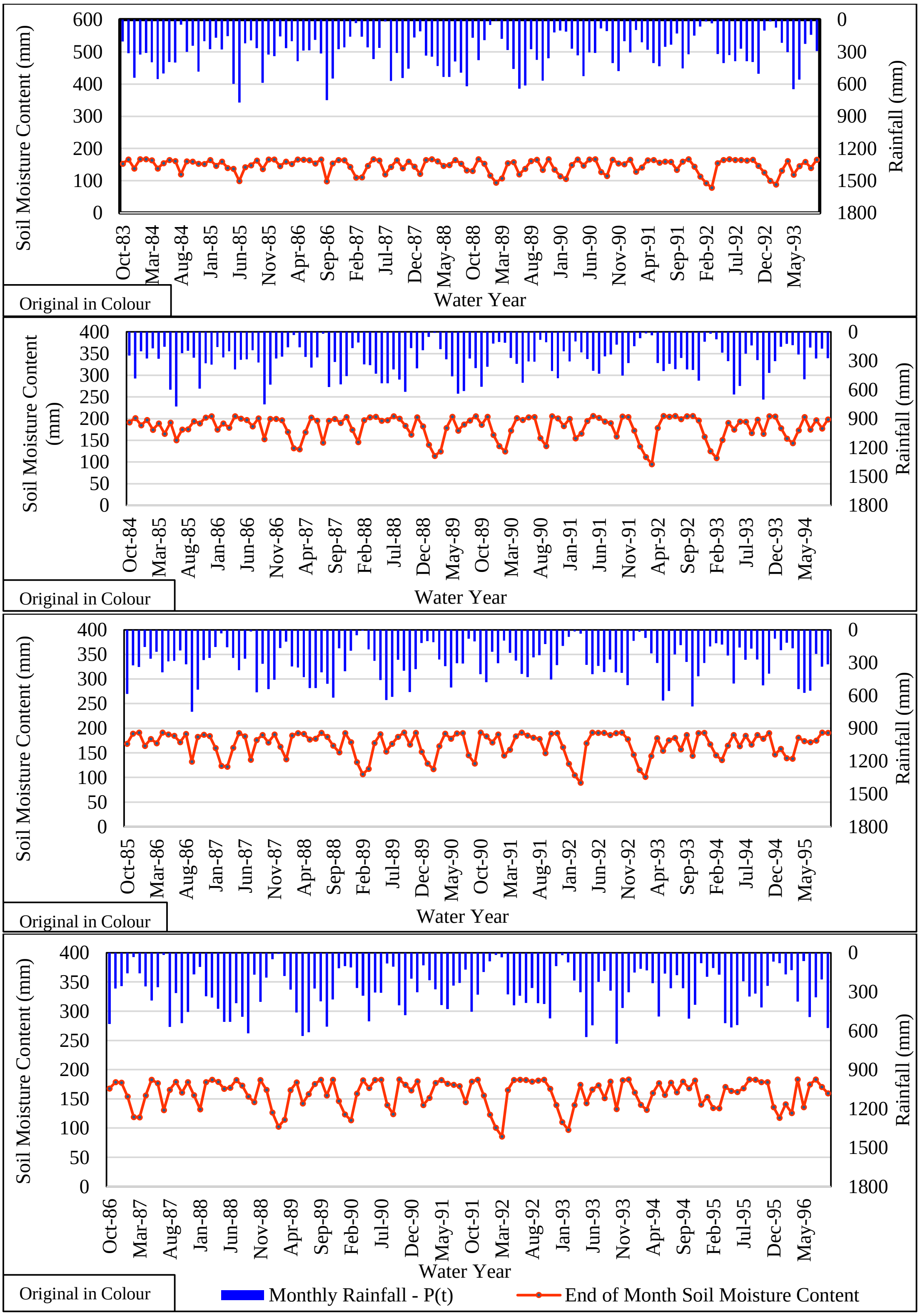


Figure D.240-D.243: Comparison of End of Month Soil Moisture Variation – 10 year Datasets – Calibration

Soil Moisture Comparison – 10 Year Datasets – Calibration (Set 5 – 8)

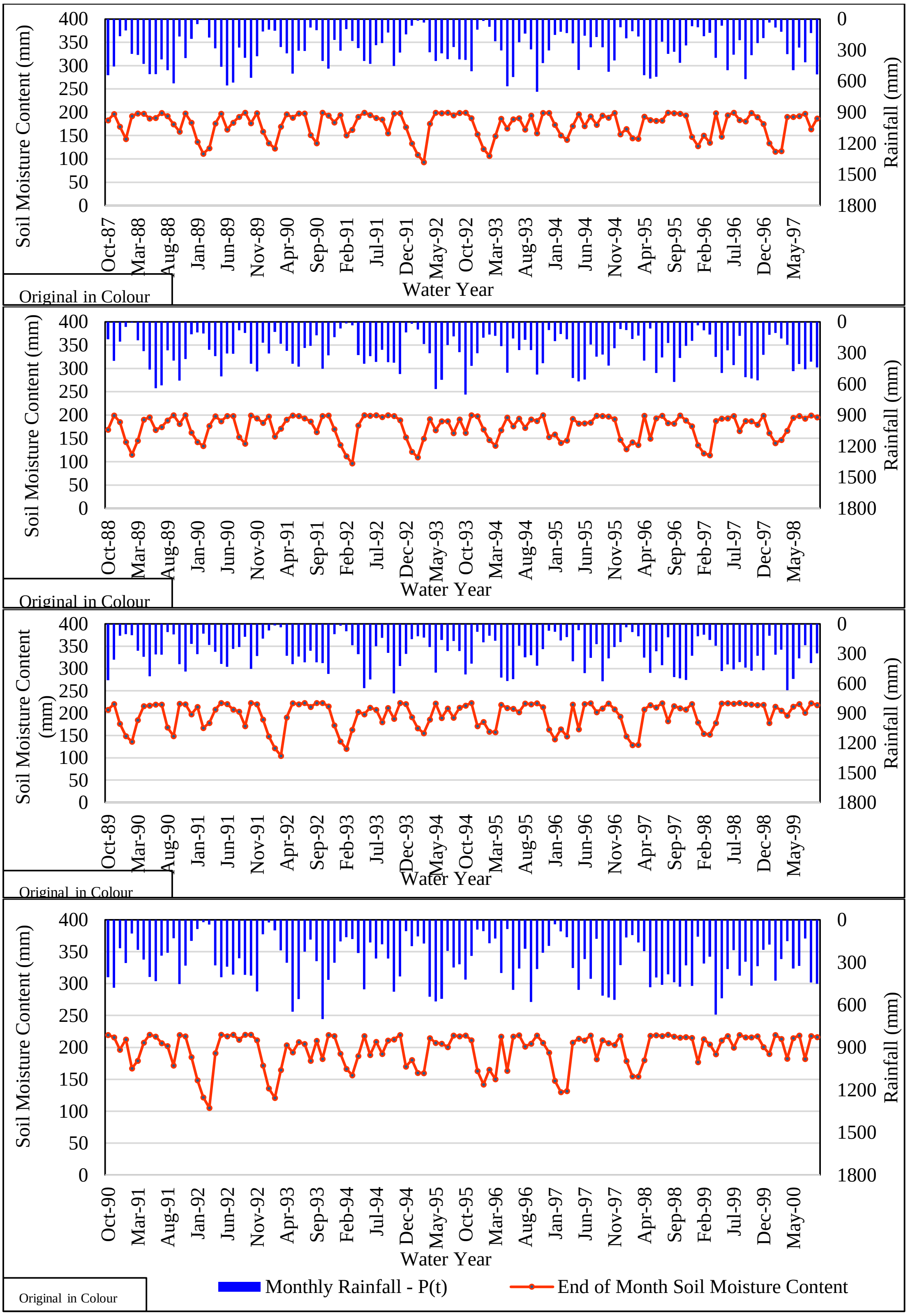


Figure D.244-D.247: Comparison of End of Month Soil Moisture Variation – 10 year Datasets – Calibration

Soil Moisture Comparison – 10 Year Datasets – Calibration (Set 9 – 12)

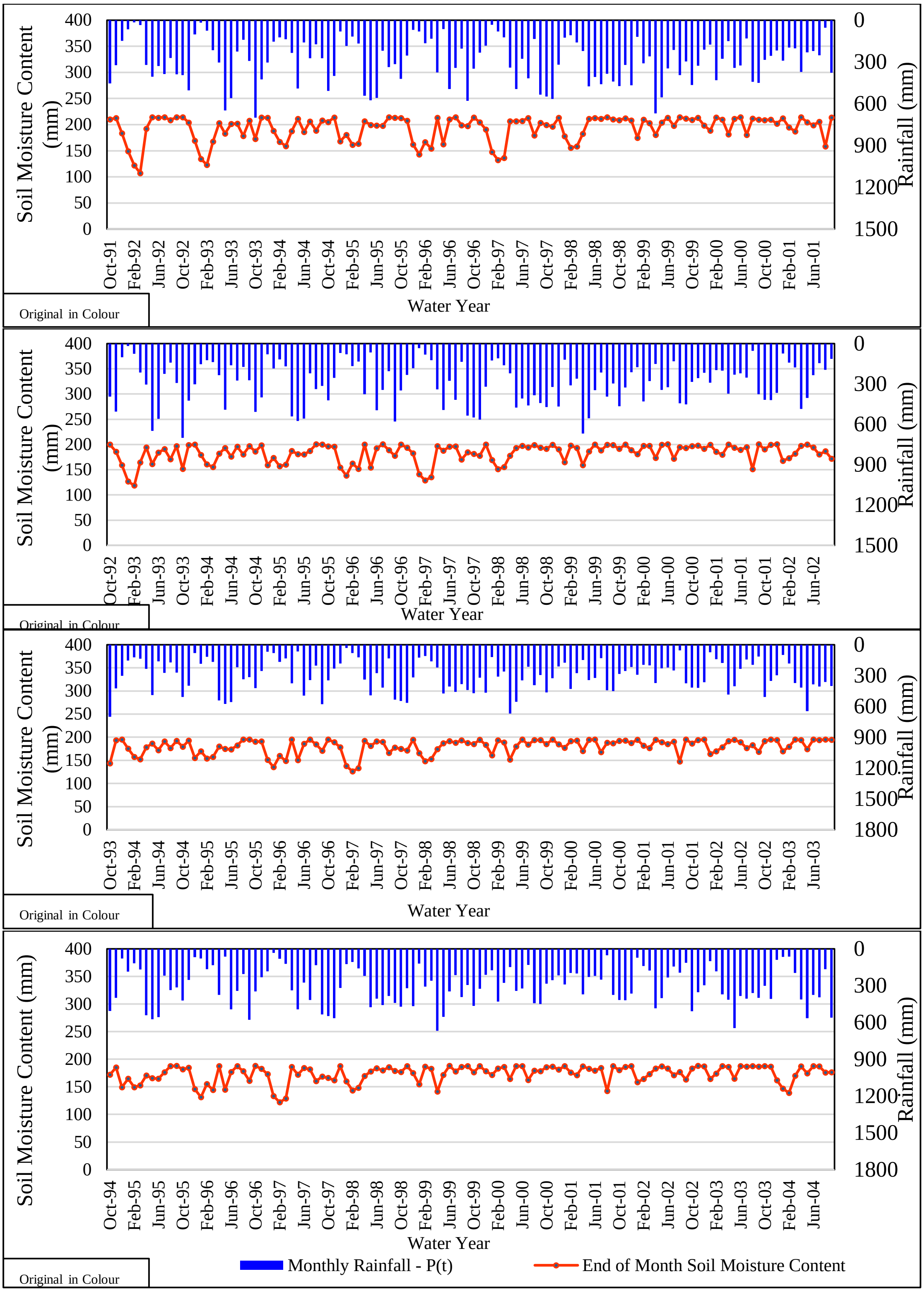


Figure D.248-D.251: Comparison of End of Month Soil Moisture Variation – 10 year Datasets – Calibration

Soil Moisture Comparison – 10 Year Datasets – Calibration (Set 13– 16)

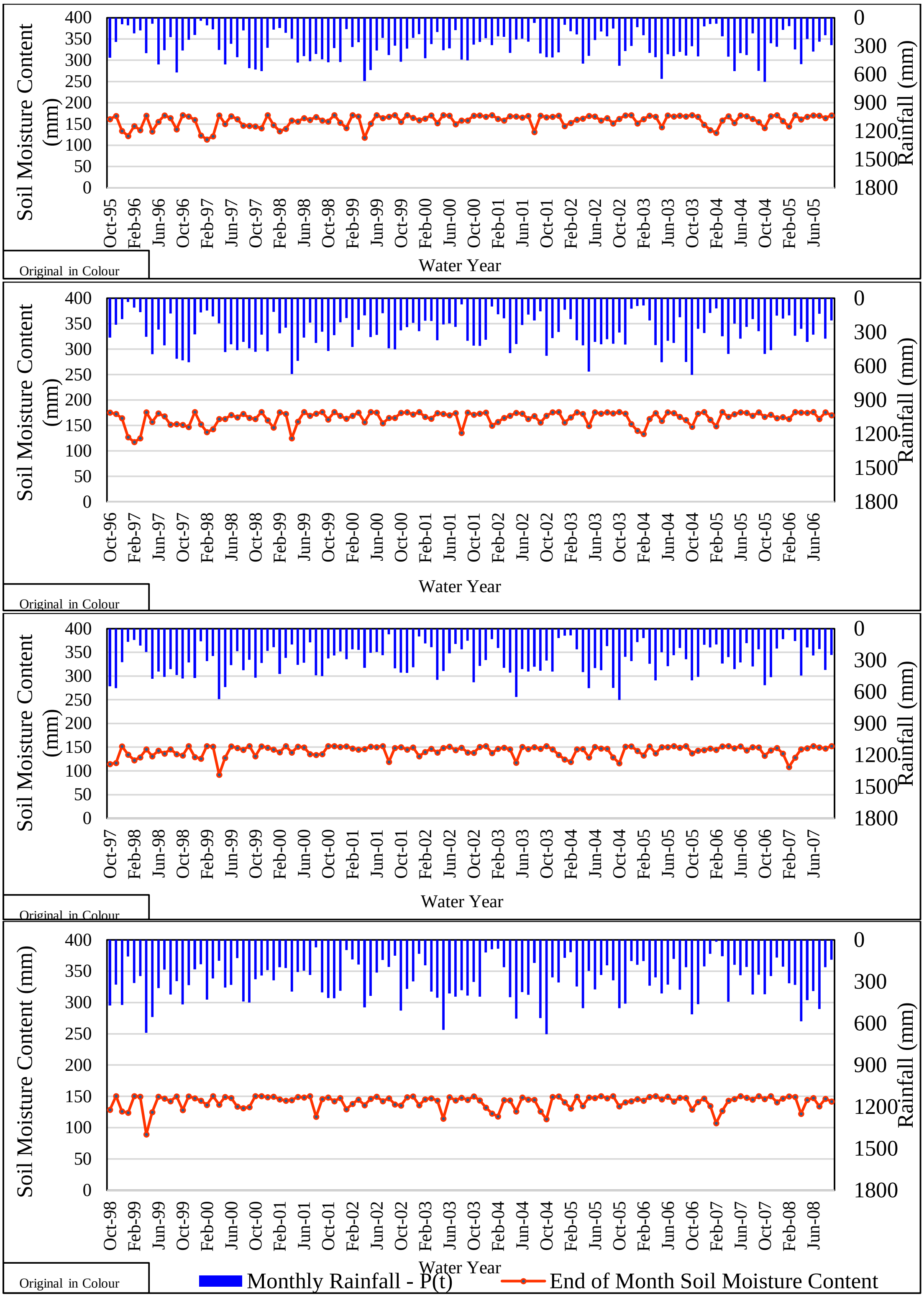


Figure D.252-D.255: Comparison of End of Month Soil Moisture Variation – 10 year Datasets – Calibration

Soil Moisture Comparison – 10 Year Datasets – Calibration (Set 17-20)

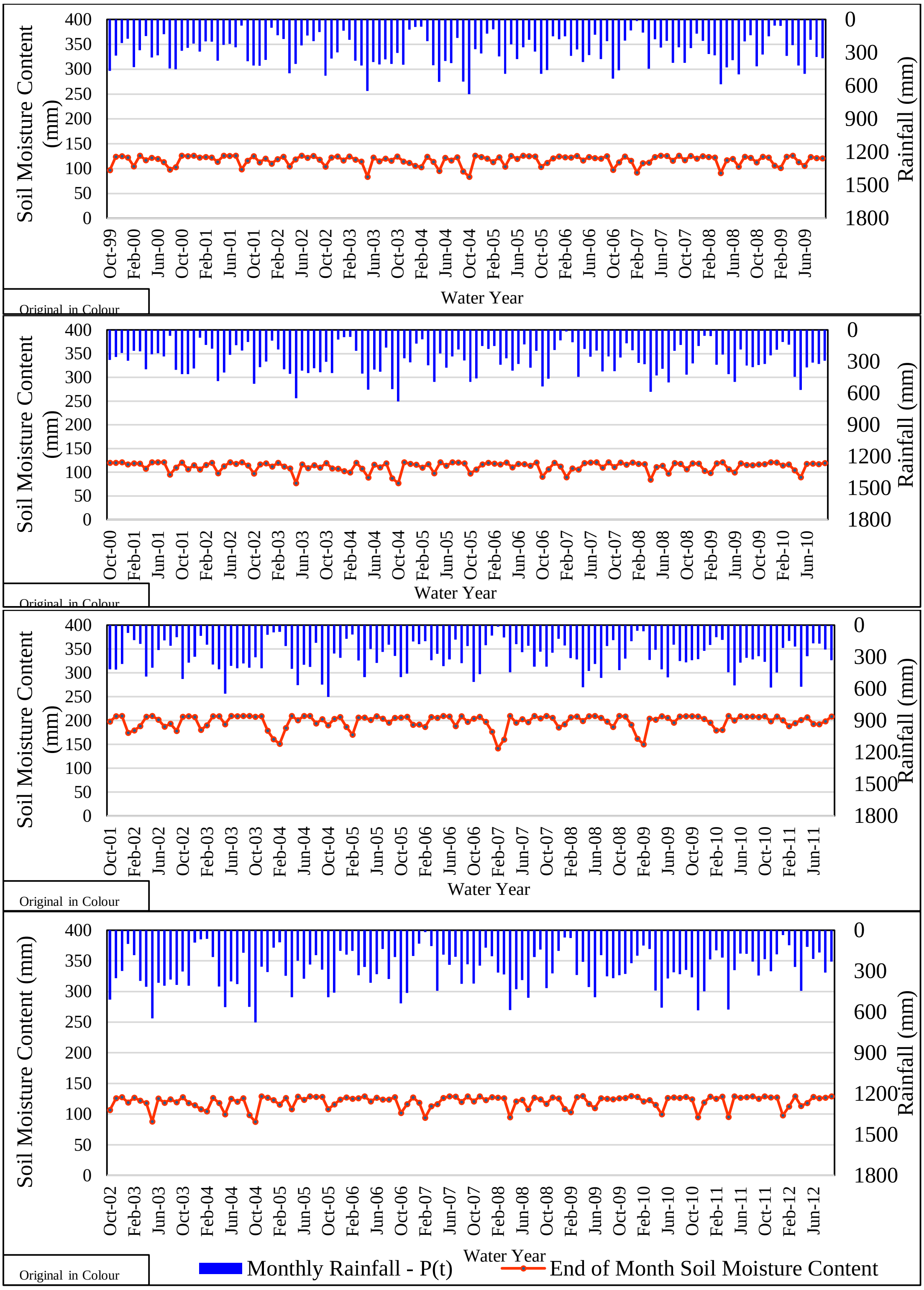


Figure D.256-D.259: Comparison of End of Month Soil Moisture Variation – 10 year Datasets – Calibration

Soil Moisture Comparison – 10 Year Datasets – Calibration (Set 21-24)

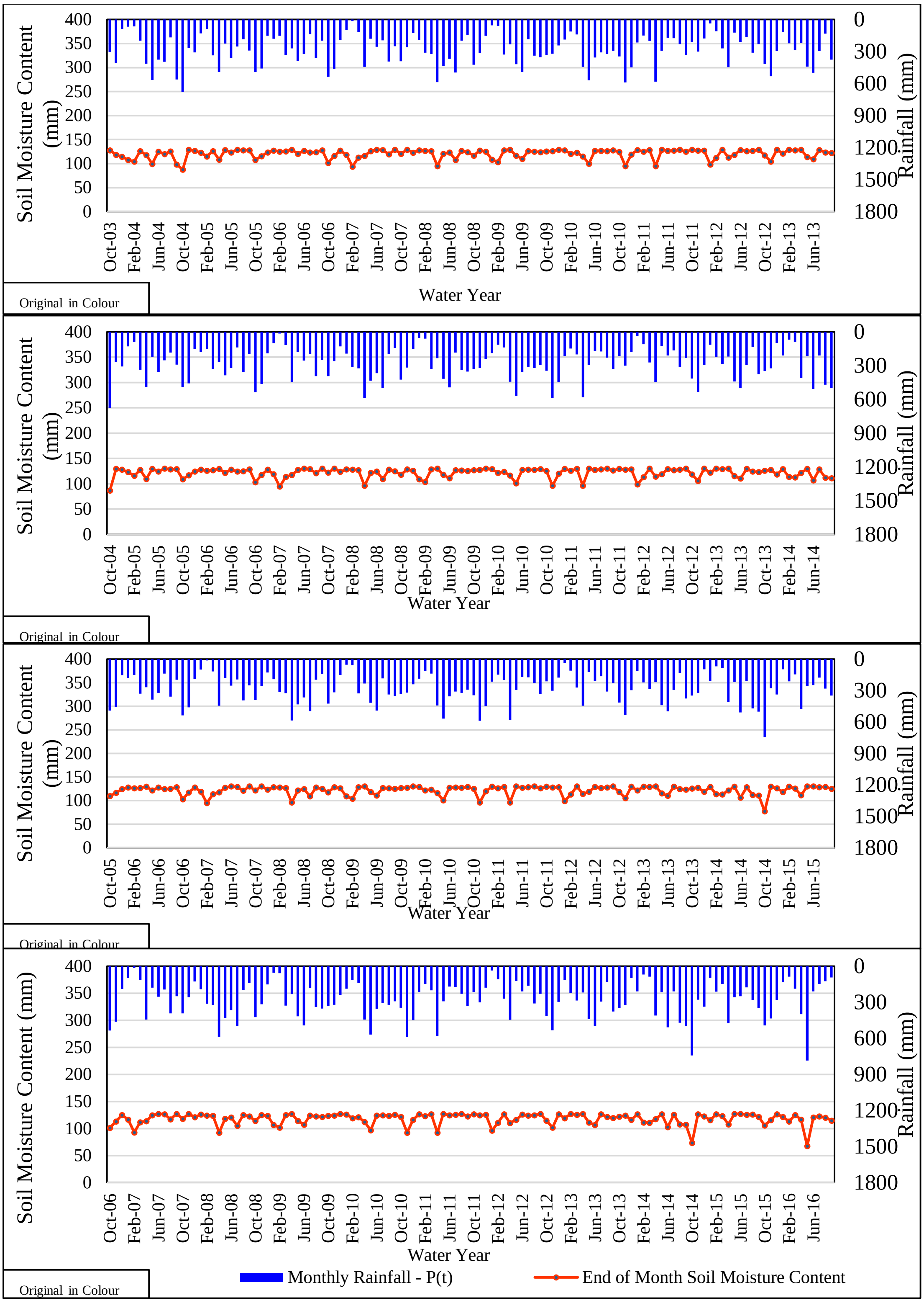


Figure D.260-D.263: Comparison of End of Month Soil Moisture Variation – 10 year Datasets – Calibration

Soil Moisture Comparison – 10 Year Datasets – Calibration (Set 25)

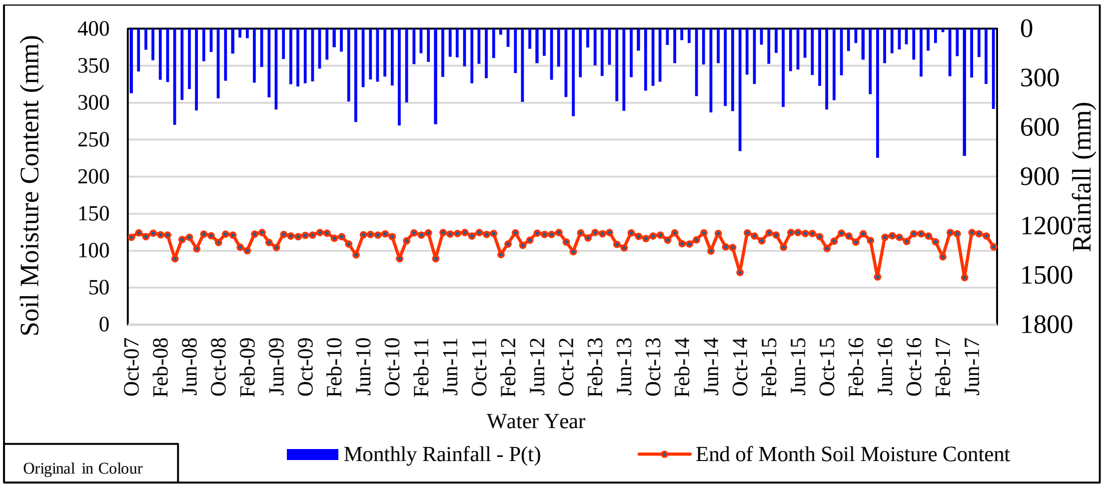


Figure D.264: Comparison of End of Month Soil Moisture Variation – 10 year Datasets – Calibration

Soil Moisture Comparison – 15 Year Datasets – Calibration (Set 1 – 4)

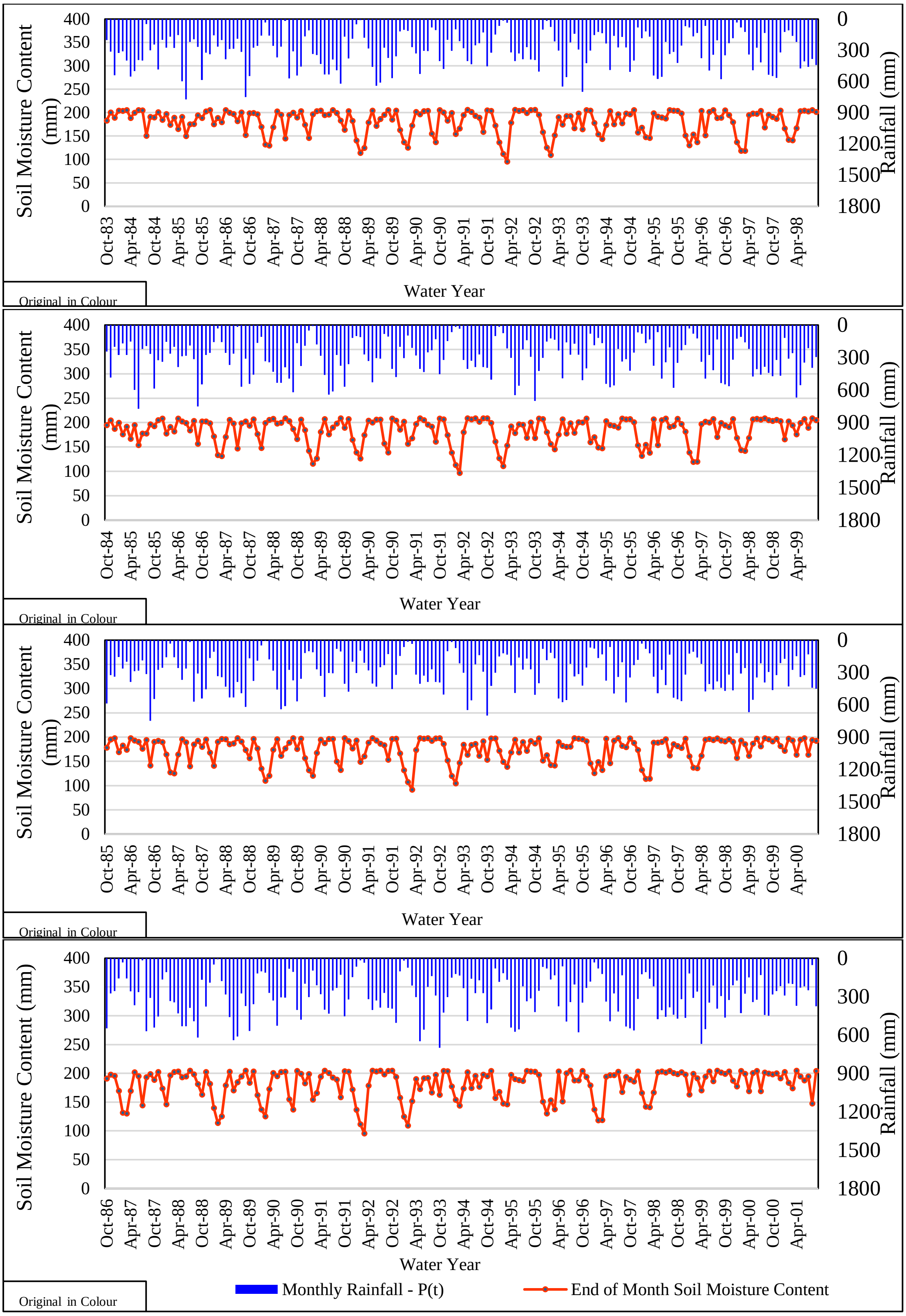
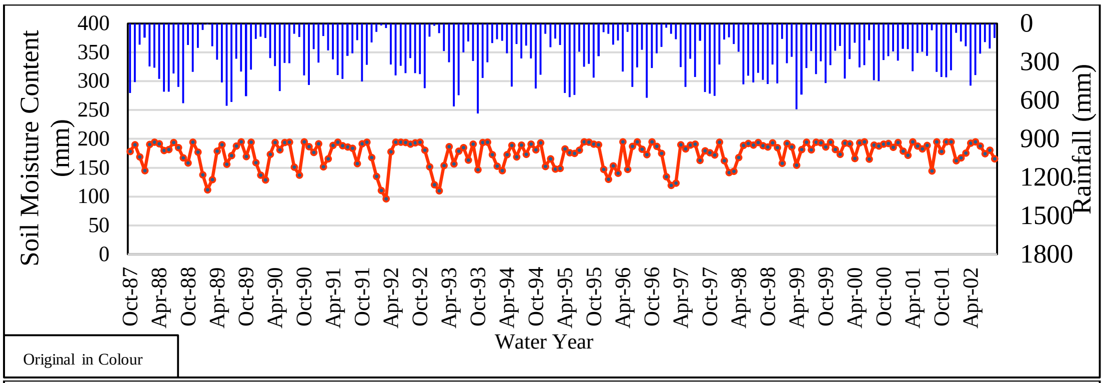
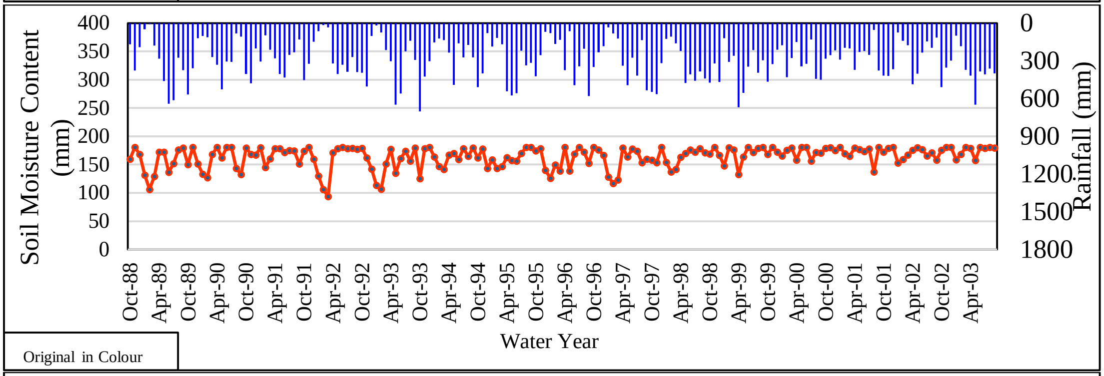
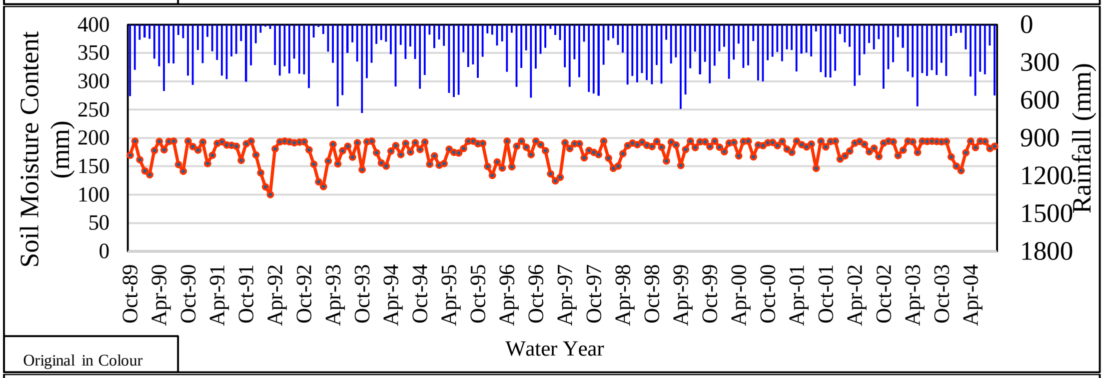


Figure D.265-D.268: Comparison of End of Month Soil Moisture Variation – 10 year Datasets – Calibration

Soil Moisture Comparison – 15 Year Datasets – Calibration (Set 5 – 8)







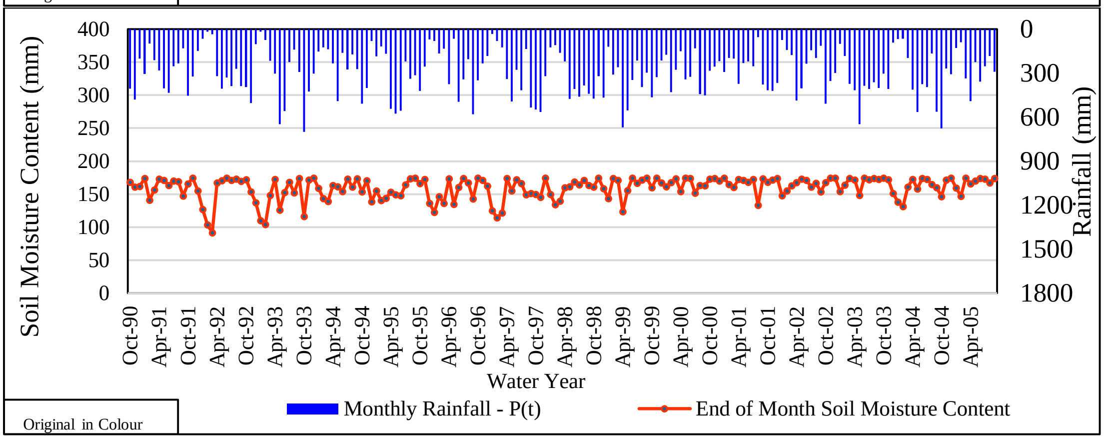


Figure D.269-D.272: Comparison of End of Month Soil Moisture Variation – 10 year Datasets – Calibration

Soil Moisture Comparison – 15 Year Datasets – Calibration (Set 9–12)

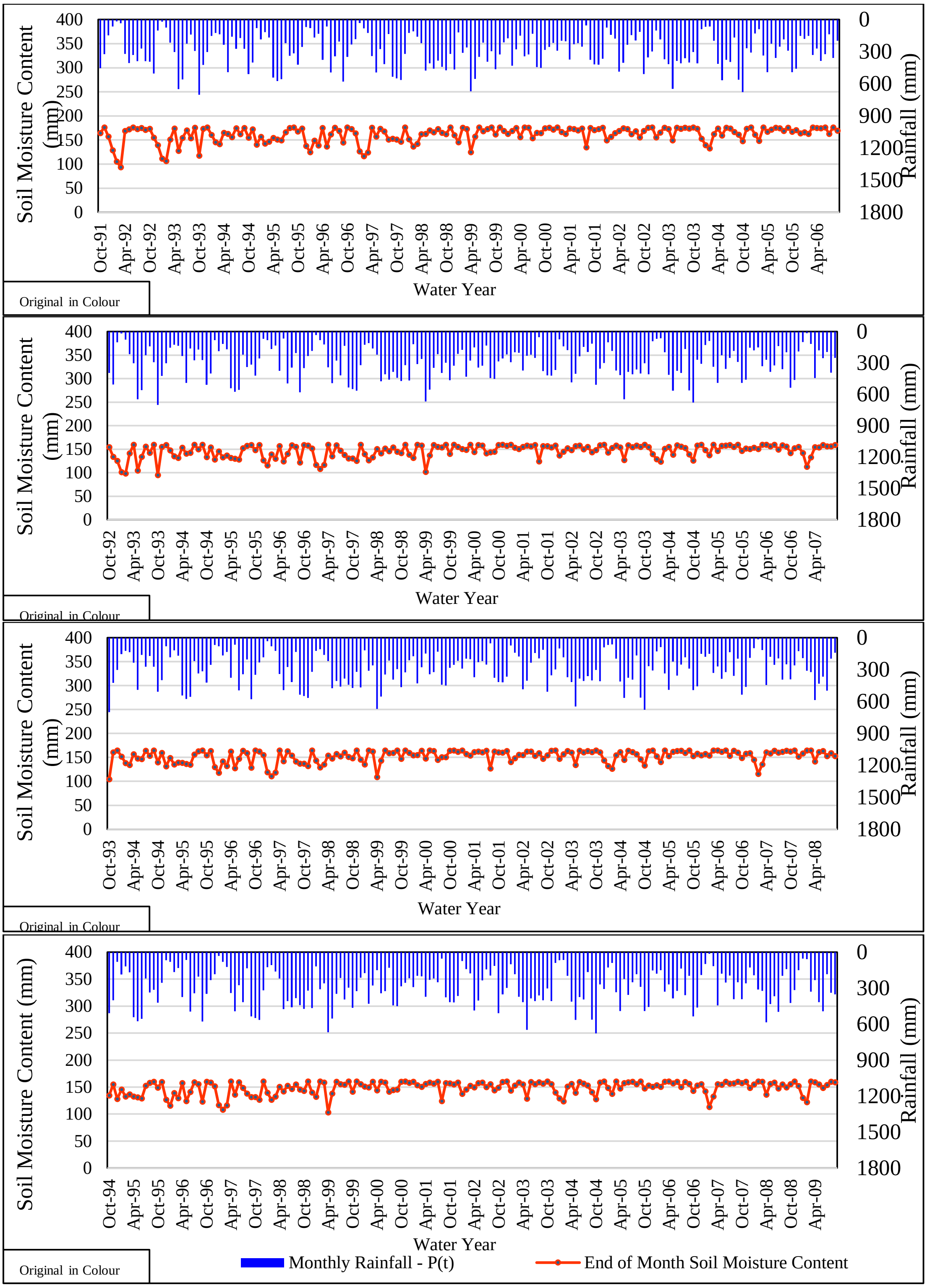


Figure D.273-D.276: Comparison of End of Month Soil Moisture Variation – 10 year Datasets – Calibration

Soil Moisture Comparison – 15 Year Datasets – Calibration (Set 13–16)

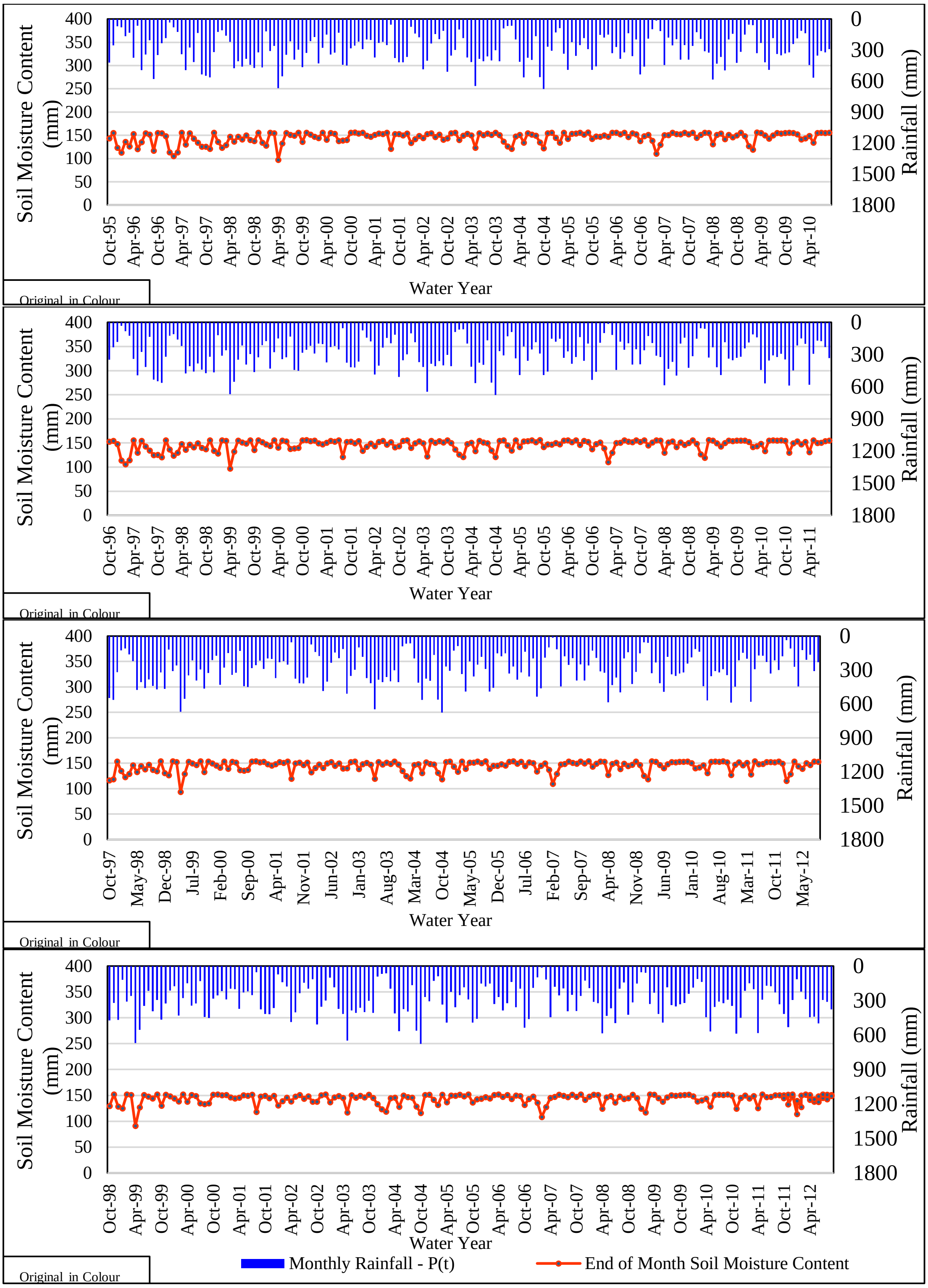


Figure D.277-D.280: Comparison of End of Month Soil Moisture Variation – 10 year Datasets – Calibration

Soil Moisture Comparison – 15 Year Datasets – Calibration (Set 17–20)

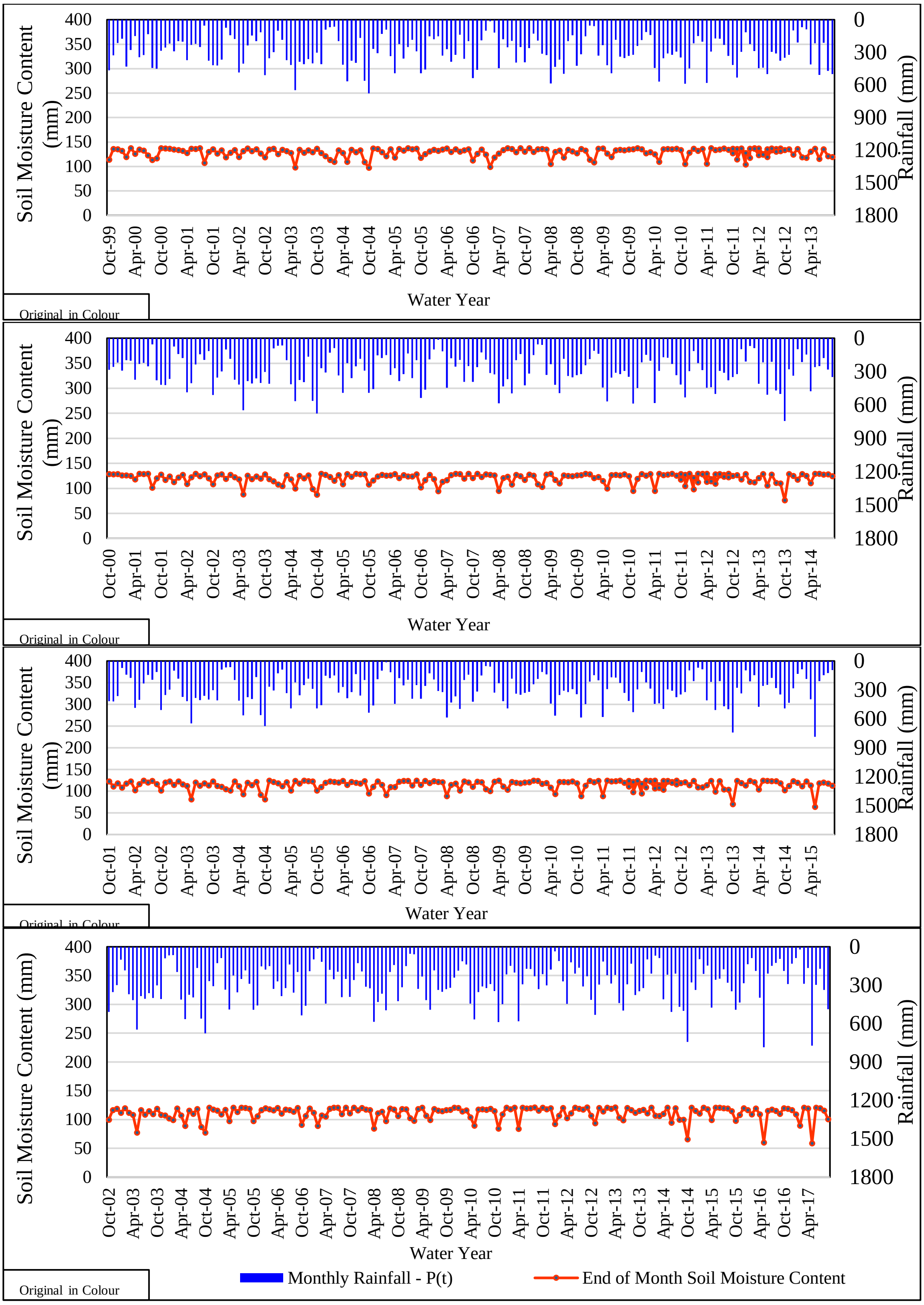


Figure D.281-D.284: Comparison of End of Month Soil Moisture Variation – 10 year Datasets – Calibration

Soil Moisture Comparison – 20 Year Datasets – Calibration (Set 1 – 4)

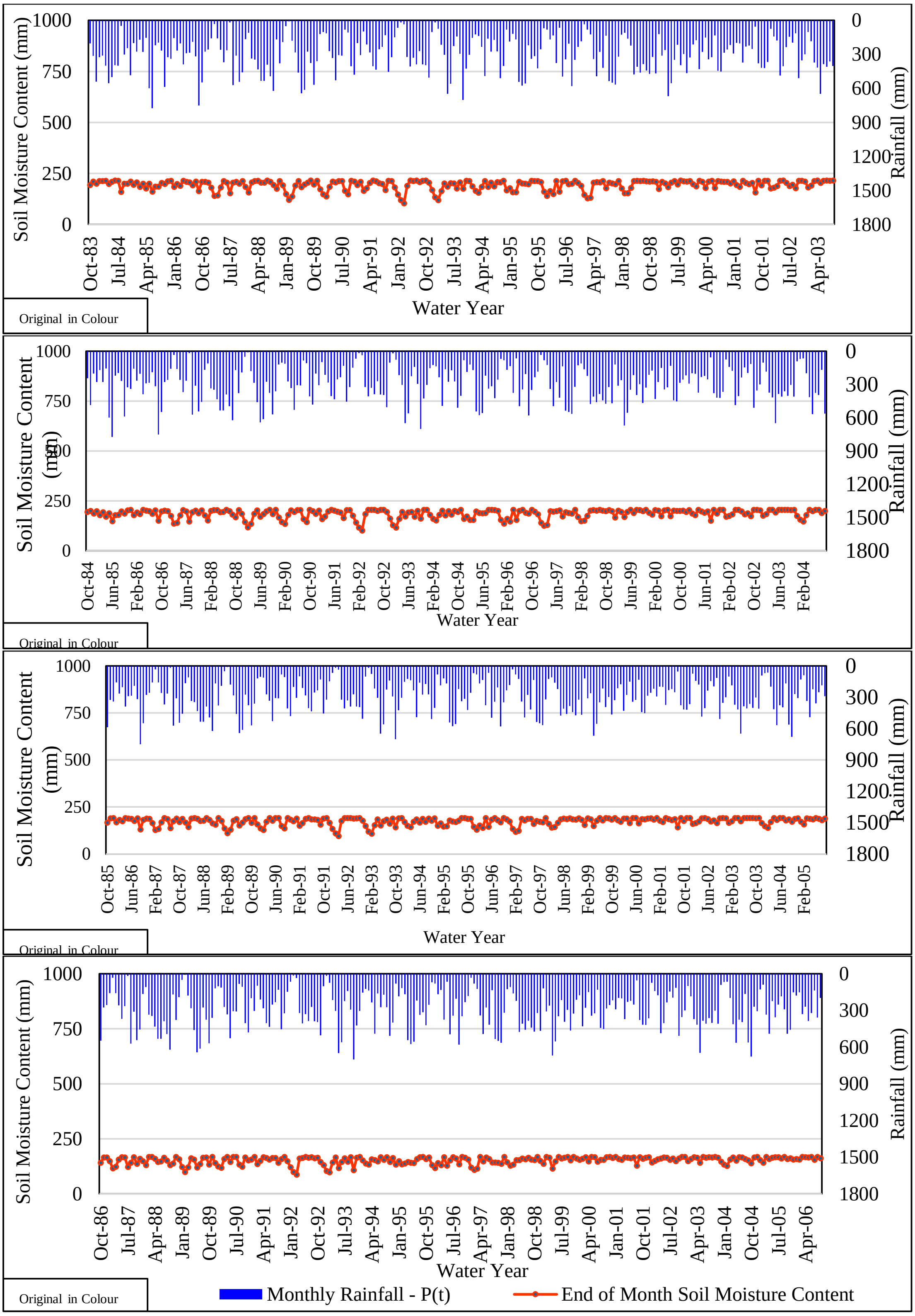


Figure D.285-D.288: Comparison of End of Month Soil Moisture Variation – 20 year Datasets – Calibration

Soil Moisture Comparison – 20 Year Datasets – Calibration (Set 5 – 8)

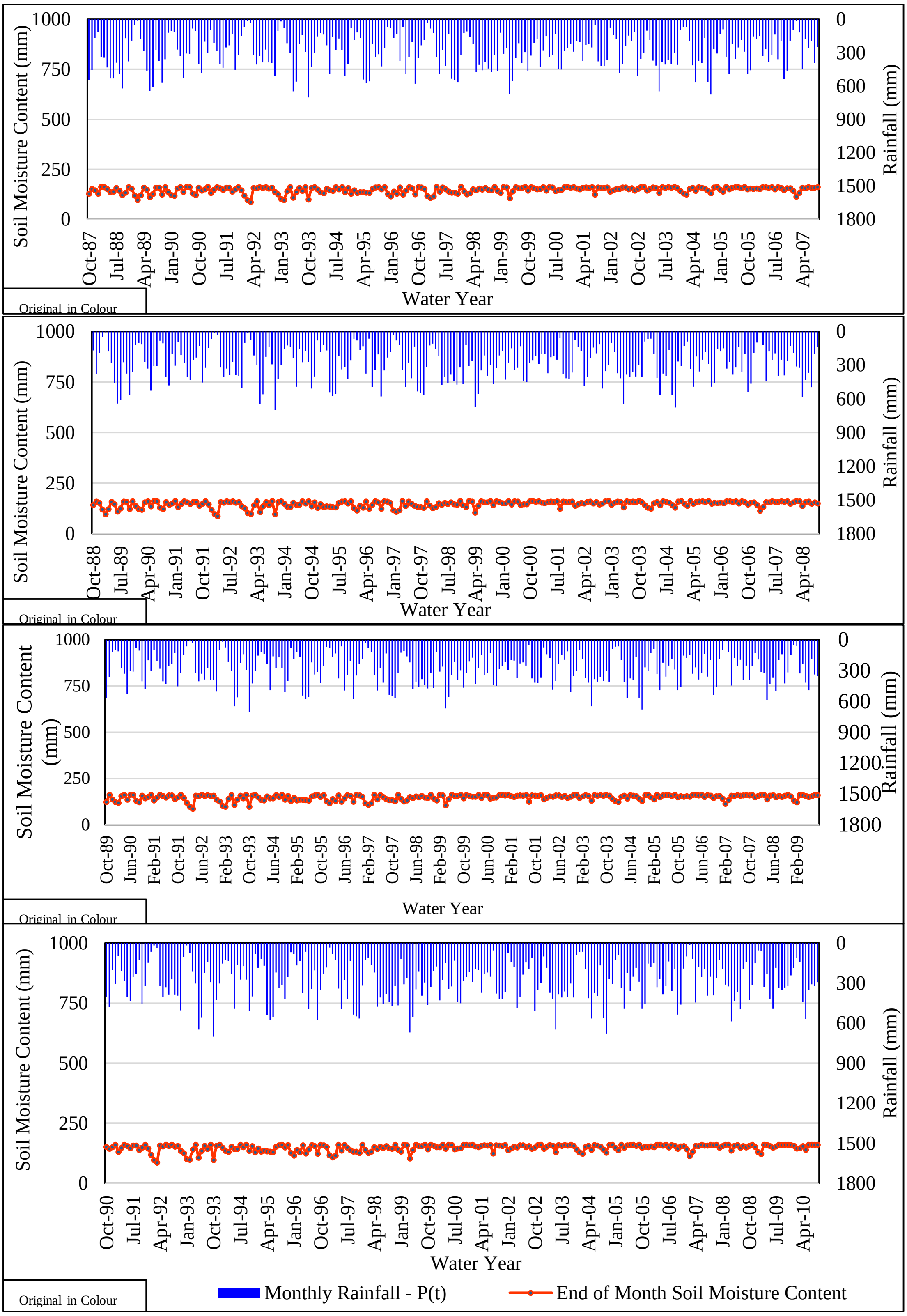


Figure D.289-D.292: Comparison of End of Month Soil Moisture Variation – 20 year Datasets – Calibration

Soil Moisture Comparison – 20 Year Datasets – Calibration (Set 9 – 12)

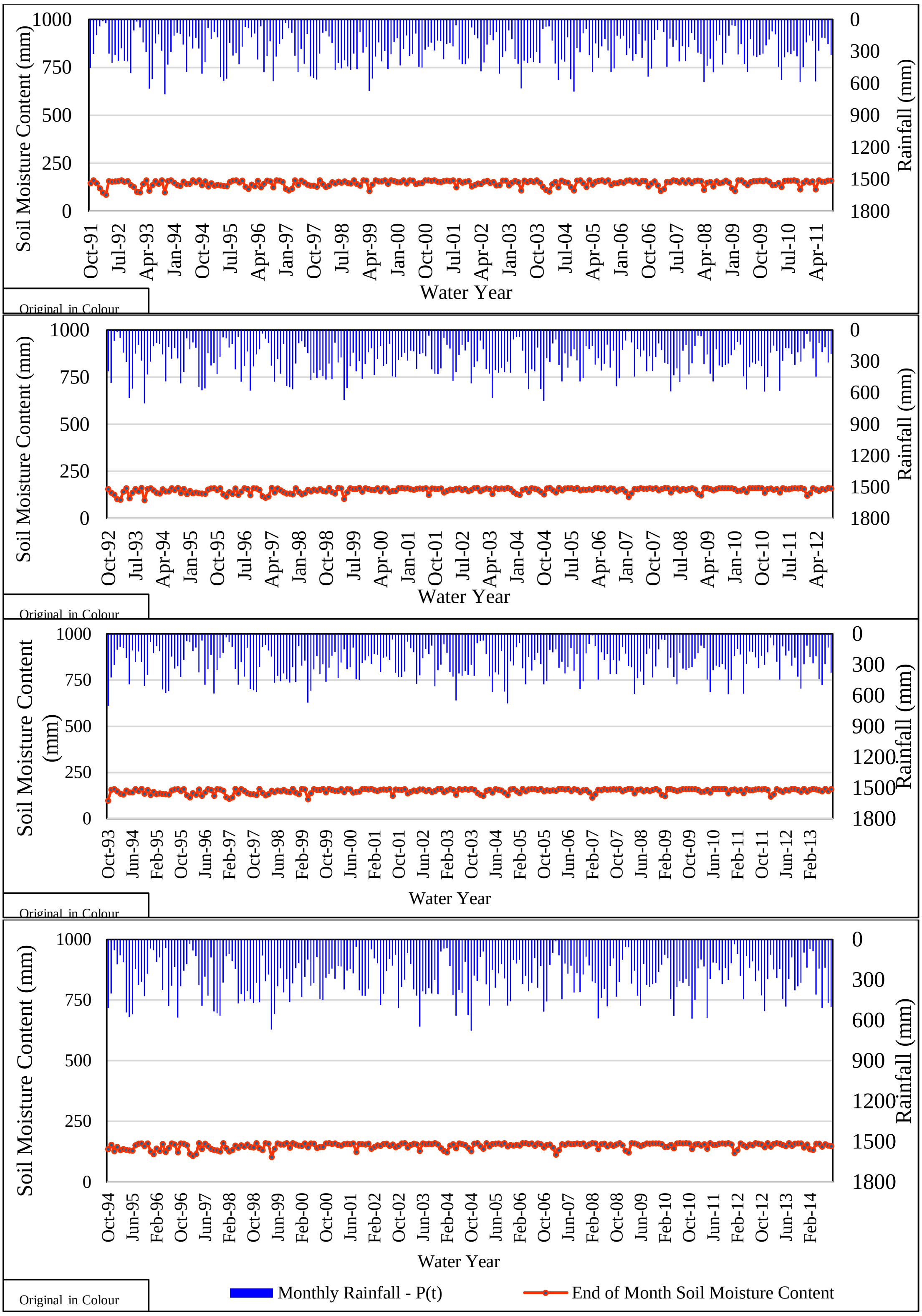


Figure D.293-D.296: Comparison of End of Month Soil Moisture Variation – 20 year Datasets – Calibration

Soil Moisture Comparison – 20 Year Datasets – Calibration (Set 13 – 15)

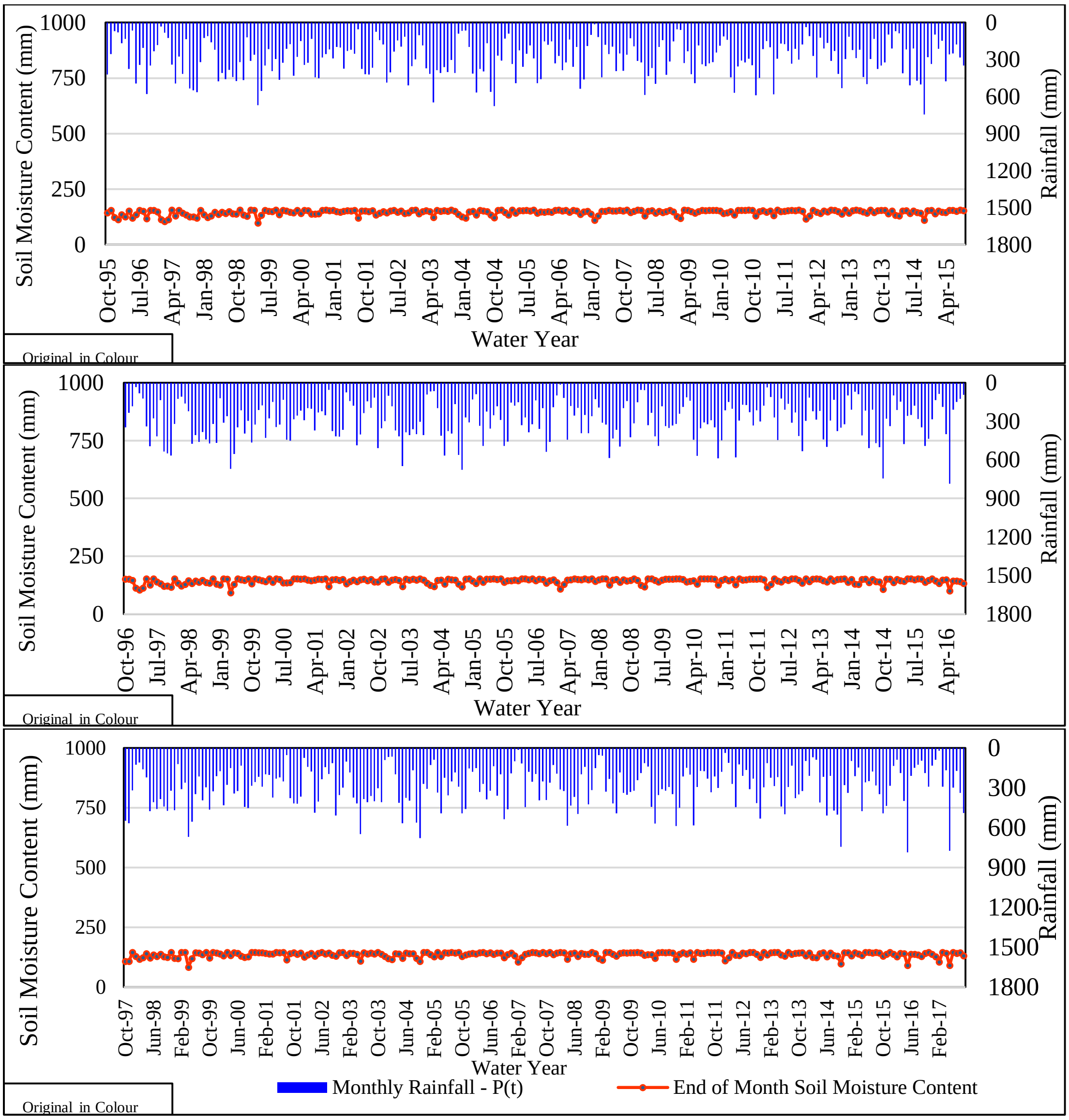


Figure D.297-D.299: Comparison of End of Month Soil Moisture Variation – 20 year Datasets – Calibration

Soil Moisture Comparison – 25 Year Datasets – Calibration (Set 1 – 4)

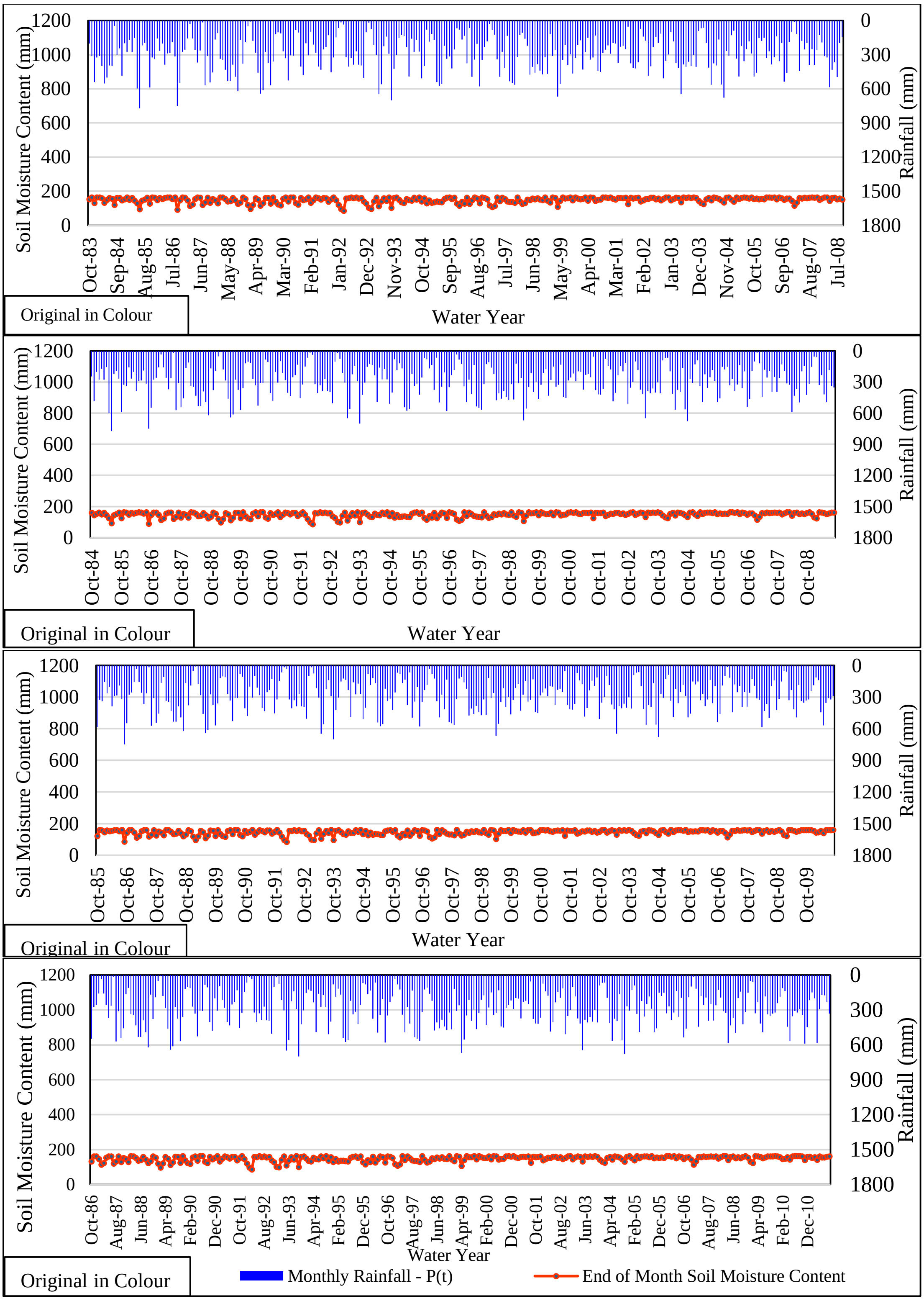


Figure D.300-D.303: Comparison of End of Month Soil Moisture Variation – 25 year Datasets – Calibration

Soil Moisture Comparison – 25 Year Datasets – Calibration (Set 5–8)

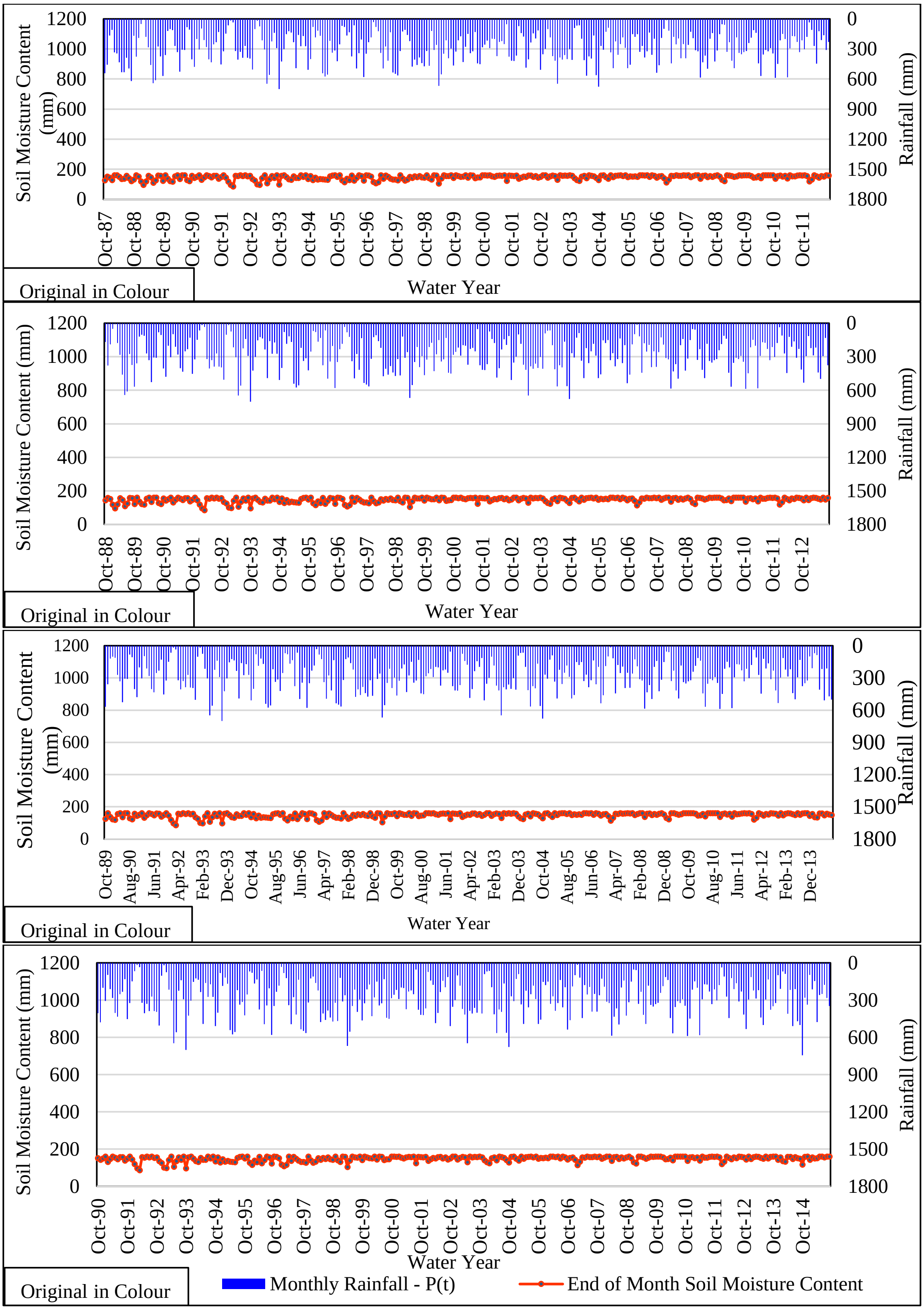


Figure D.304-D.307: Comparison of End of Month Soil Moisture Variation – 25 year Datasets – Calibration

Soil Moisture Comparison – 25 Year Datasets – Calibration (Set 9-10)

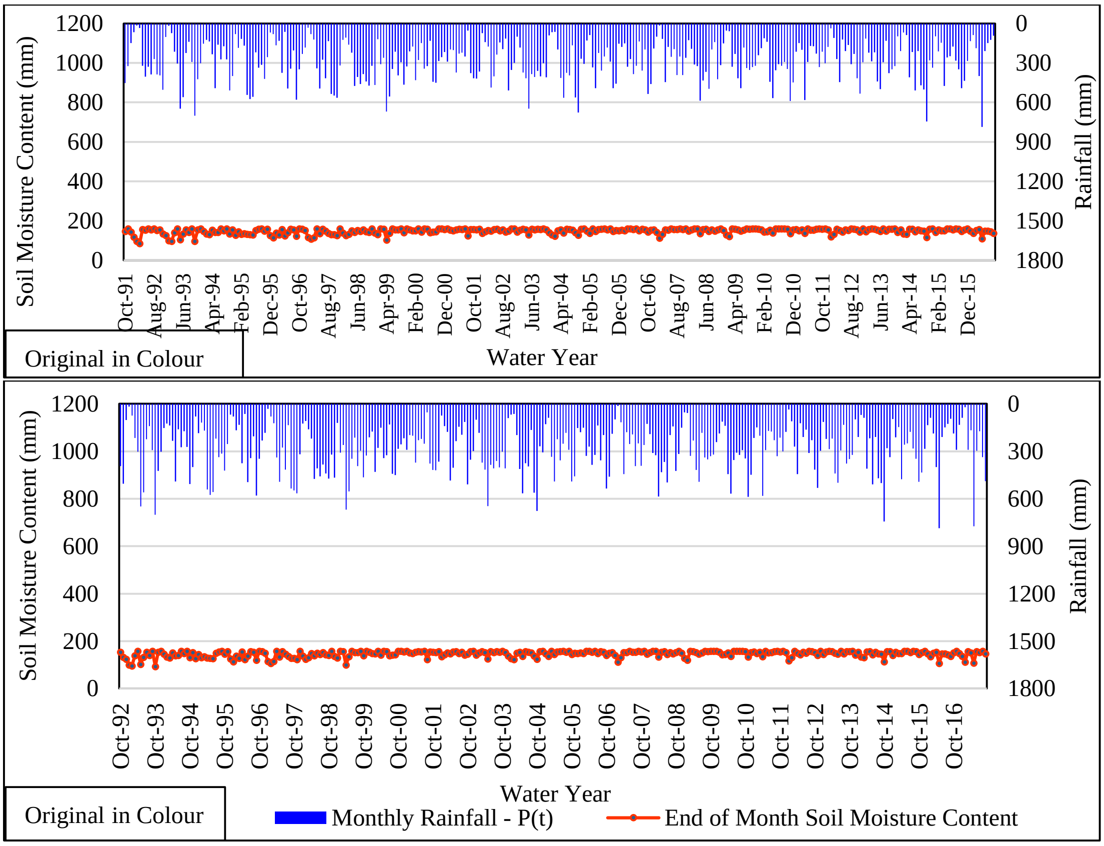


Figure D.308-D.309: Comparison of End of Month Soil Moisture Variation – 25 year Datasets – Calibration

Soil Moisture Comparison – 30 Year Datasets – Calibration (Set 1 – 4)

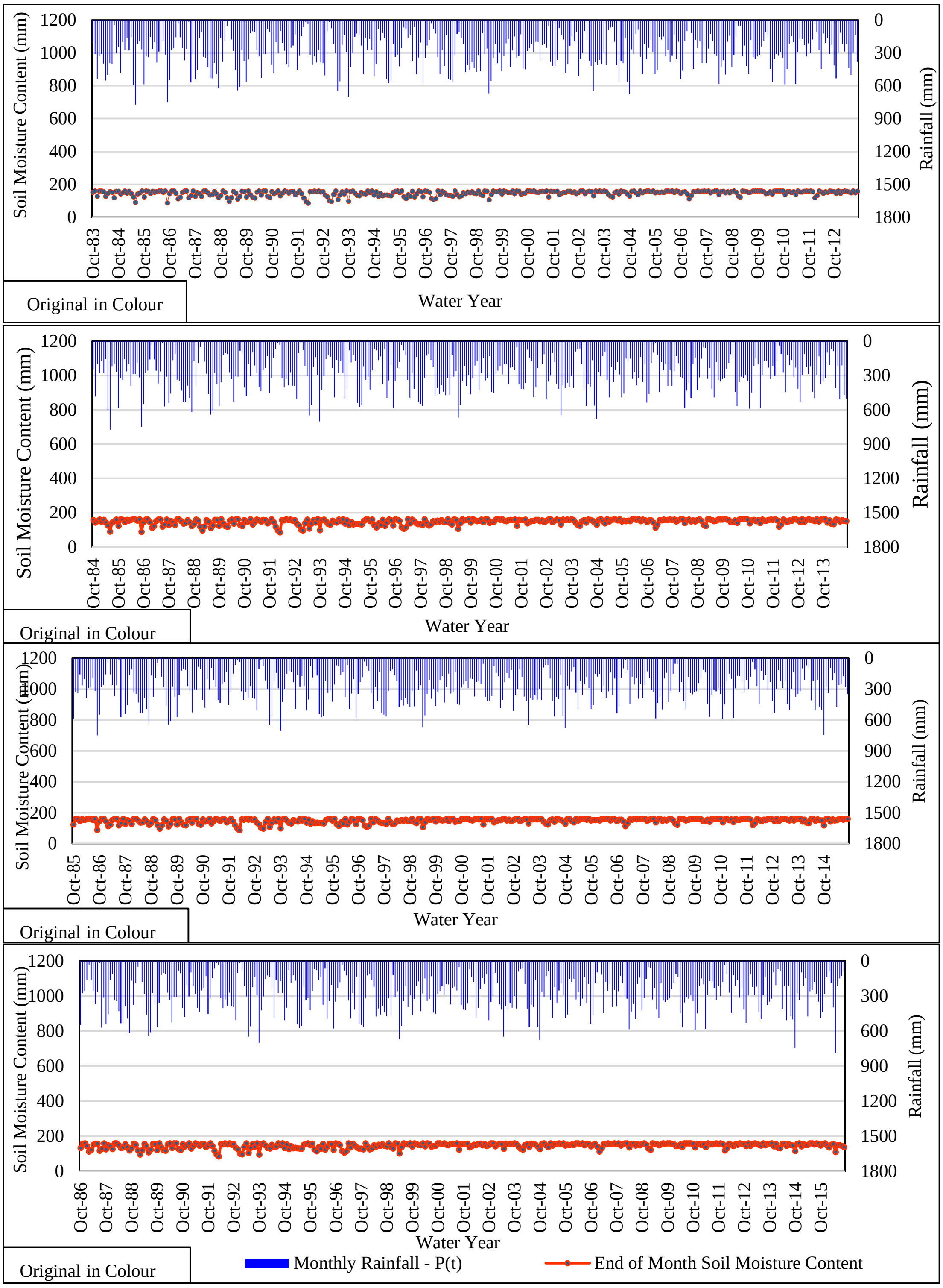


Figure D.310-D.313: Comparison of End of Month Soil Moisture Variation –30 year Datasets – Calibration

Soil Moisture Comparison – 30 Year Datasets – Calibration (Set 5)

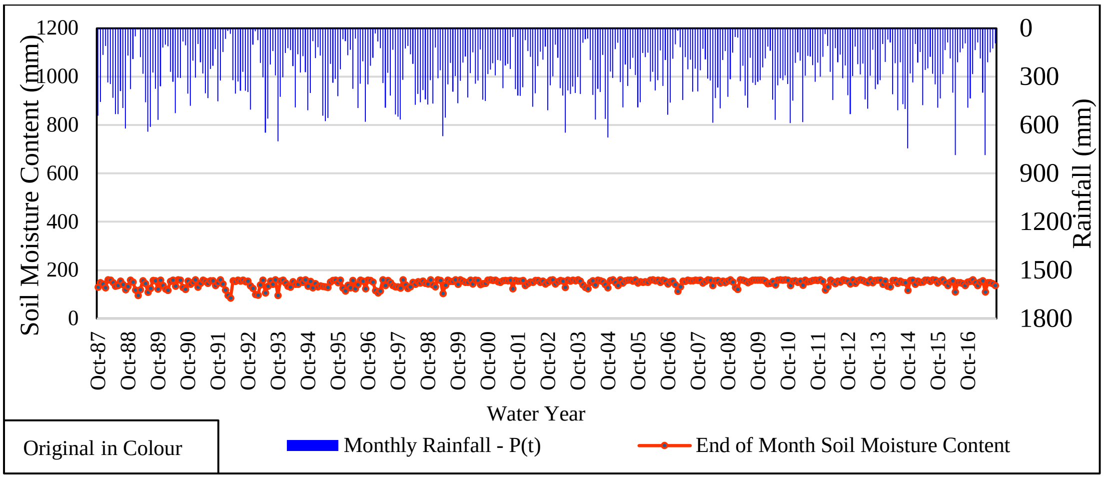


Figure D.314: Comparison of End of Month Soil Moisture Variation –30 year Datasets – Calibration

APPENDIX D.5 – Comparison of Scatter Plots

Scatter Plots Comparison – 10 Year Datasets – Calibration (Set 1 – 6)

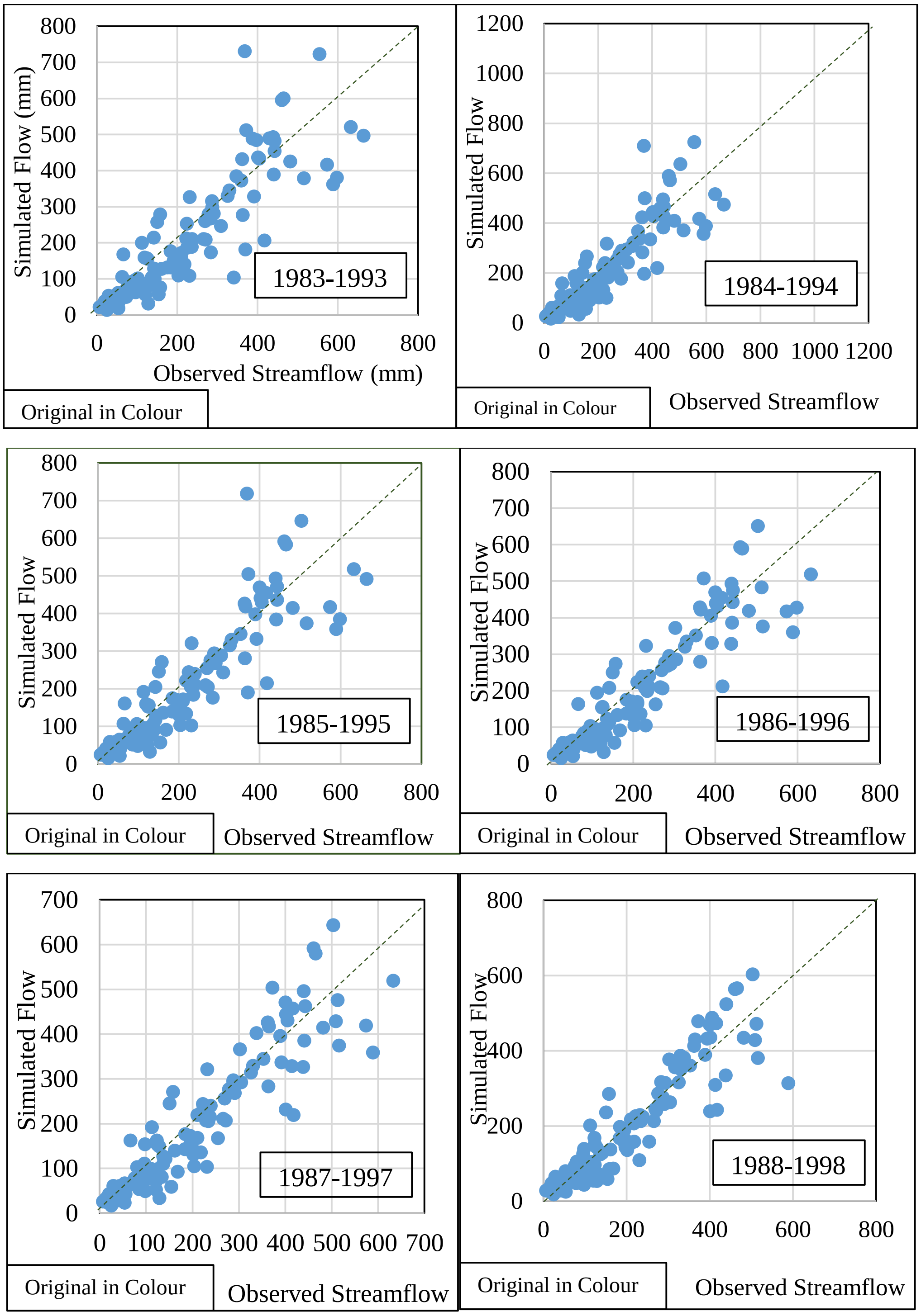


Figure D.315-D.320: Comparison of Scatter Plots –10 year Datasets – Calibration

Scatter Plots Comparison – 10 Year Datasets – Calibration (Set 7 – 12)

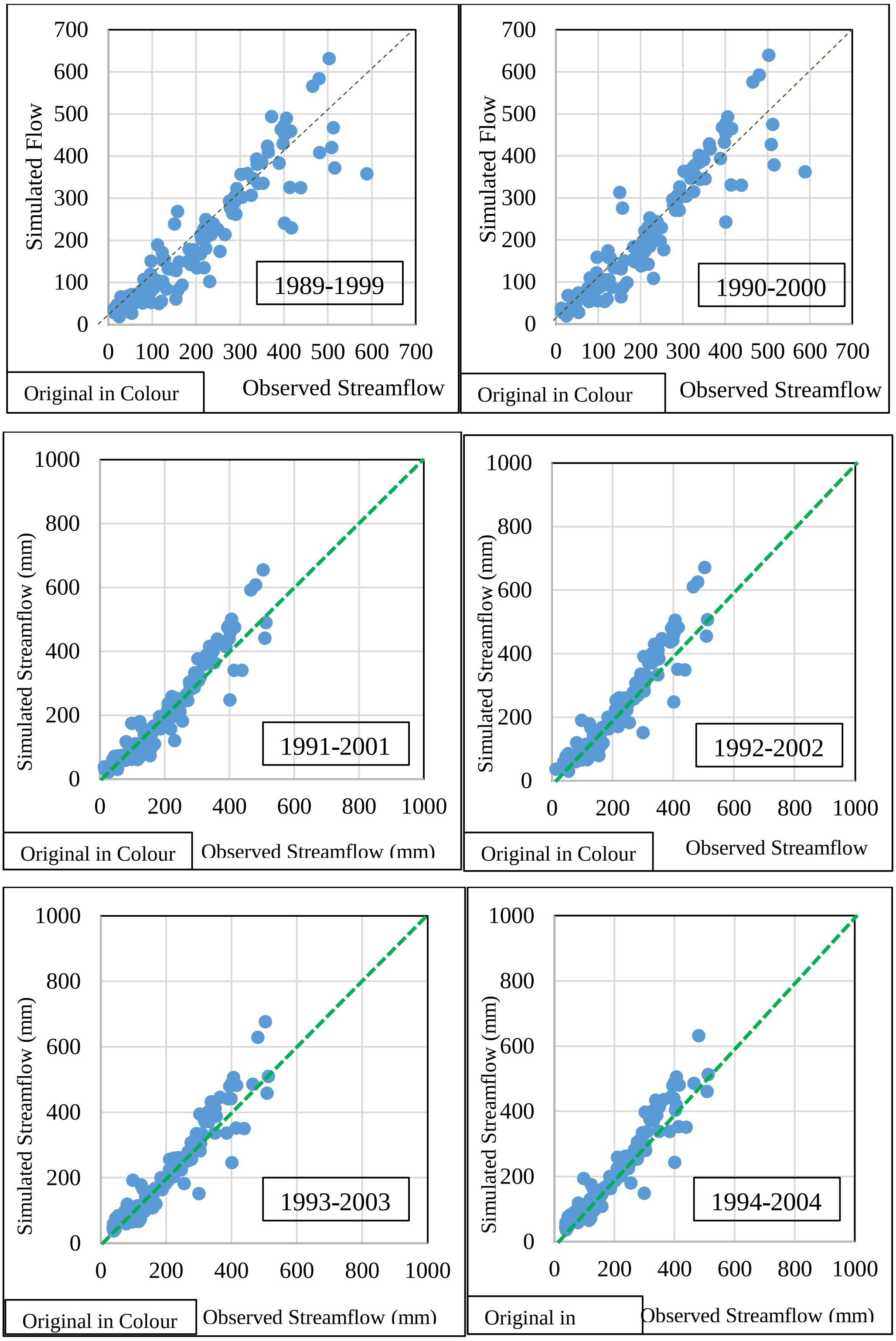


Figure D.321-D.326: Comparison of Scatter Plots –10 year Datasets – Calibration

Scatter Plots Comparison – 10 Year Datasets – Calibration (Set 13 – 18)

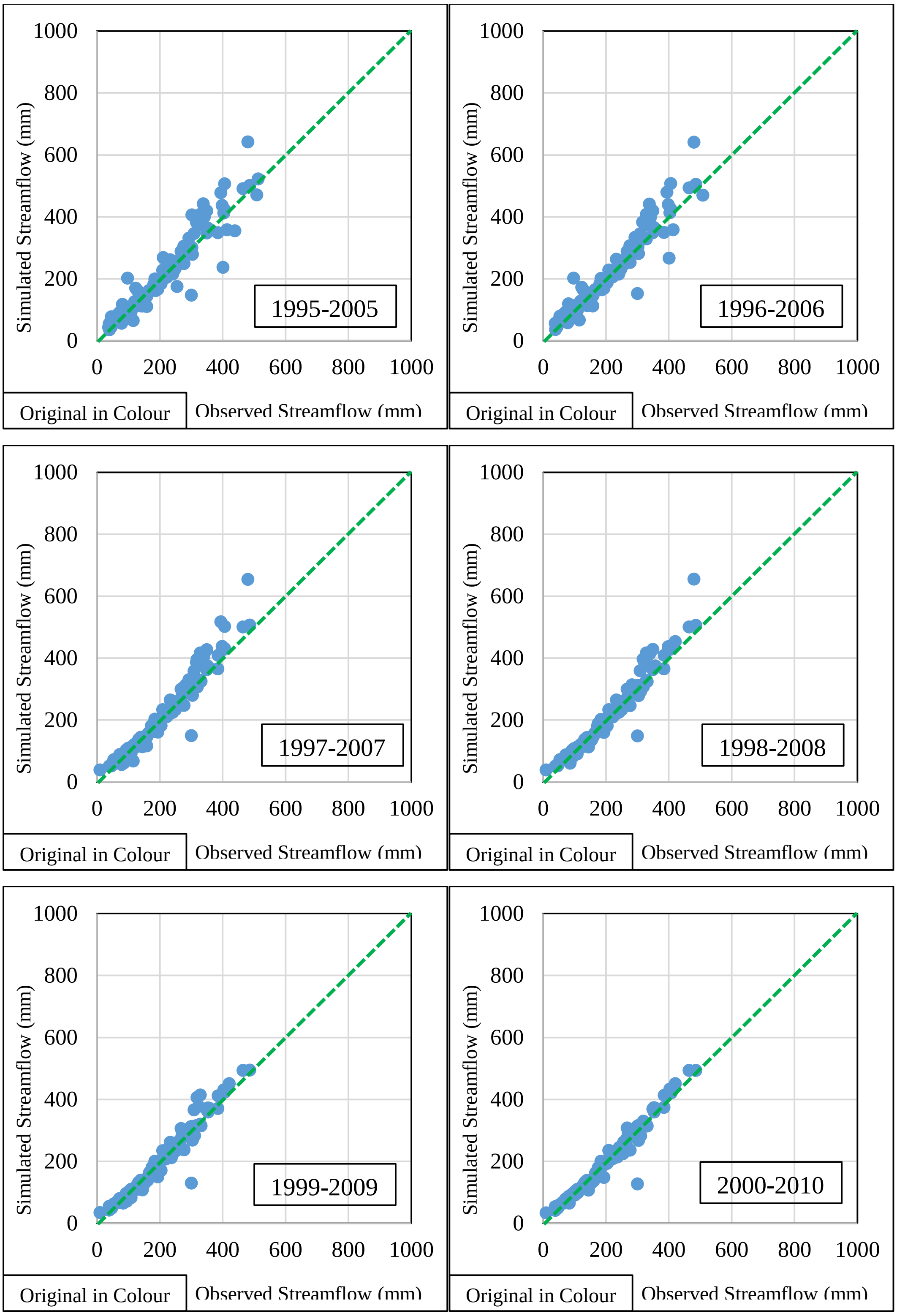


Figure D.327-D.332: Comparison of Scatter Plots –10 year Datasets – Calibration

Scatter Plots Comparison – 10 Year Datasets – Calibration (Set 19 - 24)

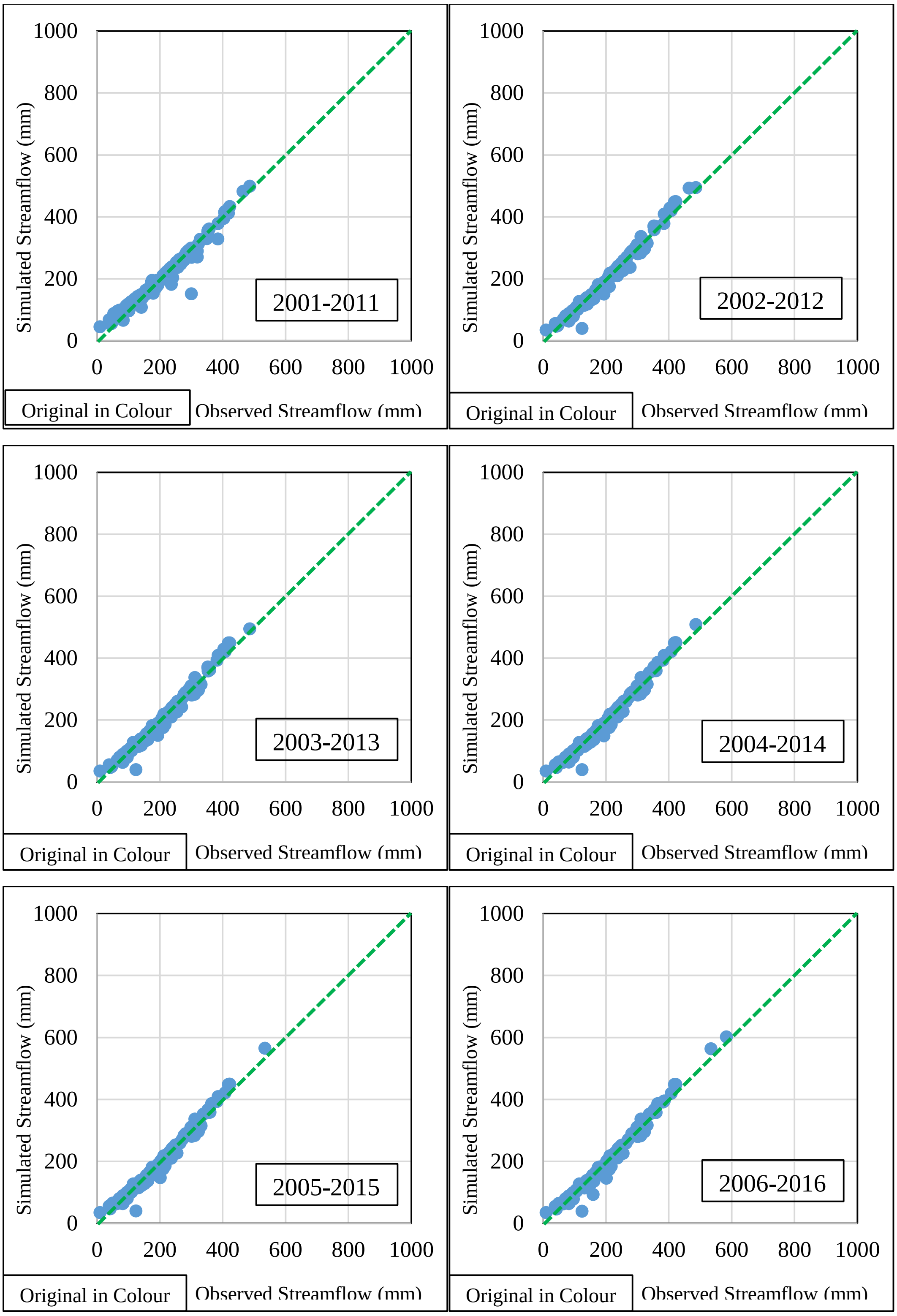


Figure D.333-D.338: Comparison of Scatter Plots –10 year Datasets – Calibration

Scatter Plots Comparison – 10 Year Datasets – Calibration (Set 25)

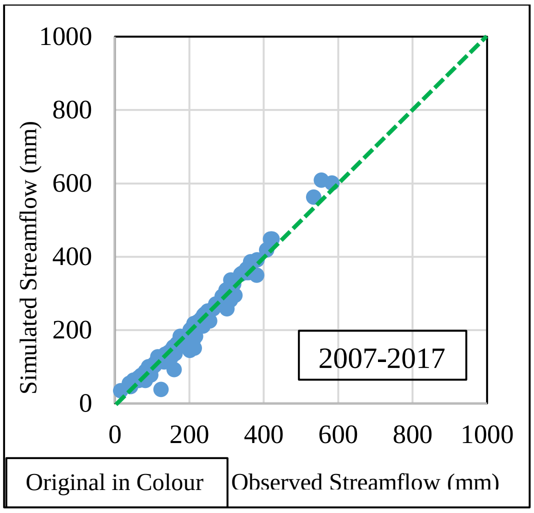


Figure D.339: Comparison of Scatter Plots –10 year Datasets – Calibration

Scatter Plots Comparison – 15 Year Datasets – Calibration (Set 1 – 6)

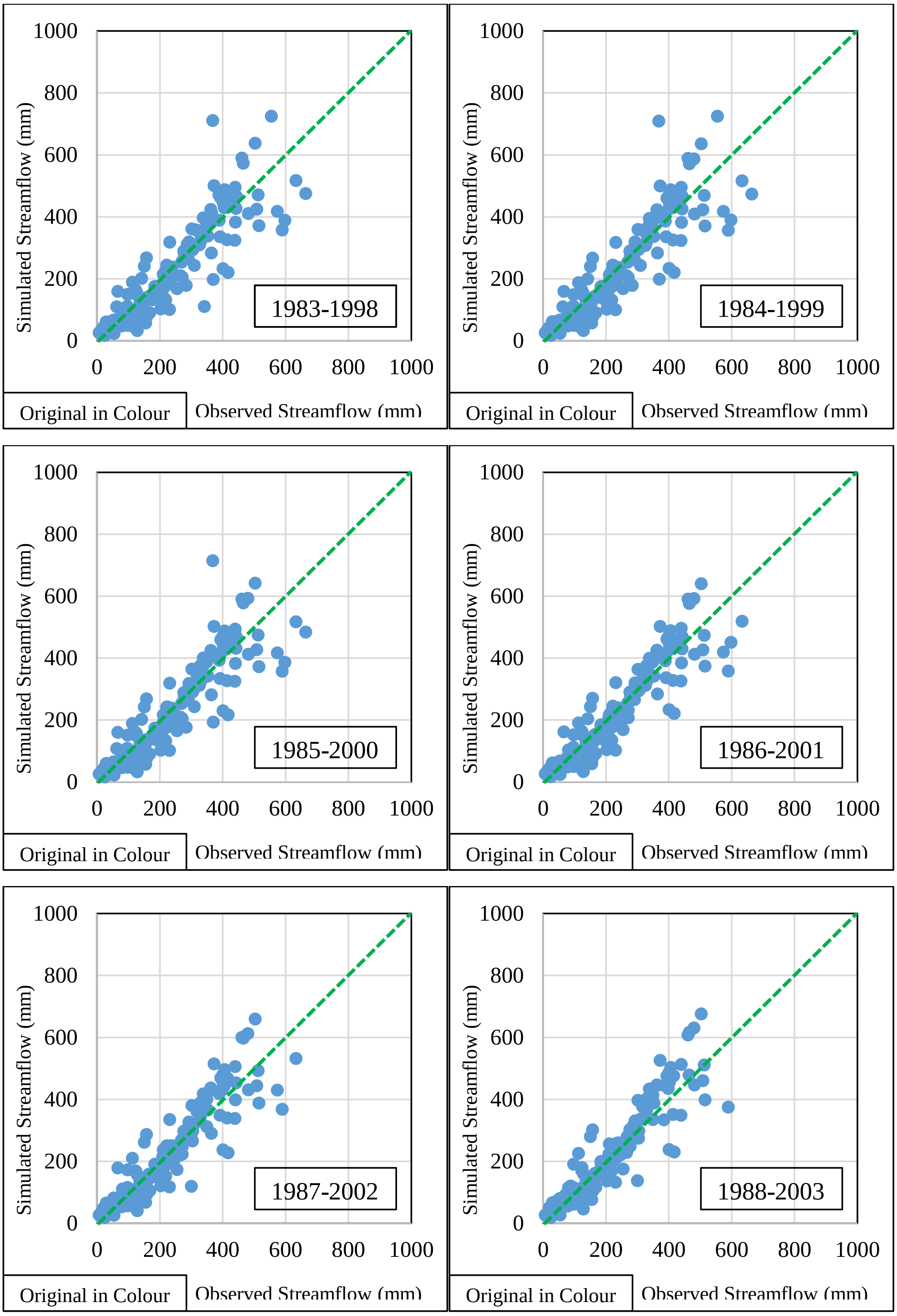


Figure D.340-D345: Comparison of Scatter Plots –15 year Datasets – Calibration

Scatter Plots Comparison – 15 Year Datasets – Calibration (Set 7 – 12)

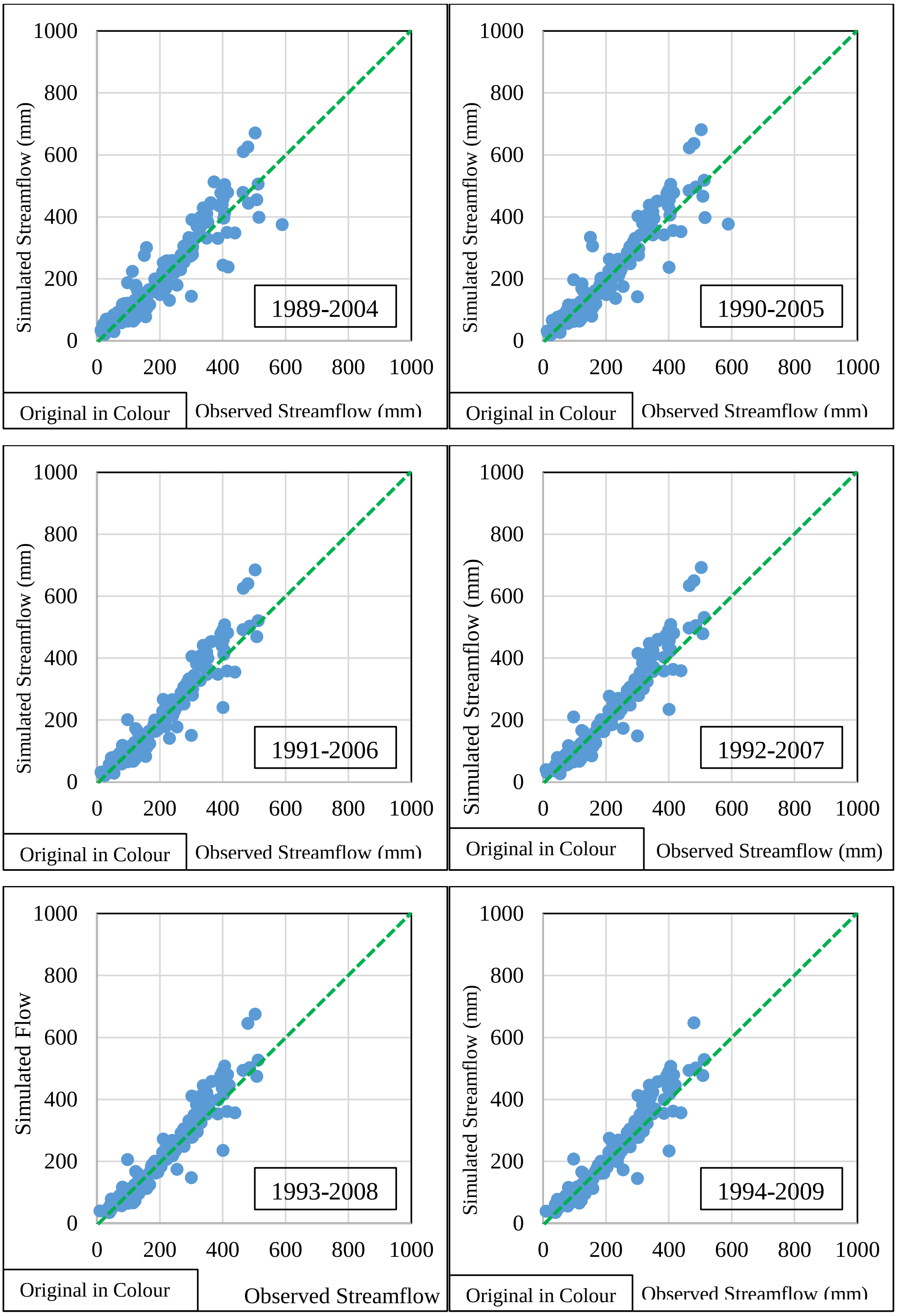


Figure D.346-D351: Comparison of Scatter Plots –15 year Datasets – Calibration

Scatter Plots Comparison – 15 Year Datasets – Calibration (Set 13 – 18)

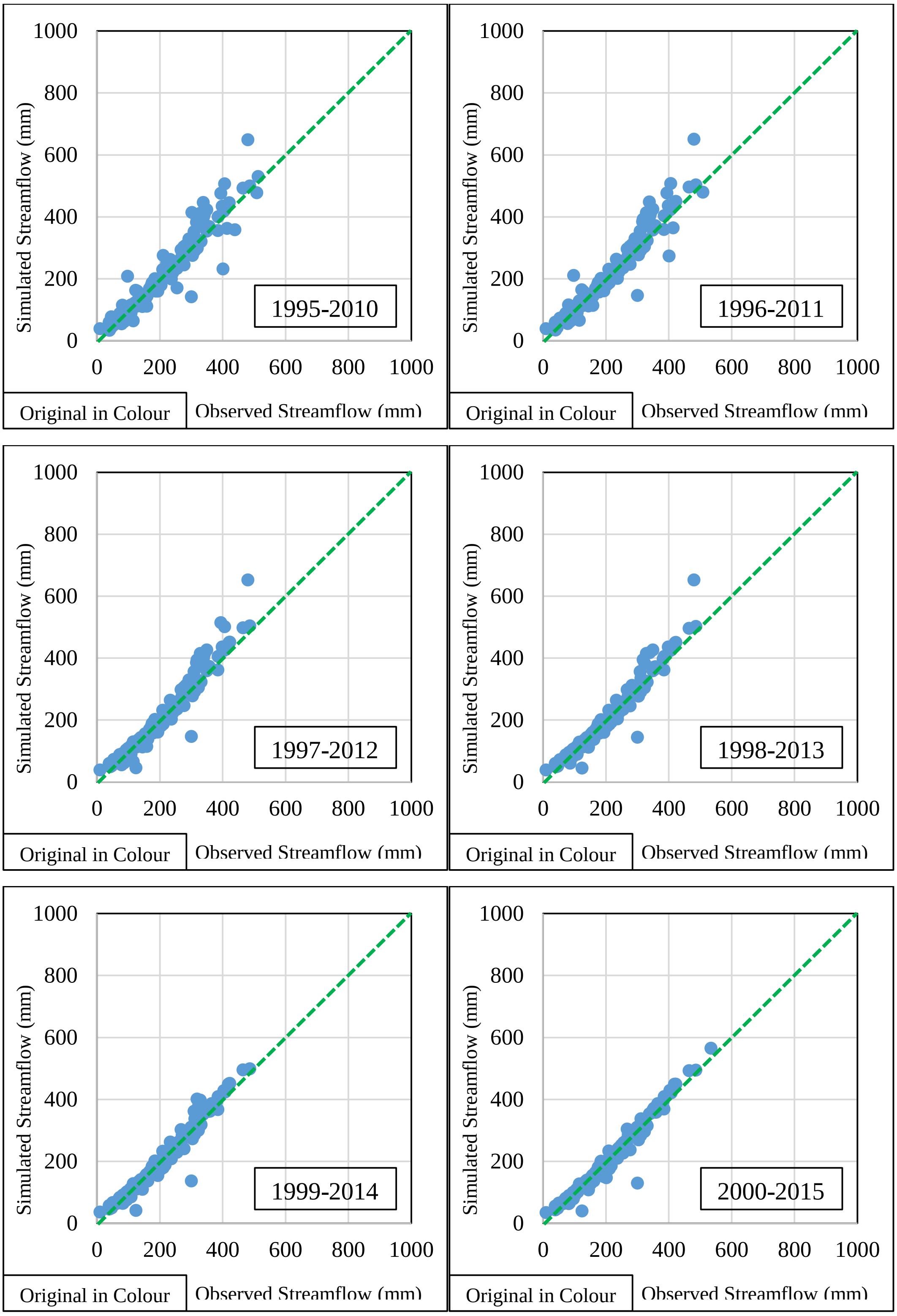


Figure D.352-D357: Comparison of Scatter Plots –15 year Datasets – Calibration

Scatter Plots Comparison – 15 Year Datasets – Calibration (Set 19 – 20)

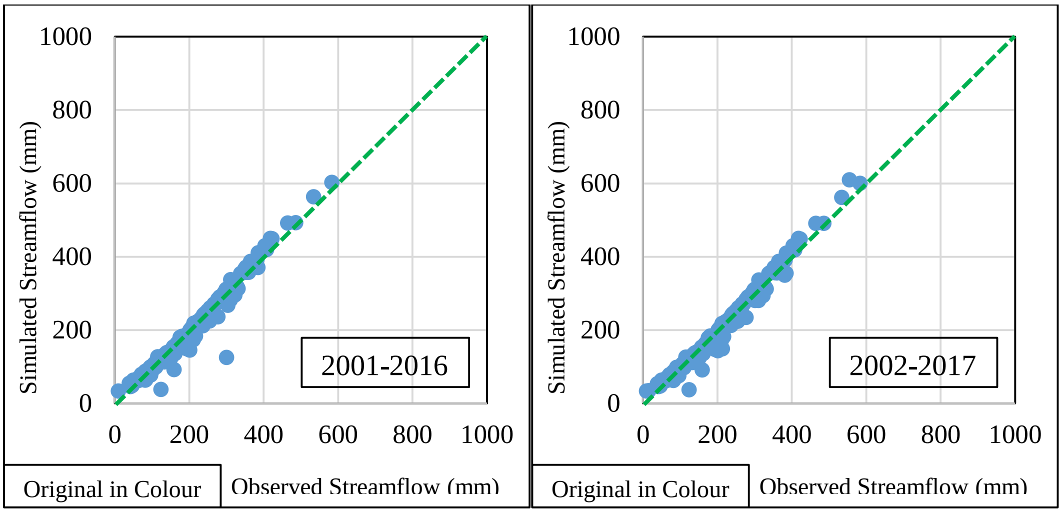


Figure D.358-D359: Comparison of Scatter Plots –15 year Datasets – Calibration

Scatter Plots Comparison – 20 Year Datasets – Calibration (Set 1 – 6)

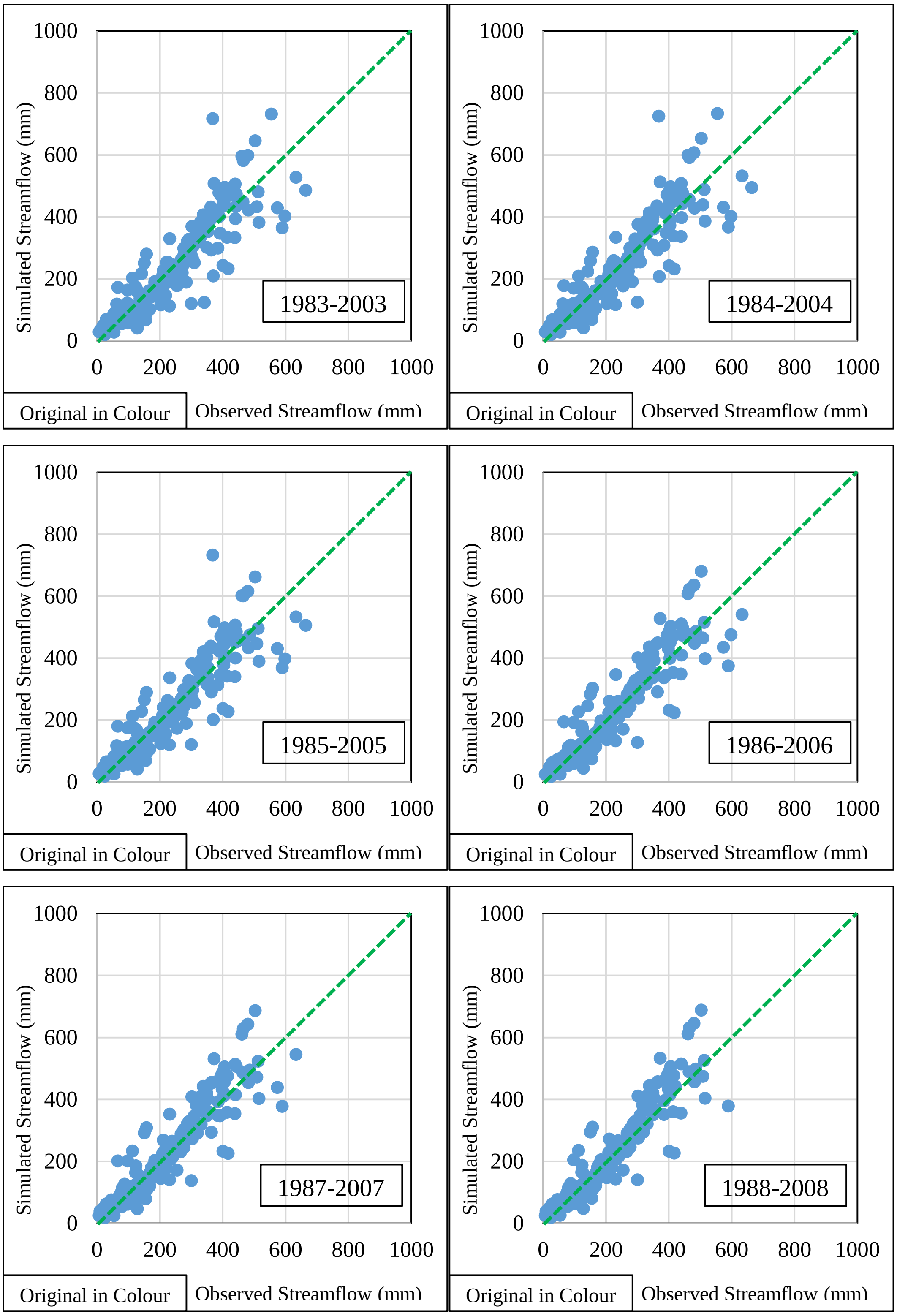


Figure D.360-D365: Comparison of Scatter Plots –20 year Datasets – Calibration

Scatter Plots Comparison – 20 Year Datasets – Calibration (Set 7 – 12)

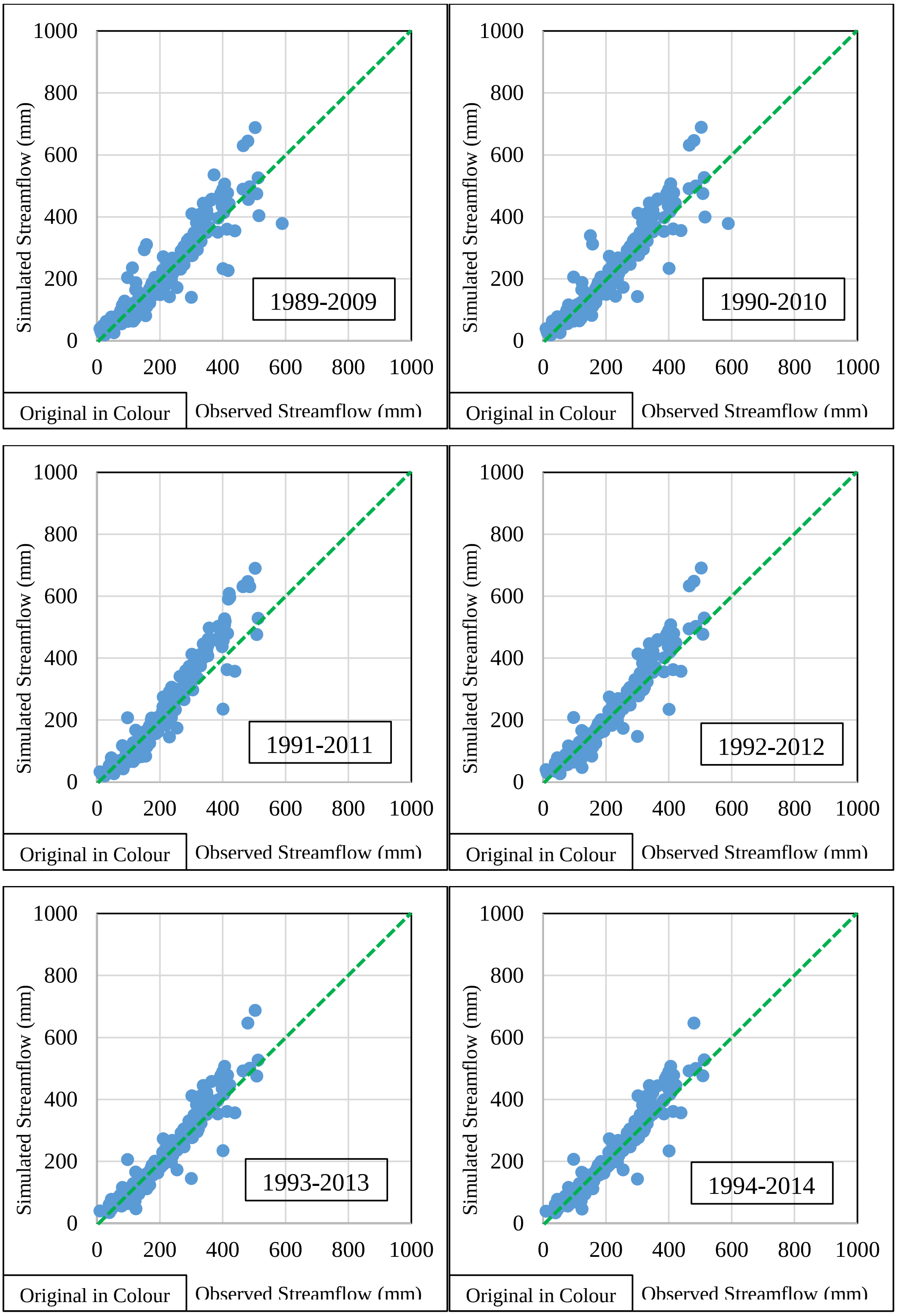


Figure D.366-D371: Comparison of Scatter Plots –20 year Datasets – Calibration

Scatter Plots Comparison – 20 Year Datasets – Calibration (Set 13 – 15)

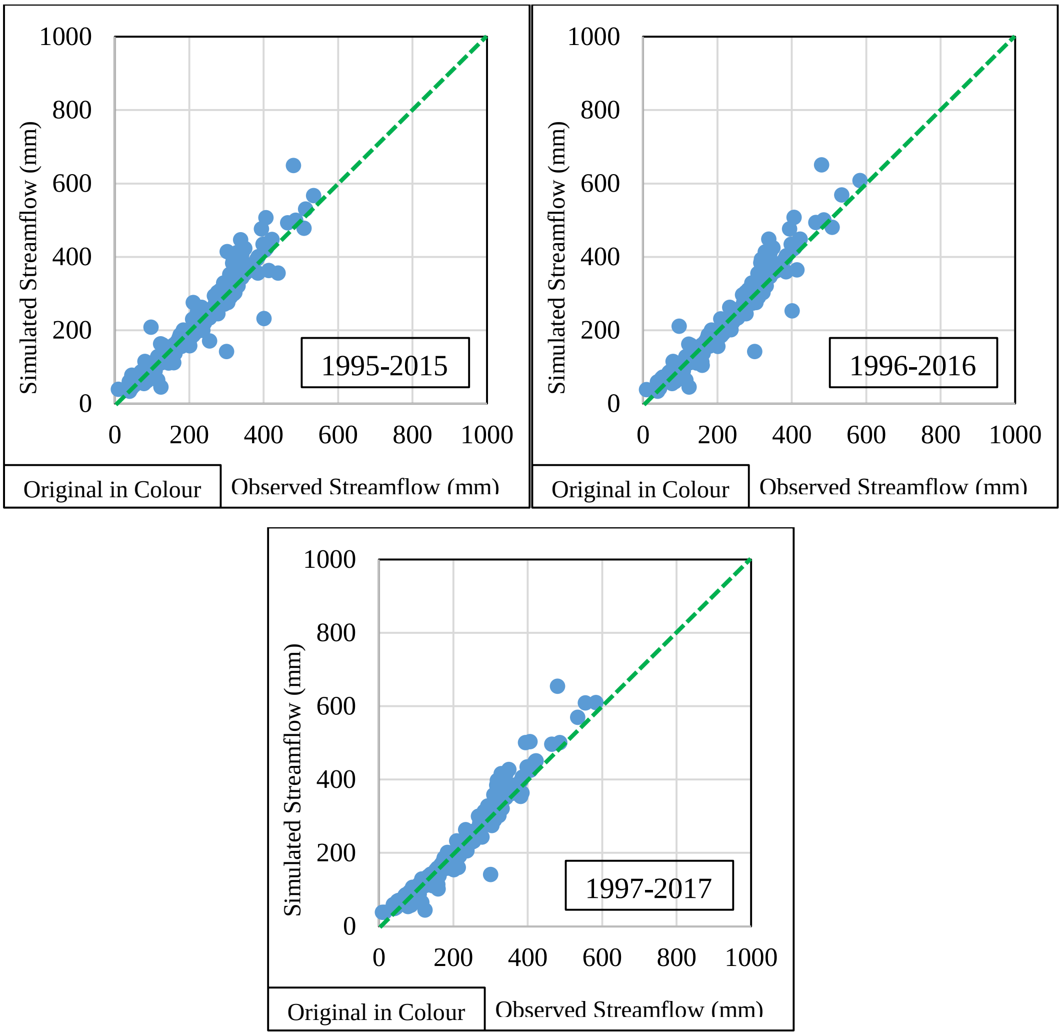


Figure D.372-D374: Comparison of Scatter Plots –20 year Datasets – Calibration

Scatter Plots Comparison – 25 Year Datasets – Calibration (Set 1 – 6)

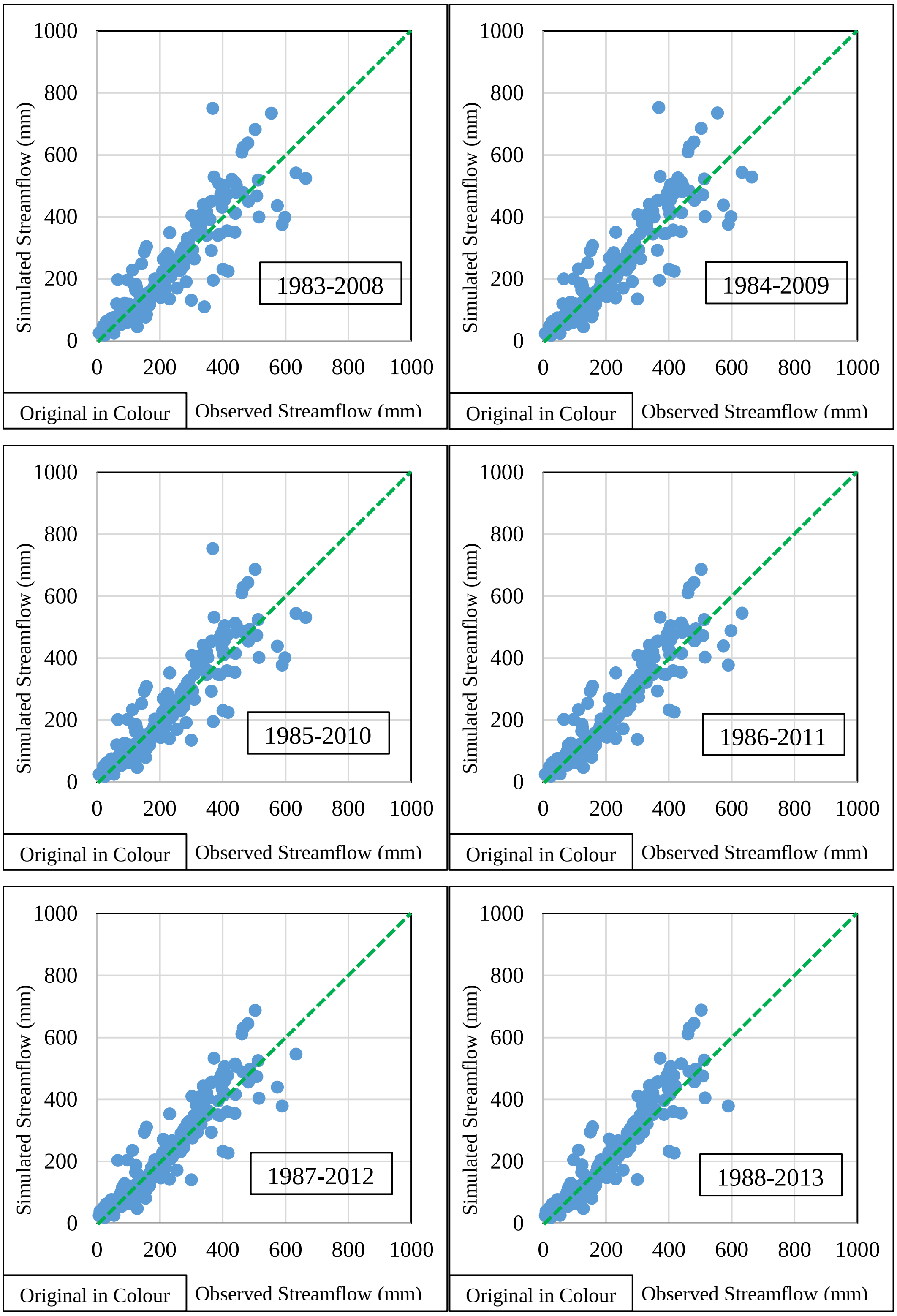


Figure D.375-D380: Comparison of Scatter Plots –25 year Datasets – Calibration

Scatter Plots Comparison – 25 Year Datasets – Calibration (Set 7– 10)

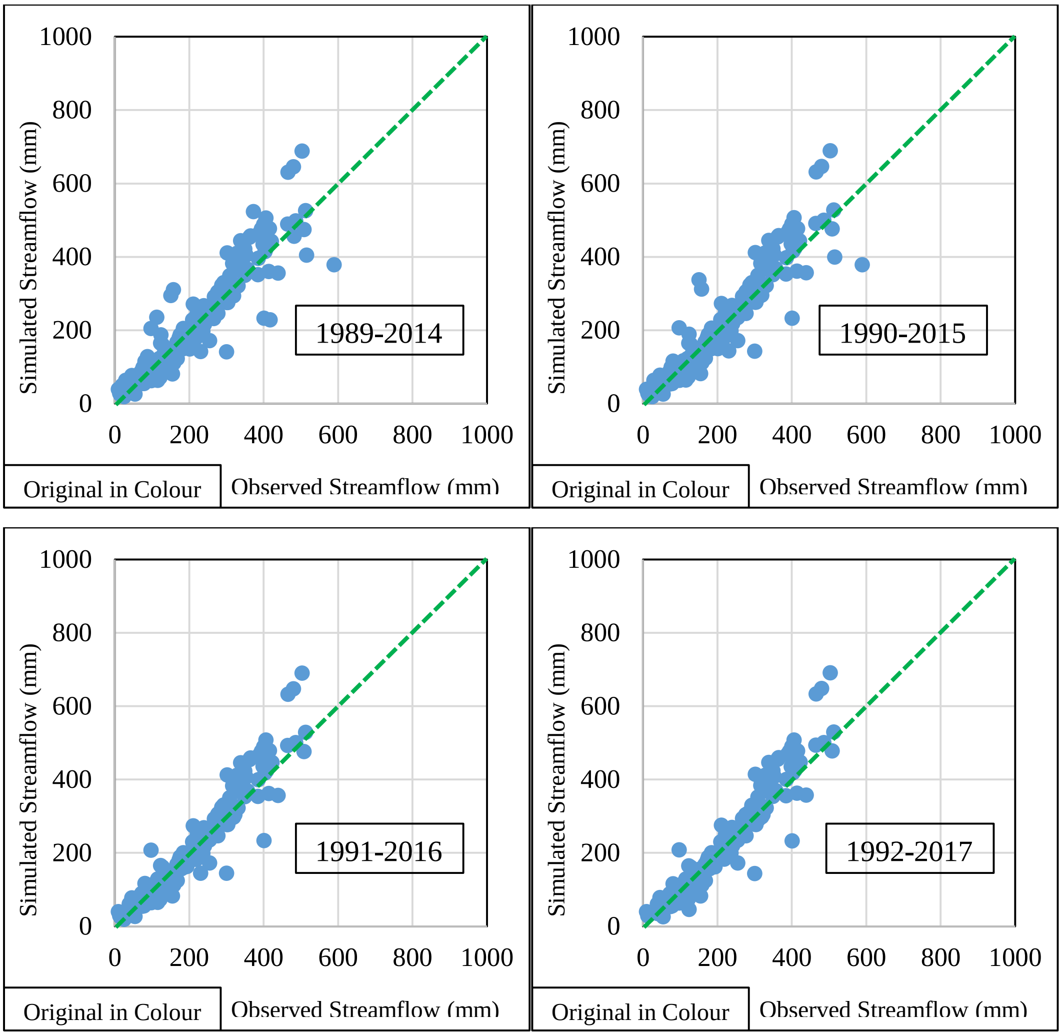


Figure D.381-D386: Comparison of Scatter Plots –25 year Datasets – Calibration

Scatter Plots Comparison – 30 Year Datasets – Calibration (Set 1 – 5)

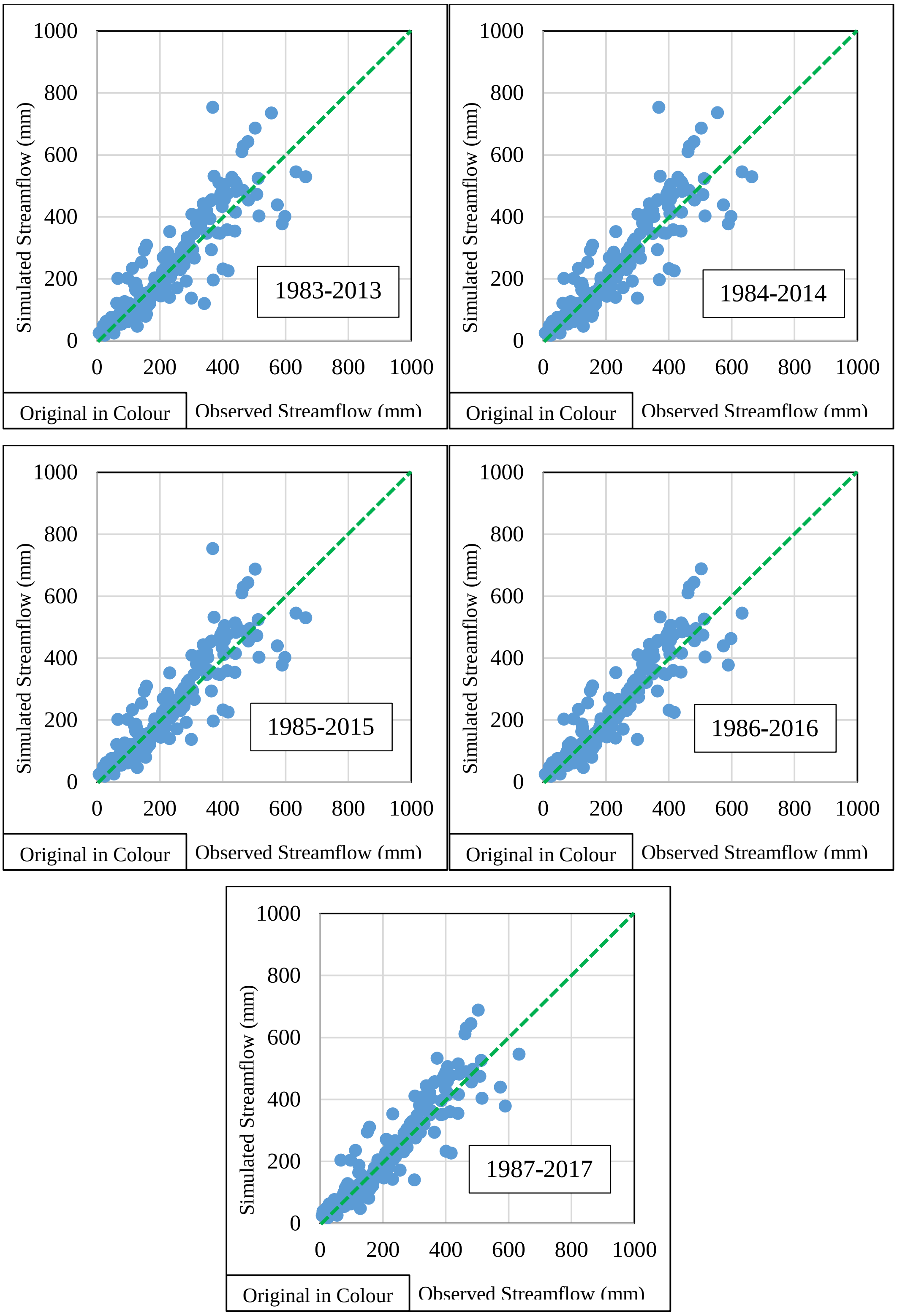


Figure D.387-D.392: Comparison of Scatter Plots –30 year Datasets – Calibration

APPENDIX D.6 –Summary of Results

Table D-1: Comparison of Calibration outputs and Indicators for 15 Year Datasets

	Data Period	MRAE - Overall	FDC MRAE - Overall	FDC MRAE - High	FDC MRAE - Intermediate	FDC MRAE - Low	Average Annual Water Balance Difference	Soil Moisture Content - Beginning	Soil Moisture Content - End	Maximum Storage	Minimum Storage	Maximum Flow	Minimum Flow	C	SC
C15-1	1983/1984 –1997/1998	0.2696	0.1177	0.0354	0.1048	0.1719	(154.75)	202.06	202.06	206.06	95.81	725.42	17.10	0.99	740.00
C15-2	1984/1985 – 1998/1999	0.2641	0.1126	0.0261	0.0964	0.1719	(147.17)	205.25	205.25	208.85	96.87	725.19	17.23	0.99	750.00
C15-3	1985/1986 – 1999/2000	0.2578	0.1104	0.0194	0.0900	0.1762	(150.13)	192.25	192.25	197.95	91.81	714.74	16.32	1.00	710.88
C15-4	1986/1987 – 2000/2001	0.2439	0.1034	0.0178	0.0763	0.1733	(129.66)	204.05	204.05	204.76	95.69	640.31	17.20	0.98	735.30
C15-5	1987/1988 – 2001/2002	0.2415	0.0962	0.0403	0.0505	0.1697	(38.26)	166.06	166.06	195.12	96.57	659.44	18.84	0.88	700.69
C15-6	1988/1989 – 2002/2003	0.2273	0.1	0.1	0.0	0.2	48.16	179.52	179.52	181.00	93.88	676.6	19.6	0.8	650.0
C15-7	1989/1990 – 2003/2004	0.2024	0.0738	0.0711	0.0217	0.1272	57.05	185.58	185.58	194.93	100.63	671.11	20.88	0.79	700.00
C15-8	1990/1991 – 2004/2005	0.1814	0.0728	0.0878	0.0327	0.1053	62.58	174.18	174.18	174.70	91.94	682.01	19.64	0.79	627.36
C15-9	1991/1992 – 2005/2006	0.1504	0.0781	0.1220	0.0341	0.1002	87.89	170.01	170.01	176.41	93.88	684.54	20.39	0.76	633.52
C15-10	1992/1993 – 2006/2007	0.1622	0.0844	0.1308	0.0256	0.1199	95.32	159.22	159.22	159.75	95.09	692.18	26.84	0.75	573.67
C15-11	1993/1994 – 2007/2008	0.1447	0.0732	0.1088	0.0186	0.1100	76.28	153.16	153.16	164.99	104.60	675.35	35.28	0.76	592.49
C15-12	1994/1995 – 2008/2009	0.1404	0.0707	0.0982	0.0222	0.1055	65.28	158.98	158.98	160.45	103.20	647.71	34.64	0.76	576.18
C15-13	1995/1996 – 2009/2010	0.1304	0.0635	0.0784	0.0246	0.0950	42.02	156.18	156.18	156.21	97.49	648.97	33.99	0.77	560.99
C15-14	1996/1997 – 2010/2011	0.1186	0.0590	0.0844	0.0195	0.0859	53.35	155.16	155.16	156.13	97.08	650.79	34.60	0.76	560.69
C15-15	1997/1998 – 2011/2012	0.1071	0.0731	0.0955	0.0234	0.1117	45.79	152.83	152.83	153.80	93.82	652.24	38.84	0.75	552.32
C15-16	1998/1999 – 2012/2013	0.0972	0.0638	0.0672	0.0258	0.1001	18.81	148.60	148.60	151.78	91.18	652.39	38.51	0.76	545.05
C15-17	1999/2000 – 2013/2014	0.0918	0.0629	0.0479	0.0298	0.1034	(10.59)	119.80	119.80	137.46	97.65	499.20	36.41	0.77	493.65
C15-18	2000/2001 – 2014/2015	0.0851	0.0618	0.0286	0.0378	0.1025	(39.61)	124.17	124.17	129.32	76.13	565.62	35.11	0.78	464.41
C15-19	2001/2002 – 2015/2016	0.0828	0.0641	0.0294	0.0450	0.1004	(48.26)	112.50	112.50	124.32	64.02	602.83	34.32	0.79	446.45
C15-20	2002/2003 – 2016/2017	0.0874	0.0670	0.0266	0.0413	0.1129	(44.25)	100.57	100.57	121.01	58.86	610.05	33.77	0.79	434.56

Table D-2: Comparison of Verification Indicators for 15 Year Datasets

	Data Period	MRAE - Overall	FDC MRAE - Overall	FDC MRAE - High	FDC MRAE - Intermediate	FDC MRAE - Low	Average Annual Water Balance Difference	Soil Moisture Content - Beginning	Soil Moisture Content - End	Maximum Storage	Minimum Storage	Maximum Flow	Minimum Flow	C	SC
V15-1	1976/1977 – 1982/1983	0.2569	0.1520	0.1433	0.1598	0.1489	(335.04)	200.57	200.57	206.06	109.82	735.74	23.91	0.99	740.00
V15-2	1976/1977 – 1982/1983	0.2555	0.1513	0.1434	0.1607	0.1463	(337.74)	203.82	203.82	208.85	110.83	734.66	23.97	0.99	750.00
V15-3	1976/1977 – 1982/1983	0.2658	0.1643	0.1451	0.1658	0.1731	(347.18)	191.15	191.15	197.95	105.00	736.64	22.69	1.00	710.88
V15-4	1976/1977 – 1982/1983	0.2566	0.1483	0.1425	0.1556	0.1441	(325.48)	198.96	198.96	204.76	110.12	737.11	24.30	0.98	735.30
V15-5	1976/1977 – 1982/1983	0.2629	0.1074	0.1322	0.1052	0.0961	(209.64)	186.45	186.45	195.09	110.78	751.63	26.59	0.88	700.69
V15-6	1976/1977 – 1982/1983	0.2836	0.0902	0.1252	0.0699	0.0915	(121.94)	168.24	168.24	181.00	107.20	763.35	27.54	0.81	650.00
V15-7	1976/1977 – 1982/1983	0.2805	0.0902	0.1225	0.0614	0.1015	(106.98)	185.20	185.20	194.88	115.04	762.23	29.38	0.79	700.00
V15-8	1976/1977 – 1982/1983	0.2931	0.0880	0.1227	0.0655	0.0915	(99.17)	160.08	160.08	174.70	102.45	766.57	27.45	0.79	627.36
V15-9	1976/1977 – 1982/1983	0.3006	0.0856	0.1199	0.0574	0.0951	(67.64)	161.89	161.89	176.41	104.19	769.47	28.33	0.76	633.52
V15-10	1976/1977 – 1982/1983	0.3138	0.0854	0.1216	0.0615	0.0896	(59.65)	140.51	140.51	159.75	82.69	771.80	26.71	0.75	573.67
V15-11	1976/1977 – 1982/1983	0.3074	0.0862	0.1216	0.0619	0.0913	(68.55)	147.37	147.37	164.99	89.44	770.61	27.09	0.76	592.49
V15-12	1976/1977 – 1982/1983	0.3097	0.0876	0.1226	0.0646	0.0916	(73.76)	141.58	141.58	160.44	83.77	770.40	26.48	0.76	576.18
V15-13	1976/1977 – 1982/1983	0.3118	0.0889	0.1236	0.0675	0.0914	(80.23)	136.17	136.17	156.22	78.58	769.94	25.87	0.77	560.99
V15-14	1976/1977 – 1982/1983	0.3158	0.0859	0.1224	0.0637	0.0881	(64.18)	135.87	135.87	156.13	78.25	771.49	26.21	0.76	560.69
V15-15	1976/1977 – 1982/1983	0.3188	0.0850	0.1225	0.0634	0.0862	(60.47)	132.78	132.78	153.80	75.32	771.88	26.04	0.75	552.32
V15-16	1976/1977 – 1982/1983	0.3189	0.0862	0.1232	0.0657	0.0865	(67.20)	130.22	130.22	151.77	72.95	771.24	25.66	0.76	545.05
V15-17	1976/1977 – 1982/1983	0.3295	0.0923	0.1249	0.0729	0.0938	(78.34)	111.47	111.47	137.46	56.25	769.34	23.81	0.77	493.65
V15-18	1976/1977 – 1982/1983	0.3350	0.1031	0.1259	0.0790	0.1148	(94.59)	100.83	100.83	129.30	47.46	766.59	22.52	0.78	464.41
V15-19	1976/1977 – 1982/1983	0.3401	0.1104	0.1262	0.0818	0.1303	(100.63)	94.23	94.23	124.28	42.10	766.45	21.77	0.79	446.45
V15-20	1976/1977 – 1982/1983	0.3428	0.1180	0.1266	0.0845	0.1467	(108.92)	89.91	89.91	121.00	38.72	765.76	21.15	0.79	434.56

Table D-3: Comparison of Calibration outputs and Indicators for 20 Year Datasets

	Data Period	MRAE - Overall	FDC MRAE - Overall	FDC MRAE - High	FDC MRAE - Intermediate	FDC MRAE - Low	Average Annual Water Balance Difference	Soil Moisture Content - Beginning	Soil Moisture Content - End	Maximum Storage	Minimum Storage	Maximum Flow	Minimum Flow	C	SC
C20-1	1983/1984 – 2002/2003	0.2387	0.0988	0.0348	0.0708	0.1602	(62.99)	215.83	212.39	215.88	104.93	732.58	19.94	0.89	775.25
C20-2	1984/1985 – 2003/2004	0.2351	0.0892	0.0329	0.0565	0.1513	(41.85)	201.84	204.60	206.94	102.16	734.36	19.86	0.87	743.13
C20-3	1985/1986 – 2004/2005	0.2289	0.0801	0.0281	0.0564	0.1308	(49.17)	189.15	184.12	191.83	95.51	733.04	18.79	0.87	688.90
C20-4	1986/1987 – 2005/2006	0.2134	0.0765	0.0533	0.0364	0.1290	3.16	161.80	161.80	167.66	86.97	680.09	18.18	0.83	602.10
C20-5	1987/1988 – 2006/2007	0.2153	0.0837	0.0726	0.0285	0.1453	43.02	161.56	161.56	162.35	86.19	686.70	18.66	0.79	583.02
C20-6	1988/1989 – 2007/2008	0.2004	0.0866	0.0932	0.0266	0.1438	58.47	149.71	149.71	160.85	86.05	688.74	18.84	0.78	577.62
C20-7	1989/1990 – 2008/2009	0.1823	0.0698	0.0811	0.0216	0.1127	52.92	160.30	160.30	161.56	86.34	688.38	18.87	0.78	580.19
C20-8	1990/1991 – 2009/2010	0.1643	0.0664	0.0859	0.0209	0.1023	60.39	160.98	160.98	160.97	86.40	689.50	19.01	0.77	578.09
C20-9	1991/1992 – 2010/2011	0.1424	0.0713	0.1071	0.0260	0.0986	69.57	161.96	161.96	162.48	87.59	690.35	19.40	0.76	583.51
C20-10	1992/1993 – 2011/2012	0.1390	0.0709	0.1036	0.0215	0.1039	61.22	159.59	159.59	161.15	97.12	690.80	26.71	0.76	578.72
C20-11	1993/1994 – 2012/2013	0.1262	0.0643	0.0867	0.0227	0.0947	44.73	160.51	160.51	162.23	99.04	687.54	34.67	0.77	582.59
C20-12	1994/1995 – 2013/2014	0.1220	0.0590	0.0762	0.0247	0.0847	36.92	148.39	148.39	160.53	103.46	646.88	34.38	0.77	576.50
C20-13	1995/1996 – 2014/2015	0.1164	0.0553	0.0646	0.0290	0.0771	25.17	154.55	154.55	156.19	97.46	648.97	33.99	0.77	560.92
C20-14	1996/1997 – 2015/2016	0.1090	0.0537	0.0678	0.0278	0.0726	23.96	132.58	132.58	152.62	92.49	651.06	33.81	0.77	548.09
C20-15	1997/1998 – 2016/2017	0.1055	0.0708	0.0763	0.0349	0.1043	22.00	131.16	131.16	145.53	82.87	654.21	37.59	0.77	522.63

Table D-4: Comparison of Verification Indicators for 20 Year Datasets

	Data Period	MRAE - Overall	FDC MRAE - Overall	FDC MRAE - High	FDC MRAE - Intermediate	FDC MRAE - Low	Average Annual Water Balance Difference	Soil Moisture Content - Beginning	Soil Moisture Content - End	Maximum Storage	Minimum Storage	Maximum Flow	Minimum Flow	C	SC
V20-1	1976/1977 – 1982/1983	0.2545	0.11	0.13	0.11	0.10	(224.00)	211.03	211.03	215.88	121.08	744.74	28.51	0.89	775.25
V20-2	1976/1977 – 1982/1983	0.2594	0.10	0.13	0.10	0.09	(198.61)	200.42	200.42	206.93	117.54	749.87	28.23	0.87	743.13
V20-3	1976/1977 – 1982/1983	0.2655	0.10	0.13	0.10	0.09	(200.74)	182.39	182.39	191.84	109.44	753.28	26.47	0.87	688.90
V20-4	1976/1977 – 1982/1983	0.2884	0.0968	0.1277	0.0822	0.0945	(147.46)	151.72	151.72	167.66	94.07	762.62	25.27	0.83	602.10
V20-5	1976/1977 – 1982/1983	0.3009	0.0917	0.1246	0.0713	0.0943	(104.49)	144.40	144.40	162.35	86.63	767.30	25.95	0.79	583.02
V20-6	1976/1977 – 1982/1983	0.3055	0.0900	0.1237	0.0684	0.0932	(90.02)	142.29	142.29	160.84	84.51	768.80	26.16	0.78	577.62
V20-7	1976/1977 – 1982/1983	0.3047	0.0899	0.1237	0.0683	0.0931	(90.91)	143.23	143.23	161.56	85.43	768.67	26.22	0.78	580.19
V20-8	1976/1977 – 1982/1983	0.3073	0.0887	0.1231	0.0664	0.0923	(81.97)	142.36	142.36	160.97	84.56	769.57	26.36	0.77	578.09
V20-9	1976/1977 – 1982/1983	0.3094	0.0865	0.1218	0.0625	0.0913	(67.84)	144.14	144.14	162.48	86.26	770.86	26.83	0.76	583.51
V20-10	1976/1977 – 1982/1983	0.3105	0.0868	0.1221	0.0631	0.0913	(68.34)	142.43	142.43	161.14	84.58	770.89	26.67	0.76	578.72
V20-11	1976/1977 – 1982/1983	0.3074	0.0878	0.1226	0.0649	0.0917	(77.34)	143.92	143.92	162.23	86.07	769.95	26.59	0.77	582.59
V20-12	1976/1977 – 1982/1983	0.3080	0.0887	0.1231	0.0663	0.0923	(80.79)	141.78	141.78	160.53	83.98	769.71	26.33	0.77	576.50
V20-13	1976/1977 – 1982/1983	0.3118	0.09	0.12	0.07	0.09	(80.26)	136.15	136.15	156.20	78.56	769.94	25.87	0.77	560.92
V20-14	1976/1977 – 1982/1983	0.3160	0.09	0.12	0.07	0.09	(75.93)	131.43	131.43	152.62	74.10	770.41	25.57	0.77	548.09
V20-15	1976/1977 – 1982/1983	0.3227	0.09	0.12	0.07	0.09	(74.43)	122.11	122.11	145.53	65.55	770.38	24.81	0.77	522.63

Table D-5: Comparison of Calibration outputs and Indicators for 25 Year Datasets

	Data Period	MRAE - Overall	FDC MRAE - Overall	FDC MRAE - High	FDC MRAE - Intermediate	FDC MRAE - Low	Average Annual Water Balance Difference	Soil Moisture Content - Beginning	Soil Moisture Content - End	Maximum Storage	Minimum Storage	Maximum Flow	Minimum Flow	C	SC
C25-1	1983/1984 – 2007/2008	0.2187	0.0860	0.0729	0.0429	0.1356	12.01	152.05	152.05	164.50	86.04	750.64	18.21	0.82	590.73
C25-2	1984/1985 – 2008/2009	0.2145	0.0789	0.0726	0.0297	0.1312	34.31	161.38	161.38	162.47	86.05	753.44	18.56	0.80	583.44
C25-3	1985/1986 – 2009/2010	0.2074	0.0707	0.0638	0.0271	0.1178	26.69	159.59	159.59	159.59	84.62	753.97	18.28	0.80	573.12
C25-4	1986/1987 – 2010/2011	0.1942	0.0715	0.0633	0.0232	0.1239	33.04	161.60	161.60	162.00	86.03	686.81	18.63	0.79	581.78
C25-5	1987/1988 – 2011/2012	0.1862	0.0731	0.0701	0.0226	0.1251	36.40	159.94	159.94	161.68	86.32	688.15	18.84	0.78	580.61
C25-6	1988/1989 – 2012/2013	0.1740	0.0760	0.0811	0.0261	0.1234	41.85	158.91	158.91	160.70	86.04	688.97	18.86	0.78	577.11
C25-7	1989/1990 – 2013/2014	0.1592	0.0602	0.0702	0.0217	0.0937	36.82	149.65	149.65	161.44	86.35	688.61	18.90	0.78	579.75
C25-8	1990/1991 – 2014/2015	0.1463	0.0580	0.0750	0.0232	0.0845	42.33	158.98	158.98	160.25	86.05	689.72	18.95	0.77	575.49
C25-9	1991/1992 – 2015/2016	0.1296	0.0625	0.0891	0.0285	0.0831	41.26	137.97	137.97	160.72	86.42	690.00	19.07	0.77	577.15
C25-10	1992/1993 – 2016/2017	0.1322	0.0650	0.0875	0.0286	0.0902	41.40	147.04	147.04	158.20	93.29	690.99	26.07	0.77	568.13

Table D-6: Comparison of Verification Indicators for 25 Year Datasets

	Data Period	MRAE - Overall	FDC MRAE - Overall	FDC MRAE - High	FDC MRAE - Intermediate	FDC MRAE - Low	Average Annual Water Balance Difference	Soil Moisture Content - Beginning	Soil Moisture Content - End	Maximum Storage	Minimum Storage	Maximum Flow	Minimum Flow	C	SC
V25-1	1976/1977 – 1982/1983	0.2935	0.0954	0.1266	0.0790	0.0948	(134.44)	147.52	147.52	164.49	89.81	764.20	25.30	0.82	590.73
V25-2	1976/1977 – 1982/1983	0.2998	0.0924	0.1250	0.0725	0.0945	(109.85)	144.62	144.62	162.47	86.86	766.77	25.80	0.80	583.44
V25-3	1976/1977 – 1982/1983	0.3017	0.0938	0.1257	0.0743	0.0958	(113.36)	140.95	140.95	159.59	83.28	766.60	25.37	0.80	573.12
V25-4	1976/1977 – 1982/1983	0.3012	0.0919	0.1247	0.0715	0.0944	(104.73)	143.96	143.96	162.00	86.19	767.30	25.90	0.79	581.78
V25-5	1976/1977 – 1982/1983	0.3042	0.0902	0.1238	0.0687	0.0932	(92.70)	143.40	143.40	161.68	85.60	768.49	26.20	0.78	580.61
V25-6	1976/1977 – 1982/1983	0.3060	0.0897	0.1236	0.0680	0.0930	(88.26)	142.09	142.09	160.70	84.31	768.98	26.19	0.78	577.11
V25-7	1976/1977 – 1982/1983	0.3052	0.0897	0.1236	0.0679	0.0929	(89.08)	143.05	143.05	161.44	85.25	768.86	26.25	0.78	579.75
V25-8	1976/1977 – 1982/1983	0.3078	0.0890	0.1232	0.0668	0.0925	(82.45)	141.44	141.44	160.25	83.66	769.57	26.27	0.77	575.49
V25-9	1976/1977 – 1982/1983	0.3085	0.0882	0.1228	0.0655	0.0919	(77.92)	141.98	141.98	160.71	84.17	769.98	26.42	0.77	577.15
V25-10	1976/1977 – 1982/1983	0.3108	0.0884	0.1231	0.0661	0.0916	(77.12)	138.72	138.72	158.20	81.01	770.18	26.16	0.77	568.13

Table D-7: Comparison of Calibration outputs and Indicators for 30 Year Datasets

	Data Period	MRAE - Overall	FDC MRAE - Overall	FDC MRAE - High	FDC MRAE - Intermediate	FDC MRAE - Low	Average Annual Water Balance Difference	Soil Moisture Content - Beginning	Soil Moisture Content - End	Maximum Storage	Minimum Storage	Maximum Flow	Minimum Flow	C	SC
C30-1	1983/1984 – 2012/2013	0.23	0.08	0.07	0.03	0.12	27.47	160.53	147.83	162.03	86.05	495.06	18.63	0.79	581.91
C30-2	1984/1985 – 2013/2014	0.23	0.07	0.07	0.03	0.11	24.68	151.19	162.46	162.46	86.25	495.11	18.66	0.79	583.42
C30-3	1985/1986 – 2014/2015	0.22	0.06	0.06	0.03	0.10	20.83	160.54	147.19	161.57	85.82	560.46	18.59	0.79	580.20
C30-4	1986/1987 – 2015/2016	0.21	0.06	0.06	0.03	0.11	19.44	136.58	156.41	159.14	84.79	599.28	18.45	0.79	571.49
C30-5	1987/1988 – 2016/2017	0.20	0.06	0.06	0.02	0.10	25.20	137.78	144.08	160.73	85.89	601.96	18.77	0.78	577.20

Table D-8: Comparison of Verification Indicators for 30 Year Datasets

	Data Period	MRAE - Overall	FDC MRAE - Overall	FDC MRAE - High	FDC MRAE - Intermediate	FDC MRAE - Low	Average Annual Water Balance Difference	Soil Moisture Content - Beginning	Soil Moisture Content - End	Maximum Storage	Minimum Storage	Maximum Flow	Minimum Flow	C	SC
V30-1	1976/1977 – 1982/1983	0.3011	0.0919	0.1247	0.0715	0.0944	(104.65)	144.01	144.01	162.04	86.24	767.30	25.91	0.79	581.91
V30-2	1976/1977 – 1982/1983	0.3008	0.0917	0.1246	0.0713	0.0942	(104.44)	144.55	144.55	162.46	86.77	767.29	25.96	0.79	583.42
V30-3	1976/1977 – 1982/1983	0.3015	0.0920	0.1248	0.0717	0.0945	(104.97)	143.40	143.40	161.57	85.64	767.30	25.84	0.79	580.20
V30-4	1976/1977 – 1982/1983	0.3039	0.0924	0.1250	0.0721	0.0949	(103.34)	140.25	140.25	159.13	82.56	767.60	25.62	0.79	571.49
V30-5	1976/1977 – 1982/1983	0.3049	0.0884	0.1229	0.0663	0.0917	(92.90)	142.17	142.17	160.72	84.41	768.53	26.09	0.78	577.20

Table D-9: Average Comparison of Model Performance

Mean	MRAE - Overall	FDC MRAE - Overall	FDC MRAE - High	FDC MRAE - Intermediate	FDC MRAE - Low	Average Annual Water Balance Difference	Soil Moisture Content - Beginning	Soil Moisture Content - End	Maximum Storage	Minimum Storage	Maximum Flow	Minimum Flow	C	SC
C10	0.17	0.09	0.06	0.05	0.14	(29.86)	163.12	163.12	170.63	96.35	613.40	29.48	0.84	612.77
V10	0.30	0.11	0.13	0.10	0.13	(159.67)	154.27	154.27	170.62	86.50	757.76	25.16	0.84	612.77
C15	0.16	0.08	0.07	0.04	0.13	(5.51)	161.01	161.01	167.75	91.81	653.83	27.48	0.82	602.41
V15	0.30	0.11	0.13	0.09	0.11	(140.37)	150.86	150.86	167.74	86.05	761.15	25.37	0.82	602.41
C20	0.17	0.07	0.07	0.03	0.11	23.17	163.33	162.95	168.58	92.97	686.88	24.85	0.80	605.42
V20	0.30	0.09	0.13	0.08	0.09	(110.87)	151.99	151.99	168.58	89.49	765.13	26.39	0.80	605.42
C25	0.18	0.07	0.07	0.03	0.11	34.61	154.71	154.71	161.16	86.72	708.13	19.44	0.78	578.73
V25	0.30	0.09	0.12	0.07	0.09	(96.99)	142.77	142.77	161.15	85.01	768.09	25.98	0.78	578.73
C30	0.22	0.07	0.06	0.03	0.11	23.52	149.32	151.60	161.19	85.76	550.37	18.62	0.79	578.84
V30	0.30	0.09	0.12	0.07	0.09	(102.06)	142.87	142.87	161.18	85.12	767.60	25.88	0.79	578.84

APPENDIX E – Verification Results

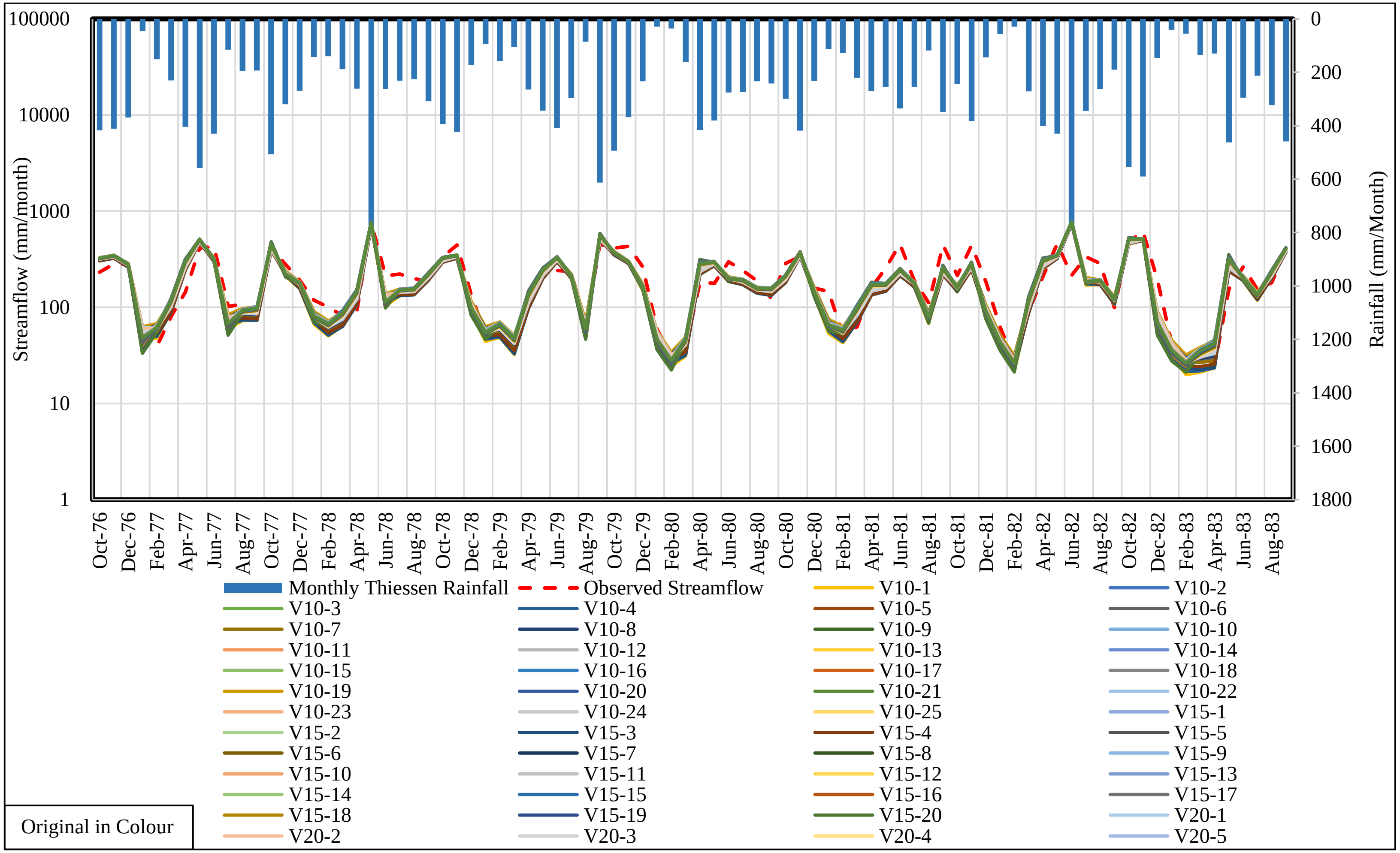


Figure E.1: Hydrograph Comparison of Verification Data

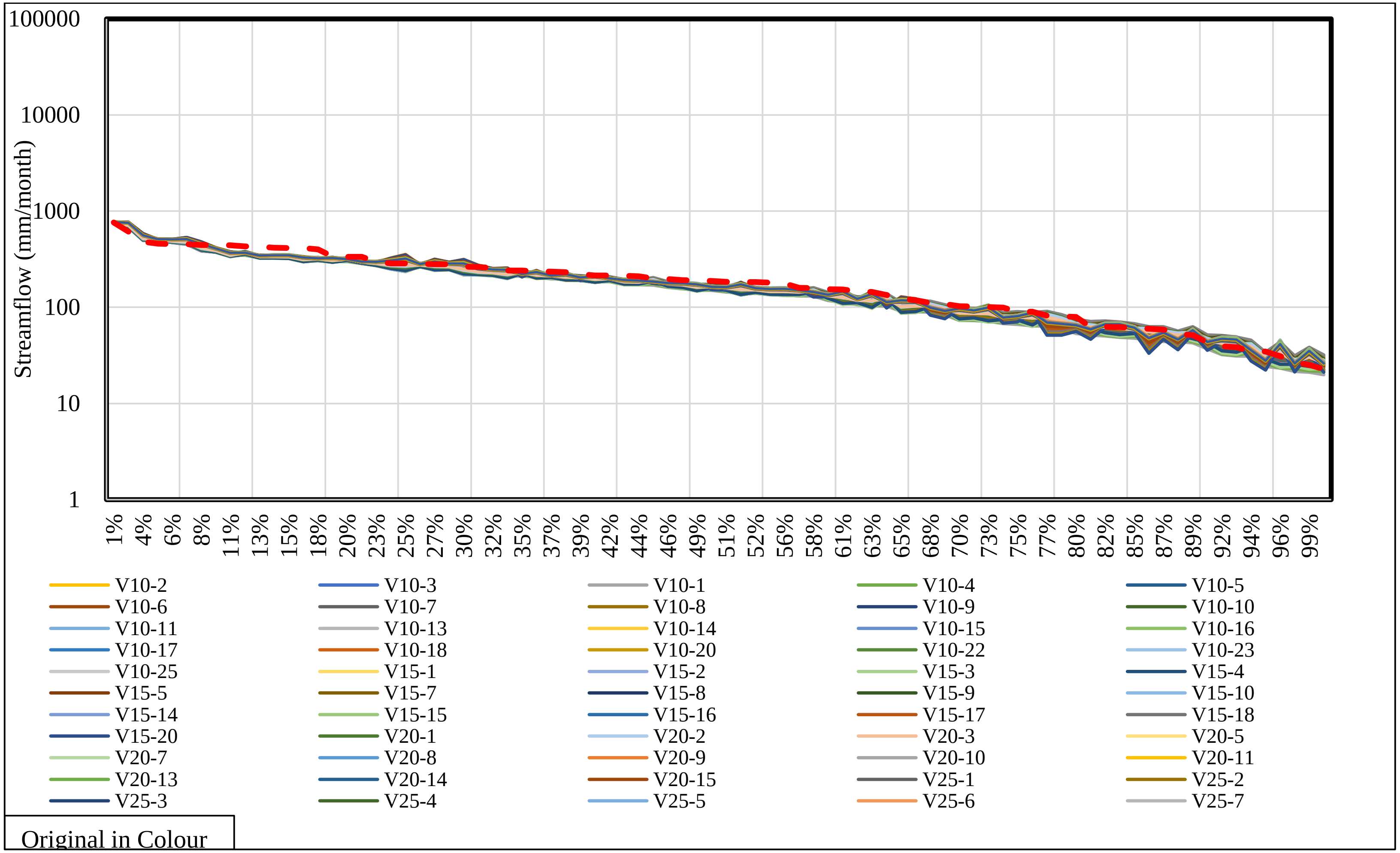


Figure E.2: Flow Duration Curve Comparison of Verification Data

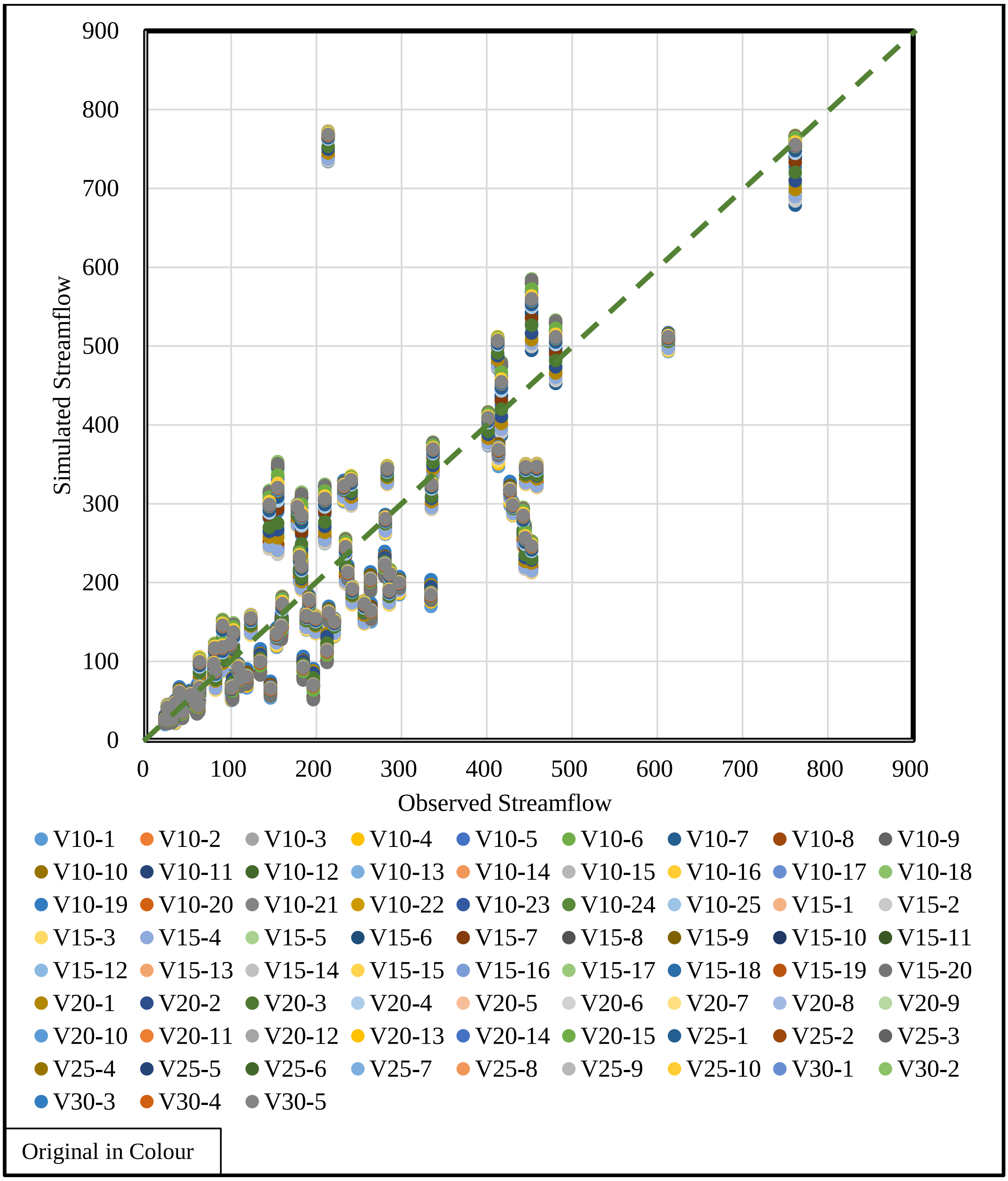


Figure E.3: Comparison of Scatter Plots - Verification Data