EVALUATION OF USING LOCAL INFORMATION FROM DONOR CATCHMENTS TO IMPROVE PERFORMANCE OF SELECTED DETERMINISTIC AND EMPIRICAL DESIGN FLOOD ESTIMATION METHODS IN SOUTH AFRICA

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Submitted in partial fulfilment of the requirements

for the degree of MSc Eng

Bioresources Engineering

School of Engineering

University of KwaZulu-Natal

Pietermaritzburg

October 2021

DECLARATION

I, Shaheil Khoosal, declare that

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ABSTRACT

There are a number of design flood estimation methods routinely used in South Africa. Flood Frequency Analysis (FFA) remains the preferred technique in instances where adequate records of observed data are available. However, in many parts of South Africa, rivers are not gauged for continuous streamflow monitoring. In the case of ungauged catchments, most hydrologists and engineers make use of methods based on deterministic and empirical approaches for design flood estimation. Due to the assumptions and limitations associated with these methods, improved approaches need to be developed for design flood estimation in ungauged catchments. International practice has shown that making use of local information transfer from nearby gauged catchments, also referred to as donor catchments, can improve flood estimation in ungauged catchments. Local information related to model parameters, hydrologic indices, and global uncertainty can be used to compensate for local variations not considered in regional models. The main considerations for implementing such methods are the type of information transferred, selection of suitable donor catchments and density of gauged donor catchments. Approaches for donor catchment selection include physical similarity, spatial proximity and integrated similarity. Some studies have also shown that the use of multiple donor catchments can offer further improvements. Thus, a methodology is proposed and evaluated for using local information from gauged donor catchments to improve the performance of selected deterministic and empirical flood estimation methods widely used in South Africa (Standard Design Flood, Rational Method, Synthetic Unit Hydrograph and HRU 1/71 Empirical Method) in a pilot study at 48 ungauged catchments with information and data provided by the Department of Water and Sanitation. The evaluation criteria used in the study include scatter plots, box and whisker plots of Relative Error and Mean Absolute Relative Error. The results of the study illustrate that, in general, information transfer from a single donor catchment can provide improved design flood estimates when used in conjunction with the existing flood estimation methods. The results also show that the degree of improvement for each of the methods is largely dependent on the approach used for donor catchment selection. When using a single donor catchment, the Standard Design Flood method performed best using the physical similarity approach for the proposed single donor transfer method and the Synthetic Unit Hydrograph method showed the best improvements using the integrated similarity approach, while both the Rational Method and HRU 1/71-Empirical method experienced the most significant improvements using the spatial proximity approach. Even though the best approach

for donor catchment selection varied for the different design flood estimation methods, the integrated similarity approach performed consistently well for all methods considered. Similar to the use of single donor catchments, the results obtained from the use of multiple donor catchments also varied for each of the methods used. The optimum number of catchments for the Standard Design Flood and Rational Method was 16 and 4, respectively. However, the Synthetic Unit Hydrograph and HRU 1/71 method did not show any further improvements when using multiple donor catchments. Due to the general improvements and promising results and success of the simple approach used in this study, it is recommended that further refinements of the proposed methodology and approaches to donor catchment selection be considered for future research projects.

ACKNOWLEDGMENTS

I would like to acknowledge and express my appreciation to the following people and institutions:

- Professor J.C. Smithers, my supervisor, for the support, guidance, patience and mentorship provided throughout the study.
- Doctor T.R. Kjeldsen, my co-supervisor, for the input and technical advice provided.
- Mr. Jeremy Naidoo and the Department of Water and Sanitation: Flood Studies Group for sharing the valuable catchment and design flood information.
- The South African National Roads Agency SOC Ltd (SANRAL) for the financial support provided.
- SANRAL colleagues and friends for their continued support and motivation.
- My family for their unwavering love, support, encouragement and always believing in me.

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LIST OF ABBREVIATIONS

AMS	Annual Maximum Series
DFE	Design Flood Estimation
DWA	Department of Water Affairs
DWS	Department of Water and Sanitation
FEH	Flood Estimation Handbook
FFA	Flood Frequency Analysis
GEV	General Extreme Value
HRU	Hydrological Research Unit
IDW	Inverse Distance Weighting
IS	Integrated Similarity
JPV	Joint Peak Volume
LN	Log-Normal
LP3	Log Pearson Type Ш
MARE	Mean Absolute Relative Error
MM	Method of Moments
MP	Model Parameter
NFSP	National Flood Studies Programme
NSE	Nash Sutcliffe Efficiency
PDS	Partial Duration Series
PS	Physical Similarity
PWM	Probability Weighted Moments
RE	Relative Error
ReFH	Revitalised Flood Hydrograph Method
RFFA	Regional Flood Frequency Analysis
RI	Recurrence Interval
RM	Rational Method
RME	Relative Mean Error
SANRAL	South African National Roads Agency SOC Ltd
SCS	Soil Conservation Services
SDF	Standard Design Flood
SP	Spatial Proximity

USDA-SCS	United States Department of Agriculture-Soil Conservation Services
USGS	United States Geological Survey
WAK	Wakeby Distribution

1. INTRODUCTION

Road networks are important for the economic, social and environmental development of a country. Thus, they are considered a critical network in terms of the consequences of their disruptions (Rogelis, 2015). Flooding poses an important threat to road transport, and can lead to massive obstruction of traffic and damage to road structures, with possible long-term effects (Rogelis, 2015). In addition, excessive runoff can lead to damage to the environment, nearby properties and in some instances also result in loss of life.

Design Flood Estimation (DFE) is a primary and critical step in the design of hydraulic structures, including road-over-river bridges and culverts (Pilgrim and Cordery, 1980). There are three primary approaches to DFE used in South Africa: statistical, deterministic and empirical. The approach that is used depends largely on the historical data that are available at the site of interest (Parak, 2007). Statistical methods make use of historical data to estimate design floods for a given Recurrence Interval (RI). Their use is thus limited to gauged catchments for which suitable flow records are available at the site of interest, or for catchments where records from adjacent gauged catchments are comparable and may be used (Van Vuuren *et al.*, 2013). Deterministic methods estimate the expected runoff from driving and contributing factors such as rainfall, based on the assumption that the Recurrence Interval (RI) of the estimated runoff is the same as the RI for the rainfall, while being influenced by catchment characteristic inputs and Model Parameters (MPs) (Gericke, 2010). According to a survey conducted by Van Vuuren *et al.* (2013), deterministic methods are the most commonly applied methods amongst hydrologists and engineers in South Africa due to the lack of available observed data for most catchments i.e. ungauged. Empirical methods relate peak discharge and derived catchment descriptors in order to establish general regional parameters or at-site quantiles (SANRAL, 2013). These methods are better suited for checking the order of magnitude of quantiles estimated using other methods.

According to Campbell *et a1*. (1987), the problems facing hydrologists and engineers in South Africa when estimating floods in catchments smaller than 100 km^2 is the lack of hydrological data and the absence of suitable guidelines on the selection and accuracies of techniques for DFE. This is especially problematic in the case of ungauged catchments.

Recent floods in South Africa highlight the need to re-assess the risks associated with floods (Smithers, 2012). The urgency for new approaches to DFE in South Africa are highlighted by Alexander (2002a), Smithers and Schulze (2002) and Görgens *et al*. (2007), Smithers (2012) and a National Flood Studies Programme (NFSP) has been initiated by Smithers *et al*. (2014) to update and modernise methods. Standard techniques for DFE in ungauged catchments have been developed for most countries. Typical methods commonly used in South Africa were developed in the 1970's and presented in HRU (1972). Many investigations have been undertaken to evaluate the performance of these methods by Kjeldsen *et al.* (2001), Van Bladeren (2005), Hogan (2007), Gericke and du Plessis (2012), Nathanael (2015) and Smithers *et al.* (2015b). These various studies have generally shown shortcomings with the DFE methods used in South Africa.

In order to improve the confidence and accuracy of flood estimation in ungauged catchments and in catchments with limited hydrological data, local information from nearby gauged donor catchments can be incorporated to improve design flood estimates using existing techniques. This approach involves the transfer of information such as Model Parameters (MPs), hydrologic indices, streamflow data and, in some cases, global uncertainty from gauged to ungauged catchments. In international studies, these gauged catchments are often referred to as donor catchments such as Kjeldsen (2007), Kjeldsen and Jones (2007), Oudin *et al*. (2008), Zhang and Chiew (2009), Patil and Stieglitz (2012), Kjeldsen *et al*. (2014) and Kjeldsen (2015). One of the most important considerations for using local information from donor catchments is the approach used for the selection of suitable donor catchments. These approaches include Spatial Proximity (SP), Physical Similarity (PS) and Integrated Similarity (IS) between the ungauged subject catchment and gauged donor catchment. The performance of these approaches has been evaluated in countries such as the United Kingdom, United States of America, Australia, France etc. The performance of the approaches for donor site selection varies for different countries. Many international studies have also shown that the use of multiple donor catchments can be used to improve the flood estimates at ungauged sites (Oudin *et al*., 2008; Zhang and Chiew, 2009; Patil and Stieglitz, 2012; Kjeldsen *et al*., 2014). Studies undertaken by Van Bladeren (2005) and Smal (2012) attempted to determine correction factors to improve current selected DFE methods, however, the use of local information from donor catchments has not been evaluated or used in South Africa. This presents an opportunity to determine the benefits of using correction factors from donor catchments with existing DFE methods.

1.1 Aim and Objectives

The aim and specific objectives of this study are to assess the performance of using local information transfer from donor catchments to improve design flood estimation for selected deterministic and empirical flood estimation methods used in South Africa.

The specific objectives can be further described as follows:

(a) **Objective 1** – Review literature containing information on the performance of existing DFE methods in South Africa.

(b) **Objective 2** – Review international literature containing research on the use of local information transfer i.e. approaches to donor catchment selection and the use of multiple donor catchments.

(c) **Objective 3** – Develop a methodology for incorporating local information transfer in conjunction with existing DFE methods used in South Africa.

(d) **Objective 4** – To assess the performance of selected DFE methods after applying correction factors based on local information transfer from donor catchments using different approaches for donor catchment selection.

(e) **Objective 5** – To determine the best method for donor catchment selection using a single donor catchment.

(f) **Objective 6** – To determine the optimal number of donor catchments when using local information transfer from multiple nearest donor catchments.

1.2 Dissertation Structure

This section provides a brief description of the structure and layout of the dissertation. Chapter 2 contains a brief literature review of each of the selected DFE methods frequently used in practice for the design of hydraulic structures in South Africa. The literature review in Chapter 2 reports on limitations, assumptions and performance of methods as determined from previous studies. Chapter 2 also introduces the concept of using information from donor catchments to improve flood estimation and highlights key principles such as donor catchment selection and provides a review of the methods and performance of local information transfer from gauged to ungauged catchments from different countries. The different methods of selecting donor catchments, the use of multiple donor catchments and the impact of gauge density are also reviewed. Chapter 3 covers the methodology used in order to apply donor site transfer using the various techniques of donor site selection with existing deterministic methods. Chapter 4 presents the results and analysis from using donor site transfer with existing deterministic flood estimation methods. Chapter 5 includes a discussion of the results, concluding remarks and recommendations for further research. Chapter 6 contains the references, followed by the appendices.

2. LITERATURE REVIEW

In this chapter a review of existing DFE techniques used in South Africa is provided on the background, application, assumptions, limitations and performance of the techniques. This is followed by a review of the key principles of the use of local information from gauged donor catchments to improve the results of existing techniques as highlighted by international studies, are discussed.

2.1 Design Flood Estimation Techniques Currently Used in South Africa

There are several flood estimation techniques available for use in South Africa. In this section the current techniques are outlined and reviewed.

2.1.1 Statistical Methods

DFE may be performed by a statistical analysis of observed flows where these are available and adequate in both length and quality (Smithers, 2012). This type of analysis can be performed using two approaches: (i) a single site analysis also referred to Flood Frequency Analysis (FFA) where a long record is available at the site of interest, or (ii) in Regional Flood Frequency Analysis (RFFA) by using data from several similar and nearby sites to estimate the regional frequency distribution. It is preferred to have sufficiently long record lengths, thus it not recommended to use record lengths shorter than 10 years and to estimate events with frequencies greater than twice the record length (Viessman *et al*., 1989: cited by Calitz, 2011). According to Gericke and Du Plessis (2013), in the cases where observed flows have a sufficiently long record length, it is generally accepted that, for RIs up to twice the record length, the probabilistic method provides the most reliable estimates. The purpose of statistical analyses is to calculate the flood magnitude-frequency (Q-T) relationship at the site (Alexander, 2002a).

Statistical analysis is generally based on fitting probability distributions to measured values of maximum annual flood peaks and the accuracy of this type of analysis depends on the reliability of the measured flow rates and the length of the recorded period (SANRAL, 2013). The length of the recorded period should be at least half of the design RI and should include both wet and dry periods (SANRAL, 2013). Records of flood peak can be analysed either as an Annual Maximum or Partial Duration Series (AMS and PDS) (Hogan, 2007). In the AMS, the highest flood peak in each year is selected for the record, even if two or more large floods were recorded in the same year whereas in PDS, all floods exceeding a certain threshold are in included in the record.

The most common probability distributions used in flood frequency studies in South Africa are (SANRAL, 2013):

(a) Log-normal (LN),
(b) Log Pearson Type 3 (LP3),
(c) General Extreme Value (GEV), and
(d) Wakeby (WAK).

Alexander (2002a) stated that the LP3/MM would fit most sets of hydrological parameters and is the recommended distribution for use in South Africa. Görgens (2007) investigated the Joint Peak-Volume (JPV) design flood hydrographs by comparing the results to at-site estimates. The comparisons were performed on a sample of 75 catchments. In general, the wide-pooled GEV approach performed consistently relative to the single-site probabilistic estimates, as opposed to both the wide-pooled LP3-based. SANRAL (2013) recommends that more than one type of distribution be used to determine which distribution best fits the historical data.

A limitation of using a single-site approach to FFA is that relatively few gauging stations in South Africa have long record lengths (e.g. > 50 years) and this limits the confidence in design floods estimated using data from a single site, particularly when using shorter record lengths and when estimating design values for longer RIs (e.g. 100 years). In addition, design floods generally need to be estimated at sites where observed flood data are not available and thus rainfall-based methods or regionalised methods need to be used. Regional approaches can be used to estimate design floods in instances were no observed flow records are available (ungauged) or only a short period of record is available at the site of interest. This type of analysis is known as RFFA. In this context of FFA, regionalisation refers to the identification of homogeneous flood response regions and the selection of an appropriate frequency distribution for the selected regions (Kachroo *et al.*, 2010). Thus, it is important for users to ensure that such an approach is not used outside of the region for which the method was developed.

There a number of RFFA methods developed for use in South Africa, these include (Nathanael, 2015):

(a) Haile Method,
(b) Mkhandi Method,
(c) Meigh Method,
(d) Van Bladeren Method, and
(e) Joint Peak Volume (JPV).

The principles of each of the RFFA methods are detailed in the literature by Kjeldsen *et al*. (2001), Smithers *et al*. (2015) and Nathanael (2015). In the more recent study, Nathanael (2015) reviewed the performance of RFFA methods. The study indicated that the Haile Method outperforms the Mkhandi and JPV Method in terms of average median relative error (RE). However, it was found the Haile Method consistently under-estimated design floods. As a result, Nathanael (2015) recommended that a new RFFA method be developed and the method should provide different approaches to estimate the design flood for different catchment area ranges, focusing particularly on methods for estimating design floods for smaller catchments with areas that are less than or equal to 100 km^2.

2.1.2 Rational Method

The Rational method is the most commonly used technique for the estimation of design floods and was developed by Kuichling in 1889 for small drainage basins in urban areas. The development of the method is also attributed to Mulvaney (Ireland) in 1851 and Lloyd-Davies (Great Britain) in 1906 (Hogan, 2007).

Hayes and Young (2005) highlighted the following assumptions associated with the use of the RM:

(a) rainfall is uniform over the entire catchment,
(b) rainfall does not vary with time or space,
(c) storm duration is equal to the time of concentration.

(d) design storm of a specified frequency produces the design flood of the same frequency,
(e) time of concentration is relatively short and independent of storm intensity,
(f) runoff is dominated by overland flow, and
(g) basin storage effects are negligible.

SANRAL (2013) provides further details for application of the method. Apart from the many assumptions, one of the primary problems of the use of the RM is the subjectivity is the selection of the coefficient of runoff. This is largely dependent on the experience of the user and highly subjective (Smithers, 2012).

Due to the above mentioned assumptions and associated shortcomings, the RM is recommended for application in catchments with areas less than 15 km^2 in South Africa (Smithers, 2012; SANRAL, 2013). Deviations from the 15 km^2 application limit is permissible depending on the choice of method used for calculating the rainfall intensity (SANRAL, 2013). The various methods used for determining design rainfall as described in SANRAL (2013) include:

(a) Alternative 1: Depth-Duration-Frequency Diagram (Adamson, 1981)
(b) Alternative 2: Modified Hershfield Equation in combination with TR102 rainfall data (HRU, 1978), and
(c) Alternative 3: Design Rainfall Estimation Software developed by Smithers and Schulze (2002).

Hogan (2007) investigated the predictive performance of the RM for catchments located in the Eastern Cape. The study showed that the RM significantly underestimated peak flows in comparison to the FFA of observed data. A study undertaken in the United States showed that the RM underestimates the peak flows based on stream gauge data for Midwest sites in Iowa (Bradley *et al*., 2009). The differences were in the order of 50 to 75 percent. Trommer *et al*. (1996) evaluated five (5) commonly utilised DFE technique in West Central Florida, one of the techniques being the RM. In this study, estimated peak discharges for 15 catchments were compared with observed peak discharges. The results indicated that the RM overestimated peak discharges for majority of the storms with only one (1) estimate equalling the observed. A more recent study performed by Naidoo (2020) in South Africa at 157 dam sites evaluated the performance of various deterministic and empirical DFE methods which included the RM. The study indicated that the RM performed the best based on the adopted assessment criteria e.g., Mean Absolute Relative Error (MARE) of 56%. Even though the RM performed the best when compared to other methods, Naidoo (2020) indicated that the reliability and accuracy of the RM requires further improvement due to the range of errors being in the order of 70%.

2.1.3 Synthetic Unit Hydrograph Method

The Unit Hydrograph Method is reported in detail in Report 1/72 of the Hydrological Research Unit (HRU), University of Witwatersrand (HRU, 1972). The method was developed using information from 96 streamflow gauges with catchment areas between 21 and 22 163 km^2 (Smithers, 2012). Dimensionless 1-hour Unit Hydrographs were derived for nine veld zone types across South Africa. The HRU (1972) also developed a co-axial diagram to estimate the average storm losses in the nine veld-type regions. The Unit Hydrograph method directly relates the rainfall hyetograph to the catchment runoff and was one of the first attempts to predict an entire hydrograph instead of just the peak flow rate and time to peak (Hogan, 2007).

The Synthetic Unit Hydrograph (SUH) method is used for the estimation of the T-year flood hydrograph based on the respective T-year rainfall for critical storm duration using a typical unit volume storm run-off hydrograph with storm losses based on regional trends (Van Vuuren *et al*., 2013). The method uses rainfall of a specific intensity and duration applied on a dimensionless one-hour unit hydrograph of an identified region, resulting in the development of a series of different hydrographs for different rainfall storm durations.

Hogan (2007) listed the assumptions and limitations of the method documented in various literature, and include:

(a) Rainfall intensity remains constant for the effective duration.

(b) Uniform distribution of excess rainfall for the entire catchment area.

(c) The base time of the direct runoff hydrograph is constant, for a given duration of rainfall.

(d) The ordinates of all direct runoff hydrographs with the same base time are proportional to the total amount of direct runoff represented by each hydrograph.

(e) The hydrograph resulting from excess rainfall reflects the unique characteristics of the catchment. The unit hydrograph model cannot reflect variations in the catchment response due to changes in the season, land use or channel characteristics.

SANRAL (2013) recommends the SUH for catchment areas ranging from 15 to 5 000 km^2. The method can be used for larger catchments when applied by experienced engineers and hydrologists. There have not been significant developments and updates of the method since 1972. Several studies have been undertaken to establish the performance of the method. The study done by Hogan (2007) in the Eastern Cape showed that the Unit Hydrograph Method under-estimated flood peaks in comparison to statistical analysis of observed streamflow data. Cullis *et al*. (2007) compared the flood estimates from the SUH method with statistical analysis for 40 gauged catchments grouped according to the nine veld-type regions and co-axial diagram groups i.e. Group A (Veld-type region 2), Group B (Veld-type regions 4, 5, 6 and 7) and Group C (Veld-type regions 1, 3, 8 and 9). The flood estimates in general compared well for Group B and were over-estimated for catchments located in Groups B and C. Görgens (2007) illustrated the performance of Joint Peak Volume (JPV) method by comparing the peak flood estimates with Unit Hydrograph Method on a data set of 75 gauged catchments across three veld zone pooling groups. It was shown that the Unit Hydrograph estimates were inconsistent and varied greatly from the at-site GEV estimates (Görgens, 2007). The SUH method was shown to be second best performing DFE method in the study performed by Naidoo (2020) with the RM being the best performing method. Similar to the RM, Naidoo (2020) recommended that the SUH be prioritised for updating and modernisation as the average interquartile range of RE and MARE across all RIs were 76% and 82%, respectively.

2.1.4 Standard Design Flood

The Standard Design Flood (SDF) was developed by Alexander (2002a; 2002b; 2003). Alexander (2002a) identified an urgent need for an alternative DFE procedure which had arisen from the damage caused by the devastating floods that occurred across majority of Southern Africa for the period December 1999 through to March 2000. The SDF method is intended to be simple and robust. It also encourages designers to accommodate engineering factors of safety and uncertainties in the hydrological analyses instead of investigating, evaluating and using alternative methods. Alexander (2002b) indicated that the representative runoff coefficients determined at each station were subjectively increased to produce a more conservative estimate of the calculated Q-T relationship. The verification studies yielded values in the range of 50% and 200% of the LP3 values which was deemed acceptable when compared to the range of uncertainties in other DFE methods.

The widely used RM for design flood determination in South Africa and internationally formed the basis of the SDF (SANRAL, 2013). Rain gauges were assigned to 29 representative gauged catchments in South Africa and the Rational runoff coefficient (C) was calibrated until the design flood estimated using design rainfall values equalled the design value computed directly from the gauge flow data using the LP3 distribution. Some subjective adjustment was performed to the calibrated runoff coefficients to incorporate engineering factors of safety. Verifications were performed at 84 sites and the results indicated a variation ranging between 50% to 200% of the LP3 values. Alexander (2002b) stated that the results were well within the acceptable limits for flood estimation methods and procedures.

Similar to that of the Rational Method, the input parameters and equations for the SDF include catchment size, slope and length of longest watercourse, time of concentration (Tc), rainfall intensity and coefficient of runoff . The difference in the SDF method is that the statistically calibrated runoff coefficients (C_2 and C_{100}) for each of the 29 drainage basins are used for calculating the calibrated runoff coefficient for a T-year RI, instead of determining the traditional runoff coefficient determined from the catchment characteristics such as, slope, vegetation cover and soil permeability.

There is no limitation on the application of the SDF method. SANRAL (2013) recommends the SDF method for all catchment sizes and RIs ranging between 2-200 years. In addition, the method is also recommended in the SANRAL (2002) on a "Code of Procedure for the Planning and Design of Highway and Road Structures in South Africa". Designers are required to provide sufficient motivation for instances when the SDF is not believed to be the most appropriate method (SANRAL, 2002; Alexander, 2003).

Numerous studies have been undertaken to determine the performance of the SDF method at a limited number of sites. Görgens (2002) found the average ratio of the flood peaks estimated by the SDF methodology to the peaks determined using the LP3 distribution of observed data to be approximately 210% for the 50-year RI.

Van Bladeren (2005) evaluated peak flows obtained using the SDF method against observed data for all 29 drainage basins. The study showed that design flood estimates calculated using the SDF method were generally higher than observed estimates in a number of the regions for particular RIs, for example, the Molopo river system showed over-estimation of approximately 100 times the observed estimates for the higher RIs when using the SDF method. Van Bladeren (2005) indicated that more regions would be required and also suggested that an equation be used to adjust estimates using the SDF method to balance the tendency of the SDF method over-estimated floods.

Gericke and du Plessis (2012) evaluated the SDF method in Basin 9 (primary study area) and in 19 of other basins (secondary study area). They established the catchment parameters and the SDF/probabilistic distribution-ratios i.e. estimates obtained with the SDF method and those obtained through the FFA of observed flow data. Further to this they also included the performance of adjusted SDF estimates as recommended by Van Bladeren (2005). The results showed that the original SDF/probabilistic distribution ratio generally overestimated the statistical flood peaks in majority of the basins. and the adjusted SDF offered minimal improvements.

In a recent study by Naidoo (2020) the SDF method was shown to generally over-estimate design floods and is ranked seventh in terms of performance when compared six other DFE methods at 157 dam sites located around South Africa. Naidoo (2020) recommended improved regionalisation of the SDF basins and the inclusion of more and up to date rainfall stations.

Since the development of the SDF, other studies have been undertaken to investigate a probabilistic approach to the RM. Parak and Pegram (2006) used the “data set” of runhydrographs (characteristic peak and volume discharges) to calibrate the C factor for given RIs at selected catchments. According to them the calibration results were reasonably encouraging while the validation results produced flood estimates from the rational formula that were on average 1.5 times larger than the flood estimates from a statistical analysis. Similarly, Calitz and Smithers (2020) calibrated C factors derived from design rainfall and design flood estimates calculated from observed flow data using the GPA parent distribution. While in theory, the C factors should increase as the exceedance probability decreases, the results at twenty sites had negative C value growth curves after the regional calibration process was undertaken. In addition, some of the results exceeded 1 for the C value with a maximum of 1.57. Hence, further investigation further is necessary to resolve this inconsistency.

Smithers and Schulze (2002) stated that the SDF method has the potential to overcome some of the shortcomings of current methods, however, the following aspects require further refinement:

(a) The uses of a single rainfall station and outdated rainfall data used for the development of the method.
(b) The subjective adjustments used.
(c) The method of regionalization.

2.1.5 Empirical Methods

The formulae used in empirical methods generally relate peak flows to catchment size and other physiographical and climatic catchment characteristics (Smithers, 2012).Van Der Spuy and Rademeyer (2021) provide a summary on each of the types of Empirical Methods which include the Midgely and Pitman Method (MIPI), Hydrological Research Unit 1/71 method and Catchment Parameter Method (CAPA). The methods are also covered in detail in previous reports and studies by Francou and Rodier (1967), Midgely and Pitman, (1971) and Kovács (1988).

The MIPI method is an Empirical-Probabilistic DFE method (Smal, 2012). The three important characteristics when using this method include catchment area, RI and homogenous flood region (Smal, 2012). SANRAL (2013) recommends the method for catchments greater than 100 km^2. According to Van Der Spuy and Rademeyer (2021), the method regularly produces acceptable estimates. Due to the small sample size (75 gauging stations) and inherent errors in the frequency distributions, the method is suitable for indicating order of magnitude or a rough check on non-statistical methods (SANRAL, 2013).

The HRU 1/71 method was developed in order to address the shortcomings of existing methods and produce a simpler approach than the SUH method, for reviewing and checking purposes (Van Der Spuy and Rademeyer, 2021). The method was developed with the SUH method as the basis by Midgly and Pitman, (1971). SANRAL (2013) recommends the method to be used for estimating floods for RIs less than or equal to 100 years.

McPherson (1983) developed the CAPA method for calculating the mean annual flood and 1:2-year floods in South Africa. The methods was further updated to include the 1:5 to 1:100-year design floods by DWS (Naidoo, 2020; Smal, 2012; Van Der Spuy and Rademeyer, 2021). This method uses a number of catchment attributes to estimate a lumped parameter with the investigation showing that four attributes namely MAP, area, average catchment slope and shape parameter being the more influential (Van Vuuren *et al*., 2013).

Smal (2012) investigated the performance and possible updating of the MIPI and CAPA methods at 53 sites in South Africa, by comparing the flood estimates to probabilistic flood peaks and then determining correction factors. The evaluation indicated that the performance of the MIPI and CAPA method varied for the various RIs and Regions/clusters. The study by Smal (2012) also assessed the updating of the methods by deriving correction factors. While the correction factors improved the performance, Smal (2012) concluded that the correction factors were not the most appropriate approach due to their simplistic derivation and cumbersome nature of its application, which may not be applicable in practice. Naidoo (2020) showed that the CAPA, MIPI and HRU 1/71 ranked 3, 4 and 5 respectively in terms of overall performance out of a total seven methods used in his study.

2.2 Improving Flood Estimation Methods Using Donor Catchments

The previous section highlighted the methods currently used for DFE as well as their limitations and shortcomings identified from previous studies. One of the ways to overcome the deficiencies of flood estimation in ungauged catchments using existing methods is to transfer local information from nearby gauged catchment(s). Information transfer has been employed successfully internationally. This section briefly describes the principle of information transfer and provides a description of the key ideas and concepts i.e. type of information transferred and selection of suitable donor catchments. The chapter includes a brief review of international studies and studies which focused on the performance of the various methods of information transfer.

2.2.1 Information transfer from donor catchments

The estimation of flow in ungauged catchments is one of the most challenging exercises in surface hydrology and required for applications such as water resource management and the design of infrastructure. It is for this reason that developing advanced strategies for improving the accuracy of flood estimation at ungauged catchments are required. (Patil and Stieglitz, 2012).

The transferring of information from nearby gauged catchments is recommended for flood frequency and continuous runoff analysis for ungauged catchments. These gauged catchments, often referred to as 'donors', aim to compensate for the local flood controlling factors that cannot easily be represented in the lumped catchment descriptor equations (Fleig and Wilson, 2013). Improved estimation of streamflow in ungauged catchments thus requires the transfer of hydrologic information such as MPs, ratios, flow quantiles and predictive uncertainty from gauged donor catchments to ungauged target catchments (Patil and Stieglitz, 2012).

2.2.2 Selection of donor catchments

The major challenge in applying the principle of information transfer from gauged to ungauged catchments is identifying suitable donor catchments (Patil and Stieglitz, 2012). Many methods exist for donor catchment selection. These include determining catchment similarity between gauged and ungauged catchments based on Physical Similarity (PS), Spatial Proximity (SP) and Integrated Similarity (IS).

The PS approach aims to transfer information between catchments which are similar in terms of observable catchment characteristics (Oudin *et al*., 2008). In some cases climatic information is considered in determining similarity (Li *et al*., 2019). This method assumes that the hydrological behavior of selected gauged catchments should be similar to that of the ungauged catchment (Heřmanovský and Pech, 2013).

The SP approach consists of transferring information from the nearest neighbouring donor catchment(s) to the target ungauged catchment with the proximity of the catchments measured by the distance between catchment centroids (Bourgin *et al.*, 2015). This approach assumes that catchments that are close to each other behave hydrologically similarly (Begou, 2016).

Zhang and Chiew (2009) describe the IS approach as a combination of the SP and PS approaches. The geographic distance between the catchment centroids forms part of the catchment attributes when determining catchment similarity.

In some cases, information transfer from multiple donor catchments are used for prediction at the target site. In the multiple donor approach, several gauged catchments are used for information transfer to one target site by output averaging of MPs (Zhang and Chiew, 2009), streamflow data (Patil and Stieglitz, 2012).

2.2.3 United Kingdom

The methods for flood frequency estimation for catchments in the United Kingdom (UK) are based on the Flood Estimation Handbook (FEH) and subsequent updates (Faulkner *et al.*, 2012). These include a statistical method based on an index flood methodology and an event-based rainfall-runoff method which can be used to develop a design flood hydrograph. One of the major developments was the incorporation of local data from nearby gauged catchments to reduce the uncertainty associated with each of the methods.

2.2.3.1 Revitalised Flood Hydrograph (ReFH)

The ReFH model is used for modelling an observed flood event or for generating a design flood event (Kjeldsen, 2007). There are four MPs used in the ReFH method which control hydrological losses, routing using a unit hydrograph and two baseflow parameters (Faulkner *et al.*, 2012).

The estimation of the parameters for the ReFH model to simulate a flood event on a particular catchment depends on the availability of data (Kjeldsen, 2007). The three methods for estimating MPs are summarised in Figure 2-1 and include the following:

(a) At a gauged site: estimate MPs directly from analysis of observed flow data (Red lines).

(b) At an ungauged site: estimate MPs from predetermined catchment descriptors (Orange lines).

(c) At an ungauged site: estimate MPs using predetermined catchment descriptors combined with transfer of information from nearby gauged donor site, i.e. a combination of the two first methods (Green lines).

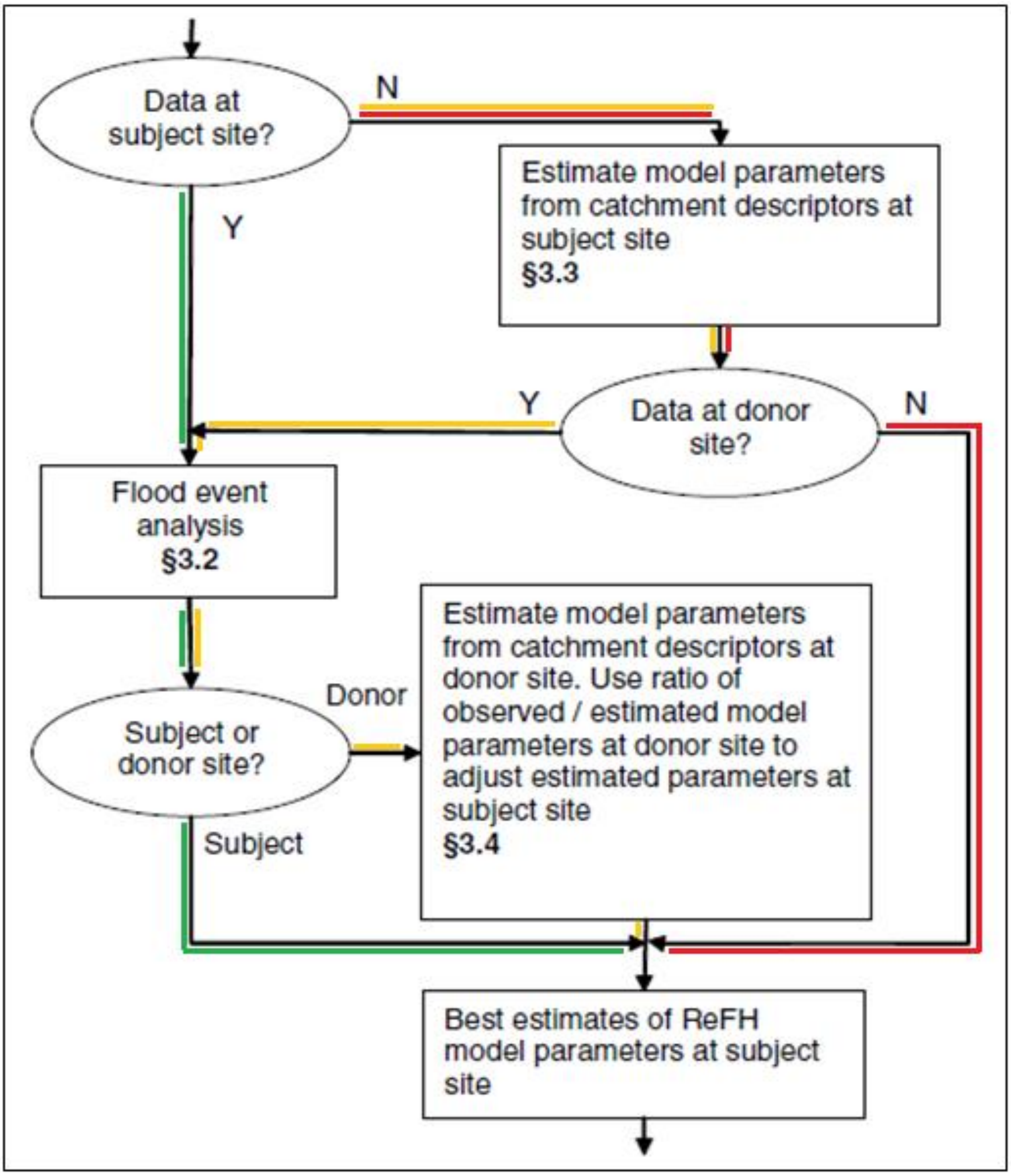

Figure 2-1 Estimation of ReFH MPs (Kjeldsen, 2007)

At ungauged sites where no hydrometric data are available, the MPs can be estimated by using catchment descriptors developed for all catchments in the UK greater than 0.5 km^2 [Method (b) above]. The determination of MPs using the predetermined catchment descriptors is not regarded as the preferred option. The recommended method for estimating MPs in ungauged catchments is using local information through information transfer from one or more nearby donor catchments [Method (c) above].

Once a suitable donor site has been identified for information transfer, each individual ReFH MP at the site of interest is estimated using Equation 2.1:

$$Y_{s,adj} = Y_{s,cds} \frac{Y_{g,obs}}{Y_{g,cds}} \tag{2.1}$$

where,

$Y_{s,adj}$ = adjusted MP at the subject site,

$Y_{s,cds}$ = estimated catchment descriptor MP at subject site,

$Y_{g,obs}$ = MP at gauged site through analysis of observed events, and

$Y_{g,cds}$ = estimated catchment descriptor MP at gauged site.

In cases where more than one suitable donor site exists, a procedure has been developed which assigns a weight to each of the donor sites according to the relative similarity compared to the ungauged site (Carr, 1999). The weighting procedure is carried out using Equation 2.2:

$$Y_{s,adj} = Y_{s,cds} \frac{\sum_{i=1}^{M} w_i Y_{g,obs}/Y_{g,cds}}{\sum_{i=1}^{M} w_i} \tag{2.2}$$

where,

M = number of suitable donors, and

w_i = weight assigned to each donor catchment.

Kjeldsen (2007) stated that at the time, no authoritative rules for selecting suitable donor catchments were available when using the ReFH method. Carr (1999) provided a set of principles for selection of donor catchments. These guidelines can be summarized as follows:

(a) The catchment descriptors should be comparable, and the area should differ by less than a factor of 5.

(b) The catchment centroids should be separated by a distance of less than 50 km.

(c) The catchments should be substantially rural.
(d) Transfer of information within the same river basin is preferred.

2.2.3.2 Index Flood Method

The Index Flood Method is a regional approach which allows the estimation of the complete flood frequency curve in gauged and ungauged catchments (Faulkner *et al*., 2012). The method is the most widely used in the UK (Kjeldsen and Jones, 2007). There are two ways in which the index flood can be estimated, which includes a direct and an indirect method. The choice of method depends on data availability at the site of interest, i.e. subject site. In the case of ungauged catchments, a multivariate regression model was developed using data from 728 gauged catchments in the UK by linking the logarithm of the index flood to catchment descriptors such as catchment area, annual average rainfall, upstream reservoir attenuation, percentage runoff based on soil responsiveness. However, due to the poor performance when using only the catchment descriptors, the FEH strongly recommends the use of data transfer from hydrologically suitable catchments of estimation in ungauged catchments (Kjeldsen and Jones, 2007).

Once a suitable a donor is identified, the index flood is adjusted at the target site using Equation 2.3:

$$m_{s,adj} = m_{s,cds} \frac{m_{g,obs}}{m_{g,cds}} \tag{2.3}$$

where,

$m_{s,adj}$ = adjusted index flood at subject site,

$m_{s,cds}$ = index flood determined using multivariate regression model at subject site,

$m_{g,obs}$ = index flood determined using observed data at gauged site, and

$m_{g,cds}$ = index flood determined using multivariate regression model at gauged site.

Equation 2.3 is similar to Equation 2.2 in that the adjustment at the ungauged subject site is a ratio of the observed versus the simulated value at the gauged donor site.

Subsequent to the above, Kjeldsen and Jones (2007) developed a new transfer scheme which introduces a weighting parameter, α, which will give a smaller weight to a donor site far away from the subject site, or if the sampling error is significantly large. The weighting parameter (α) is incorporated into Equation 2.4 as follows:

$$m_{s,adj} = m_{s,cds}\left(\frac{m_{g,obs}}{m_{g,cds}}\right)^{\alpha} \qquad (2.4)$$

The weighting factor is a function geographical distance (in km) between the centroids of the subject and donor catchments (d_{sg}), determined by:

$$\alpha = 0.4598e^{(-0.0200d_{sg})}+(1-0.4598)e^{(-0.4785d_{sg})} \qquad (2.5)$$

The objective of the weighting parameter is to decrease the effect of data transfer on the estimate as a function of distance to make sure that the estimate is never worse than what would have been obtained using regression only approach (Method C). Figure 2-2 shows the predictive performance indicated by the Root Mean Square Error (RMSE) of the two approaches i.e. FEH data transfer method verses the new data transfer method. Figure 2-3 shows that the prediction uncertainty increases rapidly from nearby donors to donor sites located further away. The increase is almost two-fold for sites located further away from the subject site.

A performance assessment by Kjeldsen (2015) at ungauged sites for a range of RIs showed that the uncertainty associated with the estimates made in ungauged catchments remains a problem, but that use of local data can help to reduce the uncertainties.

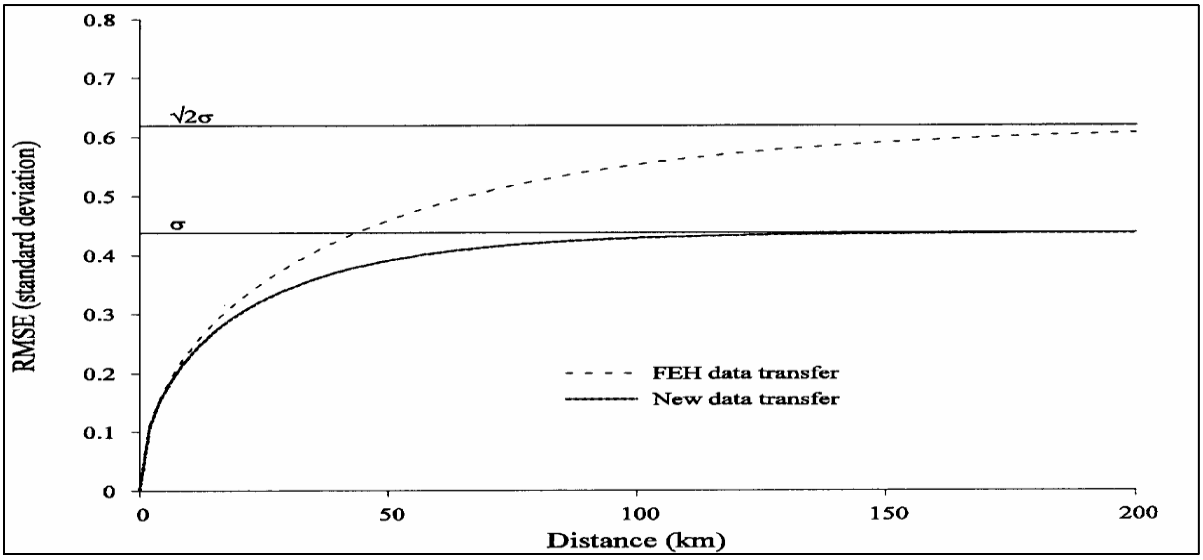

Figure 2-2 RMSE (standard deviation) plotted against geographical distance (km) for the basic FEH scheme and the new data transfer scheme (Kjeldsen and Jones, 2007)

Kjeldsen, *et al*. (2014) presented a method for adjusting the regression-based estimates of the index flood at ungauged sites in the UK using data transfer from multiple donor catchments. The inclusion of multiple donors is beneficial in terms of reducing the prediction variance. The results showed that the prediction accuracy when using multiple donor catchments is relatively insensitive to the actual number of donors, for more than five (5) donor catchments. This is illustrated in Figure 2-3.

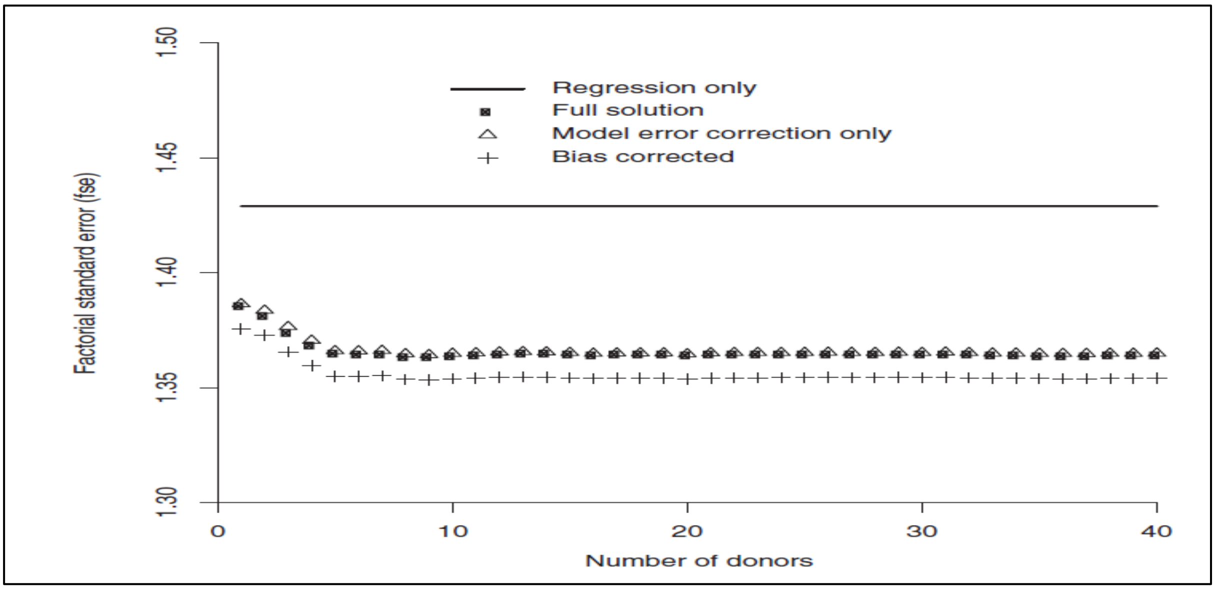

Figure 2-3 Standard factorial error plotted against number of donor catchments (Kjeldsen, *et al*., 2014)

2.2.4 Australia

Zhang and Chiew (2009) studied the relative benefits from smart selection of donor catchments to model runoff in ungauged catchments using two conceptual daily rainfall-runoff methods. The study was conducted on 210 catchments in southeast Australia. The investigation evaluated three types of educated donor selection i.e. SP, PS and IS (combination of SP and PS) when compared to random selection, which was used as a benchmark. The study also evaluated the effect of information transfer using output averaging from multiple donor catchments. In this study entire set(s) of parameter values from donor catchment(s) were used to model runoff in the "ungauged" catchments.

Two criteria were used for model assessment which included the Nash Sutcliffe Efficiency (NSE) and Water Balance Error (WBE). Each of the 210 catchments were considered as "ungauged" and parameter values from the donor catchments (selected using three different approaches) were used to model runoff in the "ungauged" catchment. For the multiple donor approach, parameter values were modelled from each donor catchment and used to model runoff in the ungauged catchment. The runoff using each donor catchment was then averaged to obtain the final runoff estimate.

Zhang and Chiew (2009) concluded from the study that the output averaging technique performs best when eight donor catchments are used when compared to a single donor catchment approach. However, it should be noted that the optimum number of donor catchments can vary depending on different modeling approaches and considerations (Zhang and Chiew, 2009).

The assessment of an educated selection of donor catchments indicated that, in general, the IS performs the best and slightly better than the SP approach. The SP approach performs better than the PS approach. The differences between the performances of the educated donor catchment selection approaches and the multiple donor catchments approach were relatively small. Notwithstanding the above, Zhang and Chiew (2009) stated that there was no evidence from the study to indicate that the performance of the three approaches is related to specific spatial locations or to drier/wetter catchments.

2.2.5 United States

Many studies have concluded that the SP approach is the most successful. However, although the applicability over a large area is still not completely understood (Patil and Stieglitz, 2012). Patil and Stieglitz (2012) investigated whether the transfer among nearby catchments was suitable across a wide range of climatic and geographic regions. The study also investigated the physiographic and hydro-climatic conditions that favour streamflow similarity amongst nearby catchments in a specific region. The study was conducted on 756 gauged catchments in continental United States for which streamflow was simulated using the Inverse Distance Weighted (IDW) method of streamflow from neighboring gauged catchments. A jack-knife procedure was used for testing each of the catchments. The performance criteria were measured using the NSE and WBE.

The results of the study established a relationship between optimal number of donors and efficiency for each of the simulations. This was done by varying the number of nearest donors from 1 to 50 and determining the associated NSE. This approach is similar to those used in other studies. The results indicate that there is a significant improvement when using 1 to 4 donor catchments followed by small increases thereafter. Using more than 15 donor catchments results in a decrease in efficiency, as shown in Figure 2-4.

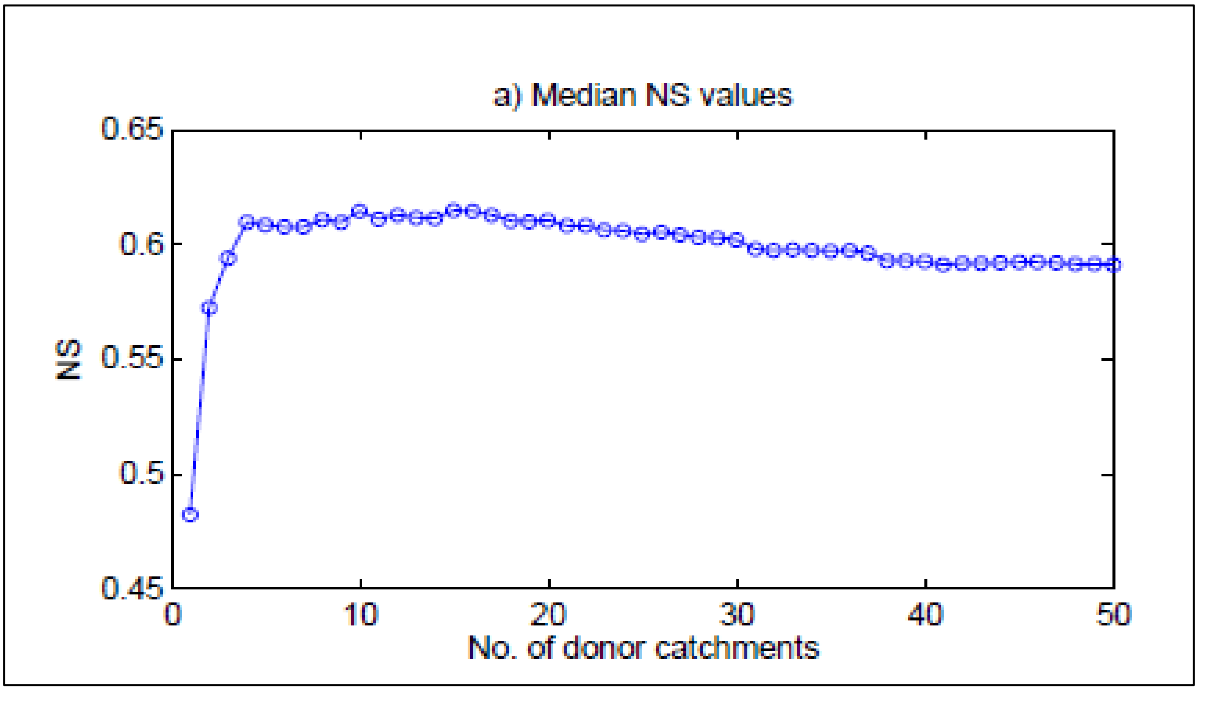

Figure 2-4 Relationship between optimum number of donor catchments and median NSE values (Patil and Stieglitz, 2012)

The catchments were divided into distinct groups shown in Figure 2-5, based on the NSE values i.e. Group 1 for NSE > 0.7, Group 2 for NSE values between 0.7 and 0.3, and Group 3 NSE < 0.3. By performing this grouping, distinct geographic patterns were identified. The observed trend of SP indicates an increase in efficiency as the distance between donor catchments and target catchment decreases (Figure 2-6).

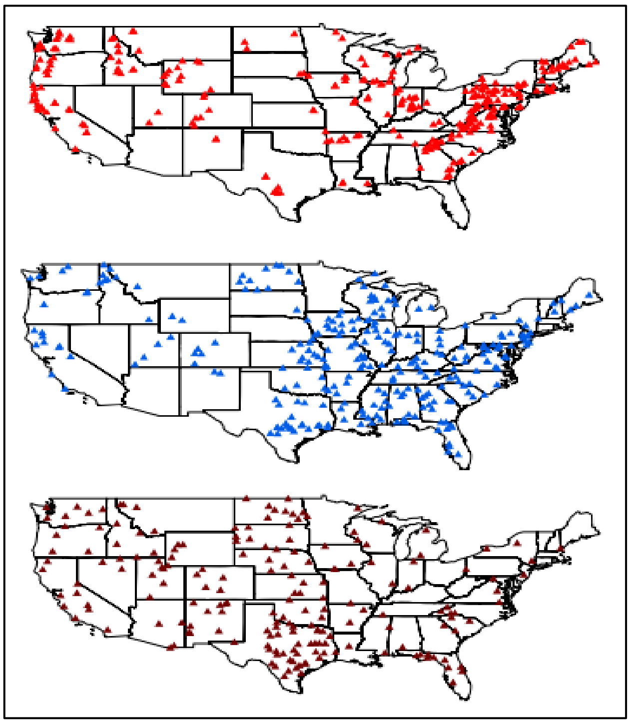

Figure 2-5 Catchment groupings: Group 1 with NSE > 0.7 (red triangle), Group 2 with 0.3 < NSE < 0.7 and Group 3 with NSE <0.3 (brown triangle) (Patil and Stieglitz, 2012)

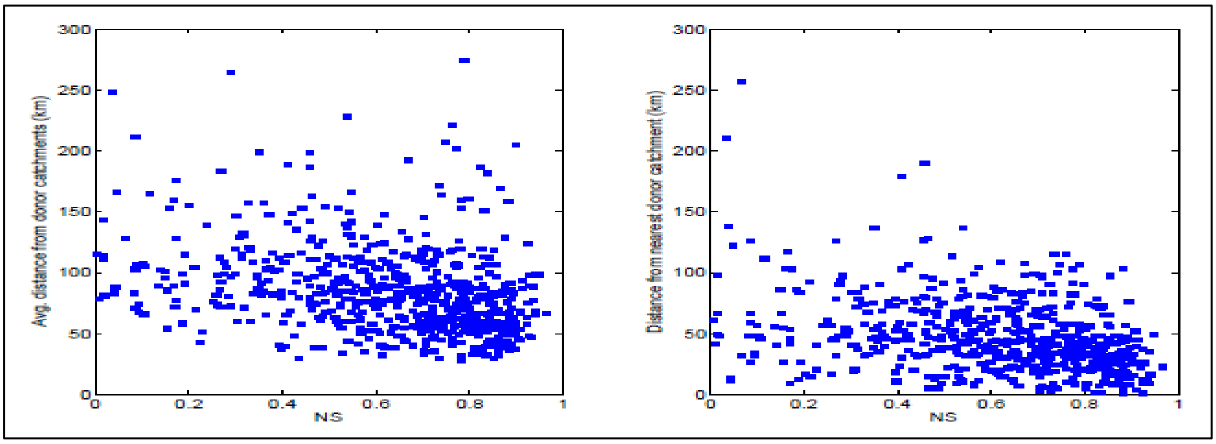

Figure 2-6 Relationship of Nash-Sutcliffe efficiency (NSE) and Average distance from donor catchments, and distance from nearest donor catchment (Patil and Stieglitz, 2012)

Despite observing a distinct trend between distance of donor catchment and simulation efficiency, SP of the donor and receiver does not completely explain the predictive performance. They determined the coefficient of correlation between the NSE and average donor distance to be 0.12, implying that SP only explains 12 percent of the spatial variability in NSE.

Another important factor to be considered when applying information transfer is the availability of gauged catchments i.e. gauge density. Patil and Stieglitz (2012) defined gauge density as the number of gauged catchments within a 200 km radius of the target site. The influence of gauge density was tested by varying the search radius between 100 km and 200 km. They showed that there was no distinct correlation between the NSE/predictability and gauge density around the ungauged catchment.

They also investigated the climatic and physical conditions that favour high streamflow similarity by reviewing the relationship between the NSE values and several climatic, physiographic, and hydrologic properties. The results indicated that high predictability is more likely to be found in regions where rainfall exceeds evaporation demand, also referred to as low energy environments, and there was evidence of high predictability to be to be in regions of high forest density (Patil and Stieglitz, 2012). High predictability catchments were also grouped amongst the mountainous environments suggesting that topography can also influence the similarity in catchment streamflows. However, they noted that the relationships and correlations of NSE with individual catchment properties was particularly weak.

Thus, they concluded that SP between donor and target sites cannot completely explain the performance at a given location and that other factors such as climatic variability and geological features can contribute to information transfer between gauged and ungauged catchments.

2.2.6 France

Oudin *et al*. (2008) reviewed the performance of different types of regionalisation techniques i.e. SP, PS and regression approach on 913 French catchments using two daily lumped rainfall-runoff models namely, the GR4J (Perrin *et al*, 2003), and TOPMO (Bevan and Kirby, 1979) rainfall-runoff models. The work conducted by they particularly looked at the transfer of MPs from donor catchments to ungauged catchments. The results showed that in densely gauged areas, SP is the best solution followed by PS and regression approaches. Figure 2-7 illustrates a comparison of the performance of the PS and SP approaches. In addition to reviewing the performance of the three regionalisation techniques, they also evaluated optimising the regionalisation techniques. Similar to other studies reported above, they investigated optimization settings such as optimal number of donors, impact of network gauge density and MP averaging versus output averaging. In order to assess the optimum number of donor required, they varied the number donor catchments between 1 and 100. For the SP approach, a selection of four (for GR4J) or seven (for TOPMO) donor gauged catchments and the model output averaging option are preferred, as shown Figure 2-7.

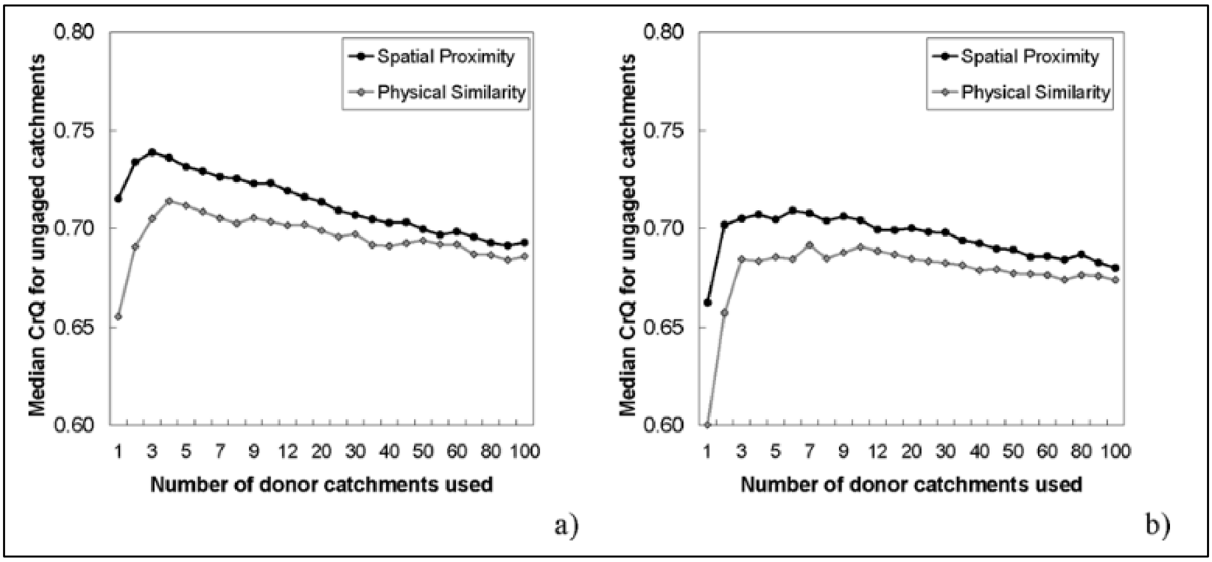

Figure 2-7 Optimum number of donor catchments for the SP and the PS regionalisation schemes for the two rainfall-runoff methods a) GR4J and b) TOPMO (Oudin *et al*., 2008)

Bourgin *et al*. (2015) presented a method of estimating and transferring global uncertainty from gauged to ungauged catchments as a follow up study to the work presented by Oudin *et al.* (2008). The study was undertaken on 907 French catchments using the GR4J and TOPMO rainfall-runoff methods and only employed the transfer based on SP along with the output averaging approach. The number of donors were set to four and seven as recommended by Oudin *et al*. (2008). The underlying idea for the proposed approach was to characterise the empirical distribution of relative errors (understood as the ratio between observed and simulated flows, i.e. considering a multiplicative model error) for each of the donors, and then transfer global uncertainty estimates to the ungauged catchment. Bourgin *et al*. (2015) assessed the relevance of the 90% uncertainty bounds by focusing on three characteristics: reliability, sharpness and overall skill. The results demonstrate that the method is generally able to reflect model errors at ungauged locations and provide reasonable reliability.

2.3 Summary of Literature Review

There are currently three general approaches to DFE used in South Africa. These include statistical (FFA and RFFA), deterministic and empirical methods. A study conducted by Van Vuuren *et al*. (2013) indicated that the deterministic approach was most commonly applied by hydrologists and engineers. They attributed the wide use of deterministic methods to the simplicity with which the methods can be used, and that the user accepts the underlying assumptions which are uncertain. Another reason for the extensive use of deterministic methods is that most catchments are ungauged. This reasoning is prevalent in the South African and international context.

It is clear from the literature presented in this chapter that there is a significant need for updating existing deterministic flood estimation techniques for use in South Africa. Most methods have been developed in the 1970's and there has been very little research to improve these methods ever since. A number of recent studies have shown the gaps and uncertainty associated with the current methods and recommend possible areas of improvement using updated data. The development of the SDF method (Alexander, 2002a, 2002b, 2003) was intended to overcome some of the deficiencies associated with current methods. However, several studies have confirmed the need for further refinement of the SDF.

The errors associated with the estimation of design flood estimates in ungauged catchments, even using well researched studies in data rich regions, is recognised internationally. One of the methods widely applied to overcome these challenges is by transferring local information from nearby gauged catchments i.e., donor catchments, to ungauged catchments using regionalised approaches. The information and studies included in Chapter 2 present simple methods of transferring local information from gauged to ungauged catchments. The primary aim of using information from gauged catchments is to compensate for local factors not included in existing regional catchment descriptor equations and to account for local variability.

The transfer of local information such as MPs, hydrologic indices and global uncertainty from donor to target sites has been shown to significantly improve the performance of existing methods. The ReFH method in the UK makes use of local information from donor catchments by adjusting each parameter by the ratio of the observed and simulated parameter value at the donor site. A similar approach is used for the index flood method. In the studies done in Australia by Zhang and Chiew (2009) and in France by Oudin *et al*. (2008b) , the entire MP dataset was transferred from donor to target ungauged sites. Patil and Stieglitz's (2012) study in the US transferred flood quantiles from donor to target ungauged catchments using an IDW method.

Kjeldsen and Jones (2007) showed a correlation between error and distance between donor and ungauged target sites when using a transfer scheme for the index flood method in the UK. A similar trend was also noticed by Patil and Stieglitz (2012) in their study in the US using the spatial proximity approach. Zhang and Chiew's (2009) study in Australia indicated that the integrated approach (combination of SP and PS) performed the best followed by the spatial proximity and physical similarity methods, respectively. Oudin *et al*. (2008b) investigated the performance of the various approaches in France and found that the SP method was the best performing method compared to the PS and regression approaches. While most studies showed donor site selection can be successfully done using the SP method (relationship of distance between donor and receiver catchment), it was also evident that other factors such as topography, catchment characteristics and other physical parameters can also play a vital role in the performance of the approach.

Many of the studies reviewed agree that the use of multiple donor catchments can offer further enhancements for local information transfer from gauged donor catchments as opposed to using a single donor catchment. The optimum number of donors can vary anywhere between one to eight donors from the various studies in Australia, France, UK and the US. The optimum number of donors was also found to vary for the different methods.

From the above, the following is concluded:

(a) DFE is an important aspect for the design of civil engineering infrastructure.
(b) Deterministic methods are the most commonly applied method for DFE in South Africa.
(c) Recent studies have indicated a need for updating of existing DFE methods in South Africa.
(d) International studies have shown improved performance when using existing methods with the inclusion of the local information from nearby donor catchments.
(e) The selection criteria for donor site selection includes SP, PS and IS.
(f) The performance of the different approaches for donor site selection varies with different countries and methods.
(g) Studies have also shown that the inclusion of multiple donor catchments can offer improvements.

Based on the above information and discussion, the following chapter presents a proposed methodology and assessment criteria for a simple approach using local information transfer from donor catchments with existing DFE methods.

3. METHODOLOGY AND APPROACH

This chapter outlines the method and procedure for data collation and donor catchment selection and includes examples. The chapter also contains the assessment criteria used to evaluate the performance of the selected deterministic and empirical flood estimation methods with the inclusion of local information from donor catchments using various techniques for donor catchment selection.

The methodology for conducting the investigation is summarised as follows:

(a) Data collation for gauged catchments containing catchment characteristics and design flood estimates using observed data, deterministic and empirical DFE methods.

(b) Selecting suitable donor catchments using the methods discussed in Chapter 3 i.e. SP, PS, IS and multiple nearest neighbours.

(c) Adjusting flood estimates using local information from nearby gauged donor catchment(s) by means of a correction factor (ratio of observed and estimated design flood values) using both single and multiple donors.

(d) Quantifying the impacts of the adjustments by comparing the adjusted flood estimates to observed values and other criteria used to measure performance.

(e) Determine if improvements are notable when using local information transfer from donor catchments.

(f) Determine the best approach for donor selection.

3.1 Data Collation

The gauged sites used in this study were obtained from Mr. Jeremy Naidoo and Department of Water and Sanitation (DWS), Flood Studies Group. The database consisted of comprehensive and high-quality information related to design flood peaks for various DFE methods from inflow records at various dam sites across South Africa (Naidoo, 2020). For the purposes of this pilot study, a group of 48 dam sites in the north eastern part of South Africa were used based on the record length of the observed inflows and spatial density of the sites. Furthermore, the synthesised dam inflow series are deemed to be more accurate and reliable than weir gauged flows by the DWS, Flood Studies Group (Naidoo, 2000). The location of these sites are in five provinces, namely, North West, Free State, Gauteng, Limpopo and Mpumalanga and spread across various veld type zones and SDF basins as illustrated in and Figure 3-2, respectively.

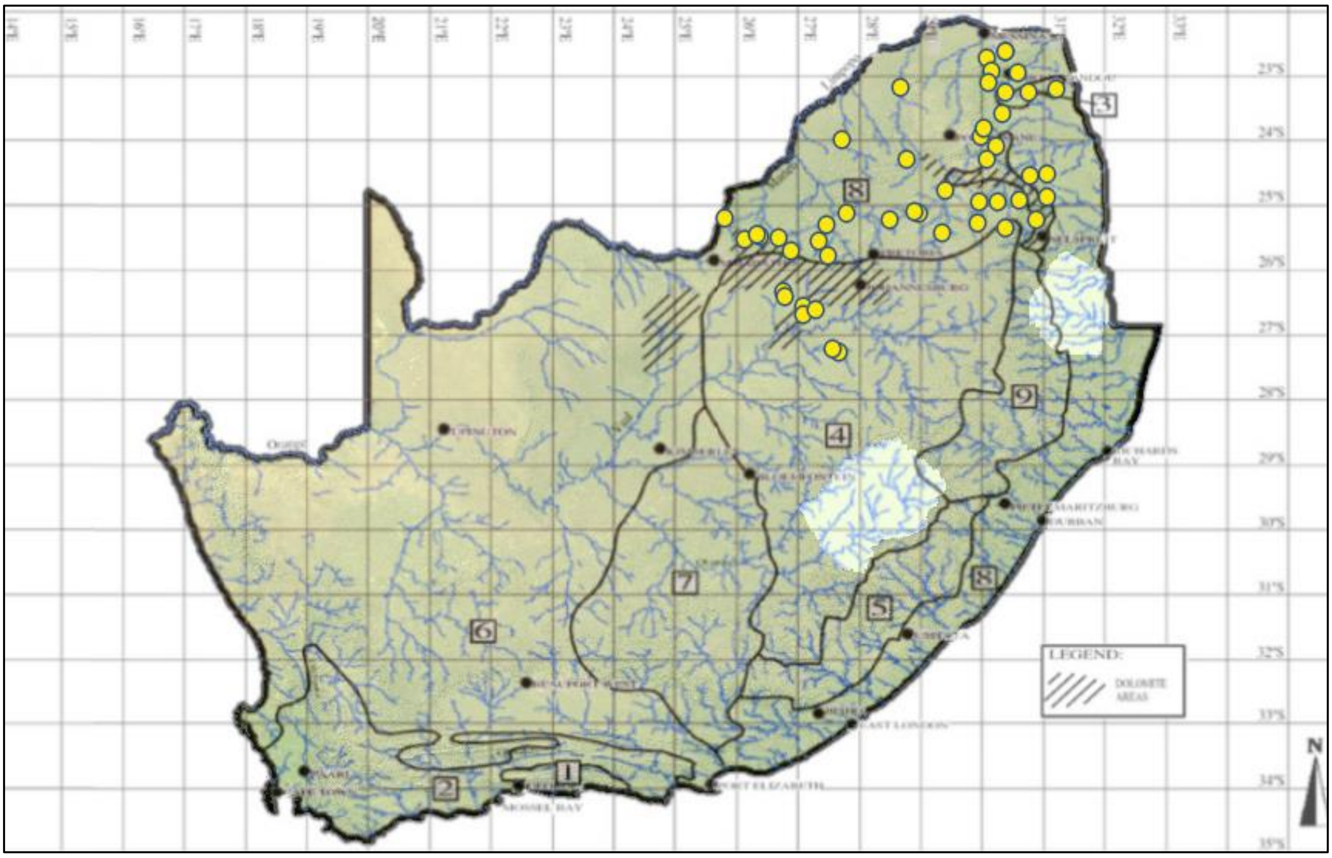

Figure 3-1   Location of the 48 sites in the various veld types

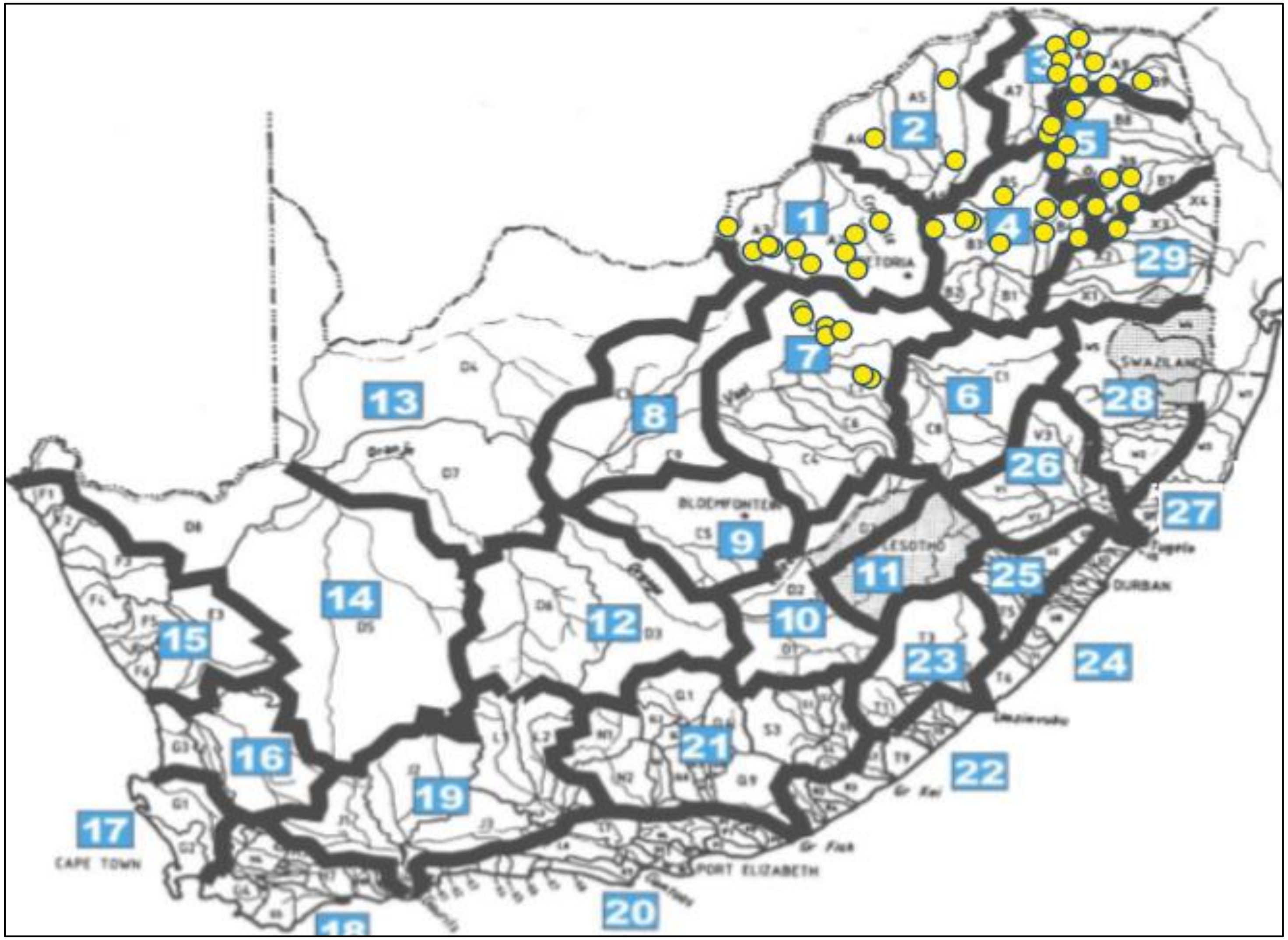

Figure 3-2 Location of the 48 sites in the SDF drainage basins

The DWS database included information such as catchment area (A), length of longest watercourse (L), length to catchment centroid (Lc), slope (S), time of concentration (Tc), MAP and DFEs using various methods. Table 3-1 indicates catchment information of the sites in the study area.

Table 3-1 Catchment characteristics for the selected 48 catchments from the DWS database

Site ID	A (km^2)	Record Length (Years)	MAP (mm)	S (m/m)	L (km)	Lc (km)	Tc (hrs)
A1R001	518	13	535	0.00320	57	31	14
A2R005	114	75	665	0.01045	18	8	3.5
A2R006	1068	87	650	0.00350	73	40	18
A2R007	719	71	875	0.02605	7	3	1.5
A2R011	286	50	597	0.00028	1061	530	164
A2R012	6160	60	921	0.01254	23	13	4
A2R014	6098	67	758	0.10133	30	16	5
A3R001	1228	75	596	0.01126	18	10	3.5
A3R002	1157	110	550	0.00275	92	54	20
A3R003	1762	110	1200	0.00500	71	34	14
A4R001	4320	52	650	0.01753	9	5	2
A6R001	585	73	297	0.00275	334	184	44
A6R002	11244	51	628	0.00708	25	12	5.2
A8R001	830	85	925	0.00308	96	58	20
A8R002	157	47	719	0.01184	53	29	8
A8R003	109	47	611	0.00393	74	41	16
A8R004	94	24	865	0.00214	28	13	9
A9R001	505	66	199	0.00301	192	99	36
A9R004	1411	71	690	0.00598	45	21	9
B3H008	4156	18	829	0.00927	27	12	5
B3R001	1133	82	595	0.00168	171	80	40
B3R002	12250	76	545	0.00321	59	21	14
B3R005	3646	27	1935	0.00227	16	7	2.5
B4R001	51	52	730	0.00823	21	9	4.5
B4R004	276	54	993	0.01618	8	5	3
B4R007	2863	60	610	0.00027	960	48	154
B5R002	23406	78	580	0.00187	129	65	32
B6R001	83	56	876	0.01026	24	11	4.5
B6R003	2169	63	585	0.00354	30	16	8
B7R001	165	62	1070	0.02399	14	5	2.5

Site ID	A (km^2)	Record Length (Years)	MAP (mm)	S (m/m)	L (km)	Lc (km)	Tc (hrs)
B7R003	45	53	120	0.01026	29	11	5
B8R001	169	63	1256	0.02477	10	4	2
B8R003	64	42	504	0.00409	129	74	24
B8R004	10	36	535	0.00330	57	32	14
B8R007	1805	24	613	0.00253	39	16	12
B8R009	339	20	670	0.00068	835	459	108
B8R011	71	18	497	0.00724	43	23	9
B9H002	822	32	1090	0.00250	60	30	16
C2R001	3480	110	473	0.00442	49	52	14
C2R004	3628	111	575	0.00212	120	54	28
C2R005	884.6	47	947	0.00532	85	40	16
C2R006	28	38	695	0.00292	51	27	12
C2R007	362	38	469	0.00305	16	160	38
C7R001	2142	92	610	0.01080	7	4	2
C7R003	63	27	670	0.00550	65	32	12
X2R003	64	62	606	0.00347	97	46	20
X2R005	954	52	686	0.00277	120	66	26
X3R002	211	39	596	0.00366	61	28	16

3.2 Donor Catchment Selection

In order to determine suitable donor catchments, three approaches were used which included SP, PS and IS. The approaches are briefly described below. The best choice in each criterion is highlighted in red and summarised in the subsequent sections.

3.2.1 Spatial Proximity (SP)

The SP criteria for the selection of a suitable donor catchment was based on the distance measured between gauges of the subject catchment and nearest gauged donor catchments determined using QGIS software. Table 3-2 provides a list of all 48 sites in the study area and their corresponding nearest donor catchments based on the SP approach.

Table 3-2 Subject and Donor Catchments based on SP

Number	Subject Catchment	Donor Catchment (based on the SP approach)	Distance Between Subject and Donor Catchment (km)
1	A1R001	A3R002	49.42
2	A2R005	A2R006	27.30
3	A2R006	A2R005	37.30
4	A2R007	A2R011	30.88
5	A2R011	A2R007	30.88
6	A2R012	A2R014	38.90
7	A2R014	A2R006	30.90
8	A3R001	A3R003	5.48
9	A3R002	A3R003	21.60
10	A3R003	A3R001	5.48
11	A4R001	A6R001	112.68
12	A6R001	B5R002	85.14
13	A6R002	A6R001	122.34
14	A8R001	A8R004	25.42
15	A8R002	A8R003	0.46
16	A8R003	A8R002	0.46
17	A8R004	A9R001	18.28
18	A9R001	A8R004	18.28
19	A9R004	B8R009	35.78
20	B3H008	B3R005	8.39
21	B3R001	B3R005	42.95
22	B3R002	B3H008	49.42
23	B3R005	B3H008	8.39
24	B4R001	B4R007	35.59
25	B4R004	B4R007	31.16
26	B4R007	B4R004	31.16
27	B5R002	B3H008	56.90
28	B6R001	B4R004	37.10
29	B6R003	B7R001	27.62
30	B7R001	B6R003	27.62
31	B7R003	B8R004	28.88
32	B8R001	B8R003	15.44
33	B8R003	B8R001	15.44
34	B8R004	B7R003	28.88
35	B8R007	B8R011	35.17

Number	Subject Catchment	Donor Catchment (based on the SP approach)	Distance Between Subject and Donor Catchment (km)
36	B8R009	A9R004	35.78
37	B8R011	B8R007	35.17
38	B9H002	B8R009	46.55
39	C2R001	C2R004	12.39
40	C2R004	C2R001	12.39
41	C2R005	C2R001	19.48
42	C2R006	C2R007	8.08
43	C2R007	C2R006	8.08
44	C7R001	C7R003	10.81
45	C7R003	C7R001	10.81
46	X2R003	X3R002	43.25
47	X2R005	B4R004	46.40
48	X3R002	B7R001	40.05

3.2.2 Physical Similarity (PS)

The PS approach was based on catchments most similar to the subject catchment based on physical catchment attributes. Catchment area (A), length of longest watercourse (L), length to catchment centroid (Lc), slope (S) and MAP were considered for determining PS. All possible donor catchments within the study area were used in this approach. For each catchment attribute, the catchment with the most similar attributes to the subject catchment was ranked number one, the catchment with the second most similar attributes ranked number two and so on. Each attribute was given an equal weighting. The rank for each attribute was summed and the catchment with the lowest value of summed ranks was chosen as the most similar donor catchment in terms of physical parameters.

Table 3-3 shows an example of donor catchment selection using the PS approach for subject Catchment A2R011. In this case, catchment B8R009 is the most physical similar catchment (see text in red). The same method was applied to the other 47 sites to determine donor catchments based on the PS approach.

Table 3-4 contains each of the 48 sites in the study area and their corresponding donor catchment based on the PS approach.

Table 3-3 Selection of Donor Catchment using the PS approach for Site A2R011

Subject Site	Possible Donor Sites	Subject Catchment					Donor Catchments					Relative Difference (%)					Rank						
		MAP mm	L km	Lc km	S m/m	A km^2	MAP mm	L km	Lc km	S m/m	A km^2	MAP mm	L km	Lc km	S m/m	A km^2	MAP	L	Lc	S	A	Sum of Ranks	Overall Rank
A2R011	A2R007	597	1061	530	0.000284	286	875	7	3	0.026051	719	47%	99%	99%	9073%	151%	34	46	47	46	23	196	47
A2R011	A2R006	597	1061	530	0.000284	286	650	73	40	0.003506	1068	9%	93%	92%	1135%	273%	15	15	16	21	28	95	16
A2R011	A3R001	597	1061	530	0.000284	286	596	18	10	0.011262	1228	0%	98%	98%	3865%	329%	1	38	38	39	31	147	33
A2R011	A2R005	597	1061	530	0.000284	286	665	18	8	0.010450	114	11%	98%	98%	3580%	60%	19	38	40	37	8	142	32
A2R011	A3R003	597	1061	530	0.000284	286	1200	71	34	0.005006	1762	101%	93%	94%	1663%	516%	45	16	18	27	33	139	31
A2R011	A2R014	597	1061	530	0.000284	286	758	30	16	0.101330	6098	27%	97%	97%	35580%	2032%	31	29	29	47	43	179	43
A2R011	C2R006	597	1061	530	0.000284	286	695	51	27	0.002921	28	16%	95%	95%	929%	90%	25	24	25	13	20	107	20
A2R011	A3R002	597	1061	530	0.000284	286	550	92	54	0.002751	1157	8%	91%	90%	869%	305%	13	12	10	10	30	75	10
A2R011	C2R007	597	1061	530	0.000284	286	469	16	160	0.003057	362	21%	98%	70%	976%	27%	29	40	3	15	4	91	14
A2R011	C2R001	597	1061	530	0.000284	286	473	49	52	0.004427	3480	21%	95%	90%	1459%	1117%	28	25	12	26	38	129	29
A2R011	C2R005	597	1061	530	0.000284	286	947	85	40	0.005329	884.6	59%	92%	92%	1776%	209%	39	13	16	28	26	122	26
A2R011	C2R004	597	1061	530	0.000284	286	575	120	54	0.002127	3628	4%	89%	90%	649%	1169%	11	8	10	5	39	73	7
A2R011	A2R012	597	1061	530	0.000284	286	921	23	13	0.012540	6160	54%	98%	98%	4315%	2054%	37	36	32	41	44	190	46
A2R011	A1R001	597	1061	530	0.000284	286	535	57	31	0.003200	518	10%	95%	94%	1027%	81%	17	21	21	17	17	93	15
A2R011	B3R001	597	1061	530	0.000284	286	595	171	80	0.001681	1133	0%	84%	85%	492%	296%	3	5	5	3	29	45	2
A2R011	C7R003	597	1061	530	0.000284	286	670	65	32	0.005500	63	12%	94%	94%	1837%	78%	20	17	19	29	16	101	19
A2R011	C7R001	597	1061	530	0.000284	286	610	7	4	0.010800	2142	2%	99%	99%	3703%	649%	6	46	45	38	35	170	38
A2R011	A4R001	597	1061	530	0.000284	286	650	9	5	0.017534	4320	9%	99%	99%	6074%	1410%	15	44	42	43	42	186	45
A2R011	B3R005	597	1061	530	0.000284	286	1935	16	7	0.002278	3646	224%	98%	99%	702%	1175%	47	40	41	7	40	175	41
A2R011	B3H008	597	1061	530	0.000284	286	829	27	12	0.009270	4156	39%	97%	98%	3164%	1353%	32	33	34	34	41	174	40
A2R011	A6R001	597	1061	530	0.000284	286	297	334	184	0.002758	585	50%	69%	65%	871%	105%	36	3	2	11	22	74	8
A2R011	B3R002	597	1061	530	0.000284	286	545	59	21	0.003213	12250	9%	94%	96%	1031%	4183%	14	20	27	18	46	125	28
A2R011	B5R002	597	1061	530	0.000284	286	580	129	65	0.001870	23406	3%	88%	88%	558%	8084%	10	6	8	4	47	75	10
A2R011	B4R001	597	1061	530	0.000284	286	730	21	9	0.008238	51	22%	98%	98%	2801%	82%	30	37	39	33	18	157	36
A2R011	B4R007	597	1061	530	0.000284	286	610	960	48	0.000275	2863	2%	10%	91%	3%	901%	6	1	13	1	37	58	3

Subject Site	Possible Donor Sites	Subject Catchment MAP mm	Subject Catchment L km	Subject Catchment Lc km	Subject Catchment S m/m	Subject Catchment A km²	Donor Catchments MAP mm	Donor Catchments L km	Donor Catchments Lc km	Donor Catchments S m/m	Donor Catchments A km²	Percentage Difference/Variance MAP mm	Percentage Difference/Variance L km	Percentage Difference/Variance Lc km	Percentage Difference/Variance S m/m	Percentage Difference/Variance A km²	Rank MAP	Rank L	Rank Lc	Rank S	Rank A	Sum of Ranks	Overall Rank
A2R011	A6R002	597	1061	530	0.000284	286	628	25	12	0.007082	11244	5%	98%	98%	2394%	3831%	12	34	34	31	45	156	35
A2R011	B4R004	597	1061	530	0.000284	286	993	8	5	0.016186	276	66%	99%	99%	5599%	3%	40	45	42	42	1	170	38
A2R011	X2R005	597	1061	530	0.000284	286	686	120	66	0.002770	954	15%	89%	88%	875%	234%	22	8	7	12	27	76	12
A2R011	B8R004	597	1061	530	0.000284	286	535	57	32	0.003300	10	10%	95%	94%	1062%	97%	17	21	19	19	21	97	17
A2R011	B8R001	597	1061	530	0.000284	286	1256	10	4	0.024771	169	110%	99%	99%	8622%	41%	46	43	45	45	5	184	44
A2R011	B8R003	597	1061	530	0.000284	286	504	129	74	0.004098	64	16%	88%	86%	1343%	78%	23	6	6	25	14	74	8
A2R011	B7R003	597	1061	530	0.000284	286	120	29	11	0.010268	45	80%	97%	98%	3515%	84%	43	31	36	35	19	164	37
A2R011	B6R001	597	1061	530	0.000284	286	876	24	11	0.010269	83	47%	98%	98%	3516%	71%	35	35	36	36	11	153	34
A2R011	X2R003	597	1061	530	0.000284	286	606	97	46	0.003477	64	2%	91%	91%	1124%	78%	4	10	14	20	14	62	4
A2R011	B6R003	597	1061	530	0.000284	286	585	30	16	0.003540	2169	2%	97%	97%	1146%	658%	5	29	29	22	36	121	25
A2R011	B8R011	597	1061	530	0.000284	286	497	43	23	0.007242	71	17%	96%	96%	2450%	75%	26	27	26	32	12	123	27
A2R011	X3R002	597	1061	530	0.000284	286	596	61	28	0.003669	211	0%	94%	95%	1192%	26%	1	18	24	23	3	69	5
A2R011	A9R001	597	1061	530	0.000284	286	199	192	99	0.003011	505	67%	82%	81%	960%	77%	41	4	4	14	13	76	12
A2R011	B7R001	597	1061	530	0.000284	286	1070	14	5	0.023990	165	79%	99%	99%	8347%	42%	42	42	42	44	6	176	42
A2R011	B8R007	597	1061	530	0.000284	286	613	39	16	0.002535	1805	3%	96%	97%	793%	531%	9	28	29	9	34	109	21
A2R011	A8R004	597	1061	530	0.000284	286	865	28	13	0.002142	94	45%	97%	98%	654%	67%	33	32	32	6	10	113	22
A2R011	A8R001	597	1061	530	0.000284	286	925	96	58	0.003087	830	55%	91%	89%	987%	190%	38	11	9	16	25	99	18
A2R011	**B8R009**	**597**	**1061**	**530**	**0.000284**	**286**	**670**	**835**	**459**	**0.000688**	**339**	**12%**	**21%**	**13%**	**142%**	**19%**	**20**	**2**	**1**	**2**	**2**	**27**	**1**
A2R011	A9R004	597	1061	530	0.000284	286	690	45	21	0.005986	1411	16%	96%	96%	2008%	393%	23	26	27	30	32	138	30
A2R011	A8R003	597	1061	530	0.000284	286	611	74	41	0.003930	109	2%	93%	92%	1284%	62%	8	14	15	24	9	70	6
A2R011	A8R002	597	1061	530	0.000284	286	719	53	29	0.011845	157	20%	95%	95%	4071%	45%	27	23	23	40	7	120	24
A2R011	B9H002	597	1061	530	0.000284	286	1090	60	30	0.002505	822	83%	94%	94%	782%	187%	44	19	22	8	24	117	23
A2R011	B4R007	597	1061	530	0.000284	286	610	960	48	0.000275	2863	2%	10%	91%	3%	901%	6	1	13	1	37	58	3

Table 3-4 Subject and Donor Catchments based on PS approach

Number	Subject Catchment	Donor Catchment (Based on the PS approach)
1	A1R001	B8R004
2	A2R005	B4R001
3	A2R006	A8R003
4	A2R007	B4R004
5	A2R011	B8R009
6	A2R012	B3H008
7	A2R014	B3H008
8	A3R001	C7R001
9	A3R002	X2R005
10	A3R003	C2R005
11	A4R001	C7R001
12	A6R001	A9R001
13	A6R002	B3H008
14	A8R001	X2R005
15	A8R002	C7R003
16	A8R003	X2R003
17	A8R004	B6R001
18	A9R001	A1R001
19	A9R004	B8R007
20	B3H008	A2R012
21	B3R001	A3R002
22	B3R002	B6R003
23	B3R005	B8R007
24	B4R001	A2R005
25	B4R004	B7R001
26	B4R007	C2R004
27	B5R002	C2R004
28	B6R001	B4R001
29	B6R003	B8R007
30	B7R001	B8R001
31	B7R003	B4R001
32	B8R001	B7R001
33	B8R003	X2R003
34	B8R004	A1R001
35	B8R007	B6R003
36	B8R009	A2R011
37	B8R011	B8R004

Number	Subject Catchment	Donor Catchment (Based on the PS approach)
38	B9H002	C2R005
39	C2R001	B6R003
40	C2R004	A3R002
41	C2R005	A8R001
42	C2R006	B8R004
43	C2R007	A1R001
44	C7R001	A3R001
45	C7R003	A8R003
46	X2R003	A8R003
47	X2R005	A3R002
48	X3R002	A8R003

3.2.3 Integrated Similarity (IS)

The IS approach incorporates both the SP and PS approaches. This was achieved by including the spatial distance between the donor catchments and subject ungauged catchment as an additional attribute. As above, the closest catchment was given a rank of number one. Once again, each rank including the SP was assigned equal weights.

Table 3-5 shows an example of donor catchment selection using the IS approach for subject site A2R011. In this case, site B3R001 is the most similar catchment in terms of IS (see text in red). It should be noted that in some cases the donor catchments for the PS and IS approaches are the same for certain target catchments. The IS approach was applied to each of the other 47 sites. Table 3-6 contains each of the 48 sites in the study area and their corresponding donor catchment based on the IS approach.

Table 3-5 Selection of Donor Catchment using the IS approach for site A2R011

Subject Catchment	Possible Donor Catchments	Distance between Catchments	Subject Catchment					Donor Catchments					Percentage Difference/Variance					Rank							
			MAP mm	L km	Lc km	S m/m	A km2	MAP mm	L km	Lc km	S m/m	A km2	MAP mm	L km	Lc km	S m/m	A km2	Distance	MAP	L	Lc	S	A	Sum of Ranks	Overall Rank
A2R011	A1R001	122.96	597	1061	530	0.000284	286	535	57	31	0.003200	518	10%	95%	94%	1027%	81%	14	17	21	21	17	17	107	14
A2R011	A2R005	60.20	597	1061	530	0.000284	286	665	18	8	0.010450	114	11%	98%	98%	3580%	60%	4	19	38	40	37	8	146	24
A2R011	A2R006	47.49	597	1061	530	0.000284	286	650	73	40	0.003506	1068	9%	93%	92%	1135%	273%	2	15	15	16	21	28	97	8
A2R011	A2R007	30.88	597	1061	530	0.000284	286	875	7	3	0.026051	719	47%	99%	99%	9073%	151%	1	34	46	47	46	23	197	42
A2R011	A2R012	110.80	597	1061	530	0.000284	286	921	23	13	0.012540	6160	54%	98%	98%	4315%	2054%	13	37	36	32	41	44	203	44
A2R011	A2R014	72.09	597	1061	530	0.000284	286	758	30	16	0.101330	6098	27%	97%	97%	35580%	2032%	6	31	29	29	47	43	185	36
A2R011	A3R001	57.10	597	1061	530	0.000284	286	596	18	10	0.011262	1228	0%	98%	98%	3865%	329%	3	1	38	38	39	31	150	27
A2R011	A3R002	78.04	597	1061	530	0.000284	286	550	92	54	0.002751	1157	8%	91%	90%	869%	305%	8	13	12	10	10	30	83	3
A2R011	A3R003	62.57	597	1061	530	0.000284	286	1200	71	34	0.005006	1762	101%	93%	94%	1663%	516%	5	45	16	18	27	33	144	23
A2R011	A4R001	207.24	597	1061	530	0.000284	286	650	9	5	0.017534	4320	9%	99%	99%	6074%	1410%	18	15	44	42	43	42	204	45
A2R011	A6R001	244.96	597	1061	530	0.000284	286	297	334	184	0.002758	585	50%	69%	65%	871%	105%	21	36	3	2	11	22	95	6
A2R011	A6R002	332.02	597	1061	530	0.000284	286	628	25	12	0.007082	11244	5%	98%	98%	2394%	3831%	26	12	34	34	31	45	182	34
A2R011	A8R001	462.41	597	1061	530	0.000284	286	925	96	58	0.003087	830	55%	91%	89%	987%	190%	42	38	11	9	16	25	141	22
A2R011	A8R002	491.94	597	1061	530	0.000284	286	719	53	29	0.011845	157	20%	95%	95%	4071%	45%	46	27	23	23	40	7	166	32
A2R011	A8R003	491.52	597	1061	530	0.000284	286	611	74	41	0.003930	109	2%	93%	92%	1284%	62%	45	8	14	15	24	9	115	17
A2R011	A8R004	450.19	597	1061	530	0.000284	286	865	28	13	0.002142	94	45%	97%	98%	654%	67%	41	33	32	32	6	10	154	28
A2R011	A9R001	435.13	597	1061	530	0.000284	286	199	192	99	0.003011	505	67%	82%	81%	960%	77%	38	41	4	4	14	13	114	15
A2R011	A9R004	482.08	597	1061	530	0.000284	286	690	45	21	0.005986	1411	16%	96%	96%	2008%	393%	44	23	26	27	30	32	182	34
A2R011	B3H008	220.63	597	1061	530	0.000284	286	829	27	12	0.009270	4156	39%	97%	98%	3164%	1353%	20	32	33	34	34	41	194	39
A2R011	**B3R001**	**170.51**	**597**	**1061**	**530**	**0.000284**	**286**	**595**	**171**	**80**	**0.001681**	**1133**	**0%**	**84%**	**85%**	**492%**	**296%**	**15**	**3**	**5**	**5**	**3**	**29**	**60**	**1**
A2R011	B3R002	248.86	597	1061	530	0.000284	286	545	59	21	0.003213	12250	9%	94%	96%	1031%	4183%	22	14	20	27	18	46	147	25
A2R011	B3R005	213.42	597	1061	530	0.000284	286	1935	16	7	0.002278	3646	224%	98%	99%	702%	1175%	19	47	40	41	7	40	194	39
A2R011	B4R001	309.26	597	1061	530	0.000284	286	730	21	9	0.008238	51	22%	98%	98%	2801%	82%	24	30	37	39	33	18	181	33
A2R011	B4R004	348.57	597	1061	530	0.000284	286	993	8	5	0.016186	276	66%	99%	99%	5599%	3%	27	40	45	42	42	1	197	42

Subject Catchment	Possible Donor Catchments	Distance between Catchments	Subject Catchment					Donor Catchments					Percentage Difference/Variance					Rank							
			MAP mm	L km	Lc km	S m/m	A km^2	MAP mm	L km	Lc km	S m/m	A km^2	MAP mm	L km	Lc km	S m/m	A km^2	Distance	MAP	L	Lc	S	A	Sum of Ranks	Overall Rank
A2R011	B4R007	318.38	597	1061	530	0.000284	286	610	960	48	0.000275	2863	2%	10%	91%	3%	901%	25	6	1	13	1	37	83	3
A2R011	B5R002	273.94	597	1061	530	0.000284	286	580	129	65	0.001870	23406	3%	88%	88%	558%	8084%	23	10	6	8	4	47	98	9
A2R011	B6R001	385.09	597	1061	530	0.000284	286	876	24	11	0.010269	83	47%	98%	98%	3516%	71%	33	35	35	36	36	11	186	37
A2R011	B6R003	413.54	597	1061	530	0.000284	286	585	30	16	0.003540	2169	2%	97%	97%	1146%	658%	35	5	29	29	22	36	156	29
A2R011	B7R001	440.15	597	1061	530	0.000284	286	1070	14	5	0.023990	165	79%	99%	99%	8347%	42%	39	42	42	42	44	6	215	47
A2R011	B7R003	382.41	597	1061	530	0.000284	286	120	29	11	0.010268	45	80%	97%	98%	3515%	84%	32	43	31	36	35	19	196	41
A2R011	B8R001	367.76	597	1061	530	0.000284	286	1256	10	4	0.024771	169	110%	99%	99%	8622%	41%	30	46	43	45	45	5	214	46
A2R011	B8R003	381.12	597	1061	530	0.000284	286	504	129	74	0.004098	64	16%	88%	86%	1343%	78%	31	23	6	6	25	14	105	12
A2R011	B8R004	356.34	597	1061	530	0.000284	286	535	57	32	0.003300	10	10%	95%	94%	1062%	97%	29	17	21	19	19	21	126	19
A2R011	B8R007	445.29	597	1061	530	0.000284	286	613	39	16	0.002535	1805	3%	96%	97%	793%	531%	40	9	28	29	9	34	149	26
A2R011	B8R009	476.61	597	1061	530	0.000284	286	670	835	459	0.000688	339	12%	21%	13%	142%	19%	43	20	2	1	2	2	70	2
A2R011	B8R011	420.32	597	1061	530	0.000284	286	497	43	23	0.007242	71	17%	96%	96%	2450%	75%	36	26	27	26	32	12	159	30
A2R011	B9H002	517.33	597	1061	530	0.000284	286	1090	60	30	0.002505	822	83%	94%	94%	782%	187%	47	44	19	22	8	24	164	31
A2R011	C2R001	97.70	597	1061	530	0.000284	286	473	49	52	0.004427	3480	21%	95%	90%	1459%	1117%	10	28	25	12	26	38	139	21
A2R011	C2R004	109.48	597	1061	530	0.000284	286	575	120	54	0.002127	3628	4%	89%	90%	649%	1169%	12	11	8	10	5	39	85	5
A2R011	C2R005	108.98	597	1061	530	0.000284	286	947	85	40	0.005329	884.6	59%	92%	92%	1776%	209%	11	39	13	16	28	26	133	20
A2R011	C2R006	72.28	597	1061	530	0.000284	286	695	51	27	0.002921	28	16%	95%	95%	929%	90%	7	25	24	25	13	20	114	15
A2R011	C2R007	79.16	597	1061	530	0.000284	286	469	16	160	0.003057	362	21%	98%	70%	976%	27%	9	29	40	3	15	4	100	10
A2R011	C7R001	188.87	597	1061	530	0.000284	286	610	7	4	0.010800	2142	2%	99%	99%	3703%	649%	17	6	46	45	38	35	187	38
A2R011	C7R003	181.45	597	1061	530	0.000284	286	670	65	32	0.005500	63	12%	94%	94%	1837%	78%	16	20	17	19	29	16	117	18
A2R011	X2R003	405.26	597	1061	530	0.000284	286	606	97	46	0.003477	64	2%	91%	91%	1124%	78%	34	4	10	14	20	14	96	7
A2R011	X2R005	352.34	597	1061	530	0.000284	286	686	120	66	0.002770	954	15%	89%	88%	875%	234%	28	22	8	7	12	27	104	11
A2R011	X3R002	430.83	597	1061	530	0.000284	286	596	61	28	0.003669	211	0%	94%	95%	1192%	26%	37	1	18	24	23	3	106	13
A2R011	B4R007	318.38	597	1061	530	0.000284	286	610	960	48	0.000275	2863	2%	10%	91%	3%	901%	25	6	1	13	1	37	83	3

Table 3-6 Subject and Donor Catchments based on IS approach

Number	Subject Catchment	Donor Catchment (Based on the IS approach)
1	A1R001	B8R004
2	A2R005	B4R001
3	A2R006	A1R001
4	A2R007	B4R004
5	A2R011	B3R001
6	A2R012	B3H008
7	A2R014	A2R012
8	A3R001	A2R005
9	A3R002	A1R001
10	A3R003	C2R005
11	A4R001	A3R001
12	A6R001	A9R001
13	A6R002	B3H008
14	A8R001	B9H002
15	A8R002	A8R003
16	A8R003	X2R003
17	A8R004	B6R001
18	A9R001	B8R003
19	A9R004	B8R007
20	B3H008	A2R012
21	B3R001	X2R005
22	B3R002	B6R003
23	B3R005	B3H008
24	B4R001	B6R001
25	B4R004	B7R001
26	B4R007	B3R001
27	B5R002	B3R001
28	B6R001	B4R001
29	B6R003	B8R007
30	B7R001	B8R001
31	B7R003	B8R011
32	B8R001	B8R003
33	B8R003	X2R003
34	B8R004	B7R003
35	B8R007	B6R003
36	B8R009	A2R011
37	B8R011	B8R004

Number	Subject Catchment	Donor Catchment (Based on the IS approach)
38	B9H002	A8R004
39	C2R001	C2R004
40	C2R004	A3R002
41	C2R005	A2R006
42	C2R006	C7R003
43	C2R007	A1R001
44	C7R001	A3R001
45	C7R003	C2R006
46	X2R003	X3R002
47	X2R005	X2R003
48	X3R002	B8R004

3.2.4 Multiple Donor Catchment Selection

The multiple donor catchment approach simply considers all possible catchments in the study area, thus the number of multiple donor catchments for each subject catchment varied from 1 to 47 donors per site based on the nearest donor catchment.

3.3 Information Transfer from Donor Catchments

This section describes the method used for information transfer after identifying suitable donor catchment(s) as discussed in Section 3.2.

3.3.1 Information transfer – single donor

In order to adjust the flood estimates at the subject catchments, the donor catchments selected using the approaches detailed in Section 3.2 were used to determine a correction factor based on the ratio of design floods estimated from the selected deterministic and empirical methods and from observed data. This correction factor was transferred to the subject catchment as a multiplicative factor used to adjust the estimated design flood estimate using the original deterministic and empirical methods at the subject catchment. This correction factor was unique for each DFE method and RI. This adjustment was calculated using Equation 3.1.

$$Q_{s,adj,T} = Q_{s,est,T} \times \frac{Q_{d,obs,T}}{Q_{d,est,T}} \tag{3.1}$$

where

$Q_{s,adj,T}$ = adjusted DFE at the subject catchment for T year RI ($m^3.s^{-1}$),

$Q_{s,est,T}$ = DFE at the subject catchment for T year RI ($m^3.s^{-1}$),

$Q_{d,est,T}$ = DFE at the donor catchment for T year RI using selected Deterministic and Empirical Methods ($m^3.\ s^{-1}$), and

$Q_{d,obs,T}$ = observed design flood at the donor catchment for T year RI ($m^3.s^{-1}$).

This step was conducted by applying a jack-knife procedure in which one catchment at a time was treated as a subject catchment and the estimates adjusted using Equation 3.1 for each of the various approaches to donor catchment selection.

3.3.2 Information Transfer – multiple donors

To establish a relationship between optimal number of donor catchments, the number of nearest donors was varied from 1 to all possible gauged catchments within the study area i.e., 47, and calculating the adjusted flood estimate $Q_{s,adj,T}$ using Equation 3.2 which is based on the output averaging technique.

$$Q_{s,adj,T} = Q_{s,est,T} \times \frac{1}{n} \sum_{i=1}^{n=47} \left(\frac{Q_{d,est,T,i}}{Q_{d,obs,T,i}} \right) \tag{3.2}$$

where,

$Q_{s,adj,T}$ = adjusted DFE at the subject catchment for T year RI ($m^3.s^{-1}$),

$Q_{d,est,T,i}$ = estimated DFE at the *i*th donor catchment for T year RI ($m^3.s^{-1}$),

$Q_{d,obs,T,i}$ = observed design flood at the *i*th donor catchment for T year RI ($m^3.s^{-1}$), and

n = number of donor catchments.

In addition to the output averaging technique, the multiple donor approach was conducted using the median ratio as a correction factor.

3.4 Evaluation Criteria

This section describes the various criteria used to determine the performance of the DFE methods before and after applying the correction factors using donor catchment(s).

3.4.1 Scatter plots

Scatter plots were produced in order to determine the performance of the DFEs from the various methods by plotting the following information:

(a) 1:1 line.
(b) Original DFEs from the selected deterministic and empirical methods vs DFEs from observed data.
(c) Adjusted DFEs using information transfer and the SP approach from the selected deterministic and empirical methods vs DFEs from observed data.
(d) Adjusted DFEs using information transfer and the PS approach from the selected deterministic and empirical methods vs DFEs from observed data.
(e) Adjusted DFEs using information transfer and the IS approach from the selected deterministic and empirical methods vs DFEs from observed data.

The scatter plots provided a general indication of the tendency of the various methods to over and under-estimate DFEs before and after applying correction factors from donor catchments. Points located above the 1:1 line indicated an over-estimation and points below the 1:1 line indicated an under-estimation. If the estimated values are equal to the observed values, points fall on the 1:1 line. The slope of the various regression lines and R-squared values (R^2) were further evaluated to determine the performance of the various methods and information transfer approaches.

3.4.2 Relative error (RE)

The Relative Error (RE) was used to provide an indication of the predictive accuracy of the DFEs before and after applying the correction factors using donor catchment(s), $RE_{original}$ and $RE_{adjusted}$, respectively. In addition to predictive accuracy, REs also provided an indication of over-estimation (positive values) and under-estimation (negative values). REs at the subject catchments were calculated for the original and adjusted DFEs using Equation 3.3 and Equation 3.4.

$$RE_{original} = \frac{Q_{s,original,T} - Q_{s,obs,T}}{Q_{s,obs,T}} \times 100 \qquad (3.3)$$

where,

$RE_{original}$ = relative error of the original DFE methods (%),

$Q_{s,obs,T}$ = observed design flood at the subject catchment for T year RI ($m^3.\ s^{-1}$), and

$Q_{s,original,T}$ = original peak flow at the subject catchment for T year RI ($m^3.s^{-1}$).

$$RE_{adj} = \frac{Q_{s,adj,T} - Q_{s,obs,T}}{Q_{s,obs,T}} \times 100 \qquad (3.4)$$

where,

RE_{adj} = relative error of the adjusted DFE methods (%)

$Q_{s,obs,T}$ = observed design flood at the subject catchment for T year RI ($m^3.\ s^{-1}$), and

$Q_{s,adj,T}$ = adjusted peak flow at the subject catchment for T year RI ($m^3.s^{-1}$)

The REs were plotted on box and whisker plots to provide a graphical representation and distribution of data for comparative reasons. The box and whisker plots show a summary of the results by displaying the minimum value, first/lower quartile, median value, third/upper quartile and the maximum value. The Interquartile Range (IQR) that lies between the first and third quartile represents 50% of the data i.e. REs. Figure 3-3 below shows an example of a generic box and whisker plot and summary data.

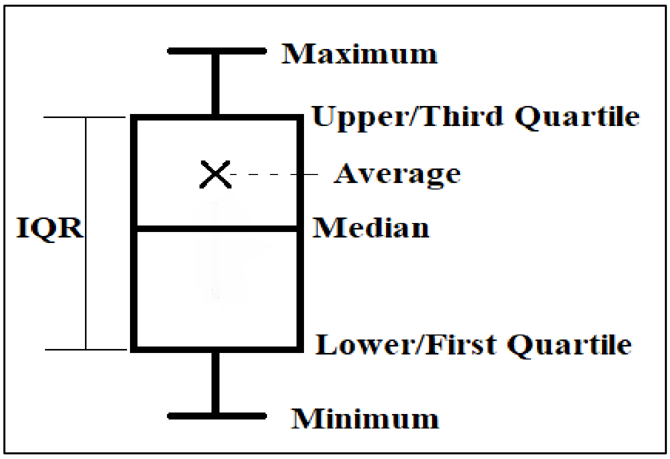

Figure 3-3 Summary of data represented on box and whisker plots

3.4.3 Mean Absolute Relative Error (MARE)

The Mean Absolute Relative Error (MARE) was determined for each site to quantify possible improvements of DFEs after applying the correction factors using donor catchment(s).

3.4.3.1 Single donor catchment

The MAREs were calculated across the seven (7) RIs for each site i.e., 2, 5, 10, 20, 50, 100, 200-year. The MAREs were determined before and after applying the correction factors, $MARE_{original}$ and $MARE_{adjusted}$, using Equation 3.5 and Equation 3.6, respectively.

$$MARE_{original} = \frac{1}{7}\sum_{T=1}^{7}\left|RE_{original,\ T}\right| \tag{3.5}$$

where,

$MARE_{original}$ = mean absolute relative error for each site for the original estimates (%),

$RE_{original,\ T}$ = relative error for each site for the original estimates for the T year RI (%),

T = number of T year RIs (7).

$$MARE_{adjusted} = \frac{1}{7}\sum_{T=1}^{7}\left|RE_{adjusted,\ T}\right| \tag{3.6}$$

where,

$MARE_{adjusted}$ = mean absolute relative error for each site for the adjusted estimates (%),

$RE_{adjusted,\ T}$ = relative error for each site for the adjusted estimates for the T year RI (%), and

T = number of T year RIs (7).

In order to determine if each site experienced an improvement in design flood estimates, the $MARE_{original}$ was subtracted by the $MARE_{adjusted}$ (see Equation 3.7). Positive values indicated an improvement in MARE and negative values indicated an increase in error, i.e. poorer estimate.

$$\Delta MARE = MARE_{original} - MARE_{adjusted} \tag{3.7}$$

where,

$MARE_{adjusted}$ = mean absolute relative error for each site for the adjusted estimates (%), and

$MARE_{original}$ = mean absolute relative error for each site for the original estimates (%).

3.4.3.2 Multiple donor catchments

In the case of multiple donor catchments, the MAREs were summarised over the seven (7) RIs and sites in the study using Equations 3.8 and 3.9.

$$MARE_{original} = \frac{1}{48}\sum_{n=1}^{48}\sum_{T=1}^{7}\left|RE_{original,\,T}\right| \tag{3.8}$$

where,

$MARE_{original}$ = mean absolute relative error for each site for the original estimates (%),

$RE_{original,\,T}$ = relative error for each site for the original estimates for the T year RI (%),

T = number of T year RIs (7), and

n = number of catchments in the study area (48).

$$MARE_{adjusted} = \frac{1}{n}\sum_{n=1}^{48}\sum_{T=7}^{7}\left|RE_{adjusted,\,T}\right| \tag{3.9}$$

where,

$MARE_{adjusted}$ = mean absolute relative error for each site for the adjusted estimates (%),

$RE_{adjusted,\,T}$ = relative error for each site for the adjusted estimates for the T year RI (%),

T = number of T year RIs (7), and

n = number of sites in the study area (48).

Similar to the single donor catchments, the difference in MARE was calculated to determine possible improvements using the Equation 3.10.

$$\Delta MARE = MARE_{original} - MARE_{adjusted} \tag{3.10}$$

where,

$MARE_{adjusted}$ = mean absolute relative error for each site for the adjusted estimates (%), and

$MARE_{original}$ = mean absolute relative error for each site for the original estimates (%)

4. RESULTS AND DISCUSSION

This chapter contains the results of the study using the methodology and assessment criteria described in Chapter 3. The results are presented per DFE technique. Section 4.1 contains the results of using the different approaches of donor catchment selection and single donor catchment transfer. Section 4.2 presents the results of using multiple nearest neighbour donor catchments.

4.1 Single Donor Catchment Transfer

This section contains the results from using the different approaches of donor catchment selection and transfer applied to various DFE methods for single donor catchment transfer.

4.1.1 Standard Design Flood

This section covers the results for the SDF method after using the various methods for information transfer from a single donor catchment to adjust design flood estimates.

4.1.1.1 Scatter plots

Scatter plots were developed to show the general performance of the original SDF method in comparison to the adjusted SDF method using the correction factors determined from the various donor catchment selection approaches. The main areas of interest for this particular plot are the slopes of the regression lines and R^2 values which provide an indication of the correlation between the data. Figure 4-1 provides an example of a scatter plot for the 1:20 year RI for the original and adjusted SDF values. Scatter plots for various RIs are shown in Appendix A1. A summary of the slopes and R^2 values are contained in Table 4-1 for 2 to 200-year RIs as well as the average values.

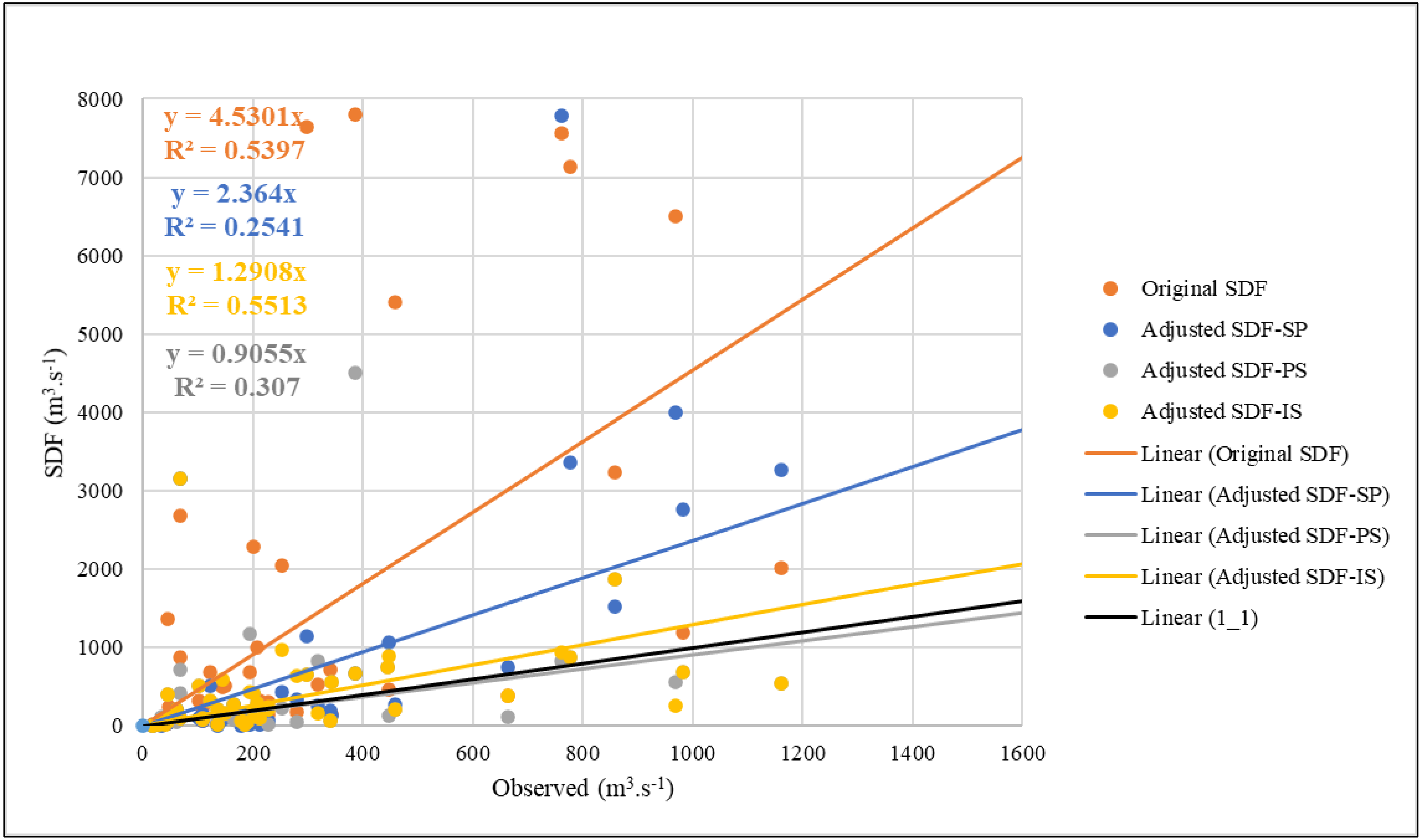

Figure 4-1 Scatter plot for estimates using the SDF method for the 1:20 year RI

Table 4-1 Summary of regression line slopes and R^2 values for the original and adjusted SDF design flood estimates for the various RIs

Method		**RI (Years)**							**Average**	**Median**
		1:2	**1:5**	**1:10**	**1:20**	**1:50**	**1:100**	**1:200**		
$SDF_{original}$	Slope	2.96	4.03	4.31	4.53	4.76	4.85	4.85	4.33	4.53
	R^2	0.55	0.55	0.54	0.54	0.54	0.55	0.55	0.55	0.55
$SDF_{adjusted,SP}$	Slope	2.06	2.15	2.27	2.36	2.38	2.29	2.34	2.26	2.29
	R^2	0.19	0.21	0.23	0.25	0.26	0.27	0.27	0.24	0.25
$SDF_{adjusted,PS}$	Slope	1.17	0.98	0.95	0.91	0.88	0.83	0.85	0.94	0.91
	R^2	0.29	0.26	0.29	0.31	0.32	0.34	0.33	0.31	0.31
$SDF_{adjusted,IS}$	Slope	1.30	1.21	1.23	1.29	1.36	1.39	1.38	1.31	1.30
	R^2	0.60	0.64	0.56	0.55	0.52	0.52	0.52	0.56	0.55

The scatter plots for the SDF illustrate a significant overestimation of design flood estimates when applying the SDF method as the majority of the points lie above the 1:1 line and the slope of the regression line (4.53) is greater than 1. The over-estimation ranges between 2.96 to 4.85 times the observed flood estimates depending on the RI. The slopes for the adjusted SDF estimates indicate a significant improvement as the slopes of the regression lines are closer to the 1:1 line. While all 3 approaches for single donor catchment selection offer improvements, the adjusted SDF estimates using the SP approach performs the worst in terms of slope and R^2 values. The adjusted SDF estimates using the PS approach performs the best in terms of slopes and the adjusted SDF method using the IS approach provides a consistent improvement in terms of the slope of the regression line and has the best correlation in terms of the R^2 values.

4.1.1.2 Relative error

The REs were calculated for the original and adjusted SDF estimates for each of the 48 sites and RIs to provide an indication of the accuracy. The REs provide a more detailed analysis of the error distribution and whether the various estimates under or over-estimate design floods. Box and whisker plots were produced to graphically represent the minimum, maximum and median REs. The IQR between the first and third quartile shows the spread and variability of the REs. Figure 4-2 provides an example of a box and whisker plot of REs for the 1:20-year design flood estimates. Box and whisker plots for the other RIs can be found in Appendix B1.

Table 4-2 provides a summary of the median REs for the original and adjusted SDF design flood estimates.

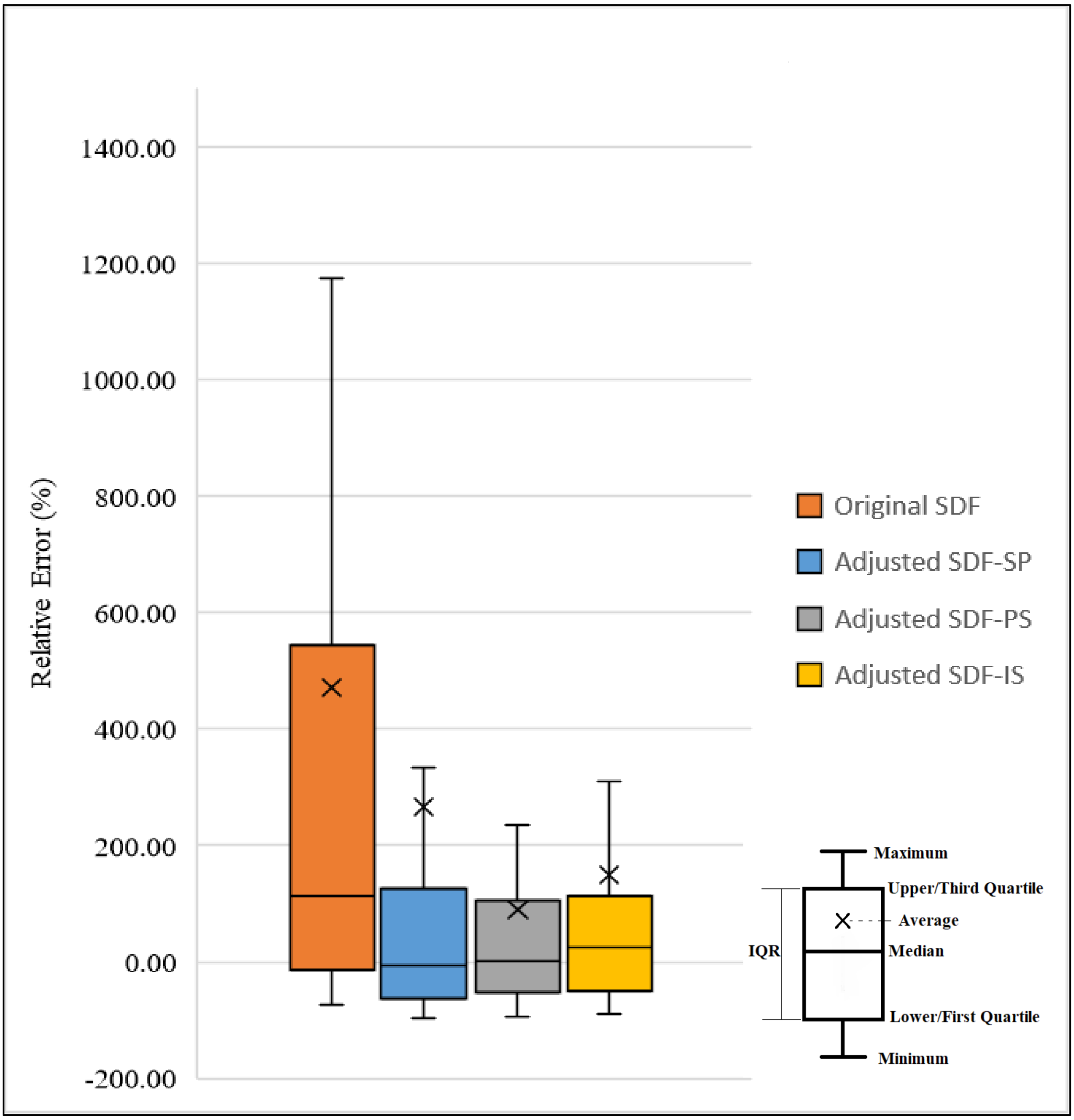

Figure 4-2 Box and whisker plot for the RE values of the Original and Adjusted SDF estimates for the 1:20-year RI

Table 4-2 Summary of median relative errors for the original and adjusted SDF design flood estimates

Method	Median Relative Error (%)			
	Lowest Quartile	Median	Upper Quartile	IQR
	(%)	(%)	(%)	(%)
$SDF_{original}$	-13.8	112.1	540.9	554.6
$SDF_{adjusted, SP}$	-63.4	-7.6	109.0	172.4
$SDF_{adjusted, PS}$	-55.2	2.2	106.1	161.4
$SDF_{adjusted, IS}$	-49.5	25.5	115.0	164.5

It can be seen from Table 4-2 and Figure 4-2 for the 1:20-year RI that the RE values for the original SDF design flood estimates are generally over-estimated by a large margin, the median value being the largest at 112.1%. The IQR value of 554.6% for the unadjusted SDF results also indicates that there is large spread and variability in the REs. This further substantiates the findings contained in Section 4.1.1 where the over-estimation is shown to be up to 4.85 times the observed flood estimates depending on the RI based on the scatter plot. The adjusted SDF design flood estimates using the correction factors from the three approaches for donor catchment selection show a significant improvement in the median REs and a large reduction in the IQR. The IQR for the design flood estimates using the SP, PS and IS approach are relatively similar i.e., 172.4%, 161.4% and 164.5%, respectively. Based on the median RE values, adjusted SDF design flood estimates using the PS approach performs the best, followed by the SP and IS approaches.

4.1.1.3 Mean absolute relative error

The analysis of the scatter plots and REs provided an indication of the performance of the original and adjusted SDF design flood estimates. The MARE was calculated to determine the performance of the correction factors on a catchment-by-catchment basis. This was achieved by computing the MARE for the original and adjusted SDF design flood estimates across the various RIs at each of the 48 catchments. The original MARE was subtracted by the adjusted MARE. A positive resultant for ΔMARE indicated an improvement i.e. $MARE_{original} > MARE_{adjusted}$ and negative resultant indicated a poorer estimate i.e. $MARE_{original} < MARE_{adjusted}$. Table 4-3, Figure 4-3, Figure 4-4 and Figure 4-5 indicate the number and percentage of sites that experienced an improvement (green) and poorer (red) MAREs after application of the correction factors using the different approaches for donor catchment selection with the SDF method.

Table 4-3 Number of sites with improved and poorer MAREs after application of correction factors using the different approaches for donor catchment selection with the SDF method

Method	Number of sites with improved MAREs	Percentage of sites with improved MAREs (%)	Number of sites with poorer MAREs	Percentage of sites with poorer MAREs (%)
$SDF_{adjusted,\ SP}$	28/48	58	20/48	42
$SDF_{adjusted,\ PS}$	30/48	63	18/48	38
$SDF_{adjusted,\ IS}$	30/48	63	18/48	38

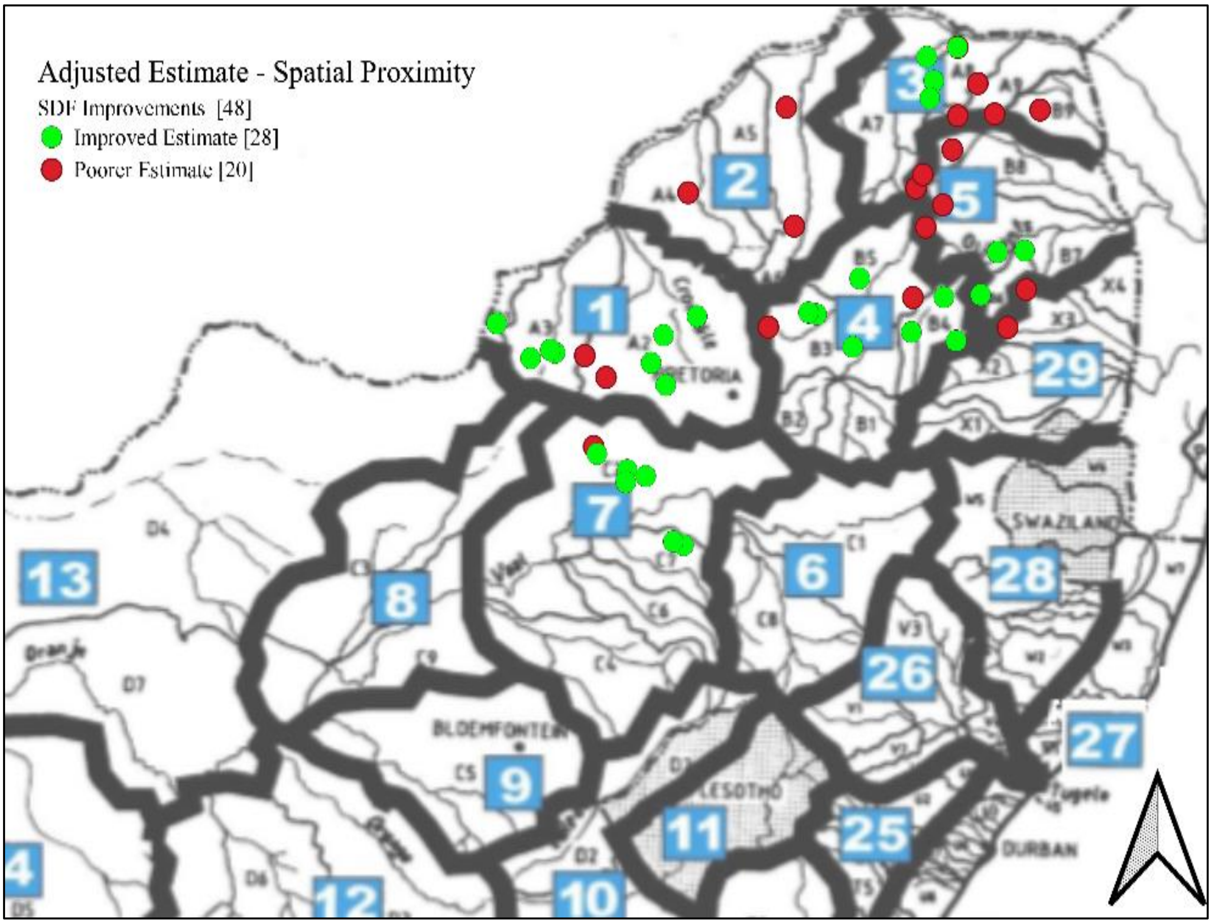

Figure 4-3 Sites with improved and poorer estimates in the various SDF basins using the SP approach

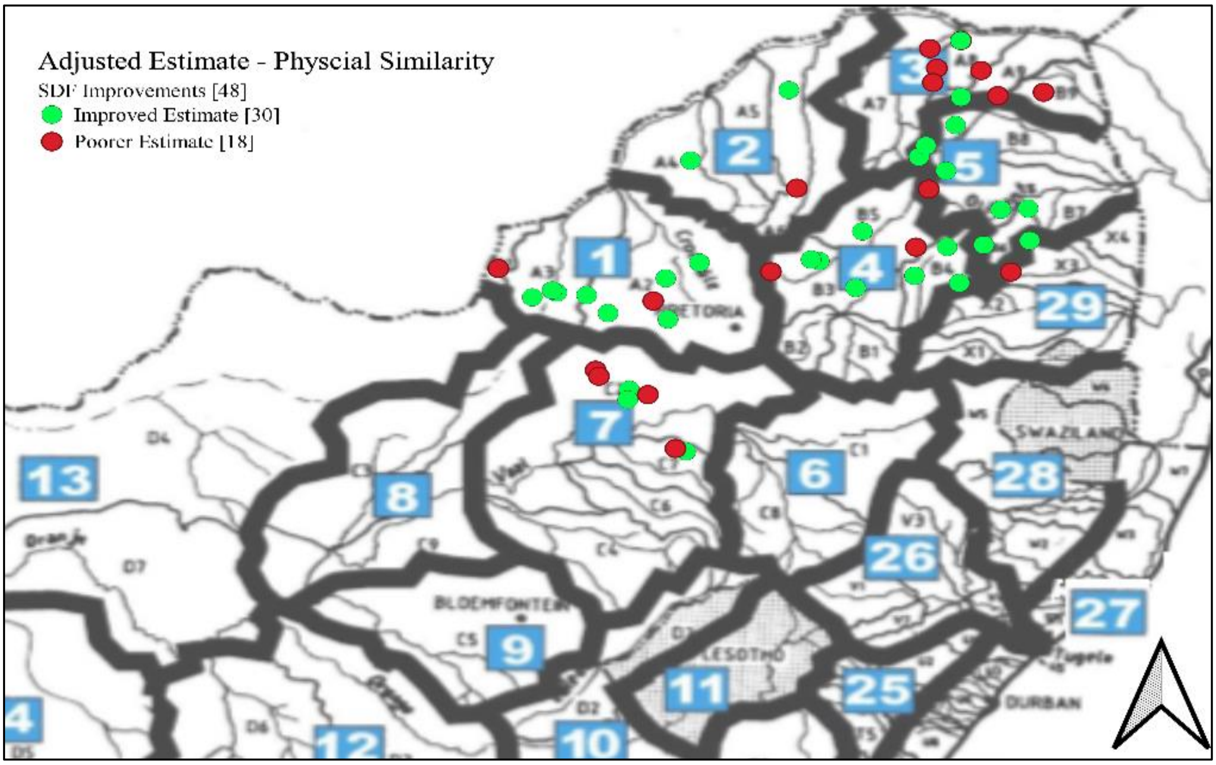

Figure 4-4 Sites with improved and poorer estimates in the various SDF basins using the PS approach

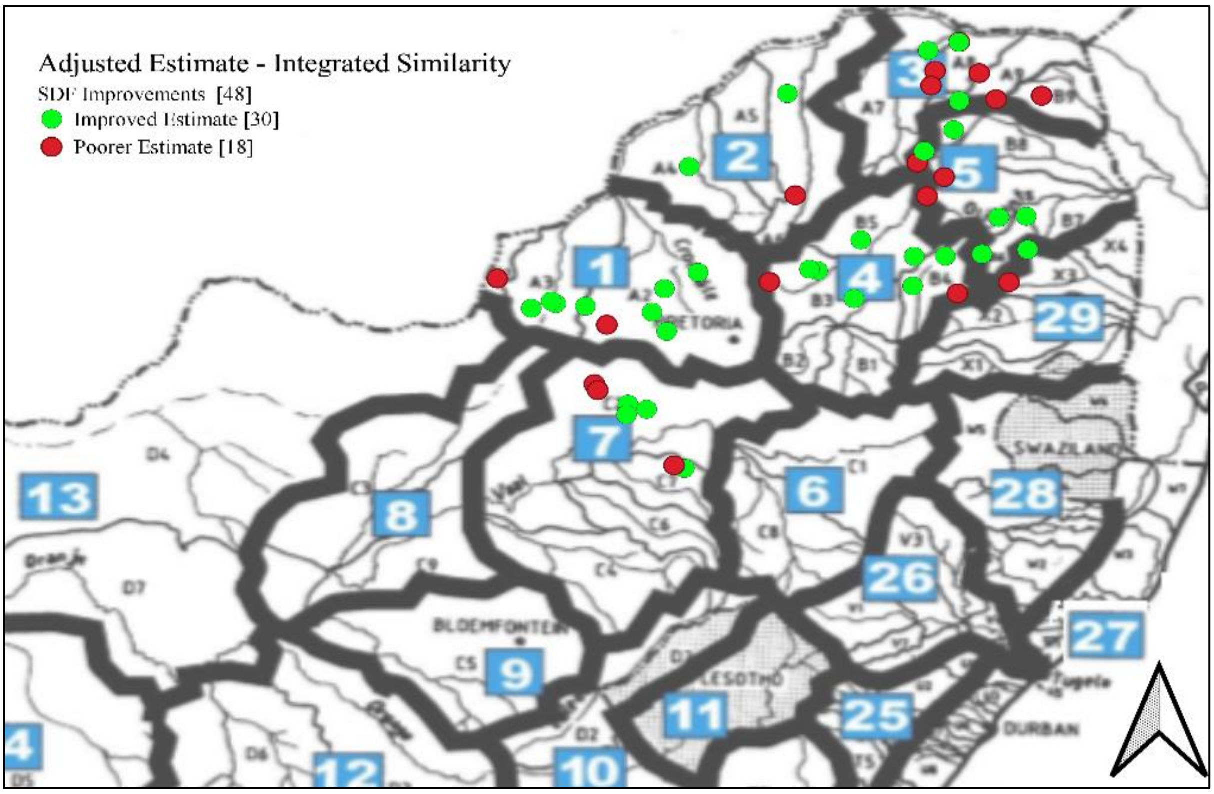

Figure 4-5 Sites with improved and poorer estimates in the various SDF basins using the IS approach

In terms of Table 4-3, the adjusted SDF design flood estimates perform equally well when using the PS and IS approach with 30 (63%) of the 48 catchments experiencing an improvement in MARE of the design flood estimates. The adjusted design flood estimates using the SP method perform the worst with only 28 (58%) of the 48 catchments experiencing an improvement. In addition, there is no clear distinction or correlation of the improvements and spatial density of the sites based on Figure 4-3, Figure 4-4 and Figure 4-5.

Although the results in the figures above showed that majority of the sites experienced improvements based on MARE, it was also important to review the catchments with poorer adjusted MAREs more closely. This was done by producing a box plot of the ΔMAREs as shown in Figure 4-6, where positive values indicate an improvement and negative values indicated poorer results.

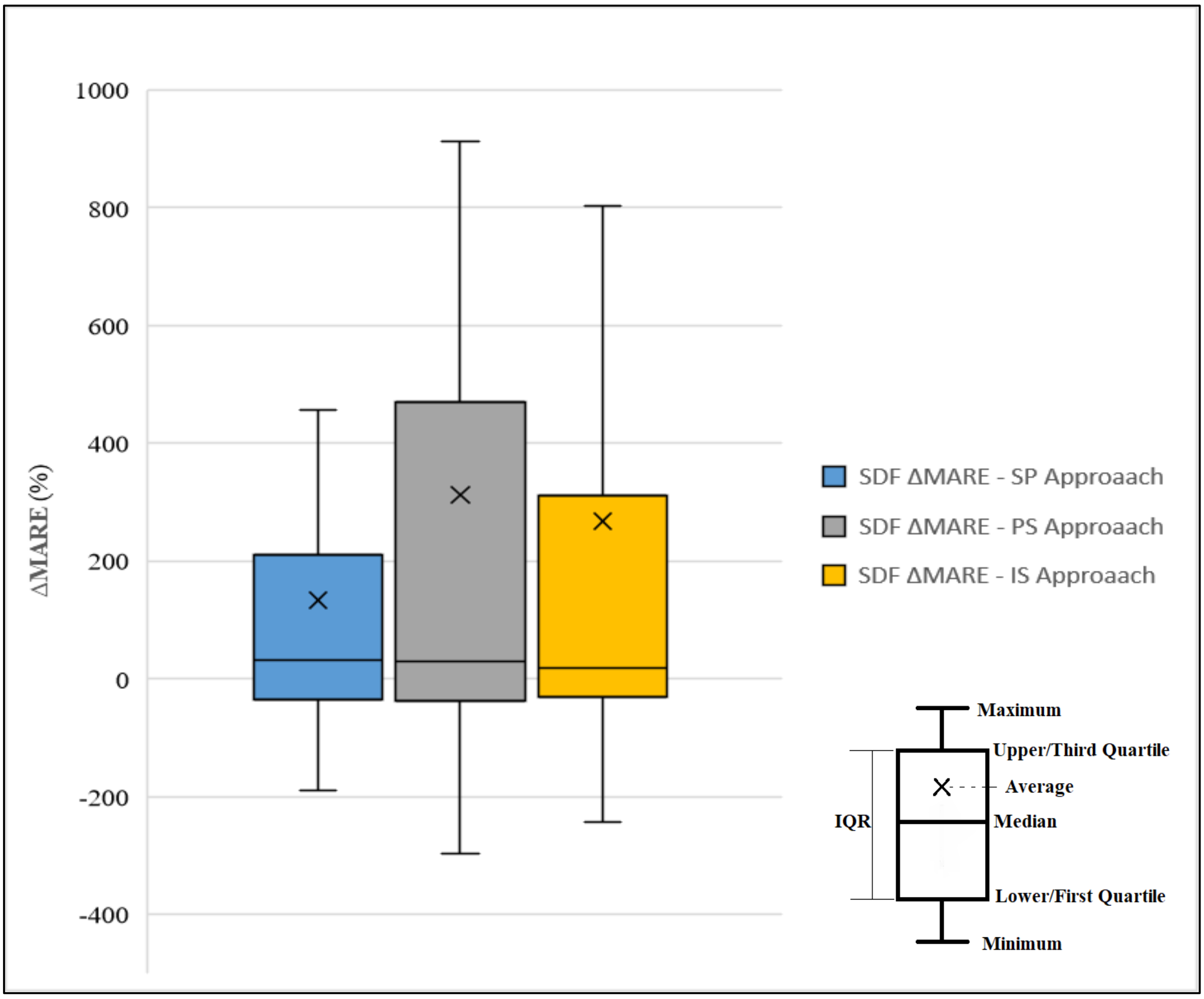

Figure 4-6 Box and whisker plot of ΔMAREs for the SDF method and various approaches for donor catchment selection

Figure 4-6 shows that the minimum values of ΔMARE i.e., poorer results are -190.50%, -297.44 and -243.88% for the SP, PS and IS approach, respectively. Thus, while the correction factors offer significant improvements for majority of the sites, it can be seen that there is significant underperformance at the catchments experiencing poorer results.

4.1.1.4 Summary of results

Table 4-4 provides a summary and comparison of the various assessment criteria and their corresponding ranks for the adjusted SDF estimates, in order to determine which of the approaches for donor catchment selection provides the best improvement. The PS approach ranks the best followed by the IS and SP approaches in the case of the SDF method for single site transfer in terms of the assessment criteria described in Chapter 3.

Table 4-4 Summary of assessment criteria and respective ranks based on the on the adjusted SDF estimates

Method	Average Slope	Rank	Average R^2	Rank	Median RE (%)	Rank	Median RE IQR (%)	Rank	Catchments with Improved MARE (%)	Rank	Min Δ MARE (%)	Rank	Sum of Ranks	Final Rank
$SDF_{adjusted, SP}$	2.26	3.00	0.24	3.00	-7.56	2.00	172.4	3.00	58	3.00	-190.50	1.00	15.00	3.00
$SDF_{adjusted, PS}$	***0.94***	***1.00***	***0.31***	***2.00***	***2.19***	***1.00***	***161.37***	***1.00***	***63***	***1.00***	*-297.44*	*3.00*	*9.00*	***1.00***
$SDF_{adjusted, IS}$	1.31	2.00	0.56	1.00	25.45	3.00	164.47	2.00	63	1.00	-243.83	2.00	11.00	2.00

4.1.2 Rational Method

This section covers the results for the RM after using the various techniques for information transfer to adjust design flood estimates using correction factors as was done for the SDF method in Section 4.1.1.

4.1.2.1 Scatter plots

Figure 4-7 provides an example of a scatter plot for the 1:20 year RI. Scatter plots for various RIs are shown in Appendix B2. A summary of the slopes and R^2 values are shown in Table 4-5 for the 2 to 200-year RIs as well as the average values.

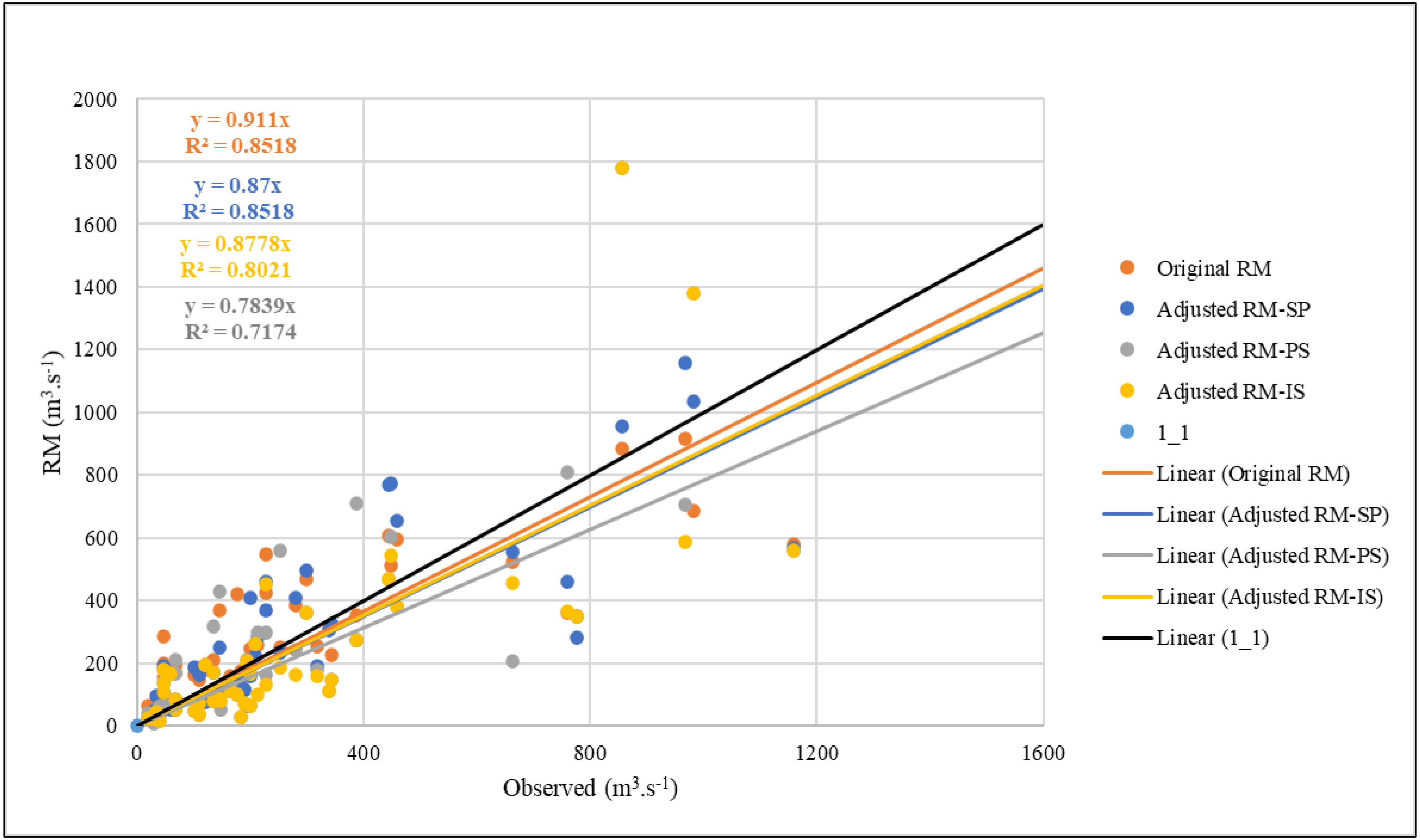

Figure 4-7 Scatter plot for the RM for the 1:20 year RI

Table 4-5 Summary of regression line slopes and R^2 values for the original and adjusted RM design flood estimates for the various RIs

Method		RI (Years)							Average	Median
		1:2	1:5	1:10	1:20	1:50	1:100	1:200		
$RM_{original}$	Slope	1.29	1.01	0.93	0.91	0.89	0.89	0.88	0.97	0.91
	R^2	0.77	0.83	0.84	0.85	0.86	0.86	0.86	0.84	0.85
$RM_{adjusted,SP}$	Slope	0.76	0.76	0.81	0.87	0.91	0.95	0.99	0.86	0.87
	R^2	0.75	0.79	0.81	0.85	0.88	0.90	0.90	0.84	0.85
$RM_{adjusted,PS}$	Slope	0.99	0.84	0.81	0.78	0.76	0.74	0.72	0.81	0.78
	R^2	0.60	0.60	0.66	0.71	0.75	0.77	0.78	0.70	0.71
$RM_{adjusted,IS}$	Slope	0.97	0.87	0.86	0.88	0.89	0.89	0.89	0.89	0.89
	R^2	0.64	0.67	0.74	0.80	0.82	0.83	0.84	0.76	0.80

Figure 4-7 and Table 4-5 show that the original RM generally performs well in terms of the average slopes as well as the average R^2. The adjusted RM estimates using the different approaches for single site transfer does not improve the original estimates as the average slope for the regression line is closer to the 1:1 line for the original RM method and the R^2 value is better than the values for the adjusted RM estimates.

4.1.2.2 Relative error

Figure 4-8 provides an example of a box and whisker plot of REs for the 1:20-year design flood estimates. Box and whisker plots for the other RIs can be found in Appendix B2. Table 4-6 provides a summary of the median REs for the original and adjusted RM design flood estimates.

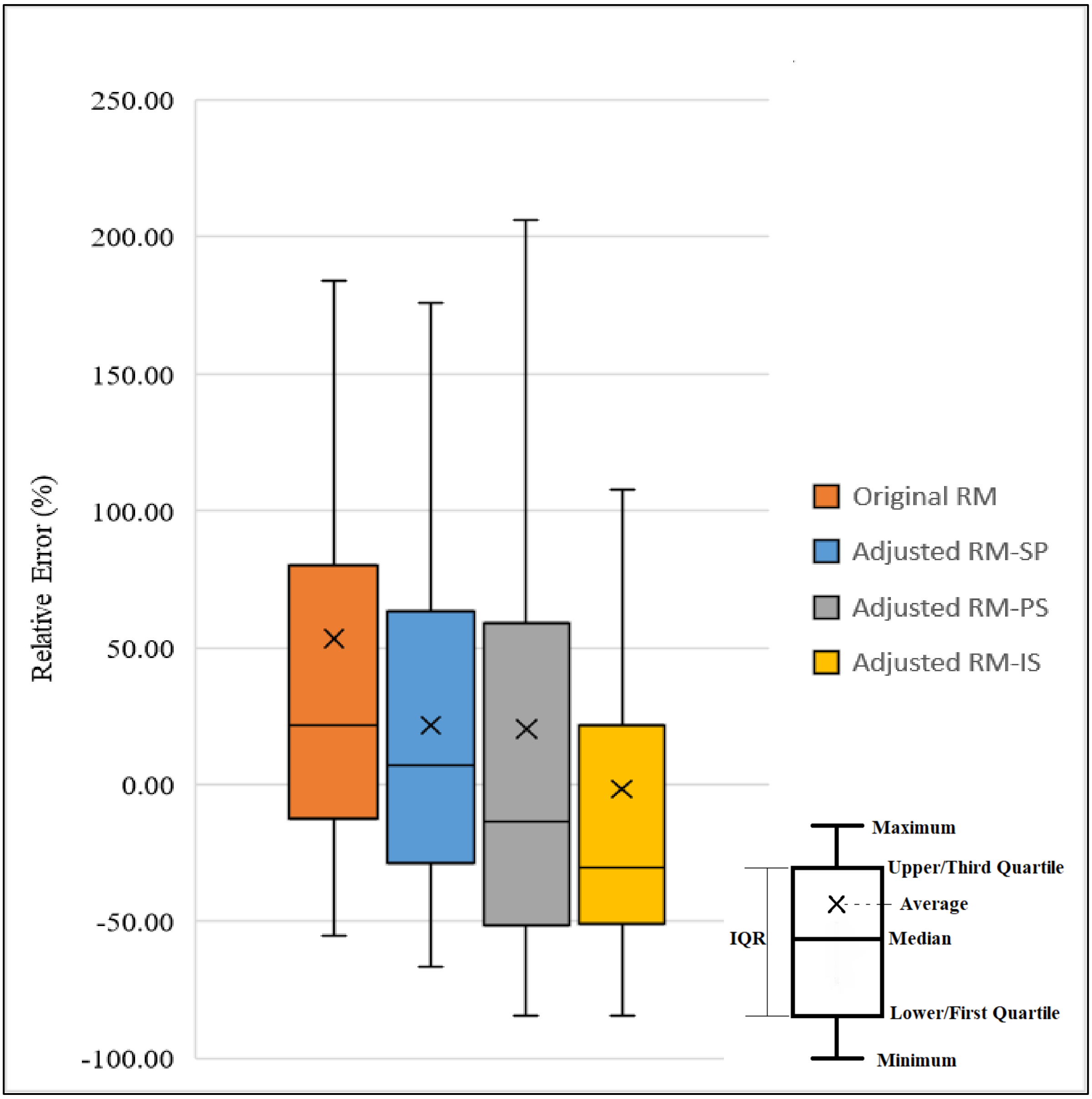

Figure 4-8 Box and whisker plot for the RE values of the Original and Adjusted RM estimates for the 1:20-year RI

Table 4-6 Summary of median relative errors for the original and adjusted RM design flood estimates

Method	**Median Relative Error (%)**			
	Lowest Quartile	**Median**	**Upper Quartile**	**IQR**
	(%)	**(%)**	**(%)**	**(%)**
$RM_{original}$	-10.2	53.8	80.3	90.5
$RM_{adjusted, SP}$	-28.1	8.9	53.6	81.7
$RM_{adjusted, PS}$	-50.6	-13.6	55.2	105.8
$RM_{adjusted, IS}$	-49.4	-29.9	23.0	72.5

It can be seen from Figure 4-8 and Table 4-6 that the median RE values for the original RM design flood estimates generally over-estimate, the median RE value being the largest at 53.8% and upper quartile of 80.3%. The adjusted RM design flood estimates using the correction factors from the three approaches for donor catchment selection show an improvement in the median error compared to the original RM median RE value, however, the IQR for the PS approach indicates an increase in the range of REs. Based on the consistent improvement in both the median RE value and reduced IQR, the adjusted RM design flood estimates using the SP and IS approach performs the best.

4.1.2.3 Mean absolute relative error

Table 4-7, Figure 4-9, Figure 4-10 and Figure 4-11 indicate the number and percentage of sites that experienced an improvement (green) and poorer (red) MAREs after application of the correction factors using the different approaches for donor catchment selection with the RM method.

Table 4-7 Number of sites with improved and poorer MAREs after application of correction factors using the different approaches for donor catchment selection with the RM method

Method	Number of Sites with Improved MAREs	Percentage of Sites with Improved MAREs	Number of Sites with Poorer MAREs	Percentage of Sites with Poorer MAREs
$RM_{adjusted, SP}$	28/48	58%	20/48	42%
$RM_{adjusted, PS}$	18/48	38%	30/48	63%
$RM_{adjusted, IS}$	20/48	42%	28/48	58%

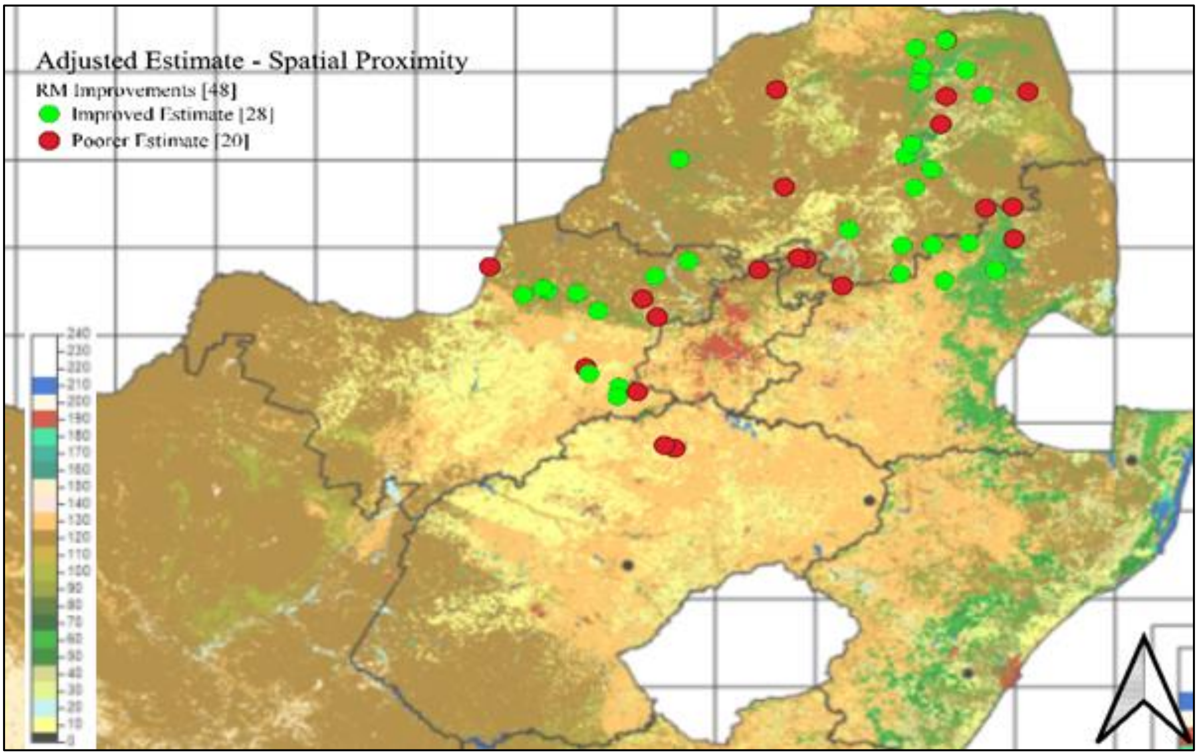

Figure 4-9 Sites with improved and poorer estimates for the various catchment locations using the RM and SP approach

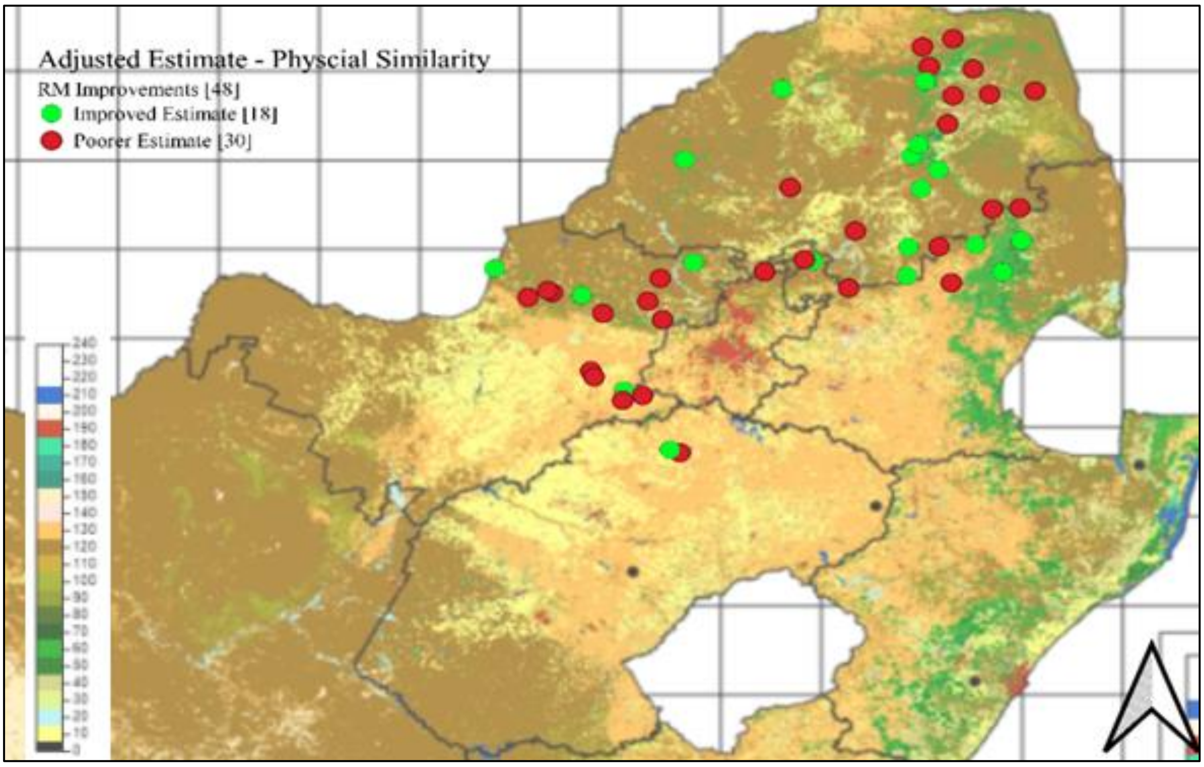

Figure 4-10 Sites with improved and poorer estimates for the various catchments using the RM and PS approach

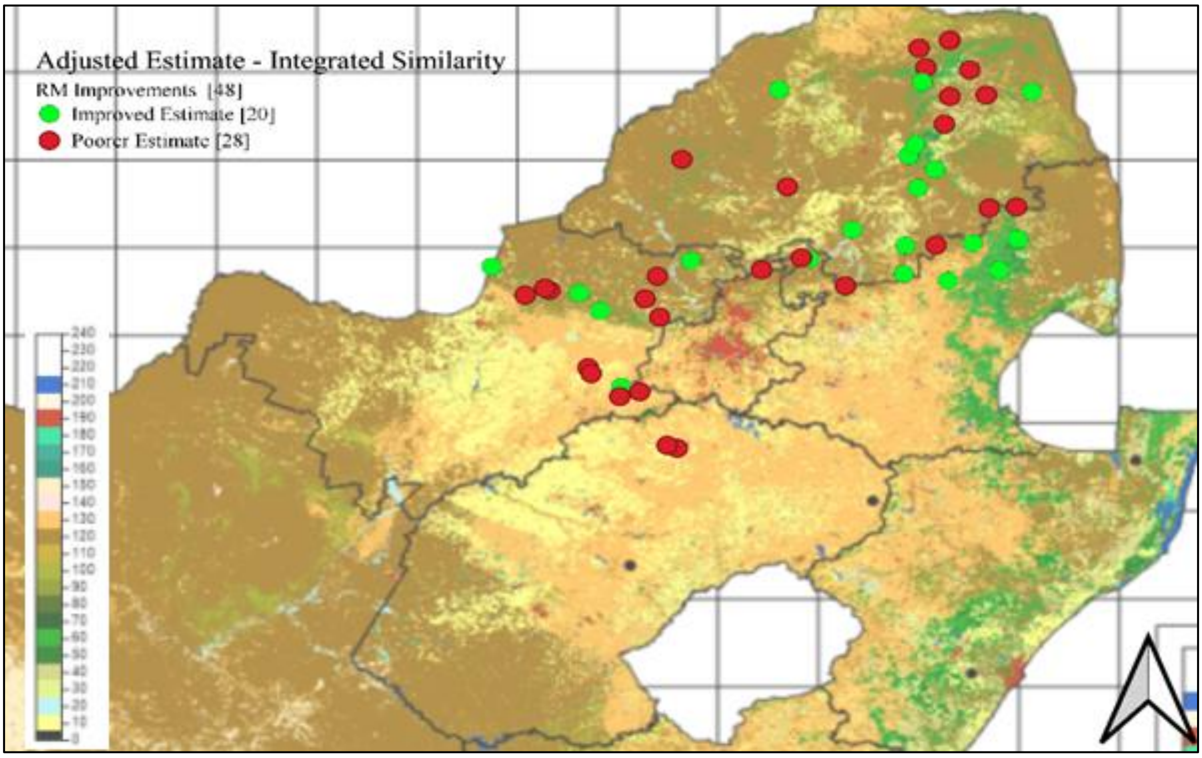

Figure 4-11 Sites with improved and poorer estimates for the various catchments using the RM and IS approach

In terms of Table 4-7, the adjusted RM design flood estimates experienced the most improvement using the SP approach with 28 (58%) of the 48 catchments experiencing an improvement in MARE of the design flood estimates. The PS and IS approach perform significantly worst with less than 50% of the sites experiencing improvements in MARE. The above figures also illustrate that there is no evidence of spatial patterns or trends with the improvements in MARE.

Figure 4-12 shows a box and whisker plot of the ΔMAREs where positive values indicate an improvement and negative values indicate poorer results.

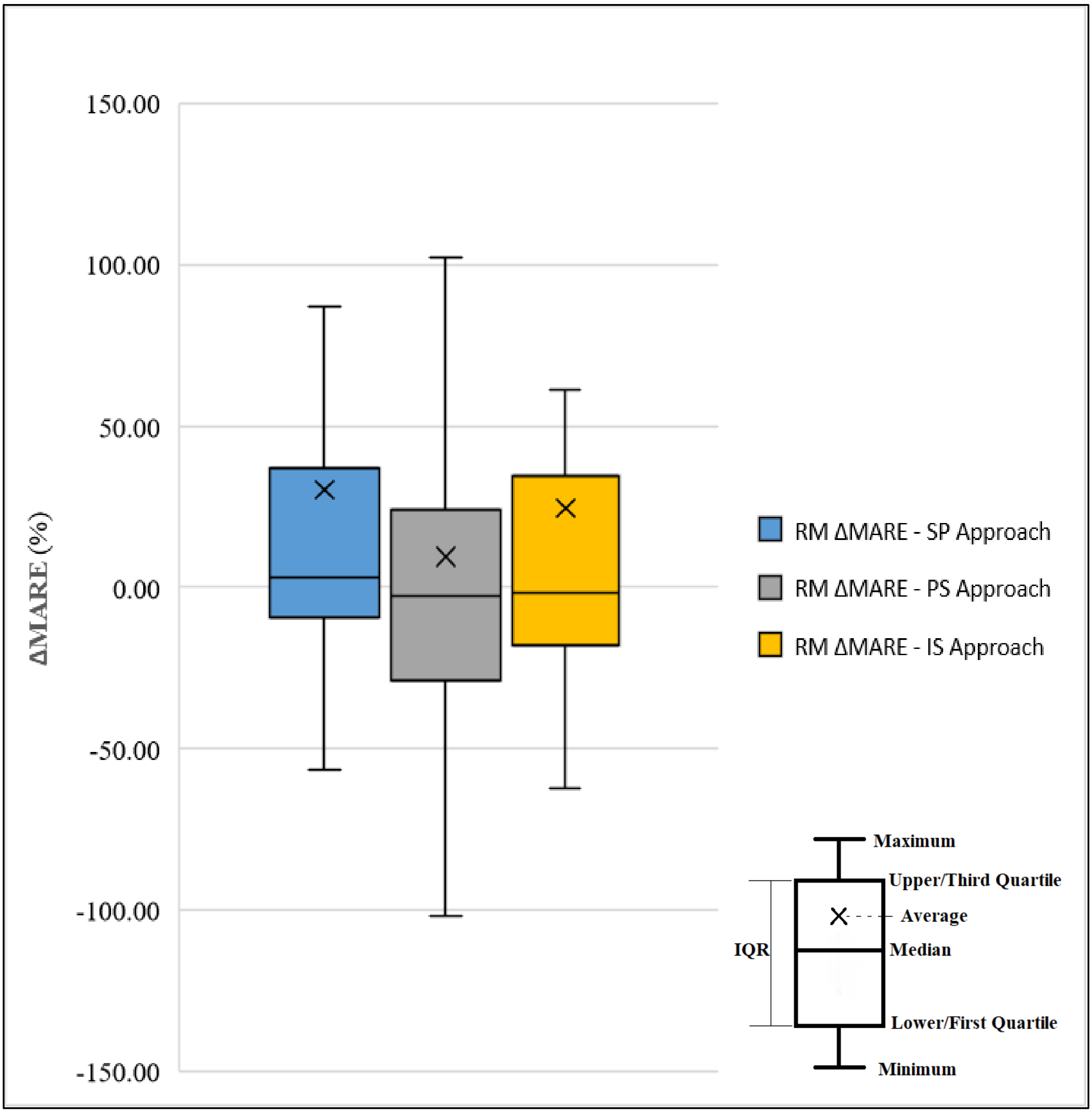

Figure 4-12 Box and whisker plot of ΔMAREs for the RM method and various approaches for donor catchment selection

Figure 4-12 shows that the minimum values of ΔMARE i.e. poorer results are -56.59%, -102.05% and -62.69% for the SP, PS and IS approach, respectively. Thus, while the correction factors offer significant improvements for majority of the sites, it can be seen that there is significant under performance at the catchments experiencing poorer results.

4.1.2.4 Summary of results

Table 4-8 provides a summary and comparison of the various assessment criteria and their corresponding ranks relative to the approaches adjusted RM estimates. The adjusted RM estimates using the SP approach performs the best followed by the IS and PS approach, respectively.

Table 4-8 Summary of assessment criteria and respective ranks based on the on the adjusted RM estimates

Method	Average Slope	Rank	Average R^2	Rank	Median RE (%)	Rank	Median RE IQR (%)	Rank	Catchments with Improved MARE (%)	Rank	Min Δ MARE (%)	Rank	Sum of Ranks	Final Rank
$RM_{adjusted, SP}$	*0.86*	*2.00*	*0.84*	*1.00*	*8.86*	*1.00*	*81.65*	*2.00*	*58%*	*1.00*	*-56.59*	*1.00*	*8.00*	*1.00*
$RM_{adjusted, PS}$	0.81	3.00	0.70	3.00	-13.59	2.00	105.82	3.00	38%	3.00	-102.05	3.00	17.00	3.00
$RM_{adjusted, IS}$	0.89	1.00	0.76	2.00	-29.89	3.00	72.47	1.00	42%	2.00	-62.29	2.00	11.00	2.00

4.1.3 Synthetic Unit Hydrograph

This section covers the results for the SUH method after using the various techniques for information transfer to adjust design flood estimates using correction factors as was done for the SDF method in Section 4.1.1.

4.1.3.1 Scatter plots

Figure 4-13 provides an example of a scatter plot for the 1:20 year RI. Scatter plots for various RIs are shown in Appendix A2. A summary of the slopes and R^2 values are shown in Table 4-9 for the 2 to 200-year RIs as well as the average values.

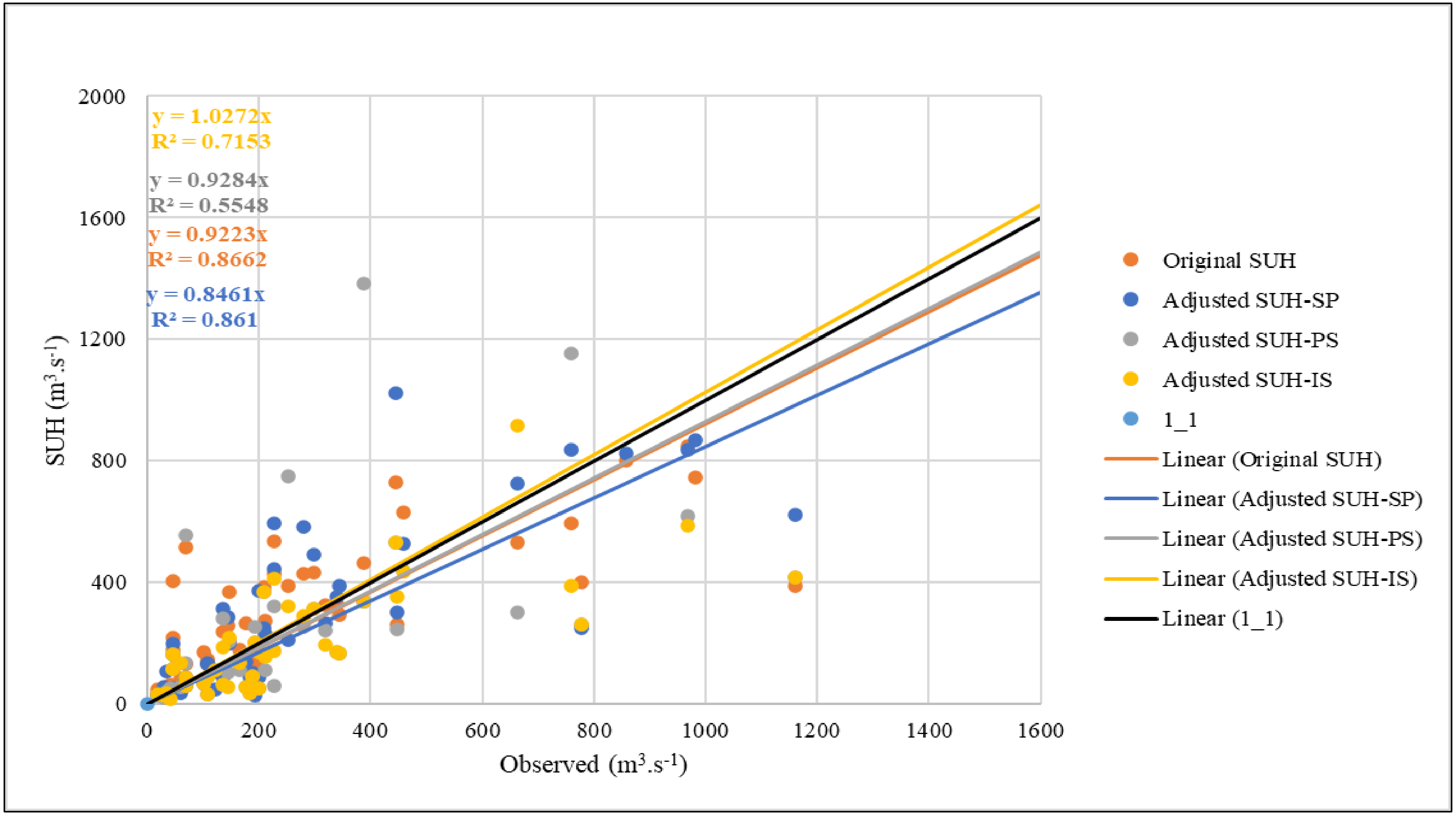

Figure 4-13 Scatter plot for the SUH method for the 1:20 year RI

Table 4-9 Summary of regression line slopes and R^2 values for the original and adjusted SUH design flood estimates for the various RIs

Method		1:2	1:5	1:10	1:20	1:50	1:100	1:200	Average	Median
$SUH_{original}$	Slope	2.00	1.20	1.01	0.92	0.85	0.82	0.79	1.08	0.92
	R^2	0.75	0.82	0.84	0.87	0.88	0.89	0.90	0.85	0.87
$SUH_{adjusted,SP}$	Slope	0.76	0.73	0.79	0.85	0.90	0.95	0.98	0.85	0.85
	R^2	0.75	0.79	0.82	0.86	0.89	0.90	0.90	0.84	0.86
$SUH_{adjusted,PS}$	Slope	1.20	1.02	0.97	0.93	0.87	0.84	0.81	0.95	0.93
	R^2	0.43	0.43	0.50	0.55	0.59	0.62	0.64	0.54	0.55
$SUH_{adjusted,IS}$	Slope	1.19	1.06	1.03	1.03	1.00	0.99	0.97	1.04	1.03
	R^2	0.50	0.53	0.62	0.72	0.78	0.82	0.85	0.69	0.72

It can be seen from Figure 4-13 and Table 4-9 that the original SUH method generally performs relatively well in terms of the average slopes as well as the average R^2 with average values of 1.08 and 0.85, respectively. The adjusted SUH method using the SP approach results in poor performance as the slope of the regression line moves further away from the 1:1 line compared the original method while the adjusted SUH estimates using the PS approach does not have a significant impact on the on the slopes compared to the original method as the average slopes are similar. The adjusted SUH estimates using the IS approach results in the best performance as the slopes of the regression lines are closer to the 1:1 line and there is a relatively good correlation of the data points i.e., average slope = 1.04 and average R^2 = 0.69.

4.1.3.2 Relative error

Figure 4-14 provides an example of a box and whisker plot of REs for the 1:20-year design flood estimates. Box and whisker plots for the other RIs can be found in Appendix B2. Table 4-11 provides a summary of the median REs for the original and adjusted SUH design flood estimates.

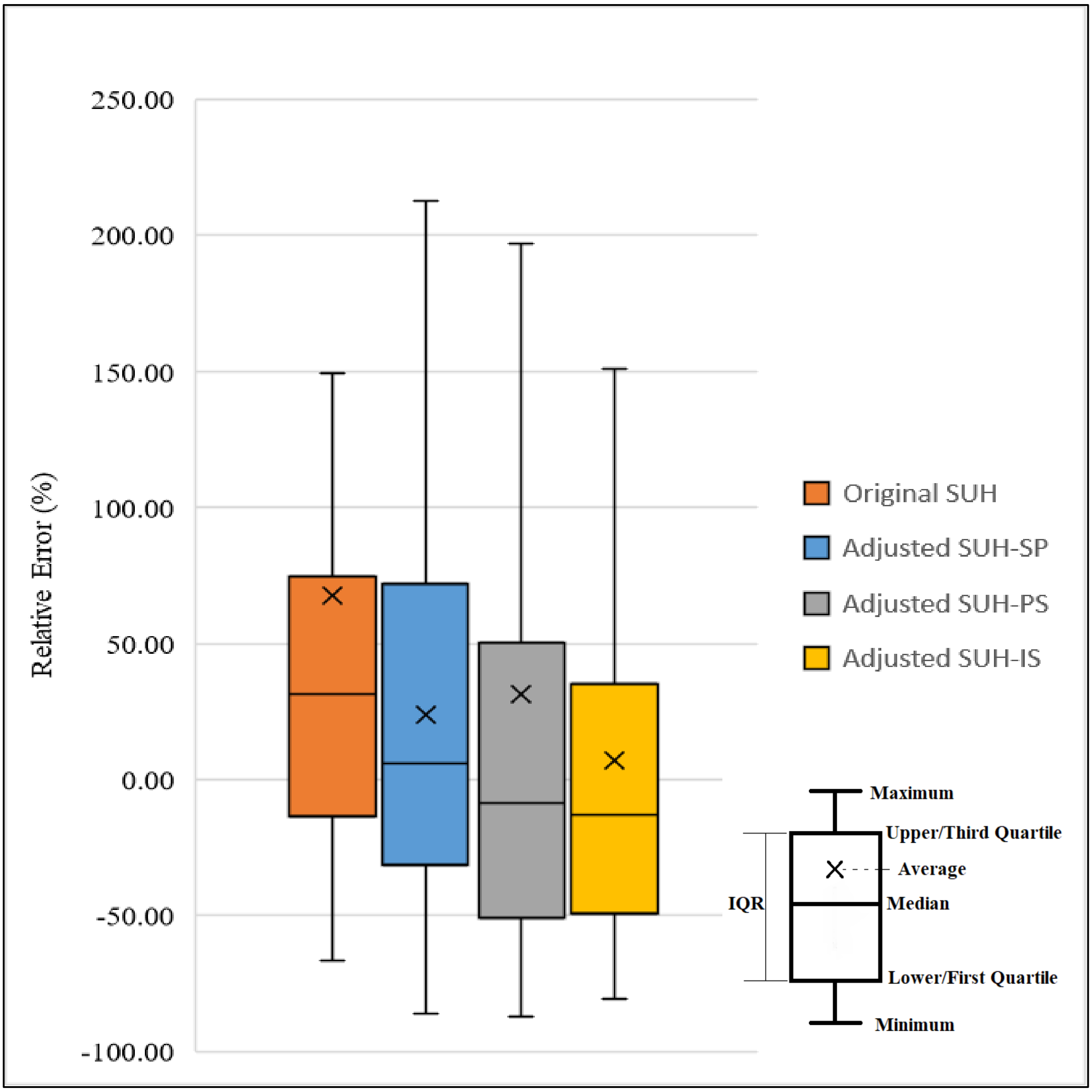

Figure 4-14 Box and whisker plot for the 1:20-year RI

Table 4-10 Summary of median relative errors for the original and adjusted SUH design flood estimates

Method	Median Relative Error (%)			
	Lowest Quartile (%)	Median (%)	Upper Quartile (%)	IQR (%)
$SUH_{original}$	-13.8	31.1	74.4	88.2
$SUH_{adjusted, SP}$	-31.5	6.5	72.2	103.7
$SUH_{adjusted, PS}$	-49.4	-8.7	50.4	99.8
$SUH_{adjusted, IS}$	-48.3	-11.4	33.9	82.2

It can be seen from Figure 4-14 and Table 4-11 that the RE values for the original SUH design flood estimates generally over-estimate, the median RE value being the largest at 31.1% and upper quartile of 74.4%. The adjusted SUH design flood estimates using the correction factors from the SP and PS approaches for donor catchment selection show an improvement in the median error compared to the original SUH median RE value, however, the IQR indicates an increase in the range of median REs. Based on the consistent improvement in both the median RE value and reduced IQR, the adjusted SDF design flood estimates using the IS approach performs the best.

4.1.3.3 Mean absolute relative error

Table 4-11, Figure 4-15, Figure 4-16 and Figure 4-17 below indicates the number and percentage of sites that experienced an improvement and poorer MAREs after application of the correction factors using the different approaches for donor catchment selection with the SUH method.

Table 4-11 Number of sites with improved and poorer MAREs after application of correction factors using the different approaches for donor catchment selection with the SUH method

Method	Number of Sites with Improved MAREs	Percentage of Sites with Improved MAREs	Number of Sites with Poorer MAREs	Percentage of Sites with Poorer MAREs
$SUH_{adjusted,\ SP}$	33/48	69%	15/48	31%
$SUH_{adjusted,\ PS}$	31/48	65%	17/48	35%
$SUH_{adjusted,\ IS}$	34/48	71%	14/48	29%

In terms of Table 4-11, the adjusted SUH design flood estimates perform the best using the IS approach with 34 (71%) of the 48 catchments experiencing an improvement in MARE of the design flood estimates followed closely by the SP approach with 33 (69%) of the 3848 catchments experiencing an improvement in MARE and then the PS approach with 31 (65%) of the 48 catchments experiencing an improvement. The improvements in MARE are fairly well distributed throughout the study area thus there is no specific veld type or area that can be associated with better performance.

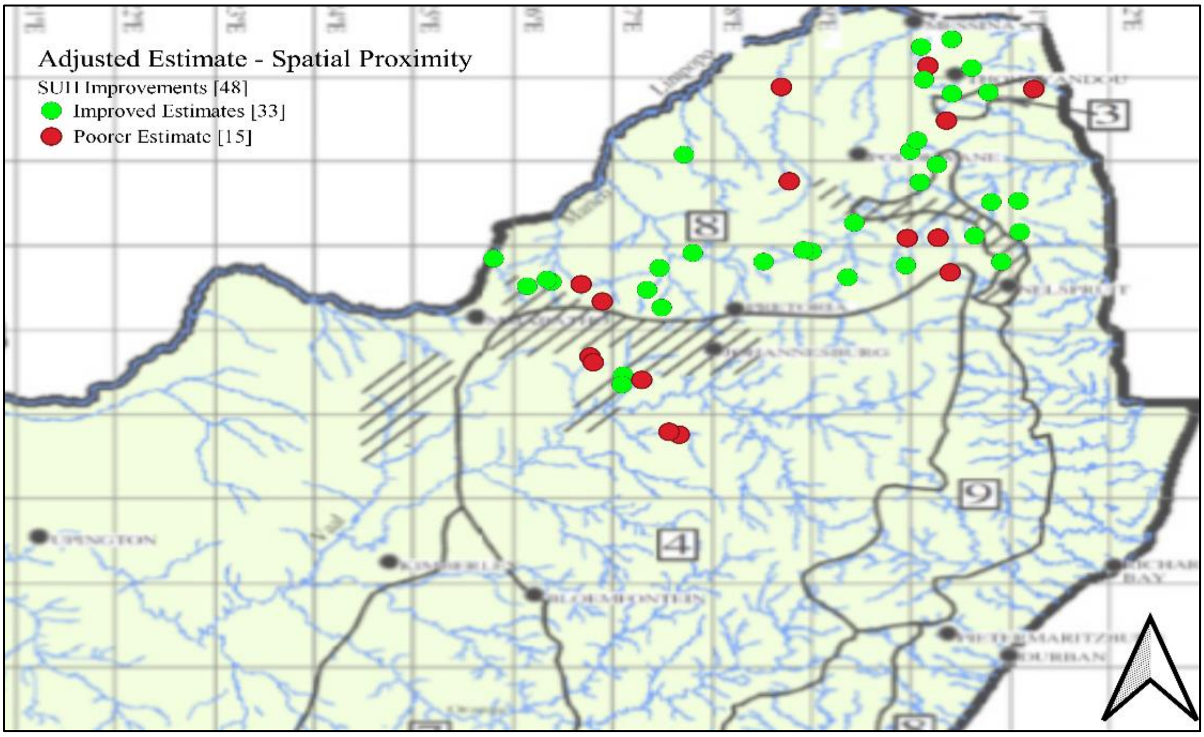

Figure 4-15 Sites with improved and poorer estimates in the various veld types using the SUH and SP approach

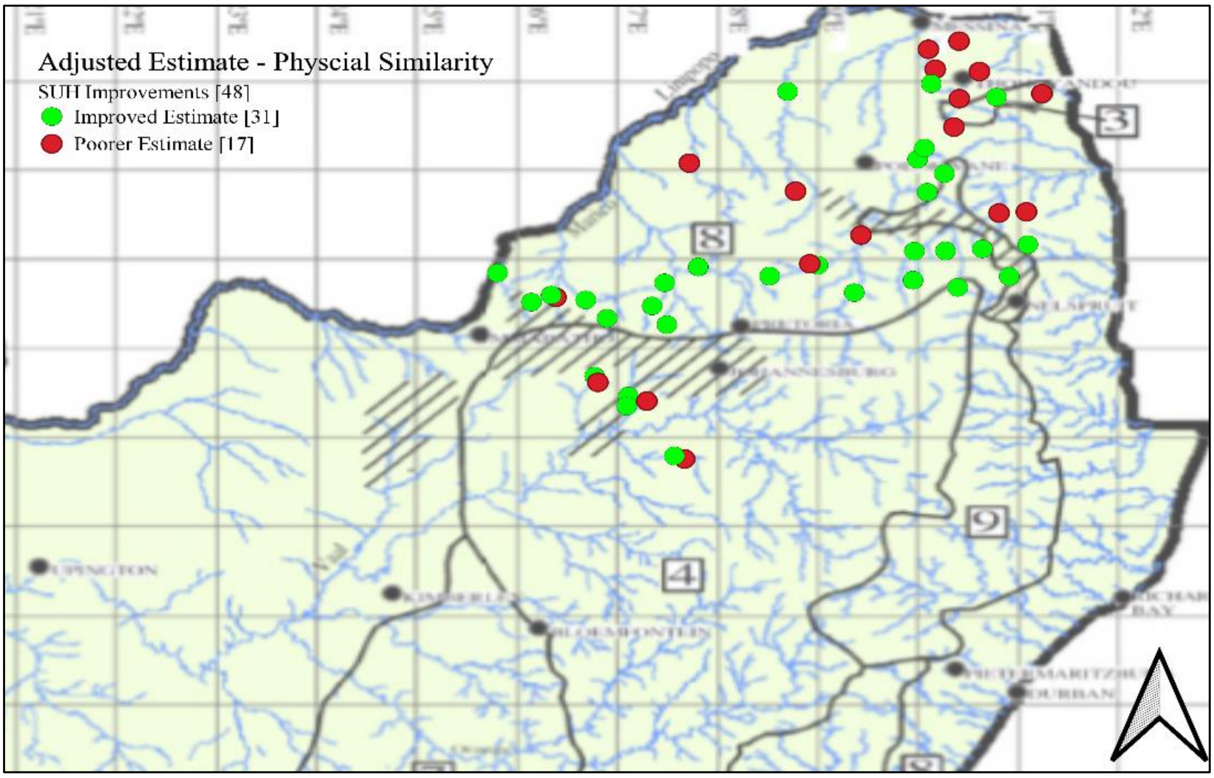

Figure 4-16 Sites with improved and poorer estimates in the various veld types using the SUH and PS approach

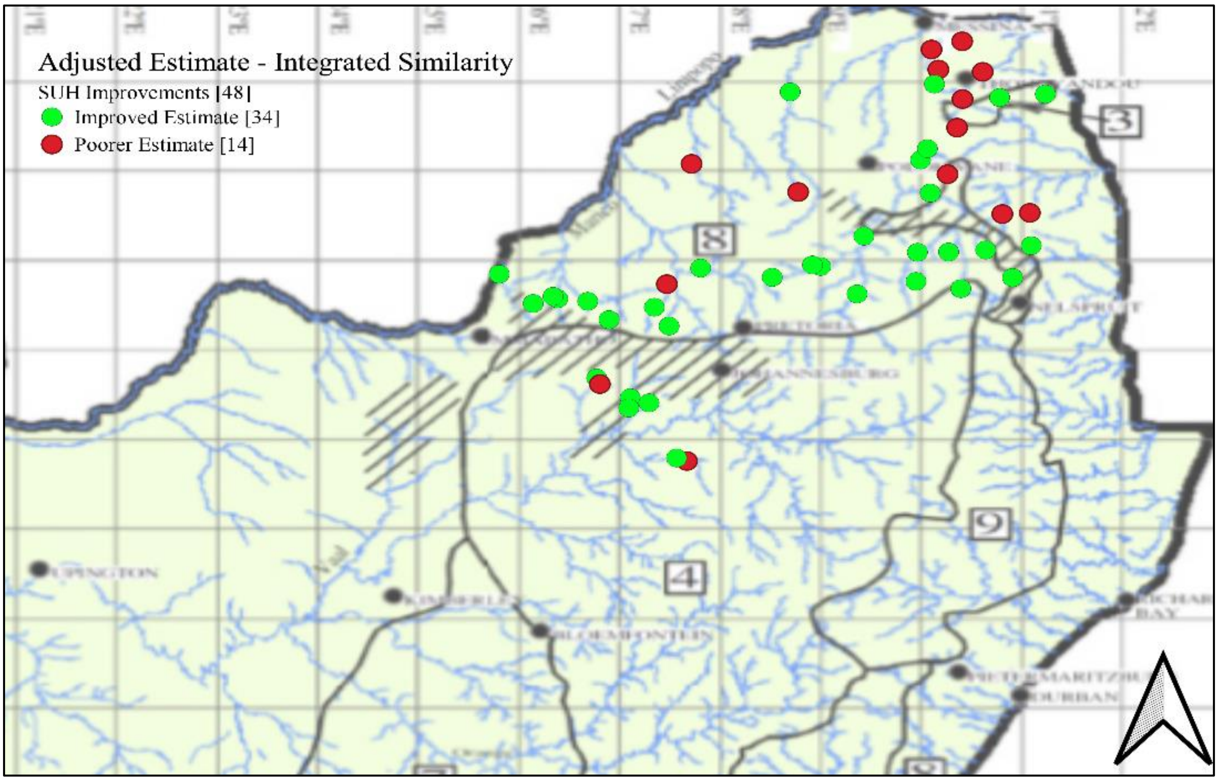

Figure 4-17 Sites with improved and poorer estimates in the various veld types using the SUH and IS approach

Figure 4-18 shows a box and whisker plot of the ΔMAREs where positive values indicate an improvement and negative values indicate poorer results.

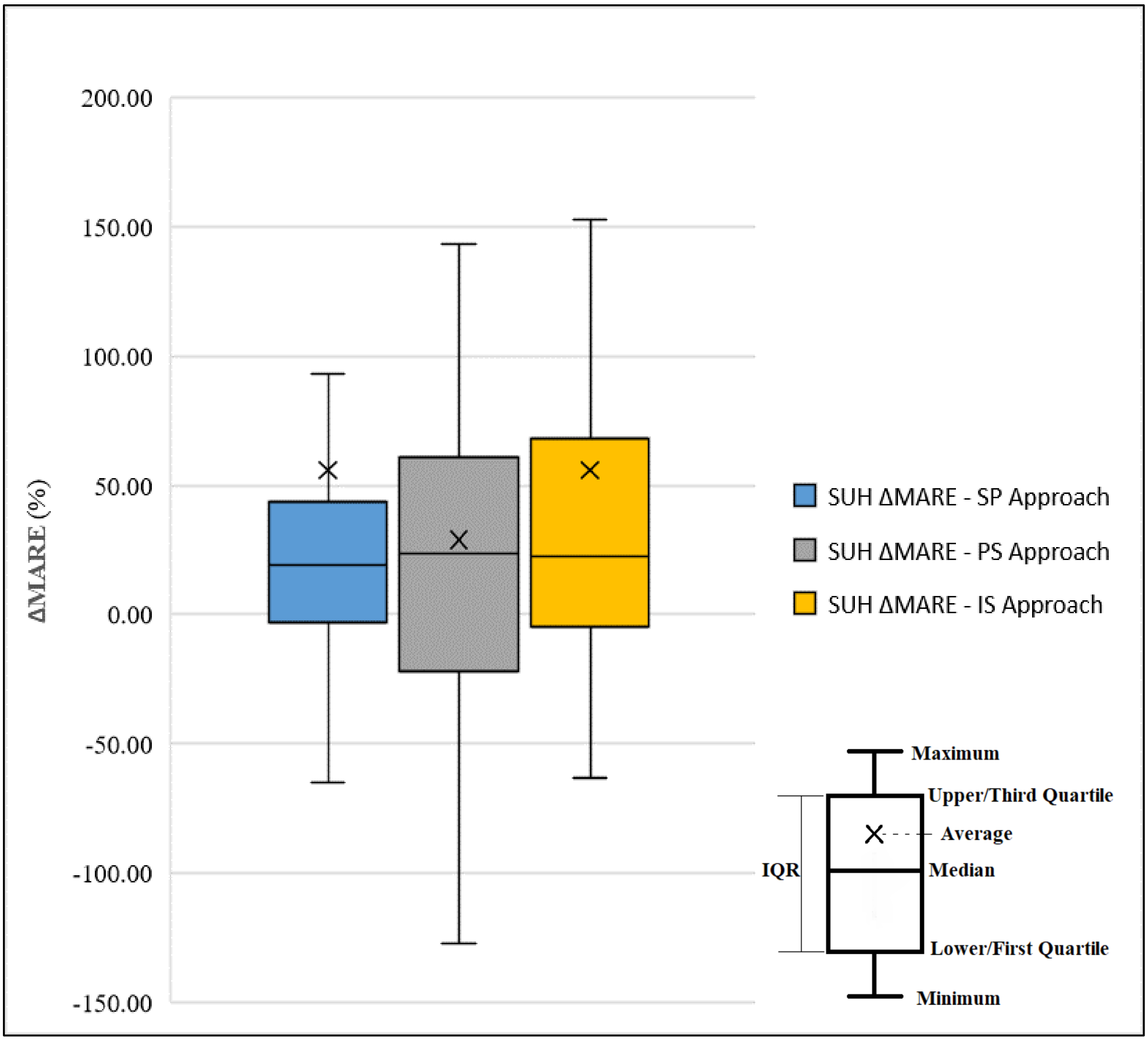

Figure 4-18 Box and whisker plot of ΔMAREs for the SUH method and various approaches for donor catchment selection

Figure 4-18 shows that the minimum values of ΔMARE i.e. poorer results are -65.10%, -127.39% and -63.50% for the SP, PS and IS approach, respectively. Thus, while the correction factors offer significant improvements for majority of the sites, it can be seen that there is significant under performance at the catchments experiencing poorer results.

4.1.3.4 Summary of results

Table 4-12 provides a summary and comparison of the various assessment criteria and their corresponding ranks relative to the approaches adjusted SUH estimates. The adjusted SUH estimates using the IS approach performs the best followed by the SP and PS approaches.

Table 4-12 Summary of assessment criteria and respective ranks based on the on the adjusted SUH estimates

Method	Average Slope	Rank	Average R^2	Rank	Median RE (%)	Rank	Median RE IQR (%)	Rank	Catchments with Improved MARE (%)	Rank	Min Δ MARE (%)	Rank	Sum of Ranks	Final Rank
$SUH_{adjusted, SP}$	0.85	3.00	0.84	1.00	6.53	1.00	103.65	3.00	69%	2.00	-65.10	2.00	12.00	2.00
$SUH_{adjusted, PS}$	0.95	2.00	0.84	1.00	-8.72	2.00	99.79	2.00	65%	3.00	-127.39	3.00	13.00	3.00
$SUH_{adjusted, IS}$	***1.04***	***1.00***	***0.69***	***3.00***	***-11.43***	***3.00***	***82.19***	***1.00***	***71%***	***1.00***	***-63.50***	***1.00***	***10.00***	***1.00***

4.1.4 HRU 1/71 Method

This section covers the results for the HRU 1/71 method after using the various techniques for information transfer to adjust design flood estimates using correction factors as was done for the SDF method in Section 4.1.1.

4.1.4.1 Scatter plots

Figure 4-19 provides an example of a scatter plot for the 1:20 year RI. Scatter plots for various RIs are shown in Appendix C1. A summary of the slopes and R^2 values are shown in Table 4-13 for the 2 to 200-year RIs as well as the average values.

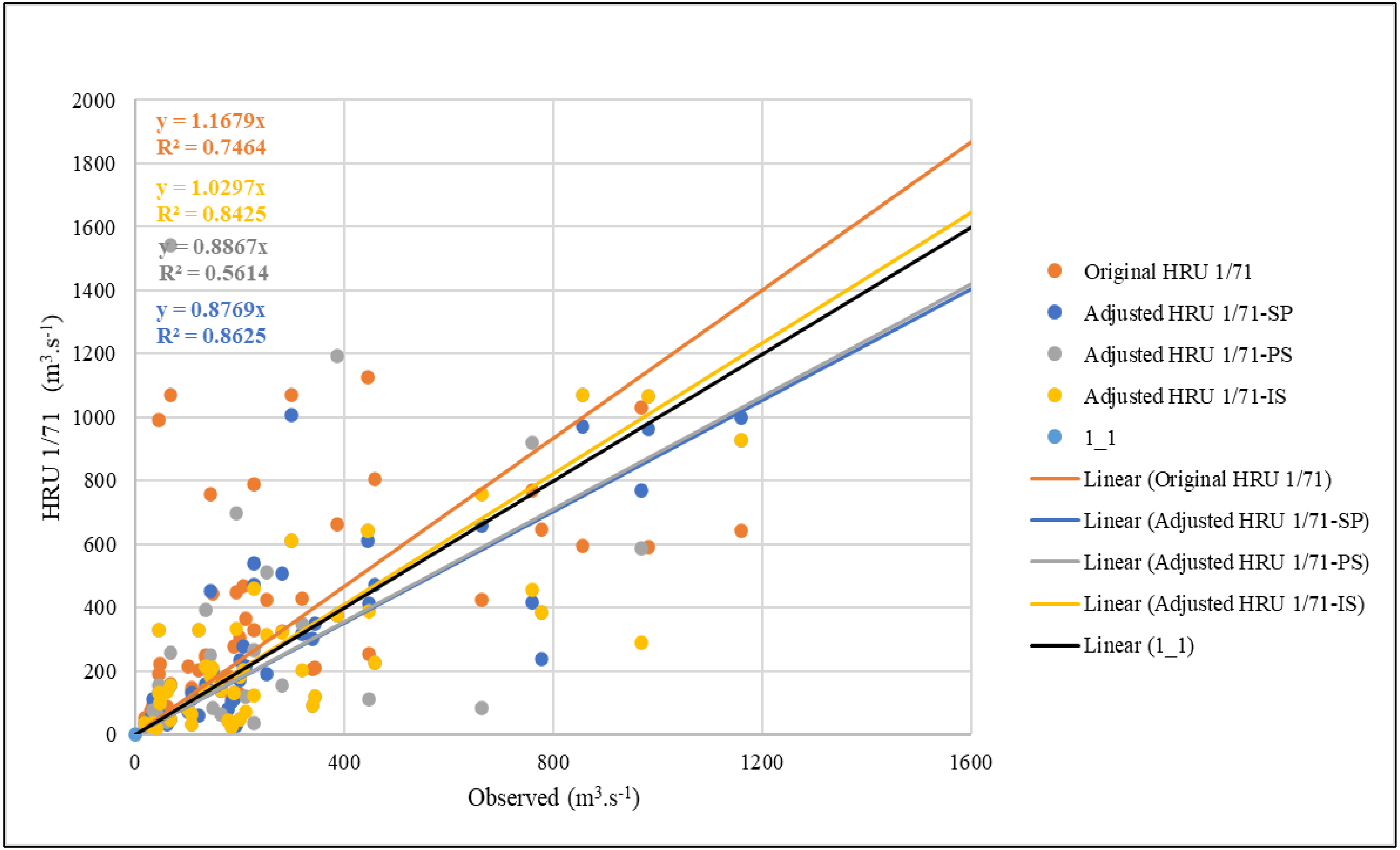

Figure 4-19 Scatter plot for the HRU 1/71 method for the 1:20 year RI

Table 4-13 Summary of regression line slopes and R^2 values for the original and adjusted HRU 1/71 design flood estimates for the various RIs

Method		1:2	1:5	1:10	1:20	1:50	1:100	1:200	Average	Median
HRU1/71$_{original}$	Slope	1.41	1.29	1.20	1.17	1.17	1.18	1.19	1.23	1.19
	R^2	0.70	0.74	0.74	0.75	0.76	0.76	0.77	0.75	0.75
HRU1/71$_{adjusted,SP}$	Slope	0.85	0.80	0.83	0.88	0.92	0.94	0.95	0.88	0.88
	R^2	0.82	0.84	0.84	0.86	0.87	0.88	0.88	0.86	0.86
HRU1/U71$_{adjusted,PS}$	Slope	1.12	0.95	0.93	0.89	0.85	0.83	0.81	0.91	0.89
	R^2	0.54	0.55	0.57	0.56	0.55	0.54	0.53	0.55	0.55
HRU1/71$_{adjusted,IS}$	Slope	1.15	1.03	1.03	1.03	1.03	1.02	1.00	1.04	1.03
	R^2	0.74	0.8	0.83	0.84	0.84	0.83	0.82	0.81	0.83

It can be seen from Figure 4-19 and Table 4-13 that the original HRU 1/71 method generally over-estimates design flood estimates by a factor of 1.41 to 1.19 depending on the RI. Based on the slopes and R^2 values it is evident that the adjusted design flood estimates using the different approaches offer improvements as the slopes are closer to 1 with the IS approach performing the best. Both the SP and PS approach generally slightly under-estimate design floods, however, the SP approach produces a better correlation.

4.1.4.2 Relative error

Figure 4-20 provides an example of a box and whisker plot of REs for the 1:20-year design flood estimates. Box and whisker plots for the other RIs can be found in Appendix C2. Table 4-14 provides a summary of the median REs for the original and adjusted HRU 1/71 design flood estimates.

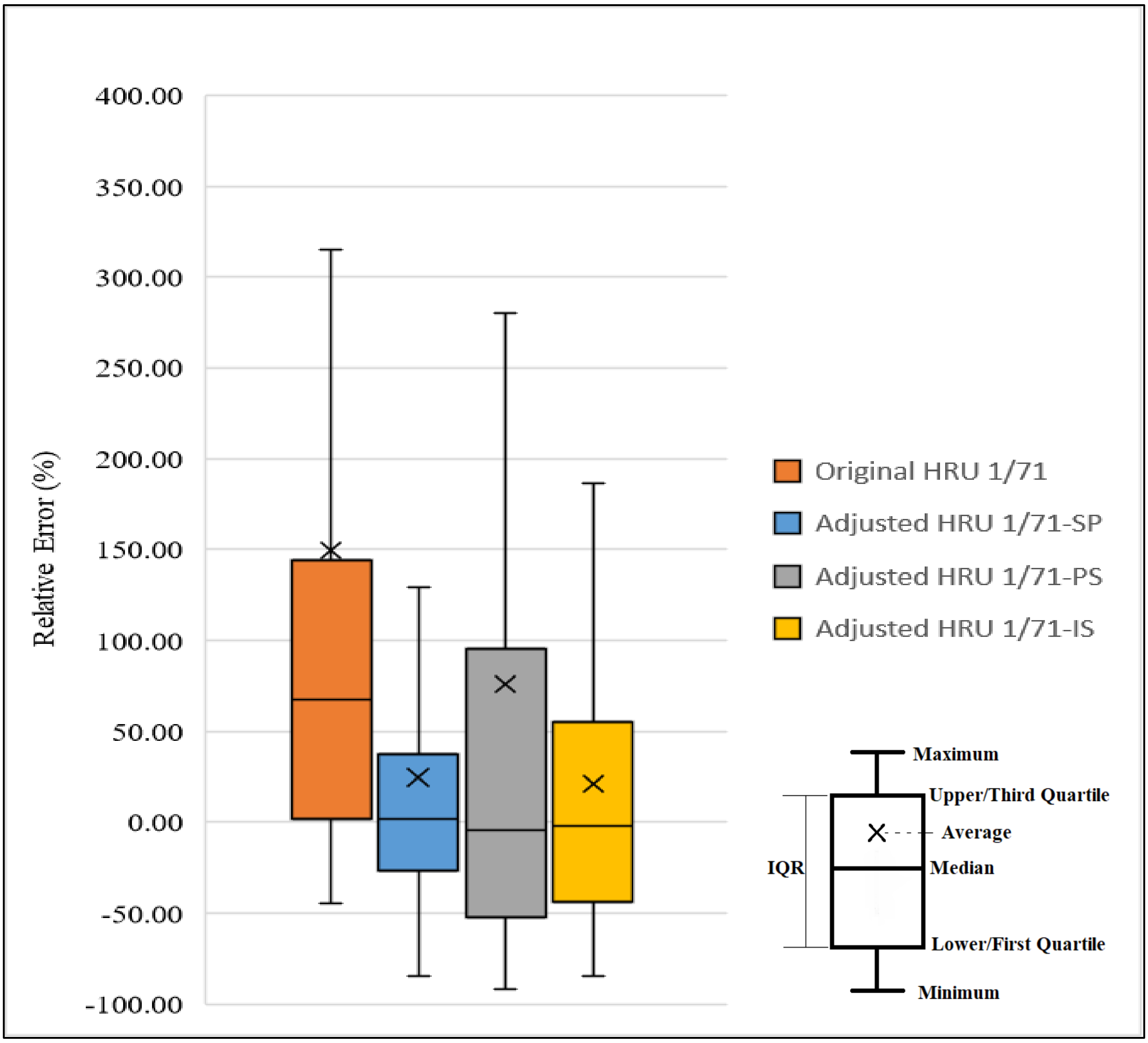

Figure 4-20 Box and whisker plot for the 1:20-year RI

Table 4-14 Summary of median relative errors for the original and adjusted HRU1/71 design flood estimates

Method	Median Relative Error (%)			
	Lowest Quartile (%)	Median (%)	Upper Quartile (%)	IQR (%)
HRU 1/71$_{original}$	1.9	67.8	143.8	141.9
HRU 1/71$_{adjusted, SP}$	-27.0	1.5	37.2	64.2
HRU 1/71$_{adjusted, PS}$	-52.1	-4.2	95.0	147.0
HRU 1/71$_{adjusted, IS}$	-43.6	-2.4	55.0	98.6

From Figure 4-20 and Table 4-14 it can be seen that the REs of the original HRU 1/71 indicate general over-estimation of design flood estimates with a median and upper quartile RE of

67.80% and 143.8% respectively. The adjusted HRU 1/71 REs show an improvement when using the SP and IS approach. The SP approach performs the best compared to the different approaches for donor catchment selection with a median RE of 1.5% as well as a significant reduction in IQR from 141.9 % for the original method to 64.2% for the SP adjusted approach. This is followed by the IS approach. The adjusted HRU 1/71 REs using the PS perform the worst as IQR increased to 147.0%.

4.1.4.3 Mean absolute relative error

Table 4-15, Figure 4-21, Figure 4-22 and Figure 4-23 indicates the number and percentage of sites that experienced an improvement and poorer MAREs after application of the correction factors using the different approaches for donor catchment selection with the HRU 1/71 method.

Table 4-15 Number of sites with improved and poorer MAREs after application of correction factors using the different approaches for donor catchment selection with the HRU 1/71 method

Method	Number of Sites with Improved MAREs	Percentage of Sites with Improved MAREs	Number of Sites with Poorer MAREs	Percentage of Sites with Poorer MAREs
HRU $1/71_{\text{adjusted, SP}}$	39/48	81%	9/48	19%
HRU $1/71_{\text{adjusted, PS}}$	25/48	52%	23/48	48%
HRU $1/71_{\text{adjusted, IS}}$	34/48	71%	14/48	29%

In terms of , the adjusted HRU 1/71 design flood estimates perform the best using the SP approach with 39 (81%) of the 48 catchments experiencing an improvement in MARE of the design flood estimates followed by the IS approach with 34 (71 %) of the 48 catchments experiencing an improvement in MARE and then the PS approach with 25 (52%) of the 48 catchments experiencing an improvement. As per the previous methods, there is also no clear evidence of spatial patterns as the catchments with improved and poorer MAREs are scattered throughout the study area.

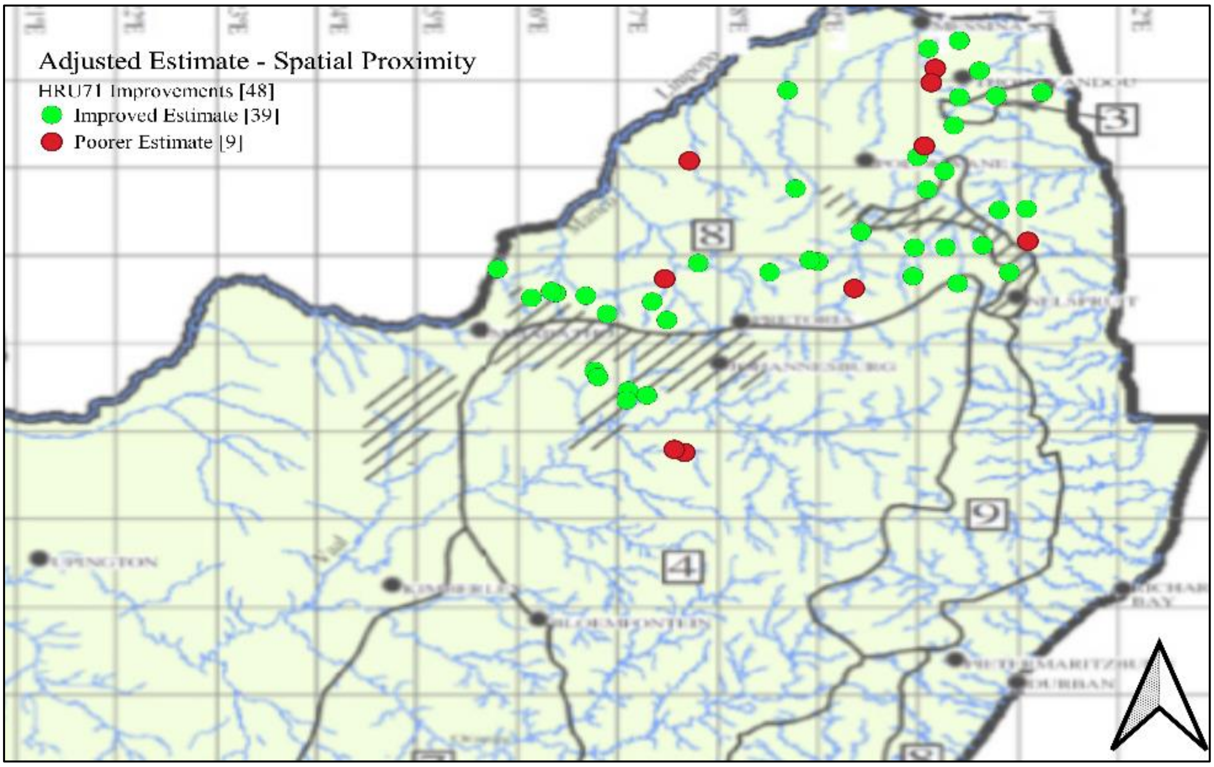

Figure 4-21 Sites with improved and poorer estimates in the various veld types using the HRU 1/71 and SP approach

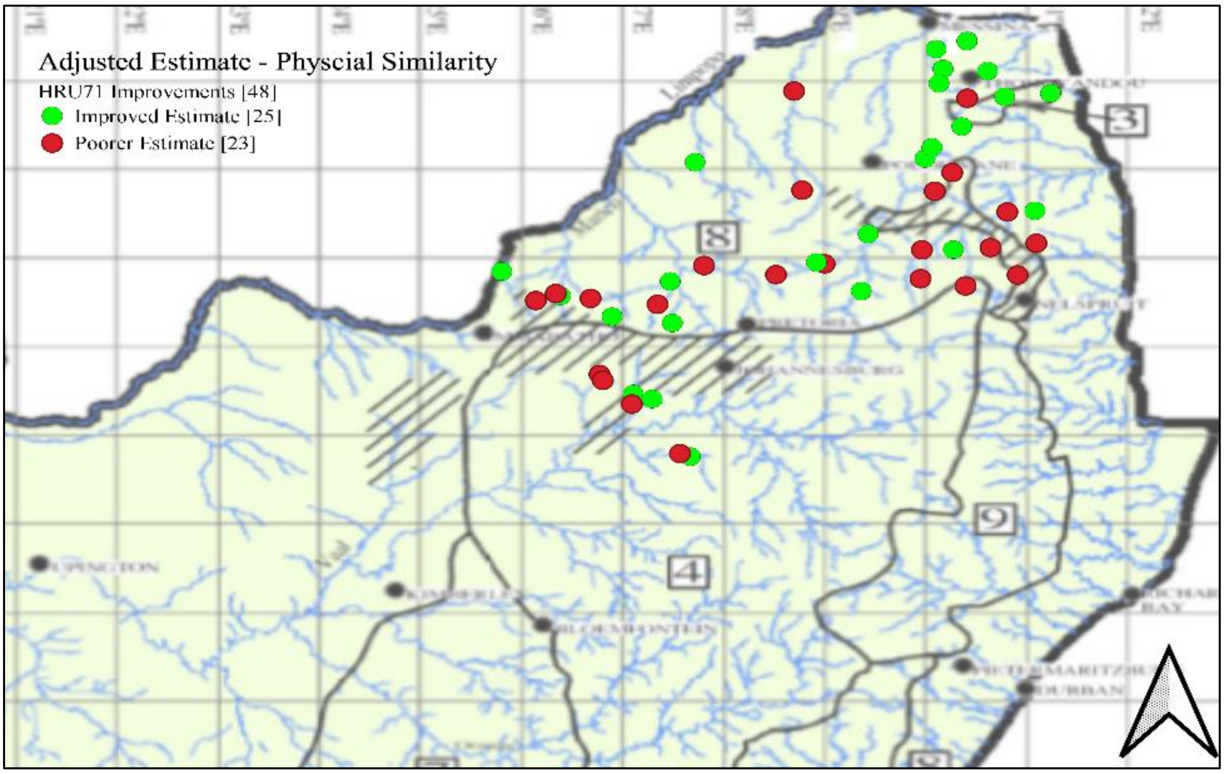

Figure 4-22 Sites with improved and poorer estimates in the various veld types using the HRU 1/71 and PS approach

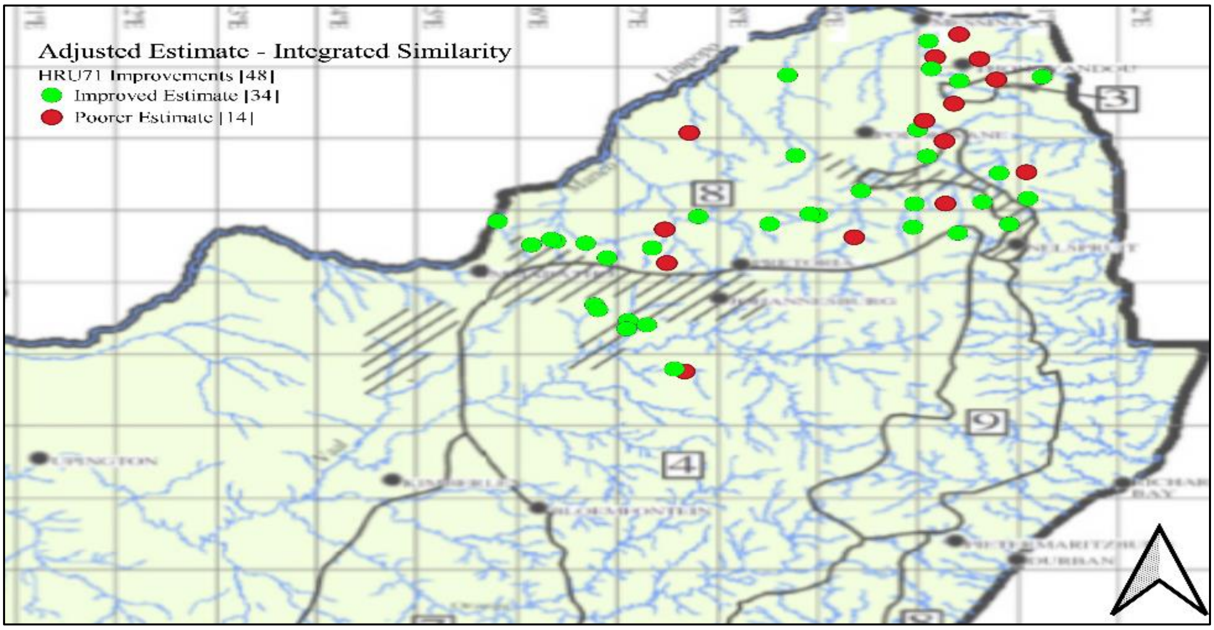

Figure 4-23 Sites with improved and poorer estimates in the various veld types using the HRU 1/71 and IS approach

Figure 4-24 below shows a box and whisker plot of the ΔMAREs where positive values indicate an improvement and negative values indicate poorer results.

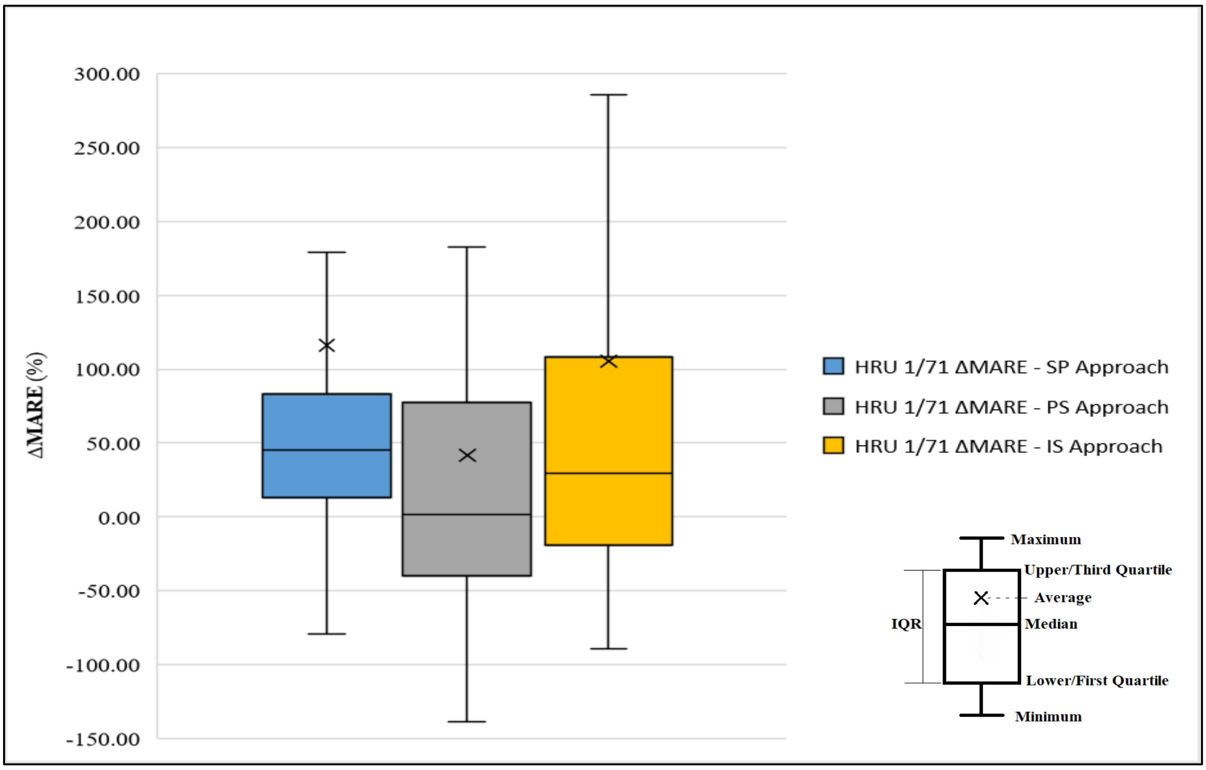

Figure 4-24 Box and whisker plot of ΔMAREs for the HRU 1/71 method and various approaches for donor catchment selection

Figure 4-24 shows that the minimum values of ΔMARE i.e. poorer results are -79.43%, -138.49% and -89.13% for the SP, PS and IS approach, respectively. Thus, while the correction factors offer significant improvements for majority of the sites, it can be seen that there is significant under performance at the catchments experiencing poorer results.

4.1.4.4 Summary of results

Table 4-16 provides a summary and comparison of the various assessment criteria and their corresponding ranks relative to the approaches used for the adjusted HRU 1/71 estimates. The adjusted HRU 1/71 estimates using local information transfer from the IS approach performs the best followed by the SP and PS approaches.

Table 4-16 Summary of assessment criteria and respective ranks based on the on the adjusted HRU 1/71 estimates

Method	Average Slope	Rank	Average R^2	Rank	Median RE (%)	Rank	Median RE IQR (%)	Rank	Catchments with Improved MARE (%)	Rank	Min Δ MARE (%)	Rank	Sum of Ranks	Final Rank
HRU 1/71$_{adjusted, SP}$	*0.88*	*3.00*	*0.86*	*1.00*	*1.51*	*1.00*	*64.2*	*1.00*	*81*	*1.00*	*-79.43*	*1.00*	*8.00*	*1.00*
HRU 1/71$_{adjusted, PS}$	0.91	2.00	0.55	3.00	-4.20	3.00	147.04	3.00	52	3.00	-138.49	3.00	17.00	3.00
HRU 1/71$_{adjusted, IS}$	1.04	1.00	0.81	2.00	-2.36	2.00	98.61	2.00	71	2.00	-89.13	2.00	11.00	2.00

4.1.5 Overview: Single donor catchment

This section provides an overview of the adjusted flood estimates for the various DFE methods performance using a single donor catchment based the SP, PS and IS approach. Table 4-17 below shows the performance of the various approaches for donor catchment selection in terms of their final rank and the number of catchments with improved estimates. The SDF method experiences the best improvements using the PS approach while the RM and HRU 1/71 experiences the best improvements using the SP approach and the SUH experiences the best improvements using the IS approach. Even though the best performing donor catchment selection approach differs for each DFE method, the IS approach performs consistently with all methods as it is generally ranked 2 and it improves more than 63% of the sites for all DFE methods.

Table 4-17 Overview of the performance of Single Donor Catchment Approaches

DFE Method	Approaches to Single Donor Catchment Selection					
	SP		PS		IS	
	Final Rank	Catchments with Improved MARE (%)	Final Rank	Catchments with Improved MARE (%)	Final Rank	Catchments with Improved MARE (%)
SDF	3	58	1	63	2	63
RM	1	58	3	38	2	71
SUH	2	69	3	65	1	71
HRU 1/71	1	81	3	52	2	71

4.2 Multiple Donor Catchments

The previous sections contain the results of information transfer from a single donor catchment using three approaches for donor catchment selection. This section contains the results from using information transfer from multiple nearest donor catchments using the procedure and methodology detailed in Sections 3.2.4 and 3.4.3. The aim of this part of the study was to determine the optimum number of donor catchments for information transfer when using multiple nearest neighbouring catchments. The correction factors were calculated by using an output averaging technique using Equation 3.2. In addition, median correction factors from the multiple donor catchments were also used for information transfer. The performance of the two techniques of calculating correction factors are compared. The sections below present the results of information transfer from multiple donor catchments per method.

4.2.3 Standard Design Flood

The original SDF estimates were adjusted using correction factors determined from multiple donor catchments. In order to obtain general trends, the ΔMARE was calculated across the various RIs for each site. Figure 4-25 shows a plot of ΔMARE versus number of donor catchments. Positive values of ΔMARE and a rising trend indicate improvements while negative values and a downward trend indicate worsening of the MARE.

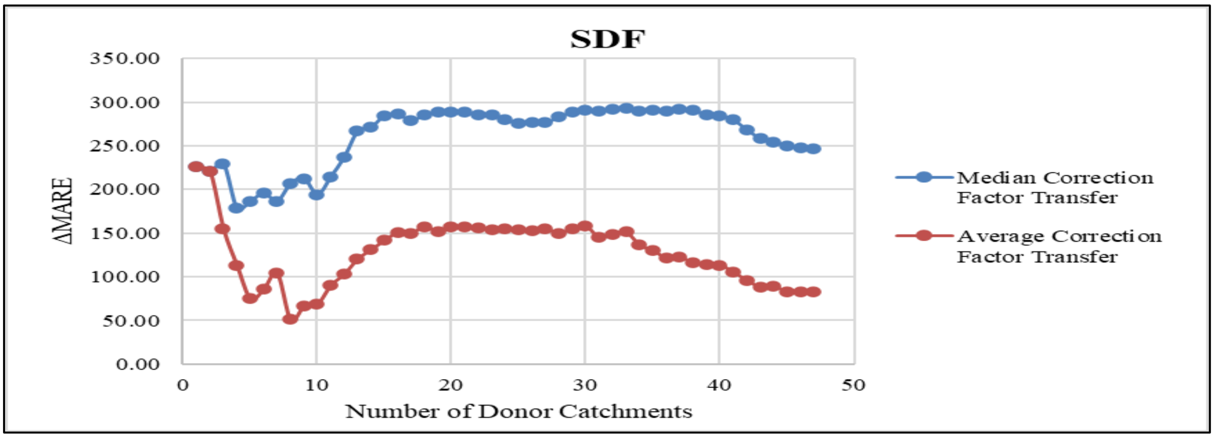

Figure 4-25 ΔMAREs of original and adjusted SDF estimates using multiple donor catchments

There are a number of observations that can be made from Figure 4-25. Firstly, the ΔMAREs using the median correction factors perform better than method transferring average correction factors. Secondly, the ΔMAREs using the average correction factor transfer performs best when using 1 donor catchment and increasing the number of donor catchments does not offer further improvements. Furthermore, the ΔMAREs using the median correction factors show an improvement after increasing the number of donor catchments. A closer look at Figure 4-25 shows that the optimum number of donors using the median correction factors for the SDF method is about 16 donor catchments which improve the ΔMAREs from 220.37% to 286.18%, after which there are no significant improvements.

4.2.4 Rational Method

This section covers results of using multiple donor catchments to adjust estimates using the RM. Figure 4-26 shows a plot of ΔMARE versus number of donor catchments.

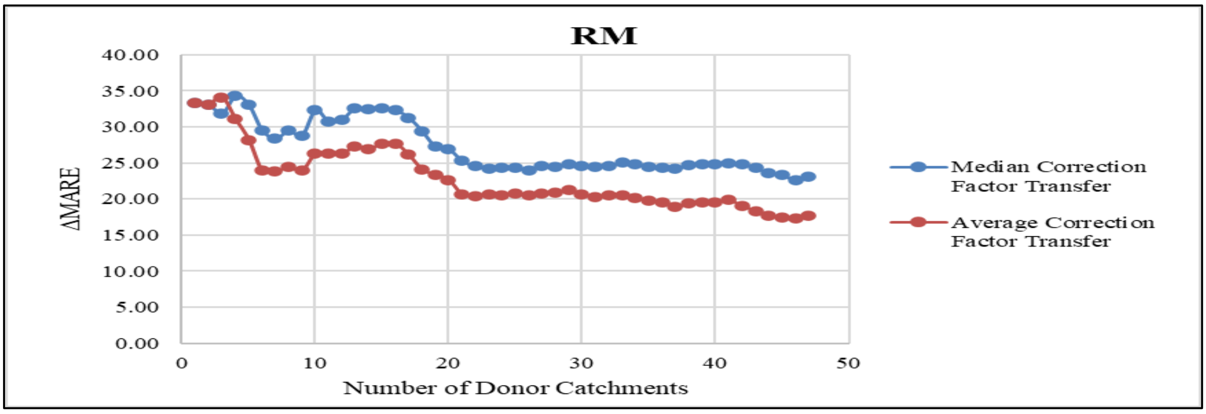

Figure 4-26 ΔMAREs of original and adjusted RM estimates using multiple donor catchments

It can be seen in Figure 4-26 that the median correction factor performs slightly better than average correction factor approach when adjusting the RM estimates. The average correction factor performs best with 3 donor catchments with a ΔMARE of 34.13% as opposed to a ΔMARE of 33.35% using a single donor catchment. The median correction factor perform bests using 4 donor catchments with a ΔMARE of 34.30% as opposed to a ΔMARE of 33.35% using a single donor catchment. The improvements using multiple donor catchments offered in both cases are small compared to using a single nearest donor catchment.

4.2.5 Synthetic Unit Hydrograph

This section covers results of using multiple donor catchments to adjust estimates using the SUH method. Figure 4-27 shows a plot of ΔMARE versus number of donor catchments.

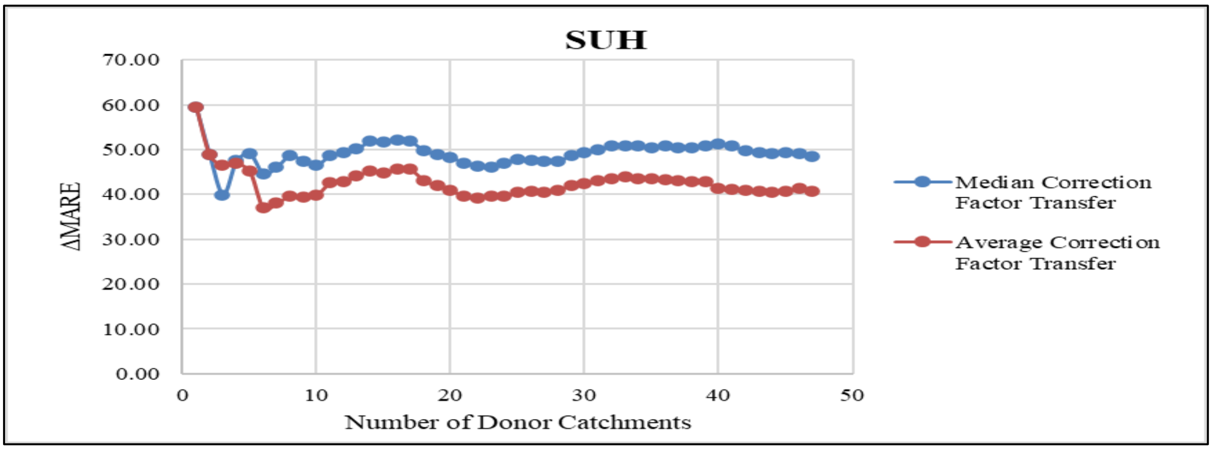

Figure 4-27 ΔMAREs of original and adjusted SUH method estimates using multiple donor catchments

Figure 4-27 shows that the median correction factor performs slightly better than average correction factor approach when using multiple donor catchments to adjust the SUH estimates. However, in both cases, the adjusted estimates perform best when using a single nearest donor catchment as opposed to using multiple donor catchments.

4.2.6 HRU 1/71

This section covers results of using multiple donor catchments to adjust estimates using the HRU 1/71 method. Figure 4-27 shows a plot of ΔMARE versus number of donor catchments.

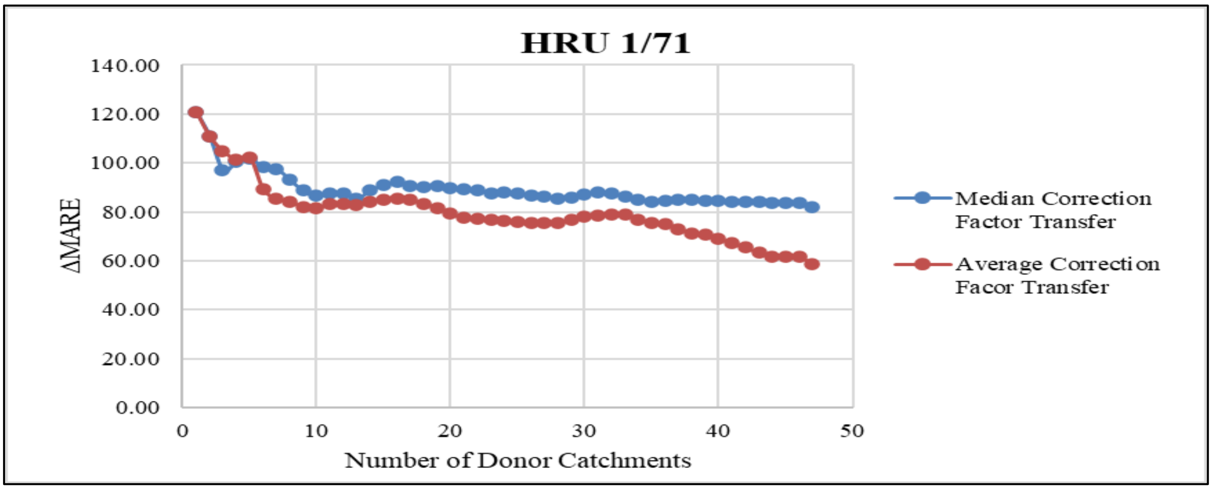

Figure 4-28 ΔMAREs of original and adjusted HRU 1/71 method estimates using multiple donor catchments

Figure 4-27 shows that the median correction factor performs slightly better than average correction factor approach when using multiple donor catchments to adjust the SUH estimates. Similar to the RM and SUH, in both cases, the adjusted estimates perform best when using a single nearest donor catchment as opposed to using multiple donor catchments.

4.2.7 Overview: Multiple donor catchments

This section provides an overview of the adjusted flood estimates for the various DFE methods performance using multiple donor catchments.

Table 4-18 Overview of the performance of single donor catchment approaches

DFE Method	Optimum Number of Donors	Correction Factor Method
SDF	16	Median
RM	4	Median
SUH	1	Not Applicable
HRU 1/71	1	Not Applicable

Table 4-18 above shows best correction factor method i.e. average or median (Equation 3.2), and optimum donor catchments when using multiple nearest donor catchments. The SDF method experiences the best improvements using median correction factor and 16 nearest donors. The RM performs the best when using the median correction factor and 4 nearest donor catchments, though the improvements observed were relatively small. Both the SUH and HRU 1/71 showed no improvements when using multiple nearest donor catchments when compared to using a single nearest donor catchment.

The following chapter will provide a summarised discussion and concluding remarks on the results of the study using single and multiple donor catchments.

5 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

The study entailed the evaluation of the use of local information from donor catchments to improve design flood estimates calculated from selected deterministic and empirical methods for 48 sites located in the North-Eastern part of South Africa. Synthesised dam inflow series were used as these are deemed to be more accurate and reliable than weir gauged flows by the Department of Water and Sanitation (DWS), Flood Studies Group (Naidoo, 2000). The selected deterministic and empirical methods included the Standard Design Flood (SDF), Rational Method (RM), Synthetic Unit Hydrograph (SUH) and HRU 1/71 methods. This chapter contains a discussion of the results, concludes on the aim and objectives of the study and includes recommendations on possible further research and extension of the study.

5.1 Discussion and Conclusions

The **first objective** of the study required a review of literature containing information on the performance of existing Design Flood Estimation (DFE) methods in South Africa. Chapter 2, Section 2.1 provided details of the current techniques used in South Africa for DFE such as governing principles, application, and limitations. Recent studies by numerous authors have shown shortcomings, poor performance and a lack of regional trends in performance associated with each of the methods. This highlighted the need for improved techniques for flood estimation and thus led to the development of the NFSP and this particular research project.

Objective 2 was to review international literature on the use of local information transfer to improve flood estimates from existing methods. Chapter 2, Section 2.1 contains a summary and synthesis of studies from the UK, Australia, USA, and France covering the types of information transferred from donor catchments, approaches for selecting donor catchments and the use of multiple donor catchments. The literature provided insight and evidence that the use of local information from donor catchments can successfully improve estimates.

Objective 3 involved the development of a methodology for using local information transfer with existing DFE methods. Chapter 3 details a methodology of determining correction factors based on a ratio of design floods estimated from the selected deterministic and empirical methods and from observed data. Further to this, the chapter also details the selection of donor catchments based on three different approaches, i.e. SP, PS and IS.

Objective 4 of the study was to determine the performance of the selected deterministic and empirical methods before and after applying correction factors based on local information transfer from donor catchments using the different approaches for donor catchment selection i.e. SP, PS, and IS. The performance was assessed by evaluating the slopes and R^2 values of the trendlines of scatter plots; median REs and IQRs of box plots; and MAREs before and after applying the correction factors. The results of the three approaches were ranked in terms of the assessment criteria to determine which approach performed the best with each DFE method. The first stage of the assessment was used to establish the performance of the original DFE methods. The results showed that the original methods resulted in relatively large errors. This further confirms the results from the other studies reviewed in Chapter 2.

When using a single donor catchment approach and applying the correction factors, the SDF method experienced the best improvement with the PS approach. The IQR of the median REs decreased from 554.6% to 161.7% and the median RE decreased from 112.1% to 2.2% across the different RIs. The original RM performed relatively well before application of the correction factors. The RM performed the best in terms of improvements using the correction factors from the SP approach with a slight reduction in the range of median REs from 90.5% to 81.7% amongst improvements in the other criteria. Similar to the RM, the original SUH method also performed relatively well based on the assessment criteria. The adjusted SUH estimates using the IS approach ranked first with slight improvements in the IQR from 88.2% to 82.2%. The correction factors based on the SP approach performed the best with the HRU 1/71 method. The adjusted HRU 1/71 method using the SP approach showed a large improvement and ranked first for all of the assessment criteria.

Thus, the best approach for the selection of suitable donor catchments varied for each of the DFE methods. This can be expected as the selected DFE methods in this study varied in terms of input parameters, information used to develop each method and different homogenous regions, i.e. SDF basins and veld zones. However, the quantum and quality of the improvements vary amongst the DFE methods, for example, the adjusted SDF and HRU 1/71 methods experienced more notable improvements than the adjusted RM and SUH method.

It can also be noted that the methods with the highest original error showed the most notable improvement when using local information transfer from single donor catchments i.e. HRU 1/71 and SDF. This could possibly have resulted from the limited local information used in the development of the original methods.

Objective 5 involved determining the best approach for donor catchment selection. Based on the results and findings of Objective 4, the SDF method performed the best using the PS approach while both the RM and HRU 1/71 method performed the best using the SP approach. The SUH method performed the best using the IS approach. Furthermore, the IS approach consistently performed well for the SDF, RM and HRU 1/71 methods with improvements between 63% and 71% of the sites.

Objective 6 was to determine the optimum number of donor catchments using multiple nearest donor catchments. The assessment undertaken and presented in Section 4.2 illustrates that the optimum number of donor catchments differed per DFE method using to the two different transfer approaches i.e. average correction factor transfer and median correction factor transfer. In general, the results showed that the median correction factor transfer performed better than the average correction factor transfer. The optimum number of donor catchments for the SDF and RM using the median correction factor transfer was 16 and 4 donor catchments, respectively. It should be also noted that, although the RM showed improvements using 4 donor catchments, the improvements are less significant compared to using 1 donor catchment. The SUH and HRU 1/71 did not show any further improvements using multiple nearest donor catchments. According to Zhang and Chiew (2009) and as presented in previous studies, it is likely that the optimum number of donors will vary for different approaches and models.

Thus, it can be seen from the results, that the methodology presented in this study for a simple approach using local information from donor catchments has the potential to offer improvements for estimating design floods using various DFE methods.

5.2 Recommendations

While the study has shown promising results for improving the selected DFE methods using local information transfer from donor catchments, there still remains further scope for future research on this topic. Hence, the following should be considered as recommendations for future investigations:

(a) **Original DFE methods:** The original selected DFE methods used in this study showed inconsistencies and inaccuracies based on the REs and MAREs when compared to at-site FFA, thus highlighting the need for updating of these methods or the development of more reliable methods.

(b) **Number of Sites:** The pilot study included 48 sites in the north eastern portion of South Africa. Therefore, consideration should be given to increasing the number of sites (reliable dam and weir sites) and expanding the study area across the country in order to evaluate the results at a national scale.

(c) **Correction Factors:** The correction factors determined in this particular study using donor catchments were calculated for each RI. Consideration can be given to calculating an average correction factor across the various RIs for information transfer from donor to target catchments.

(d) **Selected DFE methods:** The study considered four selected DFE methods, namely, the SDF, RM, SUH and HRU 1/71. The results showed that certain approaches for donor catchment selection performed better for certain DFE methods. Other DFE methods should be investigated using the methodology proposed in this particular study.

(e) **Physical and Integrated Similarity approaches:** The PS and IS approaches for donor catchment selection used for single donor catchment transfer considered various catchment attributes where each attribute was given an equal weighting. Further investigation should be considered to assign specific weights to each attribute based on their influence on runoff/catchment response to determine catchment similarity.

(f) **Multiple Donor Catchments:** The multiple donor catchments considered the nearest donor catchments thus, relying on the proximity of donor catchments to the target catchment. The multiple donor catchment approach can be used by also considering the PS and IS instead of the nearest donor catchments.

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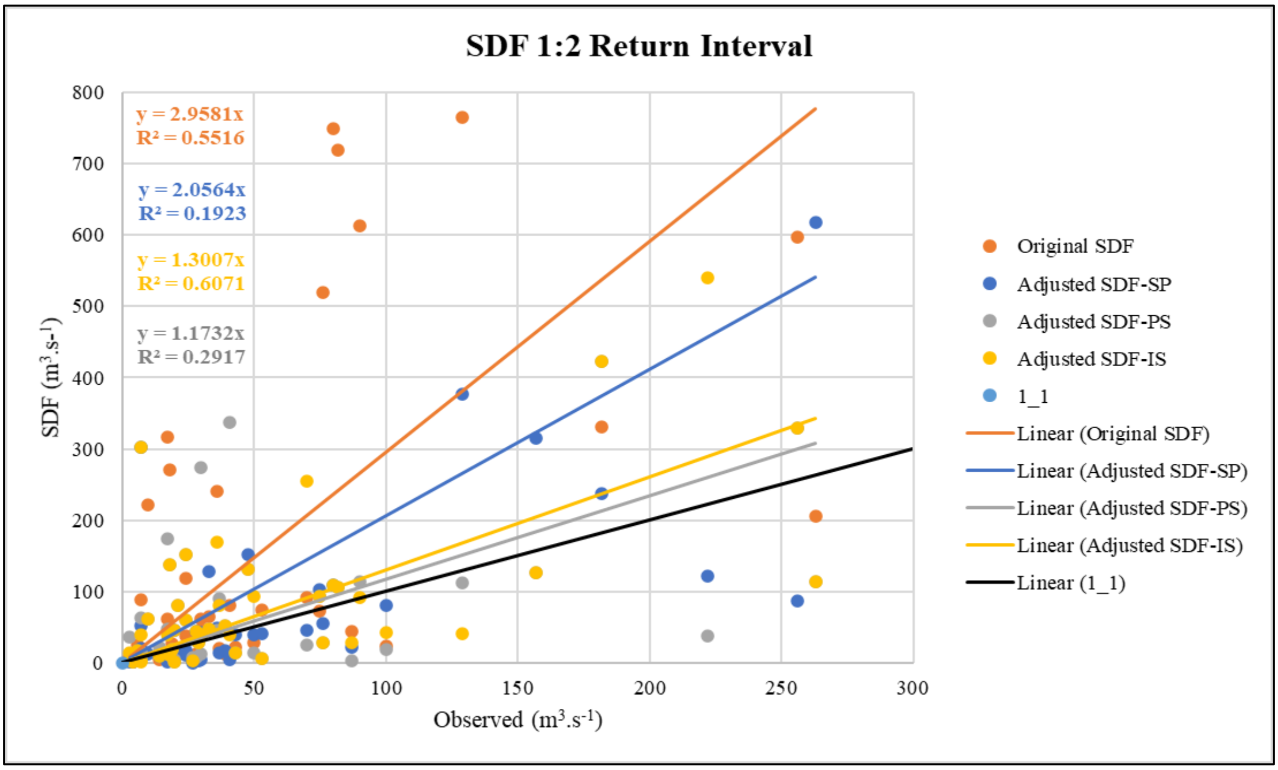
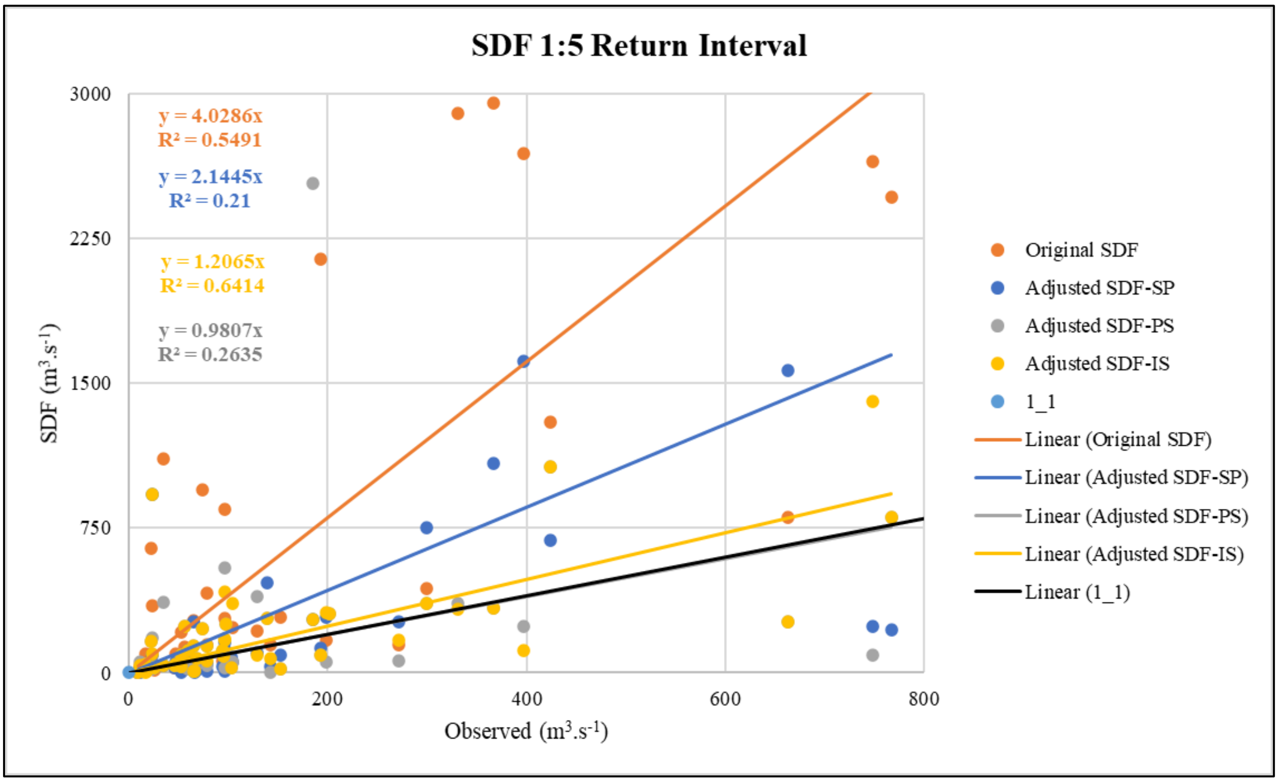
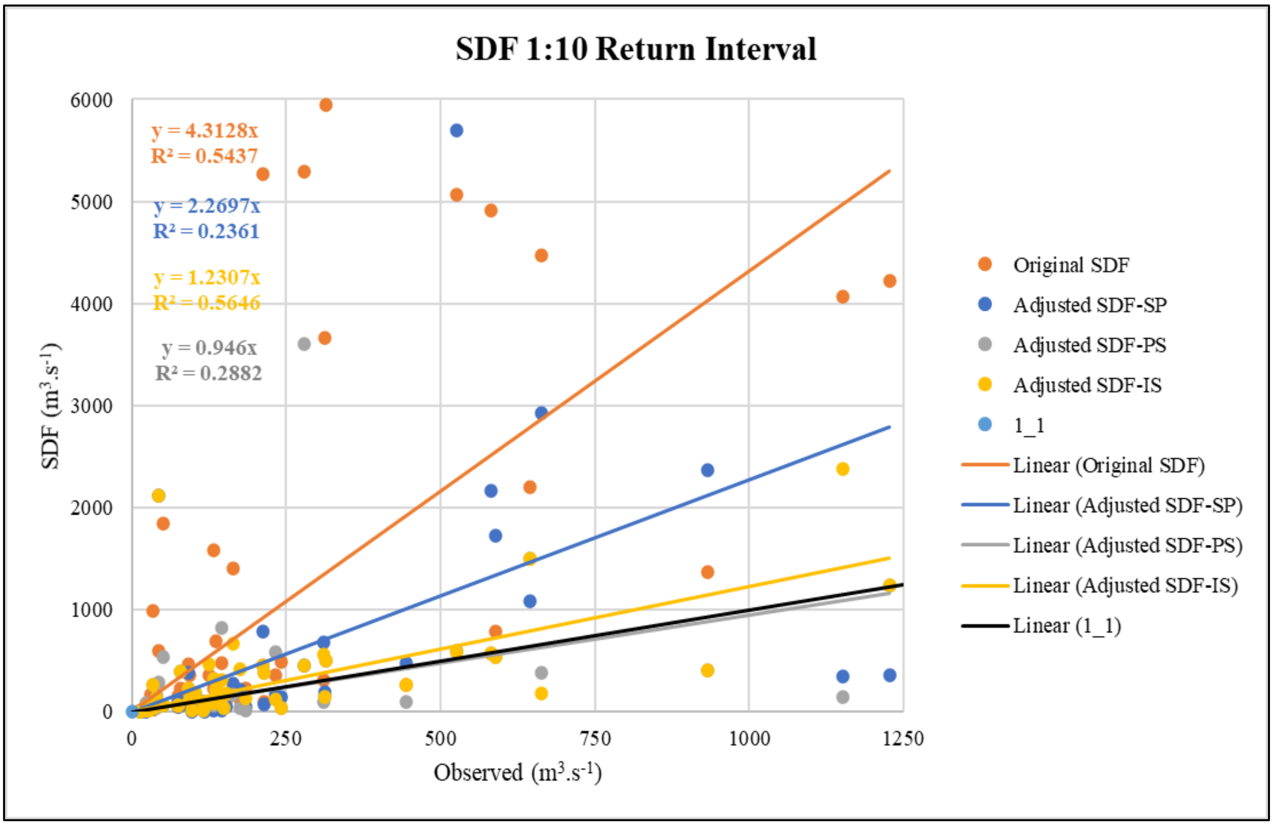
APPENDIX A1 SDF SCATTER PLOTS



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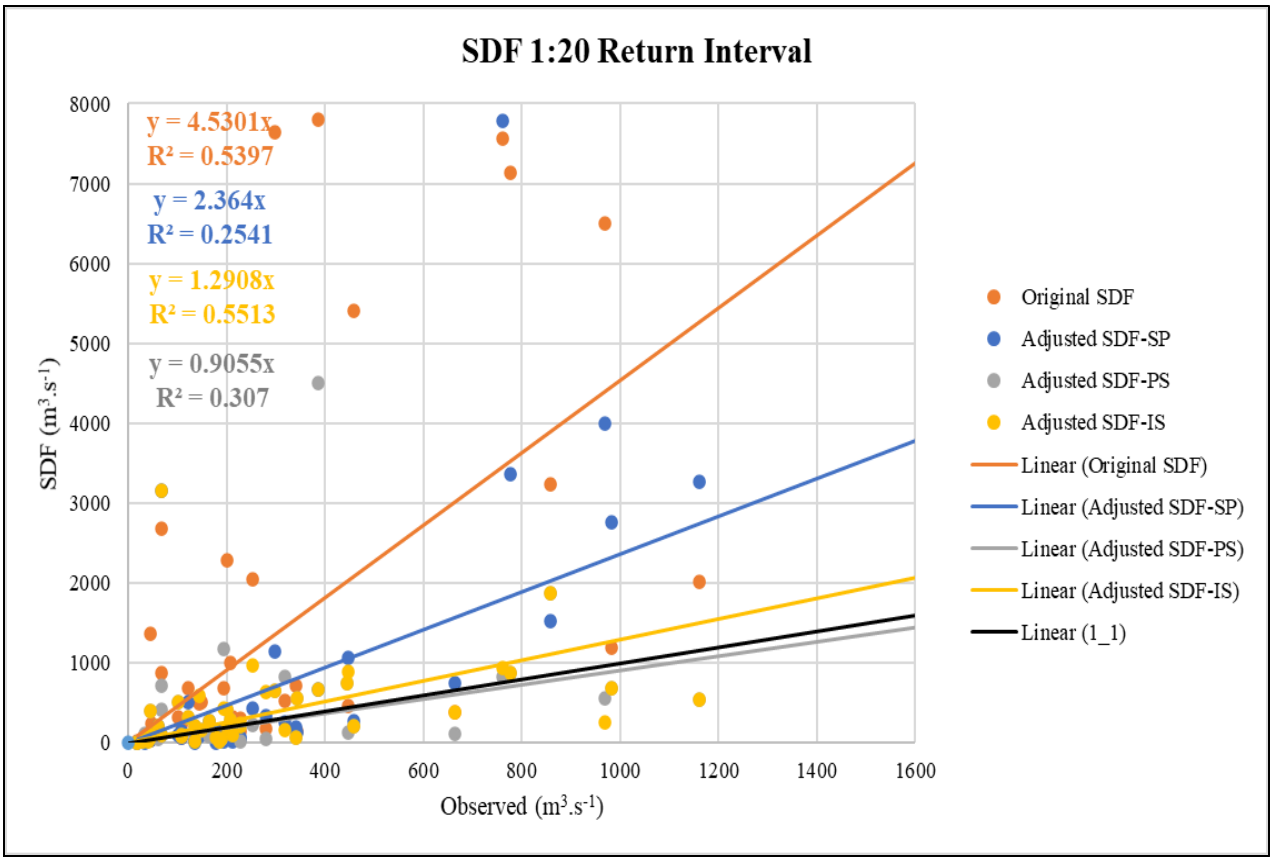
y = 4.3128x
R² = 0.5437
y = 2.2697x
R² = 0.2361
y = 1.2307x
R² = 0.5646
y = 0.946x
R² = 0.2882
SDF (m³.s⁻¹)
Observed (m³.s⁻¹)
Original SDF
Adjusted SDF-SP
Adjusted SDF-PS
Adjusted SDF-IS
1_1
Linear (Original SDF)
Linear (Adjusted SDF-SP)
Linear (Adjusted SDF-PS)
Linear (Adjusted SDF-IS)
Linear (1_1)


SDF 1:20 Return Interval
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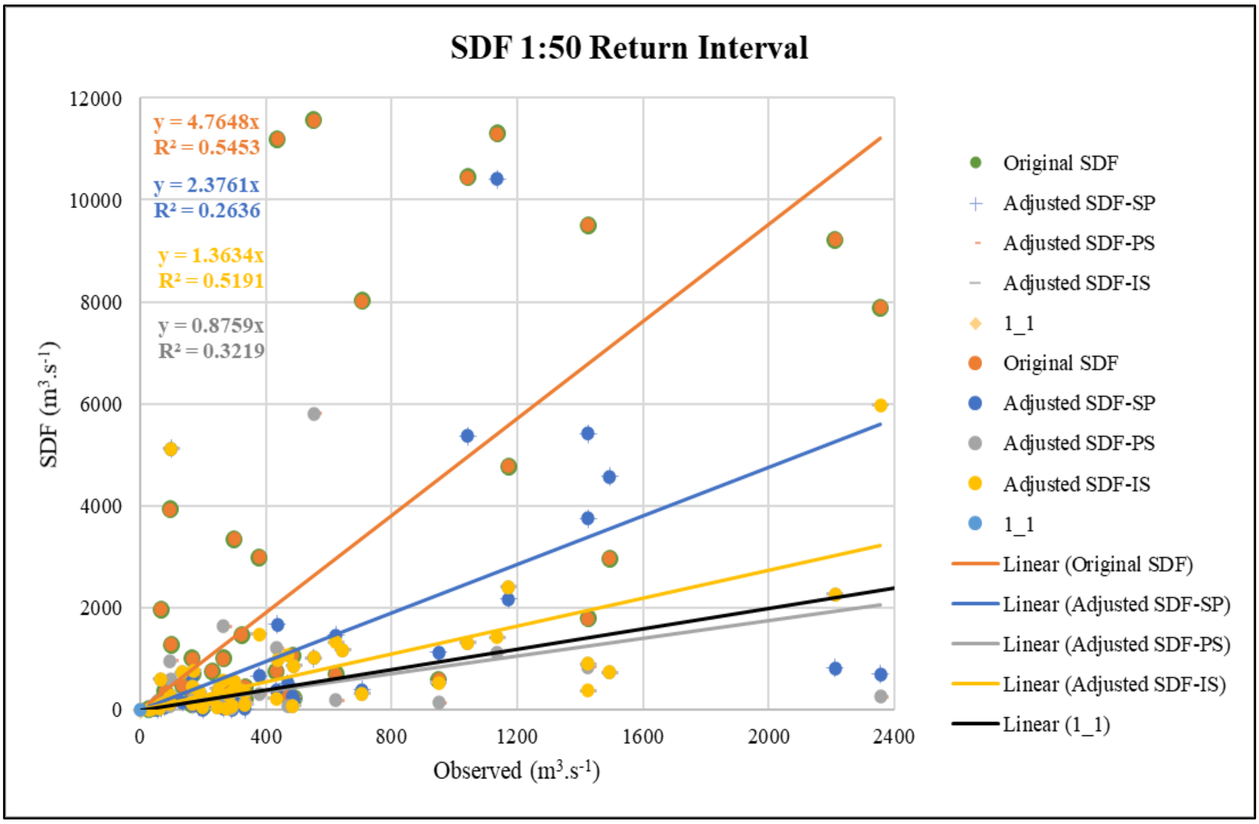
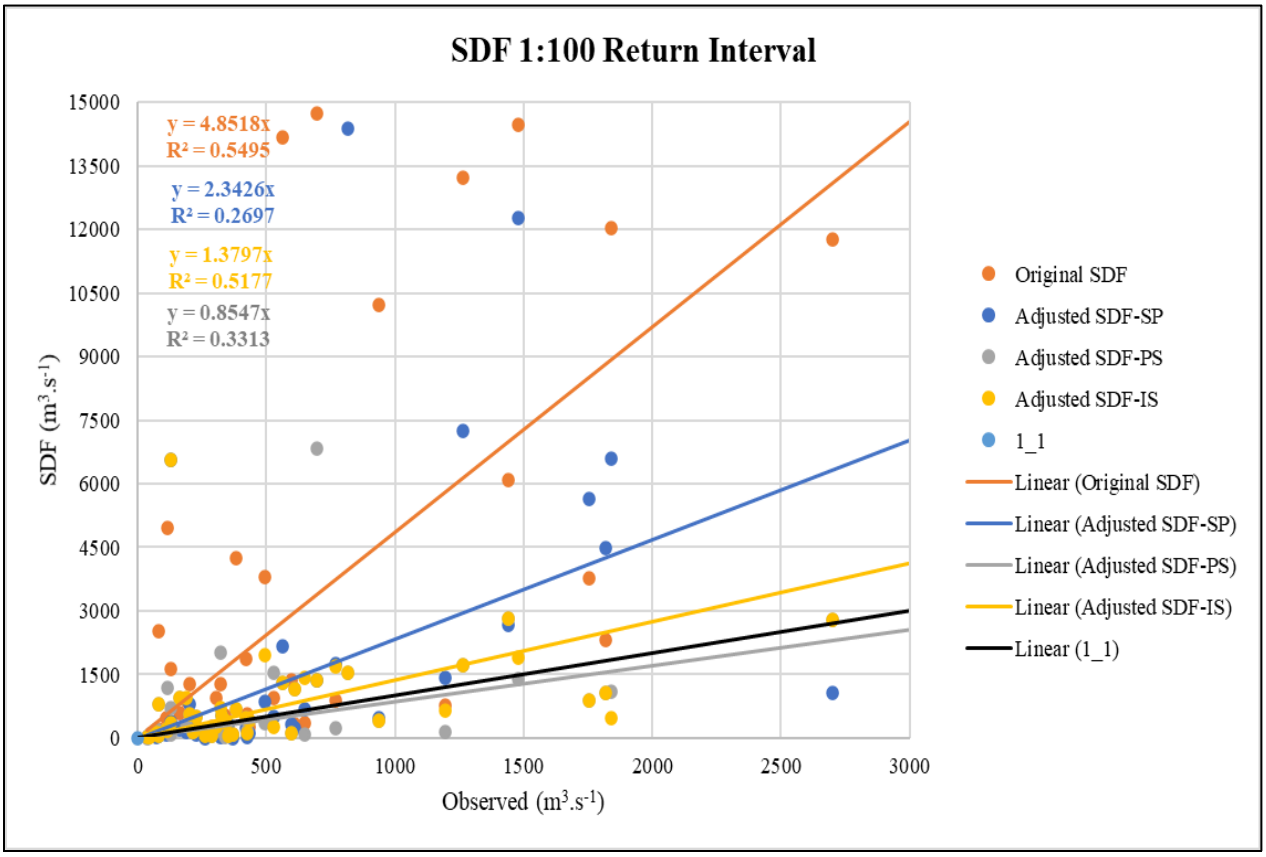
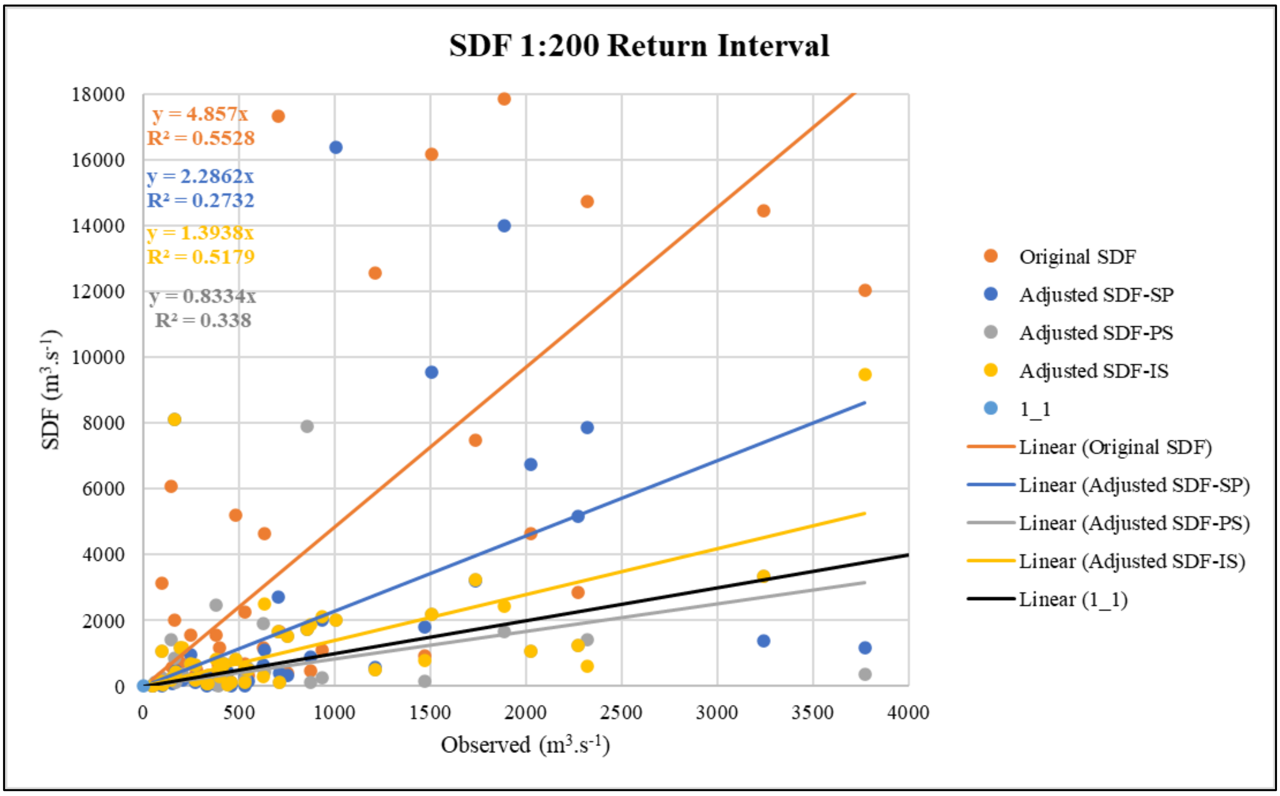
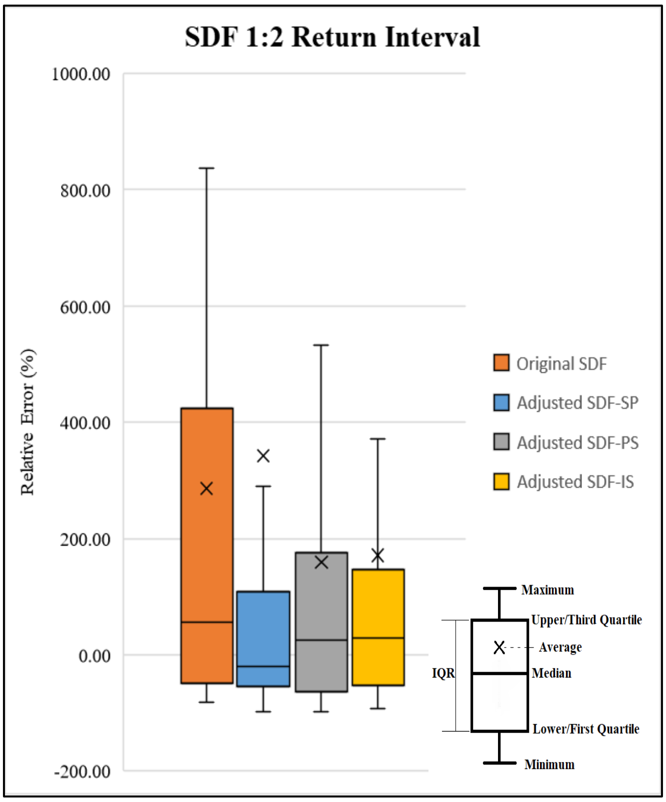
R² = 0.5397
y = 2.364x
R² = 0.2541
y = 1.2908x
R² = 0.5513
y = 0.9055x
R² = 0.307
SDF (m³.s⁻¹)
Observed (m³.s⁻¹)
Original SDF
Adjusted SDF-SP
Adjusted SDF-PS
Adjusted SDF-IS
Linear (Original SDF)
Linear (Adjusted SDF-SP)
Linear (Adjusted SDF-PS)
Linear (Adjusted SDF-IS)
Linear (1_1)

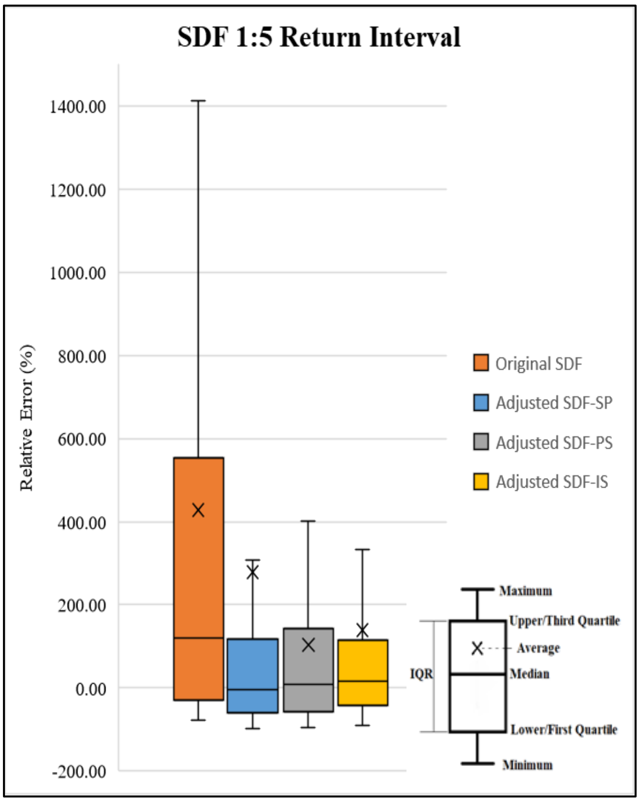

SDF 1:50 Return Interval
y = 4.7648x
R² = 0.5453
y = 2.3761x
R² = 0.2636
y = 1.3634x
R² = 0.5191
y = 0.8759x
R² = 0.3219
SDF (m³.s⁻¹)
Observed (m³.s⁻¹)
0
2000
4000
6000
8000
10000
12000
0
400
800
1200
1600
2000
2400
Original SDF
Adjusted SDF-SP
Adjusted SDF-PS
Adjusted SDF-IS
1_1
Original SDF
Adjusted SDF-SP
Adjusted SDF-PS
Adjusted SDF-IS
1_1
Linear (Original SDF)
Linear (Adjusted SDF-SP)
Linear (Adjusted SDF-PS)
Linear (Adjusted SDF-IS)
Linear (1_1)

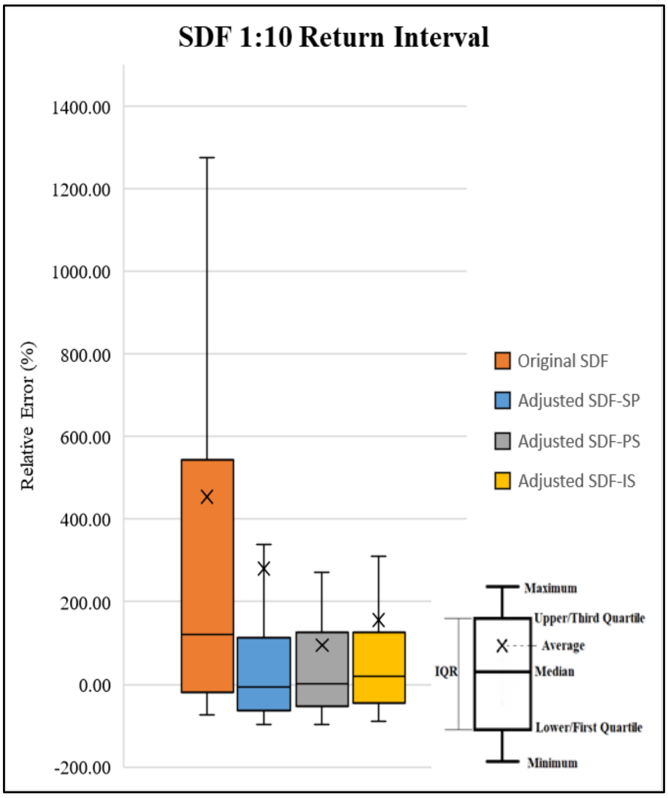

SDF 1:100 Return Interval
y = 4.8518x
R² = 0.5495
y = 2.3426x
R² = 0.2697
y = 1.3797x
R² = 0.5177
y = 0.8547x
R² = 0.3313
SDF (m³.s⁻¹)
Observed (m³.s⁻¹)
0
1500
3000
4500
6000
7500
9000
10500
12000
13500
15000
0
500
1000
1500
2000
2500
3000
Original SDF
Adjusted SDF-SP
Adjusted SDF-PS
Adjusted SDF-IS
1_1
Linear (Original SDF)
Linear (Adjusted SDF-SP)
Linear (Adjusted SDF-PS)
Linear (Adjusted SDF-IS)
Linear (1_1)

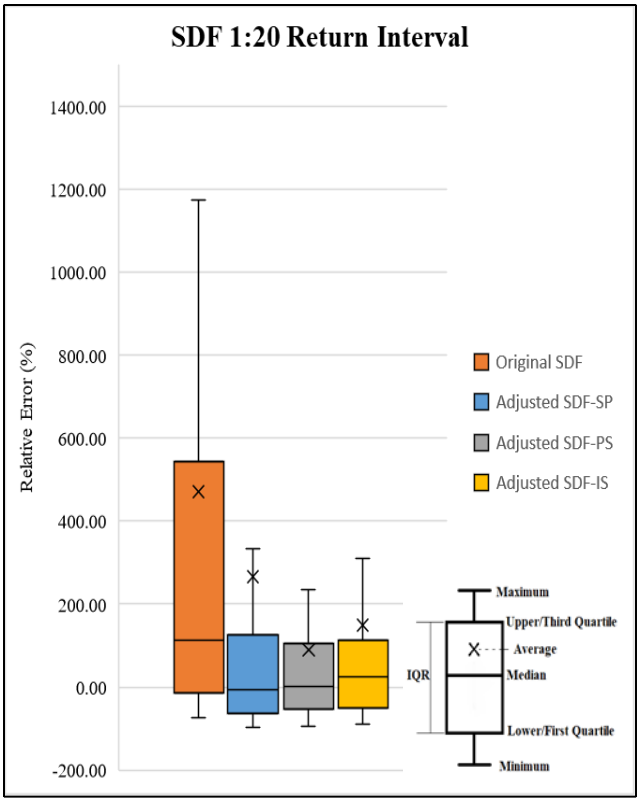

SDF 1:200 Return Interval
y = 4.857x
R² = 0.5528
y = 2.2862x
R² = 0.2732
y = 1.3938x
R² = 0.5179
y = 0.8334x
R² = 0.338
SDF (m³.s⁻¹)
Observed (m³.s⁻¹)
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
0
500
1000
1500
2000
2500
3000
3500
4000
Original SDF
Adjusted SDF-SP
Adjusted SDF-PS
Adjusted SDF-IS
1_1
Linear (Original SDF)
Linear (Adjusted SDF-SP)
Linear (Adjusted SDF-PS)
Linear (Adjusted SDF-IS)
Linear (1_1)

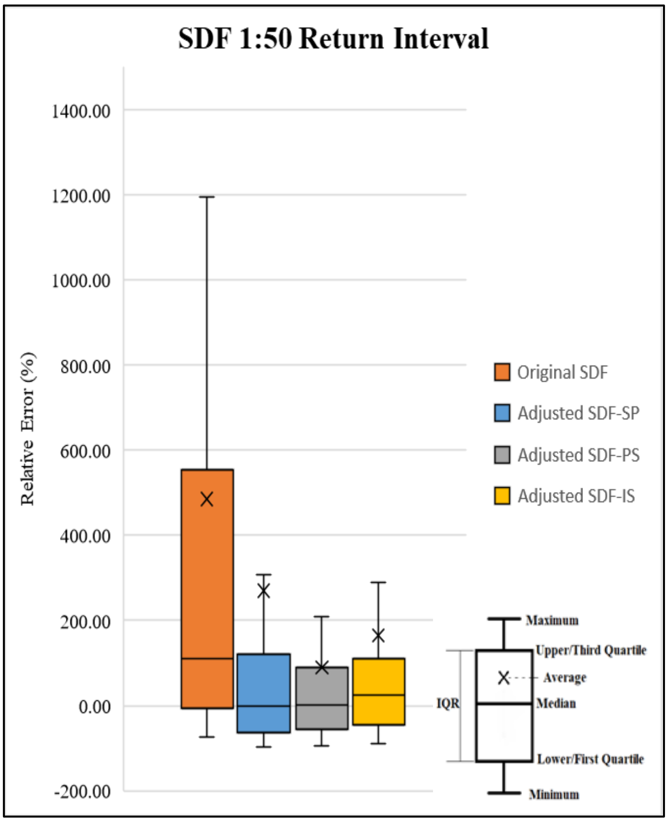
APPENDIX A2 SDF BOX AND WHISKER PLOTS OF REs

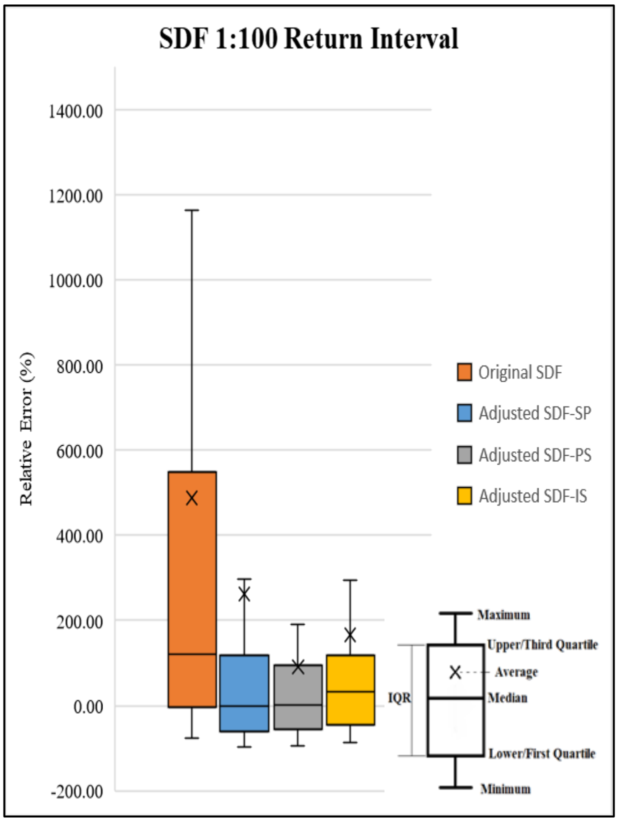


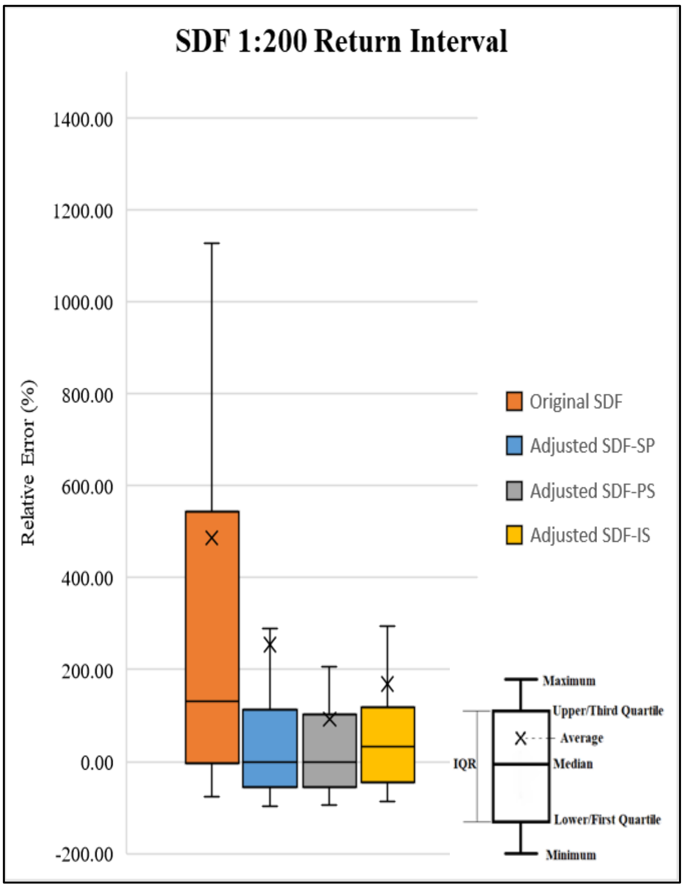


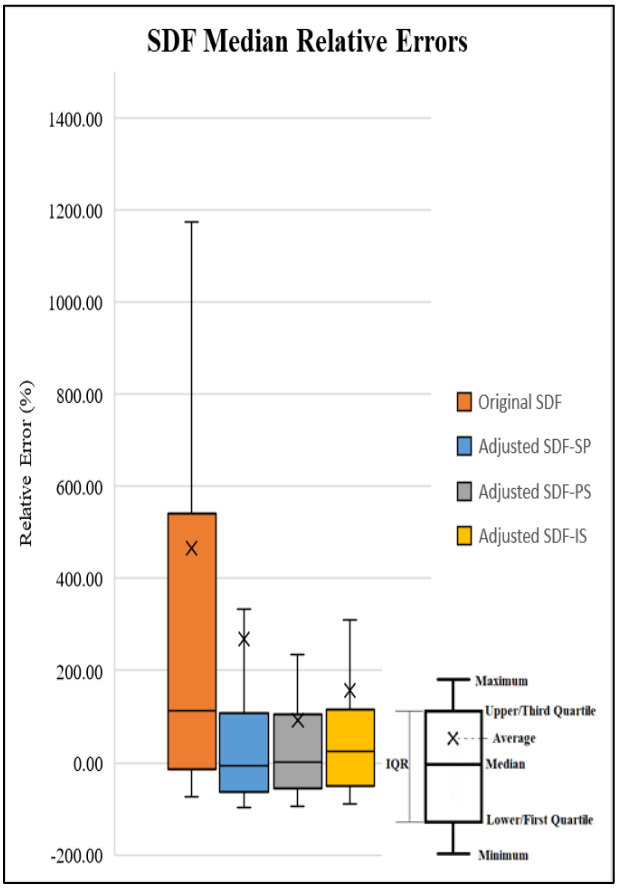




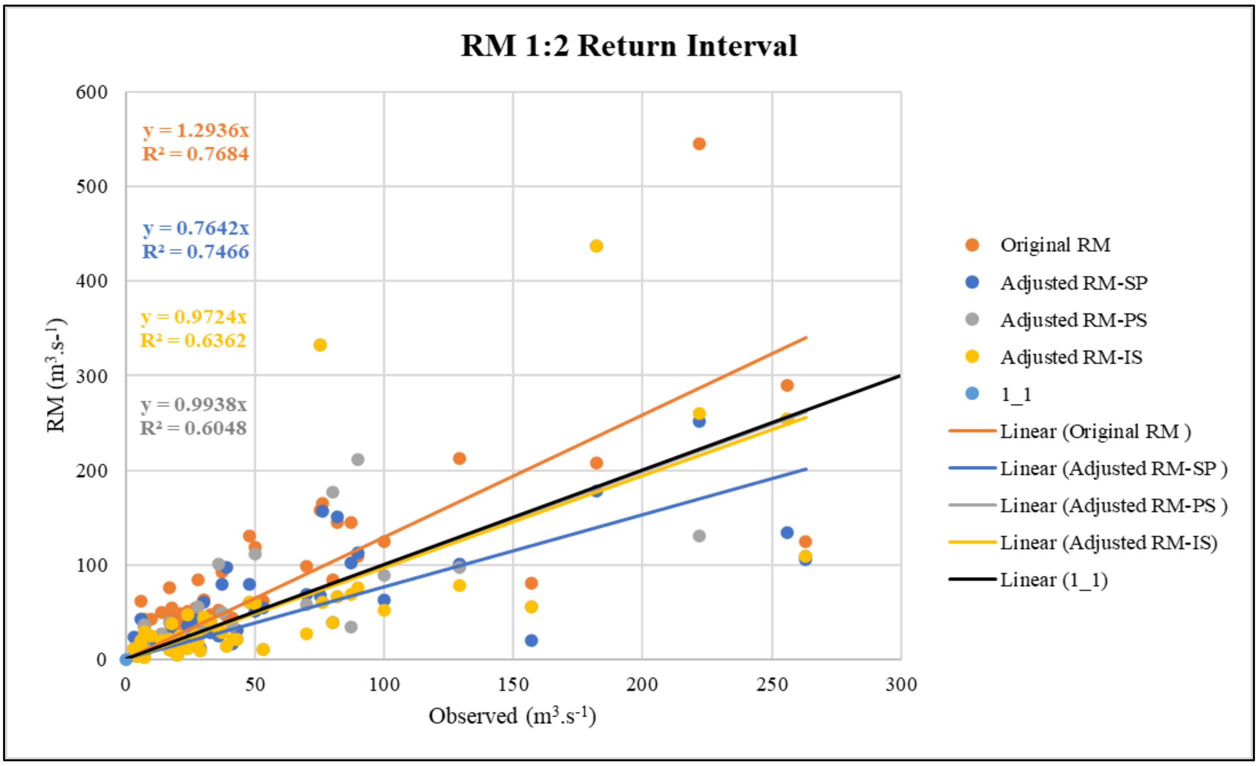

SDF 1:50 Return Interval
Relative Error (%)
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
-200.00
Original SDF
Adjusted SDF-SP
Adjusted SDF-PS
Adjusted SDF-IS
Maximum
Upper/Third Quartile
Average
Median
IQR
Lower/First Quartile
Minimum

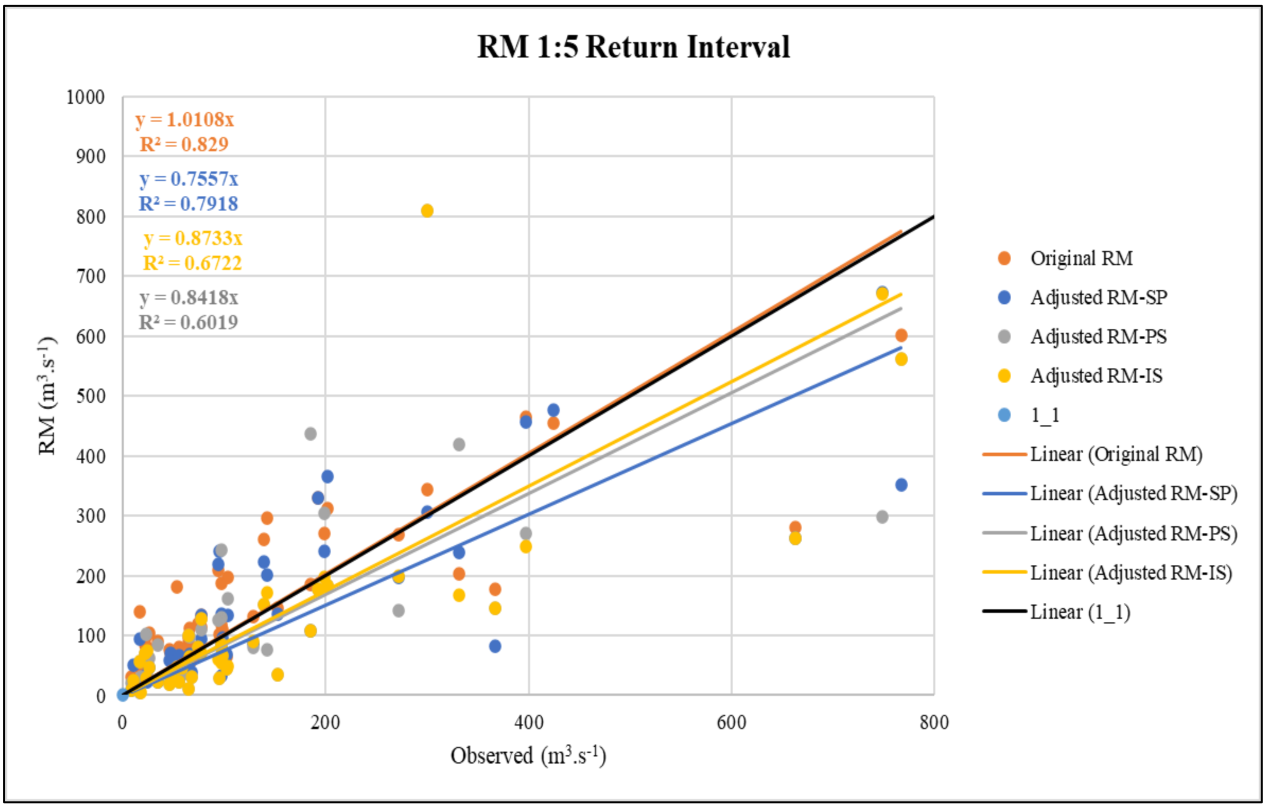

SDF 1:100 Return Interval
Relative Error (%)
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
-200.00
Original SDF
Adjusted SDF-SP
Adjusted SDF-PS
Adjusted SDF-IS
Maximum
Upper/Third Quartile
Average
Median
IQR
Lower/First Quartile
Minimum

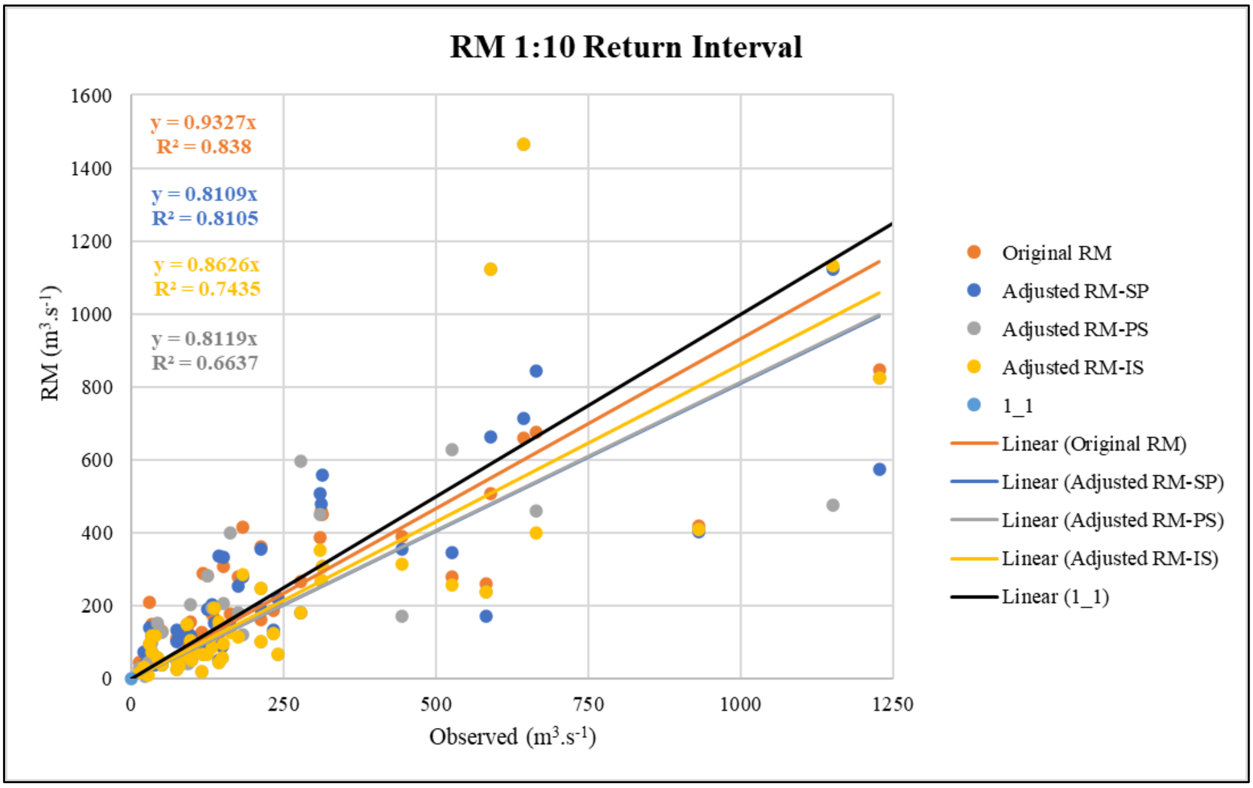

SDF 1:200 Return Interval
Relative Error (%)
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
-200.00
Original SDF
Adjusted SDF-SP
Adjusted SDF-PS
Adjusted SDF-IS
Maximum
Upper/Third Quartile
Average
Median
IQR
Lower/First Quartile
Minimum

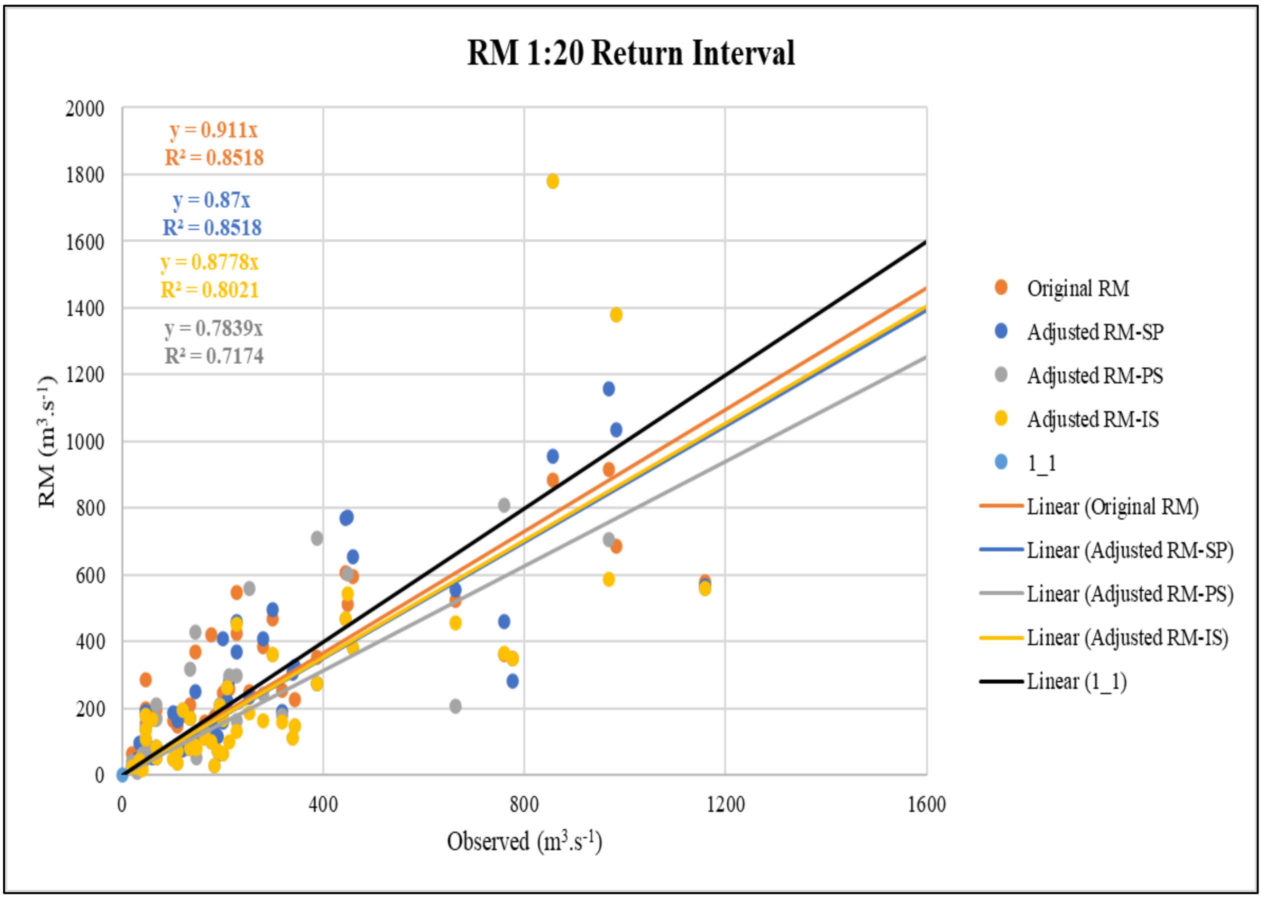

SDF Median Relative Errors
Relative Error (%)
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
-200.00
Original SDF
Adjusted SDF-SP
Adjusted SDF-PS
Adjusted SDF-IS
Maximum
Upper/Third Quartile
Average
Median
IQR
Lower/First Quartile
Minimum

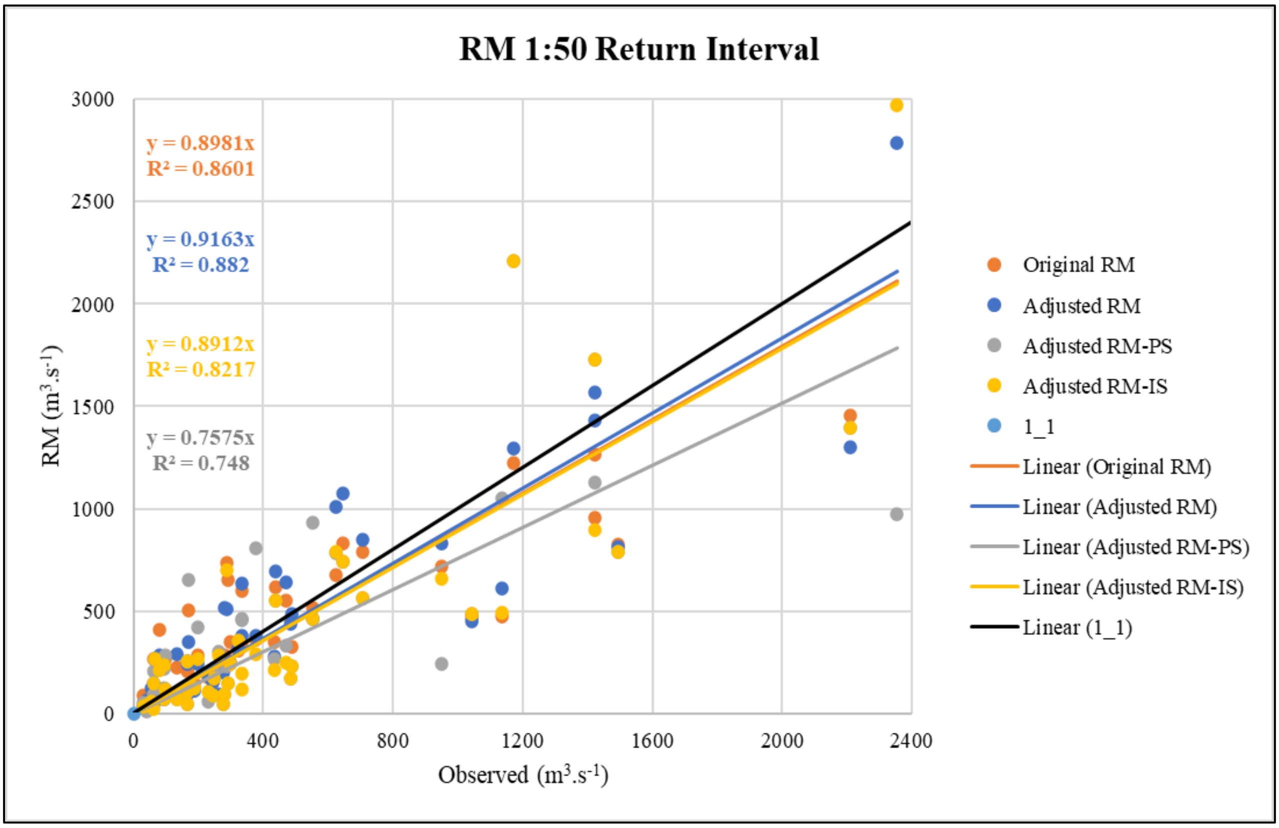
APPENDIX B1 RM SCATTER PLOTS

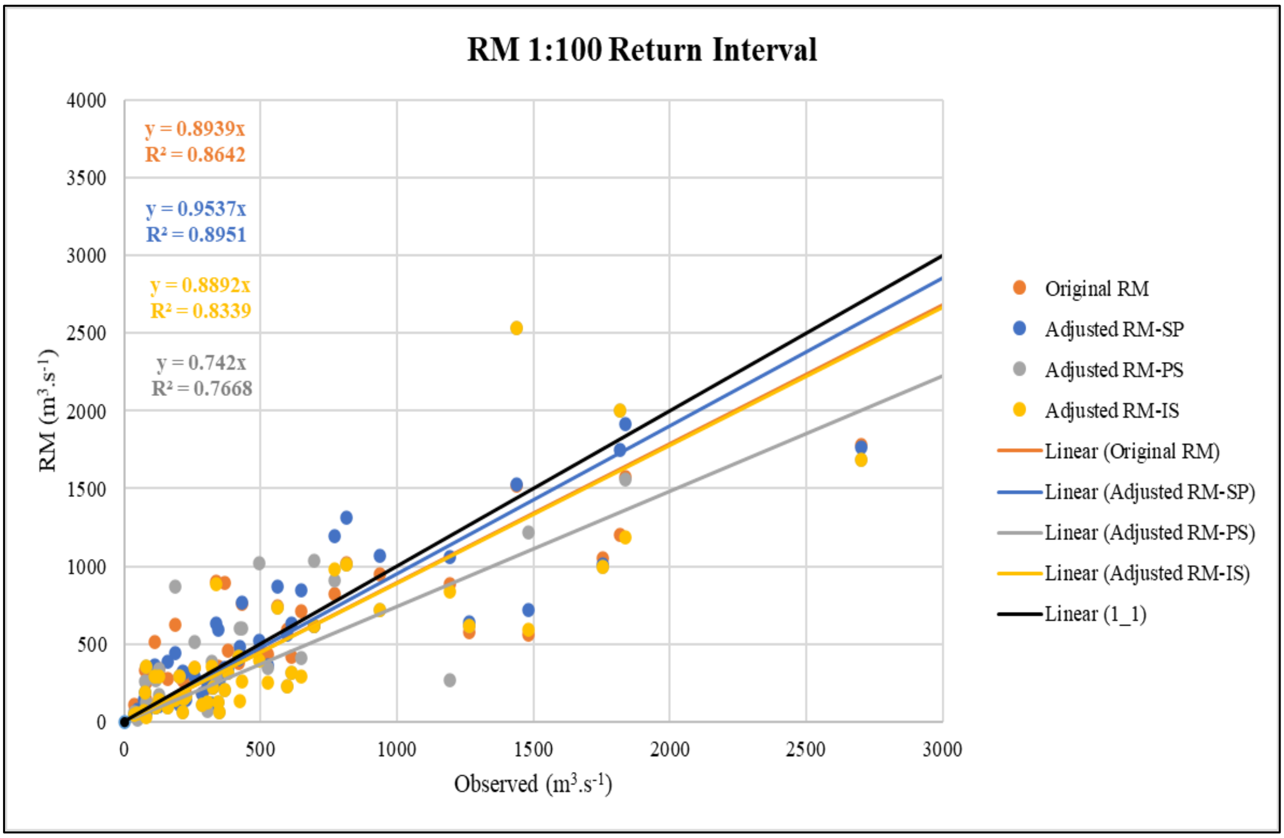


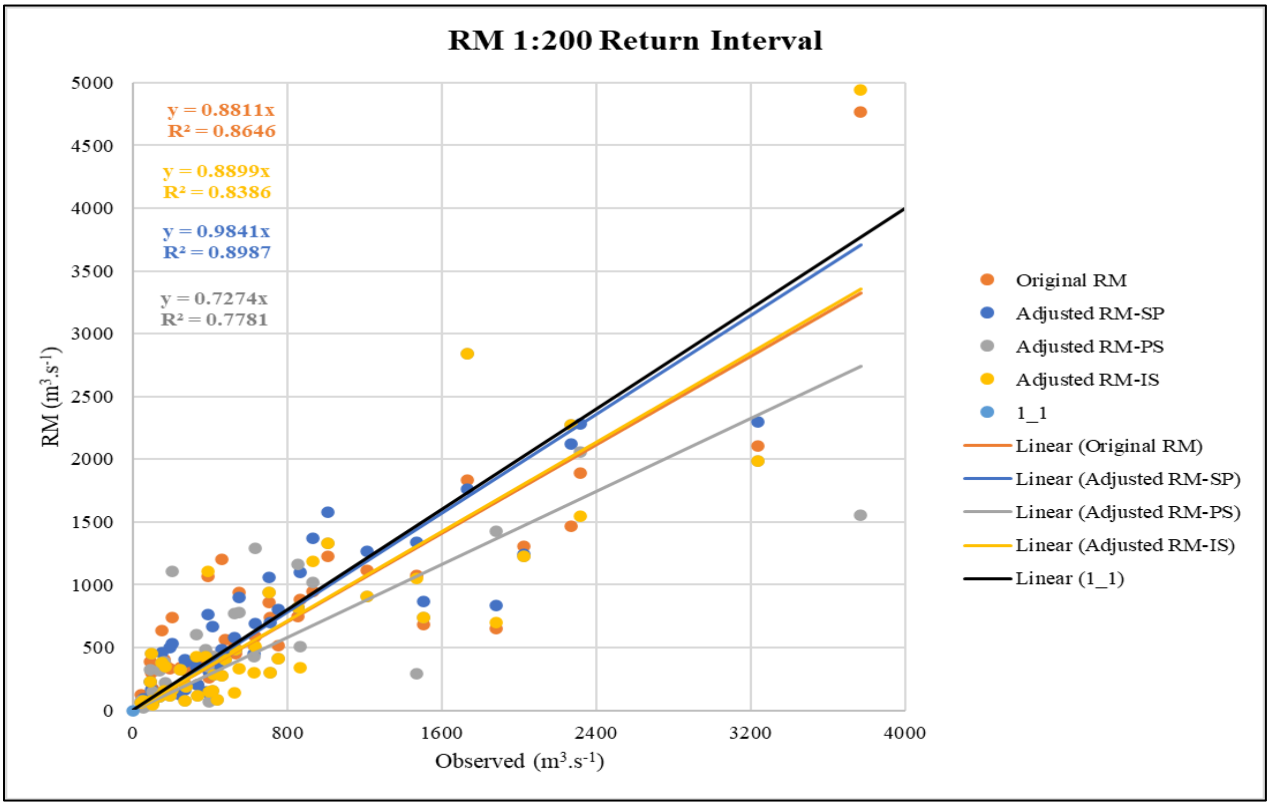



RM 1:10 Return Interval
y = 0.9327x
R² = 0.838
y = 0.8109x
R² = 0.8105
y = 0.8626x
R² = 0.7435
y = 0.8119x
R² = 0.6637
RM (m3.s-1)
Observed (m3.s-1)
Original RM
Adjusted RM-SP
Adjusted RM-PS
Adjusted RM-IS
1_1
Linear (Original RM)
Linear (Adjusted RM-SP)
Linear (Adjusted RM-PS)
Linear (Adjusted RM-IS)
Linear (1_1)


RM 1:20 Return Interval
y = 0.911x
R² = 0.8518
y = 0.87x
R² = 0.8518
y = 0.8778x
R² = 0.8021
y = 0.7839x
R² = 0.7174
RM (m3.s-1)
Observed (m3.s-1)
Original RM
Adjusted RM-SP
Adjusted RM-PS
Adjusted RM-IS
1_1
Linear (Original RM)
Linear (Adjusted RM-SP)
Linear (Adjusted RM-PS)
Linear (Adjusted RM-IS)
Linear (1_1)

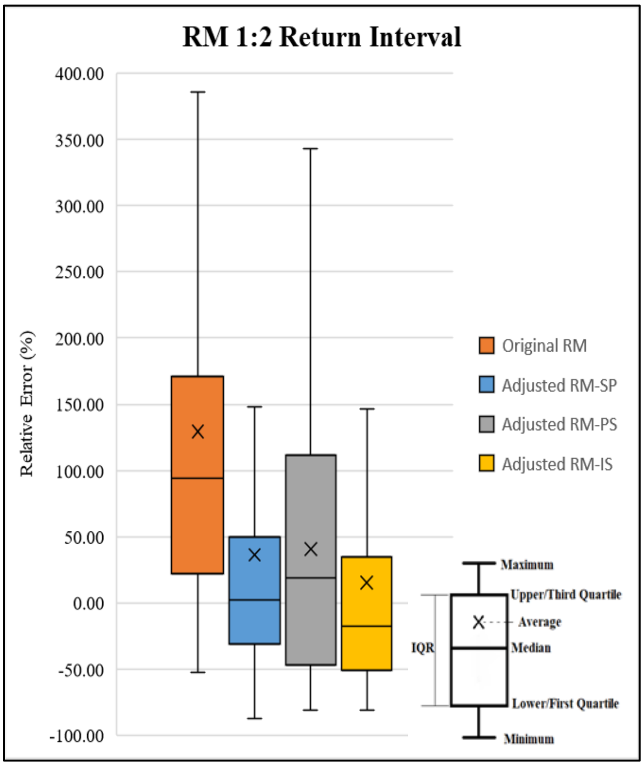

RM 1:50 Return Interval
y = 0.8981x
R² = 0.8601
y = 0.9163x
R² = 0.882
y = 0.8912x
R² = 0.8217
y = 0.7575x
R² = 0.748
RM (m3.s-1)
Observed (m3.s-1)
0
500
1000
1500
2000
2500
3000
0
400
800
1200
1600
2000
2400
Original RM
Adjusted RM
Adjusted RM-PS
Adjusted RM-IS
1_1
Linear (Original RM)
Linear (Adjusted RM)
Linear (Adjusted RM-PS)
Linear (Adjusted RM-IS)
Linear (1_1)

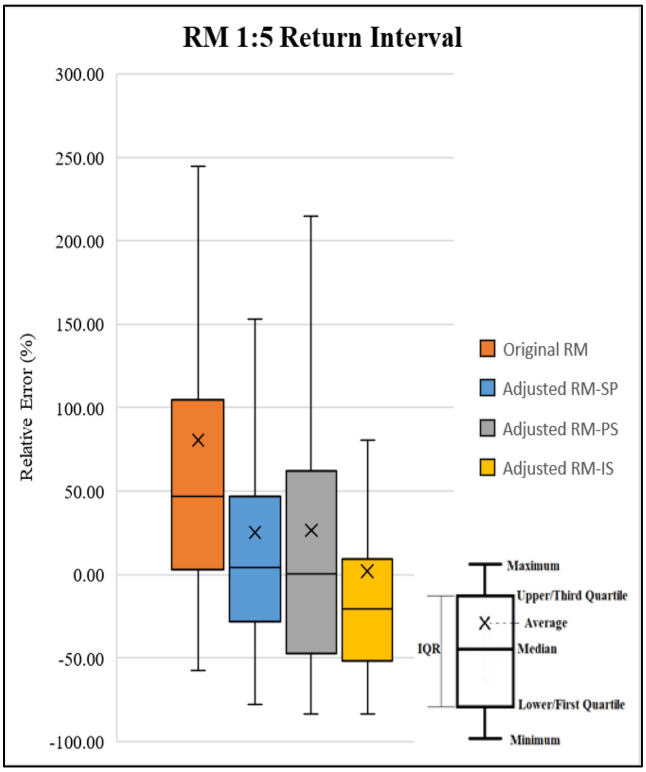

RM 1:100 Return Interval
y = 0.8939x
R² = 0.8642
y = 0.9537x
R² = 0.8951
y = 0.8892x
R² = 0.8339
y = 0.742x
R² = 0.7668
RM (m3.s-1)
Observed (m3.s-1)
0
500
1000
1500
2000
2500
3000
3500
4000
0
500
1000
1500
2000
2500
3000
Original RM
Adjusted RM-SP
Adjusted RM-PS
Adjusted RM-IS
Linear (Original RM)
Linear (Adjusted RM-SP)
Linear (Adjusted RM-PS)
Linear (Adjusted RM-IS)
Linear (1_1)

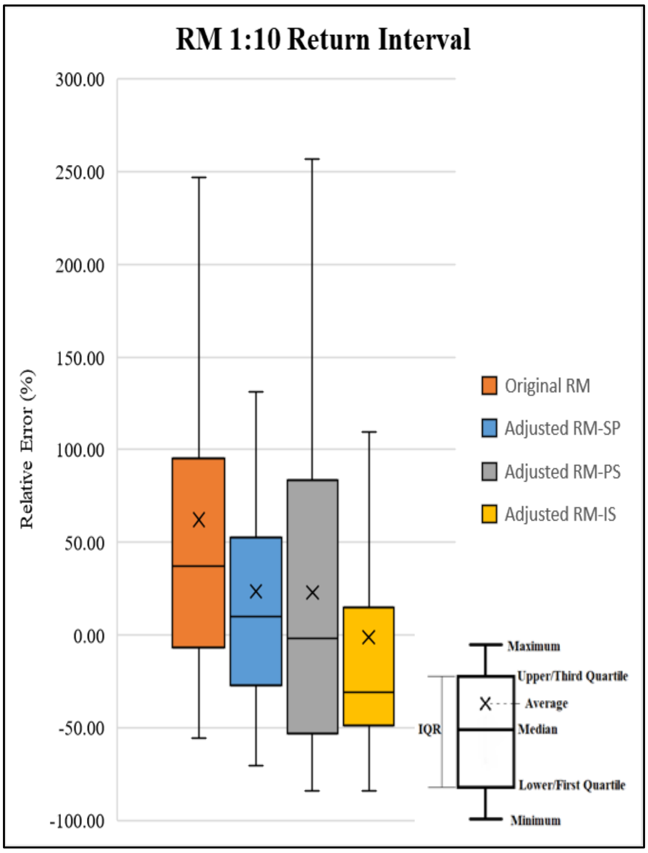


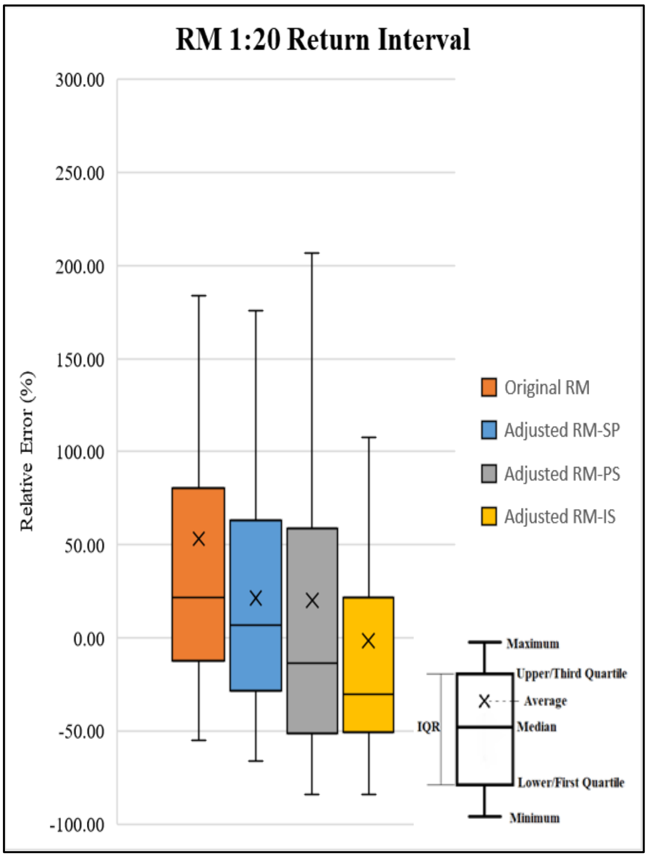
RM 1:200 Return Interval
y = 0.8811x
R² = 0.8646
y = 0.8899x
R² = 0.8386
y = 0.9841x
R² = 0.8987
y = 0.7274x
R² = 0.7781
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
800
1600
2400
3200
4000
RM (m3.s-1)
Observed (m3.s-1)
Original RM
Adjusted RM-SP
Adjusted RM-PS
Adjusted RM-IS
1_1
Linear (Original RM)
Linear (Adjusted RM-SP)
Linear (Adjusted RM-PS)
Linear (Adjusted RM-IS)
Linear (1_1)

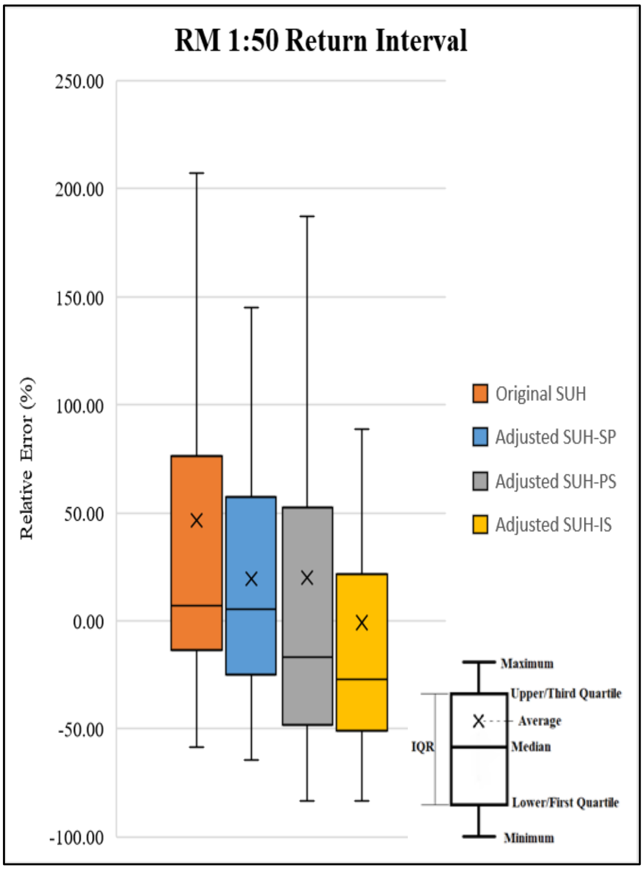
APPENDIX B2 RM BOX AND WHISKER PLOTS OF REs

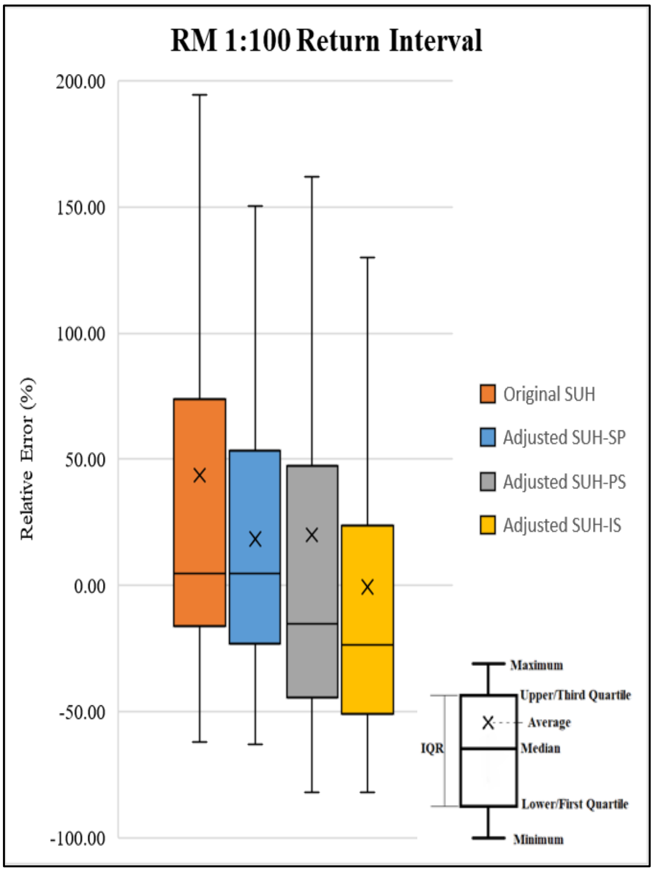


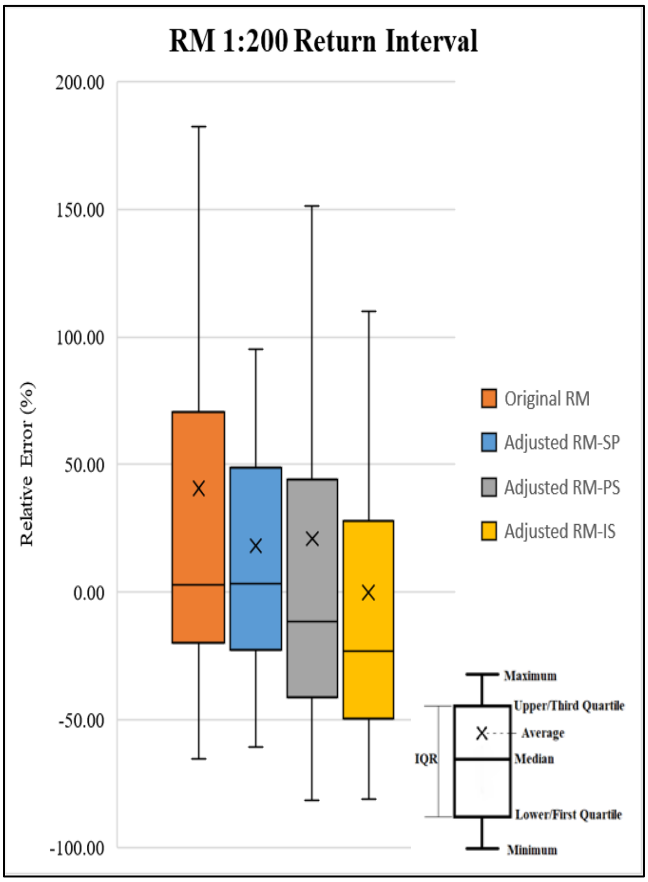


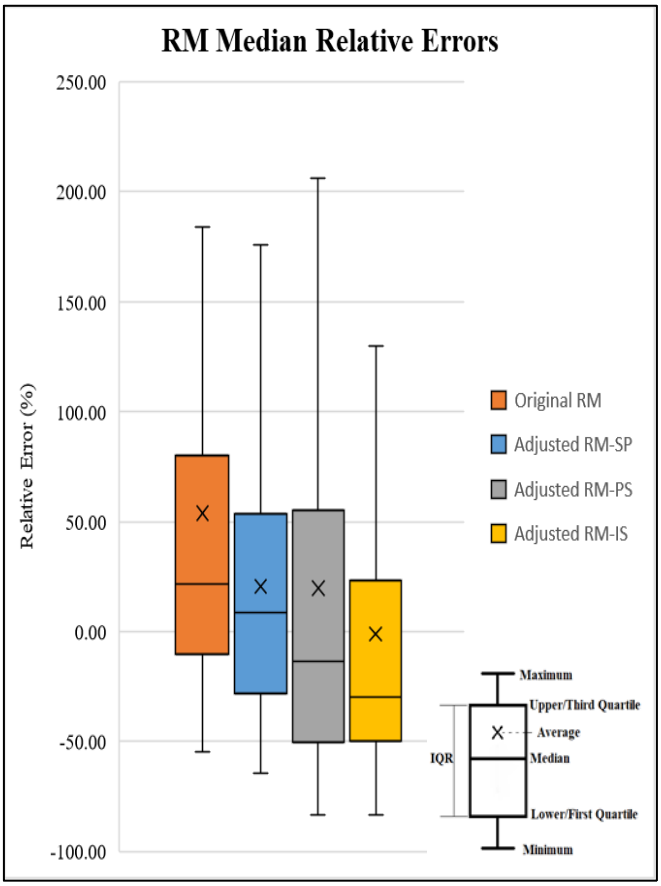




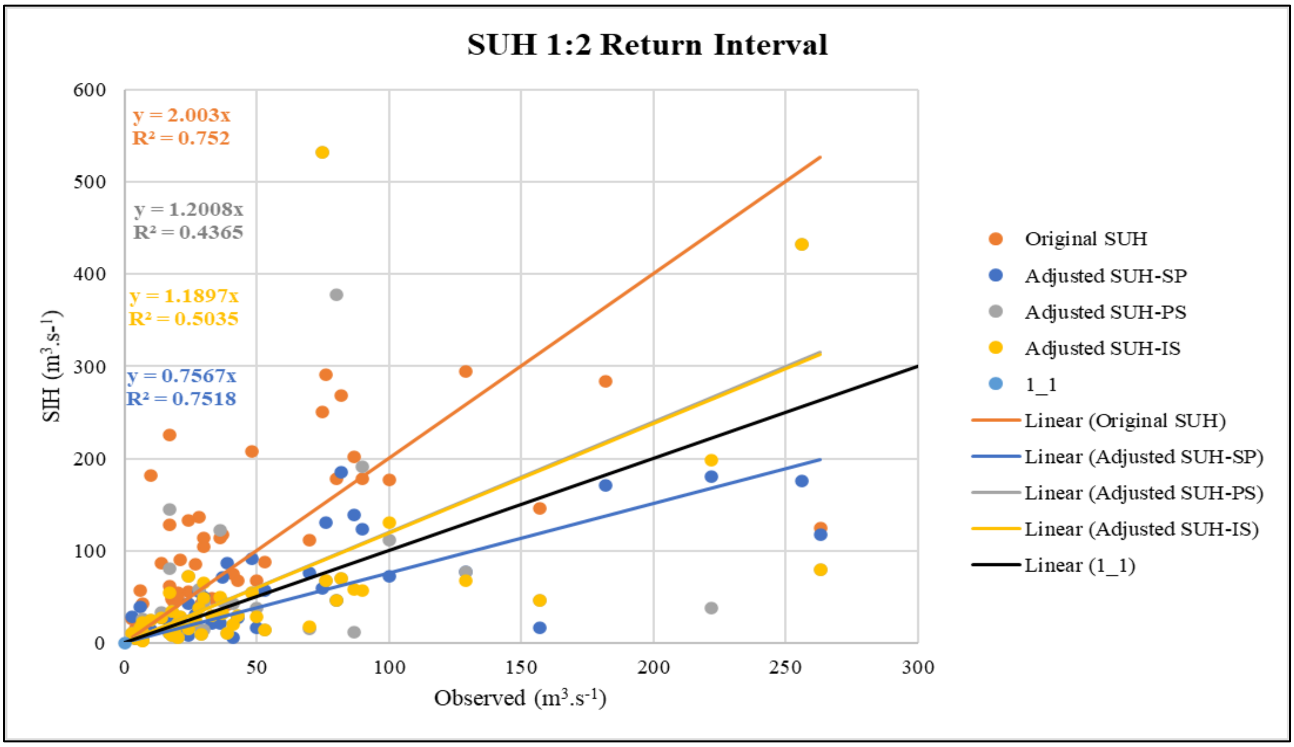

RM 1:50 Return Interval
250.00
200.00
150.00
100.00
50.00
0.00
-50.00
-100.00
Relative Error (%)
Original SUH
Adjusted SUH-SP
Adjusted SUH-PS
Adjusted SUH-IS
Maximum
Upper/Third Quartile
Average
IQR
Median
Lower/First Quartile
Minimum

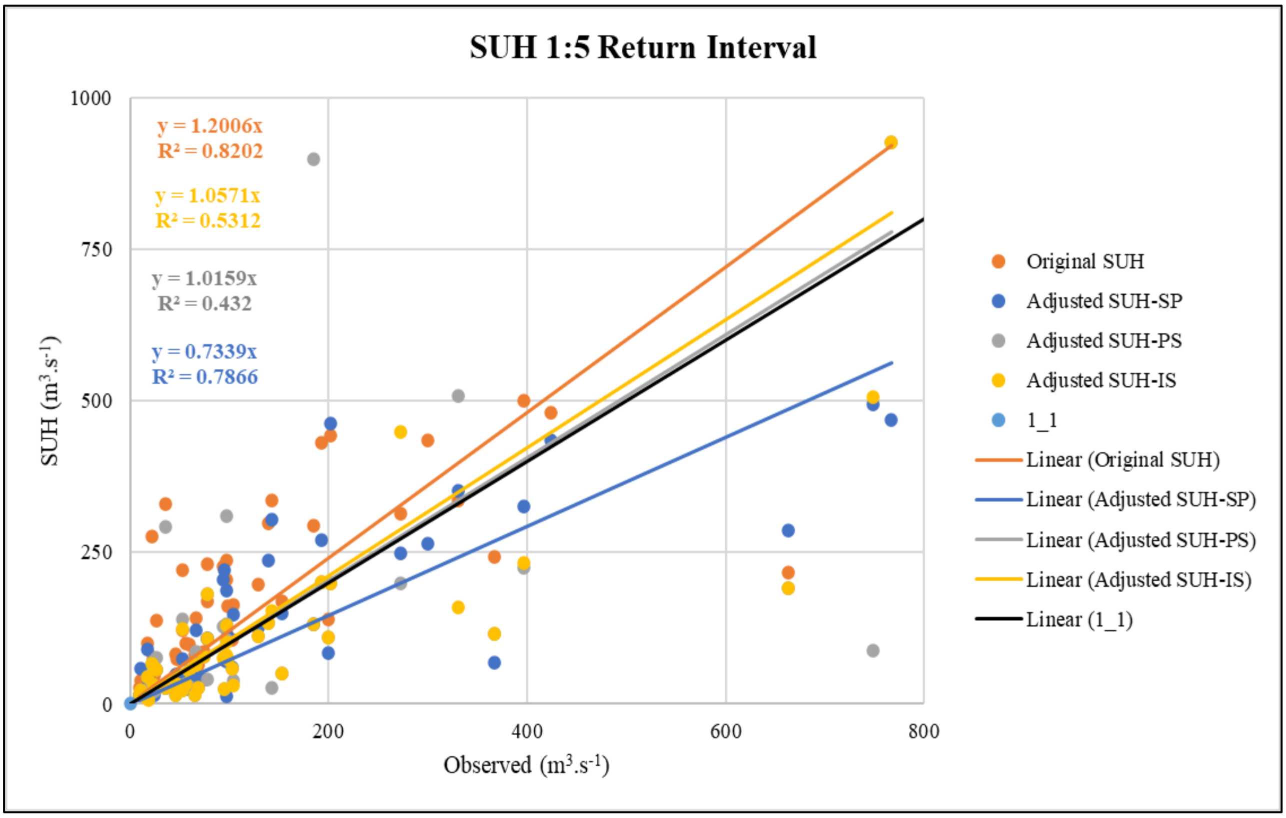

RM 1:100 Return Interval
200.00
150.00
100.00
50.00
0.00
-50.00
-100.00
Relative Error (%)
Original SUH
Adjusted SUH-SP
Adjusted SUH-PS
Adjusted SUH-IS
Maximum
Upper/Third Quartile
Average
IQR
Median
Lower/First Quartile
Minimum

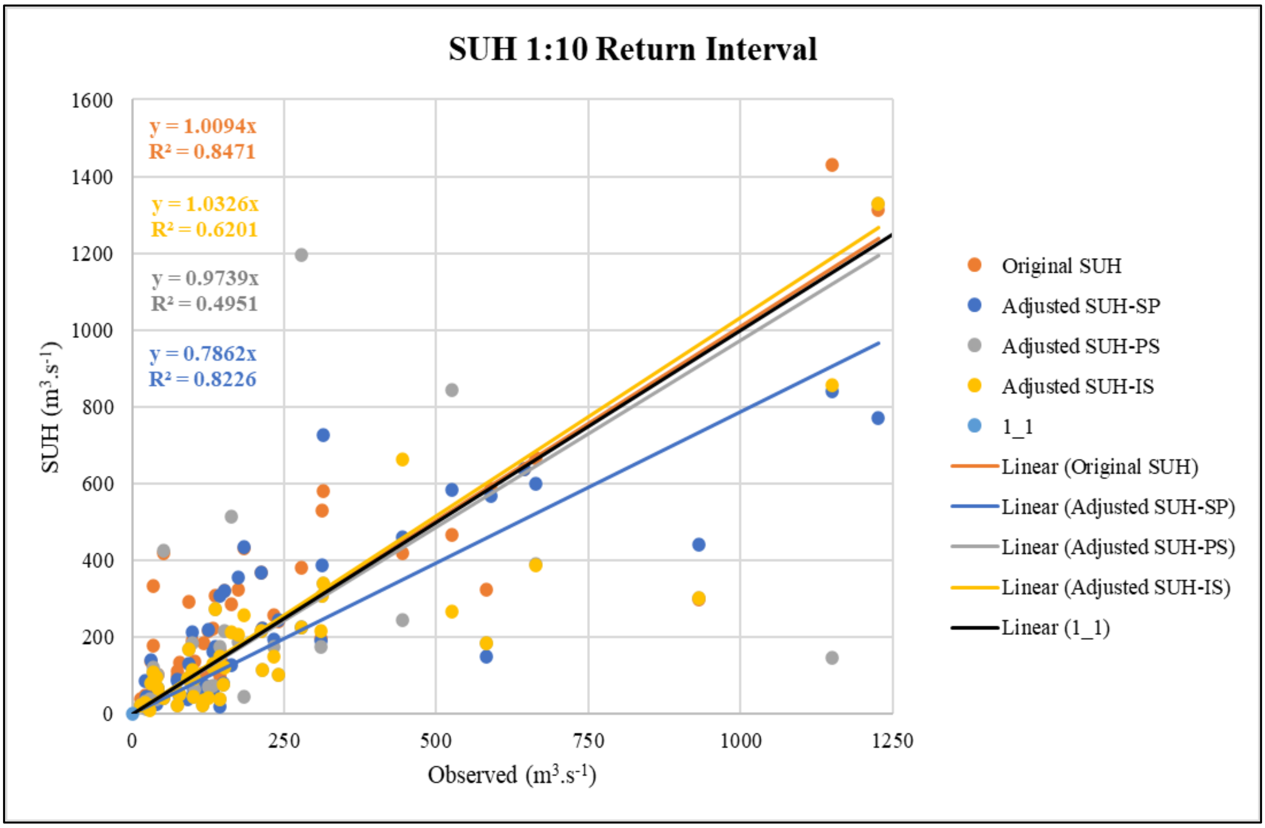

RM 1:200 Return Interval
200.00
150.00
100.00
50.00
0.00
-50.00
-100.00
Relative Error (%)
Original RM
Adjusted RM-SP
Adjusted RM-PS
Adjusted RM-IS
Maximum
Upper/Third Quartile
Average
IQR
Median
Lower/First Quartile
Minimum

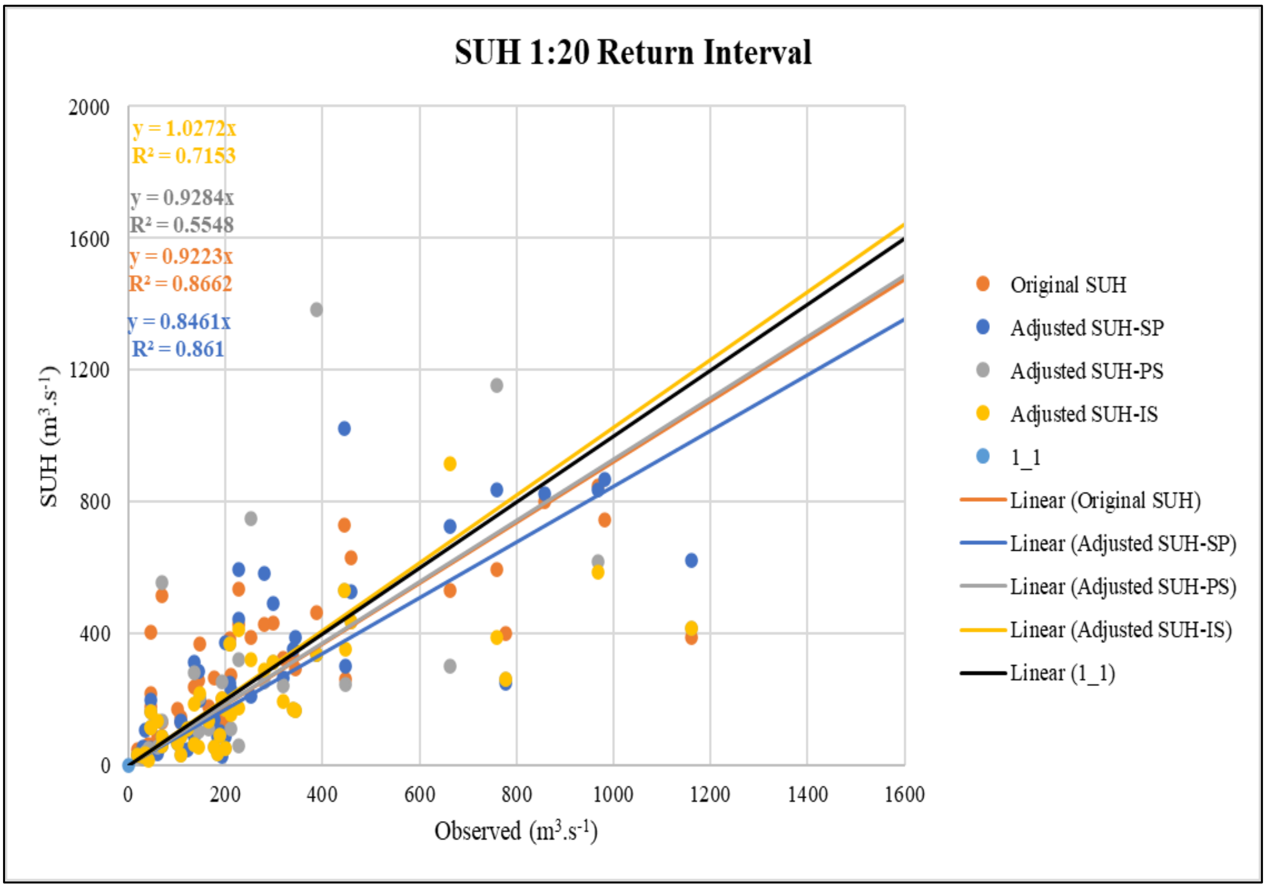

RM Median Relative Errors
250.00
200.00
150.00
100.00
50.00
0.00
-50.00
-100.00
Relative Error (%)
Original RM
Adjusted RM-SP
Adjusted RM-PS
Adjusted RM-IS
Maximum
Upper/Third Quartile
Average
IQR
Median
Lower/First Quartile
Minimum

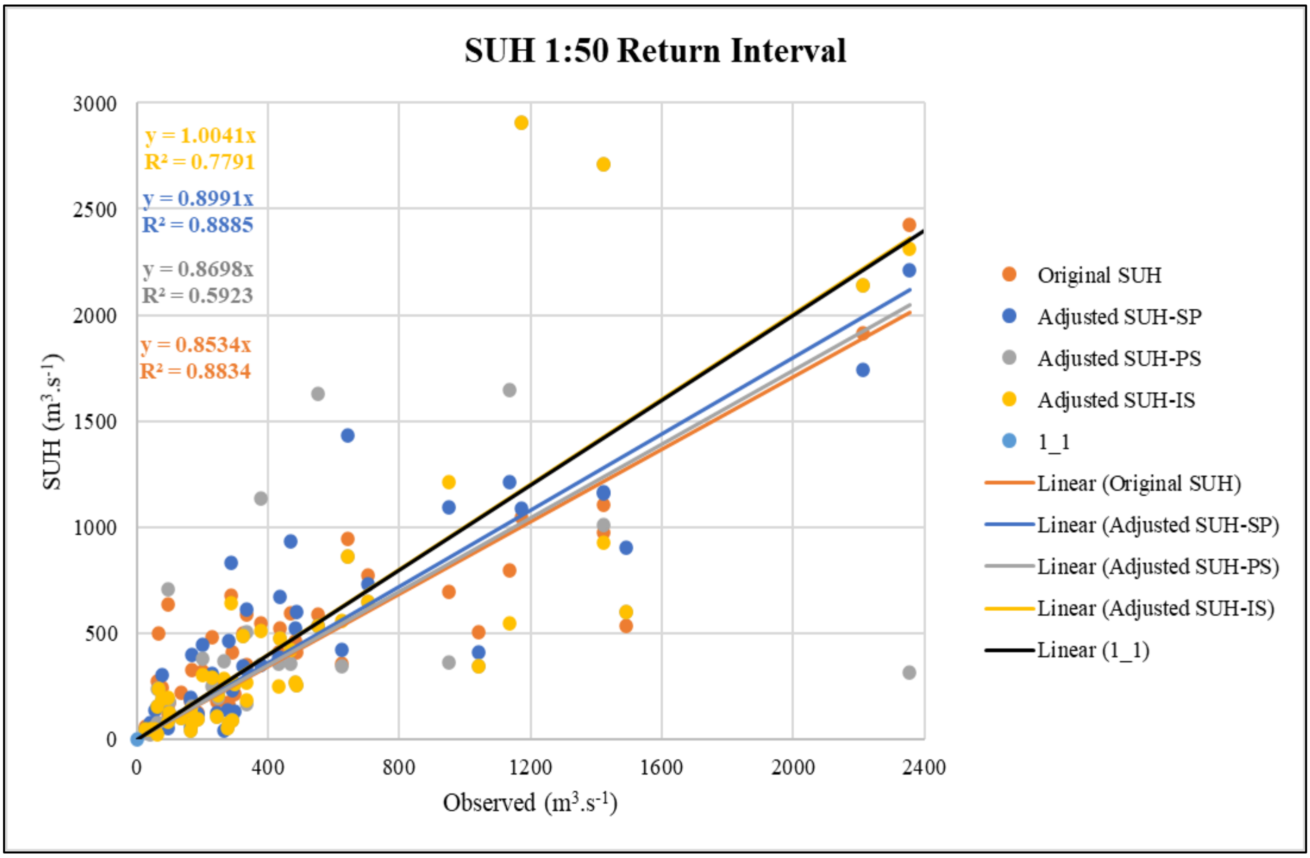
APPENDIX C1 SUH SCATTER PLOTS

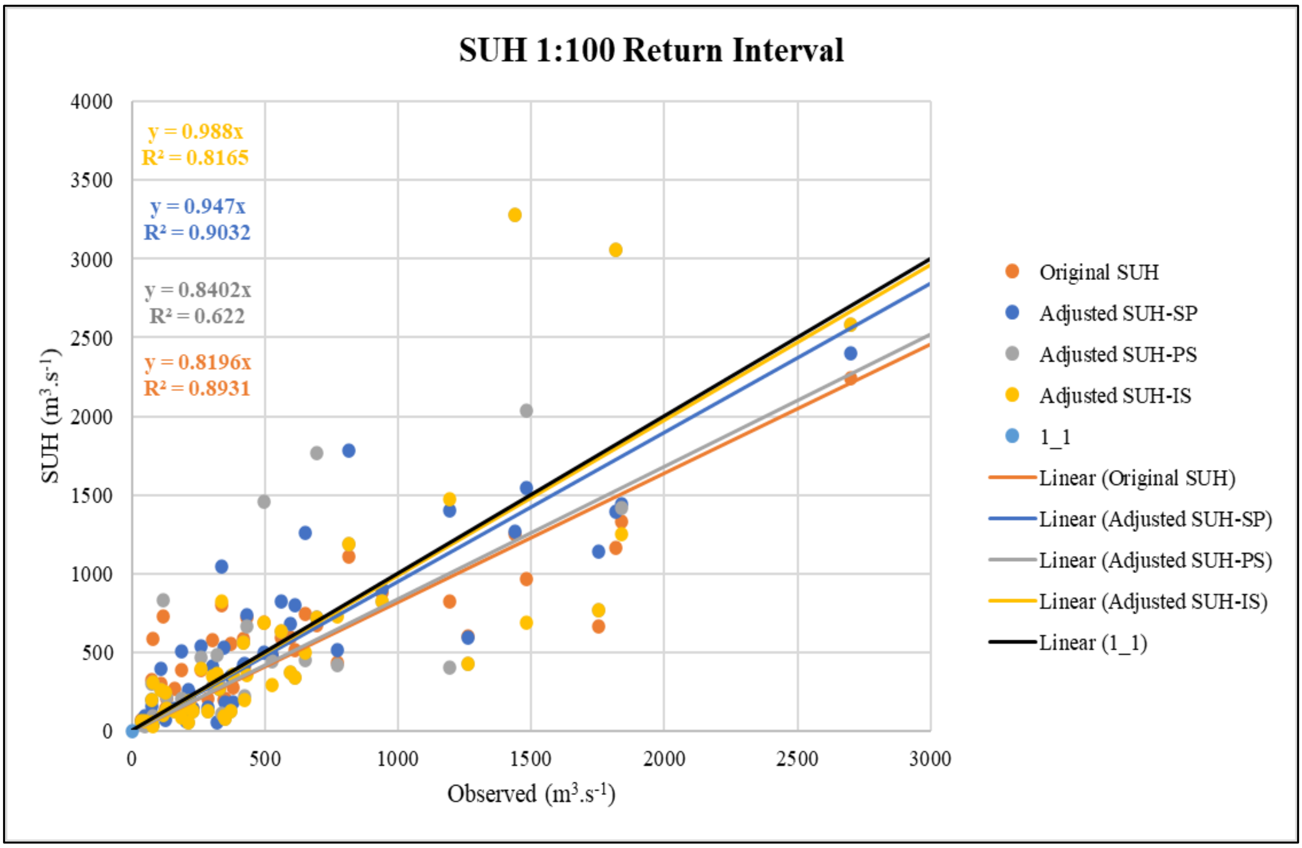


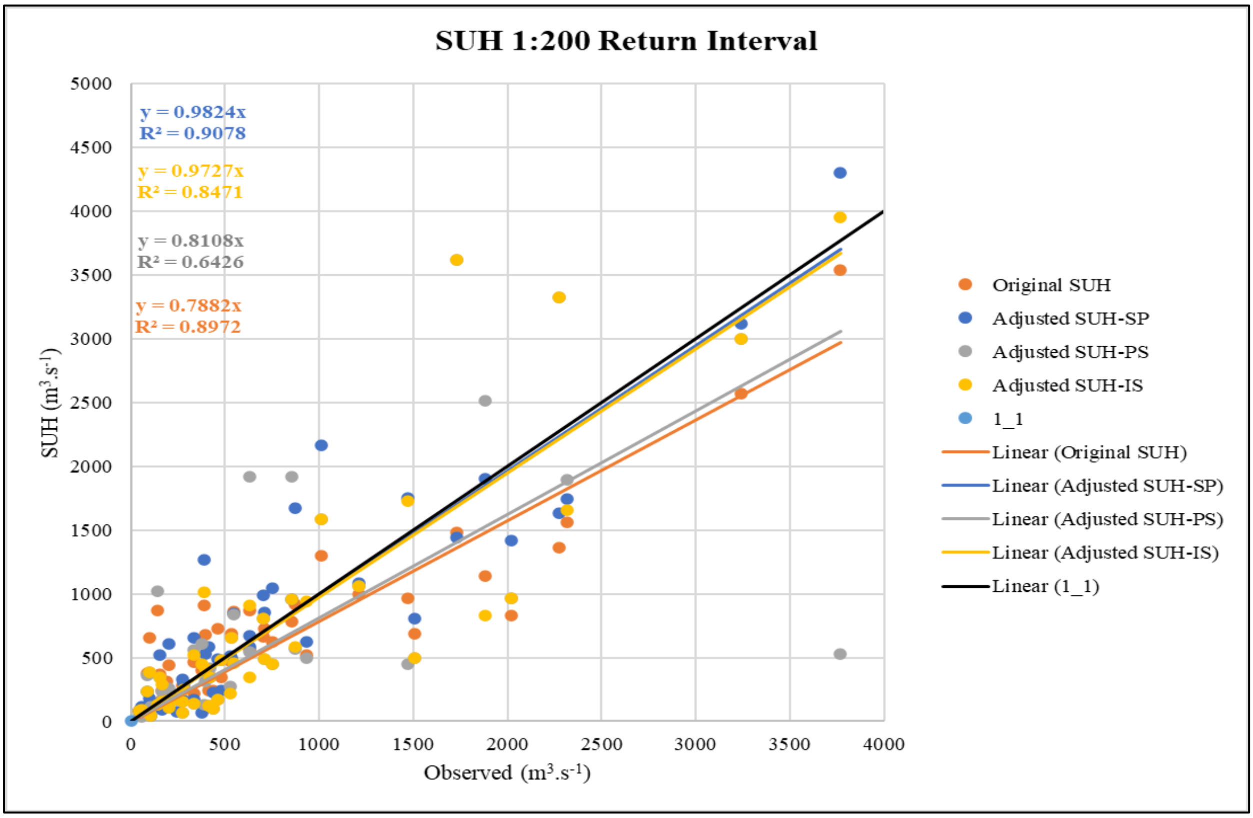



SUH 1:10 Return Interval
y = 1.0094x
R² = 0.8471
y = 1.0326x
R² = 0.6201
y = 0.9739x
R² = 0.4951
y = 0.7862x
R² = 0.8226
SUH (m³.s⁻¹)
Observed (m³.s⁻¹)
0
200
400
600
800
1000
1200
1400
1600
0
250
500
750
1000
1250
Original SUH
Adjusted SUH-SP
Adjusted SUH-PS
Adjusted SUH-IS
1_1
Linear (Original SUH)
Linear (Adjusted SUH-SP)
Linear (Adjusted SUH-PS)
Linear (Adjusted SUH-IS)
Linear (1_1)


SUH 1:20 Return Interval
y = 1.0272x
R² = 0.7153
y = 0.9284x
R² = 0.5548
y = 0.9223x
R² = 0.8662
y = 0.8461x
R² = 0.861
SUH (m³.s⁻¹)
Observed (m³.s⁻¹)
0
400
800
1200
1600
2000
0
200
400
600
800
1000
1200
1400
1600
Original SUH
Adjusted SUH-SP
Adjusted SUH-PS
Adjusted SUH-IS
1_1
Linear (Original SUH)
Linear (Adjusted SUH-SP)
Linear (Adjusted SUH-PS)
Linear (Adjusted SUH-IS)
Linear (1_1)

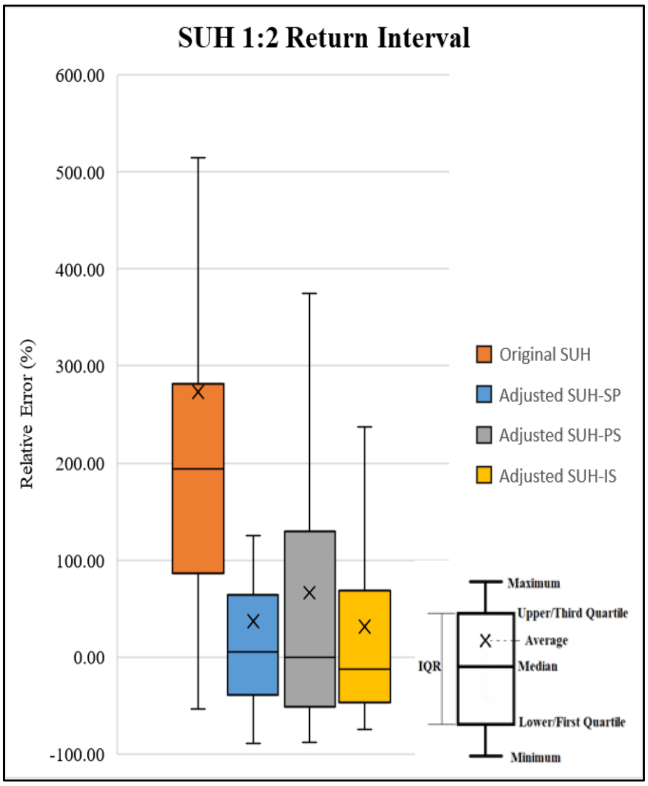

SUH 1:50 Return Interval
y = 1.0041x
R² = 0.7791
y = 0.8991x
R² = 0.8885
y = 0.8698x
R² = 0.5923
y = 0.8534x
R² = 0.8834
SUH (m³.s⁻¹)
Observed (m³.s⁻¹)
0
500
1000
1500
2000
2500
3000
0
400
800
1200
1600
2000
2400
Original SUH
Adjusted SUH-SP
Adjusted SUH-PS
Adjusted SUH-IS
1_1
Linear (Original SUH)
Linear (Adjusted SUH-SP)
Linear (Adjusted SUH-PS)
Linear (Adjusted SUH-IS)
Linear (1_1)

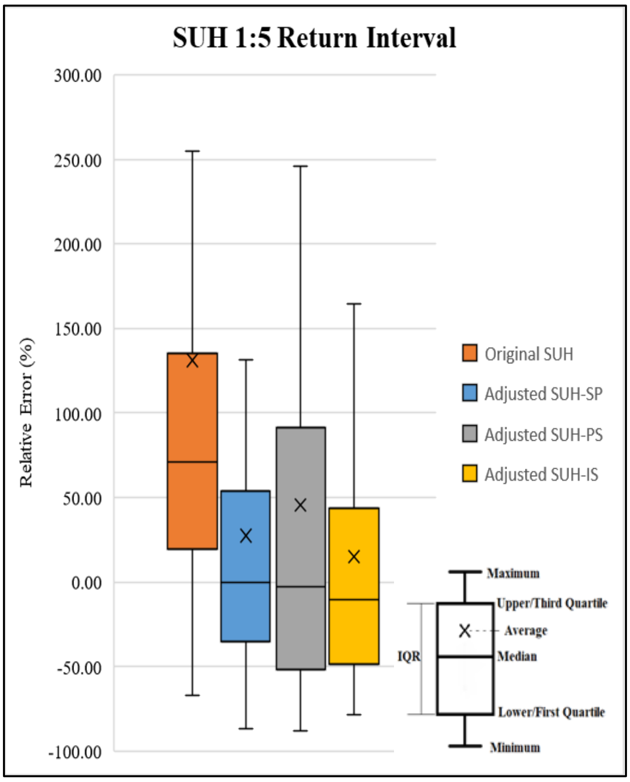

SUH 1:100 Return Interval
y = 0.988x
R² = 0.8165
y = 0.947x
R² = 0.9032
y = 0.8402x
R² = 0.622
y = 0.8196x
R² = 0.8931
SUH (m³.s⁻¹)
Observed (m³.s⁻¹)
0
500
1000
1500
2000
2500
3000
3500
4000
0
500
1000
1500
2000
2500
3000
Original SUH
Adjusted SUH-SP
Adjusted SUH-PS
Adjusted SUH-IS
1_1
Linear (Original SUH)
Linear (Adjusted SUH-SP)
Linear (Adjusted SUH-PS)
Linear (Adjusted SUH-IS)
Linear (1_1)

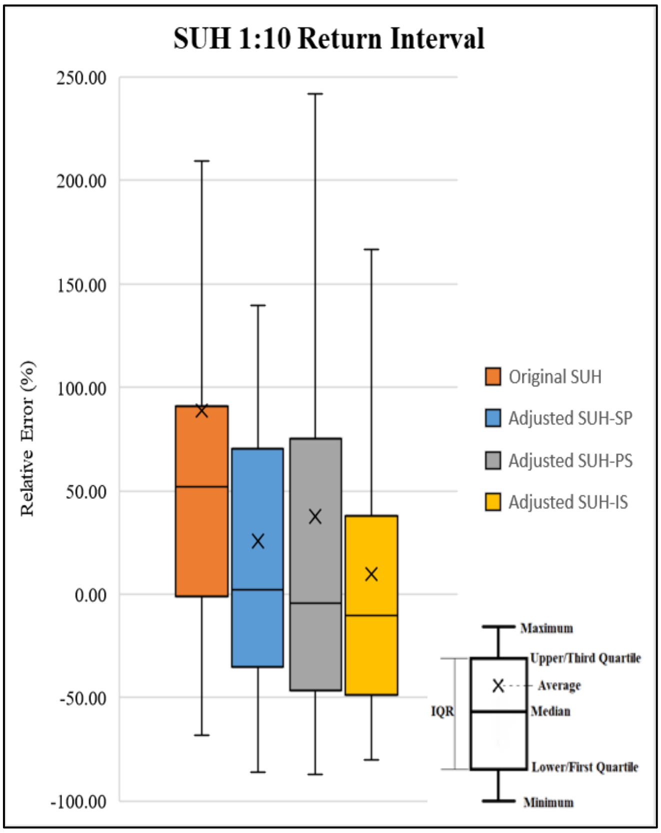


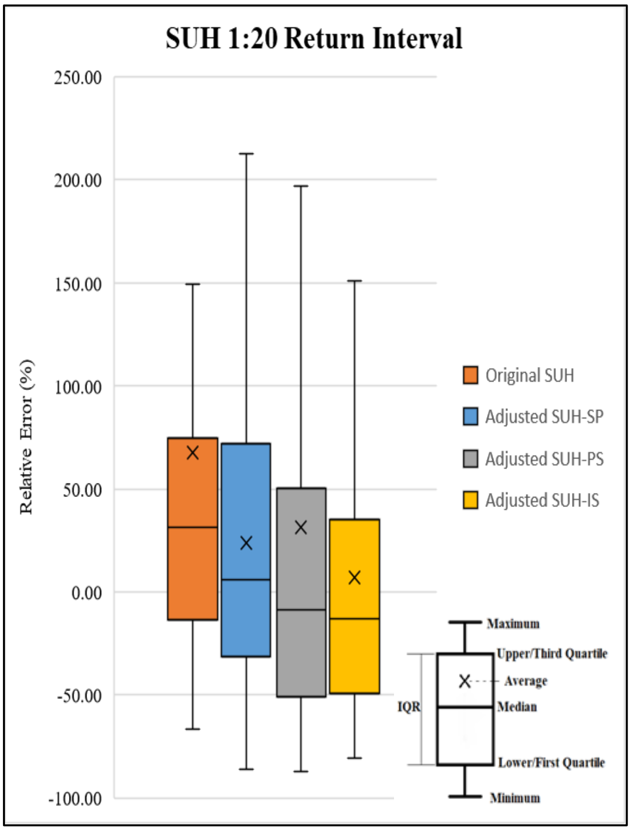
SUH 1:200 Return Interval
y = 0.9824x
R² = 0.9078
y = 0.9727x
R² = 0.8471
y = 0.8108x
R² = 0.6426
y = 0.7882x
R² = 0.8972
SUH (m³.s⁻¹)
Observed (m³.s⁻¹)
Original SUH
Adjusted SUH-SP
Adjusted SUH-PS
Adjusted SUH-IS
1_1
Linear (Original SUH)
Linear (Adjusted SUH-SP)
Linear (Adjusted SUH-PS)
Linear (Adjusted SUH-IS)
Linear (1_1)

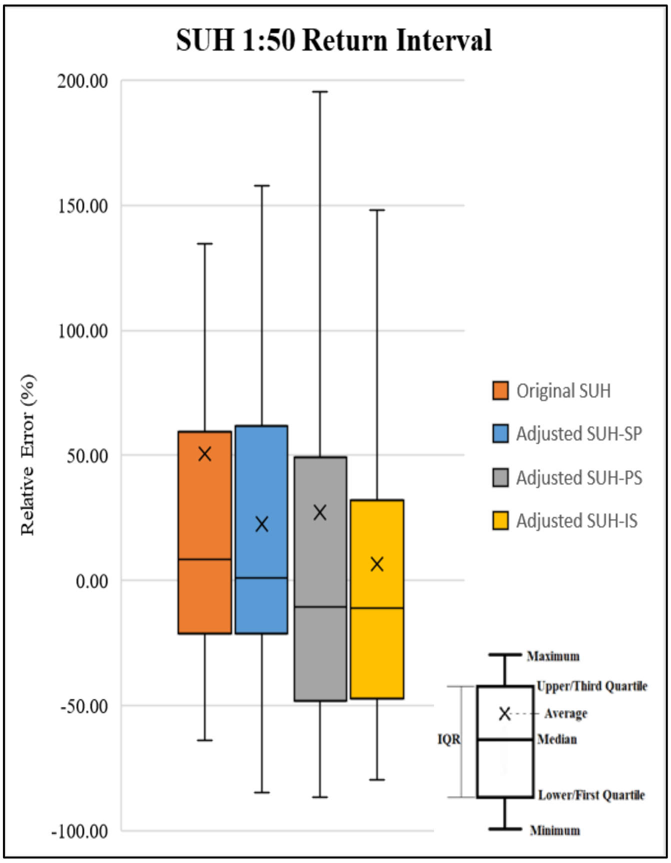
APPENDIX C2 SUH BOX AND WHISKER PLOTS OF REs

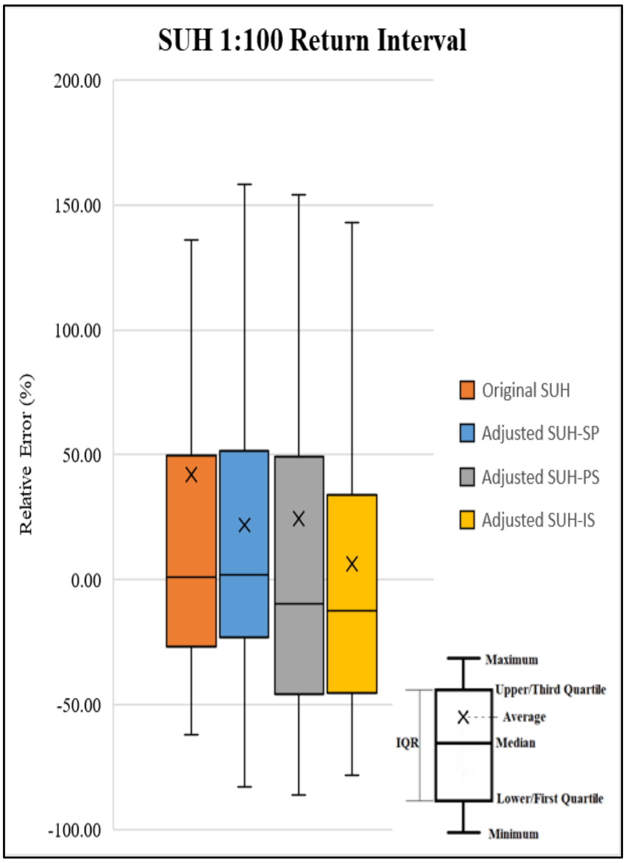


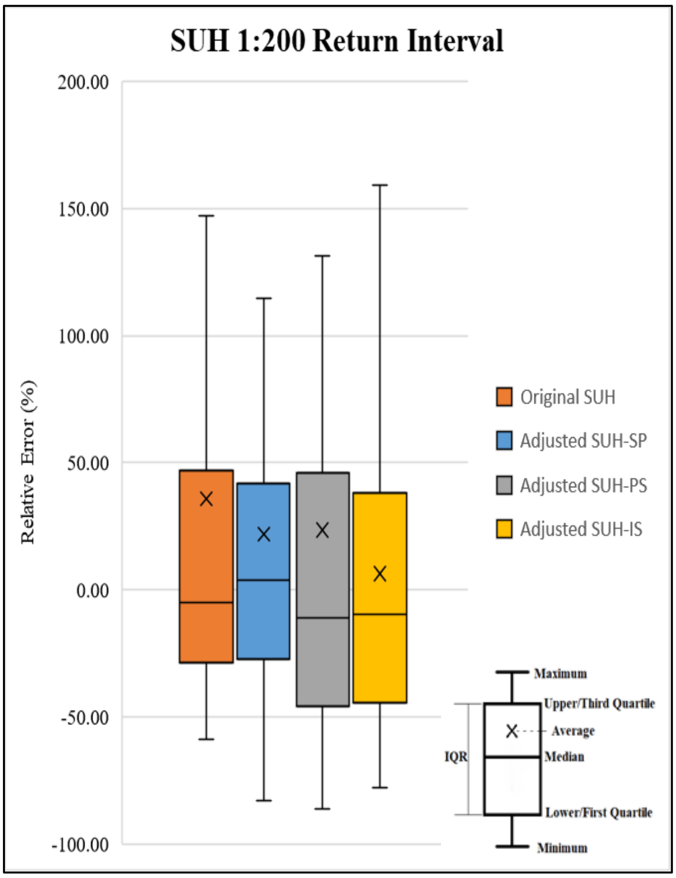


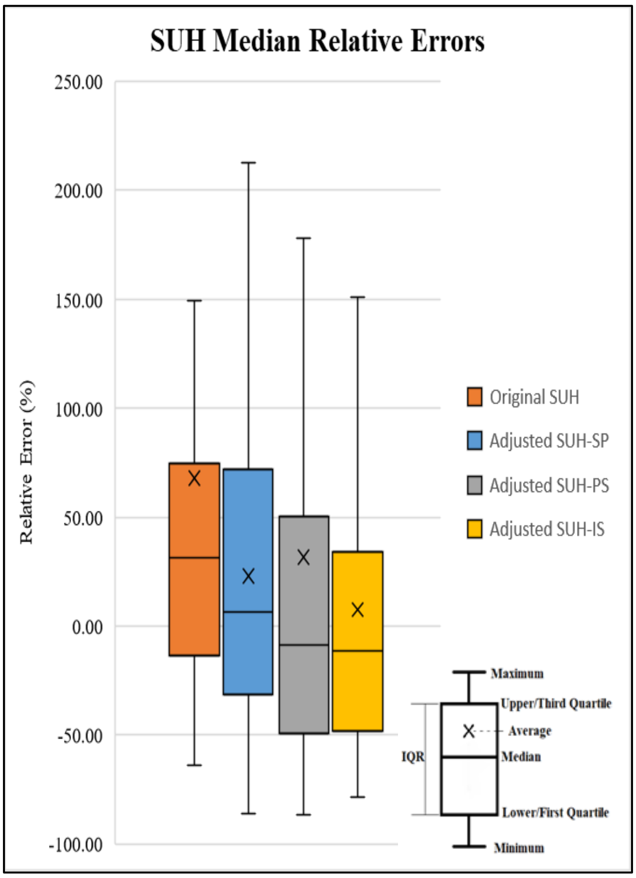




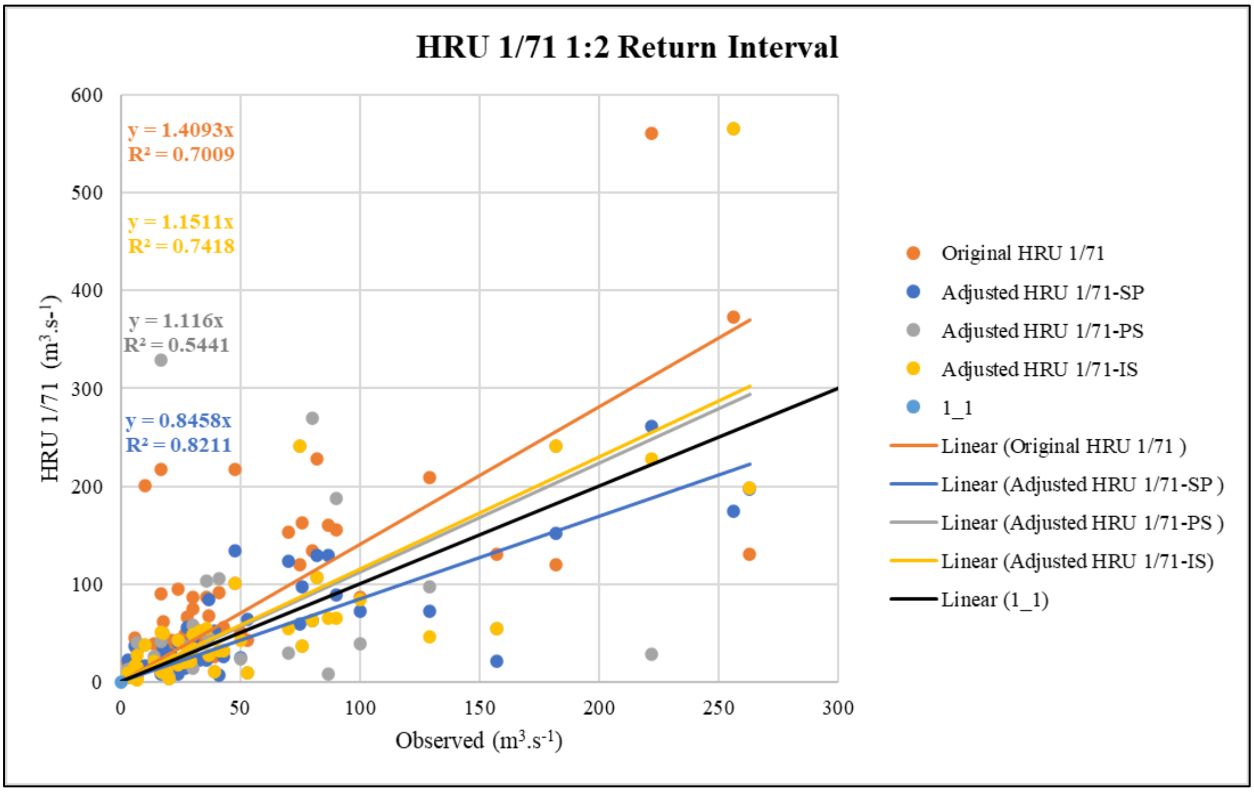

SUH 1:50 Return Interval
Relative Error (%)
200.00
150.00
100.00
50.00
0.00
-50.00
-100.00
Original SUH
Adjusted SUH-SP
Adjusted SUH-PS
Adjusted SUH-IS
Maximum
Upper/Third Quartile
Average
Median
IQR
Lower/First Quartile
Minimum

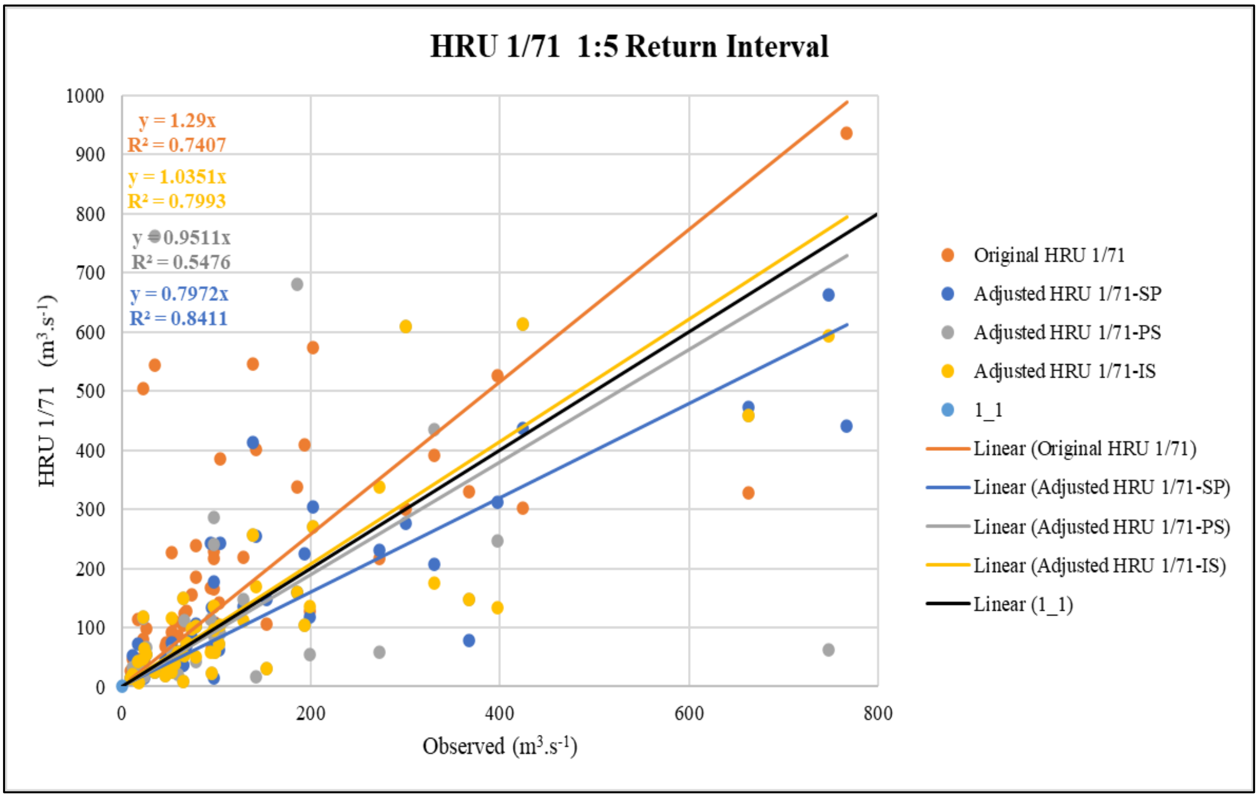

SUH 1:100 Return Interval
Relative Error (%)
200.00
150.00
100.00
50.00
0.00
-50.00
-100.00
Original SUH
Adjusted SUH-SP
Adjusted SUH-PS
Adjusted SUH-IS
Maximum
Upper/Third Quartile
Average
Median
IQR
Lower/First Quartile
Minimum

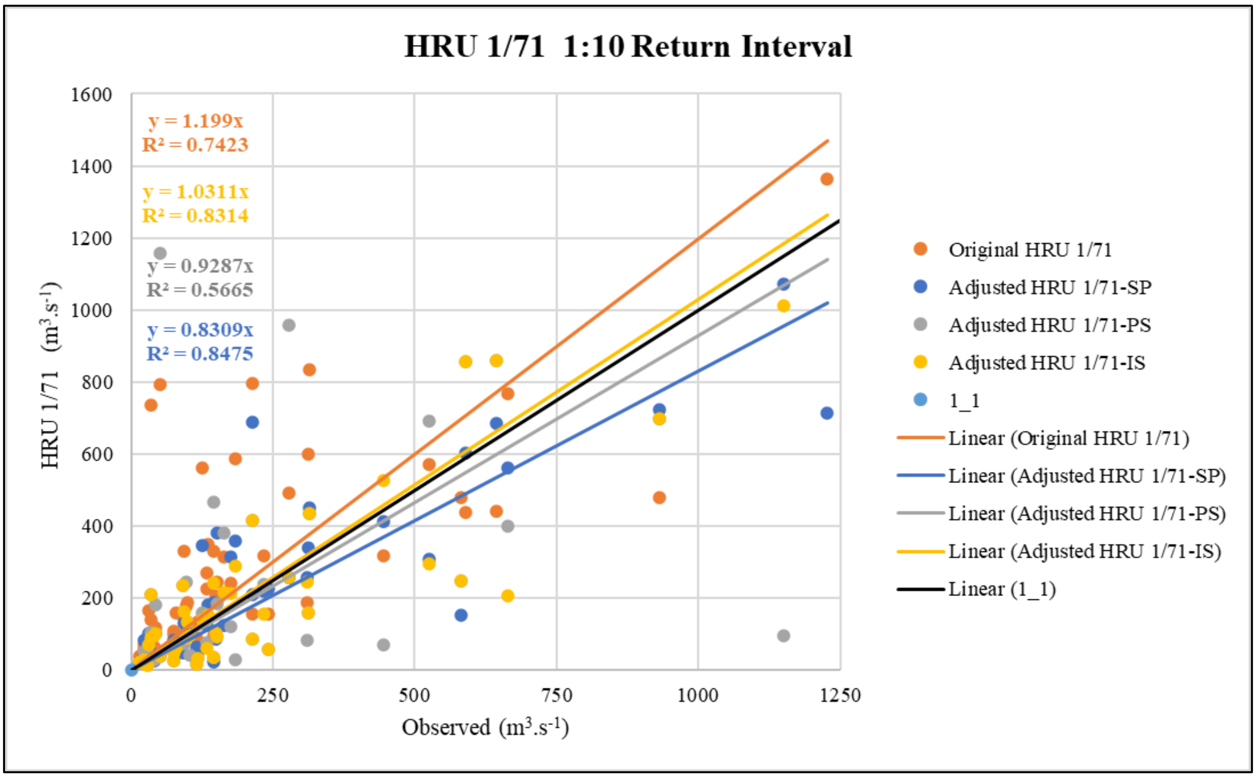

SUH 1:200 Return Interval
Relative Error (%)
200.00
150.00
100.00
50.00
0.00
-50.00
-100.00
Original SUH
Adjusted SUH-SP
Adjusted SUH-PS
Adjusted SUH-IS
Maximum
Upper/Third Quartile
Average
Median
IQR
Lower/First Quartile
Minimum

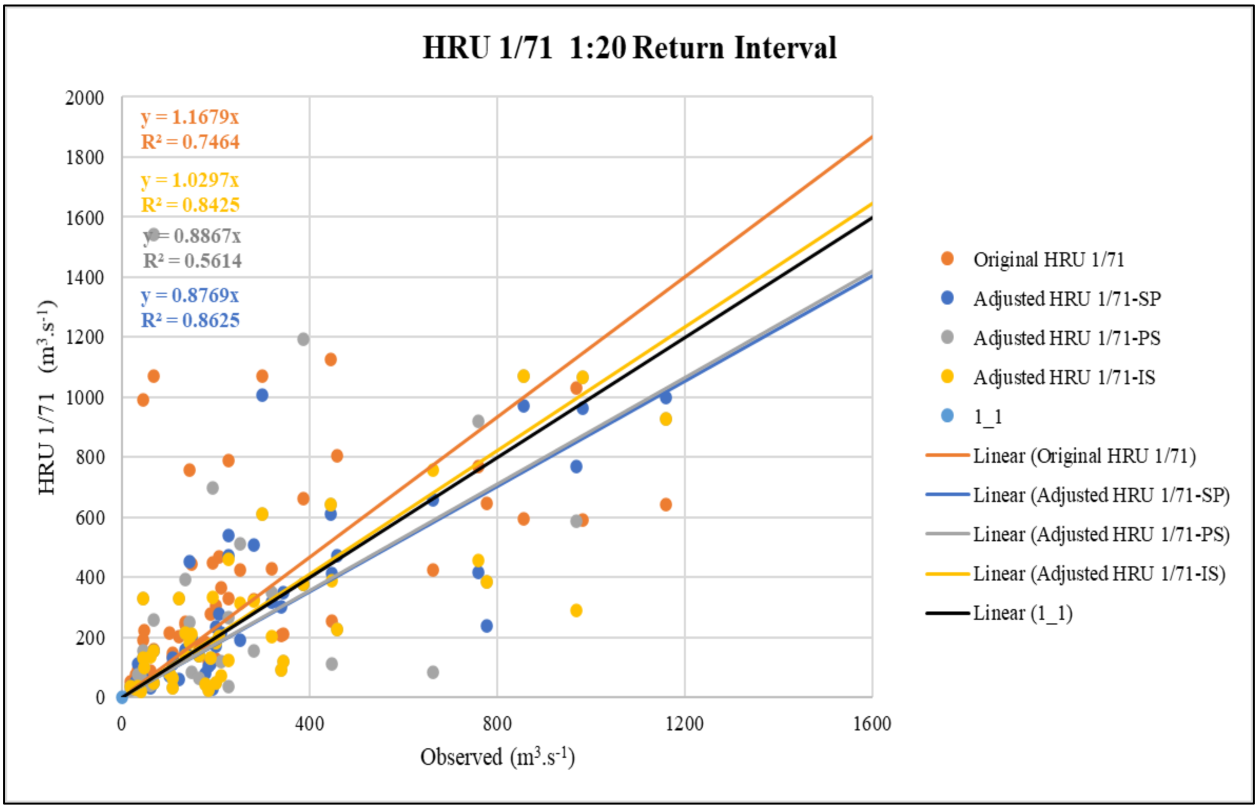

SUH Median Relative Errors
Relative Error (%)
250.00
200.00
150.00
100.00
50.00
0.00
-50.00
-100.00
Original SUH
Adjusted SUH-SP
Adjusted SUH-PS
Adjusted SUH-IS
Maximum
Upper/Third Quartile
Average
Median
IQR
Lower/First Quartile
Minimum

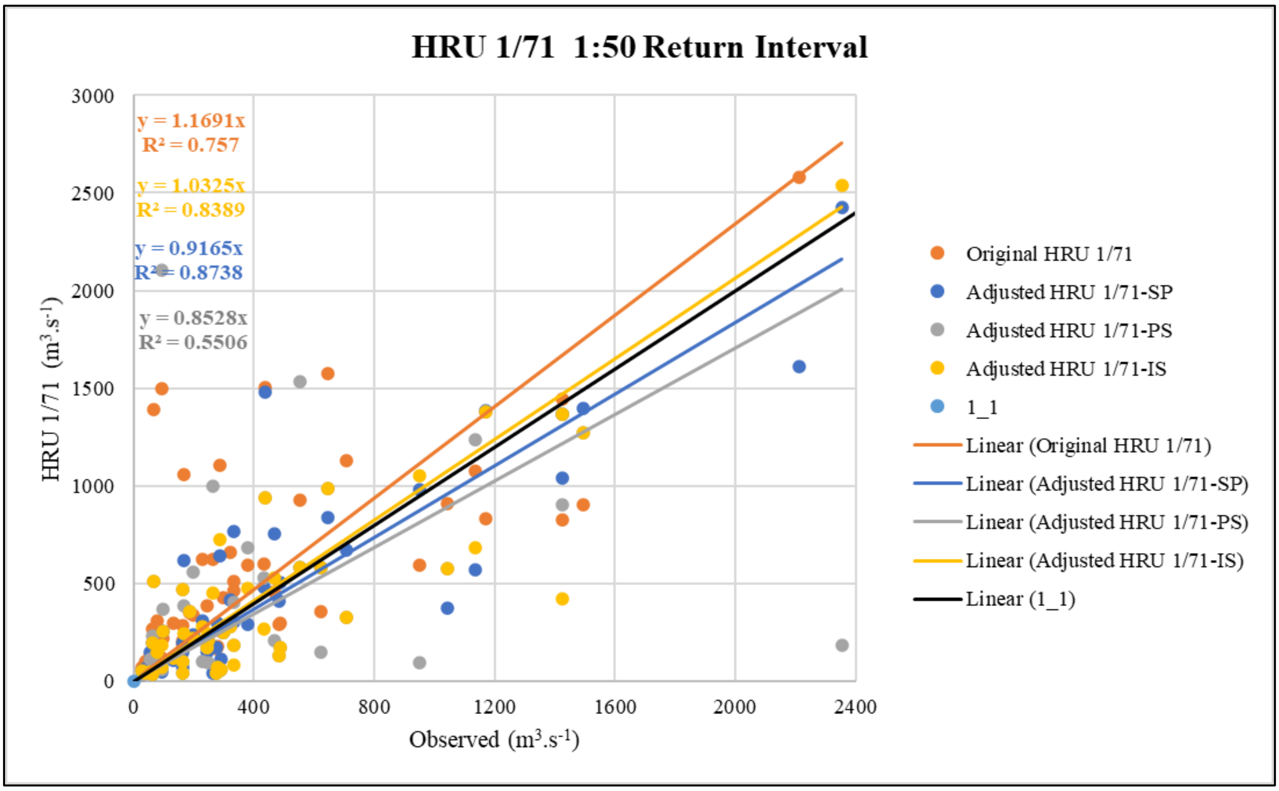
APPENDIX D1 HRU 1/71 SCATTER PLOTS

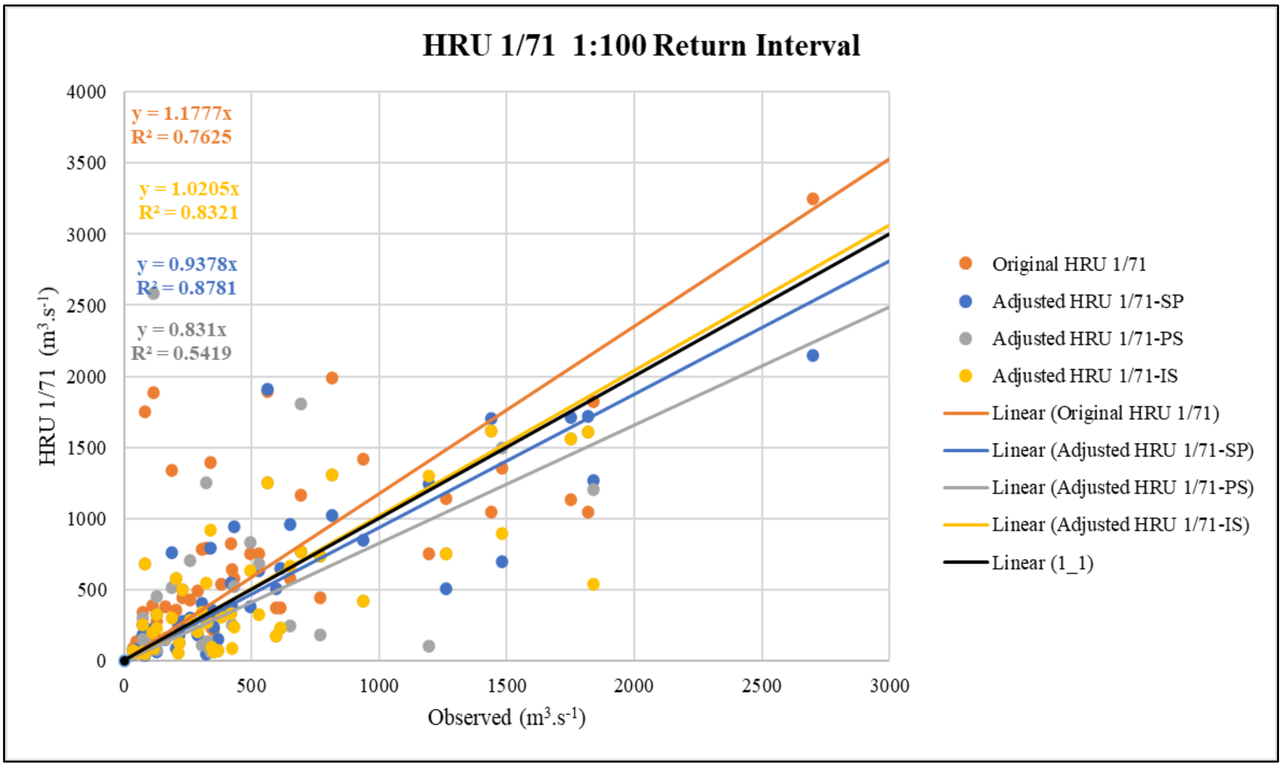


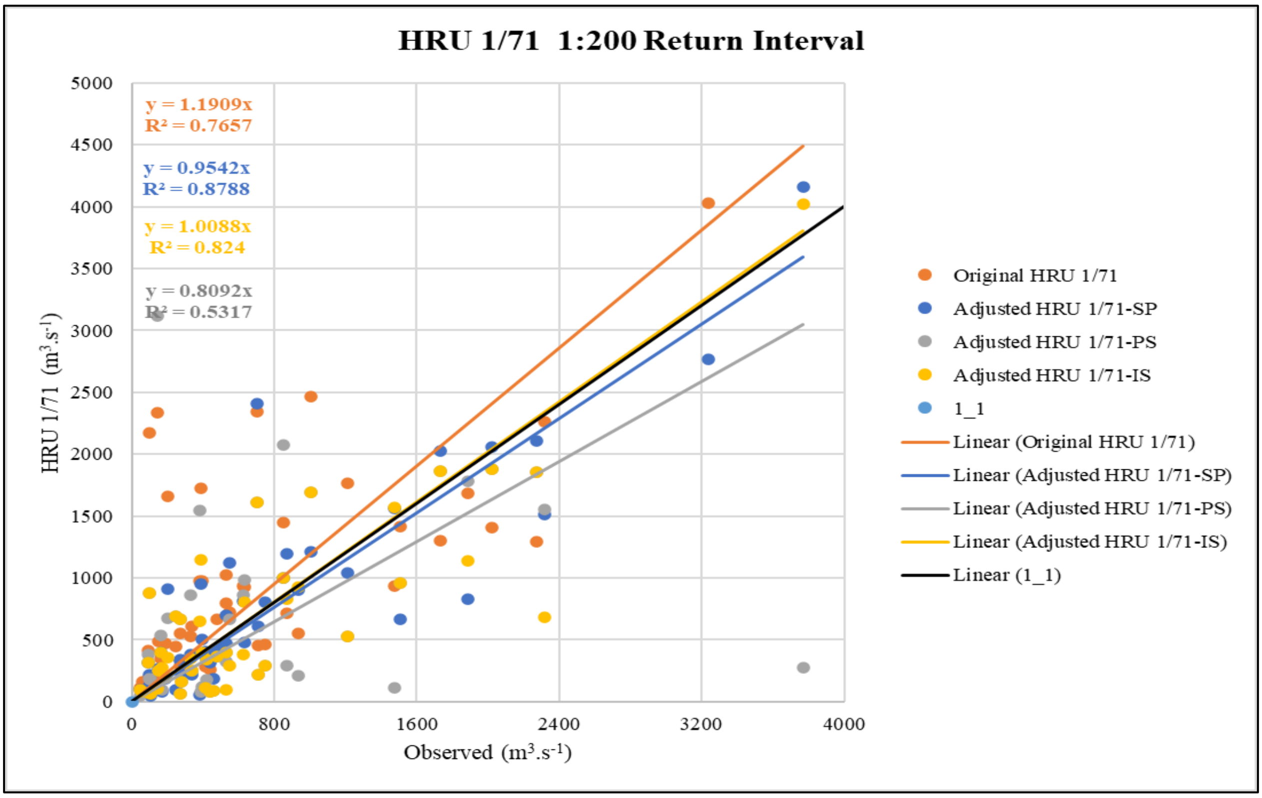



HRU 1/71 1:10 Return Interval
y = 1.199x
R² = 0.7423
y = 1.0311x
R² = 0.8314
y = 0.9287x
R² = 0.5665
y = 0.8309x
R² = 0.8475
HRU 1/71 (m3.s-1)
Observed (m3.s-1)
Original HRU 1/71
Adjusted HRU 1/71-SP
Adjusted HRU 1/71-PS
Adjusted HRU 1/71-IS
1_1
Linear (Original HRU 1/71)
Linear (Adjusted HRU 1/71-SP)
Linear (Adjusted HRU 1/71-PS)
Linear (Adjusted HRU 1/71-IS)
Linear (1_1)

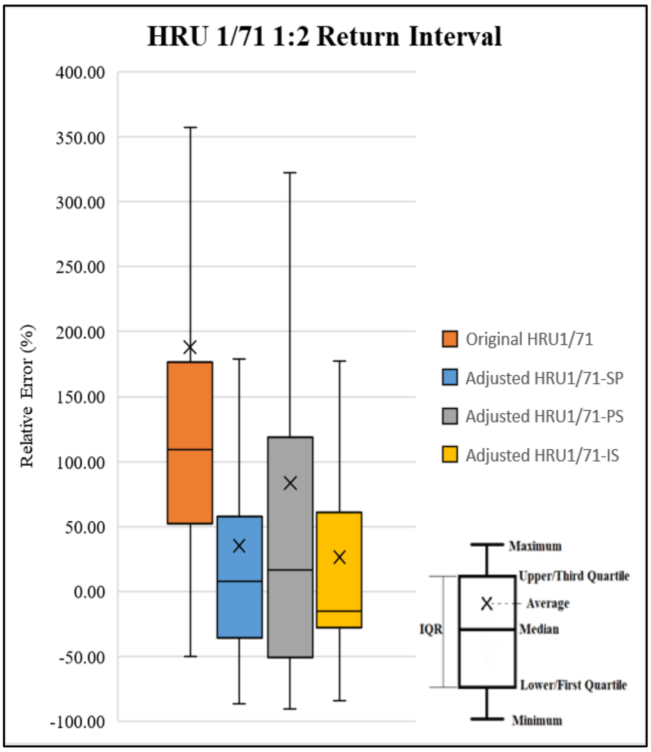

HRU 1/71 1:20 Return Interval
y = 1.1679x
R² = 0.7464
y = 1.0297x
R² = 0.8425
y = 0.8867x
R² = 0.5614
y = 0.8769x
R² = 0.8625
HRU 1/71 (m3.s-1)
Observed (m3.s-1)
Original HRU 1/71
Adjusted HRU 1/71-SP
Adjusted HRU 1/71-PS
Adjusted HRU 1/71-IS
1_1
Linear (Original HRU 1/71)
Linear (Adjusted HRU 1/71-SP)
Linear (Adjusted HRU 1/71-PS)
Linear (Adjusted HRU 1/71-IS)
Linear (1_1)

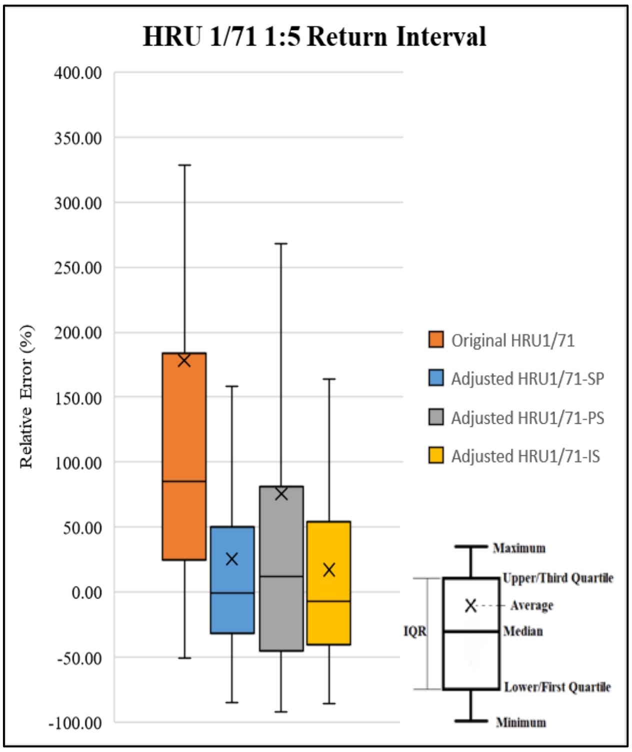

HRU 1/71 1:50 Return Interval
y = 1.1691x
R² = 0.757
y = 1.0325x
R² = 0.8389
y = 0.9165x
R² = 0.8738
y = 0.8528x
R² = 0.5506
HRU 1/71 (m³.s⁻¹)
Observed (m³.s⁻¹)
Original HRU 1/71
Adjusted HRU 1/71-SP
Adjusted HRU 1/71-PS
Adjusted HRU 1/71-IS
1_1
Linear (Original HRU 1/71)
Linear (Adjusted HRU 1/71-SP)
Linear (Adjusted HRU 1/71-PS)
Linear (Adjusted HRU 1/71-IS)
Linear (1_1)

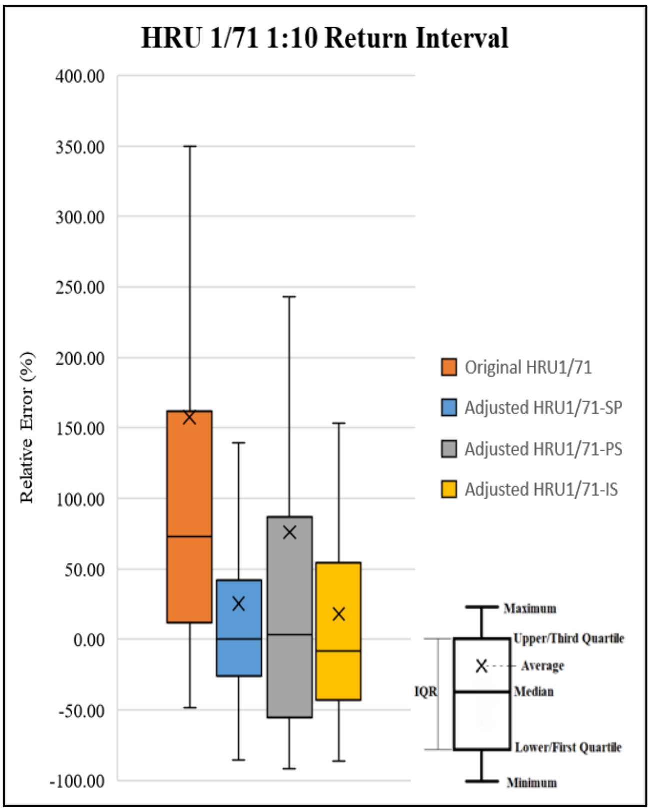

HRU 1/71 1:100 Return Interval
y = 1.1777x
R² = 0.7625
y = 1.0205x
R² = 0.8321
y = 0.9378x
R² = 0.8781
y = 0.831x
R² = 0.5419
HRU 1/71 (m³.s⁻¹)
Observed (m³.s⁻¹)
Original HRU 1/71
Adjusted HRU 1/71-SP
Adjusted HRU 1/71-PS
Adjusted HRU 1/71-IS
Linear (Original HRU 1/71)
Linear (Adjusted HRU 1/71-SP)
Linear (Adjusted HRU 1/71-PS)
Linear (Adjusted HRU 1/71-IS)
Linear (1_1)

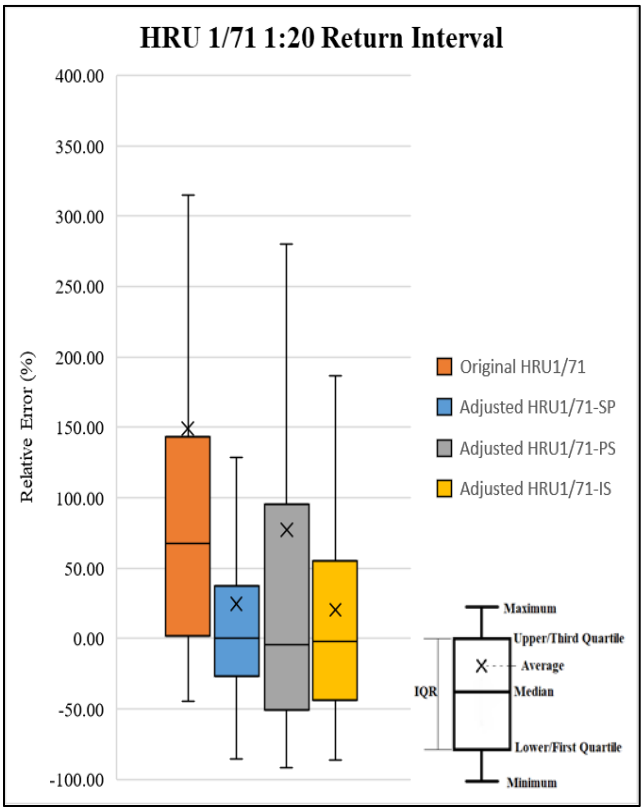

HRU 1/71 1:200 Return Interval
y = 1.1909x
R² = 0.7657
y = 0.9542x
R² = 0.8788
y = 1.0088x
R² = 0.824
y = 0.8092x
R² = 0.5317
HRU 1/71 (m³.s⁻¹)
Observed (m³.s⁻¹)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0
800
1600
2400
3200
4000
Original HRU 1/71
Adjusted HRU 1/71-SP
Adjusted HRU 1/71-PS
Adjusted HRU 1/71-IS
1_1
Linear (Original HRU 1/71)
Linear (Adjusted HRU 1/71-SP)
Linear (Adjusted HRU 1/71-PS)
Linear (Adjusted HRU 1/71-IS)
Linear (1_1)

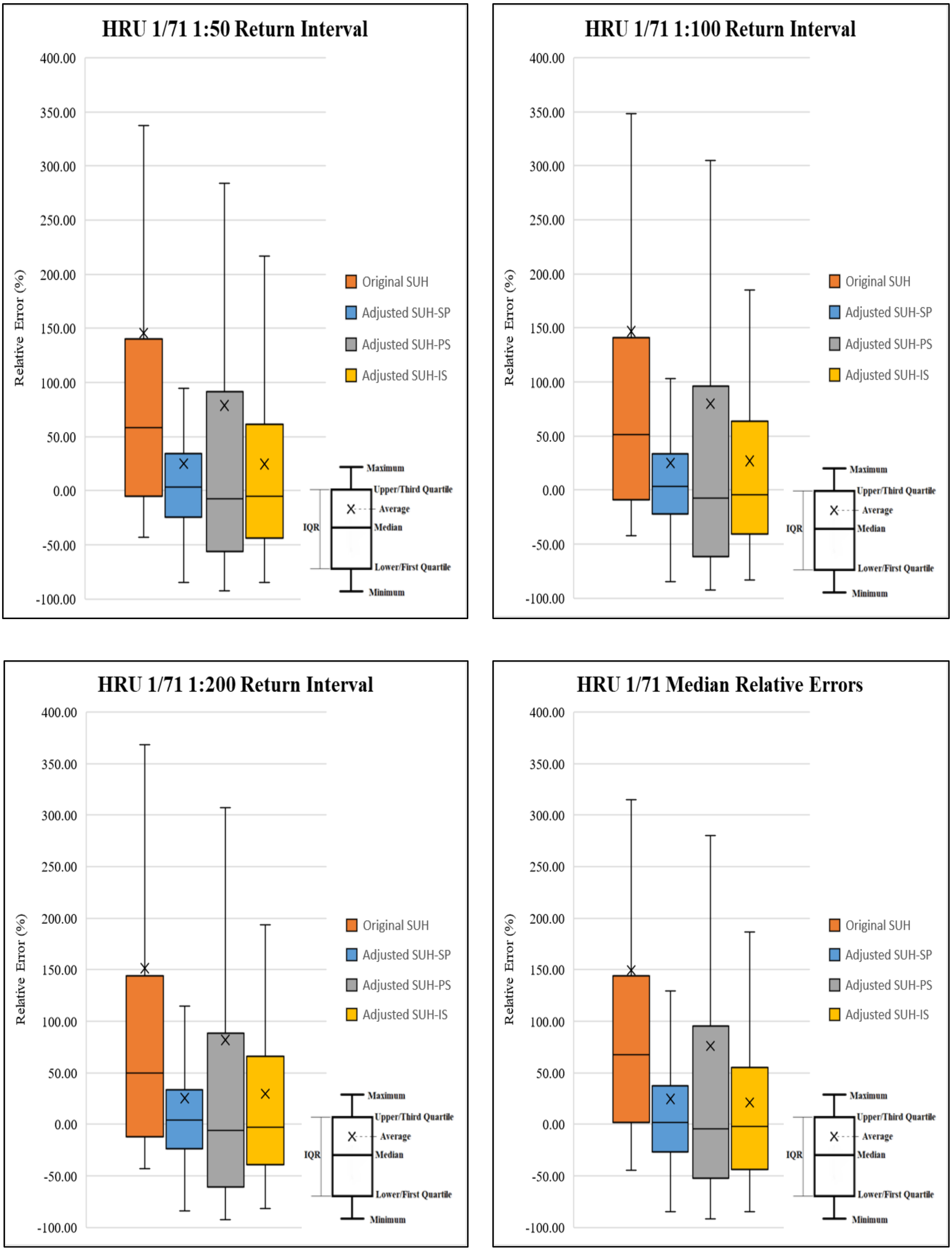
APPENDIX D2 HRU 1/71 BOX AND WHISKER PLOTS OF REs










HRU 1/71 1:50 Return Interval
HRU 1/71 1:100 Return Interval
HRU 1/71 1:200 Return Interval
HRU 1/71 Median Relative Errors
Relative Error (%)
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
-50.00
-100.00
Original SUH
Adjusted SUH-SP
Adjusted SUH-PS
Adjusted SUH-IS
Maximum
Upper/Third Quartile
Average
Median
IQR
Lower/First Quartile
Minimum