EVALUATION OF THE PERFORMANCE OF FREQUENCY AND CHRONOLOGICAL PAIRING TECHNIQUES IN SYNTHESISING LONG-TERM STREAMFLOW

by

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Abstract

The mountainous regions of British Columbia, Canada, are unique landscapes that are providing opportunities for the development of small, run-of-river hydropower projects. To design these projects effectively, long-term streamflow records are required. Ideally, such designs would utilize long-term records directly from a Project site and hydrologic models used to generate site streamflow estimates would not be necessary. However, these projects are rarely located in streams with long-term records, and hydrologic models are invariably required.

This research evaluates the performance of two pairing techniques that are used hydrotechnical consultants to derive long-term streamflow; Chronological Pairing (CP) and Empirical Frequency Pairing (EFP). Three hydro-climatic regimes, common in British Columbia, were investigated, including Pluvial, Glacial and Nival regimes. The evaluations discussed in this research were based on comparisons of derived long-term streamflow estimates through pairing studies, to actual measured streamflow records.

The research found that EFP, which is a relatively new approach to synthetically generating long-term streamflow records, consistently out-performed CP techniques. EFP accurately and precisely modelled extremely high and low runoff percentiles (1st and 99th percentiles) as well as the mean annual discharge and Flood Frequency Analysis parameter inputs, such as the mean and standard deviation of the annual flood maxima. A key finding of this research was that between three and four years of high quality project streamflow data were necessary to provide a representative sample to derive a synthetic series that will not significantly improve with the incorporation of additional data. The results of this research will be useful when selecting hydrologic models for derivation of long-term streamflow estimates from short-term records in mountainous watersheds. The research also found several cautions in the use of both methods, but particularly in the CP method. The binding CP relationship and the influence of outliers, resulted in poor performance of CP in modelling long-term streamflow. Extrapolation above maximum measured values within the concurrent period was a technique that has a significant bearing on the accuracy and precision of the very highest percentiles, but especially on defining the variability of annual floods.
Preface

The techniques discussed in this paper, as they relate to generating long-term synthetic runoff data through an Empirical Frequency Pairing approach, were first proposed by Craig Nistor and Dr. Jaime Cathcart, of Knight Piésold Ltd. (Canada) in early 2007. These concepts were further developed in collaboration with Mr Kyle Terry and Mr Toby Perkins, for use on small hydropower and mining projects in British Columbia.

Other workers in this field include Dr. Younes Alila, from the University of British Columbia, and Dr. Robert G. Millar, the Lead Supervisor of the present research. Dr. Alila has used Frequency Pairing as a means of more reliably assessing land use effects during Flood Frequency Analysis: effects that go undetected using standard Chronological Pairing techniques (Alila et al, 2009). Dr. Millar has investigated the principles of Frequency Pairing to synthesize long-term precipitation by establishing and correlating frequency paired short and long-term frequency distributions (Millar, 2013).

The author gratefully and respectfully acknowledges these individuals for their technical guidance and ongoing contributions to this growing body of work.
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1.1 CONTEXT

Canada contains an estimated 7% of the world’s entire renewable surface water supply and the Province of British Columbia (BC), on the Pacific West Coast, arguably contains among the world’s most complex and diverse hydro-climatic regimes. Such diversity makes understanding and managing the Province’s water resources a great challenge as well as a serious and sobering responsibility. The hydrology and physiography of BC provides opportunities for the development of small, run-of-river hydropower projects. These projects are being encouraged in order to provide sources of renewable energy for the Province. In response to this opportunity and need, numerous hydropower projects are being proposed and developed across BC and the responsible exploitation of these water resources present opportunities for the sustainable future of the Province by protecting the environment, supporting economies, and attracting investment and residents to remote communities.

Feasibility of a hydropower project is dependent on numerous factors. A consistently critical component of feasibility is the accurate and precise estimation of streamflow; hydropower production is directly dependent on available streamflow. The Water Survey of Canada (WSC), a branch of Environment Canada, operates and maintains over 2,500 hydrometric monitoring stations across Canada, including public access to real-time data collected at over 1,700 stations. These stations have become essential in reducing uncertainty associated with project streamflow estimates. However, many hydropower projects are located in remote and rugged regions of the Province, on ungauged rivers and streams. Consequently, directly applicable long-term streamflow records are not generally available. Regional approximation of these streamflow records will suffice for preliminary estimates of Project feasibility, but increased accuracy and precision is required as projects move forward into full feasibility and detailed design.

In recognition of the importance of streamflow on project viability, on-site streamflow data collection are often initiated as one of the first monitoring activities for hydropower Projects, and proponents will collect a few years of streamflow data for their project site. These short-term data, by themselves, are generally
not of sufficient length to characterize streamflow for project design. Hydrologic analysis techniques, such as “Pairing”, present a means of deriving long-term streamflow estimates from short-term streamflow records. These long-term estimates can be used to derive important project-specific design and environmental parameters.

Inaccurate and imprecise streamflow estimates can have a substantial effect on viability, constructability, safety, and environment compliance of these Projects.

1.2 OBJECTIVES OF RESEARCH

The objectives of this research were to evaluate the performance of two principal pairing techniques: Chronological Pairing (CP) and Empirical Frequency Pairing (EFP) in deriving long-term streamflow estimates at sites with short-term records. Three hydro-climatic regimes in BC were investigated and long-term streamflow records were derived for a catchment in each of these regimes using CP and EFP techniques. The derived records were then compared to the equivalent long-term measured records. These comparisons provided a quantitative assessment of the general performance of these hydrologic modelling techniques. The results of this research will be useful to practitioners when selecting hydrologic models for deriving long-term streamflow estimates from short-term records.

1.3 HYDROLOGIC MODELLING

Although highly variable and influenced by numerous factors that are complex, integrative and difficult to quantify, runoff within any given watershed is unique, but not entirely random. Runoff is a stochastic process that occurs randomly, but within the constraints of a derived frequency distribution which, at the commencement of many Projects, is largely undefined and often only vaguely understood based on a priori knowledge of regional runoff characteristics. Runoff is stochastic because it is largely a function of its stochastic inputs – namely precipitation, but temperature can be the most prominent in some regions or at certain times of the year when snowmelt or glacial melt is significant. Other secondary factors can have a significant bearing on the frequency distribution of runoff, such as drainage area, latitude, regional physiography, elevation, vegetation, land use, and the types of rock, soils and antecedent moisture, but these factors are often secondary to precipitation and temperature.
1.3.1 Units of Runoff

Although any conventional unit of discharge could be used, this research uses unit runoff, which is discharge calculated as a function of drainage area. Unit runoff is calculated by:

\[ UR = \frac{Q \times 1000}{CA} \]

Where, \( UR \) is the unit runoff, given in L/s/km\(^2\), \( Q \) is the discharge, given in m\(^3\)/s, and \( CA \) is the catchment area, given in km\(^2\).

1.3.2 Pairing Overview

The primary objective of pairing is to develop a physically-based mathematical relationship between the project (short-term) and regional (long-term) sites, and to use this relationship to derive a synthetic long-term record for project sites. Pairing is a common modelling tool in engineering and science and is used to develop relationships between like parameters, based on either their time of occurrence, in the case of CP (discussed further in Section 1.3.5), or their frequency of occurrence, in the case of EFP (discussed further in Section 1.3.8).

Through application of pairing techniques, it is widely assumed in the consulting community that the more site data available for inclusion into a pairing model, the more accurate and precise resultant long-term estimates will be. This assumption is often the basis for the extensive periods of baseline data collection required that are recommended in order to refine streamflow estimates for many of these projects.

Pairing requires the development of relationships between streamflow datasets that are expected to show physically similar characteristics within the sample and across the population. Hence, pairing overcomes the necessity to quantify and model secondary parameters by correlating the relationship between the required parameters only, and assumes that the influence of secondary parameters on required parameters is not only captured within the model but is consistent throughout the population. For example, antecedent moisture content (AMC) is an important driver in runoff generation but its effect is highly variable and extremely difficult to estimate. Pairing assumes that the developed relationship between streamflow records encapsulates the effect of AMC and that the developed relationship will
model this effect, in its entirety, across the entire population dataset. Similarly, temperature is an important determinate in the phase of precipitation (liquid or solid), and the rate of glacial and snowmelt, which in turn will determine runoff characteristics. Thus, correlating streamflow records directly will overcome the need to integrate temperature into a model.

The derived long-term streamflow estimates therefore have many practical applications, such as Flood Frequency Analysis (FFA), Low Flow Analysis (LFA), and assessment of Return Period Wet and Dry Years. FFA is dependent on an accurate and precise estimation of return period flood magnitudes for design inputs. Low flow studies, including 7-Day low flows are of particular importance to environmental assessments, project operations and feasibility studies. Hydropower developments in particular are wholly reliant upon long-term synthetic streamflow estimates as the principal input to energy generation calculations.

Pairing, in its many forms, has been used extensively for development of long-term precipitation and streamflow estimates for hydropower projects throughout British Columbia.

1.3.3 Runoff Mechanisms and Hydrograph Segregation

For streamflow estimates, hydrometric data from monitoring stations located in key catchments, are paired based on an underlying assumption that, though physically separate, may nonetheless exhibit similar runoff characteristics if certain key physical criteria show evidence of similitude. This is given on Figure 1.1, which shows concurrent data from a single year (2011 in this case) from two separate datasets. Without knowing where these catchments were located, one could deduce that:

1) They are subject to similar hydro-climatic influences, due to similarities in the timing of runoff events,

2) The watersheds are likely of similar size and subject to similar runoff mechanisms, due to similarities in the magnitude of the peak unit runoff events.

However, as is frequently the case, a notable divergence in the runoff relationship is evident between these catchments in summer months (June to September). In this case, these differences are the result of different proportions of glacial melt between these catchments; the short-term catchment is known to
have lower proportional glacial cover than the long-term catchment. This is an important physical consideration when pairing. Segregation of the annual hydrograph into discrete periods (seasons or months) may be required to account for these different runoff mechanisms that are active at different times of the year and to avoid diluting the effect of these unique runoff generating mechanisms. Segregation will assume that these mechanisms are approximately constant within any given season or month for both the sample and population dataset. In addition to summer runoff, fall storm events, resulting from the passage of higher intensity, convective storm systems result in significant runoff events from September to October. These single events are the largest floods within the record shown, and it is clear that a similar trend to that observed during summer months is evident, where the long-term station shows higher proportional runoff. Finally, winter flows at both stations show a great deal of similarity with flows being proportional and showing similar responsiveness to runoff events.

1.3.4 Stationarity

The application of pairing assumes that the relationship between datasets is stationary and unchanging. However, such a condition can rarely be verified as many projects that utilize pairing techniques frequently contain only a short-period of record. This is an important consideration as many factors can impact the relationship between concurrent short-term data, such as changing land-use in one of the datasets (Alila et al., 2009). Changing land-use and climate factors potentially impact the stability and stationarity of the paired relationship, but in the context of pairing, these changes are primarily impacting the relationship between flow frequency distributions, by creating a divergence in the relationship between distributions. Furthermore, a changing climate, both in the context of climate change as well as climate oscillations, may also impact the stationarity of the flow distribution within and outside the constraints of the population dataset. Pairing techniques may model the impact of a changing climate within the population, but we will assume that any such changes will be equally impacted between datasets. As pairing is principally a method of hind-casting it will not predict estimates of the impact of a changing climate on future runoff, but will recreate historic runoff patterns that may incorporate the effects of a changing climate. The implications of climate change on long-term streamflow estimates are beyond the scope of this research.
Figure 1.1  Typical hydrograph relationship between paired catchments.
1.3.5 Pre-selection Criteria

Pairing is based on selection of catchments with similar characteristics including climate, size, aspect, elevation, and presence of lakes and glaciers (Oosterbaan, 1994). British Columbia may be divided into hydrologic zones, and within any one hydrologic zone, it is common that one, maybe two regional monitoring stations will satisfy some pre-selection requirements and may be incorporated into a hydrologic model. However, the effect of some of these parameters is negligible and often necessary to ignore for the sake of others. For example, a substantial difference in catchment area may be acceptable if the site has an extensive period of record (and will therefore create a long-term record that may be more statistically relevant). By contrast, a site that is, for all intents and purposes, identical to the project site, may be removed from further consideration if it is subject to attenuation from an upstream reservoir, wetland, or lake.

Once a candidate site has been selected and the pairing model is developed, applicable quantitative and qualitative model evaluation techniques can be used and will vary depending on the pairing technique. This is discussed further from Section 1.3.7 to Section 1.3.10.

1.3.6 Uncertainty

Measured data are inherently uncertain, but uncertainty is rarely able to be considered in establishing or evaluating a hydrologic model. Willmott (1981) and ASCE (1993) recognize that measured data are not error free, but that measurement error is often not considered in recommendations and modelling conclusions because of the relative lack of data on measurement uncertainty. Furthermore, even if information related to measurement uncertainties were available, it is not clear how to handle such uncertainties when developing models and presenting modelling results. Harmel et al. (2006) suggested that the uncertainty of measured data, which varies based on measurement conditions, techniques, and type, must be considered when evaluating watershed models. However, this is a reasonable suggestion with difficult implications for hydrologic models and techniques, such as pairing. Measurement uncertainty is often able to be quantified (such as stage measurement uncertainty), but an issue of transposition arises in how to tangibly utilize this uncertainty, and quantify its influence during analyses.
As a consequence, the uncertainty inherent in any data set is often disconnected during the modeling process, and, in most watershed models, model output is compared to corresponding measured data with the assumption that all error variance is contained within the predicted values and that measured values are error free (Moriasi et al., 2007). References to measurement uncertainty are made as a way of explaining some aspects of variability in model evaluation, but the ongoing issue of incorporating and quantifying uncertainty is crucial and complex, and not able to be incorporated into this research.

1.3.7 Chronological Pairing

Chronological Pairing (CP) is the “default” approach that seems intuitive to most hydrologists. CP is in widespread use (Harmel et al., 2006, Legates and McCabe, 1999, Moriasi et al., 2007, Willmott, 1981) and requires that streamflow records be paired chronologically (e.g. values from the same day or month) and that a usually linear relationship be developed between concurrent long-term regional data and the short-term Project site. An example of a typical CP relationship is given on Figure 1.2, which shows six years of chronologically paired January data from two paired watersheds. The relationship shown here is typical of chronologically paired data, with five characteristics evident in the relationship;

1) An increased density of paired points at the lower end of the relationship, reflecting generally more frequency runoff events,

2) The presence of anomalous data, particularly at the high end of the relationship,

3) The possible range of values in the Project creek associated with any one discharge value from the long-term regional creek,

4) The biasing effect of outliers on the entire regression equation, particularly at low flows,

5) Heteroscedasticity, which shows that variances in measured data along the line of best fit will increase within increasing runoff.
Figure 1.2  Typical Chronologically Paired relationship using simple linear equation

As shown on Figure 1.2, a line can be fitted to describe chronologically paired data, and the slopes and offsets of these lines can be used to define the CP relationship. Regression lines describing CP data are not necessarily always confined to simple linear equations, as shown here and investigated herein. Multi-linear, polynomial or other power functions may be used to define these relationships. However, as the purpose of these models is often to model runoff well beyond the extents of the calibration period, some non-linear equations can result in extrapolations that may make no physical sense. An example is a single parameter, multi-order polynomial equation, which may be used to more precisely fit an equation to the non-linear distribution of runoff within the sample period. Although such equations may be a more reasonable fit to concurrent paired data, when applied to the long-term record the regressor values that lie beyond the extents of the calibration range may lead to erratic regression results. Hence, it is widely accepted that linear, and where possible multiple linear regression equations, are the preferred CP model. This research investigates CP in the context of simple linear regressions, as they are in the widespread use and practitioners frequently lack sufficient data for interpreting and managing components required for multi-linear regressions, especially in the consulting environment. In a simple
linear chronologically paired regression model, a single response measurement (short-term project runoff) is related to a single predictor (long-term regional runoff) for each observation, and expressed as a standard linear equation, as given on Figure 1.2. Software programs such as Microsoft Excel have simplified the development of simple linear regression equations. Hence, once paired, the linear equation defining the line of best fit becomes the model and may be used to estimate long-term streamflow. The coefficient of determination ($R^2$) has become an important statistical test and is used to calculate the proportion of the variance in measured data that is explained by the linear equation. $R^2$ will range between 0 to 1, with higher values indicating less error variance, and is given by the equation:

$$R^2 = \left\{ \frac{\sum_{i=1}^{n}(o_i - \bar{o})(s_i - \bar{s})}{\sqrt{\sum_{i=1}^{n}(o_i - \bar{o})^2 \sqrt{\sum_{i=1}^{n}(s_i - \bar{s})^2}}} \right\}^2$$

Where, $o$ is the observed variable, $s$ is the synthetic variable, and $n$ is the number of samples. A traditional CP model evaluation requires the practitioner to calculate the $R^2$ as an indicator of the performance of a model and values greater than 0.5 are typically considered acceptable (Moriasi et al., 2007, Santhi et al., 2001, Van Liew et al., 2003). The determination of $R^2$ has become the focal point of model evaluation for simple linear regression analysis and is frequently presented alongside linear regression equations (Harmel et al., 2006). The derived CP relationship is applied to the long-term regional record to produce a long-term synthetic flow series for the Project site.

1.3.8 Empirical Frequency Pairing

Empirical Frequency Pairing (EFP) establishes an empirical relationship between discharges that are paired by their probability of non-exceedence. Daily flows for a concurrent period of record are ranked in descending order of magnitude with each flow value of equal rank having an equal probability of exceedence within its respective data set. Hence, the correlation of ranked flows amounts to a correlation between values that are assigned the same probability of non-exceedence (frequency). The probability of non-exceedence can be represented using the equation:
\[ p = \frac{n + 1 - m}{n + 1} \]

Where \( p \) is the probability of non-exceedence assigned to each record rank \( m \), \( n \) is the number of records in the sample, and \( m \) is the record rank (\( m = 1 \) = largest value on record). EFP assumes that flow frequency relationships developed from the sample (concurrent record) are generally representative of the population (long-term record), and that increasing the quantity of data available in the sample (i.e. additional years of data collection) will increase the match to the (commonly hypothetical) population dataset. A typical EFP relationship is shown on Figure 1.3. The term EFP is used because no statistical distribution is assumed, while Parametric Frequency Pairing (PFP) is based on fitting data to parametric statistical distributions (Millar, 2013).

**Figure 1.3**  Typical Empirical Frequency Paired Relationship

The ranking of data required for EFP, and the empirical relationship developed to describe these ranked data suggests that statistical tests such as the coefficient of determination will not apply to evaluate the model development. The EFP relationship is not a line of best fit between all data points, and there is therefore no variance unless the user specifically elects to ignore points during extrapolation of the EFP
relationship, as shown on Figure 1.3. Hence, development and validation of an EFP model is done so using:

1) Interpretation of the Frequency Paired relationship,

2) Interpretation against the line of equal unit runoff,

3) Comparison of the matching of Flow Duration Curves (FDC).

1.3.8.1 Interpreting the Distribution of Frequency Paired Data

A frequency paired distribution of data may exhibit characteristic patterns that are indicative of:

1) Characteristic catchment specific responses,

2) An artefact of the uncertainty in each dataset,

3) The result of discharge frequency and differences in inputs leading to runoff.

The latter two are especially prevalent during highest flows, and often lead to uncertainty in interpreting outlier data. Outliers that may have been difficult to identify in a CP relationship become obvious in an EFP relationship and, if accepted without further interpretation, may lead to erroneous conclusions about extrapolation of the EFP relationship, and under or overestimation of high flows. This research found that outliers in the ranked datasets, (specifically high flow outliers) are present no matter what length the dataset. Forty concurrent years of frequency paired data, shown on Figure 1.4, includes numerous outliers, despite the length of these data. These outliers are a function of either uncertainty (perhaps associated with rating curve uncertainty), or simply of the stochastic nature of their return period, which may have been slightly different for each catchment. When establishing an EFP relationship, these outliers need to be identified and managed. As shown on Figure 1.4, although outliers number only 10-15 data points out of 12,000, they will be crucial to accurately characterise as these data will be the important peak flows that will be extracted for FFA.
Furthermore, the distribution given on Figure 1.4 contains nearly 45% of its record between 0 and 60 L/s/km², which is a scale barely discernible in this Figure but which, if incorrectly characterized in an empirical model, will have a significant impact on the resultant synthetic series. This is a particular strength of the EFP method, where the distribution of lower flows will more rapidly approach the population distribution as they occur more frequently, and the modelling method will precisely fit a relationship to frequency paired data points.

1.3.8.2 The Line of Equal Unit Runoff

The line of equal unit runoff is a means of describing the relative responsiveness of paired catchments. Paired catchments may have certain marked differences in their watershed characteristics and the patterns attributable to these differences should be evident in the position of points, relative to the line of equal unit runoff. A line of equal unit runoff is delineated, as shown on Figure 1.3 and, in conjunction with the distribution of frequency paired records, assessments are able to be made as to whether proportional flows are consistent with the hydrologic characteristics of the respective systems. For example, it would be expected that as the sites used for Figure 1.1 approach summer months, the EFP relationship will
deviate farther from the line of equal unit runoff as proportional differences in runoff result in a relative increase in flows in the catchment with larger glacial coverage.

1.3.8.3 Flow Duration Curves (FDC)

A FDC is a graphical representation of the runoff distribution, and is developed by calculating the percentiles of runoff that are equal to, or above a given percentile. Matching the synthetic FDC to the measured FDC (for the concurrent period) can be a diagnostic means of validating the quality of the EFP relationship (as well as the CP relationship). An EFP relationship that perfectly matches all measured points within the concurrent record will produce a perfect match between the synthetic and measured FDC. Hence, in areas where judgement and experience require the EFP relationship to deviate from the measured flows (is not uncommon due to uncertainty associated with high and low flow regions), differences will occur in the comparison of the measured and synthetic flow duration curves. A flow duration curve is developed by calculating the probability of exceedence for each discharge value in a series, and is given by:

$$P = 100 \times \left( \frac{M}{n + 1} \right)$$

Where $P$ is the probability (given as a percentage) that a given flow will be equaled or exceeded, $M$ is the (dimensionless) ranked position of a discharge value within the dataset, and $n$ is the total number of discharge events for the period of record. The base time unit used in preparing a flow-duration curve will affect its appearance, and mean daily discharges are generally the most common. When longer periods are used (such as mean monthly flow), the curve will tend to be flatter due to the averaging of short-term hydrograph peaks with intervening smaller flows. Extreme values are averaged out more and more, as the time period gets larger (e.g., for a flow duration curve based on annual flows at a long-record station). Shorter duration intervals, such as hourly flows, tend to make flow duration curves steeper, especially at the extremes. The upper and lower regions of a flow-duration curve are particularly significant in evaluating the stream and basin characteristics at high flows. The shape of the curve in the high-flow region indicates the type of flood regime the basin is likely to have, whereas, the shape of the low-flow
region characterizes the ability of the basin to sustain low flows during dry seasons. A very steep curve (high flows for short periods) would be expected for rain-driven floods on small watersheds. Snowmelt floods, which last for several days, or regulation of floods with reservoir storage, will generally result in a much flatter curve near the upper limit. In the low-flow region, an intermittent stream would exhibit periods of no flow, whereas, a very flat curve indicates that moderate flows are sustained throughout the year due to natural or artificial streamflow regulation, or due to a large groundwater capacity which sustains the base flow to the stream.

1.3.9 Synthetic Long-Term Streamflow Records

The derived EFP and CP relationships are applied to the long-term regional record to produce long-term synthetic discharge time-series for each pairing technique. The distinctive characteristic of the EFP technique, when compared with CP, is that the former was originally developed as a means of more reliably establishing the relationship between the frequency of runoff magnitudes, which was especially useful for hydropower projects interested in accurately characterizing flow volumes for energy assessments. By contrast, CP is a technique designed to model specific event magnitudes on specific days and is therefore substantially impacted by variability in chronologically paired data. However, despite its original intent, EFP techniques have been used to not only model long-term streamflow records, but to model extreme flows through Flood Frequency Analysis (Knight Piésold Reports) for both hydropower and mining projects. It is at this point that importance and relevance of pre-selection criteria, used in all pairing models, be re-emphasised. Both EFP and CP models do not disconnect the relationship between timing and magnitude. Rather, CP assumes that the relationship is binding, while EFP assumes that over time, the relationship will become more representative of the population.

The comparison of the timing and magnitude of measured and synthetic records is valid for a CP relationship, where the model was developed through pair-wise comparisons. However, EFP relationships are not necessarily reliant upon the same pair-wise comparisons and it could be argued that chronologically-paired comparisons of the measured and synthetic records derived from EFP relationships may be misleading (the purpose of the EFP method is to recreate the frequency distribution, and not specific flows). However, the process of pre-screening requires that the long-term regional and
project sites be reasonably well correlated, which implies, among other things, that these catchments contain some degree of chronological correlation, and subject to similar stochastic inputs.

1.3.10 Evaluation of the Accuracy and Precision of the Synthetic Series

According to Refsgaard (1997), model validation is the process of demonstrating that a given model is capable of making “sufficiently accurate” simulations. The precise definition of what “sufficiently accurate” means has resulted in the development of numerous model evaluation techniques. Once a model has been developed and applied to generate synthetic records, whether through CP or EFP techniques, tools to evaluate the degree of “closeness” between the measured and synthetic record can be used. Usually included in these tools are “goodness-of-fit” or relative error measures (bounded statistics, such as the coefficient of determination or the Nash-Sutcliffe Efficiency) to assess the ability of a model to simulate reality. The quality of hydrologic models and the accuracy and precision of long-term streamflow estimates require evaluation, but there is uncertainty regarding technique (Krause et al., 2005, Legates and McCabe, 1999, Moriasi et al., 2007). It is widely accepted that comparison of synthetic data with measured data must be a component of an evaluation, and should be undertaken using concurrent synthetic series and measured records. Further, techniques employed must be recognisable and technically sound. Finally, quantification of the uncertainty associated with all aspects of the model should be understood and clearly laid out (Moriasi, et al, 2007).

A common primary goal of modeling physical processes is prediction of a variable in time and/or space from a given set of inputs, and evaluation is largely determined by how well modelled data fit observed data (Legates and McCabe, 1999). This is usually achieved through pair-wise comparisons of the ability of a hydrologic model to recreate measured data in both timing and magnitude. This is often a focus in determining whether a model has been accurate (Gupta et al., 1999).

Chronologically-paired event-matching is a component of model evaluation and is often performed by visually comparing concurrent measured and synthetic streamflow data. Hence, visual inspection of the synthetic and observed hydrographs remains one of the most fundamental subjective approaches to assessing model performance, where the practitioner may formulate assessments of model behaviour
through simple comparisons of magnitude and timing of runoff during specific events, as well as low flow
thresholds and the characteristics of the ascension and recession curves (Gupta et al., 1999, Boyle et al.,
2000). Reliability and confidence in the interpretation and assessment of closeness in regard to these
subjective assessments is often the function of the extent of exposure one has had to such modelling and
familiarity with hydrologic processes.
SECTION 2.0 - METHODOLOGY

2.1 PROJECT LOCATIONS

The Province of British Columbia encompasses a range of hydro-climatic regimes, and a rigorous assessment of the comparative performance of pairing techniques necessitates that a number of the most dominant regimes be incorporated. Three regimes were considered and data used in this research were obtained from the Water Survey of Canada (WSC), with daily discharge data acquired from watersheds representative of pluvial, nival and glacial regimes. Pluvial regimes are those where runoff is primarily driven by rainfall events, nival regimes are those in which runoff is driven by the melting of the winter snowpack during early to late Spring, and Glacial regimes are those in which runoff is driven primarily by the melting of headwater glaciers and is characterised by increased runoff during the warmer summer months. Each of these regimes may be subject to additional runoff mechanisms, such as low flow periods in summer and/or winter, or a prominent storm season during fall months, in response to high intensity storm systems.

2.1.1 Pluvial Regimes

A pluvial regime is one that is characterised by runoff driven primarily by precipitation as rainfall. Carnation Creek near the Mouth (08HB048) (Figure 2.1) is situated approximately 20 km northeast of Bamfield on the south shore of Barkley Sound, southwestern Vancouver Island (48°54'56" N, 124°59'52" W). The catchment is in the Coastal Western Hemlock Biogeoclimatic Zone, having cool summers and mild, wet winters and is typical of those that span the west coast of North America from the Oregon Coast Range and High Cascades to the Queen Charlotte Islands and southeast Alaska (Tschaplinski, 2004). The watershed area is 10.3 km² and contains rugged terrain between 0 and 800 m elevation. The mainstream channel is approximately 7.8 km in length and the valley walls have gradients up to 80%. The coarse, well-drained soils, forest cover, hydrology, and heavy annual precipitation (varying from 210 to over 500 cm/yr) are typical of western Vancouver Island and many other areas of coastal British Columbia. About 95% of the annual precipitation falls as rain, primarily during autumn and winter, with
the remaining 5% occurring as snow, which does not generally accumulate for longer than a few hours to a few days. High variations in seasonal rainfall cause stream discharge to range from 0.03 m$^3$/s in summer, to 64 m$^3$/s in winter. Streamflow may increase 200 fold within 48 hours because of rapid runoff from rainstorms that can deliver up to 26 cm of precipitation within that period.

Tofino Creek near the Mouth (08HB086) (Figure 2.2) has a drainage area of 38.6 km$^2$, and is located approximately 26 km north east of Tofino (49°14'58" N, 125°34'50" W). Leckie et al., (2005) described Tofino Creek as a typical west coast mountain stream (Leckie et al, 2005). The catchment is located within the Clayoquot Sound area of Vancouver Island, British Columbia and consists of a 5 km stream length that rises 250 m from tidewater to an upper, more mountainous stream.
Figure 2.1 Carnation Creek at the Mouth (Knight Piésold Ltd, 2013)
Figure 2.2 Tofino Creek Near the Mouth (Knight Piésold Ltd, 2013)
Both Tofino Creek and Carnation Creek contain 15 years of concurrent streamflow data, collected between 1996 to 2010, inclusive. Carnation Creek was assumed to represent a conceptual Project location for this research, while Tofino Creek was assumed to represent a long-term regional watershed. The following discussion relates to the long-term measured characteristics of both catchments. The average unit runoff for Tofino Creek is 177 L/s/km², while for Carnation Creek, the (known) average unit runoff is 79 L/s/km². These results indicate that the marginally more interior and mountainous Tofino Creek catchment is substantially wetter than the more coastal Carnation Creek catchment.

The unit runoff hydrographs of 1996 and 2005 are given on Figure 2.3 and Figure 2.4, respectively, with these figures demonstrating typical runoff characteristics in these two catchments. Chronological timing of runoff events during winter is consistently strong, indicating that weather systems causing these events are widespread and relatively uniform across the region. A low flow period in the summer months (June to August) is evident in the occurrence of very low flows, especially prominent in 1996. Fall months tend to have a higher concentration of runoff events, reflecting the occurrence of higher intensity, shorter duration storm events.

Figure 2.5 is a comparison of the average daily unit runoff hydrograph. Each day was calculated as the average of all average unit runoff events that occurred on that day throughout all years. This hydrograph tends to mask runoff events as high events do not tend to occur on the same day, year in and year out. However, Figure 2.5 reveals that Tofino Creek unit runoff tends to be substantially higher than Carnation Creek, which is also reflected in the relative proportions of runoff on the flow duration curve, chronological and frequency paired figures (Figure 2.6, Figure 2.7 and Figure 2.8, respectively). The annual hydrograph also shows the impact of winter frontal systems and fall storms as base flows rise in each creek during these periods. The summer period tends to show low flows, with minimal runoff.

Figure 2.6 contains the long term flow duration curves for each site. This Figure demonstrates that although the chronological timing of runoff may at first appear strong, as discussed above, the relationship of proportional runoff between these two sites is markedly different. Not only are the magnitudes of comparative runoff different, but so too is the distribution of runoff within each curve.
Extreme low flows at Tofino Creek tend to drop off sharply in the lowest 10th percentile, while Carnation Creek low flows tend to remain high until the final percentile, where a noticeable drop is then evident, suggesting that runoff in Carnation Creek may drop sharply at the extreme low summer flows. However, the log scale used in Figure 2.6 tends to exaggerate this effect.

Figure 2.7 and Figure 2.8 are the chronological and frequency paired data for the entire periods of record, respectively. Figure 2.8 suggests that the EFP relationship between these two sites is largely linear, but Figure 2.9, a closer inspection of the lower flows shows that the relationship is non-linear. This latter Figure contains close to 85% of all data points, adding weight to the importance of recognising the non-linearity of the EFP relationship. Figure 2.9 also shows that at extremely low flows, the EFP relationship tends to converge closer to unity for each site.

This study utilized EFP and CP relationships to model long-term runoff at Carnation Creek, from Tofino Creek.
Figure 2.3 1996 Unit Runoff Hydrograph for Pluvial Regime

Figure 2.4 2005 Discharge Hydrograph
Figure 2.5  Average Annual Unit Runoff Hydrograph for Pluvial Regime

Figure 2.6  Flow Duration Curve of Long-Term Record for Pluvial Regime
Figure 2.7 Chronologically Paired Unit Runoff for Pluvial Regime

Figure 2.8 Frequency Paired Unit Runoff for Pluvial Regime (Insert box is Figure 2.9)

See Figure 2.9 for details
Figure 2.9 Low flow distribution of Frequency Paired Unit Runoff for Pluvial Regime
2.1.2 **Nival Regimes**

A Nival regime is one that is characterised by runoff driven primarily by snowmelt. Little Wedeene River below Bowbyes Creek (08FF003) (Figure 2.10) is situated approximately 14 km north of Kitimat (54°8'11" N, 128°41'24" W). The watershed flows generally eastward, with a drainage area of 180 km² and contains rugged terrain between 70 m at the hydrometric monitoring station and 2050 m at the summit of Mount Holt, at the catchment headwater. The stream is comprised of approximately five major tributaries, and the mainstream channel is approximately 20 km in length.

Zymoetz River above O.K. Creek (08EF005) (Figure 2.11) is situated approximately 18 km east of Terrace (54°29'26" N, 128°19'8" W). The watershed flows generally eastward from as far as Hudsons Bay Mountain, near Smithers to the east and Morise Lake to the South, with a drainage area of approximately 2,850 km², and containing rugged terrain between 130 m at the hydrometric monitoring station, and 1769 m at the summit of Miligit Peak. The stream is comprised of approximately three major tributaries. Two of these tributaries are northeast flowing, converging approximately 20 km upstream of the hydrometric station. The third stem is the larger of the three, at 110 km in length and flows from Hudsons Bay Mountain near Smithers, westward then turning sharply at Legate Peak to flow southward.

The annual hydrograph is distinctly bi-modal at both sites, with high unit runoff responding to freshet melting of the winter snowpack commencing in late March and peaking at the start of June (Figure 2.12 and Figure 2.13). Runoff recedes until August where a short period of low flows occurs. Following these summer low flows, Fall storms tend to result in higher runoff events. These storms are highly variable, but can account for the largest annual runoff events with the year. Runoff gradually recedes to low winter flows in December. Low flows persist until late March, when freshet melting commences.

Zymoetz River drainage area is almost 16 times larger than Little Wedeene River, and it is therefore expected that the hydraulic response of these catchment will be significantly different. However, similarity in catchment area is often a compromise that is required on many projects and as such, an evaluation of the performance of pairing techniques in this context is applicable. There are 44 years of concurrent runoff data, collected from 1967 to 2010, inclusive. Zymoetz River was assumed to represent a
conceptual Project location for this research, while Little Wedeene was assumed to represent a long-term regional watershed. The following discussion relates to the long-term measured characteristics of both catchments. Data collection was relatively uninterrupted throughout this time, with only a short period of unavailable data from late-1978 and mid-1979. The average unit runoff for 08FF003 is 98 L/s/km², while at the much larger 08EF005, the average unit runoff is 37 L/s/km². Maximum measured daily unit runoff within the 44 year record was 2240 L/s/km², recorded at Little Wedeene River. The concurrent runoff in Zymoetz River during this event was 635 L/s/km², with the maximum recorded at Zymoetz River throughout the 44 years being 694 L/s/km². The unit runoff hydrographs of 1988 and 2005 are given on Figure 2.12 and Figure 2.13, respectively. These Figures demonstrate typical characteristics of runoff in these two catchments.

Chronological timing of runoff events during all months is similar, indicating that the weather systems causing events are generally widespread and relatively uniform across the region. However, there are pronounced events in one catchment that are virtually absent from the other, such as early July and early November, 2005. These differences are crucial when interpreting the different factors that are impacting each of these catchments. Spring freshet runoff events tend to be similar and these similarities are derived from factors causing snowmelt to occur within each catchment similarly. Pronounced rain on snow events during late April and early May are evident in each hydrograph. The most distinctive feature of the hydrographs is the relative magnitude of Fall storms. Although the highest proportion of annual runoff tends to occur in the Spring (nival) phase at each site, the highest runoff events in the Little Wedeene tend to occur in the fall. This difference is in response to the smaller and steeper catchment of Little Wedeene, which tends to be more responsive to these higher intensity runoff events.
Figure 2.10  Little Wedeene River below Bowbyes Creek (Knight Piésold Ltd, 2013)
Figure 2.11  Zymoetz River Above O.K. Creek (Knight Piésold Ltd, 2013)
Figure 2.14 is the average daily unit runoff hydrograph. Each day was calculated as the average of all average unit runoff events that occurred on that day throughout all years. The pronounced freshet peaks of both sites are evident, while the extremely high Fall flows in Little Wedeene, identified in Figure 2.12 and Figure 2.13, tend to be masked as high events do not tend to occur on the same day, year in and year out. Figure 2.14 reveals that Little Wedeene unit runoff tends to be significantly higher than Zymoetz. Figure 2.15 presents the long term flow duration curves for each site. This figure demonstrates that although the magnitudes of comparative runoff are substantially different, the relative distribution of runoff within each curve is similar. Figure 2.16 and Figure 2.17 are the chronological and frequency paired data for the entire periods of record, respectively. These figures both show the much higher unit runoff in Little Wedeene.

This study utilized EFP and CP relationships to model long-term runoff at Zymoetz River, from Little Wedeene River.
Figure 2.12  1988 Unit Runoff Hydrograph for Nival Regime

Figure 2.13  2005 Unit Runoff Hydrograph for Nival Regime
Figure 2.14  Average Annual Unit Runoff Hydrograph for Nival Regime

Figure 2.15  Flow Duration Curve of Long-Term Record for Nival Regime
Figure 2.16 Chronologically Paired Unit Runoff for Nival Regime

Figure 2.17 Frequency Paired Unit Runoff for Nival Regime
2.1.3 Glacial Regimes

A glacial regime is one that is characterised by runoff driven primarily by glacial melt in summer months. Big Creek below Graveyard Creek (08MB007) (Figure 2.18) is a north flowing glacial catchment, situated approximately 120 km northeast of Tatla Lake, and 45 km south of Downton Lake (51°15'37" N, 123°5'33" W). The watershed area is 232 km² and contains rugged terrain between 1660 m at the hydrometric monitoring station, and 2610 m at Dorrie Peak. The catchment consists of one main stem channel, approximately 24 km in length, and four major tributaries. The entire catchment is within deeply incised, steep-walled valleys. These valley walls contain numerous avalanche paths and glaciers at the headwaters, which provide high flows during summer months. A large glacial lake, called Lorna Lake is located at the far eastern end of the catchment.

Hurley River (08ME027) (Figure 2.18), is a north flowing glacial catchment, situated approximately 18 km south of its confluence with Carpenter and Downton Lake, and 45 northeast of Pemberton, within the Squamish-Lillooet Regional District (50°43'52" N, 122°56'32" W). The watershed area is 312 km² and contains rugged terrain between 1030 m at the hydrometric monitoring station, and 2780 m at Mount Sampson. The catchment consists of five main channels, with the longest channel being approximately 23 km in length. The entire catchment is within deeply incised, steep-walled valleys. These valley walls contain numerous avalanche paths and glaciers at the headwaters, which provide high flows during summer months.

Big Creek and Hurley River contain 15 years of concurrent runoff data, collected between 1996 to 2010, inclusive. Hurley River was assumed to represent a conceptual Project location for this research, while Big Creek was assumed to represent a long-term regional watershed. The following discussion relates to the long-term measured characteristics of both catchments.

Prominent runoff is in response to glacial melting and begins in April, peaking from June through to the end of July, and gradually receding to low flows again in December. A short period of storm-driven runoff is evident in late September and October. The average annual unit runoff for Hurley River is 43 L/s/km², while the average unit runoff of Big Creek is 11.6 L/s/km². There are pronounced events in Hurley River
that are virtually absent from Big Creek, such as late-January, 2005 and mid-November, 1996. The maximum measured daily unit runoff within the 15 year record was 471 L/s/km², recorded at Hurley River in October 2003. Concurrent runoff in Big Creek River during this same event was 2.78 L/s/km² and was unaffected by whatever storm system had caused the Hurley River runoff. The unit runoff hydrographs of 1996 and 2005 are given on Figure 2.20 and Figure 2.21, respectively. These figures demonstrate typical characteristics of runoff in these two glacial catchments. Hurley River has a larger glacial coverage than Big Creek, which results in higher summer runoff.

Hurley River has substantially and consistently higher runoff at all times of the year. Runoff at Hurley River exceeds 20 L/s/km², 50% of the time, while at Big Creek, runoff is closer to 4 L/s/km² for the same percentage of time. This difference can be partially attributed to the differences in catchment area but is mostly attributed to differences in glacial fraction, with Hurley River containing a significantly larger proportion of glaciers.

Figure 2.22 is the average daily unit runoff hydrograph. Each day was calculated as the average of all average unit runoff events that occurred on that day throughout all years. The pronounced freshet peak of both sites is evident, followed by glacial runoff during summer months. However, Figure 2.22 reveals that Hurley River unit runoff tends to be marginally higher than Big Creek, which is also reflected in the relative proportions of runoff on the flow duration curve, chronological and frequency paired Figures (Figure 2.23, Figure 2.24 and Figure 2.25, respectively).

Figure 2.23 contains the long term flow duration curves for each site. This figure demonstrates that although the magnitudes of comparative runoff are substantially different, the relative distribution of runoff within each curve is similar. Figure 2.24 and Figure 2.25 are the chronological and frequency paired data for the entire periods of record, respectively. The noticeable drop in runoff at the very highest percentiles area expected to be a function of river freezing effects.

This study utilized EFP and CP relationships to model long-term runoff at Hurley River, from Big Creek.
Figure 2.18   Big Creek Below Graveyard Creek (Knight Plésold Ltd, 2013)
Figure 2.19  Hurley River Below Lone Goat Creek (Knight Piésold Ltd, 2013)
Figure 2.20 1996 Unit Runoff Hydrograph for Glacial Regime

Figure 2.21 2005 Unit Runoff Hydrograph for Glacial Regime
Figure 2.22  Average Annual Unit Runoff Hydrograph for Glacial Regime

Figure 2.23  Flow Duration Curve of Long-Term Record for Glacial Regime
Figure 2.24  Chronologically Paired Unit Runoff for Glacial Regime

Figure 2.25  Frequency Paired Unit Runoff for Glacial Regime
2.2 **CALCULATION METHODS**

2.2.1 **Overview**

Engineers generally have a few years of project specific streamflow records available and are often required to develop pairing models to derive long-term streamflow estimates. A representative sample of models were developed to describe the performance of both CP and EFP models. A general outline of the methodology is given on Figure 2.26.

*Figure 2.26  Research Methodology*

2.2.2 **Calculation Methods**

All calculations were completed using Microsoft Excel. Concurrent daily average streamflow data were obtained from the WSC and converted to daily unit runoff by dividing the discharge by the drainage area. One site from each hydro-climatic regime pair was selected as a short-term project site and for each calculation, it was assumed that only a discrete period of record was available for this site. For each EFP calculation, concurrent data from the short and long-term station were ranked from highest to lowest. An empirical relationship was then developed to relate regional data to project data and this relationship was then applied to the long-term regional record in order to derive a long-term estimate for the project. As the extent of streamflow within the concurrent period does not often contain the lowest and highest flows within the long-term record, extrapolation was invariably required to ensure that the empirical relationship would apply to the entire record. A typical EFP relationship is given on Figure 1.3. For each CP
calculation, concurrent data from the short and long-term station were paired chronologically. A line of best fit was developed to describe the relationship between paired data and a linear equation and coefficient of determination was calculated. A typical example of a CP relationship is given on Figure 1.2.

2.2.3 Hydrograph Segmentation

Hydrograph segmentation distinguishes between mechanisms that drive runoff, such as those driving runoff during the snowmelt period, with those driving runoff during Fall storm events. This is shown on Figure 2.27. Mechanisms behave differently between catchments and hence hydrograph segmentation avoids diluting these important differences. Segmentation of the Hydrograph is undertaken immediately prior to pairing and in practice monthly segmentation is common when there is more than 1 or 2 years of data are available. Seasonal segmentation is recommended when minimal concurrent data are available. For all concurrent years, pairing is performed on each season or month separately. For example, 3 concurrent years of January streamflow data will be paired and CP and EFP relationships will be developed for these January data.

![Image](image_url)

**Figure 2.27** Hydrograph Segmentation distinguishes between runoff mechanisms
2.2.1 Model Period

Each model used between 1 and up to 7 years of concurrent paired streamflow data. Multiples periods were used as it is assumed that incorporating additional years of data strengthens paired hydrologic models and provides a more accurate and precise long-term synthetic streamflow series by capturing a more representative sample of low, medium and high flows that may take multiple years to occur.
SECTION 3.0 - RESULTS

A total of 1,624 evaluations were completed, with an equal number of CP evaluations (812) and EFP evaluation (812). A breakdown of these evaluations is given on Figure 3.1.

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>ANNUAL SEGMENTATION</th>
<th>SEASONAL / MONTHLY SEGMENTATION</th>
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Figure 3.1 Summary of Calculations

Evaluation of individual models, with respect to assessment of long-term synthetic streamflow hydrographs, were not considered in this research. Rather, assessment of model performance was made on the accuracy and precision of the resultant synthetic record, when compared with the equivalent long-term observed record. Visual (subjective) assessment of the synthetic versus observed long-term runoff series was not incorporated in the evaluations due to the volume of computations. Two alternative measures were used to evaluate the performance of these techniques. These measures were;

1. Flow Duration Curve Comparisons (Section 3.1), and
2. Frequency Distribution Comparisons (Section 3.2)

3.1 FLOW DURATION CURVE COMPARISONS

The objective of any pairing should be to match, within the uncertainty bounds inherent in each dataset (discussed further in Section 4.3), the long-term measured Flow Duration Curve. As described in Section 1.3.8.3, the Flow Duration Curve is a means of presenting the distribution of runoff as a probability of exceedence. A perfect match between observed and synthetic Flow Duration Curves would indicate that the model is perfectly recreating the probability distribution of runoff.

The following pages present a series of Figures that demonstrate typical pairing model results and are presented according to runoff regime (Pluvial, Nival and Glacial), and pairing type (Chronological Pairing and Empirical Frequency Pairing). For each pairing type, two Figures are shown to distinguish between hydrograph segmentation (annual and monthly/seasonal segmentation). Within each pairing and segmentation type, eight Flow Duration Curves are shown. Seven of these curves are representative samples of results using 1 through to 7 years of concurrent streamflow data within a model. The eighth curve (a black dashed line) is the long-term measured flow duration curve. This curve (which varies depending only on regime type) is the target curve for hydrologic models.

3.1.1 Pluvial Regime

Figure 3.2 and Figure 3.4 show CP results of 1 through to 7 years of streamflow data for Carnation Creek, through an annually and seasonally segmented hydrograph, respectively. These Figures show that CP tends to overestimate runoff in the low flow regime, and underestimate runoff in the high flow regime at Carnation Creek. For example, target runoff for the probability of exceedence of 0.8 was 5.5 L/s/km². Using 7 years of concurrent record from Carnation Creek and Tofino Creek, the same probability of exceedence was 14 L/s/km² using annual segmentation, and 10 L/s/km² using seasonal segmentation. These results suggest that although seasonal segmentation will refine low flow estimates the results will be significantly higher than the target runoff for this creek. Figure 3.3 and Figure 3.5 show EFP results of 1 through to 7 years of streamflow data for Carnation Creek, through an annually and seasonally
segmented hydrograph, respectively. These Figures show that with 3 or more years of data EFP tends to model all flow regimes accurately and precisely, with noticeable improvement in accuracy and precision with the incorporation of additional streamflow data. This is especially pronounced in the lower flow regime, where 1 and 2 years of data returned less precise results.

3.1.2 Nival Regime

Figure 3.6 and Figure 3.8 show CP results of 1 through to 7 years of streamflow data for Zymoetz River, through an annually and monthly segmented hydrograph, respectively. These Figures show that CP tends to overestimate runoff in the low flow regime, and underestimate runoff in the high flow regime at Zymoetz River. The distribution of flow duration curves should approach (near) the long-term measured flow duration curve as new data are incorporated (this is the premise behind collecting a representative number of years of record). However, Figure 3.6 demonstrates that CP flow duration curves tend to be both inconsistent and inaccurate with, for example, the closest match to the probability of exceedence of 0.9 (using annual segmentation) being with the incorporation of just 1 year of data, while the farthest match from the measured was when using 6 years of data. This same inconsistent characteristic is present in the medium and higher flow regime CP results, where the closest match was when using 3 years of data. Target runoff for the probability of exceedence of 0.05 was 120 L/s/km², while the closest match was 80 L/s/km² (3 years of concurrent record). Segmentation of the hydrograph into months (refer to Figure 3.8) substantially improved the match to the long-term measured flow duration curve, though high flows (less than 0.1 probability of exceedence) tended to continue to underestimate high flows and to show little improvement in both accuracy and precision. These results suggest that although monthly segmentation is preferred for refining long-term CP estimates, the results do not approach the target flow duration curve.

Figure 3.7 and Figure 3.9 show EFP results of 1 through to 7 years of streamflow data in the nival regime, segmented annually and monthly, respectively. These Figures show that EFP tends to model all flow regimes accurately and precisely with noticeable improvement in accuracy and precision with the incorporation of additional streamflow data. As with the CP technique, annual segmentation did not as
accurately model the flow duration curve, while monthly segmentation substantially improved the match to the long-term measured. The difficulty in modelling the long-term flow duration curve is primarily the result of the substantially different physical mechanisms that are driving runoff at different times of the year, and incorporating all of these into a bulk regression will bias all flow regimes. Figure 2.12 and Figure 2.13 show this characteristic, where comparative high flows during the freshet melting are generally consistent, while high flows during fall storms, which are generally the highest flows within any given year at Little Wedeene Creek, result in very low runoff magnitudes for Zymoetz River. This is largely a consequence of catchment area, which is substantially different between these two catchments.

3.1.3 Glacial Regime

Figure 3.10 and Figure 3.12 show CP results of 1 through to 7 years of streamflow data for Hurley River, through an annually and monthly segmented hydrograph, respectively. These Figures show that CP tends to reasonably represent the long-term measured Flow Duration Curve, with some notable exceptions. CP curves tend to be unpredictable in their results with the closest match to low flows (using annual segmentation) is with the incorporation of 3 years of data, while the farthest match from the measured was when using 7 years of data (this is similar to the results discussed in Section 3.1.2). This same inconsistent characteristic is present in the medium and higher flow regime CP results. By contrast, EFP tended to improve in accuracy in all runoff percentiles with incorporation of additional years of data for both annual and seasonal hydrograph segmentation, as shown on Figure 3.11 and Figure 3.13, respectively. These (deceivingly similar) results are in response to the higher coefficient of determination of the glacial regime \( R^2 0.82 \), shown on Figure 2.24, in that it would be expected for CP results to be reasonably close to the long-term measured, especially in catchment regimes that are driven primarily by the same largely ubiquitous mechanism (temperature variability driving glacial melt), rather than mechanisms that tend to show much greater spatial and chronological variability (precipitation and snowmelt).

Figure 3.11 and Figure 3.13 shows an anomalous drop in the EFP FDC using 1 year of record. This drop is not unexpected using only a short period of record, and results from the runoff characteristics of that
particular year. However, it is also not known if the issue is a consequence of inaccurate data at one or both sites (such as an unidentified rating shift). Incorporation of additional years of data tends to dilute the effect.

The discussion given above is built upon the review of a sample of pairing results, but these results are consistent with the discussion given in Section 3.2. In general, EFP steadily improves with incorporation of a larger period of record, while the Flow Duration Curve match for CP shows that the match does not generally improve using a larger periods of record. CP generally overestimates low flows and underestimates high flows. These results suggests that although just one or two years of runoff data may yield a relatively average fit for a EFP (particularly at the lowest flows), three or more years tends to show a significant improvement in the fit of the EFP Flow Duration Curve. By contrast, the results of the CP suggest that incorporation of additional data was not able to result in a substantial improvement in performance, except in specific cases where monthly segmentation is used, as it yields reasonable results across most runoff percentiles, except for extremely low and high flows.
Figure 3.2  FDC for CP results from Annual Segmentation of the Pluvial Hydrograph

Figure 3.3  FDC for EFP results from Annual Segmentation of the Pluvial Hydrograph
Figure 3.4  FDC for CP results from Seasonal Segmentation of Pluvial Hydrograph.

Figure 3.5  FDC for EFP results from Seasonal Segmentation of the Pluvial Hydrograph.
Figure 3.6  FDC for CP results from Annual Segmentation of the Nival Hydrograph

Figure 3.7  FDC for EFP results from Annual Segmentation of the Nival Hydrograph
Figure 3.8 FDC for CP results from Monthly Segmentation of the Nival Hydrograph

Figure 3.9 FDC for EFP results from Monthly Segmentation of the Nival Hydrograph

Discussed in Section 3.1.2
Figure 3.10  FDC for CP results from Annual Segmentation of the Glacial Hydrograph

Figure 3.11  FDC for EFP results from Annual Segmentation of the Glacial Hydrograph
Figure 3.12  FDC for CP results from Monthly Segmentation of the Glacial Hydrograph

Figure 3.13  FDC for EFP results from Monthly Segmentation of the Glacial Hydrograph
3.2 COMPARISON OF FREQUENCY DISTRIBUTIONS

Runoff can be characterised by runoff percentiles, which are an alternative (numeric) representation of the components of the flow duration curve. Given the large volume of results, the comparative accuracy and precision of the Pairing techniques were represented visually through an assessment of the deviation of parameters that define the runoff percentiles from the known measured parameter. The following sections describe the results of these comparisons. Of particular interest was the accuracy and precision in modelling extremely high and extremely low runoff as well as the mean annual discharge. All evaluations are presented as the percent deviation from the long-term measured data, with a reduction in the range of percent deviation in regression results suggesting an improvement in the precision of results, while a density of results centred around zero suggests a high degree of accuracy and precision.

3.2.1 Low Runoff Percentiles

The 1st percentile represents the lowest 1% of flows within the entire record. Accurate modelling of the lowest flows is an important requirement of model evaluation as these flows will be used to provide low flow assessment that are used by many projects to determine potential water supply requirements and environmental in stream flow requirements. Figure 3.14 is the distribution of results for all CP models using annual hydrograph segmentation. These results suggest that CP is generally overestimating low flows, with the majority of 1st percentile runoff being between 100% and 500% higher than the long-term measured record. Despite an apparent increase in precision from incorporation of additional data, CP continues to overestimate low flows and in some cases, worsen. The exception is the pluvial regime, where shorter periods of record tend to overestimate and longer periods of record tend to underestimate. CP improves in precision (especially in the glacial regime) but in all cases is unpredictably inaccurate. These inaccuracies tend to diminish using seasonal/monthly hydrograph segmentation, as shown on Figure 3.16, and in particular, accuracy in the nival regime shows substantial improvement. However, given the scale of this Figure, the accuracy is still far removed from the target value. The glacial and pluvial regime results tend to underestimate low flows (in contrast to annual segmentation, where the results tended to overestimate). Figure 3.15 is the distribution of results for all EFP models using annual hydrograph segmentation. These results suggest that EFP models will not only return accurate long-
term low flow estimates, but that these estimates will improve in precision with incorporation of additional years of data in all flow regimes, improving from +/- 60% using 1 year of concurrent data to +/- 20% using 7 years of concurrent data. Figure 3.17 is the distribution of results for all EFP models using seasonal/monthly hydrograph segmentation. These results suggest that EFP will yield accurate and precise results, within the majority of results falling within +/-20% after inclusion of 4 years of concurrent data. Other Low Runoff percentiles, such as the 5th, and 25th percentile have shown similar results. These findings are consistent with 1st percentile results shown on the flow duration curves discussed in Section 3.1.

3.2.2 Mean Annual Discharge

Mean Annual Discharge is a common parameter used to define general catchment characteristics. Both CP and EFP techniques tended to synthesize Mean Annual Discharge with similar accuracy and precision, regardless of hydrograph segmentation, and with an improvement in precision with the inclusion of additional years of data. This is shown on Figure 3.18 and Figure 3.20 for CP, and Figure 3.19 and Figure 3.21 for EFP.

3.2.3 High Runoff Percentiles

The 99th percentile represents the highest 1% of runoff. Figure 3.22 is the distribution of results for all CP models using annual hydrograph segmentation. These results suggest that CP will be inaccurate in synthesizing high flows, and it is expected that this inaccuracy will be unpredictable. Through annual segmentation, the glacial regime is consistently overestimated, while the Nival and pluvial regimes are consistently underestimated. There is a general improvement in precision between all regimes, but with the degree of inaccuracy, such improvement may not be relevant. Figure 3.24 is the distribution of results for all CP models using monthly/seasonal segmentation, which shows similar results to the annual segmentation, except that the glacial regime tends to be more accurate. Both Pluvial and Nival regimes continued to underestimate the 99th percentile flows despite segmentation. Figure 3.23 is the distribution of results for all EFP models using annual segmentation. These results suggest that model results will tend to improve, with increased precision with the incorporation of additional data. Figure 3.25 is the
distribution of results for all EFP models using seasonal segmentation. These results suggest that hydrograph segmentation will increase overall precision, especially when using few years of record. These findings are consistent with 99th percentile results shown on the flow duration curves discussed in Section 3.1.
Figure 3.14  Difference between the observed and synthetic record in modelling the 1st percentile runoff from Chronological Pairing (Annual Segmentation).

Figure 3.15  Difference between the observed and synthetic record in modelling the 1st percentile runoff from Empirical Frequency Pairing (Annual Segmentation),
Figure 3.16 Difference between the observed and synthetic record in modelling the 1st percentile runoff from Chronological Pairing (Seasonal/Monthly Segmentation).

Figure 3.17 Difference between the observed and synthetic record in modelling the 1st percentile runoff from Empirical Frequency Pairing (Seasonal segmentation)
Figure 3.18 Difference between the observed and synthetic record in modelling the Mean Annual Discharge from Chronological Pairing (Annual Segmentation)

Figure 3.19 Difference between the observed and synthetic record in modelling the Mean Annual Discharge from Empirical Frequency Pairing (Annual Segmentation)
Figure 3.20 Difference between the observed and synthetic record in modelling the Mean Annual Discharge from Chronological Pairing (Seasonal Segmentation)

Figure 3.21 Difference between the observed and synthetic record in modelling the Mean Annual Discharge from Empirical Frequency Pairing (Seasonal Segmentation)
Figure 3.22  Difference between the observed and synthetic record in modelling the 99th percentile runoff from Chronological Pairing (Annual Segmentation)

Figure 3.23  Difference between the observed and synthetic record in modelling the 99th percentile runoff from Empirical Frequency Pairing (Annual Segmentation)
Figure 3.24  Difference between the observed and synthetic record in modelling the 99th percentile runoff from Chronological Pairing (Seasonal Segmentation)

Figure 3.25  Difference between the observed and synthetic record in modelling the 99th percentile runoff from Empirical Frequency Pairing (Seasonal Segmentation)
3.3 **INPUTS TO FLOOD FREQUENCY ANALYSIS**

Flood Frequency Analysis is used by Engineers to provide design inputs to structures that are required to withstand flood magnitudes that have a specified probability of occurrence. One of the most common methods of performing FFA is to use the annual maximum flood for the entire period of record. On many projects, this invariably requires that the long-term synthetic streamflow records be used. From the annual maximum floods, the Mean, Standard Deviation, and (depending on the distribution) Skewness are derived. Return period flood estimates are then estimated by fitting these data to a frequency distribution, such as the Gumbel or Log-Pearson Type III. For the purpose of FFA, both the glacial and pluvial regimes contained insufficient record from which to reliably assess the performance of pairing techniques in recreating the mean and standard deviation of annual maximum floods. However, the nival regime contained approximately 40 years of streamflow record and was incorporated for comparative purposes.

Figure 3.26 shows the results of the average annual maximum flood, derived using CP and EFP pairing models, and using annual hydrograph segmentation. Similar to the Figures given in Section 3.2, the results present the effectiveness of each pairing model in recreating the mean of the annual flood maximum, which was derived from the long-term measured record. The results show that EFP provides a marginally superior estimate of long-term average annual maximums, with results spread relatively evenly about the long-term measured data. The results also show that with increasing volume of data used in EFP models, the precision of annual flood maximums improves, from +/- 45% using one year of record, to +/- 15% using 7 years of record. CP results tend to show a similar level of precision improvement, while clearly showing that the method is not able to improve in accuracy, consistently underestimating the annual average maximum floods by approximately 10%.

The standard deviation is used to model the variability in maximum annual floods. The results given on Figure 3.27 suggest that the EFP technique will tend to model the standard deviation more accurately than the CP technique, while the CP technique will tend to provide greater precision, while significantly underestimating, by approximately 30%. Additional results, using segmentation of the hydrograph, have
not been provided, but it is expected that each method will improve through hydrograph segmentation. As FFA (in its simplest form) is a function of both the mean and standard deviation, results that show both parameters are underestimating may compound the effect. This is demonstrated on Figure 3.28, which is the 500 year return period event, calculated assuming a Gumbel distribution. EFP results tend to suggest a reasonably even distribution, while the CP results are consistently underestimating by approximately 30%.

![Figure 3.26 Percent Deviation of Average Annual Maximum Floods](image)

**Figure 3.26** Percent Deviation of Average Annual Maximum Floods
Figure 3.27  Percent Deviation of the Standard Deviation of Annual Maximum Floods

Figure 3.28  Percent Deviation of the 500 year event, assuming a Gumbel distribution
SECTION 4.0 - DISCUSSION

Long-term streamflow data are required for the Feasibility evaluation of many Projects. Pairing techniques are used to model long-term runoff from short-term gauged watersheds and a comparison of the performance of pairing techniques, for three hydro-climatic regimes in BC, has been provided in this thesis. This research compared the performance of Empirical Frequency Pairing (EFP) and Chronological Pairing (CP) in generating long-term synthetic streamflow data, and used comparisons between runoff frequency distributions, across a range of hydrologic regimes, to provide estimates of the relative and absolute accuracy and precision of these methods. The key findings of this research that will be discussed include;

1. Overall performance of pairing methods
2. Static and dynamic pairing methods
3. Managing and integrating outliers, and
4. Diminishing returns
5. Implications for Flood Frequency Analysis

4.1 PERFORMANCE EVALUATION

The principle objective of pairing is to derive long-term streamflow at a Project site and EFP was found to be more accurate and precise in synthesizing long-term streamflow than CP. As shown and discussed in Section 3, the poor performance of CP is largely attributed to the application of a single line of best fit that is used to describe the relationship between catchments. The line of best fit is established by minimizing the sum of squared errors between chronologically paired data points which results in a scatter of data around this line, as shown on Figure 2.7, Figure 2.16, and Figure 2.24. Larger runoff events in the paired relationship (such as outliers discussed in Section 4.2) have a pronounced impact on the slope of the linear regression equation that defines the line of best fit.
CP is a method requiring that data be permanently coupled by their time of occurrence. The consequence of this static pairing is that as new data are incorporated into a CP model, the linear regression line, equation(s) and coefficients of determination, that may have been established using only a short period of data, will tend to remain fixed. Despite the addition of more data, the relationship will not tend to become more accurate. Rather, the addition of more data will merely reinforce the initial paired relationship and result in little refinement. This characteristic is shown on Figure 4.1, where CP models using 1 or 7 years of record, provide very little change in the line of best fit, the linear regression equation and the coefficient of determination.

Reliance upon static CP techniques is problematic when recommendations are made related to a need for on-going data collection as a requirement for refining pairing model results and long-term estimates. It has been shown that the level of accuracy and precision reached using a minimal period of record in CP, is generally the same level of accuracy reached using up to seven times longer periods of record.
Figure 4.1  Comparison of Chronological Paired Regression using 1 and 7 years of concurrent streamflow data

An additional consequence of this lack of improvement is that the regression relationship established using a single year of data, which has been shown to be simply reinforced using a second, third, or more years, may lead practitioners to draw the conclusion that such consistency indicates optimal accuracy in results when in fact this has been shown to be the case. As shown on all CP Flow Durations Curves described in Section 3.1, the initial Flow Duration Curve developed using a single year of data was not only inaccurate in the first instance, but additional data did not bring the long-term synthetic record closer to the long-term measured record. By contrast, EFP, a relatively new technique for streamflow, tended to recreate assessed flow conditions accurately and also showed improved precision with incorporation of additional data. EFP continually reorganises data, resulting in a dynamic regression that is continually refining itself as more data are incorporated into the analysis. This reorganisation resulted in a progressive improvement in both accuracy and precision, leading to a very precise match in runoff percentiles. This was discussed further in Section 3.1. The last runoff percentiles to achieve similarity with the population dataset tend to be the low flows and high flows. These flows are often subject of return periods greater than the period of site record, suggesting that this is not an unexpected result.
However, given the overall accuracy and precision in the EFP method in all but these percentiles, extrapolation to the lowest and highest runoff events was a standard requirement.

4.2 OUTLIERS

All streamflow time-series tend to contain outlier data. These outliers are generally associated with:

- Extremely high flow events that may be well above the maximum measured discharge and therefore too high for standard confidence in the site rating curves.
- Freak, perhaps artificial event/s that were confined to only one of the paired catchments (uncorrected ice-dam breaks, for example, are a common cause of streamflow outliers).
- Real occurrences of runoff resulting from either different return periods events in each catchment (especially common at higher flows), or
- An artefact of non-stationarity in the runoff frequency distribution, which pairing methods are not yet able to readily identify.

No matter their cause, outliers result in a number of issues that have the potential to increase uncertainty in any pairing method. Outliers are not able to be readily identified using the CP method. This is best demonstrated in Figure 4.2. Although in this case the outlier is able to be identified, it is not known to actually be an outlier and it would be extremely difficult to be reliably corrected and/or accounted for. Further, the influence of this outlier on the line of best fit is significant, altering the entire CP relationship.

The same dataset as an EFP relationship is provided on Figure 4.3. As shown, the EFP approach tends to reveal outliers more clearly than the CP method. At first glance, these outliers unnecessarily complicate what may be a relatively simple EFP relationship. It is difficult to assess a physical justification for the presence of outliers and as such, EFP relationships should not be fitted through these points without assessment of their validity. This may require an investigation into the particular anomalous event(s), in order to determine origin and to decide upon a method of resolution. In practice, authors have found that such things as backwatering effects, which may have gone unidentified in the site Rating Curve (as these effects were above the maximum measured discharge), have been revealed as the presence of a systematic anomaly in the EFP relationship.
Figure 4.2  Outliers in Chronological Paired Relationship

Figure 4.3  Outliers in Empirical Frequency Paired Relationship
The significant difference between EFP and CP is in the manner in which outliers affect long-term estimates. For CP, all correlated points have an influence on the linear regression relationship and the alteration of a single point anywhere in the regression will alter the entire regression equation, as shown on Figure 4.4. EFP does not suffer from this limitation, and although an uncorrected or poorly extrapolated outlier may have an impact on the flow ranges within which it is located, it will have no impact on any other aspect of the regression. It is expected that this is largely the reason that EFP resulted in consistently more precise and accurate synthetic long-term streamflow records. For example, for all runoff percentiles in all hydro-climatic regimes, the variability of results, when incorporating up to and beyond 5 years of data into an EFP model, did not increase precision.

An uncorrected outlier in both CP and EFP results in over or underestimation of synthetic runoff, especially in high flow regimes. Removal or correction of outliers tended to improve the resultant synthetic record, but identification and management of outliers for CP is difficult.

Figure 4.4  Chronological Pairing with three outliers removed. Removed outliers are shown in red
4.3 DIMINISHING RETURNS

Figures discussed in Section 3.2 show that, despite an overall improvement in precision as additional data are integrated into the regression analysis, there comes a point where improvement in precision may be inconsequential and that additional data will not greatly improve the match between the resultant long-term synthetic series and the measured record. This is lack of improvement is expected to result from a number of factors, including:

- The actual physical relationship between the two catchments,
- Uncertainty that is inherent in each dataset,
- Delineation and selection of EFP hydrograph segmentation,
- Uncertainty in extrapolation above the maximum runoff within the concurrent regression period,
- Uncertainty in extrapolation below the minimum runoff within the concurrent regression period.

These factors will largely determine the ultimate range of uncertainty that any long-term synthetic series will have. Unfortunately, these uncertainties are not able to be readily verified and/or quantified. However, for all intents and purposes, the Figures given in Section 3.2 demonstrate that between 3 and 5 years of data will reduce variability in the resultant long-term synthetic series. These results suggest that ongoing data collection for the purpose of refining long-term estimates of streamflow using EFP techniques is entirely justifiable and that increasing data volume will lead to a stronger, more accurate and precise regression, but that for many runoff percentiles, it was found that between 3 to 5 years of data will provide a level of precision that will not be greatly improved upon. This is consistent with the findings of Gan et al. (1997), who suggested that between 3 and 5 years of site data would be required for developed of a robust model, and that these years should incorporate a representative sample of low, mid and high flows (Gan et.al., 1997).

4.4 IMPLICATIONS FOR FLOOD FREQUENCY ANALYSIS

Flood Frequency Analysis (FFA) is a common application in engineering and long-term synthetic streamflow records are often the primary input. Although a detailed analysis of FFA is beyond the scope
of this research, it is important to know whether these long-term synthetic records are accurately and precisely representing long-term conditions for the purpose of FFA and engineering design. A widely used FFA technique sees the extraction of the annual maximum flood, for each year of record. These series of records are fitted to a statistical distribution, such as a Gumbel or Log Pearson Type III, utilizing location and scale parameters such as the Mean, Standard Deviation and Skewness, of annual flood maxima.

A preliminary assessment of the effectiveness of pairing techniques, for the purpose of generating inputs to FFA was undertaken. Pluvial and glacial regime long-term synthetic records were not incorporated into this assessment due to their relatively short period of record. A discussion of the limitations in data extents are given in Section 5. Results of this preliminary study were limited to the comparison of the range of mean and standard deviations derived from each pairing model. Further research into the derivation of inputs to FFA, using long-term synthetic streamflow data derived from pairing, is required, but these preliminary results suggest that EFP will provide FFA inputs that are more representative of long-term conditions.
SECTION 5.0 - CONCLUSIONS AND RECOMMENDATIONS

This research evaluated the performance of pairing techniques in modelling long-term runoff from short-term gauged watersheds and long-term regional watersheds. Magnitude and timing are not directly related in so far as discharge in one catchment will correlate in both timing and proportional magnitude to discharge in another catchment, regardless of how well correlated these catchments may at first appear to be. Such correlations are also subject to non-linearity with discharge magnitude, meaning that as discharge increases (or decreases), the correlation between two catchments may vary. A large component of this variability, especially in higher flow regimes, is expected to be in response to the variable return periods of individual events as they pass through the respective catchments (for example, a 100 year flood in one catchment may be a 125 year (or 25 year) flood in its paired catchment). The variability may also be related to specific catchment dynamics that are variable, both spatially and temporally so that a hypothetical storm event that may provide identical inputs to each catchment, will lead to differential runoff, in response to these dynamic in-catchment processes. Whatever the source, variability leads to the inevitable scatter that is seen in the standard CP regression plots. This scatter has been viewed as not only unavoidable, but in fact an intrinsically important signal in determination of the quality of a paired correlation. This research has revealed that a pairing technique that incorporates both frequency distributions of magnitude and timing, simultaneously, demonstrates improved accuracy and precision in modelling all flow regimes.

A major finding of this Thesis relates to the extent of project baseline streamflow data collection required to characterise long-term conditions. Many hydropower projects in British Columbia are collecting baseline data from Project watersheds with the principle purpose being to collect a sufficient length of data to incorporate into a hydrologic model (commonly Pairing) with minimal uncertainty. The extent of baseline data required for a Project is the subject of some debate. Project proponents, Consultants and Regulators recognise that uncertainty in the quality of project streamflow records increases the uncertainty associated with long-term estimates, and that the suitability of nearby regional stations for pairing will be just as critical in characterising uncertainty in long-term estimates. It is therefore extremely difficult to categorically state the extent of baseline data collection required for all Projects. For example,
the latest “Water and Air Baseline Monitoring Guidance Document for Mine Proponents and Operators” (BCMoE, 2012), stipulates the need for a minimum of two years of data in order to evaluate the accuracy of rating curves, but goes on to state that “The length of hydrologic record required for a baseline hydrology study will vary depending on the quality of existing onsite data and nearby stations or regionalized data, and it may be longer than two years”. The research found that as models incorporated additional years of baseline data, there was a progressive reduction in the variability of EFP results. Furthermore, the research found that following the incorporation of between three and five years of high quality baseline streamflow data, the variability in long-term synthetic runoff, from pairing models with a nearby and representative long-term regional station, was generally reduced to the point where there was little improvement in precision with incorporation of additional data. Hence, for the express purpose of incorporating into EFP models, incorporation of beyond five years of high quality record did not tend to improve the accuracy and precision of resultant long-term synthetic records, and that more years of data were generally required to provide improved precision of those discharges that have a lower probability of exceedence, particularly for the purpose of Flood Frequency Analysis. This is not to say that once reached, resultant long-term estimates will not improve as data quality and the appropriateness of regional site selection may have a significant impact on results. Variability in precision will be present no matter how many years of data are incorporated, and as projects develop, this variability, although potentially viewed as an improvement in accuracy, may actually be more representative of the actual variability in the sites that are the subject of measurement error, and error and/or influence of parameters that are not able to be captured within the pairing models.

There are many studies that may be carried on from this work and to build upon these findings. Some of these recommendations are given below:

- Perform comparative analyses using records longer than 15 concurrent years for Pluvial and Glacial regimes. The relatively short extent of concurrent data used for two of the hydro-climatic regimes incorporated into this study was a limiting factor. Ideally, attempts to model up to 40 years of record would be ideal.
• Perform comparative analyses using multiple (more than 2) catchments within each regime. This research used two sites within each hydro-climatic regime. To reduce uncertainty in these results, incorporation of additional site combinations into EFP and CP models would be useful.

• Perform similar analyses in regions subject to extremely localised precipitation events. Preliminary studies into the use of EFP and CP in extreme climate regimes (such as found in areas of central America, south east Asia, northern Australia and northern Africa) suggest that where CP will be largely ineffectual in modelling long-term flow conditions due to large variability in both timing and magnitude, EFP provides improvement, but it is expected that the extents of record required to define baseline conditions would differ from the findings of this research. Analyses of datasets from the regimes subject to extremely localised precipitation is difficult given that many datasets are of insufficient length and are frequently of low quality.

• The research found the correction of outliers in the EFP method, which may have biased the results. It is recommended to re-evaluate these comparisons following removal of the top 1% of CP data.

• Explore the use of EFP with non-concurrent streamflow records. A problem frequently encountered by many practitioners is the presence of non-concurrent long-term regional streamflow stations near a Project area. Given the constraints of concurrency in pairing, these decommissioned stations often provide very little usefulness for pairing apart from secondary reference information. Preliminary investigation into the use of non-concurrent data in an EFP model has yielded promising results, and the ability to use non-concurrent but long-term streamflow estimates may be a particular strength of the EFP technique. Such opportunities, if explored, must carefully consider any source of non-stationarity that may bias non-concurrent runoff, such as forestry of mining, as well as larger climate cycles (such as El Nino and La Nina) which, if mixed, may also bias results.

• An exploration into the comparison of EFP techniques with more complex chronological pairing techniques such as multi-linear regression analysis is strongly recommended.
• Low Flow studies are important for water availability concerns especially during times of extended droughts. An assessment of the performance of a variety of pairing techniques in synthesizing return period low flows is recommended.

• The improvement in the precision and accuracy of long-term synthetic streamflow estimates have been provided in this research as the deviation of the synthetic from the measured, as a percentage. Investigation of other methods to numerically represent the improvement in modelling results would be useful.

• This research assumed that only up to 7 years of streamflow data were available for incorporation into pairing models. Review of modelling results using greater than 7 years of streamflow records has been recommended.
References


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