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Validation of the SCS TR-55 method on Whangarei District Watersheds and Soil Types

A draft dissertation submitted by

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Abstract

The design of hydraulic structures relies heavily on the estimation of rainfall generated runoff. The TR-55 method is widely used throughout the world by engineers and hydrologists. This is the method prescribed by the local council for use in the Whangarei District. Both local consulting engineers and the author have concerns over the suitability of TR-55 as no local validation has been undertaken, with flood levels often being estimated above any known events.

This research project aimed to assess the suitability of TR-55 in the Whangarei District. In particular, assessing where the primary local soil types fall into the method's hydrologic soil groups and reviewing the Type IA rainfall distribution against known rainfall events.

Field investigations and flood frequency analyses of the gauged watershed were used to complete the critical tasks of the research, which also required the estimation of baseflow using the recursive digital filter technique by Lyne and Hollick.

The results of the research neither confirm or discount the suitability of the TR-55 method, but instead resulted in a set of recommendations and limitations for its use, with recommendations for further research. It was found that the TR-55 overestimated runoff by up to 327% and that the runoff characteristics of the major soil types in the Whangarei District were not well understood.

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Limitations of Use

Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Nomenclature

Symbol	Description	Unit
Q	Runoff or Discharge	mm or m^3/s
P	Rainfall	mm
S	Maximum Potential Retention	mm
I_a	Initial Abstraction (Taken as 0.2S in TR-55)	mm
CN	Runoff Curve Number	-
A	Area	m^2 or ha
PI	Pattern Index	-
T	Time	Minutes
L	Length	m / km
S	Slope	m/m
S_a	Slope	m/km
R_h	Hydraulic Radius	-
V	Velocity	m/s
n	Mannings n	-
qf(i)	quick flow	m^3/s
q(i)	total flow	m^3/s
qb(i)	base flow	m^3/s
α	filtering parameter (Commonly 0.98)	-
m	Plotting Position or mean	-
n	Total Number of Years	-
y_i	Logarithm Flow	-
g	skewness	-
k_y	Frequency factor	-
$\bar{Y}$	Average Logarithm Flow	-
s	Standard Deviation	-
R_B	Under Peak Base Flow Ratio	-

Validation of the SCS TR-55 method on Whangarei District Watersheds and Soil Types

1.0 Introduction

1.1 Background

Whangarei District is situated on the north east coast of New Zealand's North Island, refer Figure 1. A subtropical district that receives on average 1500mm of rainfall annually. The primary land use in the district aside from urban areas are agriculture, horticulture, exotic plantation forestry and native bush (Edbrooke and Brook, 2009).

Figure 1-1: Map of New Zealand (Help.zeald.com, 2019)

In civil engineering, the analysis and design of hydraulic structures rely heavily on the estimation of runoff/discharge from a given watershed. Regional or territorial authorities often prescribe a predetermined method for use. Estimation of rainfall excess during rainfall events is an integral component in the design of hydraulic structures and devices (Ajmal and Kim, 2015).

Many methods exist for the estimation of runoff. One of the simplest and widely used methods is produced by the United States Department of Agriculture Natural Resources Conservation Service, called Urban Hydrology for Small Watersheds also known as Technical Release 55 (TR-55) (United States Department of Agriculture, 1986). TR-55 requires minimal input parameters, making this method popular among engineers and consultants.

1.2 Problem Statement

The Whangarei District Council requires the use of the TR-55 method and Type IA design rainfall distribution (WDC, 2010). WDC (2010) also recommends that the Hydrologic Soils Groups of the TR-55 method be applied as follows;

- *D - Very low permeability such as clay (e.g. Northland Allochthon/Onerahi Chaos)*
- *C - Low permeability such as loam (e.g. Maunu and Glenbervie volcanics)*
- *B - Medium permeability, coastal windblown sands (e.g. Ruakaka and Waipu coastal sands)*
- *A - High permeability such as fractured rock and deeply bedded scoria deposits.*

There is concern among the consulting civil engineers in the Whangarei District as to the suitability of the TR-55 method. No validation is locally available, with concerns being raised when apparent 100yr rainfall events do not remotely reach design flood levels.

1.3 Project Aims

This project aims to assess the suitability of the TR-55 method in the Whangarei District. In particular, reviewing where major local soil types fall in the method's hydrologic soil groups and comparing the Type IA design storm to actual rainfall events. The aim of the research project will be achieved by selecting, analysing and modelling Whangarei District watersheds which are monitored by the Northland Regional Council to make a comparison of TR-55 estimated runoff against discharge from known rainfall events. To assess the correct use of the method and enable the validation processes, field investigation will be completed to aid in the categorisation of the local geologies and soil types.

This research project will either provide a validation or develop the basis for further work to enable a better suited method to be identified.

1.4 Research Objectives

The following objectives were developed to achieve the aim of this research:

1. Complete a detailed literature review to fully understand the TR-55 method, its key parameters, and potential methods of validation.
2. Set criteria and undertake a selection process to identify suitable monitored watersheds in the Whangarei District for inclusion in this research project.
3. Confirmation of where the major Whangarei District geologies/soil types fall within the four hydrologic soil groups.
4. Complete a review of Type IA rainfall distribution for typical Whangarei District rainfall events.
5. Make a comparison of actual watershed discharge and estimated discharge, using a flood frequency analysis and TR-55 to enable potential validation.

1.5 Expected Outcomes & Benefits

The TR-55 method is highly sensitive to the simplistic parameters required, having significant implications of the results returned, with little thought often given to their effects. This research project will enhance the understanding of the TR-55 method and its uses to estimate peak watershed discharge in the Whangarei District, enabling the design of hydraulic structures that are neither conservative nor inadequate.

The expected outcomes of this project are as follows:

- Either validation of the TR-55 method prescribed by the Whangarei District Council or recommendation of an appropriate method, or further work.
- An improved understanding of the TR-55 method and CN values on the Whangarei District.
- Increased confidence/efficiency in design of local hydraulic structures.

Ultimately this project will provide a newfound understanding of the application of the TR-55 method in the Whangarei District, identifying where the local soils are placed in the existing soil categories and the appropriate use of CN values.

1.6 Report Structure

Table 1-1: Description of Report Layout

Chapter	Topic	Description
1	Introduction	Provides a brief description of the research project, stating the motivation, aims, and objectives.
2	Literature Review	A detailed review of the relevant literature is provided including exploration of the TR-55 method and its varying input parameters
3	Methodology	This chapter is split into section sections. Beginning with the process of watershed selection, moving on to the methods of analysis and validation.
4	Results	The results of the investigations, including the watershed inspections, and field testing results, are presented here with the results of the analyses presented in graphical form.
5	Discussion	Detailed discussion is provided, taking a look at the results achieved, potential sources of error and the author's thoughts during the research.
6	Practical Implications	A review of the result is made in relation to the practical implication of the research results, looking at several common hydraulic tasks.
7	Conclusion	A summary of the research project is presented along with a summary of the conclusion reached. A list of areas that require further research is provided.
9	Recommendations	A set of recommendations are made for local Whangarei District consultants to ensure the correct use of the TR-55 method.

2.0 Literature Review

2.1 Introduction

The purpose of this literature review is to explore the TR-55 method, the associated manuals issued by the United States Department of Agriculture (USDA), evaluate the use of this method in New Zealand, identify existing literature of relevance to the method and consider potential means of validation. This chapter will conclude with a summary, identifying the critical knowledge gaps before the development of a methodology.

Development of the Curve Number method occurred in the late 1950s by the United States Department of Agriculture (USDA) Soil Conservation Service (SCS) (Hawkins et al. 2008), with its origins traced back to the late 1930s, based on thousands of infiltrometer tests (Ponce and Hawkins, 1996). Although much of the literature on the development of the method has been lost, much research has been completed since to define this.

2.2 The USDA TR-55 Method

The USDA Natural Resources Conservation Service (formally SCS) Technical Release 55 (TR-55) is a procedure to estimate peak runoff from rain storms. The method is called, Urban Hydrology for Small Watersheds, however it is commonly knowns as TR-55. Since the first issue being released by the SCS in January 1975 there have been multiple significant revisions and additions, with the current version being dated June 1986.

TR-55 uses a simplified SCS equation for estimating runoff. The method uses runoff curve numbers (CN), which represent infiltration losses dependant on land use, ground cover and hydrologic soil type. Equation 2-1 is the SCS equation on which TR-55 is based:

$$Q = \frac{(P - I_a)^2}{(p - I_a) + S} \quad for\ P > I_a \qquad \text{Eq. [2-1]}$$

$$Q = 0 \quad for\ P \leq I_a$$

TR-55 is based on the primary assumption that initial losses (I_a) are equivalent to 0.2S. This assumption however often results in little to no runoff during small rainfall events (Priestley, 2015). With the substitution of I_a=0.2S, equation 2-1 is manipulated as follows:

$$Q = \frac{(P-0.2S)^2}{P+0.8S} \qquad P > I_a \qquad \text{Eq. [2-2]}$$

Maximum potential retention (S) is a depth, often in millimetres, and varies depending on ground cover, land use and soil type, related to CN in TR-55 by equation 2-3.

$$S = 254\left(\frac{100}{CN} - 1\right) \qquad \text{Eq. [2-3]}$$

The S/CN relationship is considered somewhat arbitrary with the CN values based on an assessment of pore space and initial soil moisture. Soulis and Valiantzas (2011) and Levy (2017) consider the use of a single CN value as problematic. United States Department of Agriculture (2004) provides equation 2-4 for losses:

$$Loss = S + I_a \qquad \text{Eq. [2-4]}$$

2.3 Hydrologic Soil Types

The USDA introduced four hydrologic soil groups which play a crucial role in the SCS method and TR-55. Summarised below are the USDA (2009) details of the hydrologic soil groups and the criteria of their definition. TR-55 gives more straightforward criteria base on soil texture, as presented in Table 2-1 (Hawkins, 2007).

Group A

- Less than 10% Clay
- Greater than 90% Sand or Gravel
- Gravel or Sand textures

Group B

- Typically, between 10% and 20% clay and 50% to 90% sand
- Being, loam, silt loam, or sandy clay loam textures
- Greater than 35% rock fragments
- Water table greater than 60cm
- Depth to water impermeable layer is greater than 50cm
- Saturated hydraulic conductivity of 14.5mm/hr to 36mm/hr

Group C

- 20% - 40% clay
- Less than 50% sand
- Loam, sandy clay loam, clay loam and silty clay loam textures
- Water table greater than 60cm
- Depth to water impermeable layer is greater than 50cm
- Saturated hydraulic conductivity of 1.5mm/hr to 14.5mm/hr

Group D

- Greater than 40% clay
- Less than 50% sand
- Have high shrink-swell potential
- All soils with water table less than 60cm deep
- All soils where depth impermeable layer is less than 50cm
- With water impermeable layer between 50-100cm, saturated hydraulic conductivity of less than 3.6mm/hr
- For soils deeper than 100cm to a restriction or water table, saturated hydraulic conductivity of less than or equal to 1.5mm/hr

Saturated hydraulic conductivity should not be confused with infiltration. Research of infiltration rates in the Whangarei District in relation to hydraulic design is limited. Auckland Regional Council (2013) lists infiltration rates in relation to a soil textural class, varying between Sandy Clay loams and Clays with infiltration rates between 4.5mm/hr and 0.5mm/hr respectively. A brief description of the hydraulic soil groups by Musgrave (1955), which is supported by Matell (2005) are summarised in Table 2-1.

Table 2-1: Soil Types

Soil Type	Soil Textures	Description	Infiltration Rates
A	Sand, Loamy Sand, or Sandy Loam	High Infiltration Rates	>8mm/h
B	Silt Loam or Loam	Moderate Infiltration Rates	4-8mm/h
C	Sand Clay Loam	Low Infiltration Rates	1-4mm/h
D	Clay Loam, Silty Clay Loam, Sandy Clay, Silty Clay or Clay	High Runoff Potential	0-1mm/h

A multitude of testing apparatus and procedures exist for the field determination of soil infiltration and percolation rates. An Infiltrometer, which is designed to measure vertical infiltration rates only, is the most common method (U.S Department of The Interior, 1963).

The Auckland Regional Council (2009) method (TP108) placed similar soil types in the hydrologic soil groups, based on validation in gauged watershed as presented in Table 2-2.

Table 2-2: TP108

Auckland Soil	Hydrologic Soil Group
Weathered Mudstone and Sandstone (Waitemata and Onerahi Series)	Group C
Alluvial sediments	Group B
Granular volcanic loam (ash, tuff, scoria)	Group A
Granular volcanic loam underlain by free draining basalt	Use CN=17 for all pervious areas

2.4 Soil Description

Williams (2005) details the field description of soil and rock in New Zealand, recommended by the New Zealand Geotechnical Society. This method of classification separates soils to either fine or coarse grained materials, being clay/silt, sand/gravel and organic soils, refer to Figure 2-1.

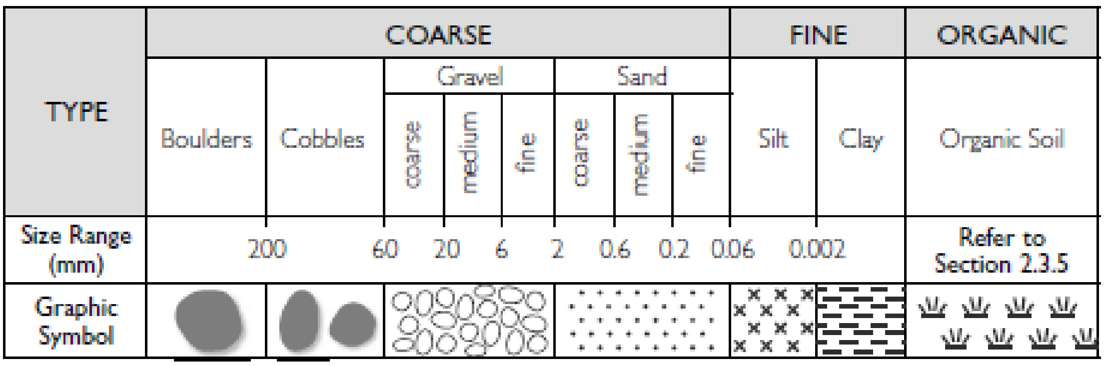

Figure 2-1: NZGS Soil Descriptions

The differentiation of sand from fine grained soils in the field can be difficult. Sand can however generally be felt between fingertips when rubbed together, as opposed to silt from clay which is indistinguishable between fingertips.

Clays and Silts are typically and technically differentiated by a particle size of 0.002mm. Williams (2005), however, provides the differentiation of clay from silt by the behaviour of the soil material. Clays are identified where the moist material behaves in a plastic manner, being continuously mouldable. Silts, on the other hand, are best identified using a basic dilatancy test where if the material softens, it is considered as quick. A field dilatancy test can be performed by placing a sample of the material in the palm of your hand and vibrating it horizontally. Williams (2005) makes a further differentiation between clay and silt, suggesting that high plasticity clays will become rock hard when dry, while material which tends towards silt that may display plastic behaviour will easily crumble.

A full description of fine grained soils shall follow this sequence of terms; fraction, colour, structure, strength, moisture, bedding, plasticity, sensitivity, other. The New Zealand Geotechnical Society has issued a field guide sheet for the field description of soils which is included in Appendix B.

2.5 Runoff Curve Number

The runoff curve numbers (CN) are one of the critical parameters in the calculation of rainfall excesses using the TR-55 method. Baltas, Dervos and Mimikou (2007) describe CN values as being largely dependent on soil type, surface condition and climate conditions, and state that they are often arbitrarily selected with little validation of their application. These values represent the runoff coefficient of the watershed. As CN values increase, so too does runoff, with impermeable surfaces such as concrete having a CN of 98. United States Department of Agriculture (1986) provides CN numbers for varying ground covers and land uses for the hydrologic soil groups. Table 2-3 provides a summarised list of CN values for different land use, and the four hydrologic soil groups. Although the calculations for peak runoff use a single CN value, a weighted average value can be determined for the given watershed or subarea as shown in Equation 2-5.

$$Weighted\ CN = \frac{\sum CN_x A_x}{A_{Total}} \qquad \text{Eq. [2-5]}$$

Table 2-3: Summary of CN Values

Cover Description	Hydrologic Condition	Hydrologic Soil Group			
		A	B	C	D
Impervious (Paved)		98	98	98	98
Residential Districts Lot Size 500m²		77	85	90	92
Pasture	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Woods	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30	55	70	77

2.6 Geology and Soil Type of Whangarei District

The Whangarei District is made up of geology beginning with the Permian aged (greater than 108 million years) Waipapa Group deposits which are primarily the basement material, outcropping in the east. Materials generally reduce in age moving towards the west, though due to faulting this can vary locally. The young materials within the Whangarei District are either Pleistocene and Pliocene age (0-5.3 million years) volcanic cones and flows or recent alluvial deposits (Edbrooke, 2009). Figure 2-2 displays the geology of the Whangarei District at a 1:250,000 scale.

A summary of Edbrooke (2009) and T&T (2008) descriptions of the typical weathering of the four main geological groups, is presented below:

- **Waipapa Group** – This material typically weathers to light brown and dark yellow clays which are very stiff to hard, predominantly containing non-swelling kaolinitic clays.

- **Northland Allochthon** – Soils developed by weathering are often light greyish white, light yellow, and light brown, being highly plastic, very soft to stiff and typically wet. Groundwater is often near the surface. These materials are also considered as having high shrink/swell potential.

- **Kerikeri Volcanics** – Pillow basaltic lava flows which weather to light and dark brown clays and are typically very well-drained.

- **Recent Alluvium** – Holocene age fluvial sediment ranged from sands to clays, varying in strength from very soft to very stiff.

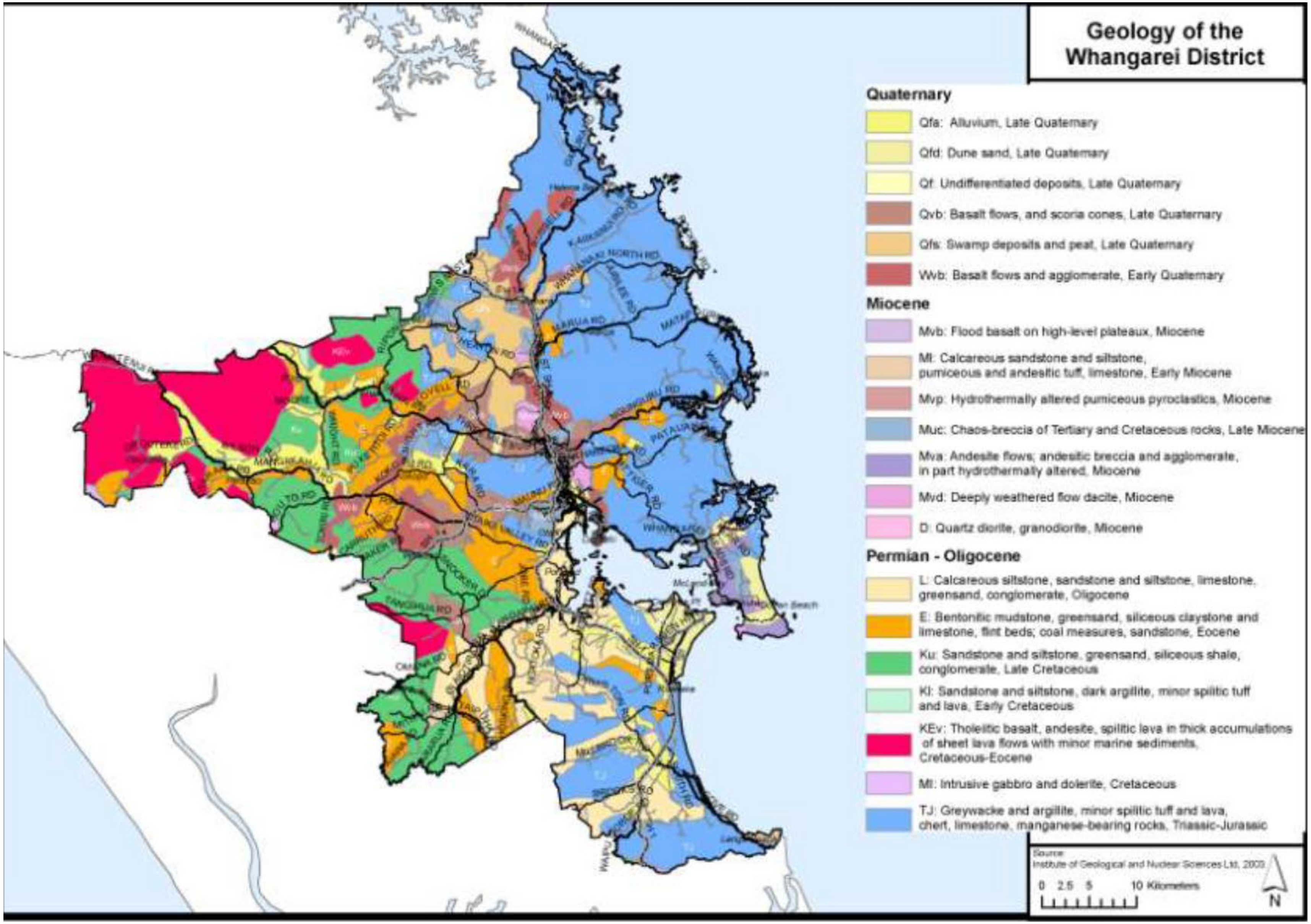

Figure 2-2: Geology of the Whangarei District

2.7 Synthetic Rainfall Distributions

Synthetic rainfall distributions require extensive effort in development, generally based on depth-duration-frequency relationships. The SCS rainfall distributions are conservative, however, are considered an adequate approach for where local rainfall distributions are not provided (Dalrymple, 1960).

Rainfall events of similar magnitude and duration often exhibit considerable variation in temporal pattern, consequently, adopting the incorrect design storm can lead to an inaccurate estimation of peak flow (Ball et al., 2019). Ball (2019) further describes that the tendency of historic design storms has been aimed at a representative or median approach, however modern techniques use an ensemble of rainfall distributions as an attempt to overcome this. A set of relatively accurate universal design storms is simply unavailable.

Kimoto, Canfield and Stewart (2011) used a Pattern index (PI) to provide a ratio of area under the normalised rainfall distribution, as a mean of quantifying differences between rainstorms. An increased pattern index generally represents an early peak intensity or burst rainstorm. Equation 2-6 is proposed for the PI.

$$PI = \frac{\sum_{i=1}^{n-1}[\frac{P_{i+1}+P_i}{2}(T_{i+1}-T_{i})]}{P_n T_n} \qquad \text{Eq [2-6]}$$

2.7.1 Type IA

The United States Department of Agriculture (1986) TR-55 method is based on a series of synthetic rainfall distributions, also known as design storms, or unit hydrographs. TR-55 presents multiple rainfall distributions, Type I, Type IA, Type II, and Type III. WDC (2010) requires the use of the Type IA rainfall distribution, which is recommended for dry summer, wet winter climates, and is likely the only reason for selection, considering the lack of validation given, shown in Figure 2-3.

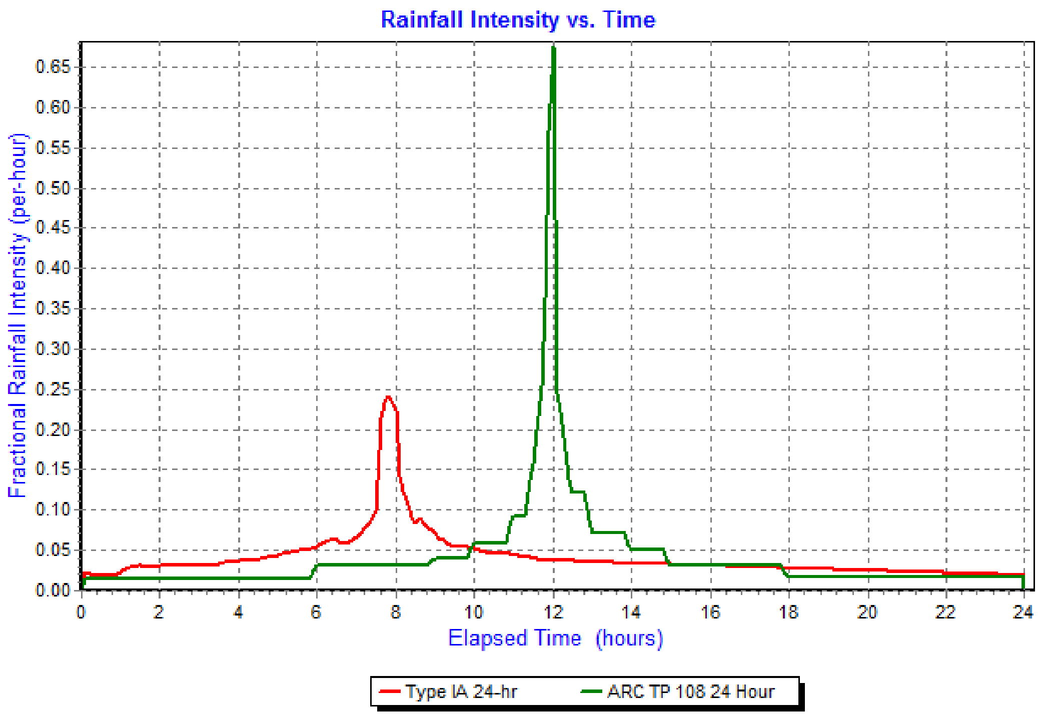

Figure 2-3: Unit Hydrograph (Source: HydroCAD)

2.7.2 Auckland Regional Council TP108

Neighbouring districts, both north and south of Whangarei use the TP108 design storm provided by Auckland Regional Council (1999). A comparison to the Type IA event is presented in Figure 2-3.

Observation of Figure 5 displays the difference between the TP108 and Type IA design storms. No formal validation or methodology on the development of the TP108 design storm is publicly available, however Auckland Regional Council (1999) provides the following summarised limits of application:

- The model has been validated for watershed up to 12km² with little storage.
- The model applies to both rural and urban (or mixed) watersheds.
- Rainfall losses and runoff have been validated for clayey and volcanic soil types.
- Validation of the model used six gauged Auckland catchments, having a standard error of 21%. The model can be expected to be within +/-25% at a 90% confidence level.

2.8 Watershed Models

Developing a model to represent the spatial variation of a watershed can range vastly in complexity, increasing from Lumped, Semi-distributed to Distributed (Ball et al. 2019). Based both on Ball et al. (2019) and Sharifi and Hosseini (2011) a summary of the models follows;

- Lumped – Treat the watershed area as a single homogenous unit, spatial variability of parameters is disregarded.
- Semi-distributed – Similar to a lumped model, with the watershed divided into areas to represent important features.
- Distributed – Complex, splitting the watershed into small elements or cells. High data demands, best suited to Digital Elevation Models.

2.9 Time of Concentration

Many methods are available for estimating time of concentration, generally based on flow length, slope, and roughness, with some methods employing watershed shape factors. Research by Salimi, 2016 assessed 22 methods of determining the time of concentration, with the Bransby-Williams equation being considered the best estimate. Lockyer 2019 extends this, by recommending an average be taken of the before mentioned equation and the Ramser and Kirpich equation for undeveloped watersheds where the main channel length exceeds 1000m.

$$Ramser\ Kirpich\ T_c = 0.0195\ L^{0.77} S_a^{-0.385} \qquad \text{Eq. [2-7]}$$

$$Bransby\ Williams\ T_c = \frac{FL}{A^{0.1} S^{0.2}} \qquad \text{Eq. [2-8]}$$

It should, however, be noted that the before mentioned equations are based on empirical correlation and should generally only be considered as acceptable with regional validation. Sharifi and Hosseini, 2011 state that due to variation in interpretation of parameters an exact global method to measure T_c does not exist, also suggesting that the velocity based methods, as presented in TR-55 are commonly selected as being the most accurate due to their strong hydraulic basis. The TR-55 method of calculating T_c is a distributed method based on parameters to determine velocity of runoff for the different segments of the flow path and channel (Sharifi and Hosseini, 2011). Sharifi and Hosseini (2011) however add that although the velocity based methods are considered most accurate, due to modelling assumptions and a large number of input parameters required the method fails to produce repeatable estimates of time of concentration. Equations 2-9 to 2-12 form the basic velocity time of concentration equations.

$$T_c = overland\ flow + shallow\ concertrated\ flow + open\ channel\ flow \qquad \text{Eq. [2-9]}$$

$$T_c\ overland\ flow = \frac{107nL^{0.333}}{S^{0.2}} \qquad \text{Eq. [2-10]}$$

$$T_c shallow\ concertrated\ flow = \frac{L}{295\ S^{0.5}} \qquad \text{Eq. [2-11]}$$

$$T_c\ open\ channel\ flow = \frac{L}{V\ 60} \quad where\ V = \frac{1}{n}\ (R_h^{\frac{1}{2}})\ (S^{\frac{1}{2}}) \qquad \text{Eq. [2-12]}$$

2.10 Baseflow

Peak flows measured during storm events consist of both quick flow (rainfall generated runoff) and baseflow, depicted in Figure 2-4. To determine actual rainfall generated runoff, baseflow must be separated. Groundwater discharge is commonly considered as baseflow, which generally reduces with time after a rainfall event (Ball et al., 2019).

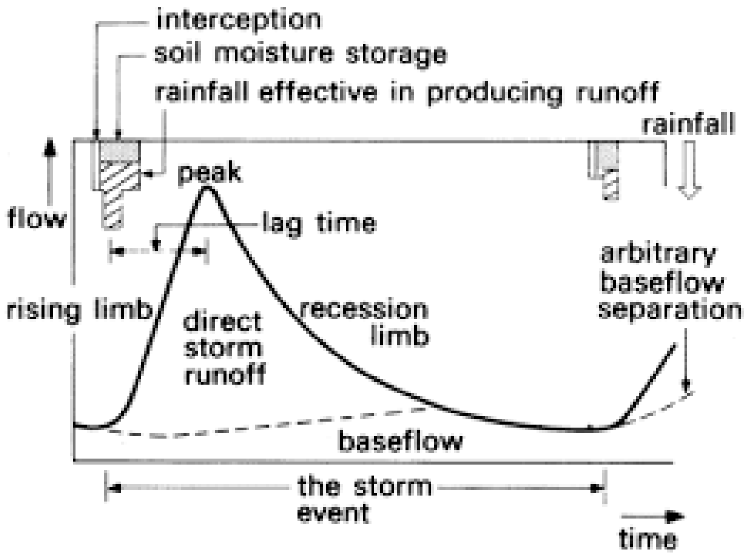

Figure 2-4: Baseflow (Knapp 1989)

Baseflows can easily be assessed using simple graphical methods. Sloto and Crouse (1996) proposed several graphical methods for separating baseflow by connecting local minima or points of inflection, however for large data sets, this may be labour intensive. Novita and Wahyuningish (2016) however describe multiple analytical methods using frequency analysis to filter low-frequency signal (baseflow) from high-frequency signal (quick flow), using a Recursive Digital Filter Method. Novita and

Wahyuningish (2016) observed that the EWMA, Lyne-Hollick and Local Minimum methods performed the best. The Lyne-Hollick is a commonly accepted method, also being used in New Zealand by Singh et al. (2019), shown in Equation 2-9 and 2-10.

$$q_f(i) = \alpha q_f(i-1) + \frac{(1+\alpha)}{2}\left[q_{(i)} - q(i-1)\right] \quad for\ q_f(i) > 0 \qquad \text{Eq. [2-9]}$$

$$q_b(i) = q(i) - q_f(i) \qquad \text{Eq. [2-10]}$$

Where

$q_f(i)$ = quick flow

q(i) = total flow (gauged)

$q_b(i)$ base flow

α = filtering parameter (Commonly 0.98)

The prediction of baseflow in relation to certain probability rainfall events is however problematic as baseflow varies dependant on many factors and will likely be dissimilar for events of a similar AEP. Murphy et al. (2011) completed a comprehensive study of Australian watershed to develop a simplistic method of baseflow calculation, using several ratios namely, the under peak ratio to represent baseflow to peak total flow. This simplified method was developed for ungauged watershed and is presented by Ball et al. (2019).

2.11 Flood Frequency Analysis

Flood frequency analysis (FFA) is a tool for use on gauged watershed to assess the probability of known flood events. Using peak discharges, two methods of FFA are available, the first being an Annual Maximum Series, and the second, a Peak-Over-Threshold Series. The former relies on extracting the peak flow in each year being ideal for rarer events, while the latter extracts any storm event which exceeds a predetermined threshold, often used for minor works, and temporary structures.

Several methods are available for FFA, namely the Generalized Extreme Value (GEV) and Log Pearson III (LP III). Although the GEV distribution is widely accepted, LP III is proven to perform best, consistently fitting flood data sets well. Ball, 2019 and ASCE, 1996 recommend LP III as the distribution of choice, however, is limited to the gamma-shaped density, where the absolute value of the skew of log Q is less than 2. Ball (2019) suggests that where the absolute values of skew are greater than 2, GEV or Generalized Pareto (GP) distributions are be better suited.

FFA are susceptible to several sources of error, particularly gaps in gauging data and rating curve errors. Ball et al. (2019) suggest for annual series, partials year are of no consequence and shall be maintained in the data set, supported by Dalrymple (1960) both recommending a reasonable estimate shall be made where a gap exists. Further to missing data, outliers can cause significant distortion of a fitting probability distribution. ASCE (1996) recommends that outliers should be discarded, particularly low flow values. Ball et al. (2019) also recommend a minimum record of 20 years, although 15 years is considered acceptable if required.

2.12 Knowledge Gap and Project Justification

United States Department of Agriculture (1986) provides the TR-55 method for determination of peak rainfall generated runoff, using simplified rainfall distributions and CN numbers for varying ground covers and four different hydrologic soil groups. Many sources of literature from New Zealand refer to the SCS and TR-55 methods discussing the four hydrologic soil groups and CN values for use with little to no validation. Hawkins et al. (2008) detail that little is known on the background and development of SCS methods on which TR-55 is based.

The calculation of peak discharge from a watershed is dependent on multiple vital parameters. Many studies have investigated the effectiveness of the varying methods to determine the time of concentration, the suitability of the rainfall distributions and the CN values. However, an assessment of the total method in relation to the Whangarei District or similar soil types is non-existent. The author was unable to locate any research into appropriate CN values for the major local soil types in the Whangarei District.

The local Basaltic soils produce little runoff during low-intensity events, likely having high initial abstraction. This is supported by the lack of well-defined natural drainage channels or flow paths. Due to the lack of drainage channels, storage is low, causing high runoff once initial abstraction is reached. This is often observed during high-intensity short duration thunderstorm type events.

Many of the clay rich residual soil types are grouped into hydrologic soil group D, however, it is likely they produce significant variation in rainfall generated runoff. The Waipapa Group soils which are the local basement geology, are mantled in a shallow depth of approximately 1.0m of residual clays which are well structured. This compares to soils of Northland Allochthon origins which have high plasticity and are massive, lacking almost any structure, and almost certainly producing high volumes of runoff with minimal initial abstraction.

Given the lack of validation and certainty, and the high likelihood of inaccuracy in the methods currently employed, the findings of this project can be directly applied to the analysis and design of hydraulic structures in the Whangarei District, leading to more efficient and practical design.

3.0 Methodology

3.1 Introduction

In this section, watersheds are selected with the parameters determined, investigations are conducted, and analysis and validation completed. The methodology of selecting/procuring the data, assessing the rainfall events and the process of analysis is detailed. In order to meet the specified project objectives, the following methodology has been proposed;

- Select watersheds for assessment. Undertake an assessment of each watershed, determining all crucial parameters.

- Undertake field inspections and investigations of the selected watershed. Assess the investigations to determine the soil categories for Whangarei District keys soil groups. Collect and analyses rainfall and river flow data.

- Compile the rainfall events corresponding to the peak annual discharge events for a minimum period of 10 years, assessing the events in comparison to the Type IA rainfall distribution. The Glenbervie Forest HG gauge monitored by the NRC will be used as it is located immediately adjacent to the Mangahahuru Stream watershed boundary.

- Undertake an annual series flood frequency analysis of each watershed.

- Complete a validation of the TR-55 method as prescribed by WDC (2010) against the flood frequency analysis completed above.

3.2 General Requirements

3.2.1 Health and Safety

The project proposal risk has been separated into two separate categories, personal risk, and project risk. Table 3-1 provides the matrix which was used to assess the identified risk, with the identified risk and minimisation techniques identified in Tables 3-2 and 3-3.

Table 3-1: Risk Matrix

Determine the risk category using the Risk Matrix below.					
Risk Matrix					
Result / **Likelihood**	Minor (1)	Moderate (2) (first aid only)	Severe (3) (serious harm)	Major (4) (permanent disabling injury)	Catastrophic (5) (Loss of life, ≥ $1 million costs)
People	First Aid	Medical Treatment	Serious Harm	Disabling Injury	Loss of Life
Project	Annoyance	Major Time Loss	Re work of Project	Difficulty Completing Project	Unable to Complete Project
Almost never (1)	Low (1)	Low (2)	Low (3)	Low (4)	Medium (5)
Unlikely (2)	Low (2)	Low (4)	Medium (6)	Medium (8)	High (10)
Possible (3)	Low (3)	Medium (6)	Medium (9)	High (12)	High (15)
Likely (4)	Low (4)	Medium (8)	High (12)	High (16)	Critical (20)
Almost certain (5)	Medium (5)	High (10)	High (15)	Critical (20)	Critical (25)
Risk Categories					
Critical	For consideration, consult immediately with your Supervisor/Manager to stop activity/process – action immediately				
High	Inform people – immediate action to be taken and applied				
Medium	Correction required				
Low	Risk perhaps acceptable – attention indicated				

Table 3-2: Personal Risk

Hazard	Risk	Minimisation
Low	Driving on public roads	Take it easy, during daylight hours. Stop often to make a visual assessment.
Medium	Field testing location on public land	Locate an area well off the road edge, protect self with vehicle as barrier
Low	Harm from equipment use and environment	Use equipment appropriately, with correct PPE
Medium	Safety around fast flowing or deep waterways	Ensure safe positioning and footing adjacent to waterways, take 5 to assess your path

Table 3-3: Project Risk

Hazard	Risk	Minimisation
Medium	Data Retrieval	Collect Data prior to project start
Low	Field testing	Allow appropriate time to complete testing
High	Use of HydroCAD	Ensure employment is maintained, Basic Version is available to purchase if required.
High	Loss of Data/Project	Use Google Drive for storage and maintain weekly a backup on pen drive.

3.2.2 Quality Assurance

To eliminate errors and ensure the quality of this project, a series of criteria will be applied, which includes:

- All field testing will be completed with the appropriate equipment and in accordance with the relevant standards, methodologies, and procedures.
- All data will be physically checked to ensure accuracy.
- Results of computational calculations and HydroCAD will be validated with simple hand calculations where suitable.

3.2.3 Required Resources

Varying resources are required to complete this project. The essential requirements are field investigations, collection of the Northland Regional Council rainfall and river gauge data and the use of HydroCAD to analysis peak flows.

A list of the resources required for this project is presented in Table 3-4 below, along with their source and cost.

Table 3-4: Required Resources

Resource	Source	Cost	Comment
Rainfall and River Gauge Data	Northland Regional Council	Nil	Available via an existing internet portal
Hand Auger	RS Eng	Nil	Afterhours access
Infiltrometer	Student	Nil	Student to Fabricate
Field Equipment	Student & RS Eng	Nil	Afterhours access and personal equipment
PC	Student & RS Eng	Nil	Afterhours access and personal laptop
MS Work	Student & RS Eng	Nil	Afterhours access and personal laptop
MS Excel	Student & RS Eng	Nil	Afterhours access and personal laptop
AutoCAD	RS Eng	Nil	Afterhours access
Hydro CAD	RS Eng	Nil	Afterhours access Hydraulic Modelling
General Supplies	RS Eng	Nil	Afterhours Access

3.3 Watershed Selection

The Northland Regional Council monitors river flow in over 30 watersheds in Northland, 24 of which are in the Whangarei District. To complete several of the main tasks of this research project, watersheds must be selected for the analysis. A basic preliminary assessment of each watershed was undertaken to aid the selection process. A strict set of selection criteria was adopted to select the final watersheds, ensuing watershed fit the proposed research and the limitations of TR-55;

- Consist of less than four major soil/geological types,
- the main channels/watershed are free of obstructions, (e.g. water supply dams, detention structures, flood mitigation schemes),
- gauging structures are not affected by tidal influence,
- consist of mostly farmland and bush/forest (minimal urban area is acceptable),
- have a time of concentration of less than 10 hours,

- are located within the Whangarei District, and
- have been gauged for greater than 20 years.

The Northland Regional Council monitored watershed located within the Whangarei District were reviewed, and the selection process completed, with the results presented in Table 3-5 along with the result of the criteria.

Table 3-5: Whangarei District Watershed

Gauge Station Name	Contains Flood Scheme, Detention Structure, Flat/Ponding Areas	Affected by Tidal Influence	Contains Minimal Urban Area	Less than Four Major Soil Types	Record Start	Time of Concentration <8hr	Suitable
Waiotu at SH1 Bridge	Hikurangi Swap Flood Scheme						No
Whakapara at Cableway	Hikurangi Swap Flood Scheme						No
Hikurangi at Moengawahine	Hikurangi Swap Flood Scheme						No
Mangakaghia at Gorge	No	None	Yes		1960		No
Oputeke at Suspension Bridge	No	None	Yes	Yes	1984		No
Wairua at Purua	Hikurangi Swap Flood Scheme						No
Mangere at Knights Rd	No	No	No	Yes	1983	<10hr	Yes
Mangahahuru at County Weir	No	No	No	Yes	1969	<10hr	Yes
Ngunguru at Kiripaka	No	Yes	-	-	-	-	No
Ngugnuru at Dugmores Rock	No	Yes	-	-	-	-	No

Mangakahia at Titoki Bridge	No	No	No	>4		>10hr	No
Wairua at Wairua Bridge	Hikurangi Swap Flood Scheme						No
Waipao at Draffins Rd	Large Ponding Area	No	No		1978		No
Waiarohia at Lovers Lane	Water Supply Dam						No
Hatea at Town Basin	No	Yes					No
Hetea at Whareora Rd	No	No	Extensive			>10hr	No
Ruamanga at Bernard St	Detention Structure						No
Ruamanga at Kotuku Dam Intake	Detention Structure						No
Whangarei Harbour at Marsden Point	No	Yes					No
Ruakaka at Flyger Rd	Large Ponding Area Caused by SH1					>10hr	No
North at Applecross Rd	Large Private Dam				1982		No
Ahuroa at Braigh Flats					1983	>10hr	No
Waihoihoi at St Marys Rd	Very Flat				1984		No
Otaika at Kay	No	No	Minimal	4	2011		No

3.3.1 Watersheds Selected

The selected watersheds are listed below. A high elevation layout plan of the Whangarei District located the watershed boundaries presented in Figure 3-1.

- Mangahahuru Stream County Weir
- Mangere River at Knights Road

Figure 3-1: Selected Watershed Location Plan

3.3.2 Spatial Parameters

Assessment and measurement of the required watershed spatial parameters will be completed using Autodesk Civil 3D, a drawing program capable of importing GIS layers. The following parameters will be measured from import topographical layers and geology maps; total watershed area, flow path length, land use areas and soil type/geology areas. The varying spatial parameters will be measured manually by tracing the extents.

Topographical layers were imported from the New Zealand 1:50,000 scale topographic maps made publicly available by Land Information New Zealand (LINZ) at Data.linz.govt.nz (2019). The GIS layers import from LINZ will include 20m interval contours, stream/river centre lines, native bush extents, and aerial photography.

The geology extents will be obtained by inserting and scaling of PDF files of the GNS Science 1:250,000 regional geology maps into the drawing file. These geological maps are publicly available at Gns.cri.nz (2019).

3.4 Field Investigations

To gain further understanding of the soil types and infiltration properties of the soil, and of the watershed characteristics, a series of field investigations were undertaken. These consisted of hand augered boreholes, infiltration tests and visual inspections where public access permitted. The borehole and infiltration tests were limited to several locations within the identified soil type.

Representative locations within the major soil types were selected where both the borehole and infiltration tests were completed. Suitable locations were selected based on the following criteria;

- Clear of excavations or embankments,
- well elevated above watercourse or standing water,
- of representative ground cover,
- minimum separation between the borehole and infiltration test of 1.5m,
- and not completed during or following a period of prolonged rainfall.

3.4.1 Visual Watershed Inspection

Where public access permitted, visual inspections were undertaken of the NRC gauging stations, the watersheds primary flow paths and ground cover/land use. This provided further insight into land coverage and an all-round greater understanding of the watershed, and so facilitating the selection of suitable locations for the field investigations.

3.4.2 Borehole

The hand augered borehole consisted of 75mmø holes bored to a depth of at least 1.0m below ground level where achievable. The soil description was recorded in terms of the New Zealand Geotechnical Society, Williams et al. (2005). Figure 3-2 displays a typical hand augered borehole in progress.

Figure 3-2: Typical Hand Auger

3.4.3 Infiltration

Infiltration testing was completed using a single ring infiltrometer within a flooded excavation, to effectively replicate the hydraulic conditions of a Double Ring Infiltrometer. The tests were completed based on the methodology and procedure of U.S Department Of The Interior (1963) and ASTM International (2003). A typical infiltration tests in progress is shown in Figure 3-3.

Infiltration testing was not completed in the Northland Allochthon materials due to their high shrink-swell potential. The alluvial based materials were also excluded from the infiltration testing as these materials are highly variable but are present in lower lying areas where groundwater levels are elevated, often being near the surface.

Figure: 3-3 Typical Infiltration Test

3.5 Assessment of Soil Categories

Assessment of the major soil types was completed using the published literature from the Whangarei District, and the field investigations completed as part of this dissertation. The process for determining the appropriate hydrologic soil groups is based on USDA (2009) presented is Section 2.3 of this report. The flow chart presented in Figure 3-4 has been prepared based on the beforementioned criteria to aid the categorisation process.

Figure 3-4 does, however, present the idea that infiltration rates are the overarching criteria for determination of the hydrologic soil groups. It must, however, be appreciated that the TR-55 method and SCS equation is not considered an infiltration equation, and consequently engineering judgement must be used on the final selection of the hydrologic soil groups.

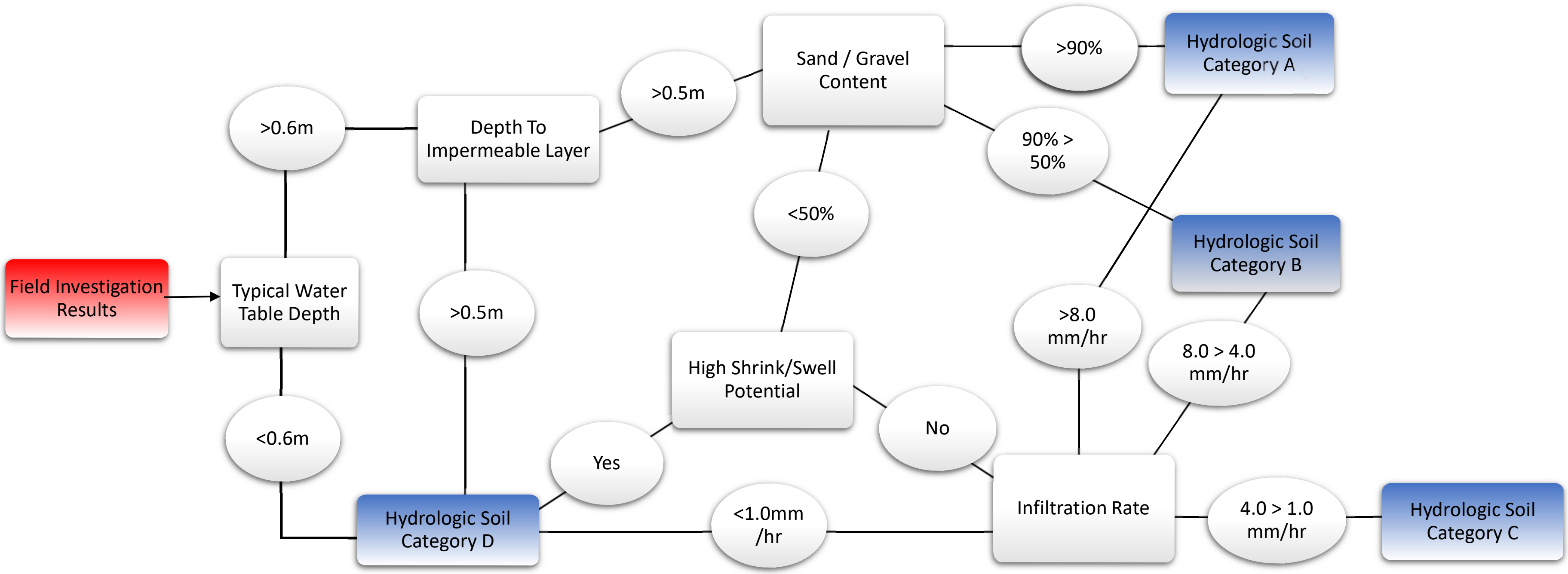

Figure 3-4: Hydrologic Soil Group Selection Chart

3.6 NRC Data Collection

The data collection phase of this project comprised two main tasks, retrieval of the separated rainfall and river flow gauging data from the Northland Regional Council.

The Northland Regional Council monitors rainfall at over 21 stations and river flow in over 30 watersheds in Northland. The rainfall and river flow data are an essential part of this project, enabling a comparison of actual rainfall generated watershed discharge and calculated discharge. The Northland Regional Council monitors the gauging stations with the data available from an internet portal NRC (2019). The portal has a map viewer system, which allows easy selection of the required gauging station. Upon selection of the desired station, a pop-up window enables selection of the date range, a plot of the data and download options to CSV or XML file types, Figure 3-4.

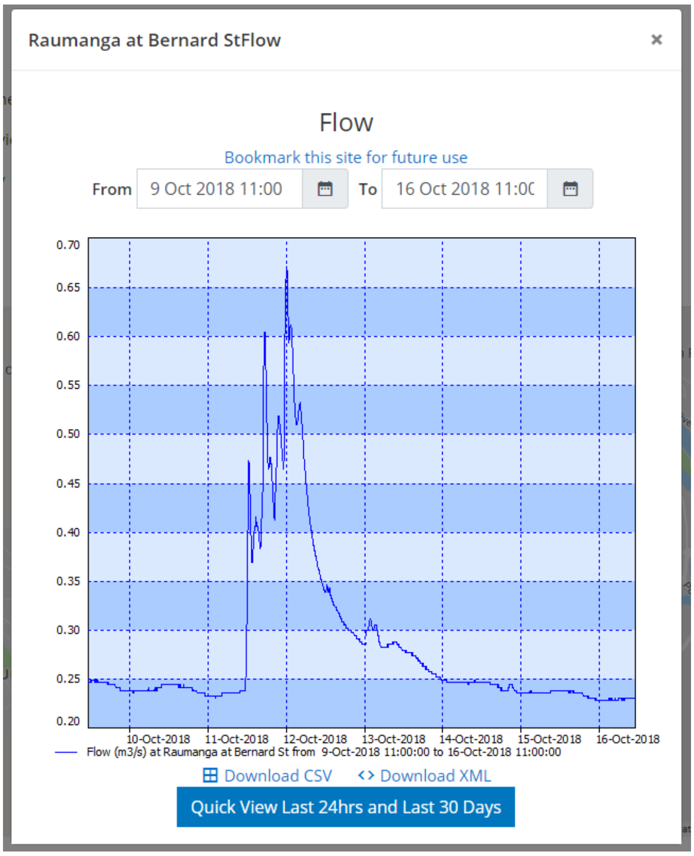

Figure 3-5: Data Selection and Download (NRC, 2019)

3.7 Rainfall Event Comparison

To review the suitability of the Type IA rainfall distribution prescribed by WDC (2010), the methodology used by Kimoto, Canfield and Stewart (2011) will generally be employed. The following tasks were completed:

i. A minimum of 10 rainfall events corresponding to annual maximum discharge events shall be isolated. Each event will be isolated in the recorded rainfall data.
ii. Once isolated, a measure of total rainfall depth and duration were taken.
iii. The maximum hour rainfall intensity was assessed by reviewing all hourly rainfall intensities.
iv. The pattern index (PI) is calculated using the method provided in Section 2.7 of this document using Equation 2-6.
v. A normalised accumulative rainfall depth and duration plot was prepared, where percentage rainfall event duration is plotted on the x-axis, against percentage total rainfall depth plotted on the y-axis.
vi. Finally, using all measures taken above a discussion will be made as to the similarities, or lack thereof to assess the suitability of the Type IA design rainfall distribution.

Table 3-6 below, provides a sample of the first three rows of calculations completed in Microsoft Excel to determine the before mentioned parameters.

Table 3-6: Sample Rainfall Event Analysis

	A	B	C	D	E	F	G
1	**Duration (min)**	**Total Rainfall (mm)**	**Time to Peak (min)**			**Peak Intensity (mm/hr)**	**Pattern Index**
2	2380	337.5	1745			46	0.423
3	**Date - Time**	**Rainfall (mm)**	**% Total Time**	**Accumulative Rainfall**	**% Total Rainfall**	**Intensity (mm/hr)**	**for PI**
4	28/03/2007 9:20	0	0.00000	0	0.00000	1.5	0.001
5	28/03/2007 9:25	0.5	0.00210	0.5	0.00148	1.5	0.010
6	28/03/2007 9:55	0	0.01471	0.5	0.00148	1.5	0.007

The summary of the spreadsheet and calculations completed is detailed in the following commentary;

a) Columns A and B from row 4, contained the recorded and isolated rainfall values.

b) Column C from row 4 contains percentage time, taken using Equation 3-1.

$$\% \, Total \, Time = \frac{T_i - T_0}{T_T} \qquad \text{Eq. [3-1]}$$

Where T_i = Time at i^{th} time step, T_0= Time at storm initiation, T_T = Total Time/Duration

c) Column D contains accumulation rainfall at each time step.

d) Column E from row 4 contains percentage rainfall, taken using Equation 3-2.

$$\% \, Total \, Rainfall = \frac{P_i - P_0}{P_T} \qquad \text{Eq. [3-2]}$$

Where P_i = Time at i^{th} time step, P_0= Time at storm initiation, P_T = Total Time/Duration

e) Column E reports hourly intensity values. This requires the summation of fall rainfall values for the 1-hour (60miniture) duration centred at the i^{th} position being considered. Careful consideration needs to be given to the data to ensure/check the time intervals of data points which may not always be uniform. In this instance, the intervals are varied, requiring further manipulation in MS excel to identify and measure the hourly intensities.

f) Column G calculates the parameter of the PI for each timestep as require for Equation 2-6, with the result provided in cell G2.

3.8 Validation of TR-55 Method

3.8.1 Introduction

Validation of the method will ultimately be completed by completing a comparison of TR-55 calculated watershed discharge against actual discharge analysed using an Annual Series Flood Frequency Analysis. The validation will be completed in four steps;

- An annual series flood frequency analysis will be completed using gauging records from the selected watershed to enable the fitting of a flood probability model.

- Peak watershed discharge will be calculated for the standard AEP events using the TR-55 method in HydroCAD.

- Baseflow was assessed from gauging station records, using a low-frequency filtering technique.

- The result will be assessed and compared to determine the adequacy of prescribed methods for calculating discharge.

3.8.2 Annual Series Flood Frequency Analysis

An annual series of flood frequency analyses were used to enable the fitting of a flood probability model to gauge records of the selected watershed. To complete this, the following tasks were undertaken:

i. The gauging records were checked for completeness, data errors, omissions, partial years. Calendar years were used for the analysis as opposed to water years as Northland, and the Whangarei District are susceptible to flood level rainfall events at any time.

ii. Once the data quality was checked, annual peak discharge values were identified and ranked from largest to smallest.

iii. Plotting the position AEP of each event was then completed using the Cunnane formula (Equation 3-3), recommended by Ball et al. (2019) for unbiased quantiles.

$$P_{(i)} = \frac{m-0.4}{n+0.2} \qquad \text{Eq. [3-3]}$$

Where;

m = Plotting position

n = Total number of years used

iv. Once plotting positions are finalised the logarithm is taken of the observed discharge values using Equation 3-4. This is then used to determine the mean (m), standard deviation (s) and skewness (g) of the dataset. If the absolute value of skewness is greater than 2 an alternative flood probability distribution should be considered. Ball et al. (2019) recommend the Generalized Extreme Values (GVE) distribution.

$$y_i = \log_{10}(q_i) \qquad \text{Eq. [3-4]}$$

Where;

q_i = Observed flow (m^3/s)

v. Once the mean, standard deviation and skewness values are determined, frequency factors (k_Y) included in Appendix C can be used to fit the Pearson III (LP III) distribution. The LP III distribution calculates logarithm flows for varying AEP using Equations 3-5.

$$\log_{10}(Q_Y) = m + k_Y(g)s \qquad \text{Eq. [3-5]}$$

Where;

m = mean

s = Standard Deviation

g = skewness

k_y = Frequency factor, included in Appendix D

vi. Values of low discharges can be detrimental to the fitting of the flood probability distribution. Low outliers generally occur in annual maximum series where a year did not experience a flood event. Multiple Grubbs-Beck test will be applied at the 0.5% and 10% significance level as recommended by Ball et al. (2019). This requires the calculation of $T_{n,}$ defined by Equation 3-6

$$T_n = \frac{(y_i - \bar{y})}{s} \qquad \text{Eq. [3-6]}$$

Where;

$\bar{Y}$ = average of logarithm flow

y_i = Logarithm flow at the i^{th} position

s = Standard Deviation

Where any values calculated using Equations 3-6 is greater than the values of T_n provided by Brubbs and Beck (1972) tables included in Appendix E, is like a low outlier and shall be discharged. As a final check, a visual check shall be made to assess the correctness of fit. Any values discarded shall be excluded, with the analysis being completed as if the year did not exist in the record.

3.8.3 Watershed Modelling

3.8.3.1 Introduction

In order to estimate the discharge of the selected watershed during rainfall events, a hydrologic model must be constructed, and the remaining watershed parameters or characteristics determined. This section details the methodology surrounding the development of a hydrologic model, estimates of time of concentration, the use of HydroCAD for the hydrological calculations and the estimation of baseflow.

3.8.3.2 Watershed Model

Several watershed models can be selected for this research however, only Lumped and Semi-Distributed are available for use with HydroCAD. For each watershed selected either a Lumped or Semi-Distributed model will be used, separating the watershed by topography, geology, and landuse to develop no more than several subareas. Ideally, the watershed will be separated into multiple subareas, however this begins to rely heavily on assumptions and interpretation by the modeller, which increases the difficulty of repetition.

3.8.4 Time of Concentration

Although there is no single correct method to determine the time of concentration, the velocity based methods are considered the most accurate, with the accuracy increasing as the level of investigation increases. Equations 2-9, 2-10, 2-11 & 2-12 shall be used to calculate the T_c for each respective sections of the watersheds main channel.

T_c requires several parameters, most notably the average slope of the watershed or channel section under consideration. The bed slope can be measured off of a long section for the channel or calculations made using the Land Information New Zealand Topo50 contours, for shorter sections. However, where a long section of the channel is to be considered which varies in slope the equal area method recommended by Auckland Regional (1999) shall be used, presented in Equation 3-6.

$$Sc = \frac{2A_d}{L^2} \qquad \text{Eq. [3-6]}$$

Where;

ΔA = Delta Area

L = Section Length (m)

Refer to Auckland Regional Council (1999) for a worked example of this method.

3.8.4.1 HydroCAD

It is a common practice among local consultants in the Whangarei District, to use a software program called HydroCAD to complete the hydrological and hydraulic calculations. HydroCAD is a software program specifically developed for hydrological and hydraulic modelling. HydroCAD Software

Solution LLC (2011) describes the program as combining the best parts of TR-20 and TR-55 for modelling of peak runoff. Using the watershed parameters, composite CN values, the Type 1A rainfall distribution and corresponding rainfall depths from HIRDS V4 as required by the WDC (2010), peak watershed runoff will be calculated. Runoff will be calculated for the following AEP rainfall events; 10%, 5%, 2%, 1.2%, & 1%. The following provides a summary of the modelling processes:

- **i.** Observe the spatial, topographical and geological variation of the selected watershed, dividing it into several subareas of similar size where variation requires.
- **ii.** Assess the parameters of sub-catchment as previously detailed, requiring Tc, A and Weighted CN.
- **iii.** Collect the HIRDS V4 Depth-Duration-Frequency (DDF) rainfall data using the centroid position of the watershed. HIRDS V4 is located at www.hirds.niwa.co.nz. Once signed in, enter the Site Information in the fields provided, selecting DDF and generates the report. The values required shall be selected, based on the AEP listed previously for the 24-hour duration.
- **iv.** With all input data collected, this can be entered with the analyses for the varying AEP rainfall depths. Refer to HydroCAD Software Solutions LLC (2011) for the use of the software.
- **v.** Finally, the model can be run, providing the calculated estimates of watershed runoff.

3.8.5 Baseflow

To assess baseflow from the gauging records, the filtering method proposed by Lyne-Hollick, recommended by Novita and Wahyuningish (2016) and Ball et al. (2019) will be used in a Microsoft Excel spreadsheet. The methodology proposed is as follows:

- **i.** Using the excel data files of the stream gauging records, the filtering technique can be applied using Equation 2-9 with the filtering parameter of α=0.98 to determine the quick flow. Quick flow will then be removed from total flow using Equation 2-10 to provide baseflow. This filtering method can only be applied to gauging data where record intervals have a frequency of less than 1hr.
- **ii.** Once the baseflow hydrograph is determined, isolation of individual events can be made to review the data fit. The fit of the baseflow filtering technique can be considered as having a good fit where baseflow meets total flow at a period of similar duration to the watershed time of concentration after rainfall subsides. This may, however, be difficult to observe where rainfall intensities vary, without the event subsides.
- **iii.** At this point, baseflow calculated which corresponds to the peak total flow or discharge will be retrieved, this is also known as under peak baseflow value.

iv. Once under peak baseflow is obtained all values of baseflow and total can be plotted against AEP to enable correlation to be derived as suggested by Ball et al. (2019). The under peak ratio can also be calculated using Equation 3-7.

$$R_B = \frac{Q_{PB}}{Q_{PT} - Q_{PB}} \qquad \text{Eq. [3-7]}$$

Where; R_B = Under peak baseflow ratio, Q_{PB} = Under peak baseflow, and Q_{PT} = Peak Discharge

v. The final step of this methodology is to make an assessment to the correlation of baseflow, in relation to AEP and/or discharge to assess the most practical baseflow factor or application factor to be applied to the calculated runoff.

3.8.6 Comparison

Finally, to a comparison was made of the TR-55 estimated total flow and the results of the flood frequency analysis. To assess the potential validation, the comparison was made both graphically and physically by plotting the fitted flood probability distribution and calculated discharge against (Q_T) AEP for visual inspection and making a comparison of tabulated results to assess the measure of error. Total flow / discharge will be calculated using Equations 3-8.

$$Q_T = Q_Q \times (1 + R_B) \qquad \text{Eq. [3-8]}$$

A wide range of variables influence the calculations of runoff and baseflow exist within the models developed, in particular the baseflow separation. Canterford (1987) suggested a margin of error of up to +/-30% is acceptable.

4.0 Results

4.1 Introduction

This chapter aims to present the results of the assessments and analysis of this research project. The analysis of the watershed selected in Chapter 3 will be presented, based on the investigation detailed within this Chapter and the data retrieved from the Northland Regional Council. This chapter is separated into the following sections;

- Designation of Major Local Soil Types,
- Rainfall Event Review,
- Mangahahuru Stream Analysis and
- Mangere Stream Analysis.

4.2 Designation of Major Local Soil Types

4.2.1 Field Investigations

4.2.1.1 Hand Augers

Three hand augered boreholes have been excavated as part of this research, being dug within two of the main local soil types, namely the Kerikeri Volcanic Group and Waipapa Group materials. The field investigations found that the residual soils of the Kerikeri Volcanic Group and Waipapa Group are similar, both clay like, without a complete sand content observed. The Kerikeri Volcanic Groups materials are very well structured, as opposed to the moderate structure of the Waipapa Group materials. A summary of these results is presented in Table 4-1.

Table 4-1: Hand Augers Summary

Hand Auger No.	Depth of Topsoil (m)	Main Soil Behaviour	Sand / Gravel Fraction (%)	Groundwater Depth (m)	Impermeable Material Depth (m)
HA1	50mm	Light Whitish Orange Low Plasticity Silt CLAY	0	Not Encountered	Not Encountered
HA2	100mm	Light Whitish Orange Low Plasticity Silt CLAY	0	Not Encountered	Not Encountered
HA3	200mm	Light Reddish Brown Low Plasticity Silt CLAY some rounded cobbles	0	Not Encountered	Not Encountered

4.2.1.2 Infiltration Testing

Five infiltration tests were completed in total, two and three each in the Kerikeri Volcanic and Waipapa Group materials respectively. All tests recorded a minimum infiltration rate greater than 8mm/hr.

Table 4-2: Infiltration Test Summary

Infiltration Test No.	Test Duration (min)	Minimum Infiltration Rate (mm/hr)	Geological Group / Soil Type
IT1	35	36	Kerikeri Volcanics
IT2	20	72	Kerikeri Volcanics
IT3	75	18	Waipapa Group
IT4	70	12	Waipapa Group
IT5	65	9	Waipapa Group

4.2.2 Hydrologic Soil Type

Based on the field Investigations and decision chart set out in Section 3 of this dissertation, the soil types under investigation have been placed into the Hydrologic Soil Groups, as presented in Table 4-3. The categorisation of the Northland Allochthon and Alluvial materials is based on the author's local experience and characteristics presented in the literature. Like the Kerikeri Volcanic Group, the Waipapa Group materials observed infiltration rates greater than the 8mm/hr threshold for Hydrologic Soil Group A. However, engineering judgement has prevailed, as this material is considered moderately expansive, well-structured and generally has a gradual transition into the free draining rock mass. The runoff characteristics are consequently better suited to placement within Hydrologic Soil Group B.

Table 4-3: Hydrologic Soil Type Classifications

Geological Group / Soil Type	Hydrologic Soil Group	Remarks
Kerikeri Volcanic Group	A	These materials often have cobbles and floating boulders. Infiltration rates are high, >8.0mm/hr
Waipapa Group	B	Infiltration rates >8.0mm/hr. Considered as moderately expansive
Northland Allochthon	D	Highly expansive. Water table commonly at or near the surface
Alluvial Sediments	D	Low lying, water table commonly at or near surface

4.3 Rainfall Event Review

Thirteen rainfall events from between 2005 and 2017 measured at the Northland Regional Council monitored gauge, forest HQ, were isolated. These events correspond to the peak annual watershed discharge events used in the Flood Frequency Analysis of the Mangahahuru Steam. Table 4-4 outlines the tabulated results of the analysis detailed in the methodology. Figure 4-1 illustrates the rainfall events plotted as percentage time against percentage of accumulative rainfall.

The Type IA rainfall distribution has a steep rate of change indicating the highest intensities nearer the centre of the storm. Multiple other rainfall events have similar steep portions, these are however generally not as steep and have longer durations. This is supported by the tabulated results, with a majority of storm events having maximum hour peak rainfall intensities greater than the Type IA event.

Table 4-4: Rainfall Event Review Results

Date of Storm	Total Rainfall Depth (mm)	Storm Duration (min)	Maximum Rainfall (mm/h)	Time to Peak (min)	Pattern Index
6-Jul-05	139.50	1460.00	28.00	570.00	0.54
27-Apr-06	46.50	210.00	30.50	120.00	0.45
29-Mar-07	337.50	2380.00	46.00	1745.00	0.42
26-Jul-08	141.00	1640.00	27.50	640.00	0.63
5-Mar-09	112.50	1300.00	11.50	285.00	0.53
5-Jul-10	113.00	2940.00	17.00	1025.00	0.39
28-Jan-11	256.50	1015.00	43.50	740.00	0.39
19-Mar-12	272.00	3020.00	26.00	1220.00	0.53
2-Aug-13	131.00	1885.00	11.50	810.00	0.47
9-Jun-14	209.00	2570.00	17.50	2365.00	0.33
5-Aug-15	68.51	1905.00	24.92	1625.00	0.38
7-Jul-16	47.50	1140.00	9.50	675.00	0.37
13-Apr-17	77.00	905.00	13.00	55.00	0.60
Type IA	-	1440	8%	588	0.57

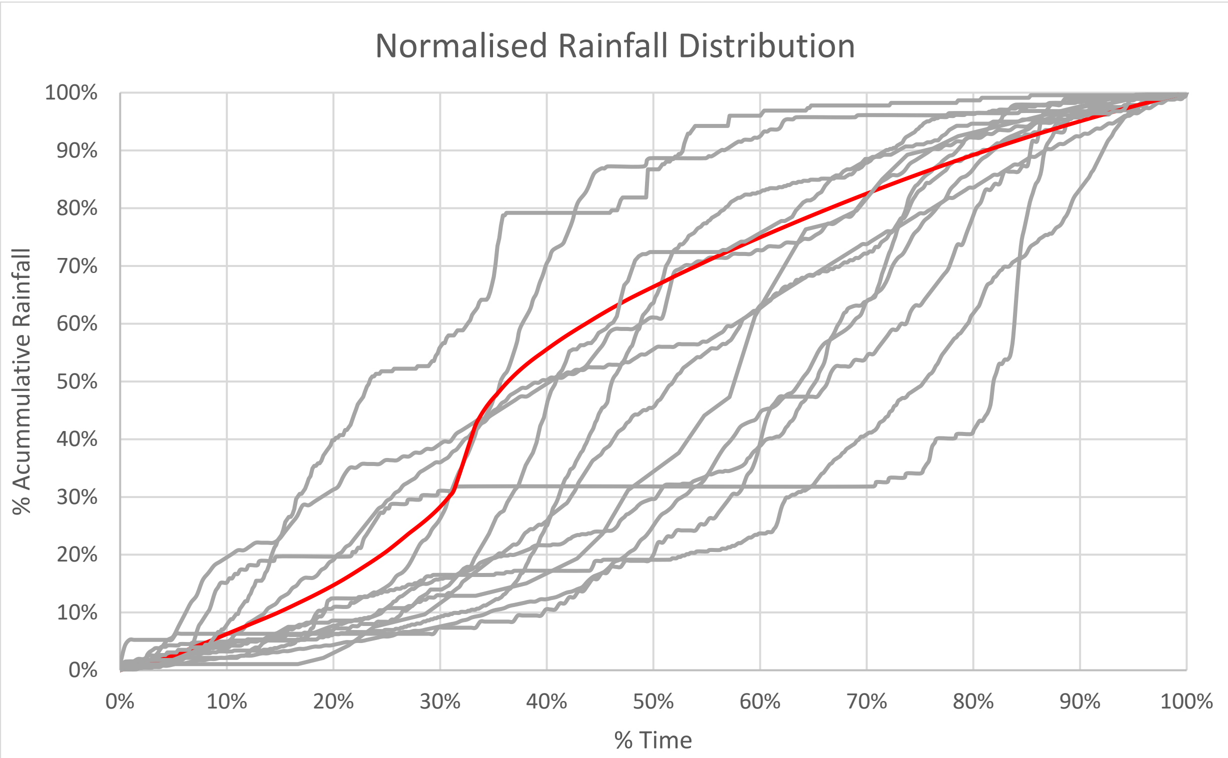

Figure 4-1: Normalised Rainfall Distributions

4.4 Mangahahuru Stream

4.4.1 Watershed Parameters

The Mangahahuru Stream watershed at the County Weir is situated on the north side of Whangarei City draining into the Hikurangi Swamp. The watershed to the gauge is 2,110ha, and is predominantly in plantation forestry and situated over Waipapa Group soil. This watershed was available for reasonably detailed inspection due to the full public access available during weekends. Table 4-5 summarise the detailed of the Mangahahuru Stream Watershed.

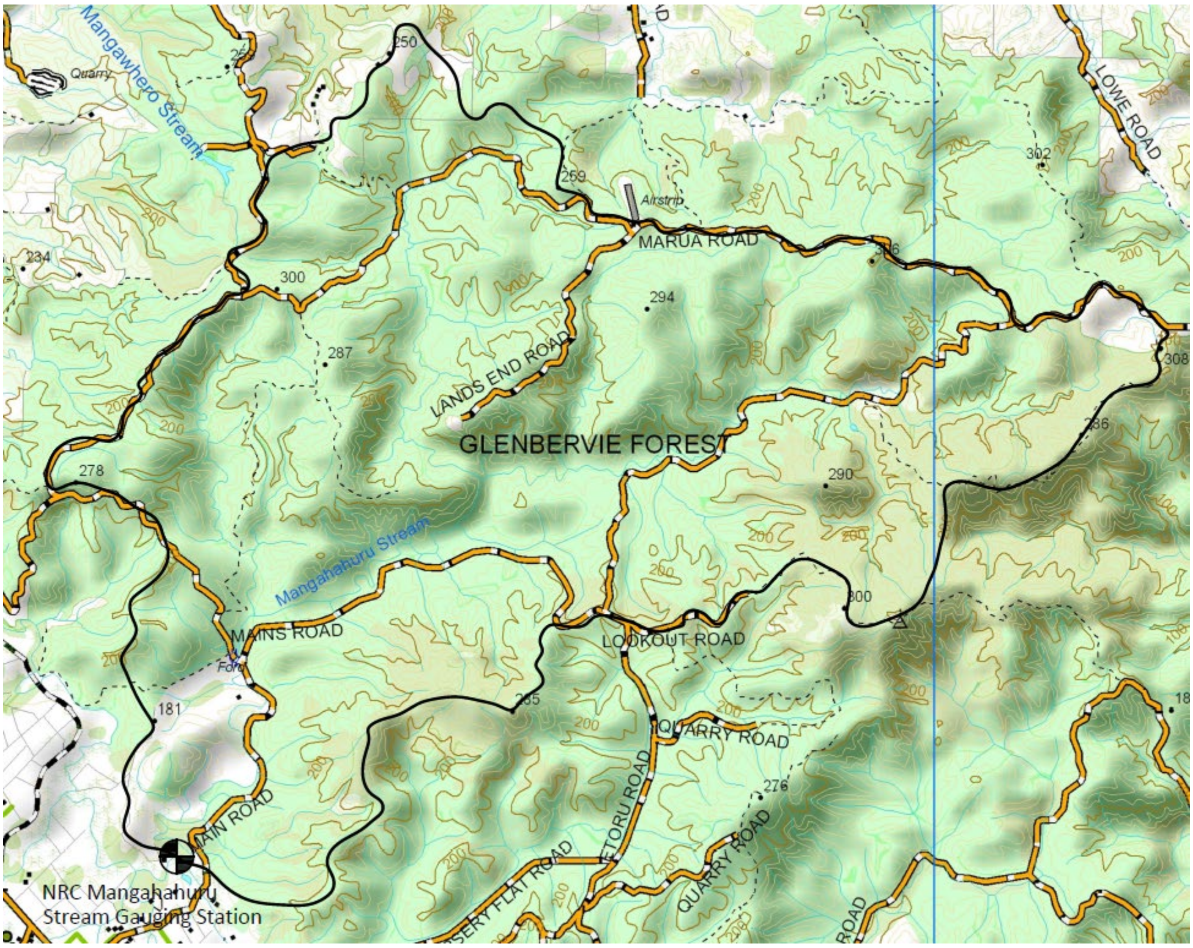

Figure 4-2: Mangahahuru Watershed Plan

Table 4-5: Mangahahuru Stream Watershed Details

	Watershed	Mangahahuru Stream
Details	Gauge Location (Lat /Long)	35°38'24.13S 174°18'43.60E
	Gauging Begin	1969
	Area (ha)	2,109.53
	Flow Path Length (m)	12730
Landuse (ha)	Pasture	88.49
	Native Forest	324.64
	Exotic Forest	1,696.40
Soil Type / Geology (ha)	Waipapa Group	2,109.53
	Northland Allochthon	0.00
	Alluvial Sediment	0.00
	Volcanic Origin	0.00

4.4.2 Modelling

Given the lack of spatial variability, singular geology / soil type and singular land use of the forest, a lumped model has been considered suitable for the Manahahuru Stream watershed. The results of this model are summarised in the following sections.

4.4.2.1 Time of Concentration

The velocity method of time concentration was applied to the longest flow path in Mangahahuru Stream where several points were observed during the field inspection. The results of the velocity based method for time of concentration are summarised in Table 4-6 below.

Table 4-6: Mangahahuru Time of Concentration

Subarea	Tc (minutes)			
	Total Tc	Sheet Flow	Shallow Concentrated Flow	Channel Flow
A	224	9	2	213

4.4.2.2 HydroCAD Model

The HydroCAD modelling was completed using the routing diagram shown in Figure 4-3 which consisted of a single node to represent the lumped model. The estimated peak rainfall generated runoff calculated for the range of AEP is presented in Table 4-7.

Figure 4-3: Mangahahuru Stream Routing Diagram

Table 4-7: Mangahahuru Stream TR-55 Estimate Runoff

Event AEP	Rainfall (mm)	Peak Runoff (m^3/s)
10%	207	32.4
5%	238	44.5
2%	279	62.2
1.2%	300	71.8
1%	310	76.5

4.4.3 Flood Frequency Analysis

Using the NRC gauging records the annual maximum discharge events between 1969 and 2015 have been identified, shown in Table 4-5. Mangahahurhu Stream flow gaugings for 1976, 1977 and 1981 have been discarded due to partial or total loss of data during that year. The mean of the logarithmic annual flow peaks is 1.373, while the standard deviation is 0.168, prior to filtering of influential low discharge vales.

The annual maximum series was checked for potentially influential low discharge which may have a detrimental effect on the results. Using Grubbs and Beck (1972) where n=43, the test values of T_n for the 0.5% and 10% significance levels were T_n=0.6296 and T_n=0.7172 respectively. This resulted in identifying seven (7) low outlying values from 1987, 1990, 1991, 1992, 2004, 2010 & 2013, which were discarded from the analysis. Table 4-8 presents the annual maximum values were used for the flood frequency analysis.

Table 4-8: Mangahahuru Annual Maximum Discharge

Year	Discharge (m^3/s)	Year	Discharge (m^3/s)
2011	33.818	1986	27.623
2007	33.15	2003	27.535
1973	33.114	1998	27.458
1971	32.195	1975	27.26
1995	31.926	2000	27.205
1997	31.601	1988	26.633
1980	31.069	1996	26.149
2012	30.725	2014	26.138
1972	29.966	2002	26.017
2008	29.339	1983	24.985
1969	29.141	1979	24.632
1974	28.679	1982	24.134
1985	28.47	1993	24.056
2001	28.195	1978	23.73
1970	28.118	2005	23.496
1989	27.986	1994	22.732
1999	27.909	1984	19.97
2009	27.832	2006	19.88

Based on the methodology, Table 4-9 and Figure 4-4 report the results of the Mangahahuru Stream flood frequency analysis, where a Log Pearson III flood probability distribution was fitted.

Table 4-9: Mangahahuru Stream Flood Frequency Results

Parameter	Value
Mean (M)	1.437
Standard Deviation (S)	0.056
Skew (G)	-0.615

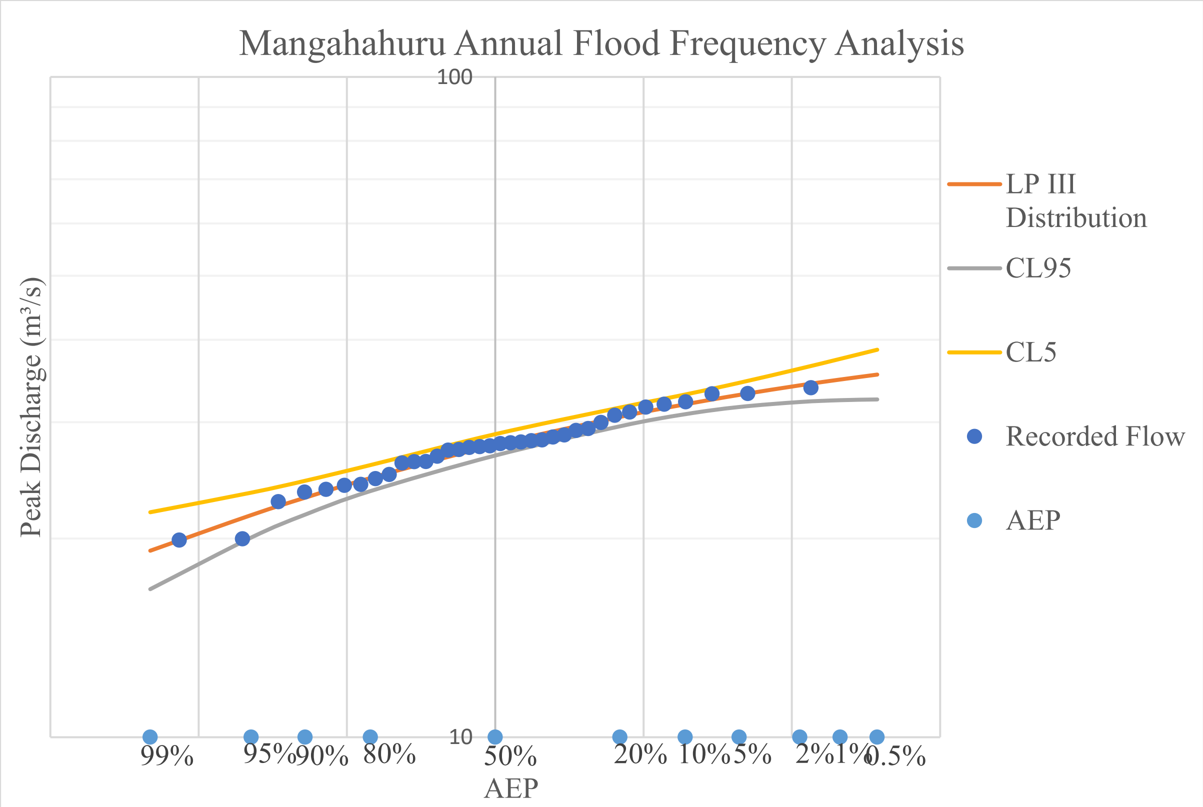

Figure 4-4: Mangahahuru Stream Flood Frequency Analysis

Observation of Figure 4-4 will find that the fitted LP III probability model wells the data set well. All data points lie within the 5% and 95% confidence limits.

4.4.4 Baseflow

Separation of baseflow was completed using the methodology detailed in this research beginning at 1969 through to 2015, excluding 1976, 1977, 1981.

Figure 4-5 displays the baseflow filtering of the rain storm measured at Forest HG which resulted in the 2011 maximum annual event in the Mangahahuru Stream, using the Lyne-Hollick method. Also shown in Figure 4-5 is the rainfall measured at the Forest HG gauge. It can be observed that the rainfall event subsides at a similar time to the peak flow and that the peak baseflow is observed approximately 4hrs beyond the rainfall event subsiding. It is worth mentioning again at this point that the Tc was 224 minutes (3.73hr).

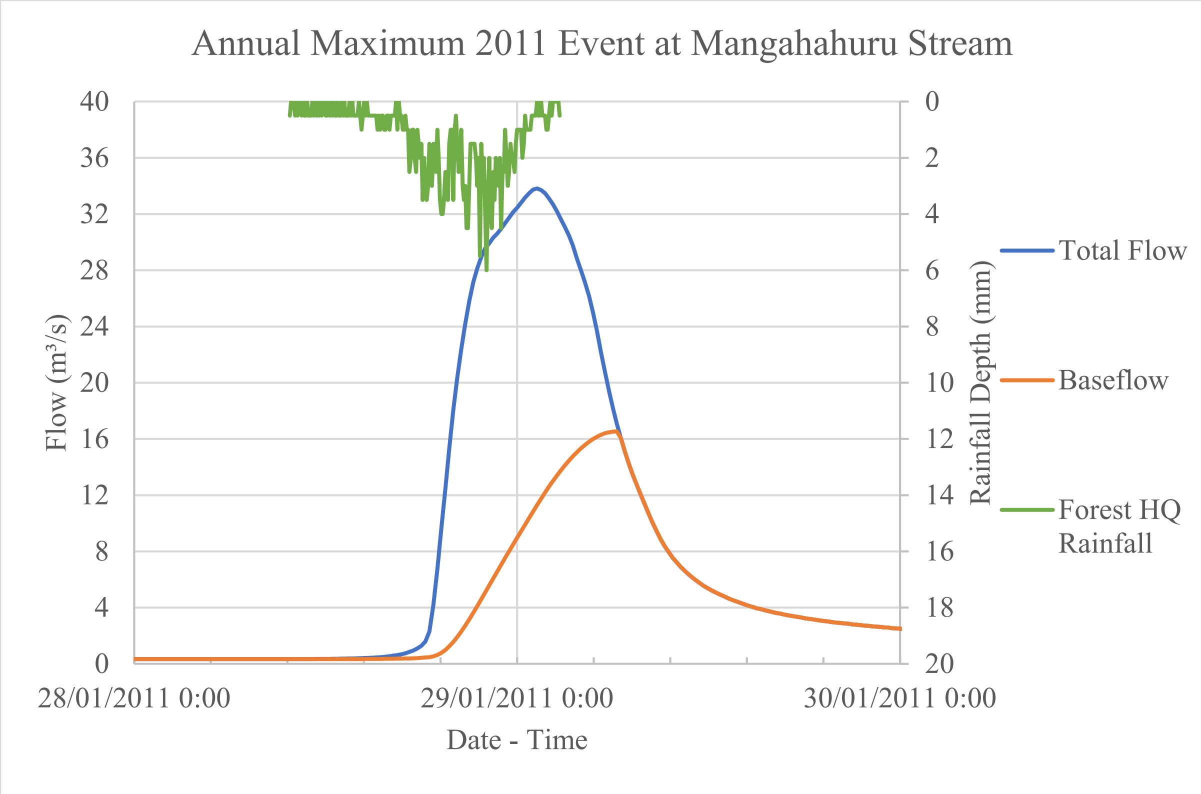

Figure 4-5: 2011 Annual Maximum Event Baseflow Separation – Mangahuru Stream

Figure 4-6 displays and Table 4-10 presents the results of the baseflow separation analysis in relation to the corresponding AEP derived by the flood frequency analysis. Under peak baseflow values varied as a ratio of peak quick flow from 8% to 600%. From observation of Figure 4-5 it is clear that there is no statistically acceptable correlation between quick flow and baseflow with the variation in the low AEP events being very high. Consequently, to provide a means of determining baseflow for this research an average of under peak ratios was taken, which results in a value of 0.49, the ratios of 6.0, and 3.71, were considered as outliers and excluded from the average.

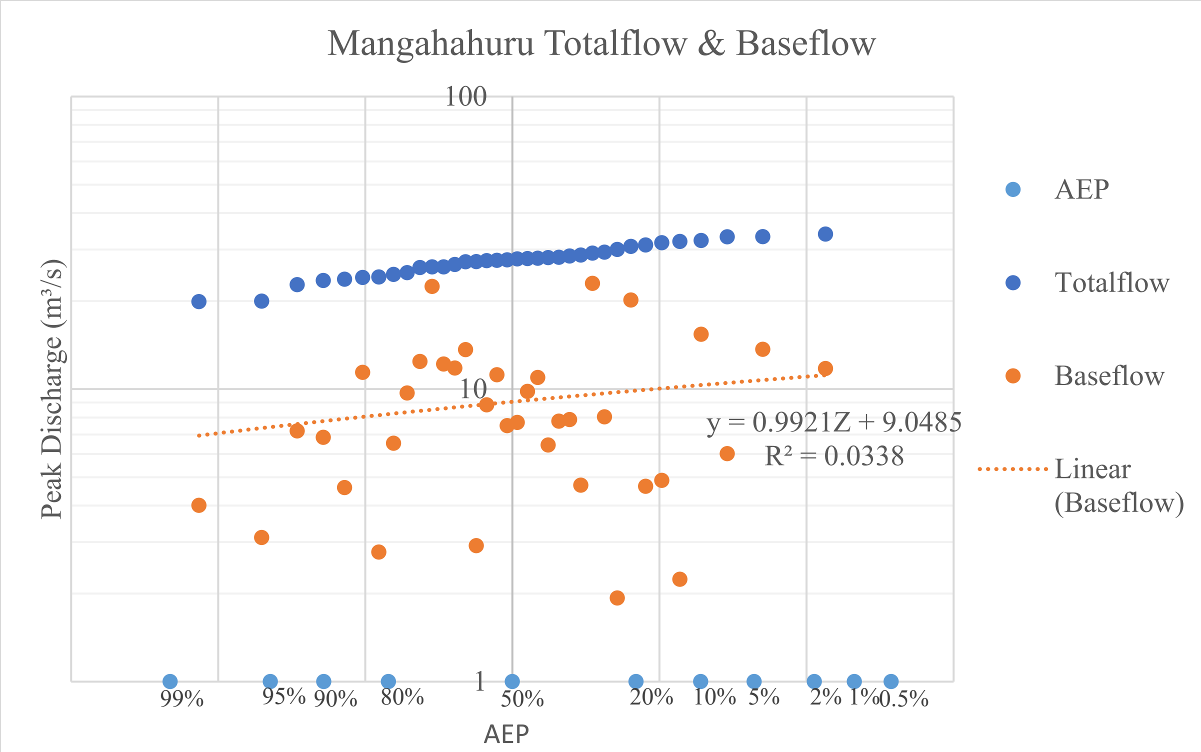

Figure 4-6: Under Peak Baseflow Separation

Table 4-10: Under Peak Baseflow Filtering Results

AEP	Total Flow (m^3/s)	Baseflow (m^3/s)	Underpeak Ratio
1.7%	33.8	11.8	0.53
4.4%	33.2	13.7	0.70
7.2%	33.1	6.0	0.22
9.9%	32.2	15.4	0.92
12.7%	31.9	2.2	0.08
15.5%	31.6	4.9	0.18
18.2%	31.1	4.6	0.18
21.0%	30.7	20.1	1.90
23.8%	30.0	1.9	0.07
26.5%	29.3	8.0	0.38
29.3%	29.1	23.0	3.71
32.0%	28.7	4.7	0.20
34.8%	28.5	7.9	0.38
37.6%	28.2	7.8	0.38
40.3%	28.1	6.4	0.30
43.1%	28.0	10.9	0.64
45.9%	27.9	9.8	0.54
48.6%	27.8	7.7	0.38
51.4%	27.6	7.5	0.37
54.1%	27.5	11.2	0.68

56.9%	27.5	8.8	0.47
59.7%	27.3	2.9	0.12
62.4%	27.2	13.6	1.00
65.2%	26.6	11.8	0.79
68.0%	26.1	12.2	0.87
70.7%	26.1	22.4	6.00
73.5%	26.0	12.4	0.91
76.2%	25.0	9.7	0.63
79.0%	24.6	6.5	0.36
81.8%	24.1	2.8	0.13
84.5%	24.1	11.4	0.90
87.3%	23.7	4.6	0.24
90.1%	23.5	6.8	0.41
92.8%	22.7	7.2	0.46
95.6%	20.0	3.1	0.18
98.3%	19.9	4.0	0.25

4.4.5 Comparison

Table 4-11 and Figure 4-7 presents the comparison of the TR-55 quick flow, total flow and the LP III floor probability distribution.

Table 4-11: Mangahahuru Stream Comparison

AEP	Flood Probability Distribution Discharge (m^3/s)	TR-55 Estimate Discharge (R_B=0.49)	Margin of Error
1%	34.8	114.0	327%
2%	34.1	92.7	272%
5%	33.0	66.3	201%
10%	31.9	48.3	151%

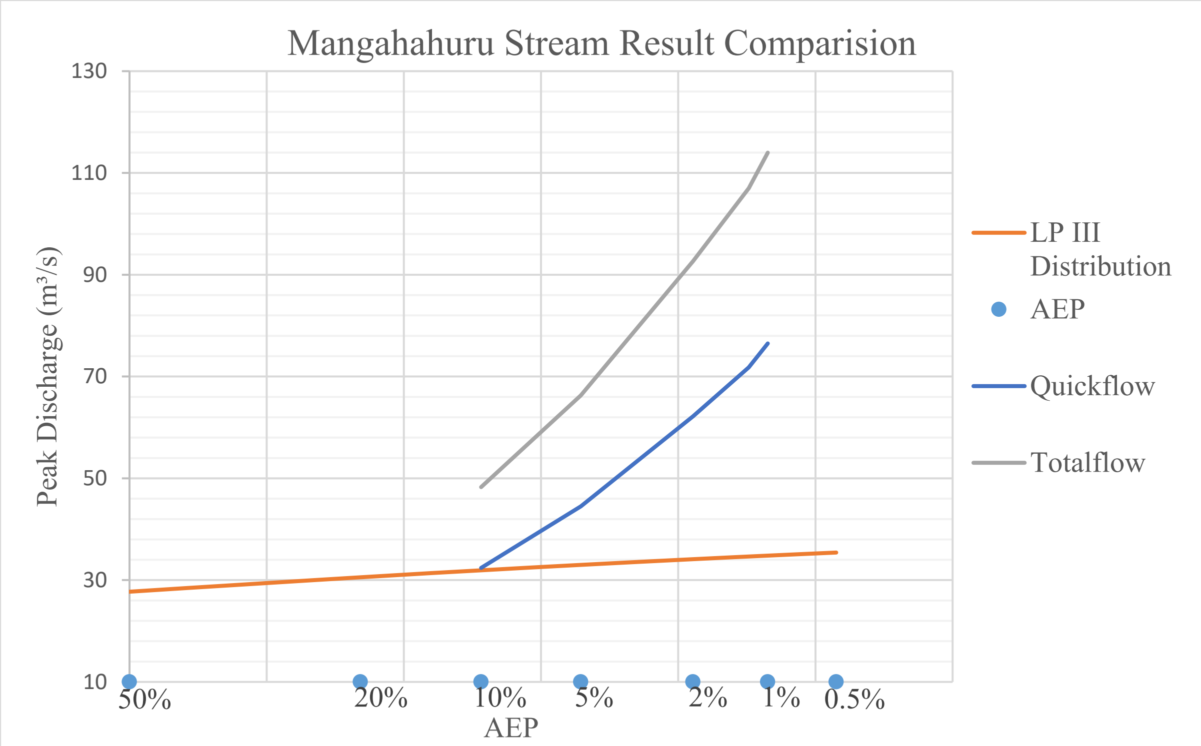

Figure 4-7: Mangahahuru Stream Comparison

4.5 Mangere Stream

4.5.1 Watershed Parameters

The Mangere Stream watershed is located to the west of the Whangarei City, being 7520ha to the Knights Road bridge. The watershed is primarily pastoral farmland (80%) and is split one third each to Waipapa Group and Northland Allochthon soils, with the remainder split between Kerikeri Volcanics and alluvial sediments. Limited access is available to the Mangere Stream 10watershed with only several points of inspection available at public roads. Table 4-12 summarises the details of the Mangere Stream watershed.

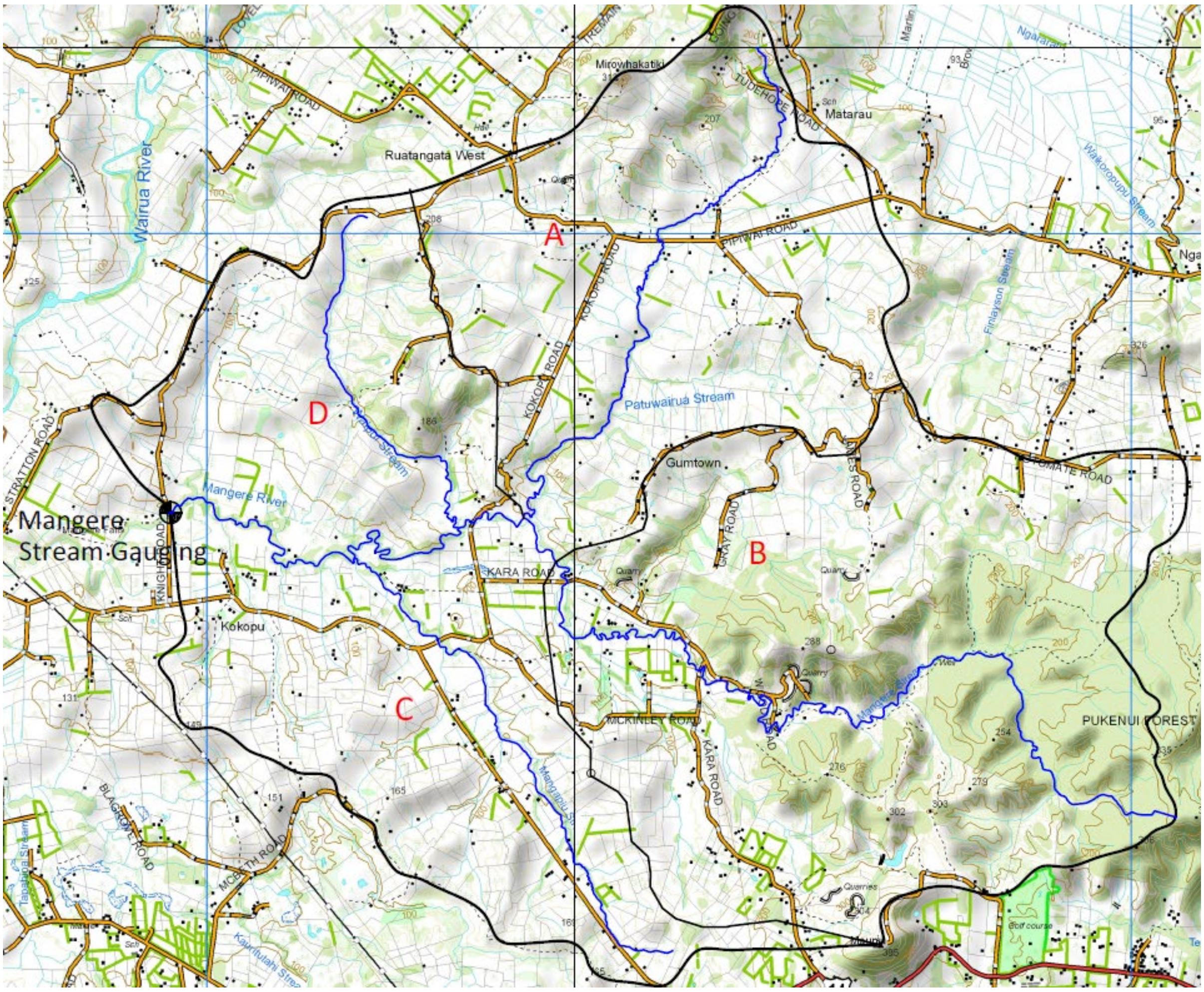

Figure 4-8: Mangere Stream Watershed

Table 4-12: Mangere Stream Watershed Details

	Watershed	**Mangere Stream**
Details	Gauge Location (Lat /Long)	35°41’51.95S 174°08’42.64E
	Gauging Begin	1984
	Area (ha)	7,519.99
	Flow Path Length (m)	20730
Landuse (ha)	Pasture	6,059.92
	Native	1,388.58
	Exotic	69.49
Soil Type / Geology (ha)	Waipapa Group	2458.98
	Northland Allochthon	2585.40
	Alluvial Sediment	1486.46
	Volcanic Origin	7,519.99

4.5.2 Modelling

The Mangere Stream watershed, varied in geology and topography, having several distinct subareas. Figure 4-8 shows the watershed boundary, subarea boundaries and main channels.

4.5.2.1 Time of Concentration

The velocity method of time concentration was applied to the longest flow paths in each subarea of the Mangere Stream. The results of the velocity based method for time of concentration are summarised in Table 4-13 below.

Table 4-13: Mangere Time of Concentration

Subarea	Tc (minutes)			
	Total Tc	Sheet Flow	Shallow Concentrated Flow	Channel Flow
A	346	10	10	326
B	536	8.2	1.3	526.5
C	281	10	0.5	270.5
D	438	11	1	426

4.5.2.2 HydroCAD Model

The HydroCAD modelling was completed using the routing diagram shown in Figure 4-9 which consists of four subareas and a node to represent the gauging station. The estimated peak rainfall generated runoff calculated for the range of AEP is presented in Table 4-14.

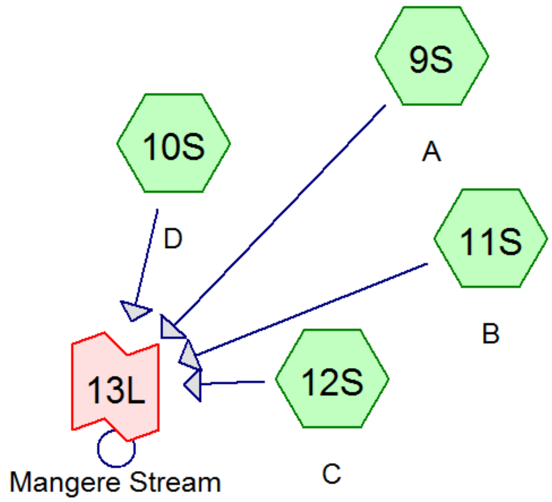

Figure 4-9: Mangere Stream Routing Diagram

Table 4-14: Mangere Stream TR-55 Estimate Runoff

Event AEP	Rainfall (mm)	Peak Runoff (m^3/s)
10%	159	88.1
5%	182	112.8
2%	214	149.2
1.2%	231	169.4
1%	239	179.1

4.5.3 Flood Frequency Analysis

Using the NRC gauging records the annual maximum discharge events between 1984 and 2014 have been identified, shown in Table 4-5. The mean of the logarithmic annual flow peaks is 1.77, while the standard deviation is 0.212, prior to filtering of influential low discharge vales.

The annual maximum series was checked for potentially influential low discharge which may have a detrimental effect on the results. Using Grubbs and Beck (1972) where n=31, the test values of T_n for the 0.5% and 10% significance levels were T_n=0.5091 and T_n=0.6455 respectively. This resulted in identified seven (7) low outlying values from 1986, 1987, 1990, 1991, 1996, 2004 & 2013 which were discarded from the analysis. Table 4-15 presents the annual maximum values were used for the flood frequency analysis.

Table 4-15: Mangere Annual Maximum Discharge

Year	Discharge (m^3/s)	Year	Discharge (m^3/s)
1984	59.643	2001	83.033
1985	71.438	2002	81.278
1988	90.866	2003	66.245
1989	89.723	2005	53.922
1992	62.875	2006	70.935
1993	69.489	2007	98.927
1994	67.733	2008	92.726
1995	52.747	2009	72.263
1997	89.761	2010	53.885
1998	54.363	2011	116.434
1999	88.397	2012	89.226
2000	59.914	2014	91.174

Based on the methodology, Table 4-15 and Figure 4-16 report the results of the Mangere Stream flood frequency analysis, where a Log Person III flood probability distribution was fitted.

Table 4-16: Mangere Stream Flood Frequency Results

Parameter	Value
Mean (M)	1.871
Standard Deviation (S)	0.097
Skew (G)	0.009

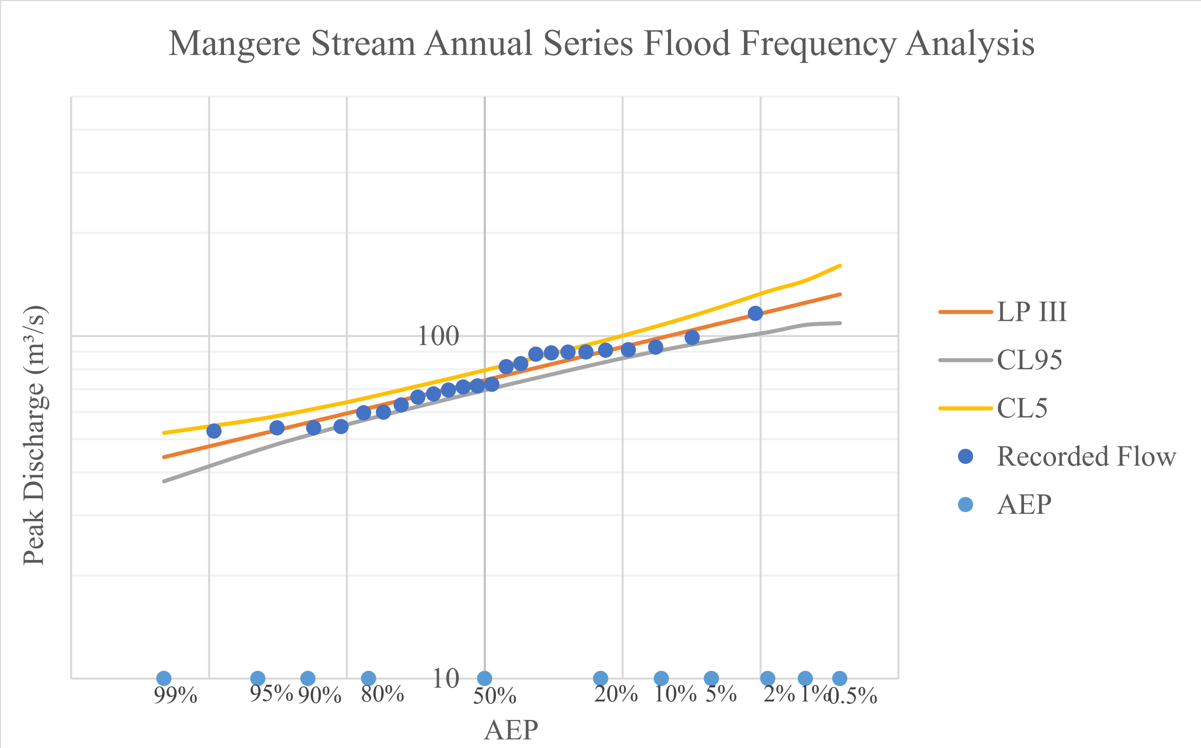

Figure 4-10: Mangere Stream Flood Frequency Analysis

Observation of Figure 4-10 will find that the LP III probability model fitted the data set well. All data points lie within the 5% and 95% confidence limits.

4.5.4 Baseflow

Separation of baseflow was completed using the methodology detailed in this research beginning at 1984 through to 2014, excluding 1986, 1987, 1990, 1996, 2004 & 2013.

The baseflow filtering of the Mangere Stream Hydrograph is displayed in Figure 4-11 during the 2011 maximum annual event. Also shown on Figure 4-12 is the rainfall measured at the Draffins gauge. It can be observed that the rainfall event subsides at a similar time to the peak flow and that the peak baseflow is observed at approximately 10hrs beyond the rainfall event subsiding. It is worth mentioning again at this point that the Tc was up to 536 minutes (8.96hr).

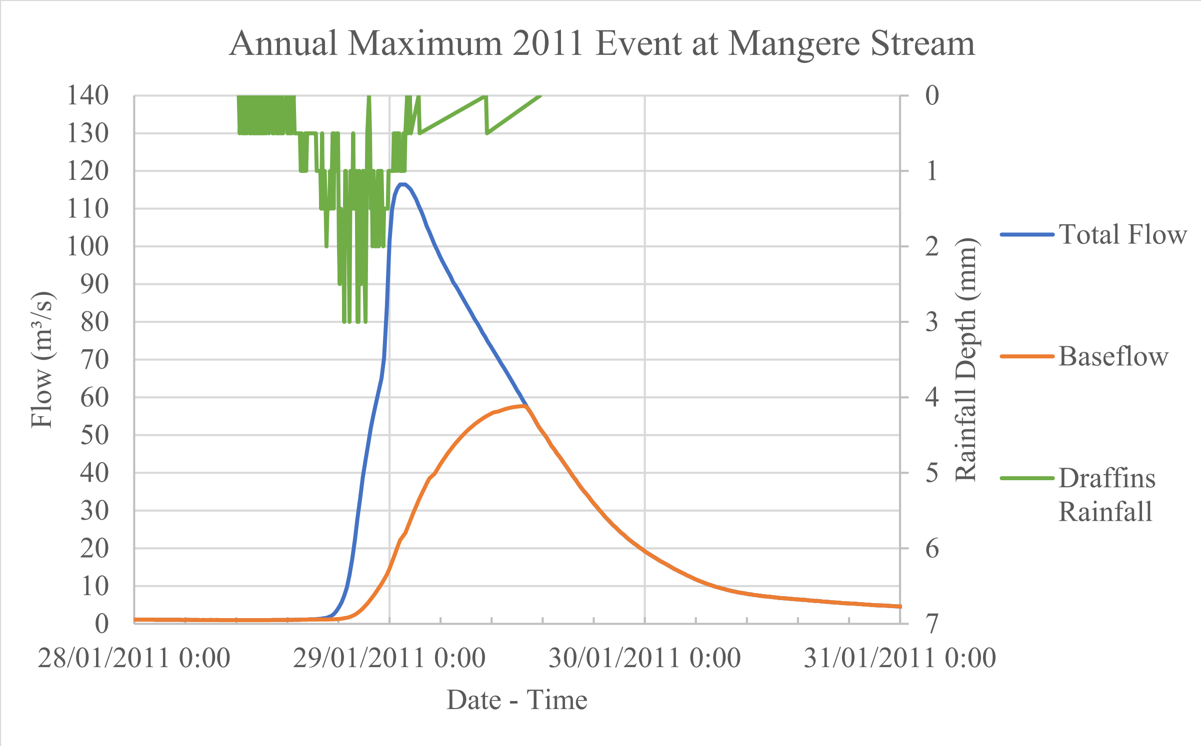

Figure 4-11: 2011 Annual Maximum Event Baseflow Separation – Mangere Stream

Figure 4-12 displays and Table 4-17 presents the results of the baseflow separation analysis in relation to the corresponding AEP derived by the flood frequency analysis. Under peak baseflow values varied as a ratio of peak quick flow from 13% to 148%. From the observation of Figure 4-5 it is clear that there is no statistically acceptable correlation between quick flow and baseflow with the variation in the low AEP events being very high. Consequently, to provide a means of determining baseflow for research an average of under peak ratios was taken, which results in a value of 0.71.

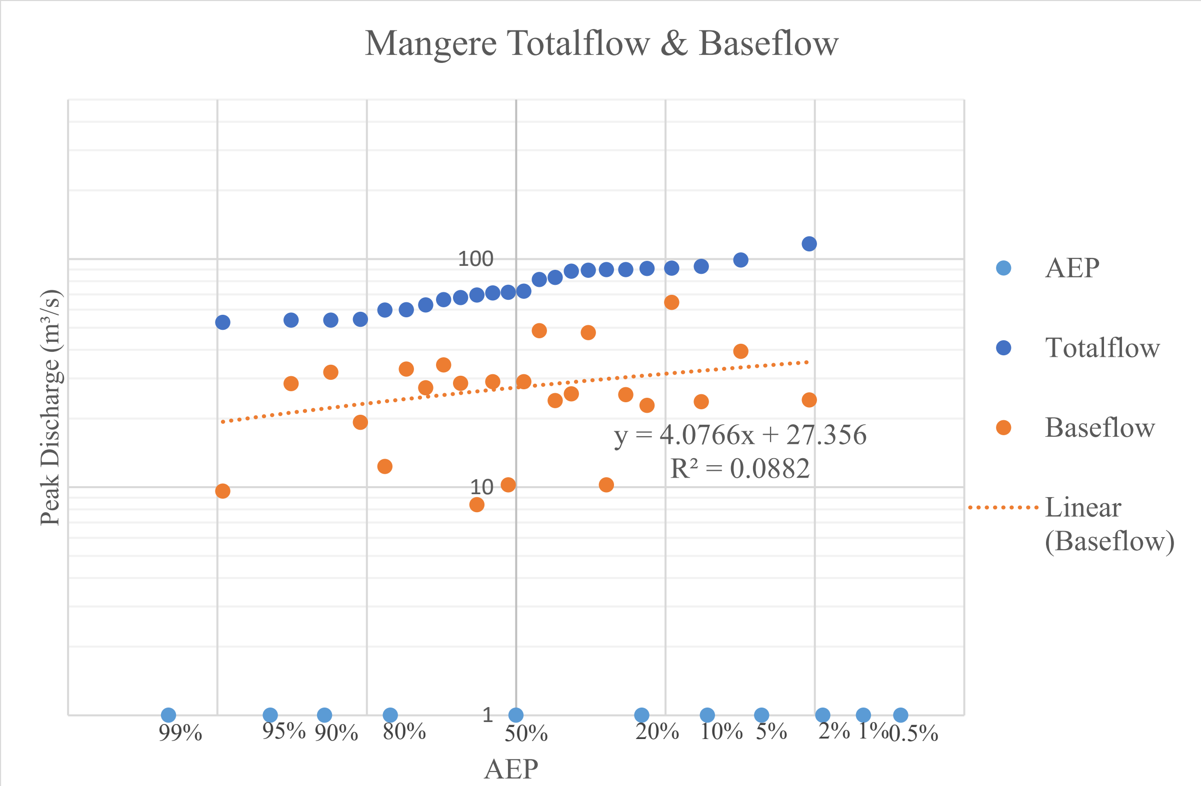

Figure 4-12: Under Peak Baseflow Separation

Table 4-17: Under Peak Baseflow Filtering Results

AEP	Total Flow (m^3/s)	Baseflow (m^3/s)	Under Peak Ratio
2.5%	116.434	24.07636	0.26
6.6%	98.927	39.38713	0.66
10.7%	92.726	23.67496	0.34
14.9%	91.174	64.51549	2.42
19.0%	90.866	22.79098	0.33
23.1%	89.761	25.41615	0.39
27.3%	89.723	10.23365	0.13
31.4%	89.226	47.53277	1.14
35.5%	88.397	25.60611	0.41
39.7%	83.033	23.95004	0.41
43.8%	81.278	48.45595	1.48
47.9%	72.263	28.95016	0.67
52.1%	71.438	10.23265	0.17
56.2%	70.935	28.9482	0.69
60.3%	69.489	8.364626	0.14
64.5%	67.733	28.48651	0.73
68.6%	66.245	34.32883	1.08
72.7%	62.875	27.24795	0.76
76.9%	59.914	32.9254	1.22

81.0%	59.643	12.31139	0.26
85.1%	54.363	19.23169	0.55
89.3%	53.922	31.87551	1.45
93.4%	53.885	28.4014	1.11
97.5%	52.747	9.608627	0.22

4.5.5 Comparison

Table 4-18 and Figure 4-13 presents the comparison of the TR-55 quick flow, total flow and the LP III floor probability distribution.

Table 4-18: Mangere Stream Comparison

AEP	Flood Probability Distribution Discharge (m^3/s)	TR-55 Estimate Discharge (R_B=0.49)	Margin of Error
1%	125.1	306.3	245%
2%	117.7	255.13	217%
5%	107.4	192.9	180%
10%	99.0	150.7	152%

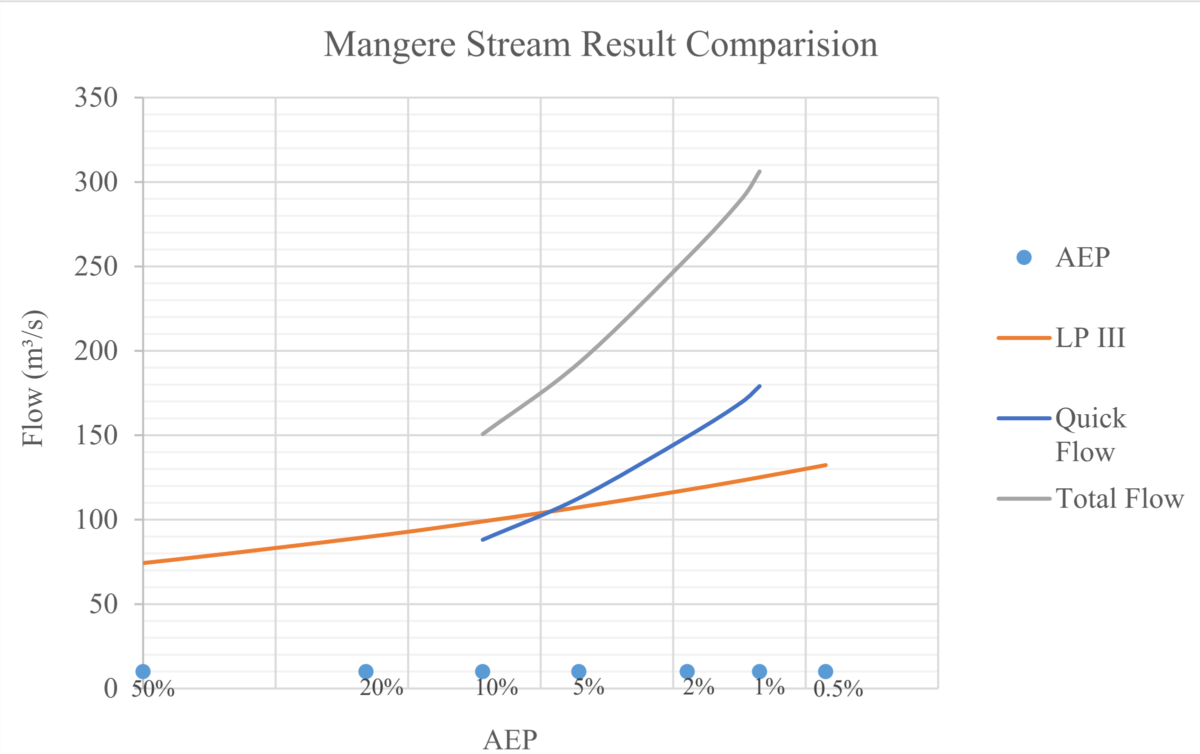

Figure 4-13: Mangere Stream Comparison

5.0 Discussion

5.1 Introduction

This chapter will discuss the identified issues of the research project, any potential sources of error and aims to gain an understanding of the results presented in Chapter 4. The results will also be discussed in relation to the literature to enable conclusions that are useful and make recommendations that ensure the correct use of TR-55 in the future.

5.2 Watershed Selection

This research project relied on the selection of Whangarei District watersheds to undertake the validation process. A set of selection criteria were set to avoid inaccurate results, errors and ensure adequate gauging durations. These criteria were reasonably restrictive, however generally by the limitation of the TR-55 method. As a result of the selection criteria, only two watersheds in the Whangarei District were suitable for selection.

The author had intended to select a minimum of five watersheds for use in this research project, however this could not be achieved. The use of watersheds beyond Whangarei District was considered, however, due to variation in geology, topography and rainfall events the decision was made to continue with a limited selection available.

The limited number watersheds in the Whangarei District which were suitable for this research project suggests that many watersheds in the Whangarei District may not be suitable for hydrological analysis using TR-55, and as a result, further research should be completed to consider a method better suited.

5.3 Hydrologic Soil Groups

To achieve the third objective of this research project, the results had to identify the corrected placement of the significant Whangarei District soil types in the TR-55 methods hydrologic soil groups. The results have not only achieved the objective but demonstrated that the placement of the local soil types differs somewhat from that suggested by WDC (2010).

The results of the borehole tests were of no surprise to the author, many years of geotechnical investigation in the district has provided a thorough understanding of these soil types. It was, however surprising to identify how incorrect WDC (2010) is in suggested the use of the hydrologic soil groups. The variation is most likely due to the lack of previous infiltration testing, but also potentially due to a perceived opinion of the materials runoff characteristics by the unnamed authors of WDC (2010). It is clear that the Kerikeri Volcanic Group materials should not be placed in the hydrologic soil group C, this supported by the lack of defined watercourses or continually running flow paths on the terrain. Auckland Regional Council (1999) also support this with their placement of basaltic volcanic soil in the hydrologic soil group A, although it is worth mentioning their soils are much younger than that of the Whangarei District.

5.4 Type IA Rainfall Distribution

The fourth objective of this research project required a review and discussion around the suitability of the prescribed Type IA rainfall distribution, in comparison with actual rainfall events. Storm events collected from the Northland Regional Council Forest HG gauge were observed and compared with the Type IA rainfall distribution, comparatively assessing rainfall normalised distributions, peak hour intensities and pattern index (PI).

The Type IA rainfall distribution is a nested design storm aimed at representing rainfall events of differing duration and intensity being suitable for a broad range watershed, which as a result may not accurately reflect a particular regions rainfall events. The results show that the Type IA event does not accurately represent the events observed at the Forest HQ gauge. The Type IA event has a maximum instantaneous rainfall intensity greater than that of any observed storm, but the observed peak hour intensities far exceeded that of the design storm. This is of importance as, depending on the time of concentration of a watershed, the critical duration of peak intensities will vary, which is supported by Kimoto, Canfield and Stewart (2011), where an observed 5% AEP rainfall event caused greater than 1% AEP flood event as a result of differing critical durations.

This part of the research was however limited to a small number of rainfall events due to time constraints. It was however clear to the author, from both the literature review and results that, nested design storms, like the Type IA event may not identify the critical discharge for a given watershed, and that an ensemble of temporal patterns or design storms similar to that required by Ball et al. (2019) should be developed. This would likely require the development of several distributions with differing durations to represent both the short duration, high intensity thunderstorm type events, and the long duration, low intensity cyclonic type events which are regularly experienced in the Whangarei District.

5.5 Validation

The fifth and final objective required the validation be completed. This required a flood frequency analysis of the gauged watershed recordings and the estimation of discharge using the TR-55 method. Estimation of baseflow was considered an essential part of this task, with the lack of certainty around the results of the analysis only became evident in the later stages of the research.

5.5.1 Flood Frequency Analysis

The flood frequency analysis found that the commonly accepted Log Pearson III distribution fitted the data sets reasonably well, however upon completion of multiple Grubbs Beck tests as required by Ball et al. (2019) and the exclusion of the potentially influential low flow values, the fitting was improved substantially.

An obvious limitation and potential source of error in this research, particularly with the flood frequency analysis, is the reliance on the rating curves given to the gauges by the Northland Regional Council. It would have been beneficial to review the rating curves and make an assessment as part of this research, however the Northland Regional Council were not forthcoming with the rating curves. Access was also not available to the Mangahahuru gauge for review, nor do elevation models of the gauging stations exist to enable a detailed review of the rating curves if supplied.

5.5.2 Baseflow Separation

The use of the Lyne-Hollick base flow filtering technique on the gauging hydrographs was successful, however achieving this result was difficult, given the volume of data, and the limitations of Microsoft Excel.

Ball et al. (2019) suggested that baseflow from events with similar AEP can be adjusted for use in the estimated discharge calculations, however considerable variation in the ratio of base flow to quick flow were identified placing doubt around the use of this method. Consequently, a simplistic use of an average adjustment ratio was used, where large outlying values were excluded. This achieved differing results across the two watershed, however, given the spatial and geological variation between the two watersheds analysed, this was expected.

The literature review did not identify any research locally around potential baseflow adjustment factors which in the author's opinion, is an import part of the estimating total flow, particularly where the average under peak ratio suggests that baseflow is up to 70% of the quick flow. Consequently, it is recommended that further research be completed in this area to establish a set of under peak baseflow factors, similar to that of Ball et al. (2019).

5.6 Watershed Modelling

The research required the construction of hydrological model within HydroCAD to simulate and estimate rainfall generated runoff. The use of the software was a simple task, however the development of the physical model, ensuring the time of concentration was correct for subareas, and differing flow paths was time consuming, with a large volume of assumptions required. Although inspection of the watersheds was completed, with multiple observations of the main channels made where access existed, less than 1% of the channels within the watershed were likely viewed. Time of concentration requires a large volume of assumptions and will vary dependant on the modeller’s assumptions (Sharifi and Hosseini 2011). Using a singular lumped model has significantly reduced the potential for error in the analysis and calculation of the time of concentration but may have increased inaccuracies between the model and the watershed itself.

5.7 Summary

This research aimed to identify the suitability of TR-55 in the Whangarei District. Observations and inaccuracies of the TR-55 are causing concern among local practitioners and as a result, the critical objective of this research requires the assessment of the TR-55 method, comparing it to the results of a flood frequency analysis.

Over estimation of total flow may result in increased water surface levels when used for flood analysis, causing uneconomic results, however, underestimation would lead to unacceptable risk of flooding to the project under consideration. The research did not validate the method in the Whangarei District, however it also did not disprove it. The method, as described by United States Department of Agriculture (1968) is a simplified method, making assumptions to increase the ease of use, at the cost of accuracy. Consideration must be given to the use of the method and desired accuracy. The TR-55 method was found to overestimate peak discharge by between 152% and 382% within the tested watershed, based on the previously stated base flow under peak factors.

The assessment was restricted to two watersheds, but also to watersheds greater than 2100ha, limiting the results of this research, with unknowns to it behaviour in smaller watershed. This has resulted in a lack of assessment in short duration events which are often critical in watershed of low time of concentration, more commonly assessed as part of land development project. High intensity short duration events (commonly thunderstorms) are often isolated, not causing widespread damage, but are generally critical.

6.0 Conclusion

6.1 Introduction

This section outlines the conclusions of this research project, linking the aims and objectives with the results, discussion, and practical implications and affirms the key knowledge gaps identified in the literature review. This conclusion presents also presented areas of recommended further research.

6.2 Project Review

The Whangarei District Council stipulates the use of TR-55 in hydrological modelling for the design of hydraulic structures. TR-55, provided by the United States Department of Agriculture in June 1986 is a simplified rainfall runoff model for the Urban Hydrology of small watersheds. A method with long historical origins, developed over many decades, being traced back to the 1930s. The early development of the method is, however generally unknown with little background publicly available, and the development being lost over time. Extensive research exists on the suitability of the method, namely the validation of Runoff Curve Numbers, particularly internationally, however little justification or validation exists for use on New Zealand watersheds, more specifically in the Whangarei District.

The research project aimed to assess the suitability of the TR-55 method in the Whangarei District. This required that the major local soil types are accurately placed in the hydrologic soil groups, the Type IA rainfall distribution is reviewed and a flood frequency analysis is completed. To complete these tasks, gain an understanding of the TR-55 method and develop the research methodology, a thorough literature review was required.

The literature review focused on three key aspects; the particulars of the TR-55 and the parameters required, the associated hydrological and hydraulic aspects, and identified any inconsistencies or knowledge gaps. As a result of the literature review, the methodology developed enabled a review and potential validation of the TR-55 method on Whangarei District watersheds.

The results of this project have provided valuable insight into the use of the TR-55 method in the Whangarei District. This project has also provided the author with an advanced understanding of the parameters of TR-55, its limitations, suitability and in particular, the accuracy of the simplified method. Although a validation was not achieved, the project aims and objectives were achieved.

6.3 Practical Implications

This section will discuss the practical implications of using the TR-55 method in the Whangarei District for the estimation of peak discharge. The literature review, results, and discussion from Chapters 2, 4 and 5 have provided a large insight in the TR-55 method, and conflict with the recommendations of WDC (2010) and standard practice of local consultants. This will cover the assessment of fluvial flood risk and design of culverts and similar hydraulic structures.

The assessment of flood risk for land development commonly requires the calculation of flood levels by first estimating peak watershed discharge at the point of interest. The correct placement of the local soils in the hydrologic soil groups has resulted in both the Kerkeri Volcanics and Waipapa Group materials being subject to reduced CN values and hence less runoff, reducing the peak estimate total flow in a watershed, compared to that recommended by WDC (2010).

The overestimation causes hydraulic structures to be inadvertently designed with an increased level of service. This comes at an additional expense, however proportionally insignificant for small structures. For large structures (e.g. box culverts and bridges), or those requiring a particular level of service, it is recommended that the full SCS method be utilised, with TR-55 perhaps being used for preliminary design, or feasibility only.

6.4 Conclusion

This project investigated the suitability of the TR-55 method for use on Whangarei District watersheds. The various key parameters of TR-55 were explored in detailed, with their respective methods or criteria reviewed to allow an accurate validation.

The literature review presented in Chapter 2 provides a detailed background of the TR-55 method and defines and reviews all the methods parameters. A further review was made to determine potential methods of validation in both New Zealand and internationally. The literature review provided a substantial increase in understanding of the TR-55, and provided the basis for the development of the methodology.

The results of the investigation and testing identified that the placement of major local soil types by WDC (2010) is incorrect, and that the TR-55 method over estimates runoff in the Whangarei District, particularly in events of low annual exceedance probability. An unexpected result of this research was the identification of the uncertainties around the estimation of baseflow, particularly in local watersheds, where little previous research could be located, let alone anything which quantified suitable baseflow factors.

Although the author wished to either validate or disprove the use of the TR-55 method, it was really, not that simple. The method may overestimate discharge, however this is far better than underestimation. The calculation of parameters and development of routing models is open for interpretation where assumption are required. Consequently, this causes a range in which a model is considered accurate, with literature suggesting +/- 30% as acceptable.

In conclusion, the TR-55 method is neither validated nor discounted but considered acceptable provided a set of limitations are applied to its use, and that the method is known as simplistic and likely to overestimate watershed discharge. Although the aim of this research was not achieved, each objective was completed, which provided the results detailed here within.

6.5 Further Work

This research project has alerted the author to varying issues and limitations of the TR-55 method. Before this project, no validation or assessment had previously been made as to the suitability of the TR-55 for use on Whangarei District watersheds. The results of the project could be considered inconclusive when considering the aim, however it was found that the method provides a conservative overestimation of watershed discharge. This was not the desired result of the research. However, it has confirmed the methods used as being acceptable, although not necessarily accurate. To improve the use of the method and provide further insight into its suitability, the author makes the following recommendations for further research:

- A limited number of infiltration tests were completed as part of this project. The results, however, identified the inaccurate suggestions made by WDC (2010), placing major local soil types within hydrologic soil groups which would not have been selected based on soil description. To provide a greater understanding of the major soil types placement, and place other less frequent soil types within the hydrologic soil groups a thorough program of infiltration tests is recommended.

- The velocity based time of concentration methods detailed by TR-55 are considered the most accurate, however, requiring an extensive watershed inspection to ensure accuracy which is time consuming and often not achievable due to public and practical access limitations. The calibration of the empirical methods discussed herein is recommended across a sample of Whangarei District watershed.

- The synthetic rainfall distributions provided by TR-55 are dated, and quite clearly are an inaccurate representation of rainfall events within the Whangarei District. It is unlikely a single design rainfall event will be adequate to provide an accurate estimate of peak discharge, consequently, it is recommended that an ensemble of rainfall events is developed to represent the varying events which are experienced in the Whangarei District.

- The watershed selection process identified only several watersheds suitable for assessment as part of this research project. While compiling a complete list of the Whangarei District gauging stations it became clear to the author that many sizeable streams and rivers are monitored. It is recommended that discharge of several smaller watersheds be monitored, with one being a watershed comprising primarily if not completely of the Kerikeri Volcanic Group material.

- Separation of baseflow from gauged watershed discharge has been subject to extensive research internationally, however little is available in the Whangarei District. To provide increased accuracy of the method used in this research it is recommend that a review of watershed is extended to include the majority of watersheds in the Whangarei District where suitable, and beyond into greater Northland.

7.0 Recommendations

As a result of this research, a preliminary set of recommendations and limitations have been assembled for the use of TR-55 in the Whangarei District. The following recommendations were developed based on both the findings of the literature review and the results of this research;

- Site-specific infiltration testing should be undertaken to ensure adequate placement of the soils present are correctly placed within the correct hydrologic soil groups.

- Only velocity based methods are used to determine the time of concentration of any given watershed.

- The TR-55 method is limited to use for assessment of peak discharge to the determination of flood levels or the design of hydrologic structures such as culverts and waterways.

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Appendix A - Project Specification

ENG4111/4112 Research Project

Project Specification

For: Matthew Jacobson

Title: Validation of the SCS TR-55 method on Whangarei District Watersheds and Soil Types

Major: Civil Engineering

Supervisor: Rezaul Chowdhury

Enrolment: ENG4111 - EXT S1, 2019
ENG4112 – EXT S2,2019

Project Aim: To assess the adequacy of, and validate the SCS TR-55 method, particularly the Type 1A design storm and the hydrologic soil groups for local soil types in the Whangarei District.

Programme: Version 3, 16 September 2019

1. Research existing studies and methods used to assess the adequacy of the SCS method

2. Compile, review, select and inspect watersheds for analysis

3. Undertake Field Investigation and Infiltration Testing

4. Review rainfall and river flow data, select storm events, assess watershed baseflow and undertake an Annual Series Flood Frequency Analysis

5. Assess watersheds, determine critical parameters, build hydrological models, analysis of design discharge for varying AEP

6. Interpretation of results to undertake sensitivity analysis and validation of results. Determine correctness of Type 1A storm, and validation of TR-55 method

7. Design implications to hydraulic structure.

If time and resources permit:

8. Recommend updated design storm suitable for Whangarei District

Appendix B - New Zealand Geotechnical Society Field Guide to Soil Description

NZ GEOTECHNICAL SOCIETY INC

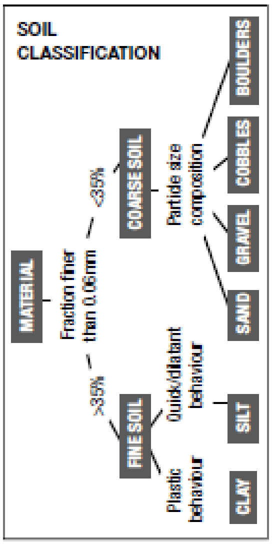
SOIL > field guide sheet

FIELD DESCRIPTION OF SOIL

SEQUENCE OF TERMS – fraction – colour – structure – strength – moisture – bedding – plasticity – sensitivity – additional

GRAIN SIZE CRITERIA

TYPE	COARSE								FINE		ORGANIC
			Gravel			Sand					
	Boulders	Cobbles	coarse	medium	fine	coarse	medium	fine	Silt	Clay	Organic Soil
Size Range (mm)	200	60	20	6	2	0.6	0.2	0.06	0.002		
Graphic Symbol											



PROPORTIONAL TERMS DEFINITION (COARSE SOILS)

Fraction	Term	% of Soil Mass	Example
Major	(….) [UPPER CASE]	≥ 50 [major constituent]	GRAVEL
Subordinate	(….) y [lower case]	20 – 50	Sandy
Minor	with some … with minor …	12 – 20 5 – 12	with some sand with minor sand
	with trace of (or slightly)…	< 5	with trace of sand (slightly sandy)

DENSITY INDEX (RELATIVE DENSITY) TERMS

Descriptive Term	Density Index (R_D)	SPT "N" value (blows / 300 mm)	Dynamic Cone (blows / 100 mm)
Very dense	> 85	> 50	> 17
Dense	65 – 85	30 – 50	7 – 17
Medium dense	35 – 65	10 – 30	3 – 7
Loose	15 – 35	4 – 10	1 – 3
Very loose	< 15	< 4	0 – 2

Note: • No correlation is implied between Standard Penetration Test (SPT) and Dynamic Cone Test values. • SPT "N" values are uncorrected. • Dynamic Cone Penetrometer (Scala)

CONSISTENCY TERMS FOR COHESIVE SOILS

Descriptive Term	Undrained Shear Strength (kPa)	Diagnostic Features
Very soft	< 12	Easily exudes between fingers when squeezed
Soft	12 – 25	Easily indented by fingers
Firm	25 – 50	Indented by strong finger pressure and can be indented by thumb pressure
Stiff	50 – 100	Cannot be indented by thumb pressure
Very stiff	100 – 200	Can be indented by thumb nail
Hard	200 – 500	Difficult to indent by thumb nail

ORGANIC SOILS/ DESCRIPTORS

Term	Description
Topsoil	Surficial organic soil layer that may contain living matter. However topsoil may occur at greater depth, having been buried by geological processes or man-made fill, and should then be termed a buried topsoil.
Organic clay, silt or sand	Contains finely divided organic matter; may have distinctive smell; may stain; may oxidise rapidly. Describe as for inorganic soils.
Peat	Consists predominantly of plant remains. ***Firm***: Fibres already compressed together ***Spongy***: Very compressible and open stucture ***Plastic***: Can be moulded in hand and smears in fingers ***Fibrous***: Plant remains recognisable and retain some strength ***Amorphous***: No recognisable plant remains
Rootlets	Fine, partly decomposed roots, normally found in the upper part of a soil profile or in a redeposited soil (e.g. colluvium or fill)
Carbonaceous	Discrete particles of hardened (carbonised) plant material.

PLASTICITY (CLAYS & SILTS)

Term	Description
High plasticity	Can be moulded or deformed over a wide range of moisture contents without cracking or showing any tendency to volume change
Low plasticity	When moulded can be crumbled in the fingers; may show quick or dilatant behaviour

MOISTURE CONDITION

Condition	Description	Granular Soils	Cohesive Soils
Dry	Looks and feels dry	Run freely through hands	Hard, powdery or friable
Moist	Feels cool, darkened in colour	Tend to cohere	Weakened by moisture, but no free water on hands when remoulding
Wet			Weakened by moisture, free water forms on hands when handling
Saturated	Feels cool, darkened in colour and free water is present on the sample		

GRADING (GRAVELS & SANDS)

Term	Description	
Well graded	Good representation of all particle sizes from largest to smallest	
Poorly graded	Limited representation of grain sizes - further divided into:	
	Uniformly graded	Most particles about the same size
	Gap graded	Absence of one or more intermediate sizes

compiled by KATE WILLIAMS design KARYN MISCHKE P

NZ GEOTECHNICAL SOCIETY INC

This field sheet has been taken from and should be used and read with reference to the document FIELD DESCRIPTION OF SOIL AND ROCK. Guideline For the Field Classification and Description of Soil and Rock for Engineering Purposes. NZ Geotechnical Society Inc, December 2005. **www.nzgeotechsoc.org.nz**

Figure B-2: NZGS Soil Decision Field Guide

Appendix C – Frequency Factor K_T for Log Pearson 3 Distribution

Table 1 -- K values for positive skew coefficients

Skew Coefficient (g)	Recurrence Interval in Years: 1.0101	1.0526	1.1111	1.2500	2	5	10	25	50	100	200
	Percent Chance: 99	95	90	80	50	20	10	4	2	1	0.5
3.0	-0.667	-0.665	-0.660	-0.636	-0.396	0.420	1.180	2.278	3.152	4.051	4.970
2.9	-0.690	-0.688	-0.681	-0.651	-0.390	0.440	1.195	2.277	3.134	4.013	4.909
2.8	-0.714	-0.711	-0.702	-0.666	-0.384	0.460	1.210	2.275	3.114	3.973	4.847
2.7	-0.740	-0.736	-0.724	-0.681	-0.376	0.479	1.224	2.272	3.093	3.932	4.783
2.6	-0.769	-0.762	-0.747	-0.696	-0.368	0.499	1.238	2.267	3.071	3.889	4.718
2.5	-0.799	-0.790	-0.771	-0.711	-0.360	0.518	1.250	2.262	3.048	3.845	4.652
2.4	-0.832	-0.819	-0.795	-0.725	-0.351	0.537	1.262	2.256	3.023	3.800	4.584
2.3	-0.867	-0.850	-0.819	-0.739	-0.341	0.555	1.274	2.248	2.997	3.753	4.515
2.2	-0.905	-0.882	-0.844	-0.752	-0.330	0.574	1.284	2.240	2.970	3.705	4.444
2.1	-0.946	-0.914	-0.869	-0.765	-0.319	0.592	1.294	2.230	2.942	3.656	4.372
2.0	-0.990	-0.949	-0.895	-0.777	-0.307	0.609	1.302	2.219	2.912	3.605	4.298
1.9	-1.037	-0.984	-0.920	-0.788	-0.294	0.627	1.310	2.207	2.881	3.553	4.223
1.8	-1.087	-1.020	-0.945	-0.799	-0.282	0.643	1.318	2.193	2.848	3.499	4.147
1.7	-1.140	-1.056	-0.970	-0.808	-0.268	0.660	1.324	2.179	2.815	3.444	4.069
1.6	-1.197	-1.093	-0.994	-0.817	-0.254	0.675	1.329	2.163	2.780	3.388	3.990
1.5	-1.256	-1.131	-1.018	-0.825	-0.240	0.690	1.333	2.146	2.743	3.330	3.910
1.4	-1.318	-1.168	-1.041	-0.832	-0.225	0.705	1.337	2.128	2.706	3.271	3.828
1.3	-1.383	-1.206	-1.064	-0.838	-0.210	0.719	1.339	2.108	2.666	3.211	3.745
1.2	-1.449	-1.243	-1.086	-0.844	-0.195	0.732	1.340	2.087	2.626	3.149	3.661
1.1	-1.518	-1.280	-1.107	-0.848	-0.180	0.745	1.341	2.066	2.585	3.087	3.575
1.0	-1.588	-1.317	-1.128	-0.852	-0.164	0.758	1.340	2.043	2.542	3.022	3.489
.9	-1.660	-1.353	-1.147	-0.854	-0.148	0.769	1.339	2.018	2.498	2.957	3.401
.8	-1.733	-1.388	-1.166	-0.856	-0.132	0.780	1.336	1.993	2.453	2.891	3.312
.7	-1.806	-1.423	-1.183	-0.857	-0.116	0.790	1.333	1.967	2.407	2.824	3.223
.6	-1.880	-1.458	-1.200	-0.857	-0.099	0.800	1.328	1.939	2.359	2.755	3.132
.5	-1.955	-1.491	-1.216	-0.856	-0.083	0.808	1.323	1.910	2.311	2.686	3.041
.4	-2.029	-1.524	-1.231	-0.855	-0.066	0.816	1.317	1.880	2.261	2.615	2.949
.3	-2.104	-1.555	-1.245	-0.853	-0.050	0.824	1.309	1.849	2.211	2.544	2.856
.2	-2.178	-1.586	-1.258	-0.850	-0.033	0.830	1.301	1.818	2.159	2.472	2.763
.1	-2.252	-1.616	-1.270	-0.846	-0.017	0.836	1.292	1.785	2.107	2.400	2.670
0	-2.326	-1.645	-1.282	-0.842	0	0.842	1.282	1.751	2.054	2.326	2.576

Figure C-1: Frequency Factors K_T for Positive Skew Coefficients

Table 2.--K values for negative skew coefficients

Skew Coefficient (g)	1.0101	1.0526	1.1111	1.2500	2	5	10	25	50	100	200
	Recurrence Interval in Years										
	Percent Chance										
	99	95	90	80	50	20	10	4	2	1	0.5
0	-2.326	-1.645	-1.282	-0.842	0	0.842	1.282	1.751	2.054	2.326	2.576
- .1	-2.400	-1.673	-1.292	-0.836	0.017	0.846	1.270	1.716	2.000	2.252	2.482
- .2	-2.472	-1.700	-1.301	-0.830	0.033	0.850	1.258	1.680	1.945	2.178	2.388
- .3	-2.544	-1.726	-1.309	-0.824	0.050	0.853	1.245	1.643	1.890	2.104	2.294
- .4	-2.615	-1.750	-1.317	-0.816	0.066	0.855	1.231	1.606	1.834	2.029	2.201
- .5	-2.686	-1.774	-1.323	-0.808	0.083	0.856	1.216	1.567	1.777	1.955	2.108
- .6	-2.755	-1.797	-1.328	-0.800	0.099	0.857	1.200	1.528	1.720	1.880	2.016
- .7	-2.824	-1.819	-1.333	-0.790	0.116	0.857	1.183	1.488	1.663	1.806	1.926
- .8	-2.891	-1.839	-1.336	-0.780	0.132	0.856	1.166	1.448	1.606	1.733	1.837
- .9	-2.957	-1.858	-1.339	-0.769	0.148	0.854	1.147	1.407	1.549	1.660	1.749
-1.0	-3.022	-1.877	-1.340	-0.758	0.164	0.852	1.128	1.366	1.492	1.588	1.664
-1.1	-3.087	-1.894	-1.341	-0.745	0.180	0.848	1.107	1.324	1.435	1.518	1.581
-1.2	-3.149	-1.910	-1.340	-0.732	0.195	0.844	1.086	1.282	1.379	1.449	1.501
-1.3	-3.211	-1.925	-1.339	-0.719	0.210	0.838	1.064	1.240	1.324	1.383	1.424
-1.4	-3.271	-1.938	-1.337	-0.705	0.225	0.832	1.041	1.198	1.270	1.318	1.351
-1.5	-3.330	-1.951	-1.333	-0.690	0.240	0.825	1.018	1.157	1.217	1.256	1.282
-1.6	-3.388	-1.962	-1.329	-0.675	0.254	0.817	0.994	1.116	1.166	1.197	1.216
-1.7	-3.444	-1.972	-1.324	-0.660	0.268	0.808	0.970	1.075	1.116	1.140	1.155
-1.8	-3.499	-1.981	-1.318	-0.643	0.282	0.799	0.945	1.035	1.069	1.087	1.097
-1.9	-3.553	-1.989	-1.310	-0.627	0.294	0.788	0.920	0.996	1.023	1.037	1.044
-2.0	-3.605	-1.996	-1.302	-0.609	0.307	0.777	0.895	0.959	0.980	0.990	0.995
-2.1	-3.656	-2.001	-1.294	-0.592	0.319	0.765	0.869	0.923	0.939	0.946	0.949
-2.2	-3.705	-2.006	-1.284	-0.574	0.330	0.752	0.844	0.888	0.900	0.905	0.907
-2.3	-3.753	-2.009	-1.274	-0.555	0.341	0.739	0.819	0.855	0.864	0.867	0.869
-2.4	-3.800	-2.011	-1.262	-0.537	0.351	0.725	0.795	0.823	0.830	0.832	0.833
-2.5	-3.845	-2.012	-1.250	-0.518	0.360	0.711	0.771	0.793	0.798	0.799	0.800
-2.6	-3.889	-2.013	-1.238	-0.499	0.368	0.696	0.747	0.764	0.768	0.769	0.769
-2.7	-3.932	-2.012	-1.224	-0.479	0.376	0.681	0.724	0.738	0.740	0.740	0.741
-2.8	-3.973	-2.010	-1.210	-0.460	0.384	0.666	0.702	0.712	0.714	0.714	0.714
-2.9	-4.013	-2.007	-1.195	-0.440	0.390	0.651	0.681	0.683	0.689	0.690	0.690
-3.0	-4.051	-2.003	-1.180	-0.420	0.396	0.636	0.660	0.666	0.666	0.667	0.667

Figure C-2: Frequency Factors K_T for Negative Skew Coefficients

Appendix D – Grubbs and Beck (1972) Table II

TABLE II

Table of Critical Values for $S^2_{n-1,n}/S^2_0$ or $S^2_{1,2}/S^2_0$ for Simultaneously Testing the Two Largest or Two Smallest Observations

Number of Observations n	Lower .1% Significance Level	Lower .5% Significance Level	Lower 1% Significance Level	Lower 2.5% Significance Level	Lower 5% Significance Level	Lower 10% Significance Level
4	.0000	.0000	.0000	.0002	.0008	.0031
5	.0003	.0018	.0035	.0090	.0183	.0376
6	.0039	.0116	.0186	.0349	.0564	.0920
7	.0135	.0308	.0440	.0708	.1020	.1479
8	.0290	.0563	.0750	.1101	.1478	.1994
9	.0489	.0851	.1082	.1492	.1909	.2454
10	.0714	.1150	.1414	.1864	.2305	.2863
11	.0953	.1448	.1736	.2213	.2667	.3227
12	.1198	.1738	.2043	.2537	.2996	.3552
13	.1441	.2016	.2333	.2836	.3295	.3843
14	.1680	.2280	.2605	.3112	.3568	.4106
15	.1912	.2530	.2859	.3367	.3818	.4345
16	.2136	.2767	.3098	.3603	.4048	.4562
17	.2350	.2990	.3321	.3822	.4259	.4761
18	.2556	.3200	.3530	.4025	.4455	.4944
19	.2752	.3398	.3725	.4214	.4636	.5113
20	.2939	.3585	.3909	.4391	.4804	.5270
21	.3118	.3761	.4082	.4556	.4961	.5415
22	.3288	.3927	.4245	.4711	.5107	.5550
23	.3450	.4085	.4398	.4857	.5244	.5677
24	.3605	.4234	.4543	.4994	.5373	.5795
25	.3752	.4376	.4680	.5123	.5495	.5906
26	.3893	.4510	.4810	.5245	.5609	.6011
27	.4027	.4638	.4933	.5360	.5717	.6110
28	.4156	.4759	.5050	.5470	.5819	.6203
29	.4279	.4875	.5162	.5574	.5916	.6292
30	.4397	.4985	.5268	.5672	.6008	.6375
31	.4510	.5091	.5369	.5766	.6095	.6455
32	.4618	.5192	.5465	.5856	.6178	.6530
33	.4722	.5288	.5557	.5941	.6257	.6602
34	.4821	.5381	.5646	.6023	.6333	.6671
35	.4917	.5469	.5730	.6101	.6405	.6737
36	.5009	.5554	.5811	.6175	.6474	.6800
37	.5098	.5636	.5889	.6247	.6541	.6860
38	.5184	.5714	.5963	.6316	.6604	.6917
39	.5266	.5789	.6035	.6382	.6665	.6972
40	.5345	.5862	.6104	.6445	.6724	.7025
41	.5422	.5932	.6170	.6506	.6780	.7076
42	.5496	.5999	.6234	.6565	.6834	.7125
43	.5568	.6064	.6296	.6621	.6886	.7172
44	.5637	.6127	.6355	.6676	.6936	.7218
45	.5704	.6188	.6412	.6728	.6985	.7261
46	.5768	.6246	.6468	.6779	.7032	.7304
47	.5831	.6303	.6521	.6828	.7077	.7345
48	.5892	.6358	.6573	.6876	.7120	.7384
49	.5951	.6411	.6623	.6921	.7163	.7422
50	.6008	.6462	.6672	.6966	.7203	.7459

Figure D-1: Grubbs and Beck (1972) Table II