Estimates of recharge for the East Coast Sedimentary Hydrogeological Units

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Executive summary

The East Coast Sedimentary Hydrogeological Units are comprised of relatively small deposits in shallow coastal basins. The volume of groundwater available from the shallow aquifers they form is relatively small. They are unlikely to sustain substantial volumes of water for abstraction compared to other parts of the region.

The National Policy Statement for Freshwater Management (2020) requires the Bay of Plenty Regional Council (BOPRC) to set environmental flows and levels; and corresponding take limits. They must give effect to how Te Mana o te Wai applies, provide for freshwater long-term visions and meet the environmental outcomes for the groundwater resource values. When setting environmental flows and levels the council must have regard for the foreseeable impacts of climate change. It must also use the best information available at the time. Bay of Plenty Regional Council's programme schedules a proposed plan change to give effect to the NPSFM 2020 in July 2024.

To set interim groundwater take limits, the Proposed National Environmental Standard on Ecological Flows and Water Levels, Ministry for the Environment (2008) was considered. It recommends 'proposed interim limits for groundwater'. Interim limits for shallow coastal aquifers (predominantly sand), such as the East Coast Sedimentary Hydrogeological Units are included. The recommended limit in the Proposed National Environmental Standard for them is the greater of; 15% of the average annual recharge as calculated by the regional council, or the total allocation on the date the standard comes into force (which did not eventuate).

Three methods incorporating eight techniques were investigated to determine the average annual recharge for the East Coast Sedimentary Hydrogeological Units. The best performing technique was based on the average annualised monthly recharge. It has been used to estimate the recharge to the East Coast Sedimentary Hydrogeological Units.

Based on the geology and topography the East Coast Sedimentary Hydrogeological Units were divided into 21 individual hydrogeological management units. The recharge and corresponding interim groundwater take limit was calculated for each of the individual hydrogeological management units. The interim take limits may be different to those recommended in a proposed plan change to give effect to the NPSFM 2020 in July 2024. However, those take limits are expected to be based on some proportion of the assessment of annual average recharge calculated in this report.

Bibliographic Reference

Fernandes R. and Millar A. 2022. Estimates of the Groundwater Recharge for the East Coast Sedimentary Hydrogeological Units. Whakatāne: Bay of Plenty Regional Council.

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Part 1: **Introduction**

A large portion of New Zealand's total water storage is in its groundwater resources (White, 2001). Demand for water is increasing as potable supply, horticulture, agricultural and other water use activities expand. This is likely to put groundwater resources in the Bay of Plenty under increased pressure.

Groundwater environmental flows and water levels can be set as limits to the amount of water that can be taken, and provide a means of managing spring flow, aquifer pressure (levels) and flows to other potentially connected surface water bodies such as rivers and wetlands. Groundwater levels (or pressures), prevent salt-water intrusion or adverse pressure gradients. To manage the region's groundwater resources sustainably an assessment of the potential limits on resource use and the implications of these is needed. Decisions on groundwater take limits are made in the context of the framework set out in Part II of the Resource Management Act 1991 (RMA), national policy statements and the regional policy statement.

Part II of the RMA sets out the purpose and principles of the Act. The meaning of sustainable management is set out in Section 5 of the RMA. Sustainable management means managing the use, development, and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their social, economic, and cultural well-being. Overall, sustainable management of groundwater requires balancing use and development with protection of the groundwater resource (subject to the provisions of other relevant statutory documents). In doing so, peoples' social, economic and cultural well-being needs to be enabled. Sustainable management of groundwater resources requires having regard to the finite characteristics of groundwater. Groundwater sustainability policy regarding take limits requires a science-policy interface. Groundwater sustainability assessment is not purely scientific. It is also subjective and depends on social values.

Groundwater resource assessment in the Bay of Plenty began in the 1980s (Gordon, 2001) when a series of reports were commissioned. The reports previously commissioned by the Bay of Plenty Regional Council (BOPRC) include a series of mass balance models that were completed between 2009 to 2015 (White, Meilhac, et al., 2009; White, Pasqua, et al., 2009; White et al., 2010, 2013; White & Tschritter, 2015). This work was undertaken by the Institute of Geological and Nuclear Science (GNS Science). It was subsequently adopted by the Bay of Plenty Regional Council as the basis for decisions on take limits.

Since 2015, BOPRC has commissioned a new series of reports to replace the mass balance models with numerical modelling[1] to determine groundwater take limits. The mass balance models were based on the limited data available at the time. The numerical models are expected to provide a greater level of certainty than the mass balance models. The numerical models are also able to provide a quantitate assessment of the effects of different potential groundwater take limits on groundwater levels and connected surface water bodies. These reports were conceptualised before the Resource Management Amendment Act 2020 introduced the requirement to notify a freshwater planning instrument to give effect to the National Policy Statement for Freshwater Management (2020), (NPSFM 2020), by 31 December 2024. The council intends to do this by July 2024. The requirement to have take limits in a proposed plan change for all freshwater bodies in the Bay of Plenty earlier than previously required under the NPSFM 2014 (amended 2017), means that in some parts of the region, they will have to be informed by a series of different models and methods. Numerical models covering the whole of the Bay of Plenty region will not be available for use in a

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[1] Three dimensional computer model representing the groundwater system and the factors that affect it.

proposed plan change by July 2024. The NPSFM 2020 requires the council to use the best information available at the time.

Two MODFLOW[2] models are currently available for developing scenarios and testing groundwater take limit regimes. These are the Kaituna-Maketū-Pongakawa MODFLOW model (Salvodelli et al., 2020) and the Tarawera-Rangitāiki-Whakatāne MODFLOW model (Taulis & Barnett, 2021). MODFLOW models for the Tauranga Water Management Area (WMA), Rotorua WMA and Ōhiwa Harbour/Ōpōtiki WMAs are expected to be available by December 2022, December 2023 and December 2027, respectively.

There will be a variety of scientific reports and projects developed to inform decisions on setting groundwater take limits across the region. The following reports are expected to be the best information available to support the proposed plan change to give effect to the NPSFM 2020.

- Tauranga WMA the mass balance models will be used, unless MODFLOW is available earlier than currently expected.
- Kaituna, Maketū and Pongakawa WMA the MODFLOW model.
- Tarawera, Rangitāiki and Whakatāne WMAs the MODFLOW model.
- Ōhiwa Harbour and Ōpōtiki WMAs the mass balance models.

There has been no work previously completed on the assessment of groundwater take limits in the Rotorua or East Coast WMAs. There has been some preliminary work completed in the Rotorua Lakes Catchment to map the likely extent of the groundwater recharge area. It can be incorporated into the assessment to inform setting take limits. A separate technical memorandum will cover the assessment of groundwater take limits for the Rotorua WMA, unless MODFLOW is available earlier than currently expected.

This work provides a preliminary assessment of the groundwater interim take limits for the East Coast Sedimentary Hydrogeological Units. The assessment is based on calculated annual average recharge and the Proposed National Environmental Standard for Ecological Flows and Water Levels, Ministry for the Environment (2008), (pNES Ecological Flows). The pNES Ecological Flows recommends 'proposed interim limits for groundwater'. The proposed interim limits in the pNES Ecological Flows were based on the expert opinion of scientists and regional council staff, who had experience with setting environmental flows and water levels. They were intended to accommodate other values, such as recreational, natural character, and cultural flows. The interim limits are expected to provide clear protection for ecological and other values from any adverse effects of water abstraction. As such they are expected to be conservative.

The East Coast Sedimentary Hydrogeological Units are comprised of relatively small deposits in shallow coastal basins. The volume of groundwater available from the shallow aquifers they form is expected to be relatively small. They are unlikely to sustain substantial volumes of water for abstraction compared to other parts of the region.

The pNES Ecological Flows interim limits for shallow coastal aquifers (predominantly sand) it is the greater of: 15% of the average annual recharge as calculated by the regional council; or, the total allocation on the date the standard comes into force. For all other aquifers, it is the greater of 35% of the average annual recharge as calculated by the regional council; or, the total allocation on the date the standard comes into force. The pNES Ecological Flows was never adopted by central government and the standard did not come into force. However, the expert opinion on the proposed interim limits in the pNES Ecological Flows are considered relevant. The interim limits for shallow coastal aquifers is more appropriate for the East Coast Sedimentary Hydrogeological Units than the less conservative alternative. It better reflects that hydrogeological environment. Shallow coastal

[2] The U.S. Geological Survey modular finite-difference hydrological model, used to simulate the flow of groundwater through aquifers and groundwater / surface water interaction.

aquifers are particularly susceptible to potential saline intrusion from groundwater level reduction caused by taking groundwater.

This preliminary assessment based on the pNES Ecological Flows 'proposed interim limits for groundwater' may be different to that adopted in a proposed plan change to give effect to the NPSFM 2020. The potential take limits recommended in a plan change are expected to include consideration of how Te Mana o te Wai[3] applies, provide for freshwater long-term visions in the regional policy statement and meet the environmental outcomes for the local groundwater resource values. However, it is expected the potential take limits will be based on some proportion of the assessment of annual average recharge in this report. The interim take limits are required to manage the groundwater resource in current environment and existing regulatory context.

The pNES Ecological Flows does not define methods used to determine the average annual recharge. It is unlikely that a universally capable method for estimating groundwater recharge is available (Anderson & Woessner, 2002). This is perhaps the reason why the pNES Ecological Flows recommended approach to calculating recharge at the national level is, *"… as calculated by the regional council"*. The geological and environmental diversity in the Bay of Plenty requires a combination of best practice approaches be used to determine the appropriate approach to determine recharge. There is no standard set of methods that has been recommended to determine recharge in New Zealand. Internationally, the work by Healy can be considered the standard guide to methods for determining recharge.

Recharge is the process by which water enters the phreatic zone[4] (Sharp, 2007). Recharge can be considered as the volume of water that becomes a part of the groundwater system. Quantification of recharge is important to enable sustainable management and protection of valuable groundwater resources (Healy & Cook, 2002). Healy covers a variety of methods that can be used to determine recharge (Healy, 2010). These methods are developed and calibrated against the Collins Lane Lysimeter (Section Part 2). They have then been applied to the East Coast Sedimentary Hydrogeological Units (Section Part 3).

[3] Te Mana o te Wai is a concept in the NPSFM 2020 recognising the fundamental importance and mauri of water. Te Mana o te Wai encompasses groundwater requiring that groundwater systems are recognised and the mauri of the water is protected.

[4] Also known as the zone of saturation. It is the part of an aquifer below the water table in which the pores and fractures are saturated with water.

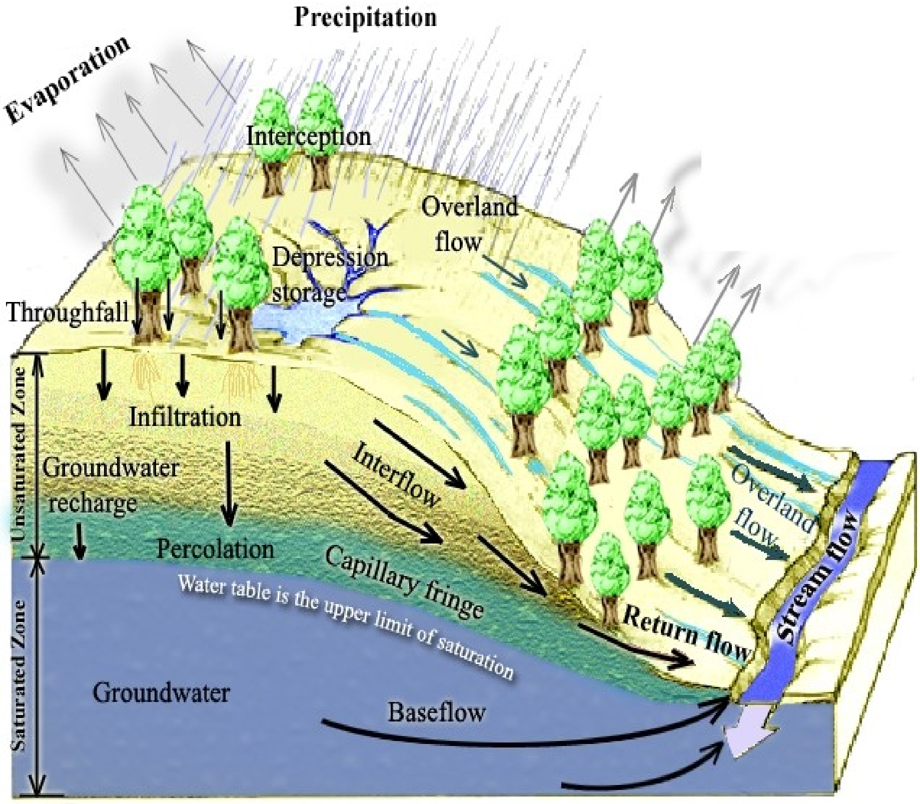

Figure 1-1 The main components of the water cycle (Tarboton, 1982).

Part 2:
Methods

There are several methods available to determine recharge. These can broadly be classified into methods based on surface water data, physical methods (saturated and unsaturated zone methods), chemical methods, mass balance methods and empirical methods (Healy, 2010).

There is very little surface water flow information available in the area to use hydrograph separation methods to determine recharge. Flow gauging data is available at some locations. However, there is not enough data available to be used for recharge analysis. Physical methods are also unable to be directly applied in the area, as infrastructure such lysimeters and water level data-loggers in wells have not been installed.

Natural chemical mass balance methods rely on knowledge of the concentration of the natural tracer elements in rainfall and groundwater (Healy, 2010). Natural chemical tracer data is not currently available for rainfall in the Bay of Plenty region. Application of natural chemical tracer methods require the ability to record and apply the data at sites in the field. The NPSFM 2020 timelines do not allow for chemical mass balance or natural tracer methods to be conducted for this assessment.

Mass balance methods require very little data and if conceptualised correctly they can be used to determine recharge. Empirical and physical methods can be indirectly used if the hydrogeological conditions for which the empirical equations were developed, are similar to those in the study area. Physical methods require installation of a lysimeter on site. There are currently no lysimeters installed in the East Coast Sedimentary Hydrogeological Units. The East Coast Sedimentary Hydrogeological Units are hydrogeologically similar to the Kaituna Plains Sedimentary Hydrogeological Units. Therefore, an indirect application of existing lysimeter data from the Kaituna Plains Sedimentary Hydrogeological Units at Collins Lane can be used to determine recharge for the East Coast Sedimentary Hydrogeological Units.

Three methods can be used to determine recharge for the East Coast Sedimentary Hydrogeological Units. These include: mass balance methods, empirical methods, and an indirect application of the physical methods (linear regressions).

2.1 Mass balance methods

Mass balance methods are based on the principal that the inflows to any water system or area is equal to its outflow, plus changes in storage during the time interval (conservation of mass). Water budgets are the most basic methods used to estimate recharge. Water budgets can be used to estimate diffuse and focussed recharge. They are unaffected by preferential flow paths within the unsaturated zone. Building a preliminary water budget is relatively simple as it does not require significant amounts of data.

Mass balance methods rely on the conceptual understanding of the water cycle. The advantage of this approach is that it estimates direct groundwater recharge using available climate data (Rushton and Ward 1979). The parameters of the mass balance method are; precipitation, surface water runoff, evapotranspiration and soil water storage.

Based on the accepted definition of recharge, the recharge equation can be expressed as;

$$R = P - ET + \Delta S_{soil} - R_o \qquad \text{Equation 1}$$

Where R is the recharge from rainfall, P is the precipitation (rainfall), ET is the evapotranspiration, ΔS_{soil} is the soil water storage and $R_o$is the surface water runoff.

During periods of rainfall, rates of evaporation and storage change are usually much less than those of infiltration and surface water runoff (Healy et al., 2007). Therefore, on an event or short term basis, the storage term can be neglected in the determination of recharge. On an annual basis, change in soil moisture and aquifer storage is often small and can be ignored (The United States Department of Agriculture & The Natural Soil Conservation Service, 2009). Thus, the storage term can be neglected in the determination of recharge. Equation 1 is valid for calculating recharge on an event or annual basis and can be rewritten as;

$R = P - ET - R_o$ Equation 2

The calculation of recharge is now dependent on three parameters; rainfall, evapotranspiration and the surface water runoff.

Measured rainfall data is available at various locations in the Bay of Plenty. However, evapotranspiration data is not collected. The National Institute of Water and Atmospheric Research (NIWA) has a Virtual Climate Station Network (VCNS) network. It provides daily estimates of rainfall, potential evapotranspiration, air and vapour pressure, maximum and minimum air temperature, soil temperature, relative humidity, solar radiation, wind speed and soil moisture. The estimates are available on a regular (~5 km) grid covering the whole of New Zealand (National Institute of Water and Atmospheric Research, n.d.). The VCNS data is based on the spatial interpolation of actual data observations made at climate stations located throughout the country.

Two of the required parameters for the water balance calculation can be determined from the VCNS network; evapotranspiration and rainfall. To determine groundwater recharge, the only parameter left to complete the equation is the surface water runoff. Surface water runoff is the portion of rainfall that runs over the soil surface (Sharp, 2007) into small ephemeral channels and streams. Ultimately, it flows towards rivers, lakes and the coast.

Different techniques can be used to determine the amount of rainfall that contributes to surface runoff. The Natural Resources Conservation Service Curve Number (NRCS-CN) technique and the maximum infiltration rate technique were chosen because of the ease of application.

2.2 Simple mass balance using Natural Resources Conservation Service Curve Numbers (NRCS-CN)

The NRCS-CN technique was developed by the US Soil Conservation Service (SCS) in 1972. The SCS was the predecessor of the Natural Resources Conservation Service (NRCS). The model makes extensive use of the runoff curve number, which is referred to as curve number (CN). It is used to estimate total storm runoff from total storm rainfall (The United States Department of Agriculture & The Natural Soil Conservation Service, 1972).

The NRCS runoff equation estimates total runoff from total storm rainfall. The relationship allows time to be excluded as a variable and rainfall intensity is ignored. The curve number equation is:

$Q = \frac{(P-0.2S)^2}{(P-0.8S)}$ Equation 3

$S = \frac{1000}{CN} - 10$ Equation 4

Where, Q is the depth of the runoff, P is the depth of rainfall and S is the maximum potential retention after runoff begins.

A desktop analysis was conducted to determine the curve numbers for the Collins Lane Lysimeter. The soil at the lysimeter site is mainly sandy (Hydrologic Soil Group A) and the predominant land use is pastoral farming. Using the process described in Part 630 of the National Engineering Handbook curve number 68 was used for the NRCS method. (The United States Department of Agriculture & The Natural Soil Conservation Service, 1972, 2004, 2007, 2010).

The daily rainfall and evapotranspiration value was obtained for all VCNS sites (five sites) within 10 km of the lysimeter starting in January 2015 to December 2021. A mean daily value for the Collins Lane Lysimeter site was obtained by averaging the daily values of rainfall and evapotranspiration across the five sites. This value is considered representative of the hydrological conditions at the lysimeter.

Qablawi, (2016) used the NRCS-CN technique to determine runoff on an annual basis. The mean annual rainfall and the curve number was applied to Equations 3 and 4 to determine the runoff for each year from 2015 to 2021. The calculated annual runoff was used in Equation 2 along with the rainfall and evapotranspiration values to determine the recharge for the Collins Lane site between 2015 and 2021. Application of the NRCS-CN technique to annual totals of rainfall and evapotranspiration yielded negative recharge values for all years at the Collins Lane Lysimeter site. The application of the Qablawi (2016) technique needed to be modified to be applied in the Bay of Plenty.

The NRCS curve number procedure is best suited to determining the runoff from a storm event. This work explored the uncertainty involved between determining the annual surface water runoff on an annual basis[5] and on an event basis[6]. A daily, three-day, and five-day event was used as the typical rainfall events for the region. The VCNS daily data was converted to a three-day and five-day sum across the dataset. The NRCS-CN technique was applied to the daily, three-day, and five-day rainfall totals to determine the runoff on an event basis. This was used in Equation 2 to determine recharge at a daily, three-day and five-day interval. The recharge for each event was annualised and compared to the annual cumulative recharge. The best approach is to then apply the NRCS-CN technique to the five-day sum of the rainfall as it is a better predictor of recharge. The comparison is discussed in Section 3.1.

[5] The application of annual rainfall to determine annual runoff.

[6] The determination of the surface runoff on an event basis and summarising by year.

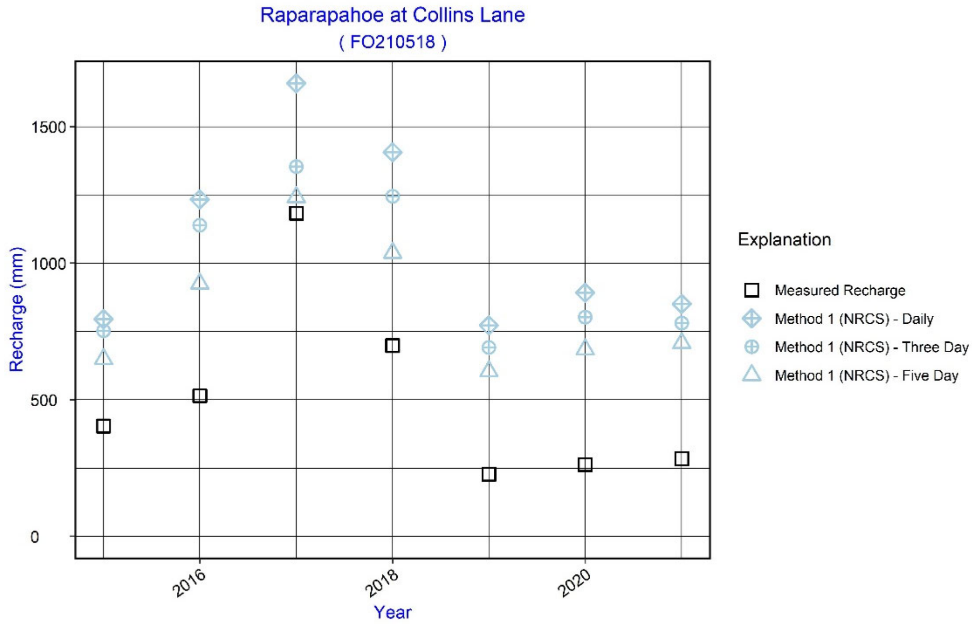

Figure 2-1 Measured recharge and modelled recharge for the Collins Lane Lysimeter using the NRCS-CN technique based on a daily, three-day and five-day totals for the year.

2.3 Maximum infiltration rate

The amount of rainfall that can infiltrate into the soils above an aquifer is dependent on the hydrogeological properties of the soils. Any rainfall that exceeds the infiltration capacity of the soil will become overland flow and runoff into surface water bodies.

The US Department of Agriculture classifies soils into four hydrologic soil groups based on soil properties such as texture, compaction, soil structure etc. The soils around the Collins Lane Lysimeter are generally sandy with low runoff potential when wet. Sand is the predominant texture (>90%) which places the soil around the site in Group A. The saturated hydraulic conductivity for Group A soils is 114 mm/hr. The S-map soil data set from Landcare Research indicate that the soils are the Ngakura sandy loam with a permeability of greater than 72 mm/hr. A range of infiltration rates between 72 mm/hr and 114 mm/hr were used with this technique. Higher infiltration rates resulted in higher recharge. To be conservative the infiltration rate for this method was set to 72 mm/hr.

A simple rule-based system was developed to determine the infiltration into the soils. If the daily-cumulated rainfall minus evapotranspiration did not exceed the daily infiltration capacity of the soil, recharge was assumed to be equal to rainfall minus evapotranspiration. If the daily-cumulated rainfall minus evapotranspiration exceeded the daily soil infiltration capacity, the maximum infiltration capacity of the soils was used as recharge.

Recharge was determined at a daily, three-day and five-day interval. This was annualised and compared to the measured annual cumulative recharge at the Collins Road site. The five-day sum of rainfall was used to estimate the recharge at the Collins Lane site as it represented the best result for this technique. The recharge estimated using this technique is discussed in Section 3.1.

$$If\ P - ET > Infiltration\ capacity, then\ R = infitration\ capacity$$

$$If\ P - ET < Infiltration\ capacity, then\ R = P - ET$$ Equation 5

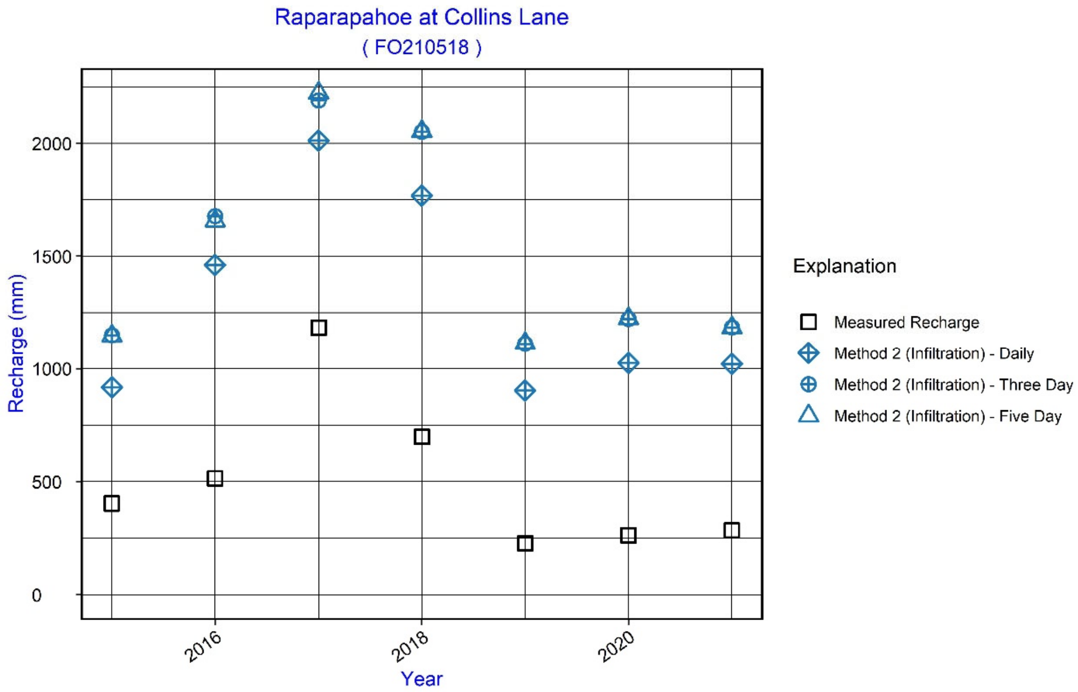

Figure 2-2 Measured recharge and modelled recharge for the Collins Lane Lysimeter using the maximum infiltration method based on a daily, three-day and five-day totals for the year.

2.4 Empirical methods

Empirical methods have been developed based on data available. There are two different types of empirical methods that can be applied to determine recharge: regional and site specific. Based on a literature review, two regional techniques, the White Recharge formula (White, Meilhac, et al., 2009), and the Chaturvedi formula (Chaturvedi, 1973) were used to determine recharge. Site specific regression analyses can be employed to scale up recharge (Male, 2015). Development of a regression analysis requires the fitting of a statistical model to recharge and rainfall values.

The Bay of Plenty Regional Council measures recharge using lysimeters. They are designed to collect water passing through the root zone and into groundwater while representing the natural flux of water held within the soil (Freeman, 2010). The Bay of Plenty Regional Council has installed nine lysimeter sites in the Bay of Plenty region. Each site consists of two or three, 500 mm diameter by 700 mm deep lysimeters. Infiltration is recorded by means of a tipping bucket rainfall recorder (Lovett et al., 2012). Each site also has a rain gauge and a soil moisture probe installed.

The data that is obtained from the sites is quality checked by the BOPRC Environmental Data Services section (EDS). This follows a standard Quality Assessment process that is reviewed by two EDS staff members (Freeman, 2010).

Development of regressions based on rainfall and recharge are complex. Aside from soil hydrogeology and evapotranspiration, the relationship between a rainfall event and a recharge event is not direct. Lag times can cause an increase in recharge events where rainfall is below a minimum threshold for the site. Peak rainfall to peak recharge event is variable and it is acknowledged that an event-based analysis is required. This is beyond the scope of this report.

The Kaituna Plains and the East Coast Sedimentary Hydrogeological Units are both comprised of late Pleistocene to Holocene aged alluvium and beach deposits. Bore logs in the two Hydrogeological Units indicate the first few metres are generally comprised of sand. The two units can therefore be considered hydrologically similar. Linear regressions were developed for the Collins Lane Lysimeter in the Kaituna, Maketū and Pongakawa WMA. Regressions were developed for the site on an annual, seasonal, monthly, and weekly event basis.

The general principle used to assess and apply the lysimeter data was:

- Identify the days that have rainfall
- Identify the days that have recharge
- Determine the minimum rainfall event that is likely to induce recharge
- Exclude data below the minimum rainfall event
- Summarise the data based on the specified time-period
- Develop a relationship between the rainfall and recharge for the site
- Apply the equations developed to the VCNS rainfall data for the site
- Select the best model to apply to the East Coast Sedimentary Hydrogeological Units.

2.5 White recharge formula

The White recharge formula was derived by GNS Science to determine the recharge in its mass balance models. Recharge is assumed to be 50% of the annual rainfall in the higher and inland areas, and 30% in the coastal lowland areas (White, Meilhac, et al., 2009). The Collins Lane Lysimeter is located in the lower coastland area. This method was applied directly to the rainfall obtained from the VCNS network to determine recharge. The recharge estimated using this technique was compared to the measured recharge at the Collins Lane site. The comparison is discussed in Section 3.2.

2.6 Chaturvedi formula

The Chaturvedi formula was based on the water level fluctuation method and amount of rainfall. According to (Chaturvedi 1973), groundwater recharge was defined as a function of the annual precipitation. The Chaturvedi formula was used in India where the climate is tropical.

According to (Kumar 1997), groundwater recharge can be predicted from the following formula (Chaturvedi 1973).

$R = 1.35(P - 14)^{0.5}$ Equation 6

Where R is the groundwater recharge due to precipitation during the year in inches, and P is the annual precipitation in inches.

The recharge estimated using this technique was compared to the measured recharge at the Collins Lane site. The comparison is discussed in Section 3.2.

2.7 Annual rainfall and recharge

Established hydrological procedures recommend using the hydrological water year (starting in July) to avoid splitting flow events across the calendar year. However, as recharge occurs mainly during autumn and winter, splitting the data by hydrological year means splitting the recharge in autumn across two calendar years. The 1st of December was used as the start of the recharge year in this analysis.

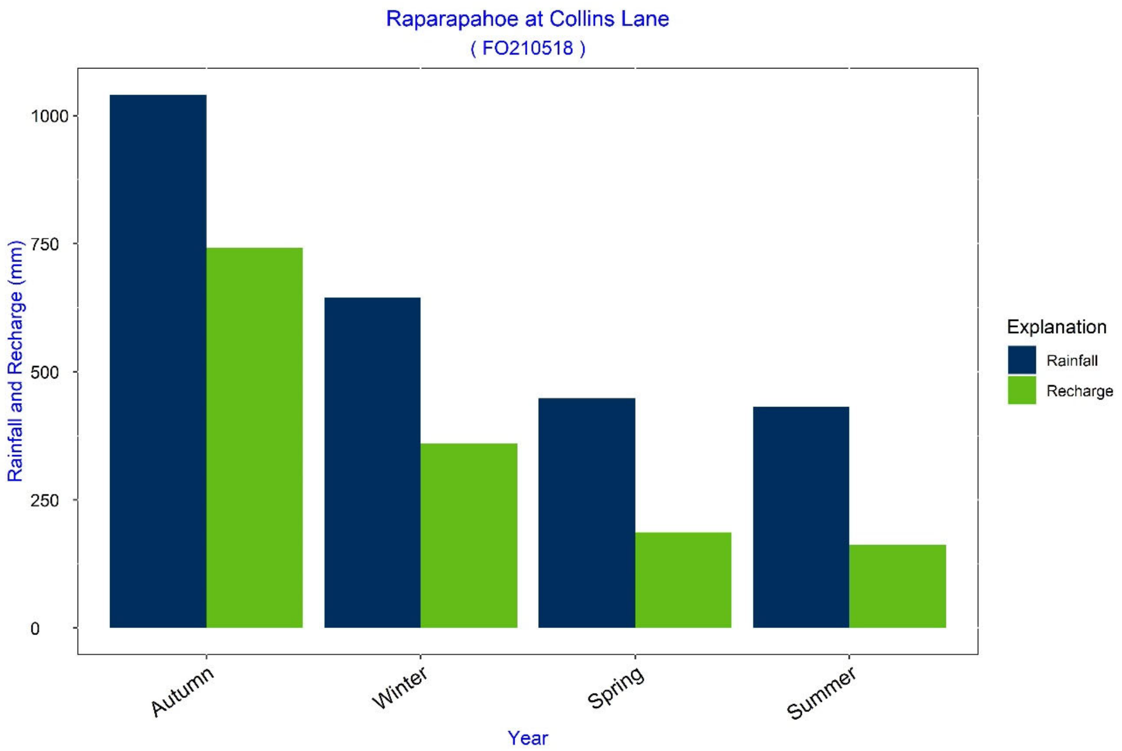

Figure 2-3 Seasonal distrubution of rainfall and recharge for the Collins Lane Lysimeter from 2015 to 2021.

The Collins Lane Lysimeter was commissioned in November 2014. Data from the site is available from then to the current year (2021). Therefore, data for the site between 1 December 2014 and 1 December 2021 was used to develop a relationship for the site between the cumulative annual rainfall and recharge. The relationship is expressed as:

$$Recharge = Rainfall * 0.68 - 531.8 \quad \text{Equation 7}$$

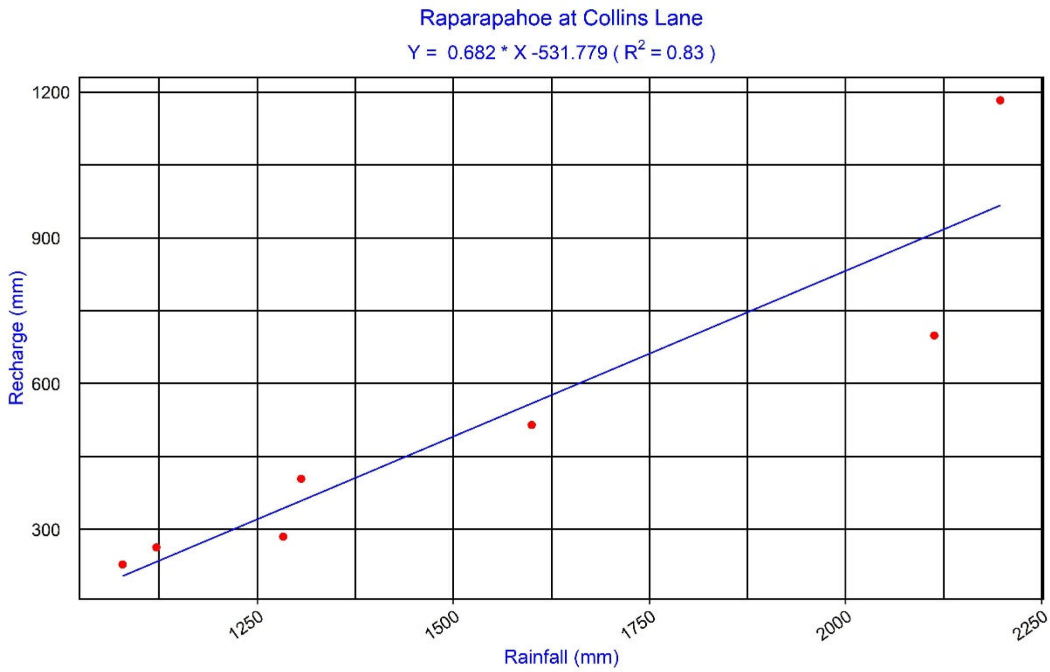

Figure 2-4 Linear regression between total annual rainfall and total annual recharge for the Collins Lane Lysimeter.

The coefficient of determination for the relationship developed using this technique indicates a good fit of the data. However, there are only seven complete years of data available to establish the regression. The lack of data requires that the relationship should be viewed with caution. The equation developed was used to estimate recharge for each year between 2015 and 2021. The recharge estimated using this technique was compared to the measured recharge at the Collins Lane site. The comparison is discussed in Section 3.3.

2.8 Seasonal rainfall and recharge

Seasons were defined as summer (December to February), autumn (March to May), winter (June to August), and spring (September to November). The seasonal total rainfall and recharge at the Collins Lane Lysimeter were obtained for each complete season on record, for each year between 2015 and 2021. Using the seasonal data, a linear regression was developed between the recharge and the rainfall for each season.

Except for autumn, there does not appear to be any distinct relationship between the rainfall and recharge on a seasonal basis. As the site has been in operation for only seven years, the lack of data-points requires that any regressions developed on a seasonal basis should be viewed with caution.

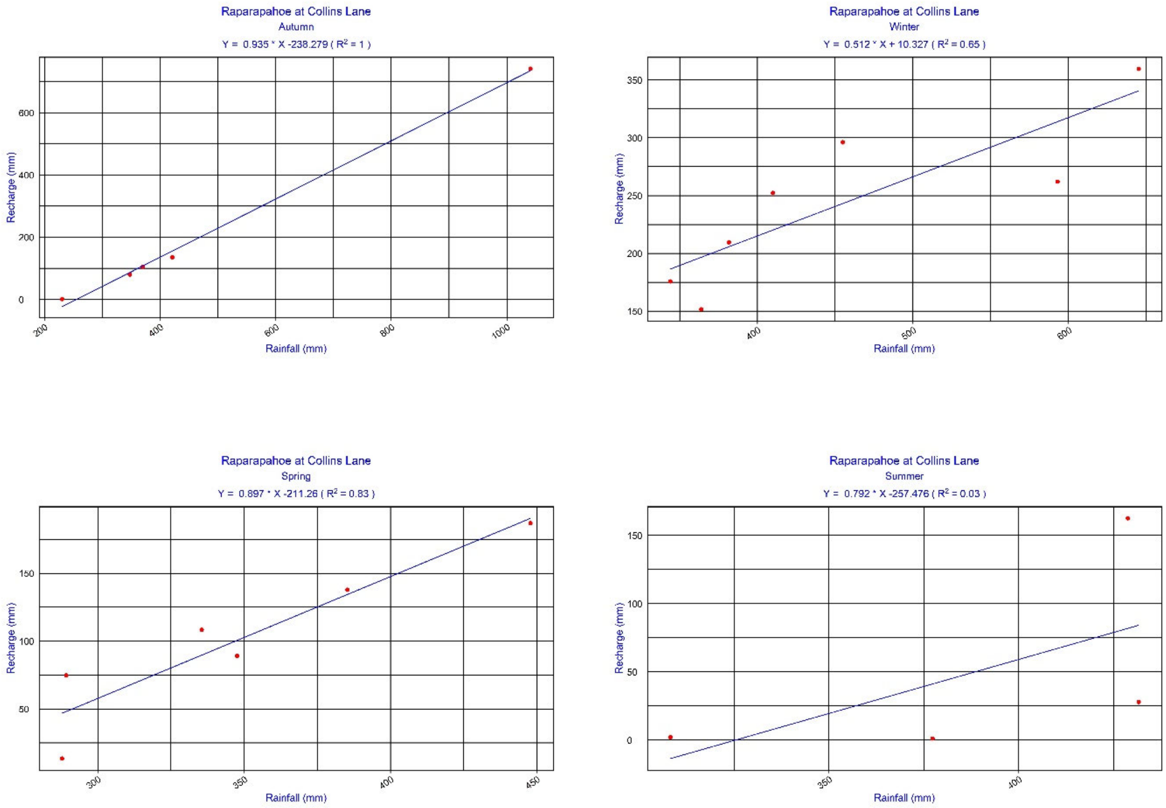

Figure 2-5 Linear regression between seasonal total rainfall and seasonal recharge for the Collins Lane Lysimeter.

$$Autumn\ Recharge = Rainfall * 0.94 - 238.28$$ Equation 8

$$Winter\ Recharge = Rainfall * 0.51 + 10.33$$ Equation 9

$$Spring\ Recharge = Rainfall * 0.90 - 211.26$$ Equation 10

$$Summer\ Recharge = Rainfall * 0.79 - 257.48$$ Equation 11

Equations 8 to 11 were used to estimate recharge for each season (seasonal technique), between 2015 and 2021. These estimates were compared to the measured recharge at the Collins Lane site. The seasonal estimates show a distinct trend with the winter months generally showing a higher recharge. The comparison is discussed in Section 3.3.

2.9 Monthly rainfall and recharge

The monthly totals for rainfall and recharge at the Collins Lane Lysimeter were obtained for each complete month on record. Using the monthly data, a linear regression was developed between the recharge and the rainfall at the Collins Lane site.

The monthly data appears to provide a reasonable fit between the rainfall and the recharge. The equation developed was used to estimate recharge for each month between 2015 and 2021. The recharge estimated using this technique was compared to the measured recharge at the Collins Lane site. The comparison is discussed in Section 3.3.

$$Monthly\ Recharge = Rainfall * 0.66 - 33.28$$ Equation 12

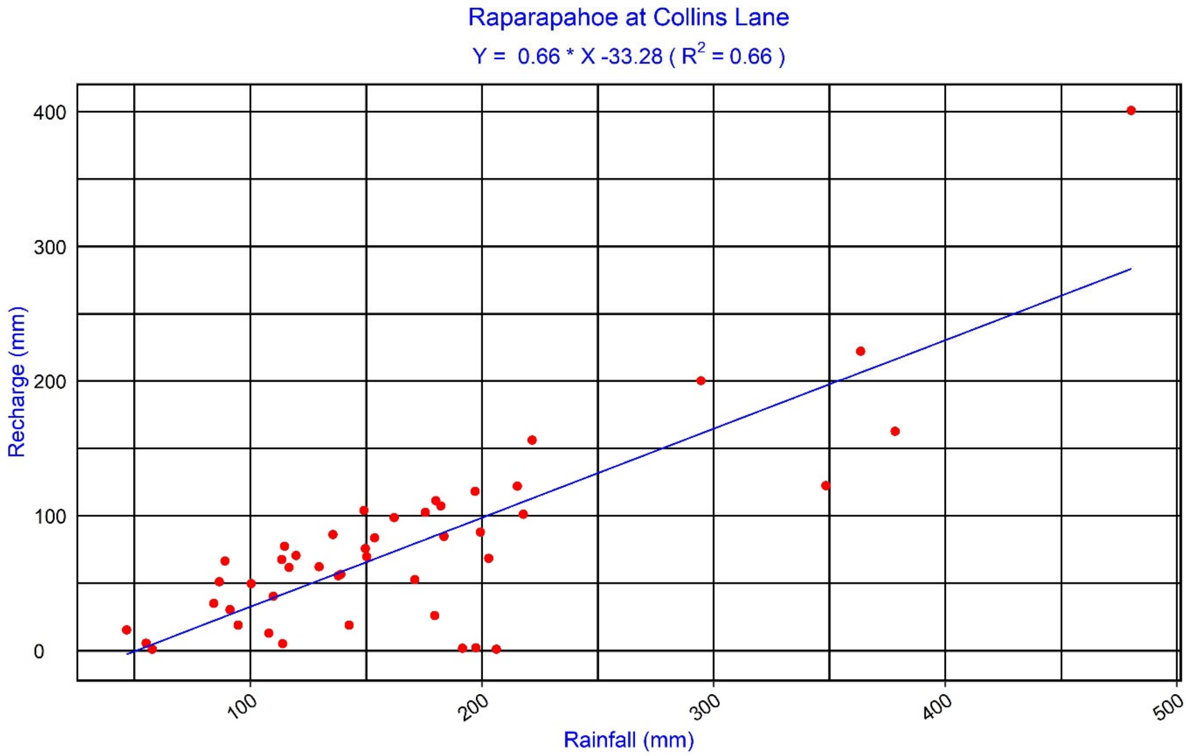

Figure 2-6 Linear regression between total monthly rainfall and total monthly recharge for the Collins Lane Lysimeter.

2.10 Weekly rainfall and recharge

The weekly totals for rainfall and recharge at the Collins Lane Lysimeter was obtained. Using the weekly data, a linear regression was developed between the recharge and the rainfall. It provides a reasonable relationship between rainfall and recharge for the Collins Lane Lysimeter.

The equation developed was used to estimate recharge for each week between 2015 and 2021. The recharge estimated using this technique was compared to the measured recharge at the Collins Lane site. The comparison is discussed in Section 3.3.

$$WeeklyRecharge = Rainfall * 0.70 - 7.29 \quad \text{Equation 13}$$

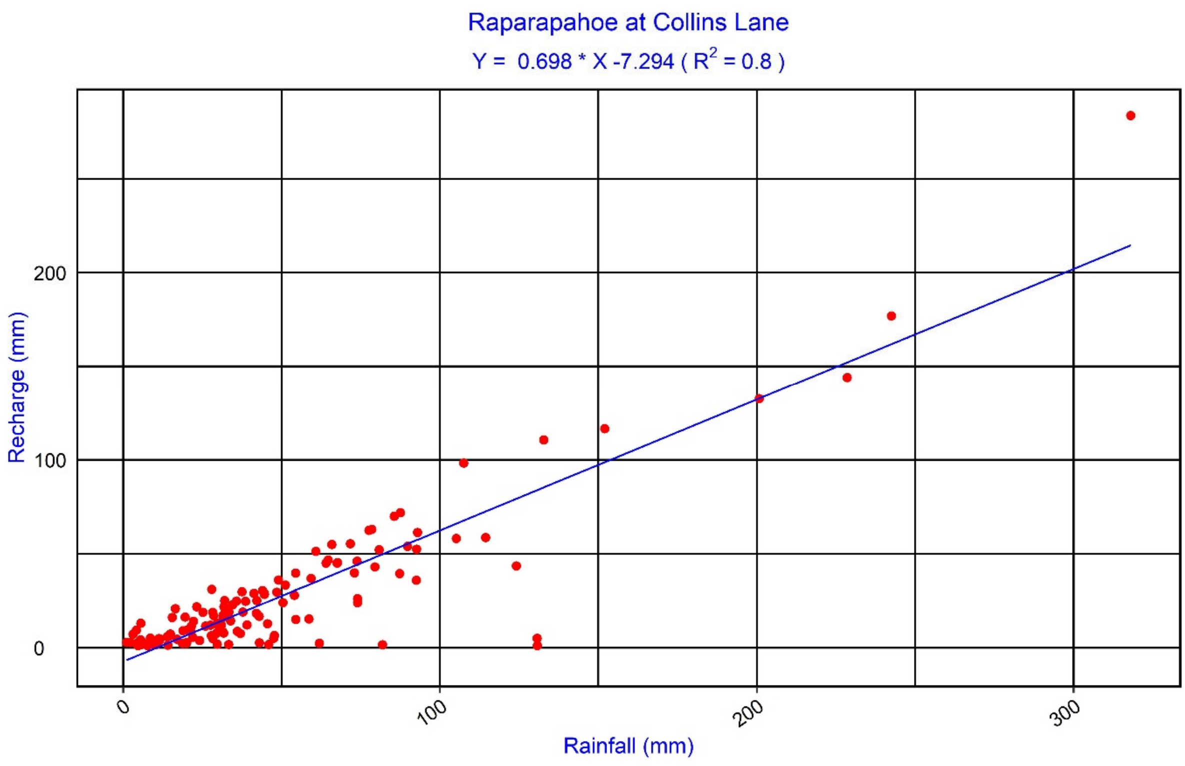

Figure 2-7 Linear regression between weekly total rainfall and weekly recharge for the Collins Lane Lysimeter.

Part 3:
Results and discussion

In areas where limited data is available to determine recharge, setting groundwater take limits must rely on the limited data that is available (Ministry for the Environment, 2020). Few field studies have been conducted on the hydrogeological nature and infiltration capacity of the soils on the East Coast. The data that is available is from national scale projects such as the digital soil map for New Zealand (SMAP) (Manaaki Whenua Landcare Research, n.d.), the 1:250,000 Geological Map of New Zealand (QMAP) (GNS Science, n.d.) and the Virtual Climate Station Network (VCNS) (National Institute of Water and Atmospheric Research, n.d.). This data has been used to estimate recharge for the East Coast Sedimentary Hydrogeological Units. It is important to note when using data developed on a small-scale, extrapolation to local areas implies homogeneity that may not apply at the local (large) scale.

Eight techniques were used to estimate recharge. These were made up of three methods: mass balance, empirical and indirect physical methods. Each technique was applied to the data at the Collins Lane. The results of the eight techniques applied to the Collins Lane Lysimeter are described below.

3.1 Mass balance

The NRCS–CN technique is designed to be used on a watershed scale and to determine the runoff based on a rain event. The runoff curve number equation does not account for time. Therefore, it does not account for rainfall duration or intensity. Prior rainfall, results in deviations from the curve numbers and inaccuracies in the estimation of runoff. As the rainfall duration and intensity is not considered, it is important that the right rainfall event be selected when applying the equations. Analysis of the available data shows the five-day total rainfall is a better predictor of recharge than the daily or three-day total.

The NRC-CN technique over-estimates the recharge for all years. Recharge is over-estimated by approximately 500 mm for all years considered, except for 2017. It is the only year that this technique provides a reasonable estimate of recharge. The over-estimation and overall reliance on curve numbers that are not developed for local conditions indicates the technique is unsuitable for the estimation of recharge for the East Coast Sedimentary Hydrogeological Units.

The infiltration method is a simple rule-based technique to enable a quick calculation of the amount of infiltration. The advantage of this technique is it only requires two parameters to be considered: the maximum infiltration rate and the rainfall. However, it does not account for antecedent soil moisture conditions or the rainfall intensity.

The infiltration technique over-estimates recharge by 750 mm to 1,000 mm for all years considered except 2017, where the over estimation is approximately 500 mm. The consistent over estimation indicates the technique is unsuitable for the estimation of recharge for the East Coast Sedimentary Hydrogeological Units.

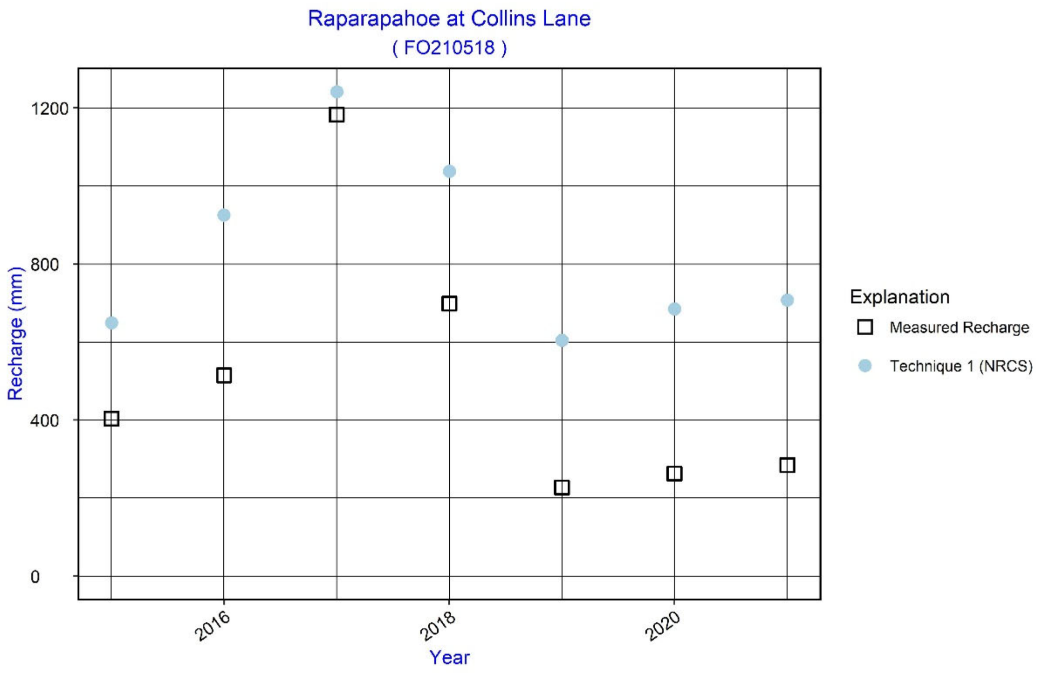

Figure 3-1 Annual total measured and modelled recharge values for the Collins Lane Lysimeter using the NRCS-CN technique.

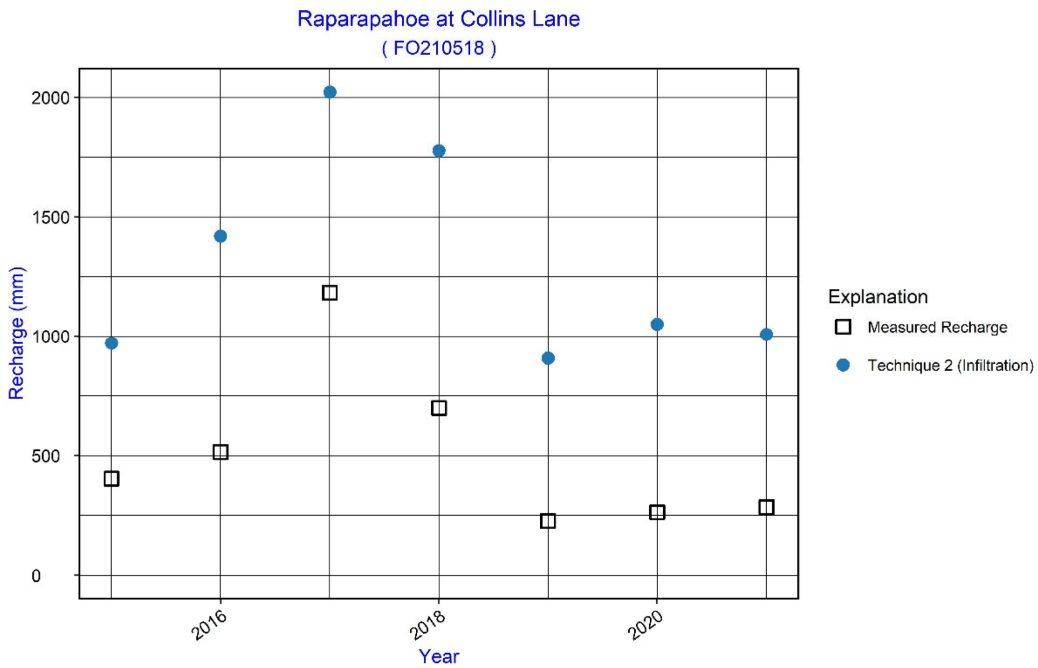

Figure 3-2 Annual total measured and modelled recharge values for the Collins Lane Lysimeter using the infiltration technique.

The mass balance methods are the worst performing of the techniques that were developed in this work. The mass balance techniques are simple and easy to use tools that rely on data that is readily available or easily determined. However, the method is not well suited to reasonably estimating recharge at the Collins Lane Lysimeter site. It should not be used to estimate recharge for the East Coast Sedimentary Hydrogeological Units.

3.2 Empirical methods

The advantage of using the White recharge formula to estimate recharge is that it only requires rainfall to estimate recharge. The application of the White approach to estimate recharge has better performance than the application of surface water runoff models. Except for 2017, the White Recharge formula provides a reasonable estimate of the recharge for each year.

The results indicate this is a reasonable method to estimate the recharge in an area with similar hydrogeological conditions. It performs better than the mass balance techniques and the Chaturvedi formula. However, it does not perform as well as the seasonal or weekly-derived regressions when estimating recharge. The White recharge formula provides a reasonable estimate of the recharge for the Collins Lane Lysimeter site. It can be used to estimate recharge for the East Coast Hydrogeological Sedimentary Units if there are no alternatives available.

Like the White approach, the advantage of Chaturvedi formula is it only requires rainfall to estimate recharge. It was developed in India where climatic conditions are impacted by the monsoonal pattern of rainfall. Monsoonal rainfall patterns and extreme patterns of wet and dry seasons do not exist in New Zealand.

As expected, the Chaturvedi formula does not perform as well as the White recharge formula. However, it has a better performance than the application of the mass balance models. The Chaturvedi formula under-estimates recharge for all years except for 2019, 2020 and 2021, where it provides a reasonable estimate of the recharge. The Chaturvedi formula is unsuitable for the estimation of recharge for the East Coast Sedimentary Hydrogeological Units.

Based on the limited data available the empirical methods are better at estimating recharge than the mass balance techniques. They are the easiest to use of the techniques developed as the only input required is rainfall and this is easily available. Of the two techniques, the White recharge formula provides a better estimate of recharge.

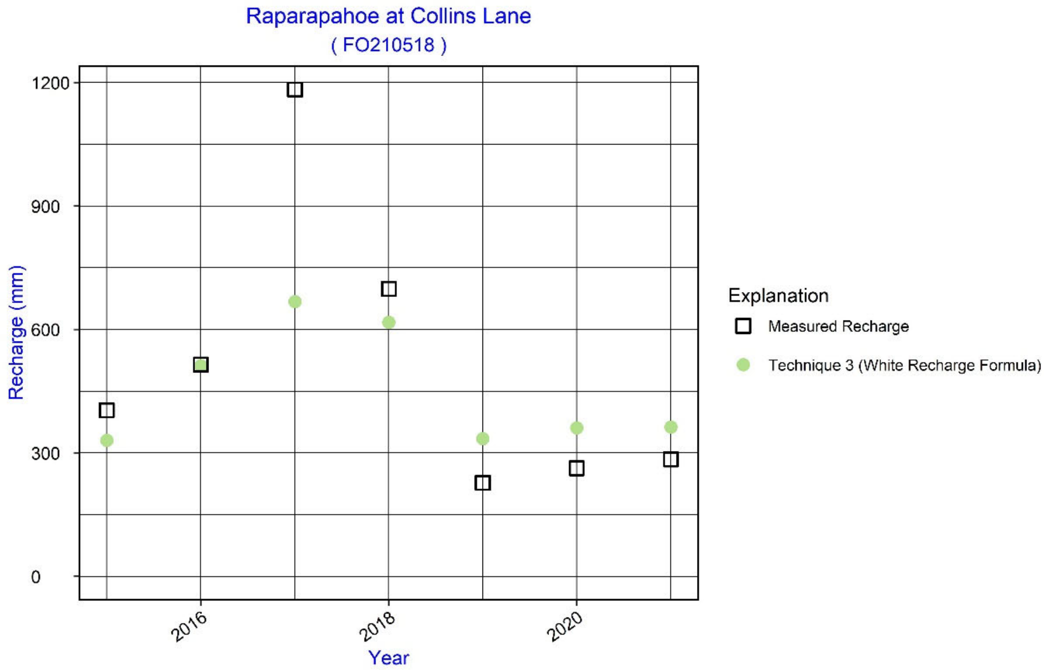

Figure 3-3 *Annual total measured and modelled recharge values for the Collins Lane Lysimeter using using the White formula.*

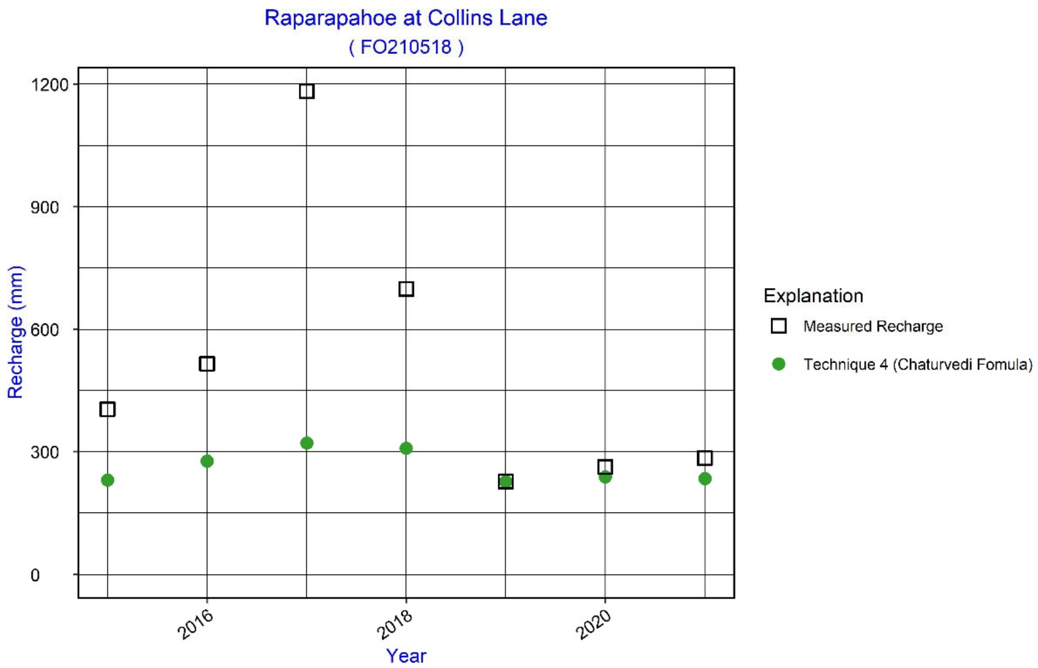

Figure 3-4 *Annual total measured and modelled recharge values for the Collins Lane Lysimeter using using the Chaturvedi formula.*

3.3 Linear regressions developed based on the BOPRC network

Application of measured site-specific recharge data is the most accurate method available to determine recharge. This approach has minimal assumptions. It requires the installation of lysimeters to measure and record the recharge data that can be applied to an area. Measured recharge data from lysimeters is only available at nine locations in the Bay of Plenty. The sites have varying geology and climate. The lysimeters installed by the Bay of Plenty Regional Council are 500 mm in diameter and record recharge as it passes through a 700 mm soil column.

The direct application of the measured lysimeter data is limited to areas with the same hydrogeologic and climatic conditions to the measured sites. This is achieved by using regressions developed on measured data. Recharge data is limited to nine types of hydrogeology and climate classes. The types of hydrogeology and climate classes at the nine current lysimeter sites, limits extrapolation of the data using regressions, to other areas.

Applying a regression developed based on the cumulative annual rainfall and recharge at the Collins Lane Lysimeter results in a better prediction of recharge than the application of the mass balance methods; or the empirical formulae developed by either White or Chaturvedi. However, the cumulative annual regression does not perform as well as the seasonal, monthly, or weekly techniques. The annual technique requires a longer-term data set that is not generally available in the region. A minimum of ten years data is needed to obtain reliable estimates from such a technique on a semi-regional basis.

Applying the regression based on the cumulative seasonal rainfall and recharge of the Collins Lane Lysimeter results is a better prediction of recharge than the application of the annual recharge equation. Similar to the annual regression technique, the seasonal recharge techniques are affected by the lack of long-term data. Once sufficient data is available, it is likely that performance of the seasonal technique will improve.

Applying the regression based on the cumulative monthly rainfall and recharge of the Collins Lane Lysimeter results in a better prediction of recharge than the application of the annual recharge equation, or the seasonal recharge equation. This is the best technique derived to estimate recharge.

Applying the regression based on the cumulative weekly rainfall and recharge of the Collins Lane Lysimeter results in a better prediction of recharge than all the other techniques, except the monthly regression technique.

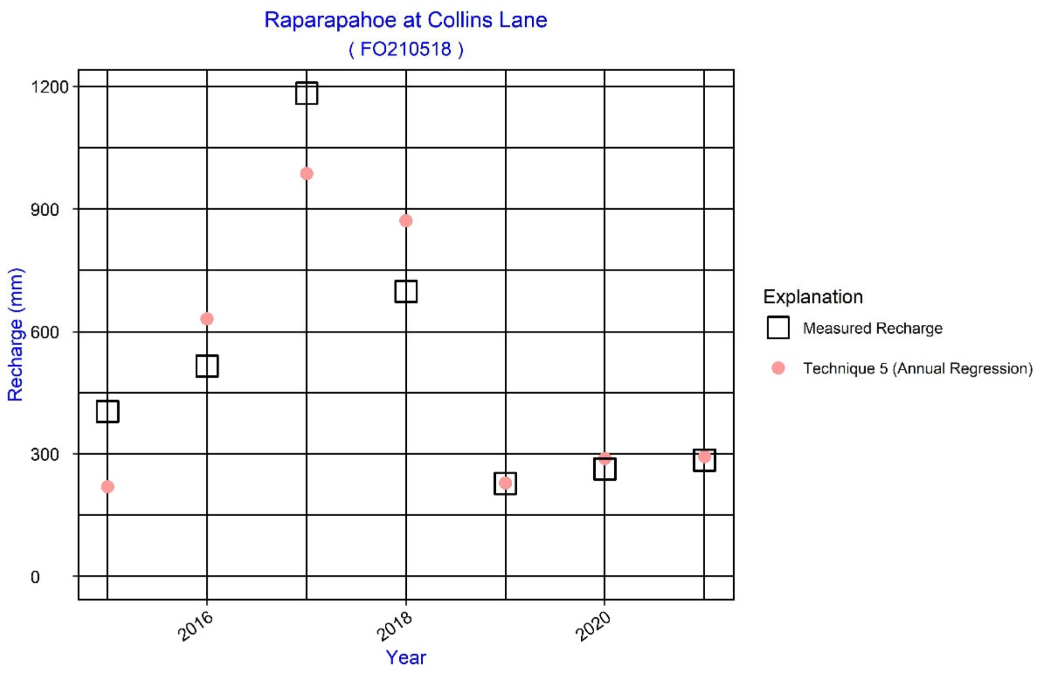

Figure 3-5 Annual total measured recharge and modelled recharge values for the Collins Lane Lysimeter using the derived annual regression.

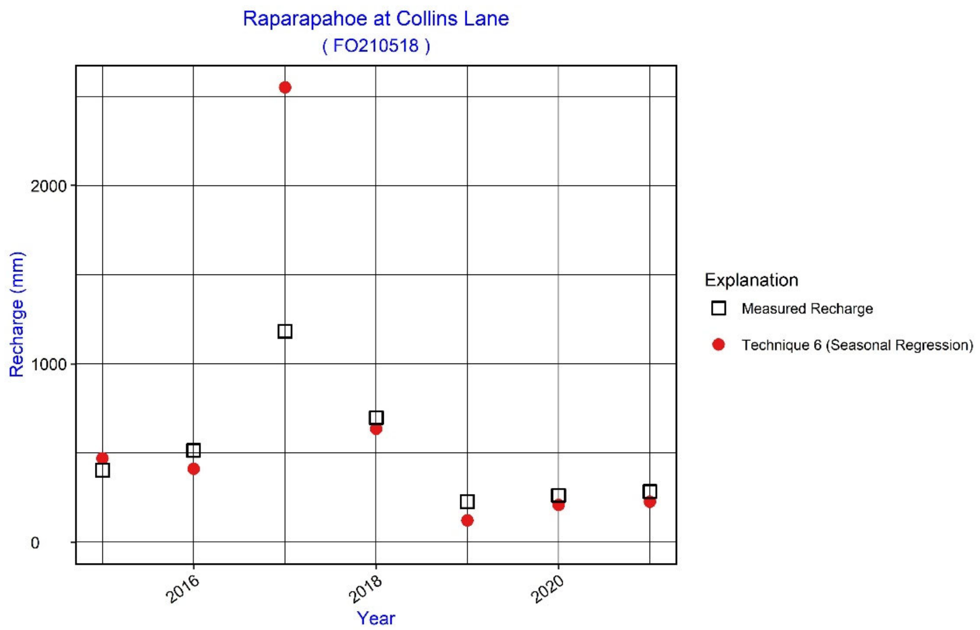

Figure 3-6 Annual total measured recharge and modelled recharge values for the Collins Lane Lysimeter using the derived seasonal regressions.

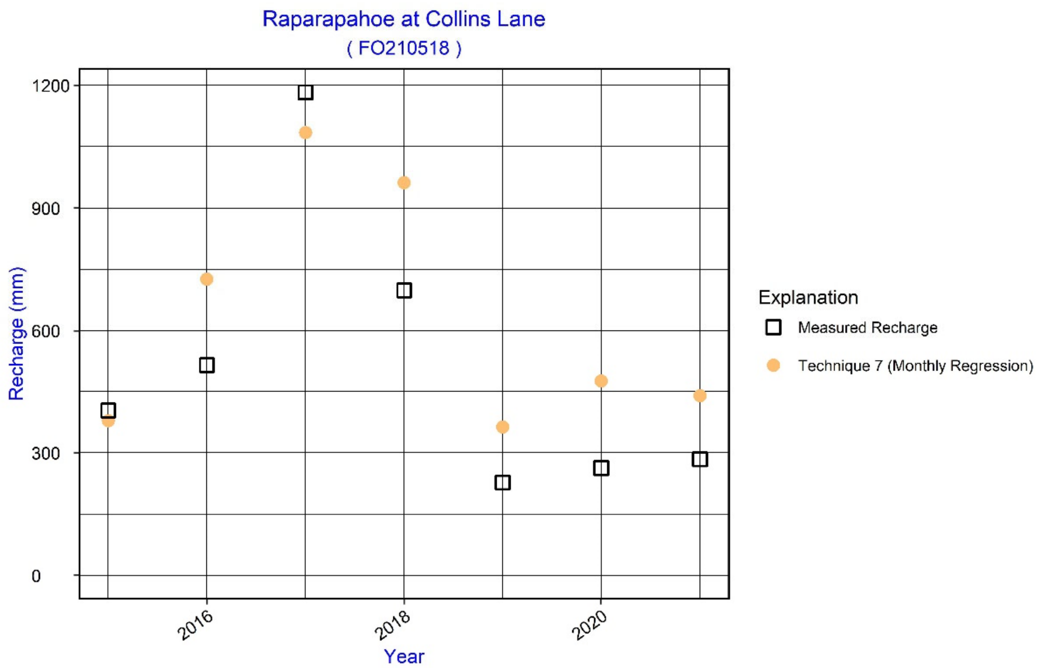

Figure 3-7 Annual total measured recharge and modelled recharge values for the Collins Lane Lysimeter using the derived monthly regression.

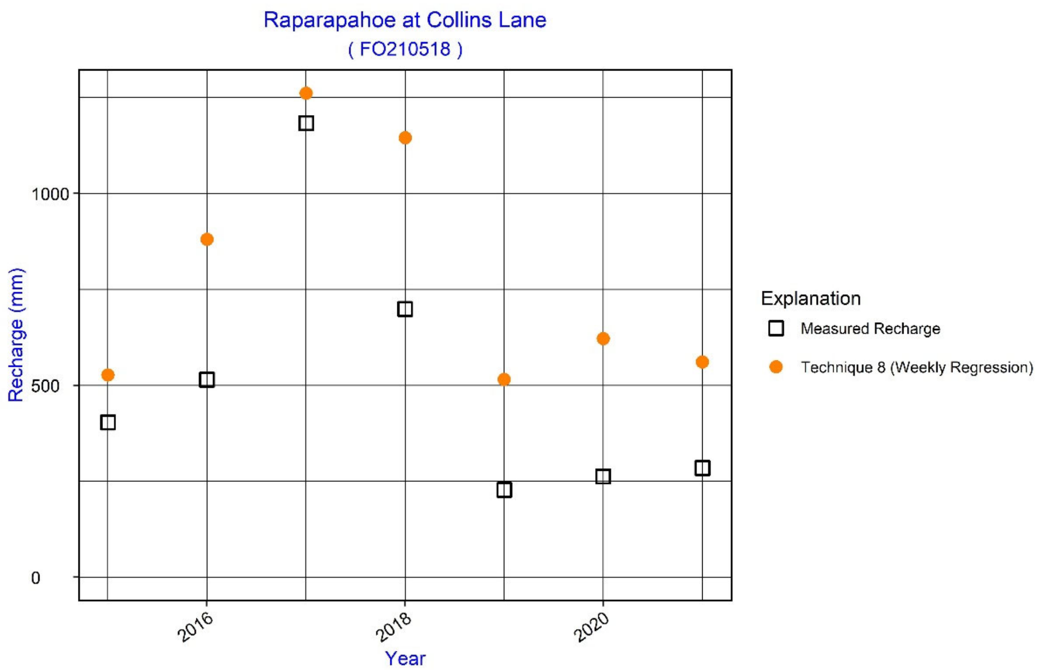

Figure 3-8 Annual total measured recharge and modelled recharge values for the Collins Lane Lysimeter using the derived weekly regression.

Eight techniques and sets of equations were developed based on the Collins Lane Lysimeter rainfall and recharge data. Overall, the application of the site derived equations results in a better performance than the mass balance or the empirical methods. The eight equations were assessed for how well the modelled data fits measured data. Assessment was based on the Akaike information criterion (AIC), Bayesian information criterion (BIC), r^2, adjusted r^2 value, root mean squared error (RMSE) and the residual standard deviation

(SIGMA). Table 3.1 shows the scores for different indices where the larger values indicate better model performance. Based on the scoring and a visual analysis, the linear regression developed by the monthly average (technique 7) is the best performing technique. This equation was used to calculate the recharge for the East Coast sedimentary basins.

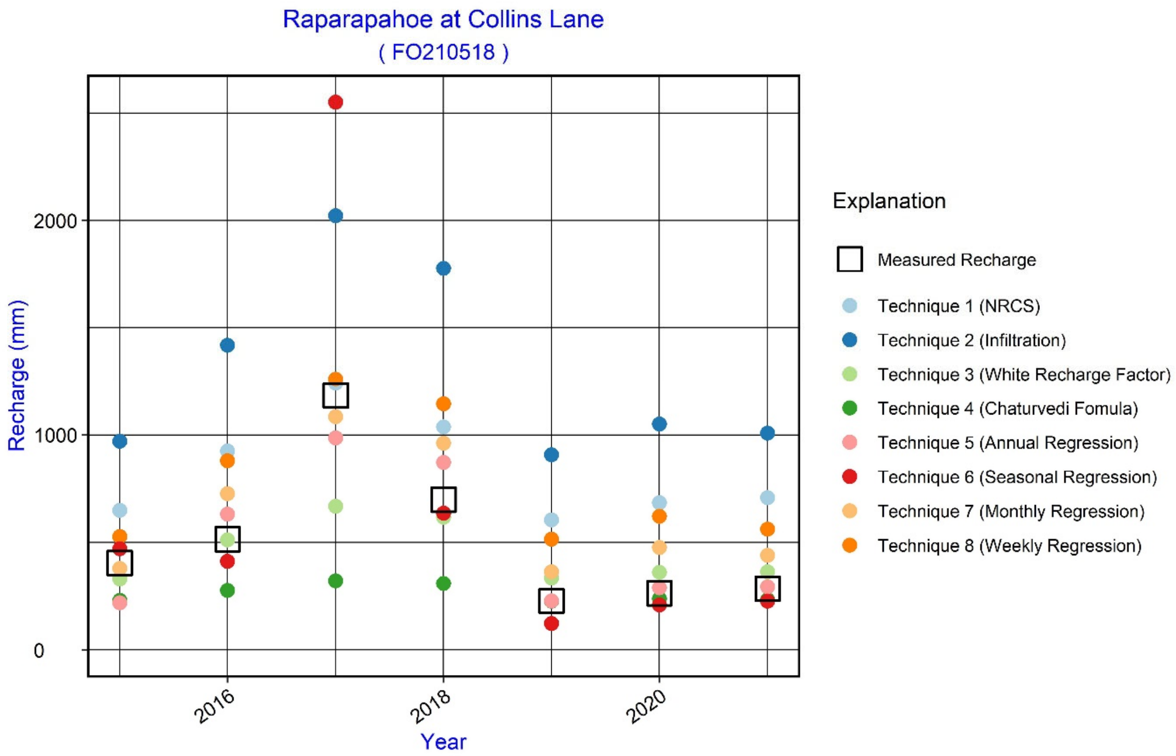

Figure 3-9 Annual total measured and modelled recharge values for the Collins Lane Lysimeter using all techniques.

Table 3.1 Performance scores for all techniques.

Technique Number	Method	Technique	AIC	BIC	r^2	r^2 adjusted	RMSE	Sigma	Performance Score
1	Mass Balance	NRCS-CN	106.46	106.30	0.21	0.06	316.35	374.31	0.17
2	Mass Balance	Max Infiltration	105.74	105.57	0.29	0.15	300.41	355.45	0.33
3	Empirical	White	105.15	104.99	0.35	0.22	288.06	340.83	0.48
4	Empirical	Chaturvedi	105.25	105.09	0.34	0.21	290.19	343.36	0.45
5	Physical (Linear Regression)	Annual	105.15	104.99	0.35	0.22	288.06	340.83	0.48
6	Physical (Linear Regression)	Seasonal	354.94	358.93	0.39	0.36	122.98	127.63	0.40
7	Physical (Linear Regression)	Monthly	862.23	869.49	0.58	0.57	42.06	42.58	0.64
8	Physical (Linear Regression)	Weekly	3213.76	3225.42	0.32	0.32	20.83	20.89	0.47

Part 4:
Recharge and take limits for the East Coast Hydrogeological Units

The Collins Lane site in the Kaituna WMA is predominantly composed of the Pleistocene age, Tauranga Group sediments. Lithologically they are a series of silts, sands and gravels. The East Coast basins are small coastal systems composed of late Pleistocene age shoreline deposits and Holocene age, river deposit sediments comprised of sands and gravels. The Kaituna Plains and East Coast Sedimentary Hydrogeological Units are hydrogeologically similar.

It is likely the amount of recharge in the East Coast Hydrogeological Units, is unable to sustain prolonged periods of abstraction for commercial use. The risk to these small sedimentary systems due to pumping-induced saltwater intrusion is expected to be higher than elsewhere in the region. The East Coast Sedimentary Hydrogeological Units are underlain by the greywacke rocks, which form the Basement Hydrological Unit. There are fractures and faults in the greywacke that may contain and transmit sufficient quantities of groundwater to be suitable water sources. Based on the geology and geomorphology found in this part of the region, it is likely that springs may be useful and reliable sources of water. Recharge and take limits for the greywacke rocks will be considered separately to the East Coast Sedimentary Hydrogeological Units.

The analysis of the lysimeter data the Collins Lane site indicates that the relationship developed using the monthly recharge and rainfall is the best predictor of recharge. Using data available from the VCNS network, rainfall was used to estimate recharge for each of the sedimentary hydrogeological units in the East Coast.

The East Coast Sedimentary Hydrogeological Units, have been divided into 21 separate hydrogeological management units based on the hydrogeology and topography. They range in area from 0.2 km^2 to 44.6 km^2. To determine recharge the centroid of each separate hydrogeological unit was determined. The mean rainfall and evapotranspiration value was determined for all VCNS sites within 10 km of the basin centroid for each day starting in January 1977 to December 2021. The resulting daily mean value was converted to a monthly mean. It was used in equation 12 to estimate the recharge for each basin, for each month, in millimetres per year.

The mean annual recharge (mm/yr) was then determined by calculating the average of the total annual recharge for each year between 1977 and 2021. This value was multiplied by the hydrogeological unit area, to estimate the mean annual recharge in cubic metres per year. Based on the pNES Ecological Flows, 15% of the mean annual recharge was used to determine an interim groundwater take limit. This preliminary assessment based on the pNES Ecological Flows, may be different to that adopted in a proposed plan change. The potential take limits recommended in a proposed plan change will include consideration of local values and Te mana o te wai, in accordance with the NPSFM 2020. However, it is expected the take limits in the proposed plan change will be based on some proportion of the assessment of annual average recharge in this report. That will be a qualitative risk assessment of the potential environmental effects from hydrological alteration (change in groundwater levels) of different take limit options. A quantitate assessment is not possible with this method of determining recharge.

The recharge and interim groundwater take limit for each separate management unit is presented in Table 4.1

Table 4.1 Estimates of recharge and interim groundwater take limit (based on 15% of the mean annual recharge) for the East Coast Sedimentary Hydrogeological Units.

Hydrogeological Unit	Area (Km^2)	Recharge (mm/yr)	Mean Annual Recharge (m^3)	Interim Take Limit (m^3/yr) (15% of Mean annual Recharge)
Awanui	1.11	496.04	549,816	82,472
Hāwai	3.07	814.37	2,499,776	374,966
Houpoto	8.21	764.94	6,276,746	941,512
Kereru	1.88	489.32	921,712	138,257
Maraehako Bay	1.75	505.81	886,224	132,934
Motu Papaka	0.62	505.81	311,776	46,766
Ōmaio	3.89	628.34	2,444,109	366,616
Orima	0.52	505.81	260,784	39,118
Pariokara	1.00	549.15	551,006	82,651
Raukokore	44.65	626.57	27,973,785	4,196,069
Te Huka	0.42	479.51	199149.58	29,872
Te Kaha East	4.09	482.71	1,974,102	296,115
Te Kaha West	2.01	492.97	992,246	148,837
Tōrere	8.95	842.93	7,547,224	1,132,084
Upper Kereru	6.03	610.64	3,681,677	552,252
Waikawa	0.23	478.81	111,372	16,706
Waiohoata	3.16	796.43	2,517,183	377,577
Waiopuoroaro	0.37	479.51	179,088	26,863
Waiorore	1.34	492.97	659,632	98,945
Whitianga	0.75	668.42	498,179	74,727
Whituare	0.51	776.15	395,776	59,366

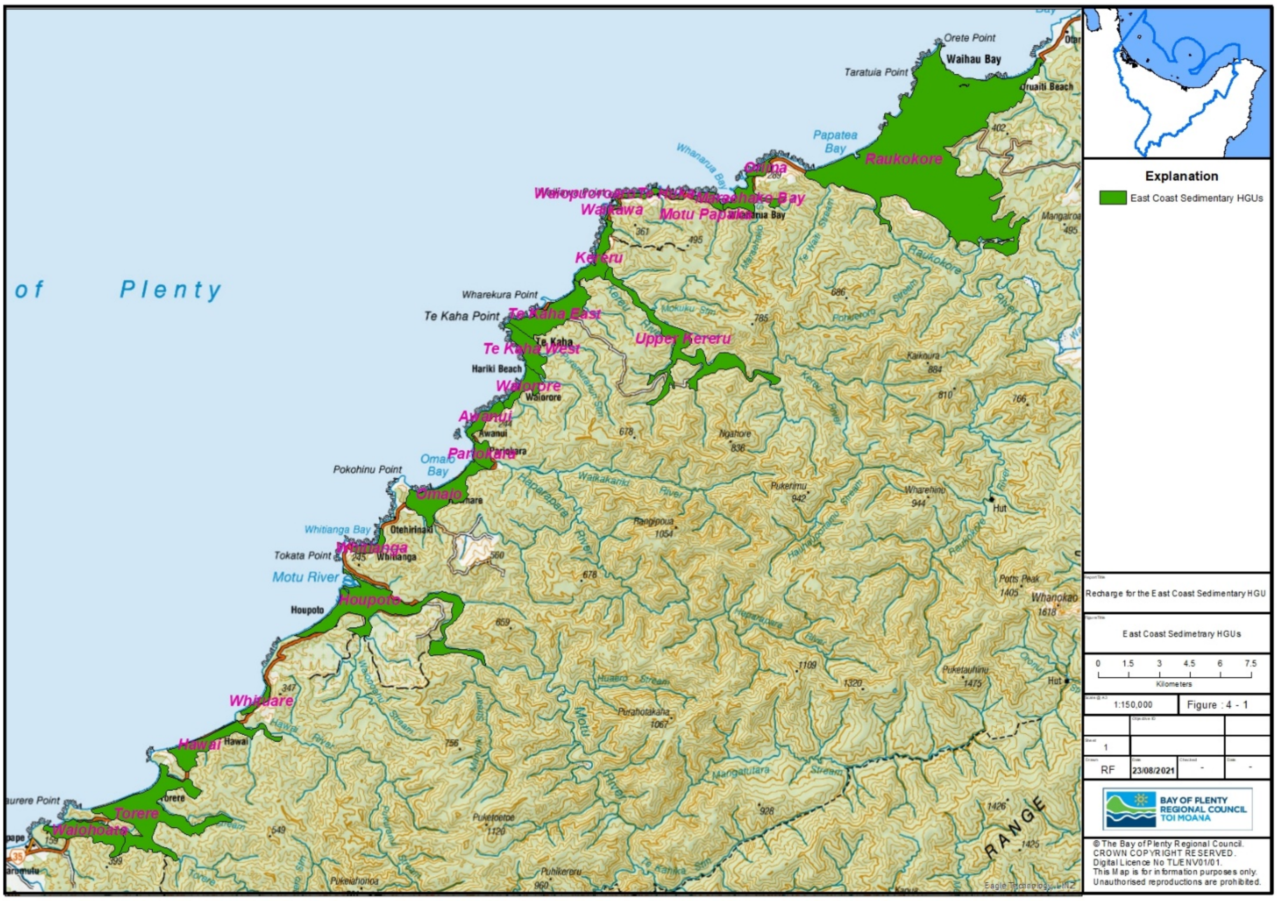

Figure 4-1 *East Coast Sedimetary Hydrogeological Units.*

Part 5: Conclusions and recommendations

Interim groundwater take limits have been determined for 21 East Coast sedimentary hydrogeological management units. Eight techniques, based on three methods were used to estimate recharge based on rainfall, evapotranspiration, and surface runoff. The best performing technique was used to determine the average annual recharge for the East Coast Sedimentary Hydrogeological Units. The author recommends that for the East Coast Hydrogeological Sedimentary Units, average annual recharge be defined as described in Section 2.9 and interim groundwater take limits be set at 15% of that figure for the Coast Sedimentary Hydrogeological Units. The interim limits will provide protection from any adverse effects of water abstraction. They are expected to be conservative. There are several ground – atmospheric, groundwater – surface and vadose zone interactions, which influence the relationship between rainfall and recharge. Understanding these relationships is vital to accurately determining average annual recharge. This requires monitoring infrastructure and a vast amount of data to be collected to consider these interactions. This is beyond the scope of this work and timeframe of this work.

The Bay of Plenty Regional Council maintains a representative network of lysimeters. The nine lysimeters are insufficient to be used in soil moisture models to accurately determine groundwater recharge on a regional scale. This network needs to be maintained for a long period of time. It will enable the regional council to understand how the changing weather patterns and storm events causes changes in groundwater recharge patterns.

The Bay of Plenty Regional Council lysimeter network also needs to be expanded. At least one additional lysimeter in an area that is representative of the East Coast hydrogeology and climate, two lysimeters in the Ōpōtiki area and an additional lysimeter in the Whakatāne area, are required. A minimum total network of thirteen lysimeters is vital to understand the recharge under different soil and geology and climatic conditions. The Bay of Plenty Regional Council also needs to initiate a field programme to conduct field infiltration tests that can be used to supplement the understanding of the relationship between rainfall and infiltration.

The pNES Ecological Flows[7] recommends that shallow coastal aquifers have an interim take limit set at 15% of the average annual recharge as determined by the council. The determination of an annual take limit is an important step in ensuring sustainable groundwater management. However, it is not the only factor that needs to be considered. At the stage of making decisions on individual resource consent applications to take groundwater, additional site-specific criteria need to be reviewed on a case-by-case basis. To adequately protect the aquifers from potential saline intrusion, a minimum freshwater head must be maintained at the coast. It is recommended that the management of groundwater also considers the cumulative allocation within each hydrogeological management unit. Maintaining a freshwater head of at least one metre above sea level at the coast will offer additional protection to these vulnerable systems.

As climatic changes and storm patterns start to affect rainfall in the Bay of Plenty, it will undoubtedly affect the recharge values within the region. Groundwater recharge is most effective when there is steady rainfall that does not exceed the infiltration capacity of the soil. Storm events that are more intense can cause increased runoff and a decrease in recharge. The NIWA forecast for the Bay of Plenty is increased intensity rainfall events. This indicates that the winter and autumn recharge to groundwater systems may decrease in the future. To better understand the impact of these changes on the hydrogeological systems of the Bay of Plenty, in addition to maintaining and expanding the lysimeter network BOPRC needs to understand how these changes are likely to impact recharge and take limits in the future.

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[7] Note: Never adopted by central government and the standard did not come into force. However, the interim limits based on expert opinion are considered relevant.

Part 6:
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