Groundwater and surface water resource investigations of the Opotiki-Ohope area stage 1 - preliminary groundwater allocation assessment

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BIBLIOGRAPHIC REFERENCE

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CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

Water is used for agricultural, commercial and domestic purposes in the Bay of Plenty's Opotiki-Ohope area (Figure 1). Water resources in the area include groundwater and surface water. The groundwater system provides an estimated 88% of all water supplied to users. To avoid inadvertent over-allocation of the water resource, Bay of Plenty Regional Council (BOPRC) commissioned the Institute of Geological and Nuclear Sciences Ltd and the National Institute of Water and Atmospheric Research to complete a preliminary assessment of groundwater and surface water availability in the area.

Four groundwater catchments were suggested in the Opotiki-Ohope area: Ohope-Ohiwa (i.e., the catchment of Ohiwa Harbour and Ohope); Waiotahi (including the surface catchment of Waiotahi River); Opotiki (including the part of the Waioeka River catchment managed by BOPRC and the Opotiki Plain); and Tirohanga (including the catchments of the Tirohanga and Waiaua rivers).

The distribution of four groupings of major geologic units mapped at the ground surface was described in a geologic model of the Opotiki-Ohope area. These groups of units included: basement (largely comprising greywacke exposed at the ground surface over most of the area); Pleistocene (with early-mid Pleistocene age mudstone of marine origin and Late Pleistocene gravel under Opotiki Plain); Holocene alluvium (which includes shallow deposits of gravel, peat, sand and pumice); and Holocene beach sediments (mapped near the coast that are an estimated 20 m thick).

Water budgets were developed in this assessment with components of: rainfall, evapotranspiration, surface water flows (quick flow and base flow) and groundwater outflow across the coastal boundary. Groundwater and surface water available for allocation were calculated from these budgets following current BOPRC practice on minimum flows, preliminary to BOPRC policy decisions on water allocation in the area.

Groundwater and surface water available for allocation were greater than current allocation. For example, groundwater available for allocation was an estimated 1622 L/s compared to current groundwater allocation estimated to be 687 L/s for the Opotiki groundwater catchment in the Holocene alluvium unit. However, groundwater available for allocation from Holocene beach sediments was very low because the area of these sediments is small and the proximity of these sediments to the sea means that they are a potential risk to salt water intrusion.

The close connection between groundwater and surface water was demonstrated by water budgets indicating that most groundwater recharge becomes surface water base flow. Therefore, this report recommends that BOPRC consider establishing the following policies: (1) definition of minimum flows for groundwater and surface water that meet environmental targets; (2) co-management of groundwater and surface water; (3) definition of water allocation as a fraction of water available for allocation; and (4) reduction in the potential for salt water intrusion to groundwater in coastal aquifers. Recommendations in this report also aimed to improve estimates of surface water minimum flows and water budget components by collecting more environmental information. This would reduce the uncertainty in the estimates of allocation limits for groundwater and surface water resources.

1.0 INTRODUCTION

Water in the Bay of Plenty's Opotiki-Ohope area (Figure 1) is extracted for agricultural, commercial and municipal purposes from groundwater and surface water. Currently, groundwater is the largest source for water users. In the future, groundwater use is predicted to increase (White, 2005). However, development of water resources has occurred without estimates of water availability in the area. To avoid inadvertent over-allocation, Bay of Plenty Regional Council (BOPRC) commissioned the Institute of Geological and Nuclear Sciences Ltd (GNS Science) and the National Institute of Water and Atmospheric Research (NIWA) to complete a preliminary assessment of water availability in the Opotiki-Ohope area.

The Opotiki-Ohope area includes the surface catchments of Ohiwa Harbour and the Waiotahi, Waioeka (part), Otara and Waiaua rivers (Figure 1). The catchment of the Waioeka River included in the area is that in the Bay of Plenty Region; Gisborne District Council manages the Waioeka River catchment to the south of the Opotiki-Ohope area. The area shares a common boundary with BOPRC's Rangitaiki Plains groundwater management zone (White et al., 2010).

This report is intended as the first step in a BOPRC programme of investigations designed to assess the sustainability of water allocation at the catchment scale in this important part of the Bay of Plenty Region. Groundwater resources are the focus of assessments in this report and surface water is also considered because groundwater and surface water are closely linked in the Opotiki-Ohope area. Therefore, this report begins with a review of existing information relevant to water resources in the area including geology, hydrogeology and hydrology. The review also includes current policies and practices, including minimum flow limits of groundwater and surface water, relevant to water use and allocation in the area.

This report provides an assessment of 'groundwater available for allocation' (GAA), which is an estimate of the maximum groundwater available for allocation, for catchments and geological units. Surface water available for allocation (SAA) is also estimated as part of this assessment. These calculations are done with the development of a geological model and water budgets. The geological model defines the major geological units in the Opotiki-Ohope area and is used to identify groundwater catchments. Water budgets are derived for these catchments using environmental information such as rainfall, evapotranspiration and surface water flows, including the major flow components of quick flow and base flow.

The sustainability of current water allocation, and estimated water use, is compared with GAA and SAA in geological units and groundwater catchments. This comparison identifies the areas where water use is greatest, where use is closest to allocation limits and where water is available for allocation. However, groundwater and surface water allocation limits are not calculated by this report because BOPRC policy decisions are required before limits can be established. Therefore the report includes recommendations for BOPRC on water allocation policies (including co-management of groundwater and surface water and water allocation as a fraction of water available for allocation) and future data collection to reduce uncertainty in the allocation limits.

2.0 REVIEW

Information on geologic formations and hydrology in the Opotiki-Ohope area (Figure 2) is reviewed here.

2.1 Geologic units

Basement rocks occur at the surface over much of the Opotiki-Ohope area and particularly the portion of the area inland from the coast (Figure 2). Quaternary sedimentary units are common near the coast and most groundwater that is used in the area comes from wells drilled in these units (Figure 2). The geology of these formations is reviewed in the following subsections of the report. These subsections draw heavily from relevant descriptions of geology in a report on groundwater resources assessment in the Rangitaiki Plains (White et al., 2010) and geologic maps (QMAPs) of the Opotiki-Ohope area (Leonard et al., 2010; and Mazengarb and Speden, 2000).

2.1.1 Basement

Jurassic-Cretaceous basement, for the purposes of the geologic model and groundwater allocation calculations is taken as: Torlesse (composite) terrane which includes Pahau terrane (Ktw) and Whakatane Mélange (Kew); Matawai Group (Kmr, Kma and Kmu) and Tinui Group (Kiw and Kit), Figure 2, Leonard et al. (2010). These rocks crop out in the west and south of the area and range in age from Jurassic to Early Cretaceous (175– 110 million years old, Ma). These comprise principally indurated, poorly sorted, mostly lithic sandstone and siltstone with variably developed but ubiquitous bedding plane shear. Terranes may be separated by mélange or broken formation units or faults.

Pahau terrane includes all Cretaceous Torlesse rocks east of Whakatane Mélange (Adams et al., 2009). Within the generally quartzofeldspathic Pahau terrane, a volcaniclastic suite (Waioeka petrofacies) and a quartzofeldspathic suite (Omaio petrofacies) can locally be distinguished (Mortimer 1995). All Pahau terrane rocks in the map area belong to Mortimer’s (1995) Waioeka petrofacies. The unit is dominated by well indurated alternating blue-grey to green-grey fine sandstone and dark grey siltstone. Veining, jointing and fracturing are observed. However, pervasive bedding plane shearing, boudinage and broken formation features are rare in comparison with the adjacent Whakatane Mélange. Macrofossils are very rare, but good age control is provided by dinoflagellates, commonly present in concretions, indicating an Early Cretaceous age (Wilson et al., 1988; Moore et al., 1989; Wilson, 1989; Wilson, 2005). Detrital zircon ages are as young as 116 Ma indicating that deposition continued until late in the Early Cretaceous (Adams et al., 2009). Metamorphism is zeolite to pumpellyite-prehnite facies (Feary, 1974; Hill, 1974; Hoolihan, 1977; Isaac, 1977).

Whakatane Mélange (Mortimer, 1995) occupies a wedge-shaped north-south belt on the western side of the Opotiki-Ohope area between Kohi Point and Waimana River. Blocks are commonly lozenge-shaped, reaching tens of metres across (e.g., marble blocks near Ruatoki; McKay, 1895). Deformation varies from rocks no more deformed than surrounding terranes, through broken formation, to mélange. Quartzofeldspathic and volcaniclastic sandstones are scattered through the mélange (Mortimer, 1995) and blocks include massive sandstone, alternating sandstone and argillite, argillite, and chaotic diamictites with sandstone, argillite or exotic clasts. Blocks from the mélange include Early Jurassic bivalve indicator fossils, Late Jurassic belemnites (Stevens, 1963) and dinoflagellates from one sample yield an age as young as Late Neocomian to early Aptian (127-118 Ma).

Matawai Group sediments crop out south of Opotiki. These are moderately indurated, fossiliferous marine deposits, of late Early Cretaceous age (Moore, 1986; Moore et al., 1989; Mazengarb and Speden, 2000) including some of the best preserved Early and Late Cretaceous sequences in New Zealand (Wellman, 1959,; Speden, 1975a; Crampton 1995). These rocks are coherent and little-deformed and rest unconformably upon Pahau terrane. The unconformity between Pahau terrane and Matawai Group is considered to be of regional extent, although locally deposition may have continued through this period (Mazengarb and Speden, 2000). Speden (1975b) mapped up to 230 m of fine- to medium-grained green, carbonaceous sandstone, with minor conglomerate, grit, breccia and siltstone between the Waimana and Waiotahi valleys, mapped as Waimana Sandstone (Mazengarb, 1993). Fossils recorded by Speden (1975b) range in age from Aptian to Albian (121-98.9 Ma).

Tinui Group sediments crop out in the south of the Opotiki-Ohope area. These sediments are of Late Cretaceous age and consist of Taharoa Formation (quartzose sandstones with minor siltstone, conglomerate and breccia) and Whangai Formation (mudstones with minor sandstone), Leonard et al. (2010).

2.1.2 Quaternary deposits

The Quaternary geology of the area is dominated by sediments of the Tauranga Group. Matahina Formation, a pyroclastic deposit from the Taupo Volcanic Zone (TVZ), is mapped near Waimana (Figure 2).

Quaternary time, in the age range 2.588 Ma to present day (Begg, 2013), is marked by repeated climatic fluctuations, represented by proxy in measured fluctuations of oxygen isotope ratios in rocks and sediments. A number of studies of oxygen isotope changes in deep marine foraminifera through sedimentary sequences (e.g., Shackleton and Opdyke, 1973; Imbrie et al., 1984; Martinson et al., 1987; Bassinot et al., 1994) are used as a standard for estimating Quaternary time (Table 1). In the following discussion and in the classification of map units, reference to geologic time is by means of oxygen isotope stages (Imbrie et al., 1984), signified by the prefix “Q”. In this scheme, Q1 represents the Holocene 0-12,000 years ago (ka), Q2-Q4 represents the Last Glaciation (12-71 ka), Q5 the Last Interglacial (71-128 ka), and subsequent even numbers represent cold climatic regimes and odd numbers represent warm climatic conditions.

Table 1 Oxygen isotope stage boundaries as used in QMAP. The stage boundaries of the listed publications (see references) were considered in deciding upon a suitable QMAP ages.

Stage Boundary	Shackleton and Opdyke (1973)	Imbrie et al. (1984)	Bassinot et al. (1994)	Martinson et al. (1987)	QMAP age (thousand years)
1 and 2	13	12	11	12	12
2 and 3	32	24	24	24	24
3 and 4	64	59	57	59	59
4 and 5	75	71	71	74	71
5 and 6	128	128	127	130	128
6 and 7	195	186	186	190	186
7 and 8	251	245	242	244	245
8 and 9	297	303	301		303
9 and 10	347	339	334		339
10 and 11	367	362	364		362
11 and 12	440	423	427		423
12 and 13	172	478	474		478
13 and 14	502	524	528		524
14 and 15	542	565	568		565
15 and 16	592	620	621		620
16 and 17	627	659	659		659
17 and 18	647	689	712		689
18 and 19	688	726	760		726
19 and 20	706	736	787		736
20 and 21	729	763	820		763
21 and 22	782	790	865		790

2.1.2.1 Tauranga Group sediments

Tauranga Group sediments in the study area range in age between early Pleistocene and Holocene age (Leonard et al., 2010). Early – middle Pleistocene sediments (Figure 2) include mudstone and sandstone deposited predominantly in a marine environment (Healy, 1967; Edbrooke, 1977). These sediments also include primary volcanic fall deposits (Leonard et al., 2010). Paltridge (1958) and Edbrooke (1977) produced geologic maps of the Whakatane to Ohiwa Harbour areas, with emphasis on the pumiceous deposits that cap the hilltops of the area. Tauranga Group sediments of this age range deposited east of Opotiki include weathered alluvial greywacke conglomerate and paleosols (Leonard et al., 2010) as well as gravels and sands with shallow marine fossils, tephra and loess (Q11b; Mazengarb and Speden, 2000). Late Pleistocene fan deposits ‘consisting of gravel and sand dominated by pumice’ (Leonard et al., 2010) are common on river valleys (lQa, Figure 2).

Holocene (Q1) age Tauranga Group sediments are common in the area. Holocene alluvium (Q1a) is deposited in valleys, including the Opotiki Plain, with beach deposits (Q1b) commonly occupying the coastal strip (Figure 2). For example, Q1b deposits along the Ohiwa Harbour coastal strip include a beach ridge that has a maximum height of 10 m above sea level and estuarine deposits consisting of sand, silt and shells (Robinson, 2012; Richmond et al., 1984).

2.1.2.2 Matahina Formation

Matahina Formation (Q9z, Figure 2) was erupted from Okataina Volcanic Centre at approximately 322 ka (Leonard et al., 2010) during the high sea level stand of oxygen isotope stage 9 (Imbrie et al., 1984). It is composed of welded to non-welded, blue to pink, cream or grey ignimbrite with c. 10% pumice clasts and a gritty, crystal-rich matix. Within the study area the pyroclastic deposits crop out in the Waimana Basin, approximately 50 km away from the source, where the ignimbrite has a thickness of more than 30 m (Kear, 1997).

2.2 Geologic structure

The Opotiki-Ohope area is east of the Whakatane Fault (Figure 2) and east of the Rangitaiki Plains. The Rangitaiki Plains are subsiding. Rates of vertical displacement have been calculated for the Edgecumbe Fault between 1.8 mm/yr and 4.2 mm/yr (Mouslopoulou, 2006). In contrast, tectonic uplift is generally occurring along the coast between Whakatane and Opotiki (Leonard et al., 2010) as evidenced by coastal erosion and the elevation of Pleistocene terraces (e.g., Paerata Ridge, Figure 1) above sea level. However, subsidence has been identified in Ohiwa Harbour (Robinson, 2012; Hayward et al., 2004) and in the nearby Waiotahi Estuary (Marra, 1997). Up to 0.7 m of localised subsidence may have occurred along the southeast shores of Ohiwa Harbour, associated with an earthquake in 1866 (Hayward et al., 2004).

2.2.1 Faults

Faults of the North Island Fault System (NIFS) are dominantly strike-slip with strike about north-south in the Rangitaiki Plains area. Faults of the NIFS, as they approach the TVZ, exhibit an increasing component of dip-slip displacement (Mouslopoulou, 2006). Development of basins such as Taneatua and Waimana are a result of this component of vertical displacement. The NIFS faults important to the geology of the Opotiki-Ohope area are the active faults (Whakatane, Waimana, Waiotahi and Koranga) and one unnamed fault that passes near Ohope, Figure 2. Faults offset basement greywacke and the top surface of basement greywacke is as much as c. 1000 m below sea level in the study area, Figure 3 (Mouslopoulou, 2006; Mouslopoulou et al., 2008).

The Whakatane Fault is the northern extension of a fault that starts in Cook Strait, south of the Wellington coastline, extends northward to the Manawatu Gorge as the Wellington Fault, continues through western Hawkes Bay as the Mohaka Fault, and takes on its northern name about the Te Hoe River. It is the most continuous fault of the NIFS and carries the greatest slip rate along most of its length. It changes in strike from northeast to north about 20 km north of Ruatahuna and continues at about this strike to Whakatane, a distance of c. 55 km. While it is a dextral strike-slip fault, its component of dip-slip increases from south to north from Ruatahuna to Whakatane (Mouslopoulou, 2006 Mouslopoulou et al., 2007a; Mouslopoulou et al., 2007b).

Data characterising displacement and timing of paleoearthquakes are available from Beanland (1995), Mouslopoulou (2006), and Mouslopoulou et al. (2007a, 2007b, 2009a, 2009b). The Ruatahuna fault-angle depression may represent deformation resulting from the change in strike of the fault from north-northeast to north (e.g., Beanland, 1995). The Taneatua basin may represent increasing dip-slip resulting from increasing proximity to the Taupo Rift faults, an analogue of the Galatea and Waiohau basins on the Waiohau Fault (Mouslopoulou et al., 2007b). Between Ruatahuna and Taneatua the strike-slip component on the Whakatane Fault decreases from c. 3 mm/yr to c. 1.5 mm/yr (Mouslopoulou et al., 2007b).

The Waimana Fault splays from the Whakatane-Mohaka Fault close to the Te Hoe River c. 110 km south of the Bay of Plenty coast. It strikes north from near Maungapohatu to cross the Bay of Plenty coast near the eastern end of Ohope. Strike-slip displacement dominates onshore, and some indication of an increasing dip-slip component is observed offshore (Davey et al., 1995; Mouslopoulou et al.; 2007b).

The Waimana Fault has the second highest slip rate of the NIFS faults in the Bay of Plenty (Mouslopoulou et al., 2007b), and paleoseismological data (Beanland, 1995; Mouslopoulou, 2006; Mouslopoulou et al., 2009a) indicate a strike-slip displacement rate of c. 1 mm/yr with a dip-slip component of only c. 0.1-0.2 mm/yr. The Waiotahi Fault crosses the Bay of Plenty coast at the Waiotahi River estuary. A strike-slip displacement rate of c. 1 mm/yr is estimated for this fault.

2.2.2 High sea level stand marine incursions

The Quaternary period has been characterised by periodic climatic changes with associated sea level change. The timing of sea level fluctuations are constrained by an international sea level curve constructed from, among other techniques, fluctuation of the isotopic composition of oxygen in the calcite shells of deep marine planktonic foraminifera (e.g., Imbrie et al., 1984). The international sea level curve provides a robust tool for correlating sequences of non-marine and marine deposits, using the principle of superposition.

Sea level high stands, analogous to today’s, have been documented during about six other stages during the middle and late Quaternary (c. 500 ka to the present). During these periods, the sea penetrated inland as far as Waimana (Healy, 1967). Subsequent to deposition of the 322 ka Matahina Ignimbrite and prior to the Holocene period, there were two periods of high sea level (similar in elevation to today’s sea level), during Oxygen Isotope Stage OIS7 (245 to 186 ka) and OIS5 (128-71 ka). In the intervening periods, sea levels were low and shorelines retreated to the edge of the continental shelf (White et al., 2010), and deposits across the Opotiki-Ohope area were non-marine.

The present warm climatic cycle commenced about 12 ka. Sea level reached its current elevation about 6.5 to 7 ka and has essentially been stable since. Between 12 and 6.5 ka sea level rose rapidly between the early Pleistocene age Tauranga Group sediment terraces. When sea level ceased rising, the sediment supply from the hinterland brought down by major rivers was deposited at the beach face, re-worked by long shore drift resulting in a shoreline that prograded seaward. As the shoreline retreated seaward, non-marine sediments were deposited on top of marginal marine and marine sediments (White et al., 2010).

These surfaces, originally deposited at a more or less consistent elevation above sea level, may be identified and correlated using well logs. Similar surfaces may be defined for older marine incursions. However, the small number of drill holes that penetrated to suitable depths, and the difficulty of interpreting drillers' logs, means that control on the top and base of the Last Interglacial marine incursion is limited.

2.3 Hydrology

The main rivers in the Opotiki-Ohope area begin in the greywacke ranges where annual rainfall is up to approximately 2,500 mm/yr (Figure 1). The Waioeka River, which flows across Opotiki Plain, is the largest river in the area with mean and maximum measured flows of approximately 31.8 m^3/s and 1521 m^3/s, respectively (Figure 1). The Otara River is another important river, with mean and maximum measured flows of approximately 11.7 m^3/s and 550 m^3/s, respectively (Environment Bay of Plenty, 2001). Large floods from these rivers have inundated Opotiki township in the past.

The Opotiki Plain has an area of approximately 62 km^2 and consists of Quaternary sediments. These sediments include aquifers that receive recharge from rainfall and possibly from the rivers and surrounding geologic units. Small spring-fed streams occur on the Plain, e.g., Mill Stream south of Opotiki with a median flow of 0.12 m^3/s (Bloxam, 2008). Groundwater and surface water use in the Opotiki-Ohope area is largest on the Plain where water supplies agriculture and the Opotiki township.

Surface flow from Pleistocene units is typically relatively low. For example, the Nukuhou River (Figure 1) has mean and maximum measured flows of approximately 1.8 m^3/s and 70 m^3/s, respectively (Environment Bay of Plenty, 2001). Agriculture on the Pleistocene terraces (e.g., Paerata Ridge) between the ranges and the coast use groundwater as a water supply.

Holocene beach sands form the coastal stip. This strip is typically 300 m to 700 m wide in the vicinity of Ohope township.

2.3.1 Minimum flow limits

The estimation of groundwater and surface water available for allocation is one of the objectives of this report and minimum flow limits are a key part of this calculation. Minimum flow limits for groundwater (MFL^{GW}) and surface water (MFL^{SW}) are used to manage water allocation in order to preserve groundwater levels, to assure stream base flow, to prevent salt water intrusion into coastal aquifers such as Holocene beach sediments (Section 4.1.1) and to maintain instream ecological values (Bloxham, 2008). BOPRC is responsible for setting these limits. As a guide to groundwater allocation, BOPRC is using interim limits from the Ministry for the Environment (2008) including:

> "For shallow, coastal aquifers (predominantly sand)
>
> An allocation limit of, whichever is the greater of:
>
> - 15% of the average annual recharge as calculated by the regional council;
> - the total allocation from the groundwater resource on the date that the standard comes into force less any resource consents surrendered, lapsed, cancelled or not replaced.
>
> For all other aquifers
>
> An allocation limit of, whichever is the greater of:

> - 35% of the average annual recharge as calculated by the regional council;
> - the total allocation from the groundwater resource on the date that the standard comes into force less any resource consents surrendered, lapsed, cancelled or not replaced.
>
> For groundwater that is shown to be connected to adjacent surface water, the environmental flow or water level set for the surface water body will also apply to the management of groundwater takes."

The close connection between groundwater and surface water in the Opotiki-Ohope area is demonstrated by the water budgets calculated in this report. Therefore, this report calculates groundwater available for allocation (GAA) considering Ministry for the Environment (2008) groundwater allocation limits based on annual groundwater recharge and minimum flow limits for surface water (Section 3.4). Current BOPRC practice is to estimate limits for surface water flow using '$Q_{5\ 7\text{-day}}$' flow (i.e., 7 day low flow minimum, which is of the annual mean flow for any 7 consecutive days, that has a 20% probability of occurring in any one year), Wilding (2003).

3.0 METHODS

3.1 Geologic model

This section lists the data sources used for the project and provides a general description of the main steps in the creation of a 3D geologic model having four groups of units, based on the surface distribution of major geologic units (basement, Pleistocene units, Holocene alluvium and Holocene beach sediments), Figure 4. Subsections are arranged in the typical order of work flow during model development, but note that there are often several iterations of data checking, development of property models, and identification of appropriate layer boundaries before the 3D geologic model is finalised. Gravel, sand and shell were chosen as the key lithologic descriptors in the 3D geologic model because of their importance as stratigraphic markers and indicators of depositional environments.

Hypothetical examples are used to illustrate the first few steps in the modelling process. These examples are presented only for general illustration of the work flow involved in the development of a 3D geologic model; interpretation of results will be discussed in Section 4.1.

3.1.1 Data sources

3.1.1.1 Topographic data

Topographic data estimate the land surface elevation across the study area. The topographic data were used to develop a digital terrain model (DTM), which interpolates ground elevation between points at which measurements have been made. The DTM used in this report was derived from BOPRC photogrammetry data acquired in 2006-2007, for the coastal and valley areas (Cusi, 2011) with twenty metre contour data from 1:50,000 topographic maps used to represent ground elevation in the hills.

3.1.1.2 Geologic maps

Surface geology of the 1:250,000 QMAP was used in the construction of the 3D geologic model to define the boundaries between geologic units and the location of faults at the ground surface, Figure 2.

3.1.1.3 Well log data

Well logs constitute the main source of data for the construction of the 3D geologic model. A typical well log includes the following information: 1) a name or number that uniquely identifies the well; 2) location (easting and northing); 3) elevation of the ground surface or the top of the well casing (this study expresses all elevations relative to mean sea level); and 4) lithologic descriptions with their associated depth intervals. Typically, this information was collected by drillers when the well was first installed, then passed to BOPRC for archiving in their electronic database.

Well log data in the Opotiki-Ohope area was provided by BOPRC in the form of an Excel spreadsheet. The dataset comprised 353 individual well logs (Figure 2, Table 2) with most wells being located in the north of the study area near the coast. Well logs for some wells outside the study area near Waimana were used to assess continuity of geologic layering near the boundaries of the study area.

In total, the 353 well logs included 2,073 individual descriptions of lithology covering a total logged length of 14,958 m. The well log data were subjected to a series of checks, prior to use in construction of the 3D geologic model (Section 3.1.3). The ground elevation (m asl) of each well was interpolated using the DTM (Section 3.1.1.1). Subsequently, unit tops, bottoms and the base elevation of each well were calculated using the interpolated ground elevation.

Table 2 Depths of wells with geologic logs.

Well depth interval (m)	Number of wells
<10	63
10-20	79
20-50	117
50-100	54
100-256	40
Total	**353**

3.1.1.4 Hydrogeologic properties of formations

Specific capacity (S_y) is calculated from pump tests (Heath, 1983) with:

$$S_y = Q/s \tag{1}$$

Q production well pumping rate (L/s)

s production well drawdown (m).

Specific capacity is a function of formation properties (i.e., transmissivity and storativity) and the effective radius of the well, length of pumping period, and pumping rate. Specific capacity is frequently measured when a well is installed because it is relatively easy and inexpensive to do, compared to a full-scale aquifer test, and can be used as a first approximation of transmissivity. Specific capacity was measured in wells with groundwater consents in the Opotiki-Ohope area (Figure 5). Aquifer tests were made mostly over a period of 24 hours and drawdowns typically stabilised during the pumping period. Formation transmissivity, calculated from measurements of groundwater drawdown in observation wells during aquifer tests, was calculated in only a few wells.

All wells with consents in the Opotiki-Ohope area take groundwater from Quaternary sediments. Geologic units that are tested in each aquifer test were assigned as either Holocene alluvium or Pleistocene sediments based on the geologic model. The geologic map (Figure 2) identifies surface sediments at the location of the aquifer tests.

3.1.1.5 Other data sources

Aside from the data sources described above, there are many other information sources that can feed into the development of a 3D geologic model, including: previously published geologic investigations, cross sections and maps, geophysical data (e.g., seismic surveys), and radiometric dates obtained for sediment and other geologic materials. Key information sources used in this study include the following:

- **Cross sections:** Geologic cross sections (e.g., Leonard et al., 2010) provide useful information on the subsurface distribution of formations and the nature of fault offsets;
- **Geophysics:** Gravity profiles were used in the interpretation of basement structure (Mouslopoulou, 2006; Mouslopoulou et al., 2008; Figure 3).

3.1.2 Digital terrain model

The DTM (Figure 6) is used to define the top surface (i.e., ground elevation) of the 3D geologic model including the elevations of geologic units and faults that are mapped at the ground surface. The DTM is also used to estimate the elevations of well heads allowing conversion of depths measured by well logs into elevations relative to mean sea level.

3.1.3 Data checking

The 3D geologic model is dependent on the accuracy and consistency of the input data from which it is developed. Hence assessment, verification and, where necessary, correction of the input data are early and critical steps in the overall 3D modelling work flow. The following discussion focuses primarily on the procedures used to check well log data, although other data sources are also checked carefully before 3D geologic modelling commences.

The first stage of checking the well log data involves editing the lithologic descriptions to ensure consistent use of terminology and spelling. This checking is performed for each individual well log and also across the entire well log dataset. For example, the lithologic descriptions in the BOPRC well log dataset use the terms “timber”, “wood”, “log”, “vegetation” and “organic”, which are all indicators of a similar depositional environment. In this study, these are all replaced with the lithologic descriptor “organic”. Spelling corrections are also required, for example to replace the word “ignambrite” with “ignimbrite”, and so on. All of these changes to the terminology and spelling in the lithologic descriptions are required for subsequent generation of pseudo-logs using the Excel *Find* function. The *Find* function is case-sensitive, and so all lithologic descriptions were converted to lower case.

In the second stage of data checking, the well logs were examined for geologic inconsistencies that may represent errors in the lithologic descriptions. For example, Figure 7 shows an example well log in which “greywacke” is reported to occur above gravel. This is geologically unlikely, and thus it is presumed that the original description refers to “greywacke gravel”, such that use of the descriptor “gravel” would be more appropriate in this case.

Although the data checking procedure was initiated prior to the development of the 3D geologic model, it often became clear through the modelling process that information from individual well logs was poor (e.g., lithologic description, well location, etc.). For example, a particular well log observation may be contradicted by neighbouring wells when the lithology is viewed in three dimensions. In such cases, additional queries to BOPRC were made for verification, and consequently corrections to the well log dataset were made throughout the development of the 3D geologic model.

3.1.4 Assignment of lithologic property codes and assessment of lithologic correlation

Once the Excel file containing the well log data has been checked and corrected as described above, it is screened for lithologic descriptions that are: 1) frequent in well logs throughout the dataset, 2) characteristic of a distinct origin or depositional environment, and 3) likely to assist with definition of the 3D geologic model layer structure. The lithologic descriptions that meet these criteria are specific to the study area and intended use for the 3D geologic model. There are several key lithologic descriptors selected for their relevance to this study, namely “gravel”, “sand”, “shells”, “organic” and “greywacke”. In addition, descriptions of gravels are also differentiated (e.g., drillers’ descriptions of “pea gravels” which are characteristic for marginally marine environments vs. gravel) to provide further information on depositional environments and lithologic boundaries.

Lithologic property codes are assigned to each well log and for each of the key lithologic descriptors (Figure 8). The lithologic property code is one of two different arbitrarily selected numbers that indicate the presence or absence of each lithologic descriptor at each depth interval. In this study, the number 200 is used to indicate the presence of certain lithology or marker, whereas the number 100 is used to indicate its absence. *Pseudo-logs* are created from the lithologic property codes by interpolation at 0.1 m increments for each well log. The pseudo-logs are then imported into EarthVision®, where they form the basis for models of property codes in three dimensions. This process assesses the distribution of each lithologic property, making it possible to search for possible correlations between wells.

3.1.5 Definition of boundary surfaces for major geologic units

A 3D geologic model is generally composed of a series of units (layers), that are assembled with respect to their chronology and structural relationships. These units are defined and demarcated by a set of boundary surfaces. Thus, a key step in the modelling work is to determine how many boundary surfaces there should be, and where they should be positioned in 3D space. Not all stratigraphic units identified on the geologic map, or subsurface data, are included as separate units into the 3D geologic model. For simplicity of the model, stratigraphic units are combined into model units. The decision on how many model units are chosen is primarily based on the available data (i.e., where the available data, such as lithologic drill hole data and geophysical data, do not allow a detailed sub-division, it is preferable to keep the model as simple as possible). In addition, the number of layers is also based on the significance of stratigraphic units for groundwater processes in the study area.

Generally, surfaces are developed to represent the top of each model layer. The bottom of each model layer is then automatically represented by the top surface of the layer underneath it. For example, the 3D model in this study includes a surface that represents the top of the (undifferentiated) basement. Where basement units crop out, the surface that defines “top of basement” is developed using ground-surface elevation data from the DTM. Where not mapped at the ground surface, the “top of basement” surface is based on well logs that penetrate as far as the basement or interpretation of geophysical data such as seismic or gravity surveys (Figure 3). Elevation data and lithologic descriptions from wells with lithologic logs are used to define the surface that represents the geologic contact between different geologic units.

Other layers are defined in a similar manner. For example, the occurrence of shells may indicate a marine depositional environment, which is often characteristic of Holocene sediments in coastal regions of New Zealand. A 3D property model of shell occurrence may then be used to define the surface representing the boundary between Holocene and Pleistocene sediments. Likewise, transitions from gravel to shell or organic sediment, as viewed on 3D property models, may be useful for defining the layer boundaries between Pleistocene units corresponding to low and high sea level.

The boundary between Holocene and Pleistocene sediments beneath the Opotiki Plain is inferred from descriptions of sediment in well logs. Assemblages of gravels, silts, peats and timber that were shallow were assumed as Holocene because this assemblage characterises deposition in a terrestrial environment (Section 2.1.2.1). The depth of gravel at the coast may identify the top of the Late Pleistocene gravel unit which is in the depth range 12 m to 47 m at the coast under the Rangitaiki Plains (White et al., 2010). The colour of gravel sediments also gives a clue to the age with brown gravel typical of Late Pleistocene sediments. The colour of Holocene gravels is typically described as blue in geologic logs although some brown gravels of Holocene age are also identified in well logs. Occurrences of gravel and mudstone (commonly known as “papa”) were assumed as Pleistocene because mudstones were deposited in a marine environment (Section 2.1.2.1).

3.1.6 Assembly of geologic model incorporating faults

The integration of faults into the 3D geologic model is an iterative process. As a first step, fault traces at the ground surface are sourced from the GNS Science Active Faults Database and from geologic maps and cross sections (principally Leonard et al., 2010). Due to the large scale of the model and the complexity of the geology in the model domain, it is not practical to include all faults in the 3D model.

The study area is sub-divided into fault blocks, forming the basis for the integration of the faults with the BOPRC well log data and boundaries of formations (Section 4.1). The principal faults that displace the major model units are identified and attributed with fault plane dips, and the upthrown and downthrown fault blocks are identified (Figure 3).

3.2 Groundwater catchments

Groundwater catchments are suggested for the purposes of managing groundwater allocation and surface water allocation. These catchments include land that provides groundwater recharge to surface water bodies. For example, a groundwater catchment may include a surface water feature such as a spring and management of the groundwater use in the catchment of the surface feature may aim to maintain base flow in the spring.

Four groundwater catchments were defined in the Opotiki-Ohope area (figures 1 and 9): 1) Ohope – Ohiwa (i.e., the catchment of Ohiwa Harbour and Ohope); 2) Waiotahi (including the surface catchment of Waiotahi River with some Pleistocene coastal terraces and Holocene beaches); 3) Opotiki (including the part of the Waioeka River catchment managed by BOPRC, the Otara River catchment, Opotiki Plain and related Pleistocene coastal terraces and Holocene beaches); and 4) Tirohanga (including the catchments of the Tirohanga and Waiaua rivers and related Pleistocene coastal terraces and Holocene beaches).

The boundaries of three groundwater catchments are coincident with surface catchment boundaries. However, the surface catchment of the Waioeka River south of the Opotiki area is not included in a groundwater catchment because this surface catchment is managed by Gisborne District Council.

3.3 Water budget and groundwater flows

A general water budget equation describes the relationships between water inflow, water outflow and water storage within a defined area of a catchment (Scanlon et al., 2002; Scanlon, 2012) and is used to estimate surface water allocation limits and groundwater available for allocation.

$$\text{water inflow} = \text{water outflow} \tag{2}$$

i.e. $$P + Q_{IN} = ET + Q_{OUT} + \Delta S \tag{3}$$

Water inflows (Q_{IN}) include:

P precipitation,

$$Q_{IN} = Q^{SW}_{IN} + Q^{GW}_{IN} \tag{4}$$

Q^{SW}_{IN} quick flow and base flow

Q^{GW}_{IN} groundwater inflow

Water outflows (Q_{OUT}) include:

ET evapotranspiration

ΔS change in water storage.

With:

$$Q_{OUT} = Q^{SW}_{OUT} + Q^{GW}_{OUT} \tag{5}$$
$$Q^{SW}_{OUT} = Q^{SW}_{IN} + Q^{SW}_{QF} + Q^{SW}_{BF} + U^{SW}$$
$$Q^{GW}_{OUT} = Q^{GW}_{COUT} + U^{GW}$$

where:

Q^{SW}_{QF} surface water quick flow from the area (i.e., interflow and runoff)

Q^{SW}_{BF} surface water base flow from the area (i.e., discharge to surface water from the saturated portion of the groundwater system)

U^{SW} consumptive surface water use

Q^{GW}_{OUT} is groundwater outflow, including consumptive groundwater use (U^{GW}) and groundwater discharge across groundwater catchment boundaries, in particular across the coastal boundary (Q^{GW}_{COUT}).

Expanding Equation 3 for groundwater and surface water terms, with the assumption that ∆S is zero, meaning that the system is in steady state with mean long-term flows constant over time, results in:

$$P + Q^{SW}_{IN} + Q^{GW}_{IN} = ET + Q^{SW}_{IN} + Q^{SW}_{BF} + Q^{SW}_{QF} + U^{SW} + U^{GW} + Q^{GW}_{COUT} \tag{6}$$

The following text discusses each of the components in this equation for the Opotiki-Ohope area (Figure 10), and summarises simplifying assumptions in the water budgets.

3.3.1 Rainfall and evapotranspiration

Mean annual rainfall (P) was estimated by GIS from the nationwide NIWA dataset based on the rainfall measurements at individual climate stations, interpolated throughout New Zealand by NIWA and averaged for the period 1960-2006 (Tait et al., 2006). Mean annual evapotranspiration (ET) was estimated by GIS as actual evapotranspiration from the land surface derived from a national-scale map developed by NIWA for the period 1960-2006 without specific consideration of land use, land cover, soil type or groundwater recharge (Woods et al., 2006).

3.3.2 Surface water inflow and groundwater inflow

Surface water inflow to the Opotiki-Ohope area (Q^{SW}_{IN}) is from the catchment of the Waioeka River that is outside the BOPRC regional boundary (Figure 9). This was calculated as the difference between flow at site 4012141 and rainfall minus ET in the “N3” catchment (Figure 11) and assumes groundwater inflow is zero.

Groundwater inflow to the groundwater catchment (Q^{GW}_{IN}) was assumed to be zero. This was because the groundwater catchment is commonly coincident with the surface catchment boundary and with relatively impermeable greywacke lithology (Figure 2). Groundwater flow through this boundary is likely to be very low due to the high runoff from greywacke and low permeability of greywacke. Faults are commonly observed on the southern boundary of the Opotiki-Ohope area (Figure 2). These faults, and associated fault zones, may provide relatively permeable pathways for groundwater flow through greywacke. However, groundwater inflow to the Opotiki-Ohope area through faults and fault zones is likely to be very low because these faults intersect deeply incised river valleys in the mountains south of the area.

3.3.3 Surface water flow: quick flow, base flow and base flow index

Surface water quick flow and base flow were calculated as these components of flow are significant in the water budget of the study area. To do this, Q^{SW}_{BF} and Q^{SW}_{QF} were assessed for eight sites with flows recorded by BOPRC or NIWA (Table 3) and for 19 sites with synthetic flow estimates (Table 4 and Figure 11). Synthetic flow estimates were obtained from Water Resources Explorer New Zealand (WRENZ), a model that among other things provides estimates of mean annual discharge across the country (Woods et al., 2006). WRENZ itself is structured around the River Environment Classification (REC) network, which at its base comprises individual reach segments along each of the mapped rivers (Snelder et al., 2010). These reach segments are assigned a unique reach ID, which has been used as the site identifier for both the study sites and the flow measurement sites. Surface catchments of measured and synthetic flow records were delineated using geospatial data encapsulated in the REC (Figure 11).

Table 3 Flow recorder sites.

Site ID	TIDEDA site number	Location
4008687	16205	Waiaua River at Edwards
4009666	16006	Otara River at Gault Rd (No. 2) Bridge
4009720(a)	15606	Wainui Stream at Pines
4009720(b)	15608	Wainui Stream at Twin Streams
4011135	15605	Nukuhou River at Old Quarry
4011726	16002	Otara River at Browns Bridge
4012141	15916	Waioeka River at Amokura Rd
4016938	15901	Waioeka River at Gorge Cableway

Table 4 Synthetic flow sites.

NZREACH	River/stream	Catchment	Location	Easting	Northing
4007551	Maraetotara Stream	Ohiwa	Pohutukawa Av	2866500	6350900
4007938	Awaraputuna Stream	Ohiwa	Ohiwa Harbour	2866600	6349500
4008273	Waiwhakatoitoi Stream	Waiwhakatoitoi	SH2	2881250	6347000
4008473	Tirohanga Stream	Tirohanga	SH35	2891400	6347400
4008420	Waiotane Stream	Ohiwa	Wainui Rd	2866500	6347500
4008506	Waiotahi River	Waiotahi	SH2	2878200	6346900
4008818	Waioeka River	Waioeka	SH2	2885150	6345400
4008881	Otara River	Waioeka	SH35	2886900	6346400
4009290	Nukuhou River	Ohiwa	Wainui Rd, near harbour	2870200	6345000
4009382	Tirohanga Stream	Tirohanga	Upstream of Tirohanga Rd	2893000	6343950
4009455	Waiotahi River	Waiotahi	Brown Rd	2879500	6344000
4010172	Unnamed Stream (Stoney Creek?)	Waioeka	Stoney Creek Rd	2886100	6344100
4009940	Te Awawairoa Stream	Ohiwa	Hiwarau Rd	2872900	6343250
4010018	Waiotahi River	Waiotahi	Rau Rd	2879150	6342950
4010057	Unnamed Stream (Stoney Creek?)	Waioeka	Matchett Rd	2887250	6341400
4010340	Waiotahi River	Waiotahi	Toone Rd	2876800	6342100
4011596	Waioeka River	Waioeka	Waioeka Pa Rd	2885900	6337600
4011726	Otara River	Waioeka	Otara East Rd	2893000	6337500
4011753	Tutaetoko Stream	Waioeka	Otara Rd	2892100	6337600

Estimating specific discharge at the study sites, partitioned into quick flow and base flow, requires a series of analytical steps:

1. Base flow separation and estimation of the base flow index (BFI, calculated as the long-term mean of the base flow divided by the total flow) for the flow sites;
2. Development of a spatial model of BFI;
3. Estimation of mean annual flows at the synthetic flow sites;
4. Estimation of BFIs at the synthetic flow sites; and
5. Estimation of the specific discharges at the synthetic flow sites.

There is no universally accepted method for extracting base flow hydrographs from total river flow hydrographs, particularly in the absence of secondary information such as chemical tracers. Many methods are in existence and in use and each has a different mix of subjectivity, physical plausibility, theoretical background, and field-testing. For the purposes of this report, the Boughton method was used (Boughton, 1993). This method is a special case of the more general Eckhardt method (Eckhardt, 2012). These methods have been used in a wide range of hydrologic conditions, including perennial and ephemeral streams in porous and hard rock aquifers (Eckhardt, 2005). A comparison by Chapman (1999) identifies the Boughton method as being superior to two other commonly used filter methods, one a one-parameter filter (Chapman and Maxwell, 1996) and the other the three-parameter IHACRES algorithm (Jakeman and Hornberger, 1993).

The Boughton method is a single-pass filter with two parameters. It models base flow, Q_b, iteratively as a function of the previous time-step's base flow and the present time-step's total flow, Q:

$$Q_b(t) = \frac{k}{1+C} Q_b(t-1) + \frac{C}{1+C} Q(t) \qquad (7)$$

subject to: $Q_b(t) \leq Q(t)$

where t refers to the time-step, and both k and C are coefficients, the first being the recession coefficient of the river.

The base flow separation procedure first required a choice of the initial base flow at the beginning of the time-series, which here is selected as being half of the total flow at that time. For even moderately sized data sets, this choice will have a negligible effect on the calculation of the BFI. This initialisation was applied each time there was a gap in the flow time-series.

The second step required the calculation of the recession coefficient, k (e.g., for site 4012141 in Figure 12). The recession coefficient was identified for each flow site based on the five longest continuous recessions contained within the record. More than five recessions were used if lengths were tied. Each recession was plotted in semilog-space to identify (by inspection) the near-linear portion corresponding to flow after quick flow has ceased, and a line fitted by least squares. No regression is conducted where near-linear portions of records are not identified.

This linearity implicitly assumes that the catchment's entire aquifer system behaves like a linear reservoir, where groundwater discharge at a given time is proportional to the groundwater level at the same time. This is a common assumption in hill- and catchment-scale applications of groundwater discharge and is generally reasonable in the context of the present study.

Selecting the time of cessation of quick flow by inspection is subjective, but by choosing multiple recession curves and by basing the analysis on the longest recessions the potential bias of doing so is reduced. The slope of each resulting line is the recession coefficient for that particular recession, the value of which will vary among recessions for various reasons (e.g., seasonal effects on evaporation). The recession coefficient for the river is subsequently set as the mean of the values identified above.

The last step in the base flow separation method required the selection of the second parameter, C (e.g., for site 4012141 in Figure 13). This is fitted, again by inspection, such that the synthetic base flow time-series reaches the total flow time-series at or near the quick flow-cessation points used in the recession analysis above. There is typically no perfect parameter value for at least two important reasons: (1) the recession coefficient is not steady throughout a year, and (2) even during a recession there may have been rainfall that confounds base flow separation. Additional weight is given to those recessions that have a more distinct quick flow-base flow break-point.

A synthetic base flow time-series was then calculated once both k and C are estimated. The base flow index (BFI) may then be calculated as the long-term mean of the base flow divided by the total flow. In order to interpolate, and potentially extrapolate, values for BFI across the study area, a relationship must first be sought between BFI and spatial features. Given the importance of the geologic substrate in partitioning vadose zone water between shallow return flow (which becomes quick flow) and deeper recharge (which becomes base flow), only one characteristic was chosen for this analysis: the underlying geologic unit.

The differences in specific discharge, be it quick flow or base flow, were the result of three principal factors: (1) the geologic conditions that partition water into shallow return flow or groundwater recharge; (2) the climatic conditions that control the spatial variation of rainfall and evaporative demand; and (3) the land cover characteristics that in turn modulate the rate of evaporation. For the present analysis, Quaternary units were grouped together into a single representative unit as the hydraulic conductivity of these units is likely to be much larger than basement rock. Values for BFI are compared with the Quaternary cover (QC, in percent) in the catchment, on an aerial basis, using the simplest possible model between the two variables as follows:

$$BFI = a\,QC + b \tag{8}$$

Least squares regression was used to estimate values for a and b in this equation. This model was then used to approximate the BFIs for the synthetic flow sites. However, because of the substantial variation of the data about the linear model, uncertainty bounds were included so that the maximum and minimum BFI for any catchment was set to the minimum and maximum of all of the flow sites, respectively.

The next stage in the quick flow and base flow assessment involved the use of the empirical mean annual flow model contained within WRENZ. It was then first valuable to assess how well this model approximates the mean flows at the measured flow sites. The differences between mean annual flow (WRENZ) and mean flows at the measured flow sites were minor. Therefore, while WRENZ provides a good model of mean annual flow in the area, a slight adjustment can still be made to improve the estimates. A correction factor (0.96) was calculated as the average ratio of measured mean annual flow to that generated by WRENZ.

One limitation of relying on WRENZ is that only rivers of a sufficient size can be modelled adequately. With an area of 0.075 km^2, the catchment of the Wainui Stream at Twin Streams was too small to be resolved within the River Environment Classification (REC), around which WRENZ is structured. Hence this catchment is consequently omitted from the analysis as WRENZ does not produce a realistic value of mean annual flow for the stream.

The final stage in the quick flow and base flow assessment followed two steps:

1. Mean annual discharge was estimated for each study site from WRENZ and was then scaled by the factor identified above (0.96);
2. The mean annual discharge was split into quick flow and base flow and divided by the catchment area to obtain catchment-specific estimates of quick flow and base flow.

3.3.4 Groundwater–surface water interaction and groundwater outflow through the coastal boundary

Groundwater–surface water interaction, i.e., Q^{SW}_{GW} (surface water discharge to groundwater) and Q^{GW}_{BF} (groundwater discharge to surface water), Figure 10, were assessed with available gauging data (Figure 14) and compared with estimates of water budget components.

Groundwater outflow through the coastal boundary (Q^{GW}_{COUT}) was estimated for two groups of sediments: 1) Holocene beach sediments calculated as the difference between P and ET, assuming that surface runoff from these sediments was zero; and 2) Holocene alluvium and Pleistocene units estimated with the water budget calculation as discussed in Section 3.3.5 by aiming to achieve a balanced water budget.

Groundwater may flow between aquifers. This flow is relevant to groundwater budgets of individual aquifers, but assuming aquifer inflows equal outflows has no impact on the basin water budget.

3.3.5 Water budget calculation to represent natural flows

Water budgets were developed for groundwater catchments in the Opotiki-Ohope area (Figure 9) in two steps. These budgets were based on Equation 6 with water use set to zero. This approach represents the natural flow case. Q^{SW}_{IN} appears on both sides of this equation and, therefore, cancels out.

Firstly, land area, P and ET (Section 3.3.1), water inflow (Section 3.3.2) and surface flows (Section 3.3.3) were determined. Water budgets were developed separately for three land areas within each groundwater catchment:

- A) Holocene beach sediments with boundaries defined by polygons representing these sediments. Runoff from this area was assumed as zero, as beach sands probably have a large capacity to infiltrate groundwater;
- B) catchments with calculations of specific Q^{SW}_{QF} and Q^{SW}_{BF} (Section 3.3.3) and boundaries defined by surface catchments;
- C) the area outside A and B. Average specific Q^{SW}_{QF} and Q^{SW}_{BF} were assumed for this area as specific baseflow and quick flow on representative geology in the same, or neighbouring, groundwater catchments.

Secondly, P and ET in land areas B and C were adjusted because surface runoff (i.e., quick flow and base flow) are commonly slightly greater than the difference between P and ET.

Adjusted rainfall (P_A) and adjusted evapotranspiration (ET_A) were calculated to balance the water budget by scaling that preserves the ratio of P and ET:

$$P_A = (Q^{SW}_{QF} + Q^{SW}_{BF}) / (1\text{-}ET/P) \qquad (9)$$

$$ET_A = (Q^{SW}_{QF} + Q^{SW}_{BF}) / (P/ET\text{-}1) \qquad (10)$$

An alternative of scaling surface water flows (i.e., Q^{SW}_{QF} and Q^{SW}_{BF}) to balance the water budget was not used for two reasons: 1) scaled Q^{SW}_{QF} and Q^{SW}_{BF} (e.g., to preserve BFI) are less than calculated by the method in Section 3.3.3 which would lead to greater water available for allocation and this is not a conservative assumption (Section 3.4); and 2) uncertainties in P and ET are probably greater than the uncertainties in Q^{SW}_{QF} and Q^{SW}_{BF}.

Water budgets were developed in each groundwater catchment for each geologic unit (basement, Pleistocene units, Holocene alluvium and Holocene beach sediments) aggregated from the geologic map (Section 3.1, Figure 4). These budgets used representative catchments to calculate Q^{SW}_{QF}, Q^{SW}_{BF}, Q^{GW}_{IN} and water available for allocation (WAA), Section 3.4. The process to calculate Q^{SW}_{QF} and Q^{SW}_{BF} is summarised with the example of Holocene alluvium in the Opotiki groundwater catchment (Figure 15). Firstly, subcatchments N4 and N11 have Holocene alluvium as the predominant surface geology (80% and 53% of land area, respectively) in the groundwater catchment. Secondly, Q^{SW}_{QF} and Q^{SW}_{BF} were estimated for these subcatchments by deducting estimates of Q^{SW}_{QF} and Q^{SW}_{BF} at the upstream boundaries of subcatchments. Then, estimates of specific quick flow and specific base flow were applied to the area of Holocene alluvium in the Opotiki groundwater catchment to calculate Q^{SW}_{QF} and Q^{SW}_{BF} of 2101 L/s and 4635 L/s, respectively. Q^{GW}_{IN} was calculated to balance the water budgets and the sum of Q^{GW}_{IN} is zero for the major geologic units mapped at the ground surface, i.e., all groundwater recharge to these units flows to rivers and streams.

3.3.6 Water allocation and estimated water use

Consumptive uses of groundwater and surface water by water consent holders (Figure 5) include: frost protection, irrigation, drinking and industrial applications. These water uses were estimated in three water use classes with assumptions on the use of current allocation (Barber, 2012) as follows:

- frost protection water use for 30 days in the year at the allocated daily rate (m^3/day);
- irrigation water use for 5 months in the year at the allocated daily rate (m^3/day) and return flows from irrigation were considered as zero to estimate the maximum consumptive use;
- municipal water use for 365 days in the year at the daily allocated rate (m^3/day).

In addition, ‘permitted takes’ from groundwater are allowed by BOPRC under the Regional Water and Land Plan for up to 35 m^3/day/property (Barber, 2012). Use of this groundwater was estimated as the number of wells with lithologic logs (Figure 2), less the number of these wells with consents (Figure 5), multiplied by 35 m^3/day/well. Surface water use by permitted takes is also allowed by the Regional Water and Land Plan for up to 15 m^3/day/property (Barber, 2012). For the Opotiki-Ohope area, permitted surface water use was assumed as zero because no recording or monitoring of takes occurs (Barber, 2012). Ideally, use would be estimated as 15 m^3/day/property for those properties that border a stream/river, less the number of surface water takes (consents) off the stream/river. Bay of Plenty Regional Council is currently undertaking these calculations (Barber, 2013).

Water for municipal purposes is supplied to Ohope Beach residents by Whakatane District Council from outside the Opotiki-Ohope area (Agas, 2013) and to the wider Opotiki township including the Otara River valley by Opotiki District Council (Mathias, 2013).

Water for domestic purposes is supplied to Ohope Beach residents by Whakatane District Council from outside the Opotiki-Ohope area (Agas, 2013) and to the wider Opotiki township including the Otara River valley by Opotiki District Council (Mathias, 2013).

3.4 Water available for allocation

WAA in a groundwater catchment includes groundwater and surface water:

$$WAA = GAA + SAA \tag{11}$$

Where:

GAA groundwater available for allocation

SAA surface water available for allocation

BOPRC policies are crucial to the implementation of a water allocation regime in the Opotiki-Ohope area (Section 5.0). In lieu of BOPRC policies, this report suggests a water allocation scheme for groundwater that is consistent with minimum groundwater flow guidelines (Ministry for the Environment, 2008) and minimum surface water flows (Section 2.3.1).

GAA was estimated from the water budget in each groundwater catchment (Section 3.3.5) as follows:

$$GAA = R - MFL^{GW} \tag{12}$$

where R (recharge) = $P + Q^{GW}_{IN} - ET - Q^{SW}_{QF}$

MFL^{GW} was derived from interim groundwater allocation limits (Section 2.3.1):

- in coastal aquifers 85% of R (i.e., the minimum groundwater flow equivalent to an allocation of 15% of R);
- in non-coastal aquifers the greater of 65% of R (i.e., the minimum groundwater flow equivalent to an allocation of 35% of R) or MFL^{SW}.

MFL^{SW} is equal to the $Q_{5\ 7\text{-day}}$ surface water flow (Section 2.3.1) which is calculated in each groundwater catchment assuming that Q^{SW}_{BF} equals median flow and:

$$MFL^{SW} = 0.43Q^{SW}_{BF} \tag{13}$$

where 0.43 is the average ratio of $Q_{5\ 7\text{-day}}$ to median flow calculated in eight rivers and streams in the eastern Bay of Plenty area (Bloxham, 2008).

SAA was estimated from the groundwater budget as:

$$
\begin{aligned}
&SAA = R - GAA - MFL^{SW},\\
&\text{where } Q^{SW}_{BF} > 0 \text{ and } MFL^{GW} > MFL^{SW},\\
&\text{otherwise, } SAA = 0. \qquad (14)
\end{aligned}
$$

Then GAA and SAA were calculated for each aquifer area using water budgets for the main geologic units in the Opotiki-Ohope area, Section 4.

Calculation of water available for allocation is demonstrated in Table 5. For a coastal aquifer, GAA is 7 L/s as MFL^{GW} is 43 L/s (i.e., approximately 85% of R) and SAA =0 L/s as runoff is zero (Section 3.3.5). GAA and SAA are both zero where Q^{SW}_{BF} is zero (other aquifer 1). GAA and SAA are both greater than zero with BFI in the range 0.25 to 1 (other aquifers 2 to 7); WAA is limited by Q^{SW}_{BF}.

Table 5 Demonstration calculation of GAA, SAA and WAA.

Demonstration unit	**Water budget**							**Water allocation**				
	P (L/s)	**Q^{GW}_{IN} (L/s)**	**ET (L/s)**	**Q^{SW}_{QF} (L/s)**	**Q^{SW}_{BF} (L/s)**	**BFI**	**R (L/s)**	**MFL^{GW} (L/s)**	**MFLSW ($Q_{5\ 7\text{-day}}$) (L/s)**	**GAA (L/s)**	**SAA (L/s)**	**WAA (L/s)**
Coastal aquifer	200	0	150	0	0	na	50	43	0	7	0	7
Other aquifer 1	1000	0	500	500	0	0	0	0	0	0	0	0
Other aquifer 2	1000	0	500	375	125	0.25	125	81	54	44	27	71
Other aquifer 3	1000	0	500	250	250	0.5	250	163	108	87	55	142
Other aquifer 4	1000	0	500	125	375	0.75	375	244	161	131	83	214
Other aquifer 5	1000	0	500	0	500	1	500	325	215	175	110	285
Other aquifer 6	1000	100	500	0	600	1	600	390	258	210	132	342
Other aquifer 7	1000	200	500	600	100	0.14	100	65	43	35	22	57

Some conservative estimates of water budget components were made in the translation of water budget components to the estimates of WAA. For example:

- P and ET are adjusted to balance the water budget (Section 3.3.5);
- groundwater inflow to Holocene beach sediments is assumed as zero, which is consistent with water budgets indicating that all groundwater recharge returns to rivers and streams in the Opotiki-Ohope area. The assumption means that WAA from these sediments was related only to water budget components for the unit.
- MFL^{GW} in non-coastal aquifers is the greater of 65% of the groundwater recharge or MFL^{SW}.

Current water allocation and estimated use (Section 3.3.6) were compared with estimates of GAA and SAA for three purposes. Firstly, current groundwater allocation in the Opotiki-

Ohope area is relevant to the Ministry for the Environment (2008) guideline because allocation limits are set to current allocation where current allocation is greater than a percentage of average annual recharge (Section 2.3.1). Secondly, an assessment of the relation between current groundwater allocation and GAA is useful to BOPRC in regards to the sustainability of current groundwater allocation; and thirdly, calculations of current groundwater and surface water allocation can be compared with MFL^{SW} to assess the sustainability of current surface water allocation.

The approach used to estimate GAA was similar to that used in the Western Bay of Plenty area (White et al., 2009) aiming to preserve base flows in streams. However, the water availability calculations for the Opotiki-Ohope area consider surface water flows because surface quick flow is a very important component of the water budget in the area. This is due to the relatively poor permeability of greywacke basement and Pleistocene units and relatively steep topographic gradients in the Opotiki-Ohope area. In contrast, surface water flow in the Western Bay of Plenty is dominated by base flow (White et al., 2009).

4.0 RESULTS

4.1 Geologic model

4.1.1 Major geologic units and unit properties

The geologic model of the Opotiki-Ohope area (figures 16-18) included the four groupings of major geologic units and fault blocks bounded by the Waimana and Waiotahi faults (Figure 4). Layer boundaries were represented above an elevation of -400 m (i.e., 400 m below sea level) because no wells with geologic logs penetrate below this elevation (Table 2). The four groupings of geologic units simplify the actual geology in the study area and represent units at the subregional scale that are important for groundwater flow, as described in the following.

Basement undifferentiated: Basement structure and faults (Figure 16) were defined by Figure 3 (Mouslopoulou, 2006; Mouslopoulou et al., 2008), geologic cross sections (Leonard et al., 2010) and well logs. Basement greywacke is penetrated by wells within the study area and the majority of these wells are located in the vicinity of greywacke outcrops (Figure 19). Therefore wells that intersect greywacke provide only limited information on the thickness of Quaternary sediments above greywacke. The basement is important for groundwater flow in the Opotiki-Ohope area as it probably constrains groundwater recharge from rainfall or rivers, in the area north of basement exposure (Figure 2), to travel toward the coast through Quaternary sediments.

Pleistocene units: The top surface of this aggregated unit was defined by the ground surface where these units crop out and by the thickness of the Holocene sediments measured in well logs elsewhere. Pleistocene mudstone is commonly identified by well logs in this unit (Figure 20). Layer boundaries that represent oxygen isotope stages within the Pleistocene units (Table 1) were not developed in the Ohope-Ohiwa area because gravel and shell lithologic descriptors are typically discontinuous within these units. However, shallow and deep gravel layers have possibly been identified in the Tirohanga area with top surfaces in the elevation ranges approximately -8 to -13 m RL and -13 to -27 m RL, respectively. Few occurrences of shell have been observed in well logs of Pleistocene sediments. For example, shallow and deep shell layers have possibly been identified in the Paerata Ridge area with top surfaces in the elevation ranges approximately 5 m to 0 m RL and -51 to -69 m RL, respectively.

Gravel sediments occur beneath much of the Opotiki Plain (Figure 21) and much of this gravel is probably Pleistocene Q2 in age (Figure 22), although the boundary of Pleistocene and Holocene units is difficult to identify (Section 3.1.5). Pleistocene-age gravels, commonly described as brown in colour, were probably associated with pre-historic channels of the Waioeka and Otara rivers. These gravels have a maximum depth of approximately -70 m RL in the Waioeka River valley and are logged to -200 m RL beneath the Otara River flats. The top surface of Pleistocene sediments is possibly at most -40 m DL near the coast beneath the Opotiki Plain (Section A, Figure 23). However, the Holocene-Pleistocene boundary may be up to approximately 50 m deep at the coast, as identified in the Rangitaiki Plains (White et al., 2010). The top surface of Pleistocene sediments is an estimated minimum of approximately - 5 m RL near the Waioeka Gorge (Section B, Figure 23).

Pleistocene units are important for groundwater flow as they occupy most of the agricultural area. These units crop out at ground level over much of the area (Figures 2 and 4) and, where they do (Figure 2), form the only groundwater supply. Q2 gravel is an important aquifer for groundwater supply beneath the Opotiki Plain because most wells with consents take water from this unit (Table 6).

The hydraulic conductivity of Early Pleistocene (eQu) and Middle Pleistocene (mQu) sediments is probably relatively low because the specific capacity of wells that take groundwater from these units is relatively low (Table 6). In contrast, the specific capacity of wells that probably take groundwater from the Pleistocene Q2 unit is relatively high (Table 6).

Table 6 Specific capacity statistics for wells with pump tests in the Opotiki-Ohope area.

Geologic unit	Specific capacity				
	Median (L/s/m)	Mean (L/s/m)	Range (L/s/m)	Standard deviation (L/s/m)	Number of measurements
Holocene[1]	27.5	27.5	na	na	1
Pleistocene Q2[1]	5.9	12.7	0.4 to 83.3	17.3	30
Pleistocene other (eQu and mQu)	0.2	0.3	0.2 to 0.6	0.2	6

[1] Most wells take groundwater from gravel aquifers.

Matahina Formation is aggregated with Pleistocene sediments for the purpose of the geologic model and the water budget. This is because the spatial distribution of Matahina Formation at the ground surface within the study area is very limited (Figure 2) and the subsurface extent of Matahina Ignimbrite could not be determined reliably from well logs. Approximately eight well logs record the occurrence of ignimbrite in the Opotiki-Ohope area, probably referring to pumice layers sourced from the Okataina and Taupo volcanic areas.

Holocene alluvium: This model unit (Figure 18) includes shallow deposits of gravel, peat, sand and pumice. The thickness of the unit has been estimated from wells penetrating into underlying Pleistocene sediments. Holocene gravel sediments are common beneath the Opotiki Plain (Figure 22). However, the boundary between Holocene and Pleistocene gravels was not clear and judgement was required to estimate this boundary. Holocene alluvium was estimated as up to 30 m thick near the coast (section A, Figure 23) and up to 15 m thick near the Waioeka Gorge (section B, Figure 23).

Holocene alluvium is important for groundwater flow because this unit occupies all of the Opotiki Plain (Figure 2). Holocene sediments take all recharge from rainfall and rivers on the Opotiki Plain. These sediments also supply groundwater to Pleistocene gravels. The hydraulic conductivity of Holocene gravel is probably relatively high because the specific capacity of a well that takes groundwater from this unit is relatively high (Table 6).

Holocene beach sediments: The distribution of this model unit (Figure 18 and section C, Figure 23) was based on: the occurrence of mapped beach deposits (Figure 2), the depth of shells in geologic logs, occurrences of sand in geologic logs and the depth of wells. The depth of Holocene beach sediments is estimated as 20 m; this is the rounded average depth of geologic logs which is consistent with the depth of sand estimated with the sand property model. However, the sand property model shows sand deposits with a thickness of up to 250 m in the vicinity of Waiotahi Beach which indicated the difficulties in determining the boundary between Holocene and Pleistocene sediments using a model of sand distribution in the area. Shell-bearing lithologies are commonly recorded in well logs of this unit with the main shell occurrences along Ohope Beach and in the vicinity of the estuary (Figure 24). Only minor occurrences of gravel were recorded in wells that intersect Holocene beach sediments.

The hydraulic conductivity of Holocene beach sediments is probably relatively high due to the occurrence of sands, gravels and shells in the unit as recorded by geologic logs. However no aquifer tests of this unit have been completed in the Opotiki-Ohope area.

4.2 Water budget with natural flows

Water budget components were estimated in groundwater catchments with Equation 6 aiming to represent natural flows using P_A and ET_A (Section 3.3.5), Table 7. Companion water budgets for groupings of geologic units in the four groundwater catchments are described in Section 4.3.

Table 7 Water budget for the Opotiki-Ohope area for natural flows.

Groundwater catchment	Area (km^2)	P_A (L/s)	ET_A (L/s)	Q^{SW}_{QF} (L/s)	Q^{SW}_{BF} (L/s)	U^{SW} (L/s)	U^{GW} (L/s)	Q^{GW}_{COUT} (L/s)
Ohope-Ohiwa	186.4	11615	6543	1132	3881	0	0	59
Waiotahi	148.0	9987	4729	1611	3641	0	0	6
Opotiki	926.2	67026	25614	14009	26362	0	0	1041
Tirohanga	150.6	14710	7297	2282	5082	0	0	49
Total	1411.2	103338	44183	19034	38966	0	0	1155

The rainfall total in the Opotiki-Ohope area water budget is approximately 103 m^3/s and evaporation is the largest outflow from the area of rainfall (Table 7). Surface water base flow, approximately 39 m^3/s, comes from the groundwater system and is relevant to the assessment of groundwater and surface water allocation (Section 4.3).

Groundwater discharge at the coast, which totals approximately 1.1 m^3/s, is a very small proportion of the water budget. This is because the water budget indicates that a large proportion of groundwater recharge returns to rivers and streams, possibly due to the predominance of relatively low permeability (Table 6) in early – middle Pleistocene sediments at the coast. Relatively large groundwater returns to surface water is a common feature of other coastal groundwater systems in New Zealand (e.g., White et al., 2012). Groundwater discharge at the coast is assumed to come from Holocene beach sediments alone (Section 4.3).

The Opotiki groundwater catchment has the largest flows in the Opotiki-Ohope area. This is because the groundwater catchment is the largest in the area. Most of this groundwater catchment consists of greywacke ranges with the largest annual average rainfall in the area (Figure 1).

The BFI at flow recorder sites in the Opotiki-Ohope area (Table 8) averages 0.70, similar to a weighted average BFI of approximately 0.66 in the 12 catchments near the coast. Therefore, surface water quick flow is a large component of the water budget indicating the importance of quick flow and base flow (Section 4.2.1) to an understanding of water budgets and to calculation of GAA and SAA (Section 4.3).

4.2.1 Estimates of quick flow and base flow

The BFI at flow recorder sites was broadly related to the coverage of Quaternary sediments in each catchment (Table 8). The correlation between BFI and QC has a Spearman rank correlation coefficient of 0.94 and a p-value of 0.001 indicating a weak correlation.

BFI mean annual quick flow, mean annual base flow, and uncertainties for the synthetic flow sites (Table 9) were estimated using Equation 8 with values of coefficients a and b of 0.0019 and 0.64, respectively, calculated from the data in Table 8. The maximum mean annual quick flow values and minimum mean annual base flow values correspond to the minimum BFI. The opposite applies for the minimum mean annual quick flow and maximum mean annual base flow. BFI in the largest rivers (Waioeka and Otara) is 0.65, which is a little lower than other rivers and streams.

Table 8 Flow recorder sites: BFI (Equation 9), quick flow and base flow.

Flow recorder site	Recession coefficient, k	Standard deviation of k	Base flow separation parameter, C	Base flow index, BFI	Quaternary coverage in catchment QC (%)	Measured mean annual flow (m^3/s)	Modelled mean annual flow (WRENZ) (m^3/s)	Mean annual quick flow (m^3/s)	Mean annual base flow (m^3/s)
4008687	0.953	0.0249	0.02	0.69	6.4	4.97	3.64	1.54	3.43
4009720(a)	0.958	0.013	0.015	0.73	82.1	0.064	0.083	0.014	0.05
4009720(b)	0.959	0.0111	0.03	0.88	90	0.0024	Too small to be resolved	0.0003	0.0021
4009666	0.951	0.0265	0.02	0.69	3.9	14.4	16.8	4.46	9.94
4011135	0.953	0.0144	0.02	0.75	64.7	1.85	2.24	0.46	1.39
4011726	0.965	0.0096	0.012	0.65	0.5	12.2	13.1	4.27	7.93
4012141	0.948	0.0196	0.02	0.68	0.5	35.8	36.5	11.46	24.34
4016938	0.961	0.0156	0.01	0.55	0.9	31.5	31.5	14.17	17.33

Table 9 Synthetic flow sites: BFI, quick flow and base flow analysis.

Site ID	Catchment number(s)	Mean annual discharge (L/s)		Catchment area (km^2)	BFI (central value [min, max])	Mean annual quick flow (L/s)			Mean annual base flow (L/s)			Specific discharge (L/s/km^2)	Specific quick flow (L/s/km^2)			Specific base flow (L/s/km^2)		
		Modelled (WRENZ)	Adjusted			Central value	Max	Min	Central value	Min	Max		Central value	Max	min	Central value	min	max
4007551	N15	194	187	8.1	0.76 [0.55,0.88]	45	84	22	141	103	164	23	6	10	3	17	13	20
4007938	N20	44	42	1.8	0.83 [0.55,0.88]	7	19	5	35	23	37	23	4	11	3	19	13	21
4008273	N21	45	43	1.7	0.83 [0.55,0.88]	7	19	5	36	24	38	25	4	11	3	21	14	22
4008473	N12+N13	587	564	19	0.69 [0.55,0.88]	175	254	68	389	310	496	30	9	13	4	21	16	26
4008420	N17	125	120	4.6	0.8 [0.55,0.88]	24	54	14	97	66	106	26	5	12	3	21	15	23
4008506	N6+N7+N16 +N18	5171	4964	139.4	0.69 [0.55,0.88]	1523	2234	596	3441	2730	4368	36	11	16	4	25	20	31
4008818	N1+N2+N3+ N11+N14+ south of zone	38008	36488	836.6	0.65 [0.55,0.88]	12799	16420	4379	23689	20068	32109	44	15	20	5	28	24	38
4008881	N4+N5+N23 +N24	17052	16370	329.1	0.65 [0.55,0.88]	5690	7366	1964	10680	9003	14405	50	17	22	6	32	27	44
4009290	N8+N10	3291	3160	102.6	0.77 [0.55,0.88]	724	1422	379	2435	1738	2780	31	7	14	4	24	17	27

Site ID	Catchment number(s)	Mean annual discharge (L/s)		Catch-ment area (km^2)	BFI (central value	Mean annual quick flow (L/s)			Mean annual base flow (L/s)			Specific discharge (L/s/km^2)	Specific quick flow (L/s/km^2)			Specific base flow (L/s/km^2)		
		Modelled (WRENZ)	Adjusted		[min, max])	Central value	Max	Min	Central value	Min	Max		Central value	Max	min	Central value	min	max
4009382	N13	380	365	12.2	0.67 [0.55,0.88]	119	164	44	246	201	321	30	10	13	4	20	16	26
4009455	N16	165	159	6.5	0.8 [0.55,0.88]	32	71	19	126	87	140	24	5	11	3	19	13	21
4010172	N11	682	655	25.4	0.73 [0.55,0.88]	174	295	79	481	360	577	26	7	12	3	19	14	23
4009940	N22	29	28	1	0.83 [0.55,0.88]	5	13	3	23	15	24	28	5	13	3	23	15	25
4010018	N18	159	152	4.3	0.78 [0.55,0.88]	34	69	18	118	84	134	35	8	16	4	27	19	31
4010057	N14	306	294	11	0.7 [0.55,0.88]	89	132	35	205	162	258	27	8	12	3	19	15	24
4010340	N7	4436	4259	111.3	0.66 [0.55,0.88]	1437	1916	511	2822	2342	3748	38	13	17	5	25	21	34
4011596	N2+N3+ south of zone	36517	35056	783.2	0.64 [0.55,0.88]	12512	15775	4207	22544	19281	30849	45	16	20	5	29	25	39
4011726	N23	13105	12581	239.8	0.64 [0.55,0.88]	4518	5661	1510	8063	6919	11071	52	19	24	6	34	29	46
4011753	N24	2989	2869	58.2	0.64 [0.55,0.88]	1026	1291	344	1843	1578	2525	49	18	22	6	32	27	43

4.2.2 Groundwater – surface water interaction

The distribution of surface water gaugings in the Opotiki-Ohope area was not suited to an assessment of groundwater-surface water interaction. Gauging measurements in the Opotiki Plain are common (Figure 14). However, sets of simultaneous low-flow gaugings are uncommon with no such sets of gaugings measuring flows in the Waioeka River. Three simultaneous gaugings in the Otara River on 7/9/2005 measured a modest gain in flow between the top of the Plain (Campbells and Browns Bridge gauging sites, with a combined flow of 5129 L/s) and Gault Road (No. 2) Bridge with a flow of 5177 L/s. Note that this apparent gain in flow could be a function of limitations in the accuracy of gauging measurements and, therefore, not necessarily a real gain. Groundwater outflow to surface water in the Opotiki Plain is indicated by two pairs of gaugings that measure an average gain in flow of approximately 170 L/s in Mill Stream between SH 2 Bridge and the Waioeka River confluence.

4.3 Water budget for geologic units and water available for allocation

Water budget components were estimated for geologic units (Section 3.3.5) in groundwater catchments consistent with the sums of water flows in each catchment (Table 7). These budgets include groundwater outflow (i.e., where Q^{GW}_{IN} is negative) for geologic units that lose groundwater to adjacent units.

Minimum flows and water available for allocation (Section 3.4) were compared with water budget estimates (tables 10-14). WAA is typically limited by $Q_{5\ 7\text{-day}}$ surface water flow as $Q^{SW}_{BF} - WAA = Q_{5\ 7\text{-day}}$ for basement, Pleistocene units and Holocene alluvium. WAA in the area of basement is approximately 72% of the total WAA in the Opotiki-Ohope area (Table 14).

The Opotiki groundwater catchment has the largest WAA and water flows in the Opotiki-Ohiwa area (Table 12 and Section 4.2). WAA in the Holocene alluvium area is larger than WAA in the Pleistocene units. Gains in flow across the Opotiki Plain are consistently measured by water budgets, river flow estimates and simultaneous low-flow gaugings. Therefore, it is likely that most groundwater recharge returns to the surface in the Plain, and groundwater use has the potential to impact on surface water flows.

Surface waters gain an estimated 2.3 m^3/s across the Plain. This gain is the difference between estimated flow near the coast (i.e., approximately 52.9 m^3/s at Waioeka River site 408818 and Otara River site 400881) and estimated flow at the top of the Plain (i.e., approximately 50.6 m^3/s at Waioeka River site 4011596 and Otara River sites 4011726 and 4011753), Figure 15 and Table 9. The few simultaneous low-flow gaugings on the Plain also indicate that the Otara River and Mill Stream gain flow (Section 4.2.2). In the Tirohanga groundwater catchment, WAA in the Holocene alluvium is larger than Pleistocene units due to the relatively large extent of alluvium (Table 13). Total WAA in the Holocene alluvium unit was larger than WAA in the Pleistocene units, because groundwater inflow to Holocene alluvium is relatively large.

Table 10 Water budget and water allocation calculations, Ohope-Ohiwa groundwater catchment.

Groundwater catchment	**Geologic unit**	**Water budget**										**Water allocation**				
		Area (km^2)	**P_A (L/s)**	**Q_{GR} (L/s)**	**ET_A (L/s)**	**Q^{SW}_{QF} (L/s)**	**Q^{SW}_{BF} (L/s)**	**U^{SW} (L/s)**	**U^{GW} (L/s)**	**Q^{GW}_{COUT} (L/s)**	**R (L/s)**	**MFL^{GW} (L/s)**	**MFL^{SW} ($Q_{5\ 7\text{-day}}$) (L/s)**	**GAA (L/s)**	**SAA (L/s)**	**WAA (L/s)**
Ohope-Ohiwa	Holocene beach	5.5	215	0	156	0	0	0	0	59	59	50	0	9	0	9
Ohope-Ohiwa	Holocene alluvium	22.8	1184	308	671	251	570	0	0	0	570	371	245	199	126	325
Ohope-Ohiwa	Pleistocene units	116.3	5896	399	3387	582	2326	0	0	0	2326	1512	1000	814	512	1326
Ohope-Ohiwa	Basement	41.8	4320	-707	2329	299	985	0	0	0	985	640	424	345	216	561
Ohope-Ohiwa	Total	186.4	11615	0	6543	1132	3881	0	0	59	3940	2573	1669	1367	854	2221

Table 11 Water budget and water allocation calculations, Waiotahi groundwater catchment.

Groundwater catchment	**Geologic unit**	**Water budget**										**Water allocation**				
		Area (km^2)	**P_A (L/s)**	**Q_{GR} (L/s)**	**ET_A (L/s)**	**Q^{SW}_{QF} (L/s)**	**Q^{SW}_{BF} (L/s)**	**U^{SW} (L/s)**	**U^{GW} (L/s)**	**Q^{GW}_{COUT} (L/s)**	**R (L/s)**	**MFL^{GW} (L/s)**	**MFL^{SW} ($Q_{5\ 7\text{-day}}$) (L/s)**	**GAA (L/s)**	**SAA (L/s)**	**WAA (L/s)**
Waiotahi	Holocene beach	0.5	20	0	14	0	0	0	0	6	6	5	0	1	0	1
Waiotahi	Holocene alluvium	18.8	937	-53	545	19	320	0	0	0	320	208	138	112	70	182
Waiotahi	Pleistocene units	29	1360	172	836	145	551	0	0	0	551	358	237	193	121	314
Waiotahi	Basement	99.7	7670	-119	3334	1447	2770	0	0	0	2770	1801	1191	969	610	1579
Waiotahi	Total	148	9987	0	4729	1611	3641	0	0	6	3647	2372	1566	1275	801	2076

Table 12 Water budget and water allocation calculations, Opotiki groundwater catchment.

Groundwater catchment	Geologic unit	Water budget										Water allocation				
		Area (km^2)	P_A (L/s)	Q_{GR} (L/s)	ET_A (L/s)	Q^{SW}_{QF} (L/s)	Q^{SW}_{BF} (L/s)	U^{SW} (L/s)	U^{GW} (L/s)	Q^{GW}_{COUT} (L/s)	R (L/s)	MFL^{GW} (L/s)	MFL^{SW} ($Q_{5\ 7\text{-day}}$) (L/s)	GAA (L/s)	SAA (L/s)	WAA (L/s)
Opotiki	Holocene beach	28.3	1771	0	730	0	0	0	0	1041	1041	885	0	156	0	156
Opotiki	Holocene alluvium	61.8	3144	5377	1785	2101	4635	0	0	0	4635	3013	1993	1622	1020	2642
Opotiki	Pleistocene units	37.8	1742	326	1085	151	832	0	0	0	832	541	358	291	183	474
Opotiki	Basement	798.3	60369	-5703	22014	11757	20895	0	0	0	20895	13582	8985	7313	4597	11910
Opotiki	Total	926.2	67026	0	25614	14009	26362	0	0	1041	27403	18021	11336	9382	5800	15182

Table 13 Water budget and water allocation calculations, Tirohanga groundwater catchment.

Groundwater catchment	Geologic unit	Water budget										Water allocation				
		Area (km^2)	P_A (L/s)	Q_{GR} (L/s)	ET_A (L/s)	Q^{SW}_{QF} (L/s)	Q^{SW}_{BF} (L/s)	U^{SW} (L/s)	U^{GW} (L/s)	Q^{GW}_{COUT} (L/s)	R (L/s)	MFL^{GW} (L/s)	MFL^{SW} ($Q_{5\ 7\text{-day}}$) (L/s)	GAA (L/s)	SAA (L/s)	WAA (L/s)
Tirohanga	Holocene beach	3.3	144	0	95	0	0	0	0	49	42	42	0	7	0	7
Tirohanga	Holocene alluvium	13.5	937	1080	545	459	1013	0	0	0	1013	658	436	355	222	577
Tirohanga	Pleistocene units	15.5	714	138	449	62	341	0	0	0	341	222	147	119	75	194
Tirohanga	Basement	118.3	12915	-1218	6208	1761	3728	0	0	0	3728	2423	1603	1305	820	2125
Tirohanga	Total	150.6	14710	0	7297	2282	5082	0	0	49	5124	3345	2186	1786	1117	2903

Table 14 Sum of water budget and water allocation calculations Opotiki-Ohope area.

Groundwater catchment	Geologic unit	Water budget										Water allocation				
		Area (km^2)	P_A (L/s)	Q_{GR} (L/s)	ET_A (L/s)	Q^{SW}_{QF} (L/s)	Q^{SW}_{BF} (L/s)	U^{SW} (L/s)	U^{GW} (L/s)	Q^{GW}_{COUT} (L/s)	R (L/s)	MFL^{GW} (L/s)	MFL^{SW} ($Q_{5\ 7\text{-day}}$) (L/s)	GAA (L/s)	SAA (L/s)	WAA (L/s)
All catchments	Holocene beach	37.6	2150	0	995	0	0	0	0	1155	1148	982	0	173	0	173
All catchments	Holocene alluvium	116.9	6202	6712	3546	2830	6538	0	0	0	6538	4250	2812	2288	1438	3726
All catchments	Pleistocene units	198.6	9712	1035	5757	940	4050	0	0	0	4050	2633	1742	1417	891	2308
All catchments	Basement	1058.1	85274	-7747	33885	15264	28378	0	0	0	28378	18446	12203	9932	6243	16175
All catchments	Total	1411.2	103338	0	44183	19034	38966	0	0	1155	40114	26311	16757	13810	8572	22382

4.4 Water allocation and use

Water allocation and estimated groundwater use is largest in the Opotiki groundwater catchment (Table 15)

Table 15 Estimated water allocation and use for current water consents and permitted groundwater takes (Section 3.3.6).

Groundwater catchment	Surface water		Groundwater				Total	
	Consented allocation (L/s)	Estimated use (L/s)	Consented allocation (L/s)	Estimated use (L/s)	Permitted use (L/s)	Total estimated use (L/s)	Allocation (L/s)	Estimated use (L/s)
Ohope-Ohiwa	27	4	0	0	29	29	27	33
Waiotahi	0	0	0	0	35	35	0	35
Opotiki	166	35	786	280	76	356	952	391
Tirohanga	59	13	23	7	18	25	82	38
Total	252	52	809	287	158	445	1061	497

Groundwater use is larger than surface water use in the Opotiki-Ohope area as total groundwater use is approximately 88% of total water use. Estimated use by permitted groundwater takes is approximately 30% of the total use. However, estimated use by permitted surface water takes was assumed as zero (Section 3.3.6), which may not be true. Water allocation is largest for frost protection, and use by irrigation is the largest, of the three consented water use classes (Table 16).

Table 16 Type of consent, type of use, allocation and estimated use.

Type of consent	Type of use	Surface water		Groundwater		Total	
		Allocation (L/s)	Estimated use (L/s)	Allocation (L/s)	Estimated use (L/s)	Allocation (L/s)	Estimated use (L/s)
Consented	Frost protection	161	14	321	25	482	39
	Irrigation	91	38	386	160	477	198
	Municipal	0	0	102	102	102	102
Permitted	Domestic and stock	0	0	0	158	0	158
Total		252	52	809	438	1061	497

4.5 Water available for allocation, current allocation and estimated use

Holocene alluvium and Pleistocene units are the most important for water allocation and water use (Table 17) because most agricultural activity occurs on these units and most of the population take their water supply from these units. Pleistocene aquifers are probably the most important groundwater source in the Opotiki-Ohope area because much of the groundwater pumped from the Holocene alluvium aquifers probably flows from the Late Pleistocene gravel aquifer (Section 4.1.1). Total WAA is largest in the basement unit. However little, if any, of this water is used (Table 17) as the area has no consents for water use (Table 17, Figure 5), few wells (Figure 2) and includes large forests held by the Department of Conservation and Te Urewera National Park.

The Opotiki groundwater catchment has the largest estimated water use and allocation in the Opotiki-Ohope area (Table 17). Geologic units in this catchment also have the largest allocation relative to water available for allocation. For example, surface water allocation is equivalent to 15% of SAA (i.e., 154/1020, Table 17), and groundwater allocation equivalent to 42% of GAA (i.e., 687/1622, Table 17), within the Holocene alluvium unit.

Table 17 GAA and SAA compared with water allocation and estimated water use.

Groundwater catchment	Geologic unit	Surface water				Groundwater			
		MFL^{SW} (L/s)	SAA (L/s)	Allocation (L/s)	U^{SW} (L/s)	MFL^{GW} (L/s)	GAA (L/s)	Allocation (L/s)	U^{GW} (L/s)
Ohope-Ohiwa	Holocene beach	0	0	0	0	50	9	0	0
Ohope-Ohiwa	Holocene alluvium	245	126	27	4	371	199	0	11
Ohope-Ohiwa	Pleistocene units	1000	512	0	0	1512	814	0	18
Ohope-Ohiwa	Basement	424	216	0	0	640	345	0	0
Ohope-Ohiwa	Total	1669	854	27	4	2573	1367	0	29
Waiotahi	Holocene beach	0	0	0	0	5	1	0	0
Waiotahi	Holocene alluvium	138	70	0	0	208	112	0	13
Waiotahi	Pleistocene units	237	121	0	0	358	193	0	21
Waiotahi	Basement	1191	610	0	0	1801	969	0	1
Waiotahi	Total	1566	801	0	0	2372	1275	0	35
Opotiki	Holocene beach	0	0	0	0	885	156	0	1
Opotiki	Holocene alluvium	1993	1020	154	32	3013	1622	687	299
Opotiki	Pleistocene units	358	183	12	3	541	291	99	50
Opotiki	Basement	8985	4597	0	0	13582	7313	0	6
Opotiki	Total	11336	5800	166	35	18021	9382	786	356

Groundwater catchment	Geologic unit	Surface water				Groundwater			
		MFL^{SW} (L/s)	SAA (L/s)	Allocation (L/s)	U^{SW} (L/s)	MFL^{GW} (L/s)	GAA (L/s)	Allocation (L/s)	U^{GW} (L/s)
Tirohanga	Holocene beach	0	0	0	0	42	7	2	5
Tirohanga	Holocene alluvium	436	222	59	13	658	355	19	11
Tirohanga	Pleistocene units	147	75	0	0	222	119	2	7
Tirohanga	Basement	1603	820	0	0	2423	1305	0	2
Tirohanga	Total	2186	1117	59	13	3345	1786	23	25
All catchments	Holocene beach	0	0	0	0	982	173	2	6
All catchments	Holocene alluvium	2812	1438	240	49	4250	2288	706	334
All catchments	Pleistocene units	1742	891	12	3	2633	1417	101	96
All catchments	Basement	12203	6243	0	0	18446	9932	0	9
All catchments	Total	16757	8572	252	52	26311	13810	809	445

5.0 RECOMMENDATIONS

This section makes recommendations on BOPRC policies in regards of water allocation in the Opotiki-Ohope area. Policies on minimum groundwater flows and minimum surface water flows could be considered by EBOP as these flows are crucial to the estimates of groundwater and surface water allocation. Co-management of groundwater and surface water would be useful because these water bodies are linked in the area and therefore policies on the management and groundwater and surface water should recognise these links. Recommendations also aim at improved estimates of minimum flows and groundwater budget components by collecting more environmental information thus allowing increased confidence in water allocation limits.

5.1 BOPRC policies

5.1.1 Minimum flows

Minimum surface water flow (MFL^{SW}) and minimum groundwater flow (MFL^{GW}) are two key numbers that control groundwater and surface water available for allocation (GAA and SAA, respectively). This report follows current BOPRC practice by defining MFL^{SW} as $Q_{5\ \text{7-day}}$ flow and MFL^{GW} based on Ministry for the Environment (2008) guidelines. However, these minimum flows may not be suitable to meet environmental targets (e.g., for water flow and water quality) in the Opotiki-Ohope area.

Therefore, BOPRC could review minimum flow targets in the area. If required, this assessment could be completed for all groundwater and surface water catchments. This assessment could include specifying environmental data requirements, and methods for calculating minimum flows.

5.1.2 Co-management of groundwater and surface water

This report demonstrates that GAA and SAA are not independent within Opotiki-Ohope area. This is because groundwater recharge returns as baseflow to rivers and streams, except in the Holocene beach sediment unit. Hence, groundwater use could impact on stream flow and MFL^{SW} is relevant to both GAA and SAA.

For that reason, it would be appropriate for BOPRC to develop a water management regime that aims to manage groundwater and surface water together. This report includes a demonstration of a catchment-scale regime that links calculations of GAA and SAA through the definitions of MFL^{GW} and MFL^{SW}. However, BOPRC may wish to use an alternative regime, for example SAA could be maximised by defining MFL^{GW} so that GAA equals zero.

Current approaches by BOPRC to manage groundwater and surface water at the local scale (e.g., assessment of stream depletion due to groundwater pumpage) should continue. This is because availability of water at the catchment scale, as assessed in this report, does not guarantee water availability at the local scale.

5.1.3 Water allocation as a fraction of GAA and SAA

BOPRC could consider policies on the proportion of GAA and SAA to allocate. GAA and SAA, as defined in this report, represent the maximum allocation available for use. However, it may not be prudent to allocate all this water (e.g., because of uncertainties in estimates of MFL^{GW} and MFL^{SW}). Therefore, it could be considered prudent to allocate up to 50% of GAA and SAA to ensure that environmental targets are met.

5.1.4 Salt water intrusion

Little groundwater is available for allocation from Holocene beach sediments (Table 17) because these sediments are restricted in distribution and the proximity of these sediments to the sea means that salt water intrusion is a risk to groundwater quality. It is therefore recommended that BOPRC develop allocation policies for the Holocene beach sediments, considering water budget components that aim to reduce the potential for salt water intrusion to groundwater.

5.1.5 Allocation from groundwater storage

BOPRC could consider policies to allocate groundwater from storage (i.e., beyond sustainable allocation limits), as allocation from storage may be suitable in emergency situations. Allocation of groundwater from storage is generally not good practice as this can lead to mining of the groundwater resource, which cannot be sustained; however, it may be suitable in emergency situations (e.g., fire or failure of drinking water supplies in natural disasters). Therefore, stringent rules around allocation of groundwater from storage in emergency situations, and rules that identify an emergency situation, could be developed.

5.2 Measurement of minimum surface flows

This report uses estimates of surface water base flow to calculate MFL^{SW} (i.e., $Q_{5\ 7\text{-day}}$ flow) and the uncertainty in these flows is quite large (e.g., Table 9). Therefore, additional measurements of surface flows would reduce the uncertainty in estimates of these flows. BOPRC holds records of low flow in the Opotiki-Ohope area. Most low-flow gaugings have occurred in streams that lack permanent flow recorder sites. This is not suitable for the assessment of $Q_{5\ 7\text{-day}}$ flow.

Generally, targeted measurements of base flow, with a programme of low-flow gaugings, will improve our knowledge of low flow and outflow from the groundwater system. Therefore it is recommended that BOPRC review its low-flow measurement programme in the Opotiki-Ohope area with regard to:

- the location of flow gauging sites to measure base flow discharge from groundwater catchments identified in this report. Ideally, gauging sites should be located at the bottom of groundwater catchments but outside the area of marine tidal influence;
- the location of sites that could indicate surface water discharge to groundwater (and vice versa);
- groundwater–surface water interaction associated with the Waioeka and Otara rivers, including spring-fed streams on the Opotiki Plain;
- prioritisation for measurement; and
- frequency of measurement.

It is also recommended that BOPRC incorporate low-flow measurements in rivers, streams and drains at priority sites in its summer gauging programme for the purpose of calculating base flow and $Q_{5\ 7\text{-day}}$ surface flow.

5.3 Groundwater budget components

BOPRC could consider further groundwater investigations in catchments that have potential stress from groundwater use to improve knowledge of groundwater recharge and groundwater use. These investigations would aim to assess, for example:

- measurements of groundwater recharge from rainfall
- estimates of base flow in streams;
- hydrologic properties (e.g., hydraulic conductivity);
- effects of groundwater use on groundwater levels at the catchment scale;
- effects of pumping on groundwater levels in neighbouring wells; and
- effects of groundwater pumping on stream flow.

It is also recommended that datasets be developed in a GIS format to allow convenient access to information including: surface water flow, groundwater flow and water allocation limits (when determined by BOPRC from GAA and SAA estimates). BOPRC could also provide a convenient information system on water allocation, linked groundwater–surface water allocation, by integrating data on surface water allocation with data on groundwater allocation within common geographic units (i.e., groundwater catchments).

5.4 Geologic model

The geologic model of the Opotiki-Ohope area has been developed with available surface geologic information and driller's log records held by BOPRC. Lithologic data collected from future drill holes will be used to refine this model. The following recommendations are for the purpose of assisting future model revisions:

- drill, log and test shallow monitoring wells to assess the distribution of key lithologies described in this report. Test wells are suggested for: 1) Ohope Beach (to assess the estimated 20 m depth of Holocene sediments and the risks of salt water intrusion); 2) between Opotiki township and the coast to assess the risks of salt water intrusion, the location of Q2 sediments near the coast and the evidence that all groundwater recharge on the Opotiki Plain discharges to surface water; and 3) near the intersection of State Highway 2 and Clark Cross Rd to assess the location of Q2 sediments.

- assess the distribution of relatively permeable sediments (e.g., gravel and sand) within Pleistocene units. This may show the locations of potential aquifers. This assessment could include the Pleistocene terraces (e.g., Paerata Ridge). Permeabilities of Pleistocene units below the Pleistocene terraces are likely to be low because the terraces are mid–early Pleistocene in age.

5.5 Salt water intrusion

Ground level is near sea level in wells located near the coast. Hence pumping groundwater from wells near the coast may drawdown water levels below sea level. Sea water intrusion is always a potential risk to groundwater near the coast. Collection of groundwater elevation data, pumping data and relevant aquifer properties (e.g., hydraulic conductivity) would be helpful in assessing the risks of salt water intrusion in the area.

It is recommended that:

- the locations of wells near the coast be surveyed;
- ground elevations and well reference points for water level measurements at the wells, are determined by surveying. This allows calculation of static groundwater elevation when water level depth below the reference point is measured;
- wells where the groundwater level is very near, at, or below sea level may be at risk from salt water intrusion;
- drawdowns during pumping and groundwater levels after pumping be considered in this analysis;
- BOPRC consult with well owners and discuss possible future actions; and
- BOPRC review estimates of groundwater available for allocation in groundwater catchments if static groundwater levels are shown to be very near, at, or below sea level.

5.6 Groundwater chemistry

Groundwater chemistry data in the Opotiki-Ohope area were not reviewed in this report. Therefore it is recommended that groundwater chemistry data be reviewed and that the potential for salt water intrusion and the suitability of groundwater from mid–early Pleistocene units as a water source be evaluated.

5.7 Assessment of uncertainty

Uncertainties have not been rigorously assessed in this report for water budget components, minimum flows, GAA and SAA. Uncertainties in quick flow and base flow components of surface water flow can be large (Table 9). Therefore, this report aims to use a conservative approach in the estimation of GAA and SAA. A rigorous approach to estimating uncertainty in GAA and SAA is recommended. Ideally, this assessment could follow targeted hydrologic, and hydrogeologic, investigations in the Opotiki-Ohope area.

5.8 Model of groundwater recharge and flow

The model of groundwater recharge and surface water flows used in this report is quite simple but is appropriate as a first-cut estimate of water budgets in the Opotiki-Ohope area. It is recommended that the BOPRC consider a more sophisticated model to improve the confidence of groundwater allocation estimates in the catchment. A steady-state MODFLOW or FEFLOW groundwater flow model would be the next logical step to assess groundwater resources in the area. This model could consider geology, rainfall recharge, groundwater flow, groundwater recharge from streams, groundwater outflow to streams, surface water flow and groundwater outflow off shore at the coast. Data sets developed in this report (e.g., the representation of geologic layers, estimates of groundwater flow and calculated surface water quick flow and base flow) are sufficient to commence development of such a model. Ideally, model development could commence after collection of some of the data recommended in the above.

6.0 SUMMARY

Water in the Bay of Plenty’s Opotiki-Ohope area (Figure 1) is extracted from groundwater and surface water for agricultural, commercial, municipal and domestic uses. Use of groundwater is greater than surface water with the groundwater system providing an estimated 88% of all water supplied to users. The use of groundwater is predicted to increase in the future (White, 2005). However, development of water resources has occurred without estimates of surface and groundwater availability. This report summarises geology, surface flow (i.e., quick flow and base flow) and water budgets with the aim of calculating groundwater and surface water available for allocation (GAA and SAA, respectively) to inform future BOPRC policy decisions on water allocation at the catchment scale.

Four groundwater catchments were suggested in this report: Ohope-Ohiwa (i.e., the catchment of Ohiwa Harbour and Ohope); Waiotahi (including the surface catchment of Waiotahi River); Opotiki (including the part of the Waioeka River catchment managed by BOPRC and the Opotiki Plain); and Tirohanga (including the catchments of the Tirohanga and Waiaua rivers). Water budgets were developed for each of these catchments from calculated rainfall, evapotranspiration, surface flows and groundwater outflow across the coastal boundary. The budget assumed that groundwater outflow across the coastal boundary occurs from the Holocene beach sediment unit. For other geologic units, the close connection between groundwater and surface water in each groundwater catchment was demonstrated by the water budgets. These budgets indicated that the balance of rainfall and evapotranspiration flows to surface water, either as stream quick flow or stream base flow and that all stream base flow comes from the groundwater system. Therefore, use of groundwater has the potential to impact on stream base flow.

A geologic model of the Opotiki-Ohope area included four groupings of major geologic units mapped at the ground surface (i.e., basement, Pleistocene units, Holocene alluvium and Holocene beach sediments) and fault blocks bounded by the Waimana and Waiotahi faults (Figure 2). The four groupings of geologic units simplify the actual geology in the study area and represent units at the subregional scale that are important for groundwater and surface water flow. Basement, largely comprising greywacke, is exposed at the ground surface over most of the Opotiki-Ohope area. Pleistocene units include early-mid Pleistocene age mudstones of marine origin that are relatively impermeable and Late Pleistocene gravels under Opotiki Plain. Holocene alluvium includes shallow deposits of gravel, peat, sand and pumice; the thickness of the unit was estimated from the geologic logs of wells penetrating into underlying Pleistocene mudstone. Holocene beach sediments occur at the coast and were an estimated 20 m thick based on the depth of wells drilled in the unit and the depth of shells in geologic logs.

Groundwater available for allocation (GAA) and surface water available for allocation (SAA) were calculated in the groundwater catchments consistent with minimum flow limits for groundwater (MFL^{GW}) and surface water (MFL^{SW}) and water budgets. MFL^{GW} was based on Ministry for the Environment (2008) groundwater allocation limits and MFL^{SW} was defined as $Q_{5\ 7\text{-day}}$ flow (i.e., a 7 day low flow minimum that has a 20% probability of occurring in any one year), following current BOPRC practice.

GAA and SAA were calculated at the catchment scale in groupings of geologic units. The main sources of groundwater are the Pleistocene and Holocene alluvium units. An assessment of GAA and SAA indicated that water is available for allocation from these sources (Table 17). For example, GAA from the Holocene alluvium unit in the Opotiki groundwater catchment was estimated at 1622 L/s and current groundwater allocation was an estimated 687 L/s. However, little groundwater is available for allocation from Holocene beach sediments because these sediments are restricted in distribution and their proximity to the sea means that groundwater quality is at risk from salt water intrusion.

Groundwater and surface water are linked in the Opotiki-Ohope area as groundwater recharge probably supplies most river and stream base flow in most geologic units (i.e., basement, Pleistocene units and Holocene alluvium). Therefore, policies to manage groundwater and surface water should recognise the links between these water bodies and this report included a demonstration of such a regime.

This report recommends that BOPRC consider groundwater and surface water allocation policies in the Opotiki-Ohope area including:

- definition of minimum flows (i.e., MFL^{GW} and MFL^{SW}) that meet environmental targets (e.g., for water flow and water quality) in the Opotiki-Ohope area;
- co-management of groundwater and surface water including the assessment of effects of groundwater use at the local scale; and

- definition of water allocation as a fraction of GAA and SAA because it may not be prudent to allocate all GAA and SAA, given, for example uncertainties in estimates of MFL^{GW} and MFL^{SW}.

Little groundwater is available for allocation from Holocene beach sediments (Table 17). Therefore, it is recommended that BOPRC consider allocation policies for the Holocene beach sediments intended to reduce the potential for groundwater salt water intrusion.

It is also recommended that work be done to reduce the uncertainties of flow estimates (i.e., minimum base flow discharge, $Q_{5\ 7\text{-day}}$ surface flow and groundwater budget components). This could be achieved by collecting more environmental information to reduce the uncertainty regarding the estimates of GAA and SAA. Further investigations of groundwater and surface water resources in the Opotiki-Ohope area could include summer low-flow gauging programmes and measurement of groundwater budget components including rainfall recharge.

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FIGURES

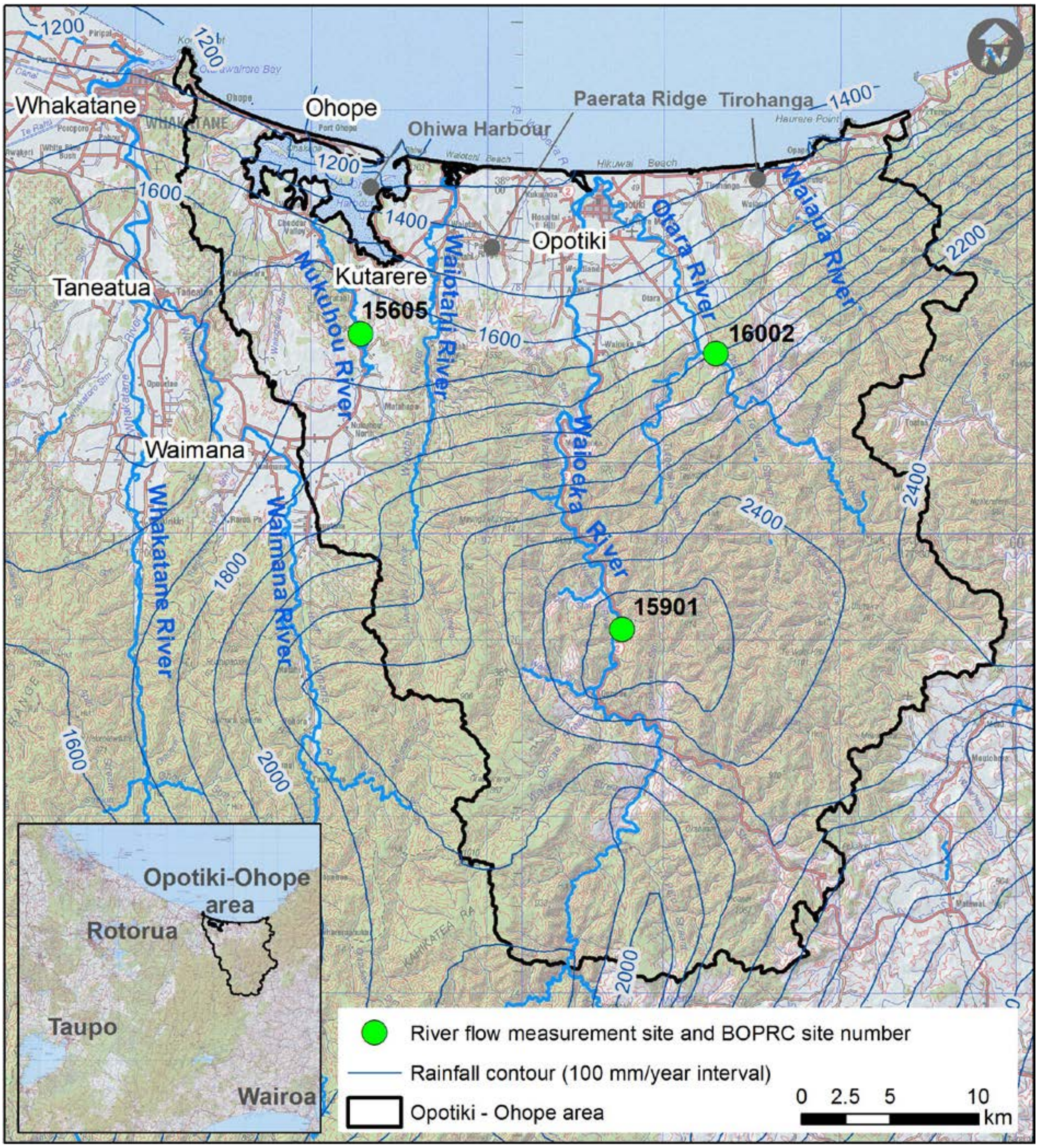


Figure 1 The Opotiki-Ohope area.

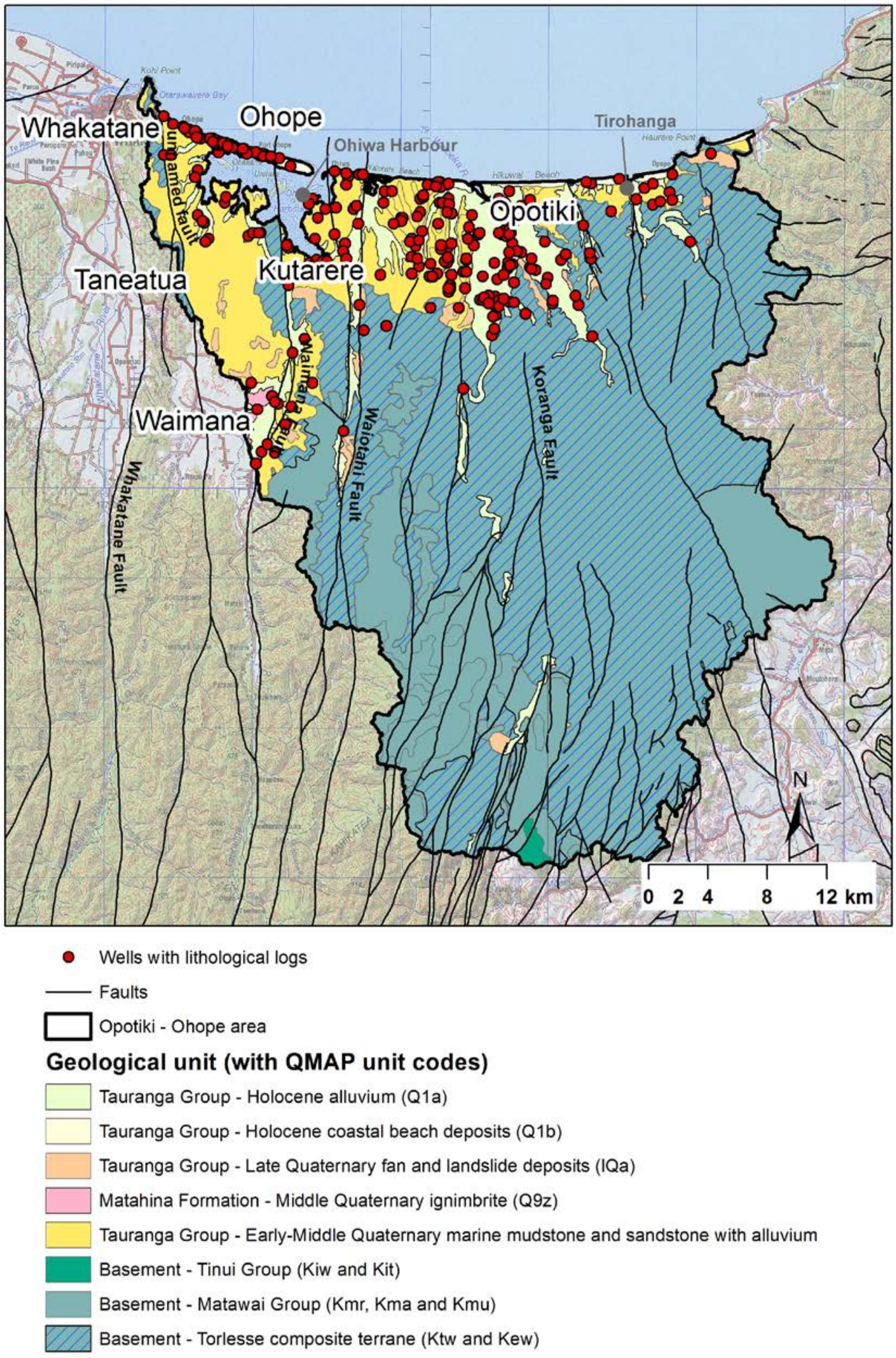


Figure 2 Geology in the Opotiki-Ohope area (after: Leonard et al., 2010; and Mazengarb and Speden, 2000) and location of wells with geologic logs (Barber, 2012).

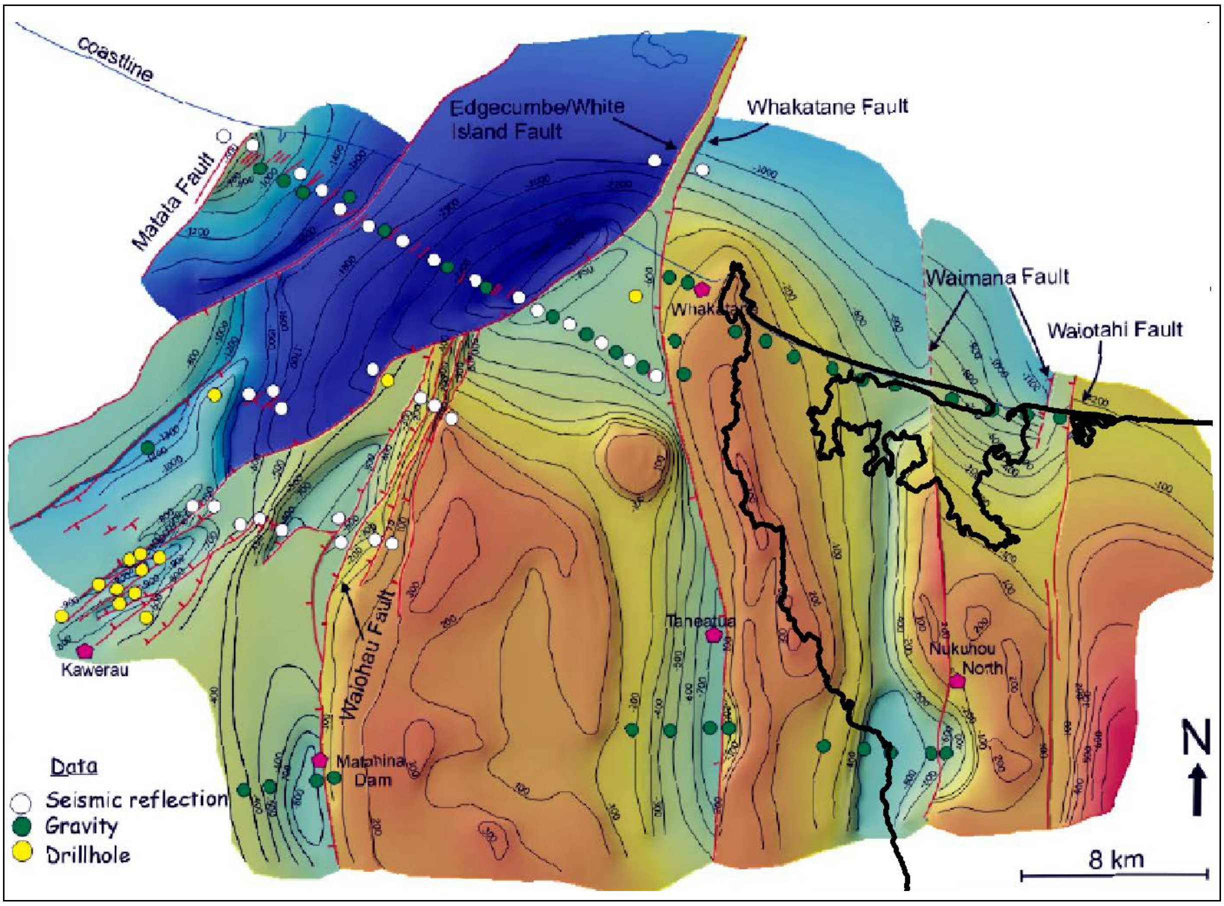


Figure 3 Elevation of the top of basement (Mouslopoulou, 2006; Mouslopoulou et al., 2008**).** The study area boundary is indicated as a black line.

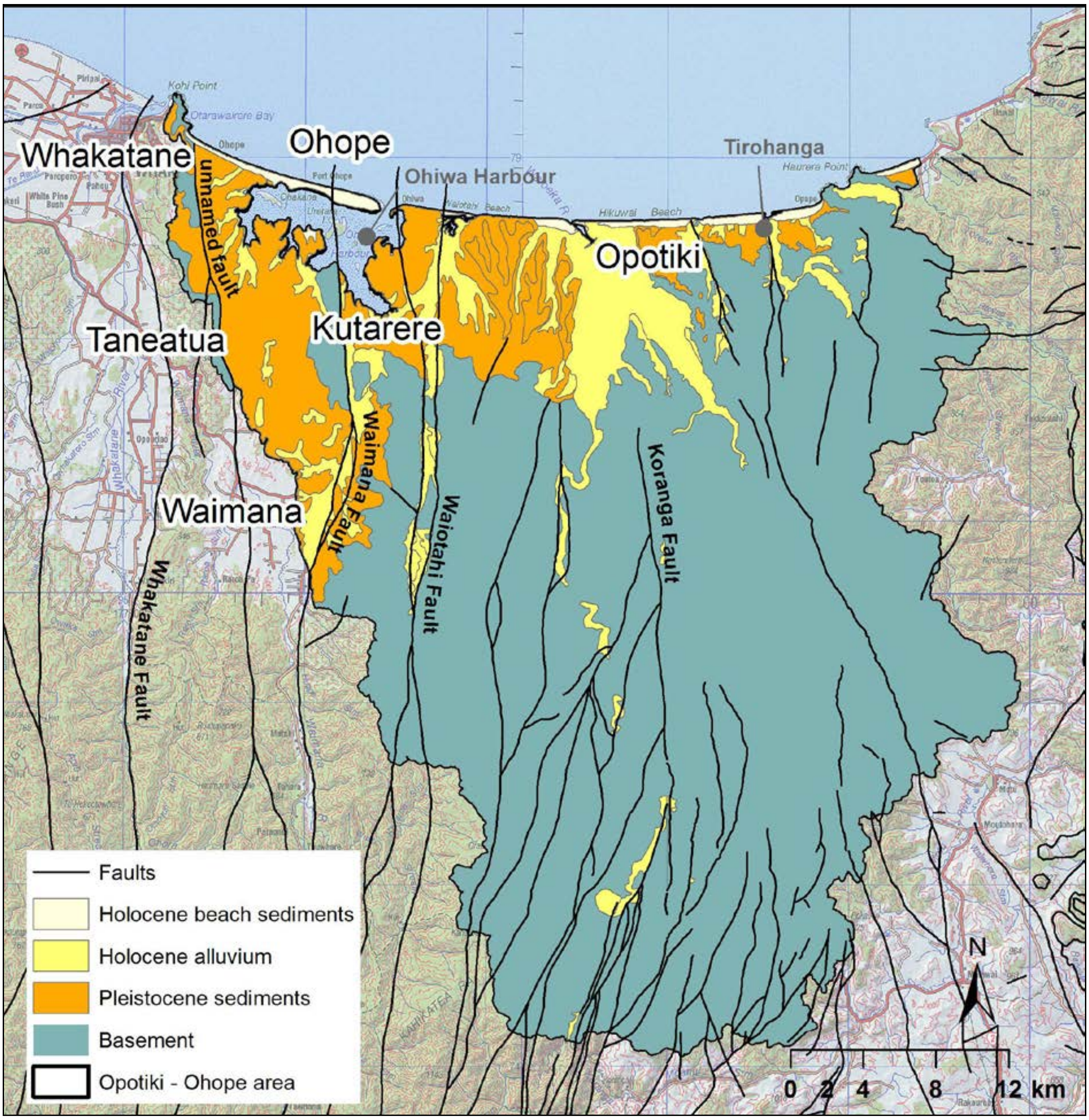


Figure 4 Distribution of grouped geologic units (i.e., Holocene beach sediment, Holocene alluvium, Pleistocene units and basement) and faults at the ground surface.

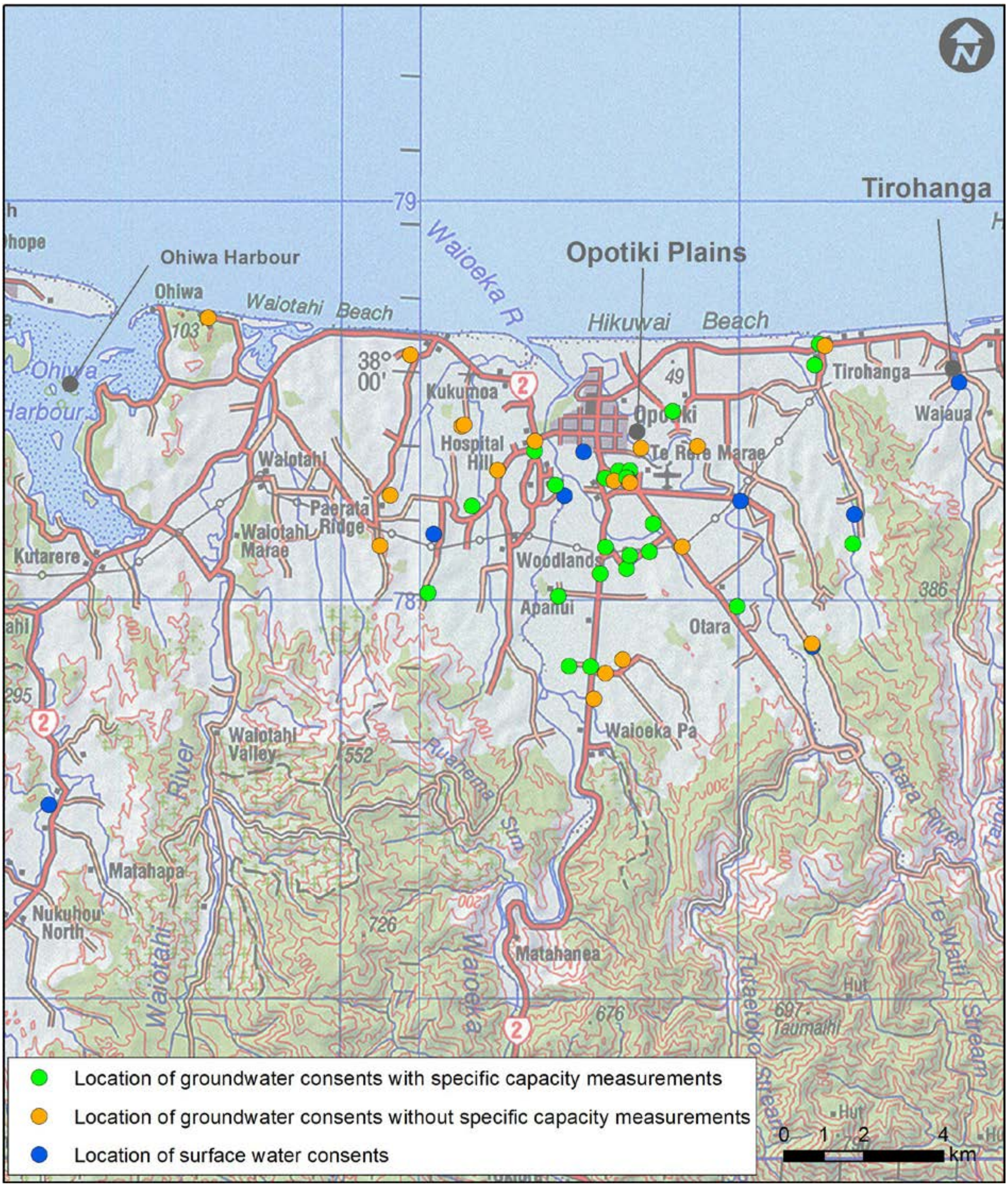


Figure 5 Location of groundwater and surface water consents in the Opotiki-Ohope area.

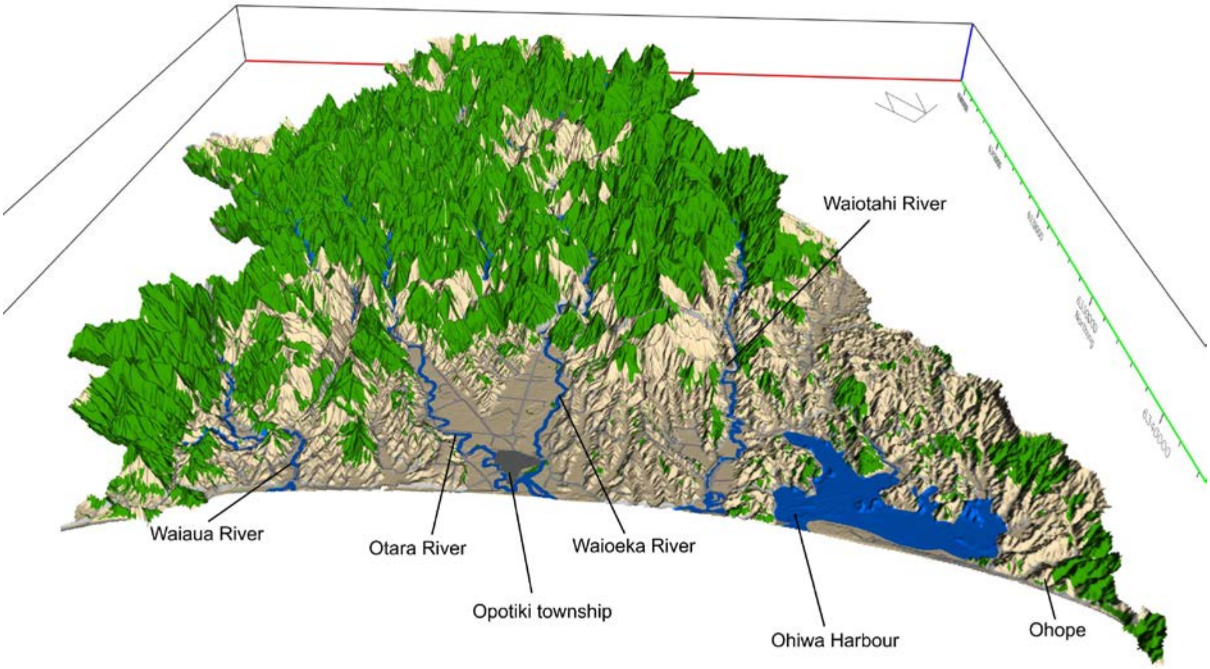
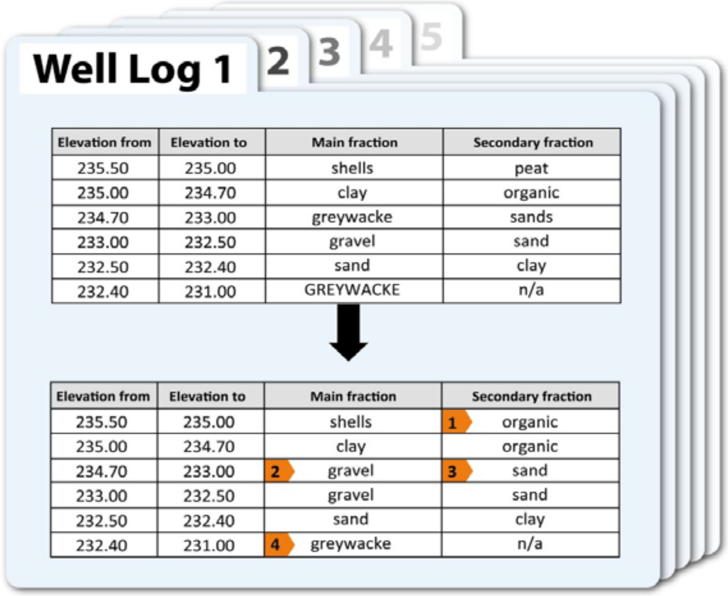


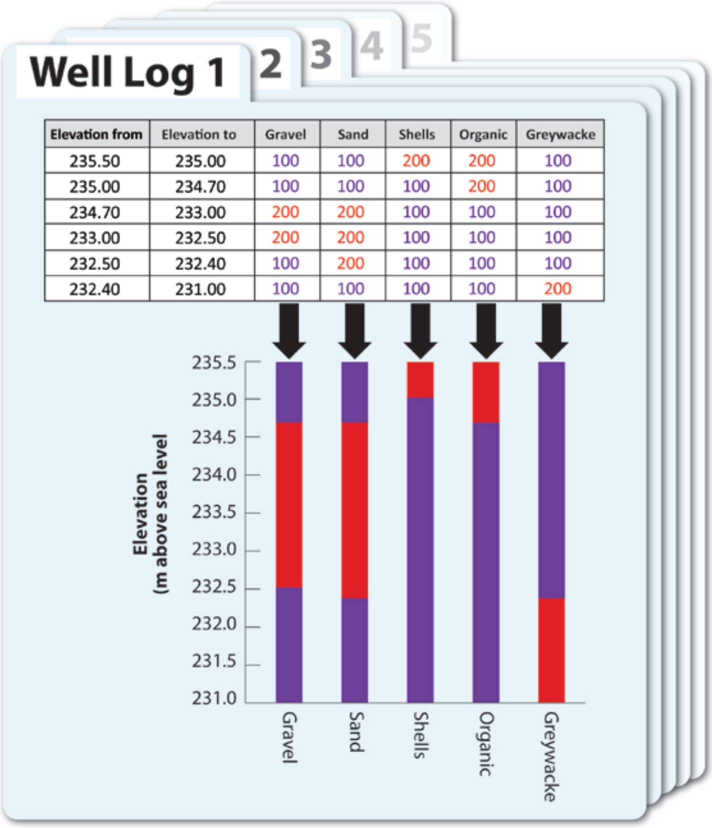
Figure 6 Digital terrain model with draped image of the 1:50,000 topographic map.



Elevation from	Elevation to	Main fraction	Secondary fraction
235.50	235.00	shells	peat
235.00	234.70	clay	organic
234.70	233.00	greywacke	sands
233.00	232.50	gravel	sand
232.50	232.40	sand	clay
232.40	231.00	GREYWACKE	n/a

Elevation from	Elevation to	Main fraction	Secondary fraction
235.50	235.00	shells	organic
235.00	234.70	clay	organic
234.70	233.00	gravel	sand
233.00	232.50	gravel	sand
232.50	232.40	sand	clay
232.40	231.00	greywacke	n/a

Figure 7 Examples of edits and corrections made during checking of hypothetical well log data. Highlighted numbers show examples, including: 1) edits to ensure consistency of terminology, e.g., universal use of the term “organic” instead of a term like “peat”; 2) corrections to probable geologic errors, e.g., greywacke occurring above gravel; 3) consistent use of singular vs. plural descriptors, e.g., “sand” instead of “sands” and 4) consistent use of lower case text.



Elevation from	Elevation to	Gravel	Sand	Shells	Organic	Greywacke
235.50	235.00	100	100	200	200	100
235.00	234.70	100	100	100	200	100
234.70	233.00	200	200	100	100	100
233.00	232.50	200	200	100	100	100
232.50	232.40	100	200	100	100	100
232.40	231.00	100	100	100	100	200

Figure 8 Assignment of lithologic property codes and creation of pseudo-logs for a hypothetical well log. Throughout this report, the lithologic property code value of 200 is used to indicate the presence of certain lithology, or marker, whereas a value of 100 is used to indicate its absence (the actual values used are arbitrary). Pseudo-log plots show the presence or absence of lithologic properties using red or purple, respectively.

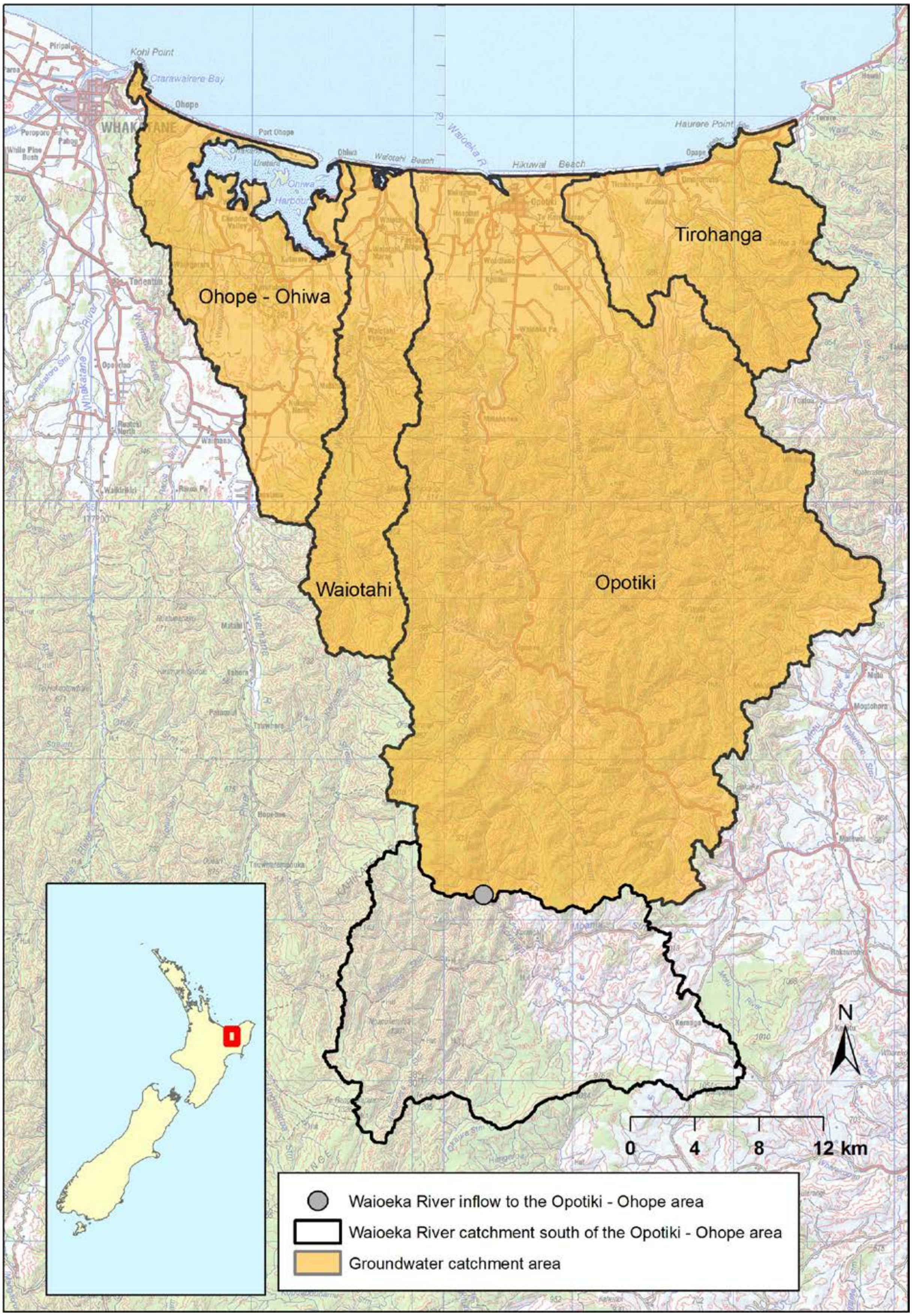


Figure 9 Groundwater catchments in the Opotiki-Ohope area.

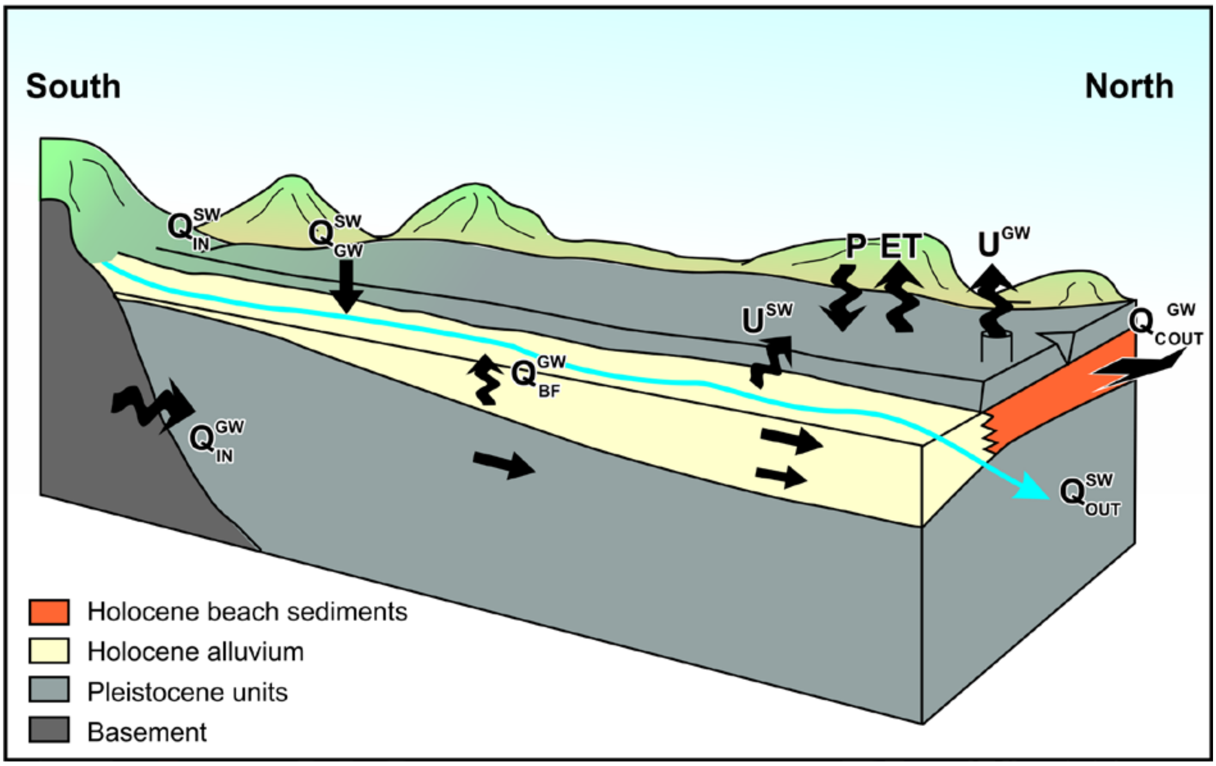
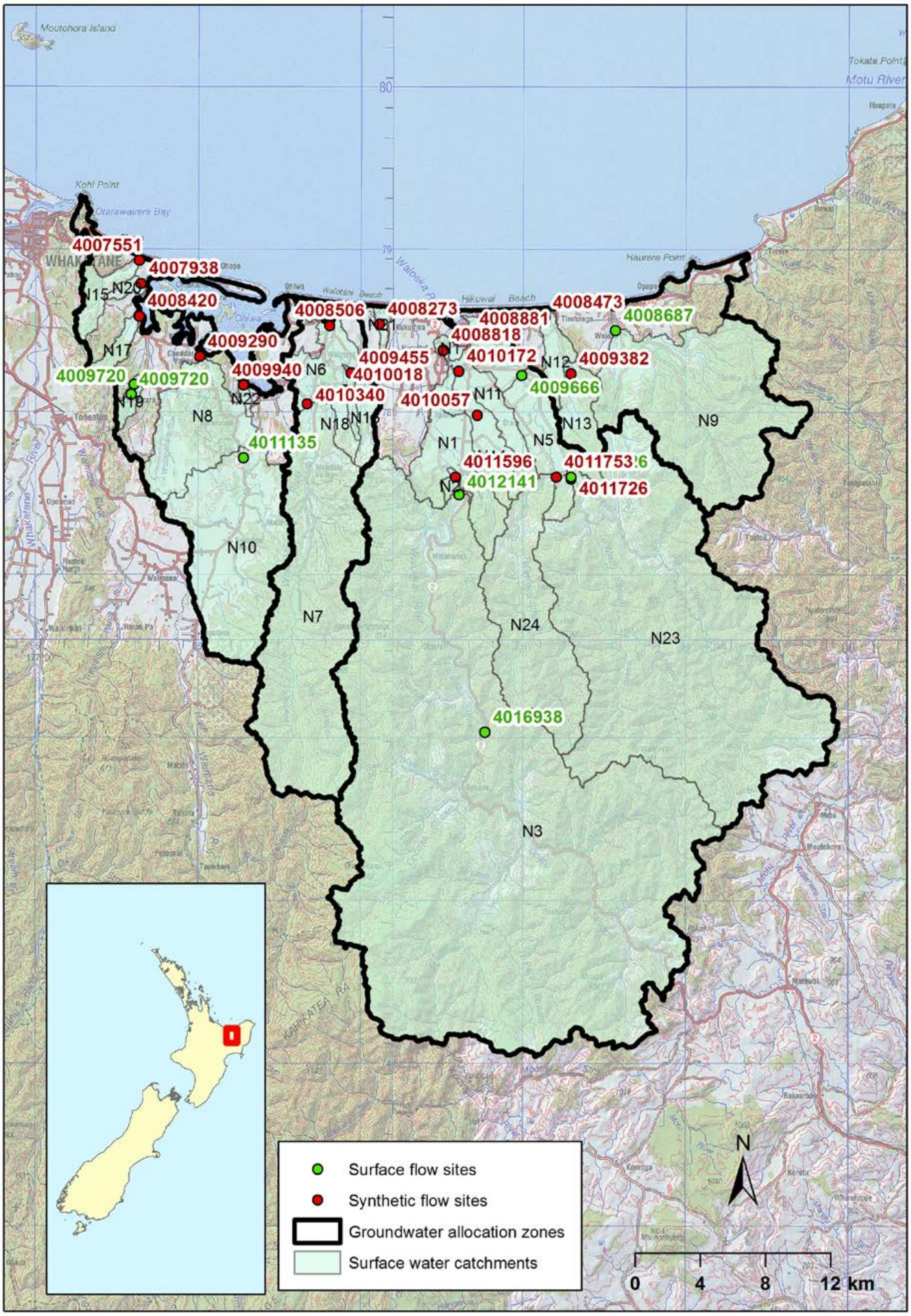


Figure 10 Conceptual model of groundwater flow in the northern part of the Opotiki-Ohope area and water budget components.



●	Surface flow sites
●	Synthetic flow sites
☐	Groundwater allocation zones
🟩	Surface water catchments

Figure 11 Location flow recorder sites, synthetic flow sites and surface catchments used in the analysis of quick flow and base flow.

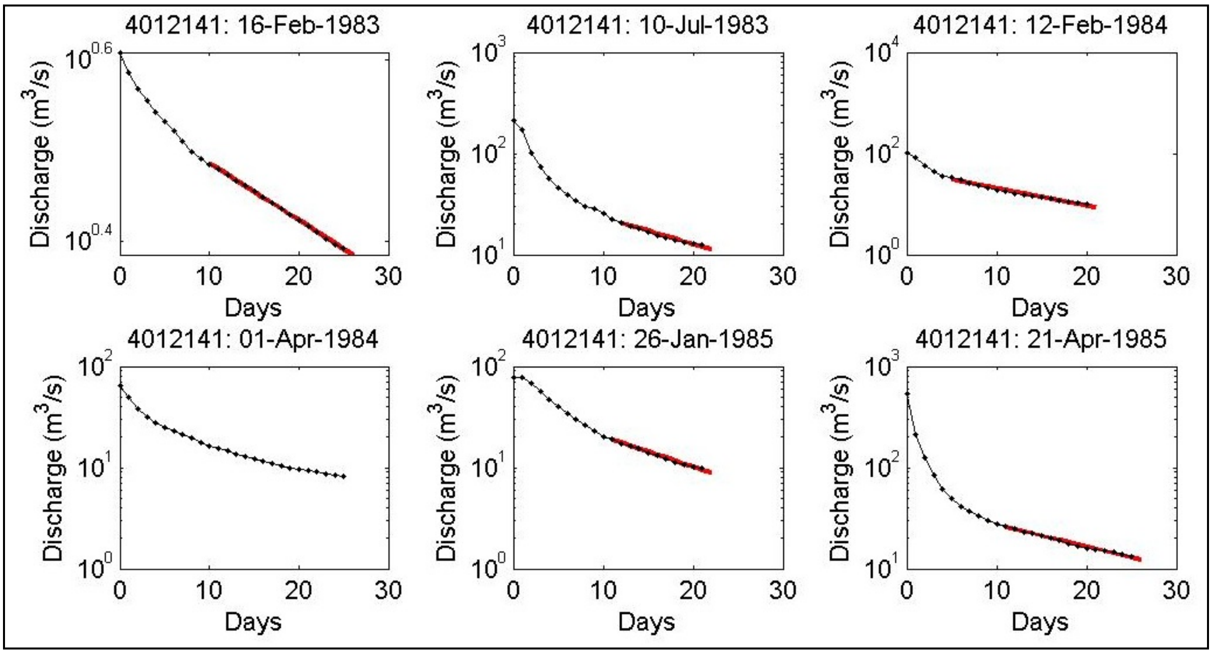


Figure 12 Recession analysis for site 4012141 (Waioeka River at Amokura Rd) includes the six longest monotonic recessions. The red lines are the regressions for the portion of the flow record assumed to be purely base flow. The start of the red lines indicates the approximate transition from mixed quick flow-base flow to pure base flow. No line is fitted for 1 April 1984 as there is insufficient evidence of a linear portion in the semilog relationship.

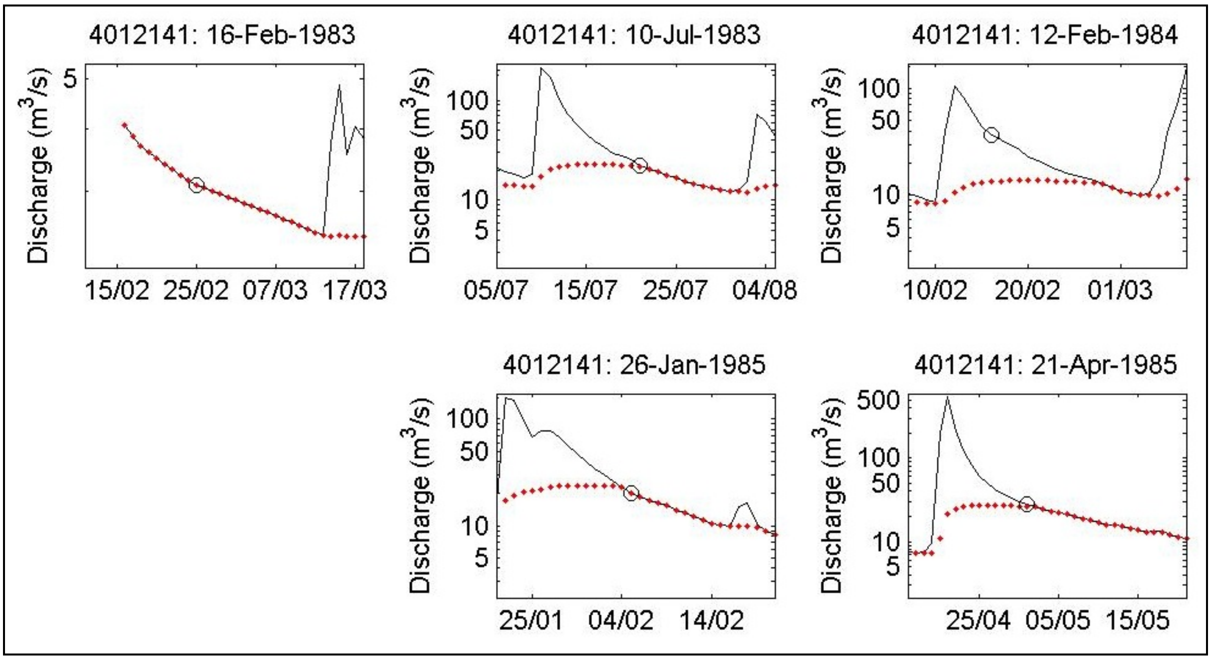


Figure 13 Synthetic base flow time-series depicting the recessions used in estimating C for site 4012141. The black circles indicate the approximate cessation of quick flow as determined in the previous analytical step. The recession that showed no distinct cessation of quick flow was not considered in the analysis.

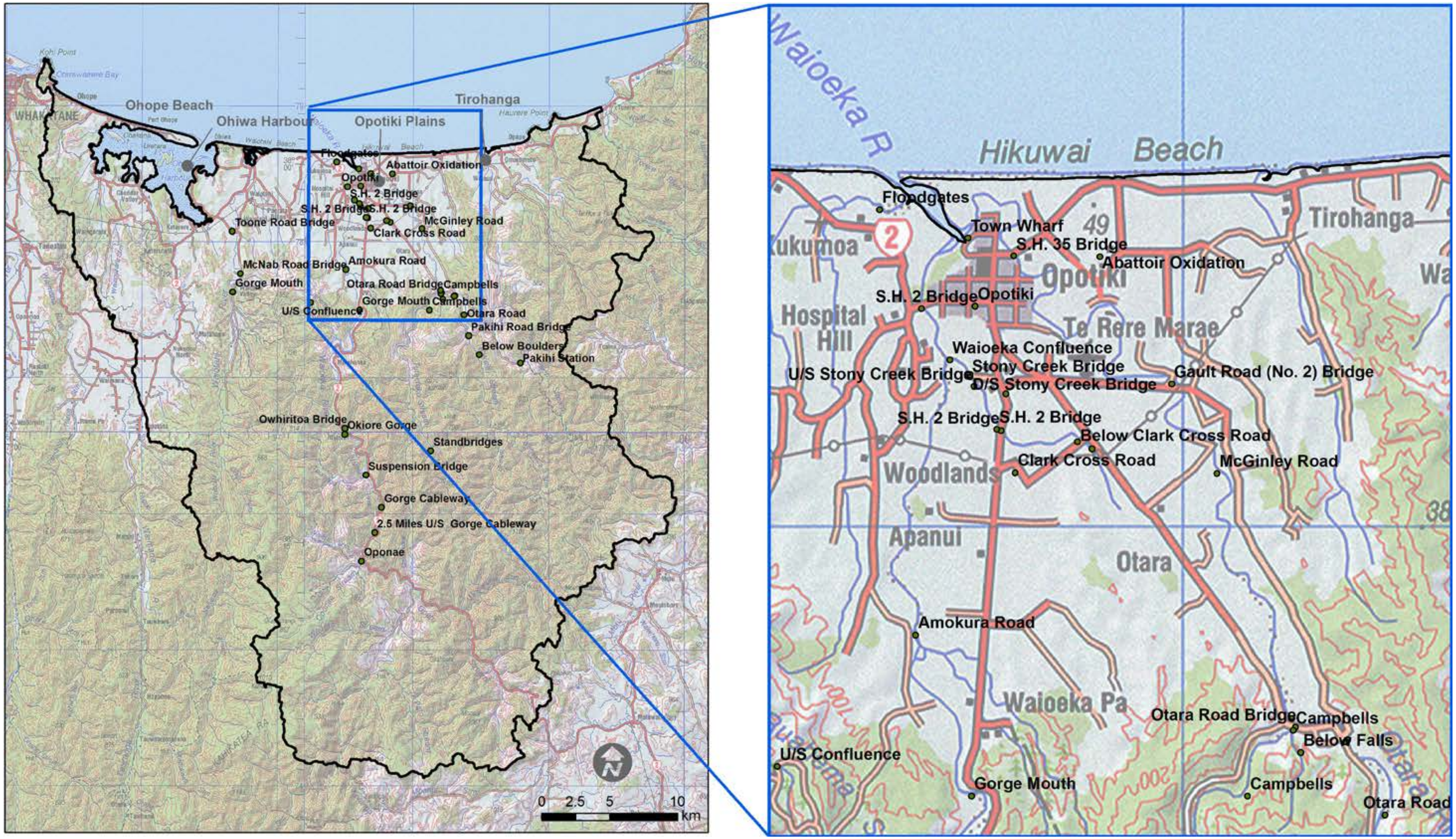


Figure 14 Location of flow gaugings measured by BOPRC.

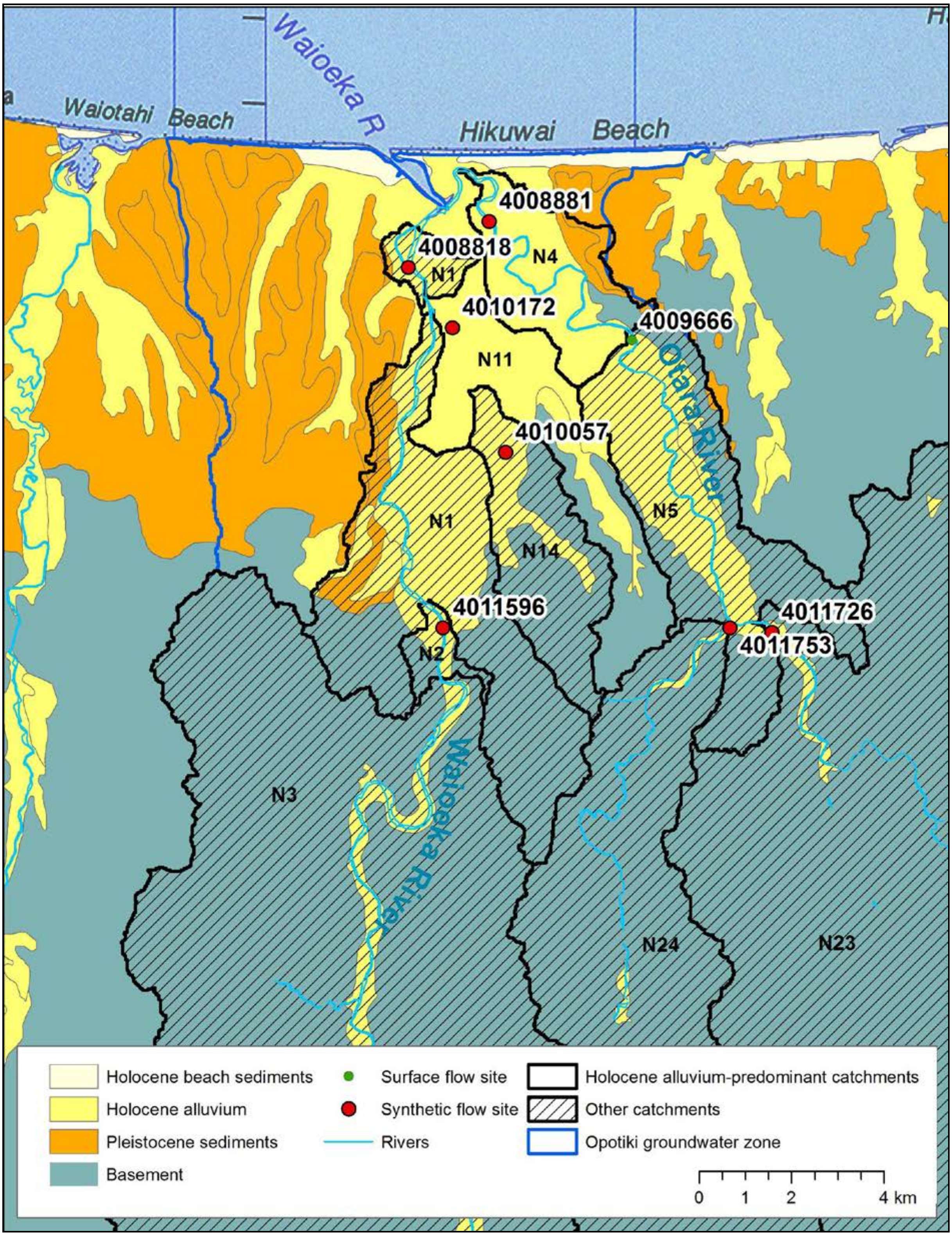


Figure 15 Surface catchments representative of Holocene alluvium in the Opotiki groundwater catchment.

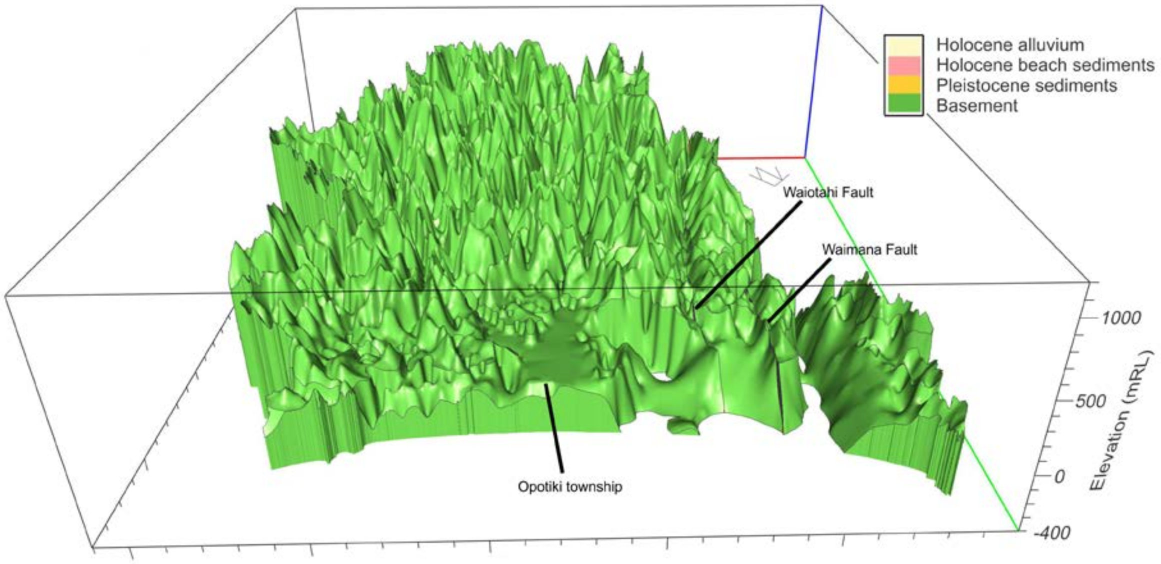


Figure 16 Three-dimensional geologic model of the Opotiki-Ohope area showing the undifferentiated basement unit (all other model units not displayed).

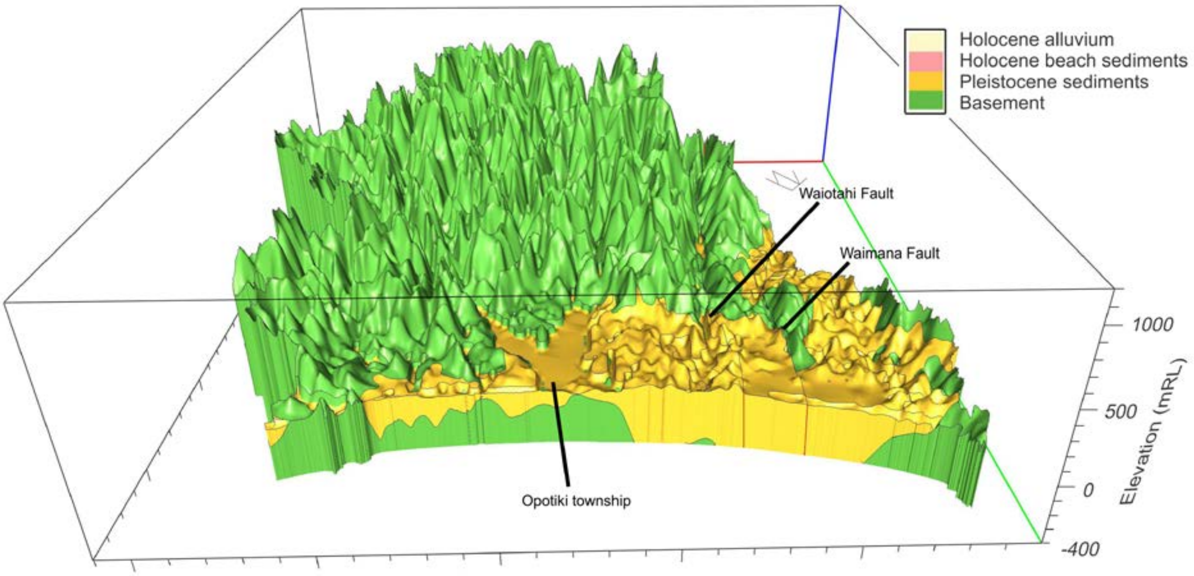


Figure 17 Three-dimensional geologic model of the Opotiki-Ohope area showing the undifferentiated basement and Pleistocene units including Matahina Formation (Holocene units not displayed).

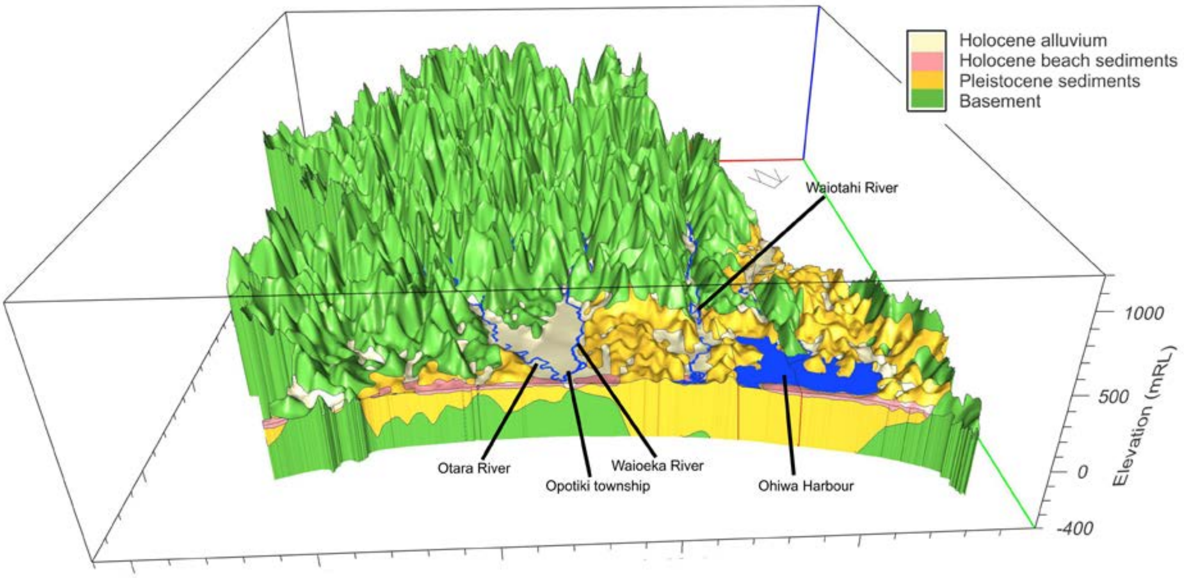


Figure 18 Three-dimensional geologic model of the Opotiki-Ohope area showing all model units.

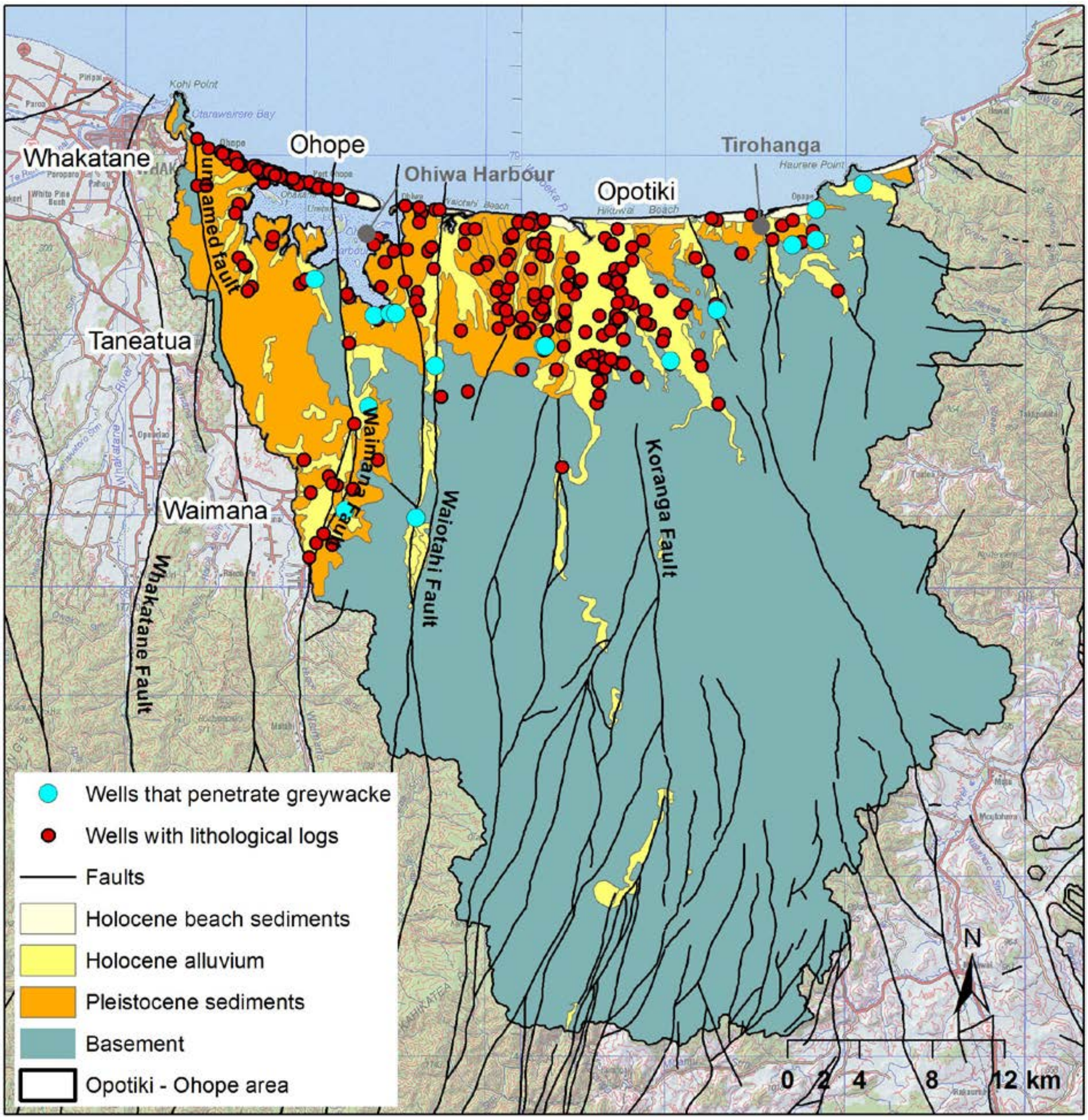


Figure 19 Location of wells that penetrate greywacke.

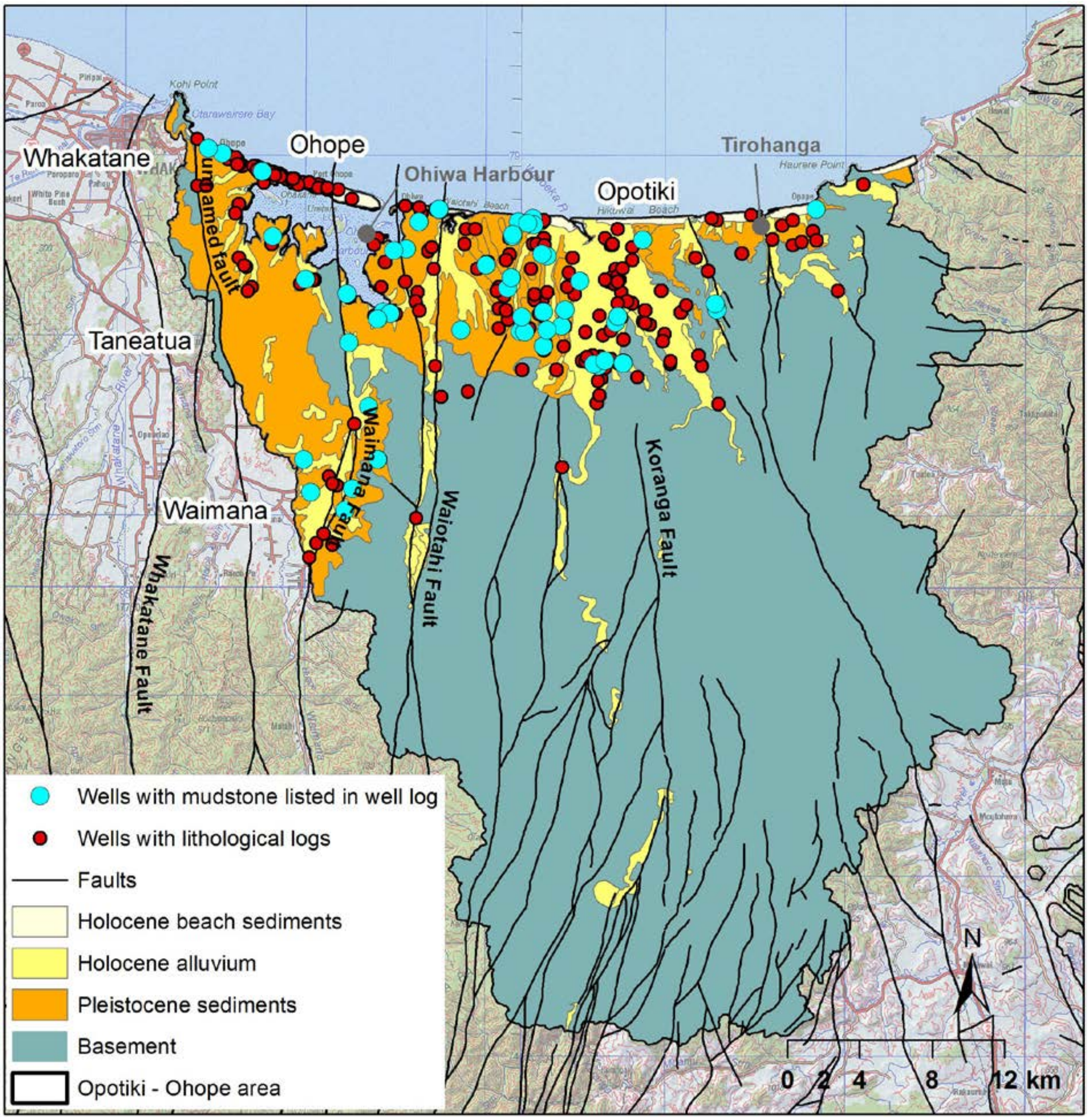


Figure 20 Wells with Pleistocene mudstone described in the well log.

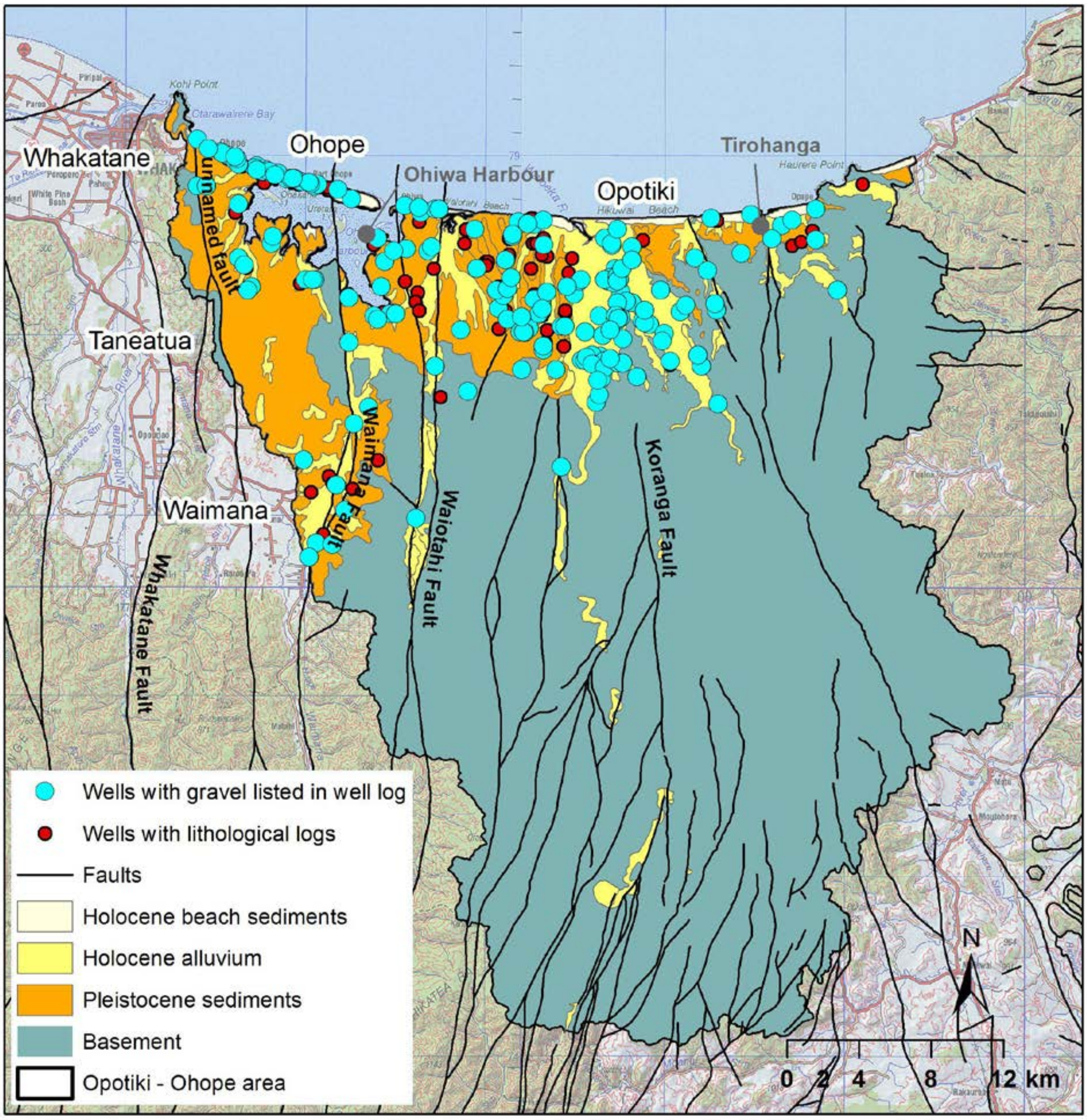


Figure 21 Wells with gravel described in well logs.

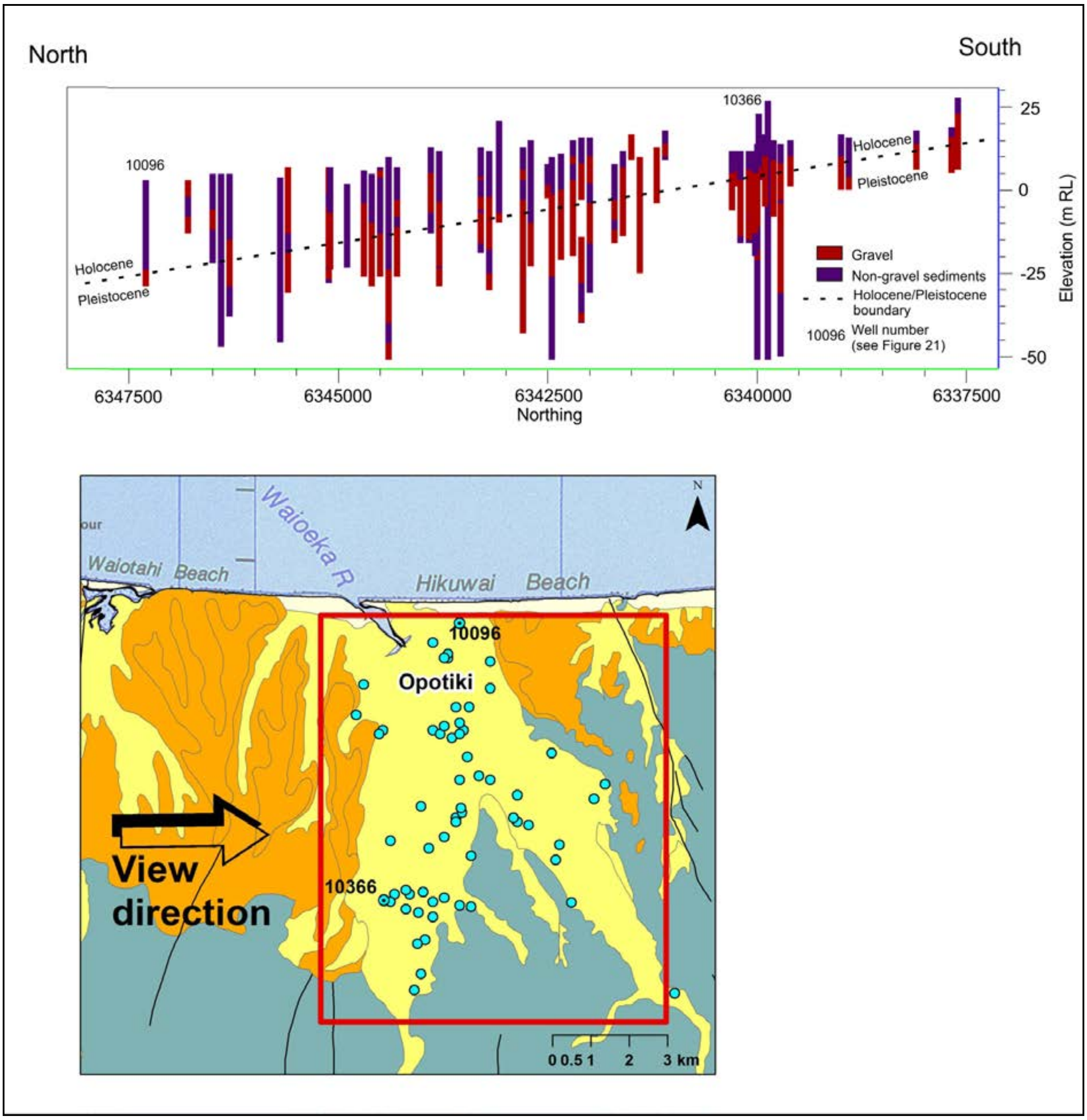


Figure 22 Gravel distribution in the Opotiki Plain area recorded in well logs above – 50 mRL and the estimated Holocene-Pleistocene boundary. Pleistocene sediments above – 50 mRL are probably mostly Q2 in age.

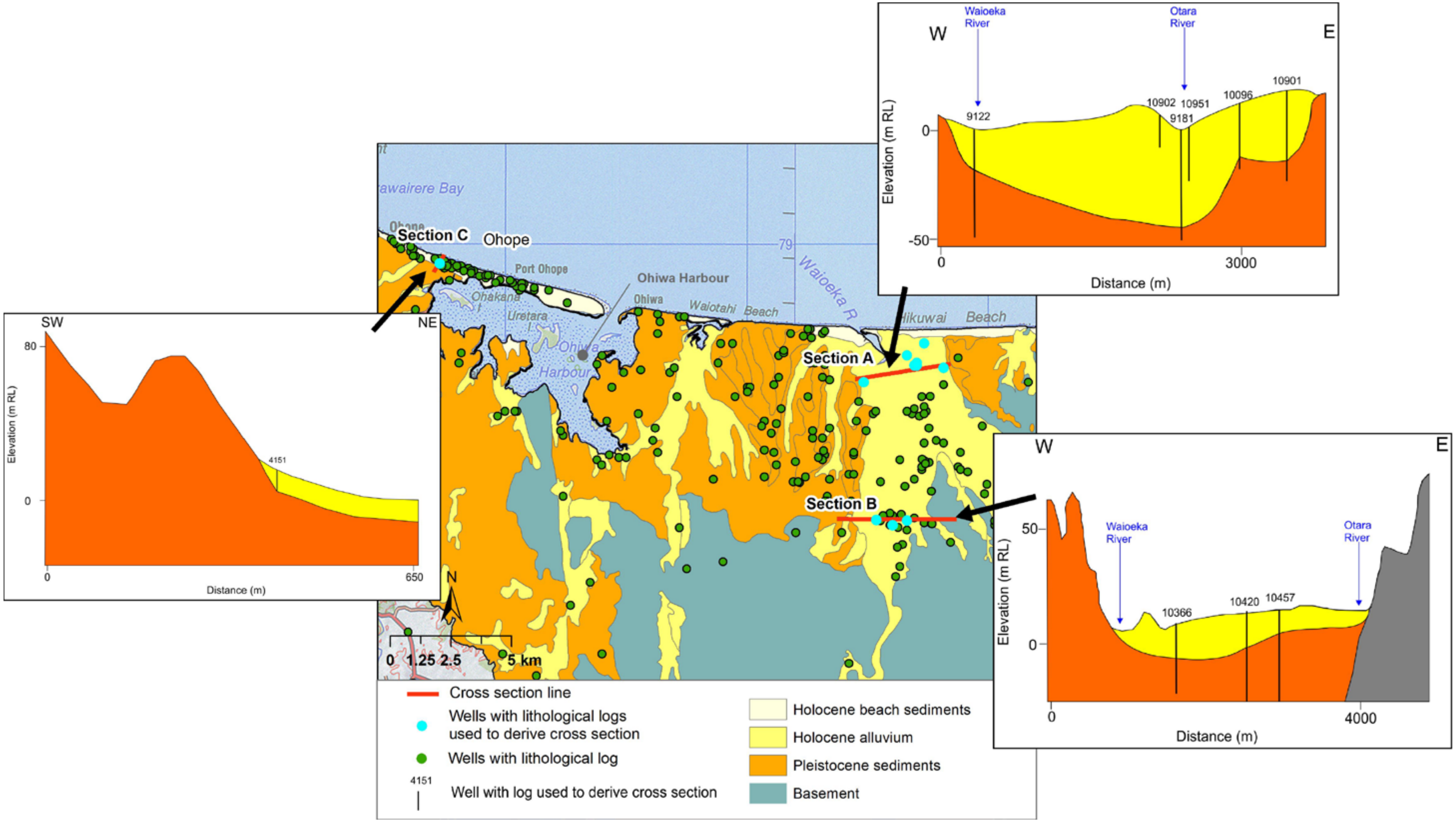


Figure 23 Geologic cross sections showing Pleistocene and Holocene sediments in the Opotiki Plain.

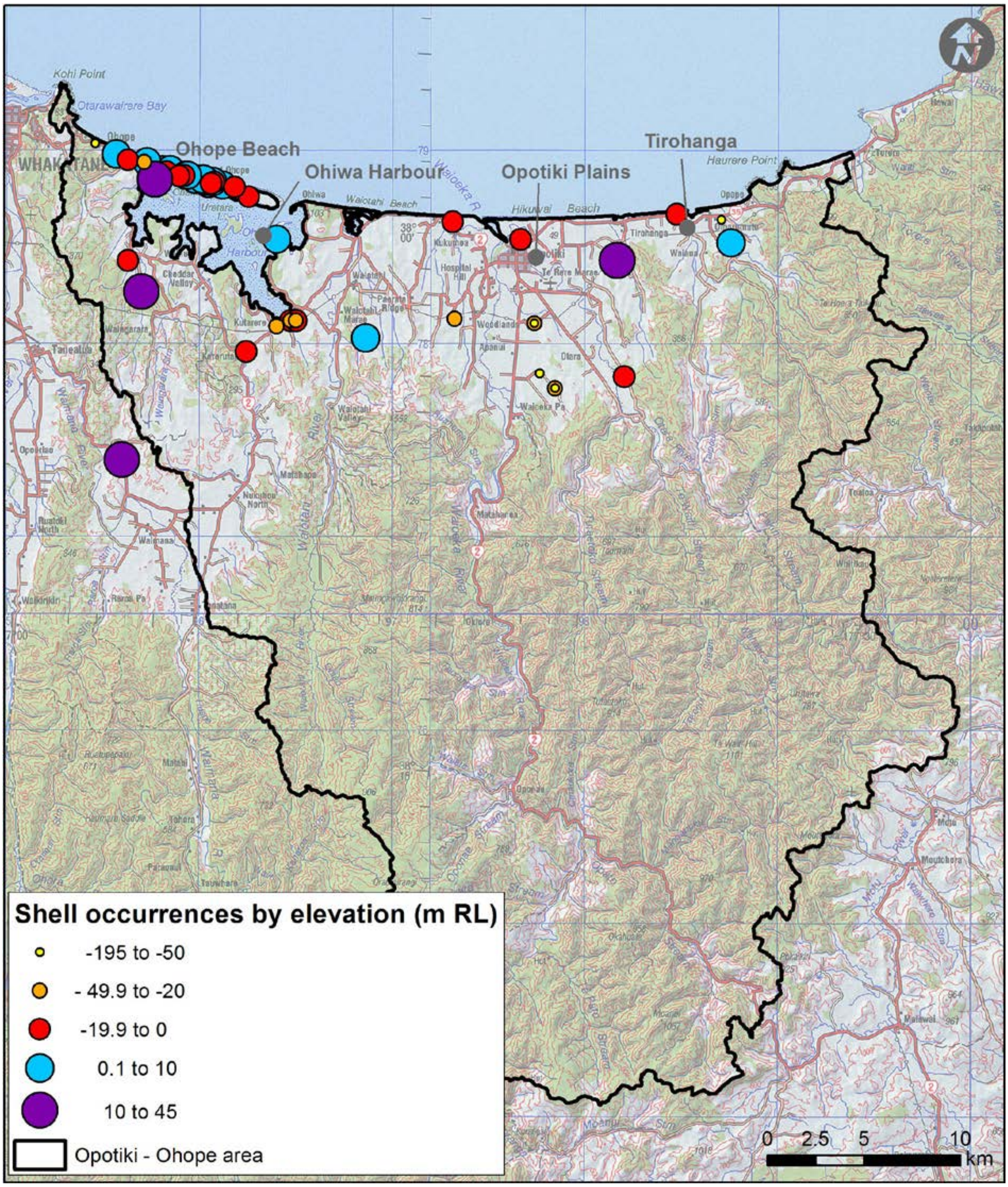


Figure 24 Elevation (m RL) of shell occurrences in the study area.

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