Groundwater in the Franklin area

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EXECUTIVE SUMMARY

Auckland Council (AC) and Waikato Regional Council (WRC) contracted GNS Science to review science of the Franklin groundwater resource following AC's intention to address the future of groundwater in their region and the two councils' aims to work together on this common resource. The importance of groundwater (e.g., to agriculture) in the Franklin area has led to resource investigations since the 1970s that culminated in the current groundwater allocation regime for the AC area.

This report reviewed these investigations, which are primarily associated with the main aquifers in the Franklin area, i.e., volcanic aquifers and the Kaawa shell aquifer. The report also provided an update to groundwater-related science in the area with new analyses of: geology, water budgets (groundwater and surface water), surface water flows, trends in surface water flow and groundwater quality (including springs) and groundwater allocation by AC and WRC.

Three-dimensional (3D) geological models were calculated for three key lithologies (volcanic rocks, shells and organic-rich sediments) and showed:

- the distribution of four major groupings of volcanics, i.e., Bald Hill, Pukekohe, Bombay and the base of the Hunua Range, and two major phases of Pukekohe volcanism, i.e., upper and lower volcanic units;
- shells of possible Holocene age in the Waikato River valley and the shores of Manukau Harbour; and
- shells of the Kaawa shell aquifer that generally dip towards the south and can form multi-layered deposits.

Major components of long-term water budgets of representative catchments in the area (i.e., the mean plus or minus the standard deviation) include:

- rainfall: 1306 +/- 38 mm/year;
- actual evapotranspiration: 822 +/-133 mm/year;
- 'shallow' groundwater flow that flows to springs to become baseflow in streams: 211 +/- 125 mm/year;
- 'deep' groundwater outflow that recharges deep aquifers including volcanics and sediments: 273 +/- 108 mm/year.

Current groundwater allocation has resulted in sustainable allocation of water quantity. Current groundwater use has had no significant impact on shallow groundwater flow because trend analyses showed that measured surface water flows and stream baseflows are not declining over time. Deep groundwater outflow is larger than AC's, and WRC's, groundwater allocation limits and consented groundwater allocation. For example, the current WRC groundwater allocation limit, and the current WRC consented groundwater allocation, were equivalent to 147 mm/year and 22 mm/year, respectively.

Two aquifers in basalt lithologies were identified by water chemistry (particularly, nitrate-nitrogen, dissolved oxygen and iron):

- shallow, oxic groundwater with high nitrate-nitrogen concentrations that discharges to springs; and
- deep, anoxic groundwater that flows to the deeper Kaawa Formation.

Nitrate-nitrogen concentrations in shallow basaltic aquifers were generally increasing over time and concentrations were consistently higher than the drinking-water standard of 11.3 mg/L and an environmental standard of 6.9 mg/L. These high concentrations, measured since the mid-1990s demonstrated the link between land use and water quality.

Recommendations in this report included:

- further characterisation of aquifers in the area using 3D geological modelling, water budgets and water chemistry;
- an integrated approach to groundwater allocation by AC and WRC; and
- technical work that leads to improvements to water quality in groundwater and spring-fed streams.

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1.0 INTRODUCTION

Auckland Council (AC) and Waikato Regional Council (WRC) contracted GNS Science to re-assess the groundwater resources in the Franklin area, with focus to assess underlying geology, recharge mechanisms, and groundwater availability. The Franklin study area (Figure 1.1), which covers a large part of the former Franklin County, includes the surface catchments associated with volcanic aquifers and the Kaawa shell aquifer that are common to AC's Manukau Harbour Watershed and WRC's lower Waikato catchment (White et al. 2015).

The Franklin area was selected as a priority area for groundwater assessment because groundwater is a key water resource for agriculture and for industry with a high demand relative to other parts of the region (Crowcroft and Smail 2001). Currently, groundwater allocation in most basalt aquifers is close to allocation limits; current groundwater allocations are also a significant portion of allocation limits in most Kaawa shell aquifer areas (see Section 2.5).

The Auckland Unitary Plan defines several aquifers in the region as High Use Aquifer Management Areas (HUAMAs). The study area has the highest density of HUAMAs in the Auckland Region and correspondingly the highest consented volume and greatest actual groundwater abstraction (Stansfield and Holwerda 2015). The existing and predicted demand for additional water take consents from Franklin aquifers is one driver of the work addressed in this report.

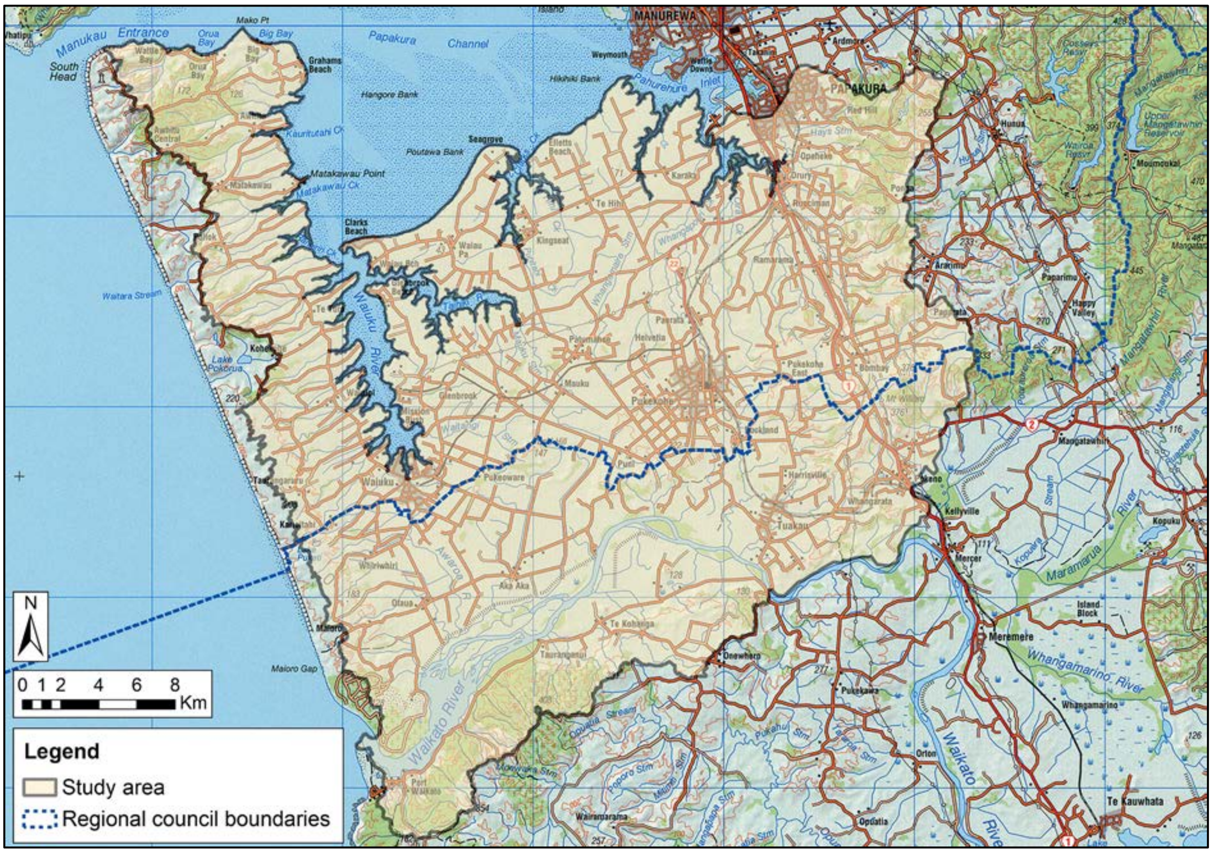

Figure 1.1 Map of the study area.

The existing and future risk of nitrate contamination is another driver of this work. The Franklin area has been highly utilised for intensive vegetable growing and livestock farming for over a century. This intensive land use has led to positive soil nitrogen balances in all rural areas of the Franklin district; conditions that allow for nitrate loss from the soil (Crush et al. 1997, Francis et al. 2003). Basalt aquifers and spring-fed streams in the Franklin District have the highest nitrate-nitrogen concentrations for aquifers and streams, respectively, in the Auckland Region (Kalbus et al. 2017) and a better understanding of recharge mechanisms will aid the understanding of nitrate transport and support current work in this area.

The geological setting, recharge mechanisms, and water use in the Franklin area have a direct influence on the extent and timing of water quality impacts from land use (Meijer et al. 2016). This study aims to increase the understanding of the likely land use impacts on the aquifers and streams in the Franklin District. The study will also contribute to the future identification of monitoring needs, e.g., the location of groundwater monitoring wells and surface water monitoring sites, that will provide a better understanding of the physical hydrogeological system.

WRC's motivation for the study differed from that of AC. Waikato's groundwater management units lump all aquifer layers into a single accounting unit whereas AC's groundwater management units recognise the vertical aquifer separation between basalt and the deep Kaawa shell aquifer. WRC's groundwater resource availability was calculated a 'tier-1' estimate from a simple equation of 50% of rainfall recharge (Environment Waikato 2008). This approach is now recognised as an over-simplification because aquifers are continuous across the two regions and groundwater is heavily utilised in the AC area. A better understanding of aquifer recharge dynamics, connectivity and resource availability will help reconcile groundwater management by the two councils into a common framework. The study is intended to assist conceptualisation of 'tier-2' sustainable yield allocation accounting, by informing three-dimensional (3D) geological structures, the deep recharge mechanism and recharge estimates of aquifer layers at various depths in the area.

Other objectives include facilitating common groundwater management practices between AC and WRC across "shared" aquifer units. Shallow basalts and deeper shell aquifers are both present and highly utilised in the two regions. However, the two regions manage groundwater differently. Therefore, a better understanding of aquifer dynamics will aid the development of groundwater management within a common framework.

This report analyses groundwater recharge in the area, and the state and trends of environmental data relevant to the groundwater resource, to inform the development of water budgets for the volcanic and Kaawa shell aquifers. Groundwater recharge is of fundamental importance to groundwater allocation in the study area. Currently, groundwater allocation of the Kaawa shell aquifer in the AC region is based on Viljevac et al. (2002). However, two factors led to a revisiting of the recharge calculations: a critique of Viljevac et al. (2002) by Earthtech Consulting Limited (Earthtech) (2013) included disagreement with regard to the conceptual model of the area with respect to recharge only deriving from volcanic cones; and new information has become available since the completion of Viljevac et al. (2002), such as 'Qmap' the new GIS-based digital geological map of New Zealand (Heron 2014), rainfall recharge measurements via additional data from the AC Pukekohe site(s), and national rainfall models.

State and trends, e.g., of groundwater quality and stream flows, are analysed to provide AC and WRC with a current understanding of the groundwater resource and of the environments that receive groundwater recharge, i.e., springs and streams. In addition, AC intends to use the results of this investigation to inform ongoing water management in the Franklin area.

2.0 REVIEW

The use of groundwater resources in the Franklin area has been recognised as a concern at least since 1957 (Auckland Regional Water Board and Waikato Valley Authority 1977). Pukekohe was ‘the area of most intensive demand on the water resource’, with market gardening being the major water user. Therefore, this area, with its relatively shallow volcanic aquifers, was the focus of early investigations (Auckland Regional Water Board and Waikato Valley Authority 1977).

By the 1980s, groundwater was being taken from the Kaawa shell aquifer. Technical assessments (including geology, chemistry and water availability) of the aquifer followed with consideration of regulatory approaches such as allocation plans (Auckland Regional Water Board 1985, 1988a, 1988b, 1989; Hadfield 1988, 1989).

This review firstly describes the published geology and groundwater chemistry of the study area. Then, measurements of groundwater flows are described, with a focus on groundwater recharge because recharge estimates are primarily used to calculate groundwater allocation. The review also summarises historical research in water allocation, with a focus on Viljevac et al. (2002) which has been used to set current-day groundwater allocation limits.

2.1 Geology

Geology in the study area is dominated by volcanic deposits of the South Auckland volcanic field and by sediments deposited in terrestrial and shallow marine environments (Edbrooke 2001; Figure 2.1). Two major aquifers, the South Auckland volcanics and the Kaawa shell aquifer, provide most of the groundwater in the Franklin area (Crowcroft and Smaill 2001).

Within the South Auckland volcanics, two volcanic aquifers, the ‘upper’ and ‘lower’ volcanic aquifers, have been identified in the Pukekohe area (Auckland Regional Water Board and Waikato Valley Authority 1977; Auckland Regional Council 1991a; White et al. 1996). The Early Pleistocene South Auckland basaltic volcanics include ‘at least 97 subaerial, mainly monogenetic volcanic centres’ (Edbrooke 2001), Figure 2.1. These deposits occur at the ground surface and form many of the distinctive landforms in the study area, such as ‘small and steep-sided’ volcanic cones with minor lava flows (Edbrooke 2001). Volcanic deposits are as much as 200 m thick (Viljevac et al. 2002).

The Pliocene Kaawa Formation is a marine deposit that includes the near-basal Kaawa shell aquifer (Edbrooke 2001). The Kaawa Formation is not exposed at the ground surface in the study area and is overlain by the Tauranga Group sediments (i.e., the Pliocene-Pleistocene Puketoka Formation), which includes fluvial sediments and peats. The Kaawa Formation is typically 50 m thick in the north of the study area and can be more than 250 m thick in the south and west (Viljevac et al. 2002). Extensive shell beds and sand deposited ‘in shallow marine and estuarine environments’ form the aquifer (Edbrooke 2001), which is commonly known as the ‘Kaawa shell aquifer’.

Faults mapped in the study area include the Waikato Fault in the south; active faults are located to the east of the study area (Figure 2.1). Numerous maps of fault distributions have been published (e.g., Figure 2.2). These faults define fault blocks in the area that have been used to develop conceptual models of groundwater flow in the deep geological units and have been a consideration in the definition of groundwater allocation zones in the Kaawa shell aquifer (Viljevac et al. 2002, Earthtech 2018).

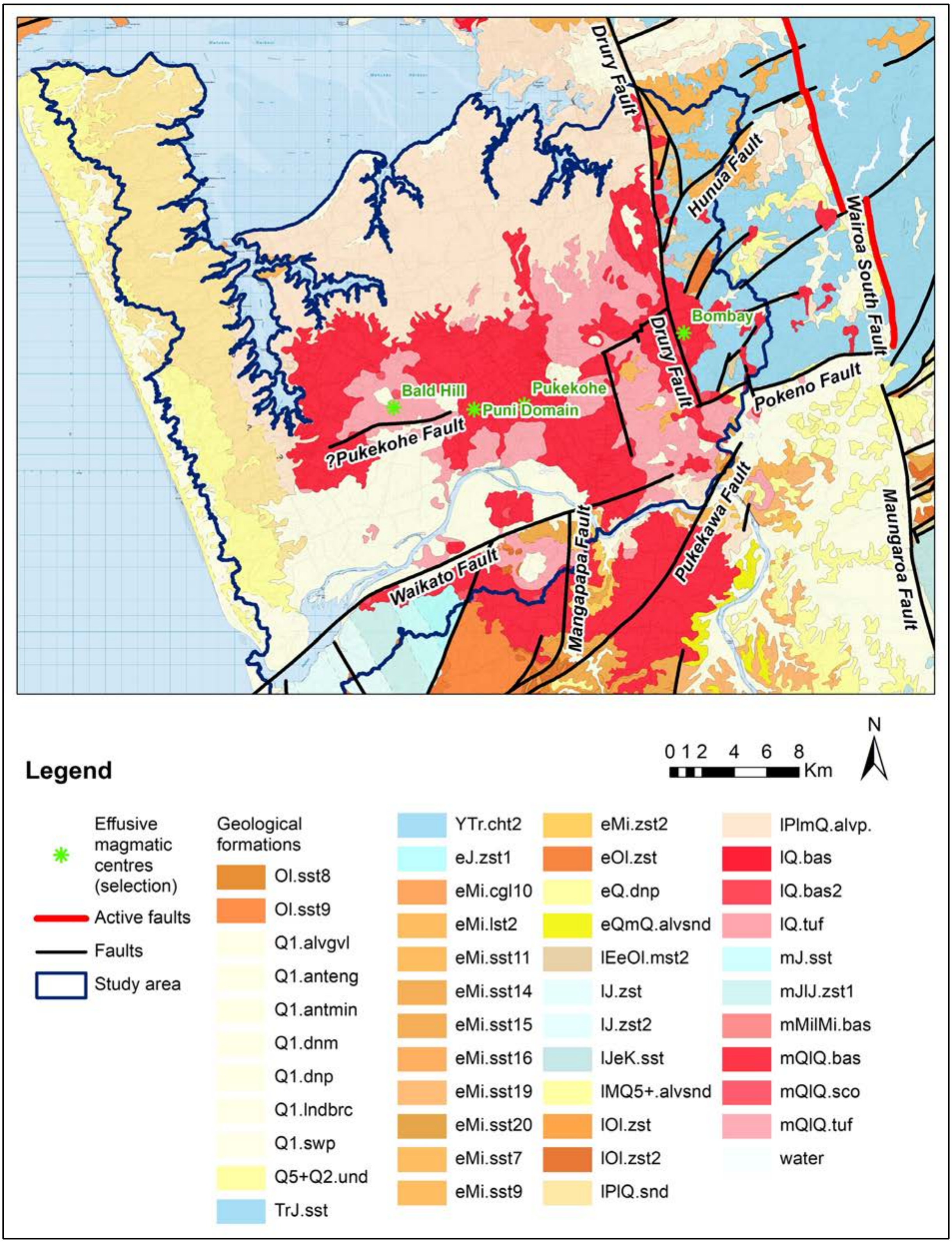

Figure 2.1 Surface geology, including faults and the main lithologies: Holocene sediments (straw-yellow colours), Pleistocene volcanics (red and yellow) and location of some effusive magmatic centres, Tertiary sediments (brown and salmon) and greywacke basement (blue) (Edbrooke 2001; Heron 2014; Taylor 2012). A full explanation of the geological formation key can be found in Edbrooke (2001).

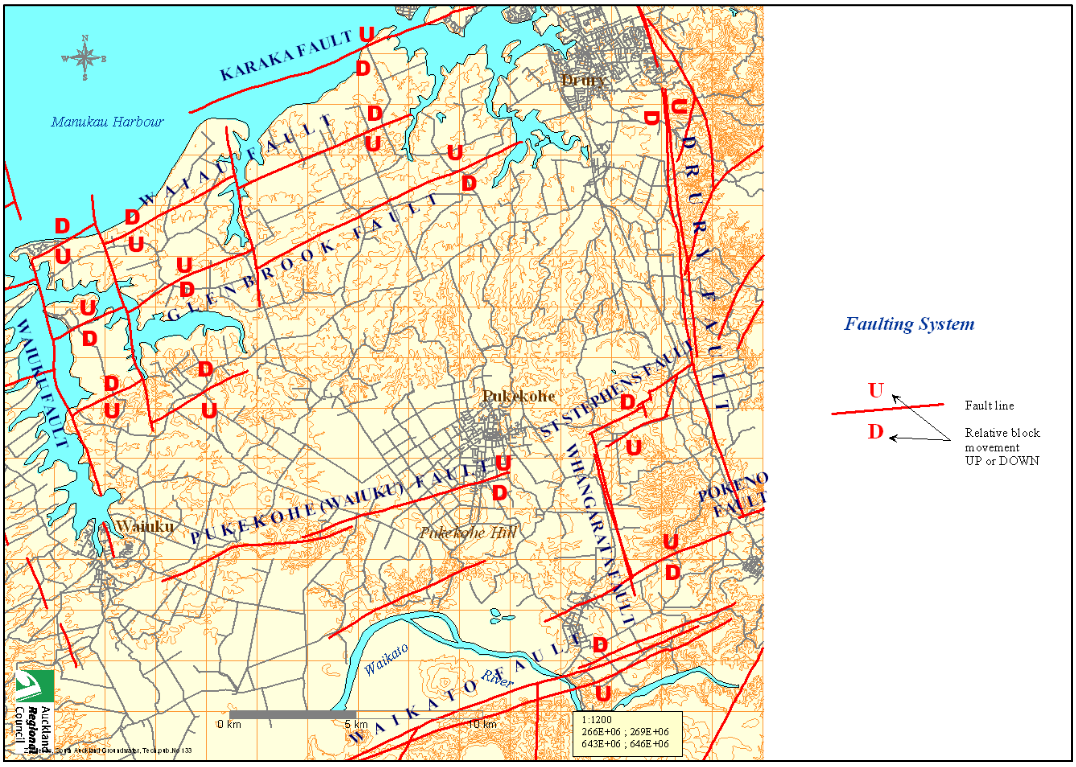

Figure 2.2 Faults in the Franklin area (Viljevac et al. 2002).

2.2 Water Budgets and Rainfall Recharge

Water budgets are fundamental to the understanding of groundwater and surface water flows and have found regular use in the study area. Commonly, groundwater recharge has been calculated with water budgets; a considerable range of groundwater recharge estimates have been derived from multiple methods (Table 2.1). This range gives some indication of the uncertainty in water budget estimates. However, rainfall recharge estimates derived with water budgets of the Kaawa shell aquifer in the AC area are generally similar (i.e., 130 to 194 mm/year).

Rainfall recharge to groundwater is of particular interest because rainfall is the sole source of groundwater to the volcanic and sedimentary aquifers in the study area; therefore, rainfall recharge estimates have been used to calculate water allocation limits. There have been various approaches to the calculation of rainfall recharge in the Franklin area (Table 2.1). For example, a conceptual model of groundwater flow was used by Viljevac et al. (2002) to calculate recharge to the main aquifers (Figure 2.3 and Table 2.1). This model considered that all Kaawa shell aquifer recharge was sourced from volcanic cones. However, Earthtech (2013) suggested that this model was incorrect because sediments (e.g., Tauranga Group and Puketoka Formation) are a source of groundwater for the Kaawa shell aquifer.

Field measurements of rainfall recharge have also been important to the characterisation of rainfall recharge. For example, rainfall recharge of 680 mm/year was calculated by Rosen et al. (2000) from field measurements of soil moisture (Rosen et al. 1999, 2000; Lincoln Environmental 1998). This estimate was used in the groundwater allocation regime for the volcanic and Kaawa shell aquifers (Viljevac et al. 2002). Generally, field measurements can reduce the uncertainty of rainfall recharge estimates. For this reason, AC has measured rainfall recharge in the Franklin District with field instruments including lysimeters and ground-level rainfall recorders since June 2016 (Lovett 2016, Section 3.3.3).

Table 2.1 Summary of groundwater recharge estimates from various studies and methods, including rainfall recharge and aquifer inflow, in the study area.

Item	Groundwater Recharge			Notes	Reference
	Flow Rate	Recharge (mm/year)	Method		
Recharge to Kaawa	21,450 m^3/day	130	Flow net	Vertical recharge, Pukekohe area	Auckland Regional Water Board (1988b, 1989)
Recharge to Kaawa	6,800 m^3/day	17	Flow net	Vertical recharge outside the Pukekohe area	Auckland Regional Water Board (1989)
Deep seepage		194	Water budget	1972–1981	Auckland Regional Water Board (1989)
Whakapipi catchment		41.4	Water budget	Recharge	Hadfield (1988)
Buckland well		118.6	Vertical head gradients	Vertical recharge	Hadfield (1988)
Pukekohe volcanic aquifer	38,500,000 m^3/year	680	Soil moisture	Net of evaporation and runoff	Viljevac et al. (2002); Rosen et al. (2000)
Pukekohe volcanic aquifer	12,459,000 m^3/year	220	Water budget	Net of stream baseflow discharge	Viljevac et al. (2002)
Recharge to Kaawa shell aquifer (Pukekohe area)	9,988,000 m^3/year	176	Water budget	Rainfall recharge net of stream baseflow	Viljevac et al. (2002)
Recharge to Kaawa shell aquifer (Franklin area)	19,000,000 m^3/year	69	Soil moisture and flow net	Average over Franklin area	Viljevac et al. (2002)
Bombay volcanic aquifer	8,220 m^3/year	500	Flow net	Rainfall recharge	Auckland Regional Council (1991b)
Franklin Deep Waitemata	6,576,900 m^3/year	27 (whole-area mean)	Flow net, modelling	The whole area includes seven management zones	Earthtech (2018)
Pukekohe area		298	Water budget	Sum of baseflow and deep groundwater recharge	Petch et al. (1991)
Waiuku area, deep groundwater recharge (Kaawa)		360	Flow model	Upper Awaroa catchment in two years	Maggs (1991)

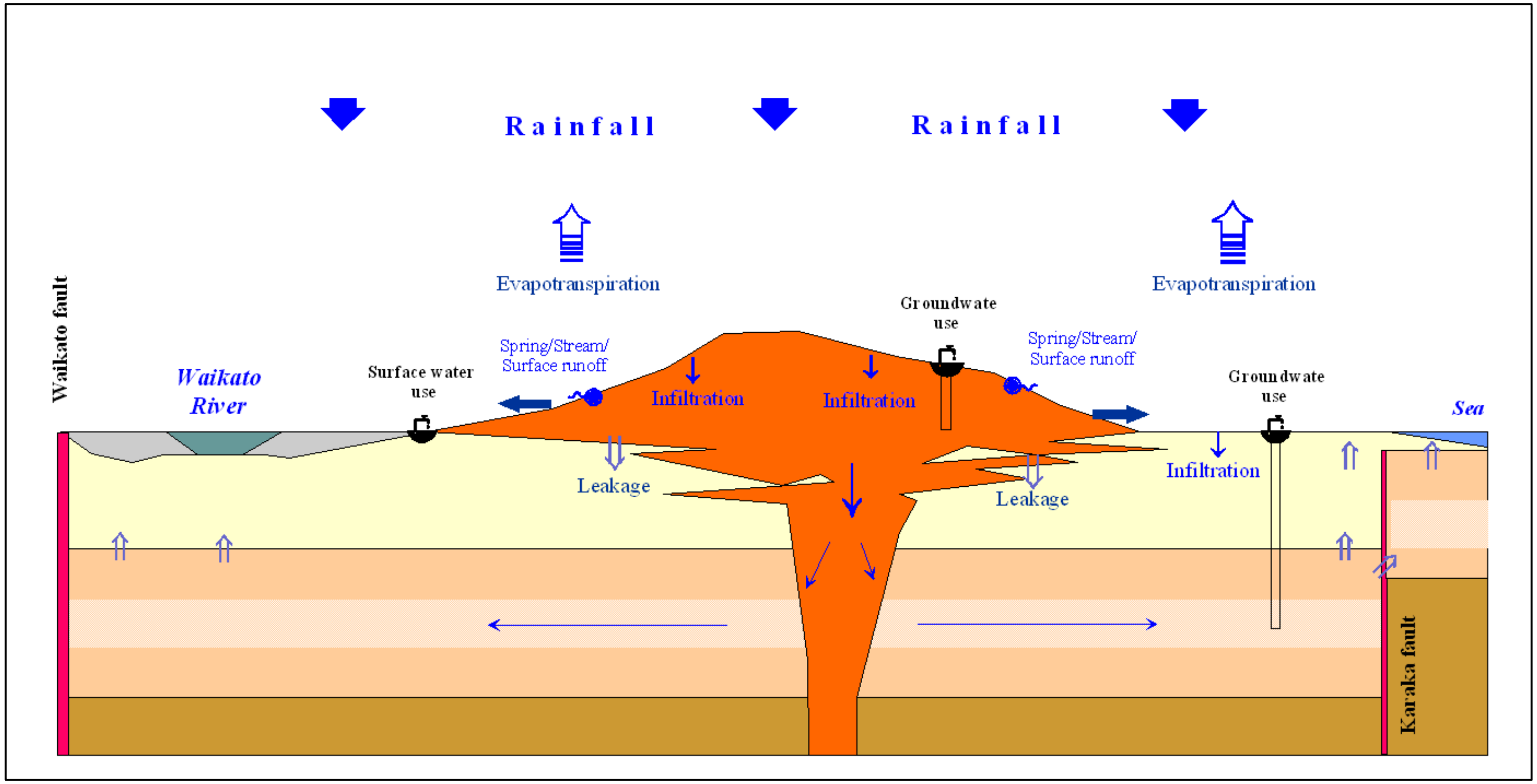

Figure 2.3 Conceptual model of groundwater recharge and groundwater flow to the volcanic aquifers and to the Kaawa shell aquifer, via volcanic feeder zones (Viljevac et al. 2002). Geological units include: volcanics (orange); Tertiary sediments (yellow), Kaawa shell aquifer (peach) and basement (brown).

2.3 Groundwater Elevation

Groundwater elevation maps were used to identify groundwater catchments and groundwater flow directions; groundwater flows from areas of high ground elevation towards the coast (Figure 2.4 and Figure 2.5). These maps have been used by AC to develop groundwater allocation zone boundaries (Section 2.5). However, multiple volcanic aquifer systems, i.e., 'shallow volcanic aquifers' and 'deep volcanic aquifers', have been identified in the area (Viljevac 1996).

Groundwater elevation is measured over time by AC (Figure 2.6). Elevations may increase or decrease over time, i.e., the Sen slope is positive or negative, respectively (Table 2.2). Sinclair Knight Merz (2010) observed that groundwater elevation was consistently declining in the Karaka area from about 2004. This declining groundwater level may be caused by declining rainfall recharge and/or increasing use. They could not separate these two causations because climate is driving both rainfall and groundwater use.

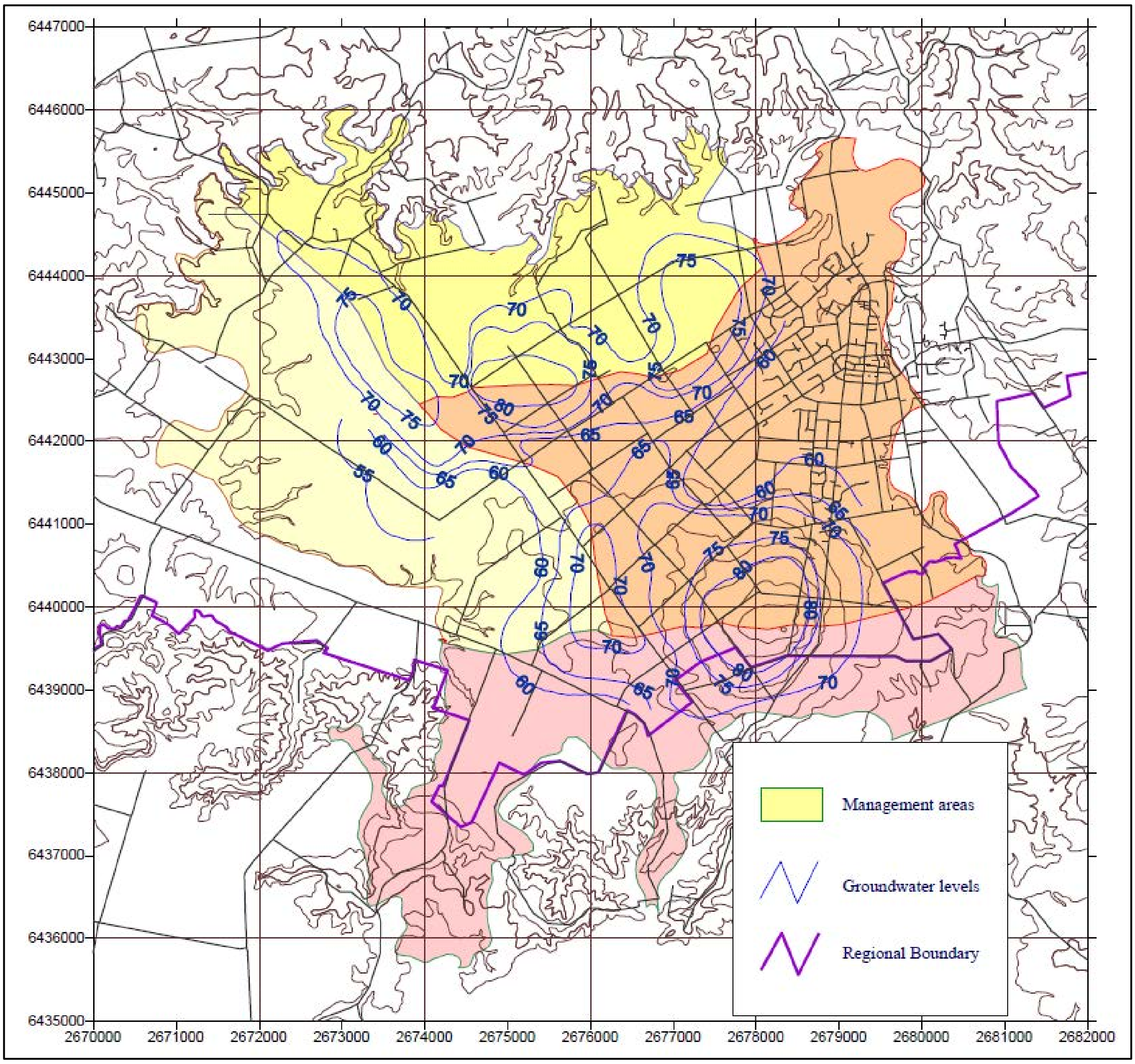

Figure 2.4 Groundwater elevation in the Pukekohe volcanic aquifer (Viljevac et al. 2002).

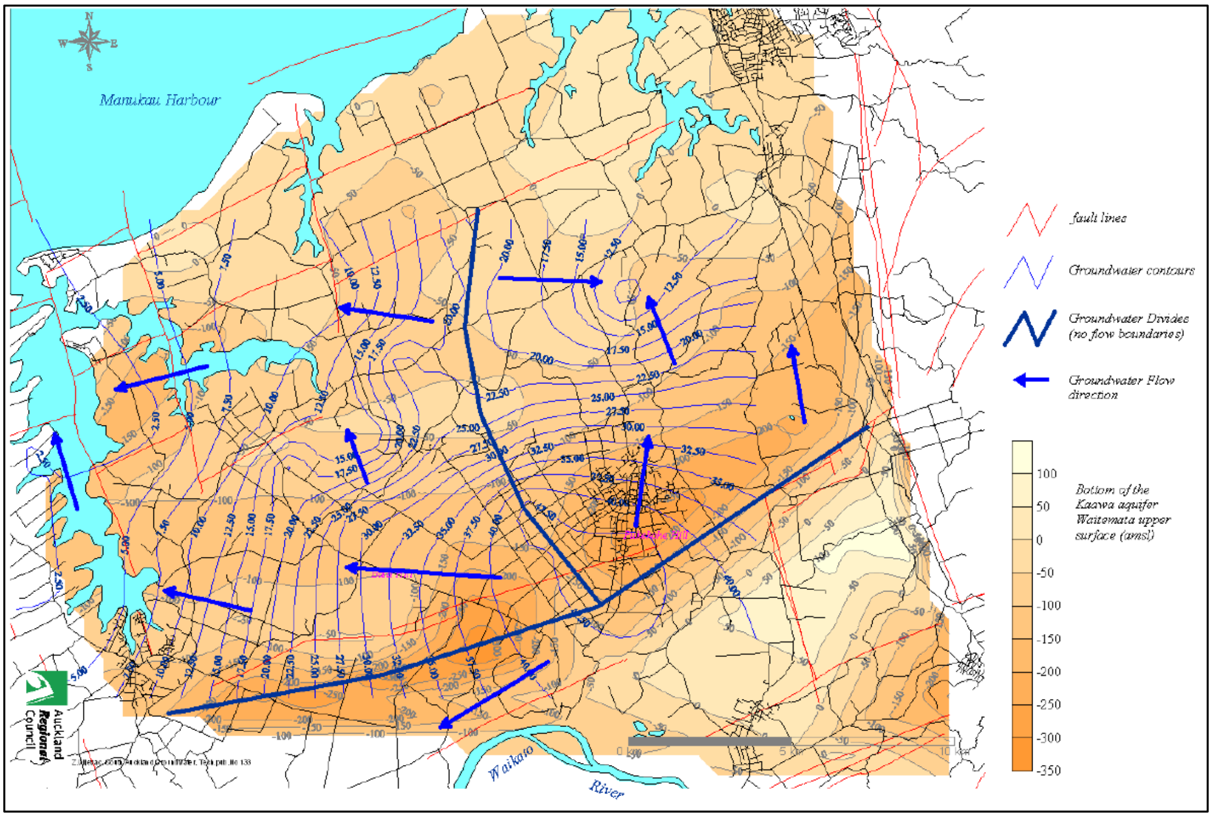

Figure 2.5 Groundwater flow directions in the Kaawa shell aquifer (Viljevac et al. 2002).

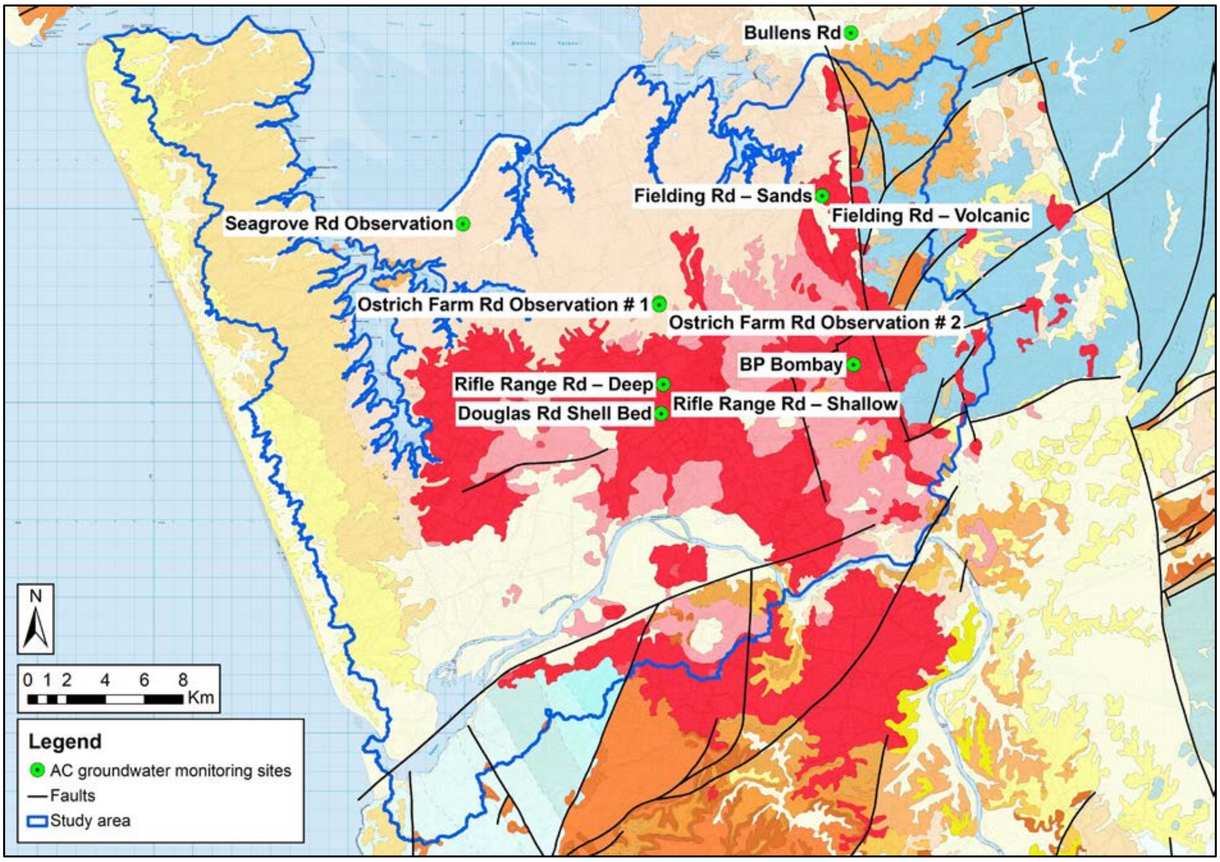

Figure 2.6 AC monitoring wells in the study area (Auckland Regional Council 2007; and Kalbus et al. 2017). See Figure 2.1 for the geological legend.

Table 2.2 Statistics of average monthly groundwater level 2006–2015 in the AC region (Kalbus et al. 2017; Table 18).

Well Name	Formation	Well Depth (m)	Groundwater Elevation	
			Median (m above sea level)	Sen Slope (m/yr)
Ostrich Farm Rd Observation # 2	Kaawa Formation – shelly and carbonaceous sandstones	47.6	20.66	-0.005
Ostrich Farm Rd Observation # 1	Kaawa Formation – shelly and carbonaceous sandstones	84	20.56	-0.006
Fielding Rd – Sands	Pleistocene sediments – alluvial sediments	64	8.81	0.164*
Fielding Rd – Volcanic	South Auckland Volcanics – basalt, scoria and tuff	46.7	14.63	-0.018
BP Bombay	South Auckland Volcanics – basalt, scoria and tuff	79.43	-	-
Rifle Range Rd – Shallow	South Auckland Volcanics – basalt, scoria and tuff	42	56.98	0.173**
Rifle Range Rd – Deep	South Auckland Volcanics – basalt, scoria and tuff	90	45.98	0.260**
Douglas Rd Shell Bed	Kaawa Formation – shelly and carbonaceous sandstones	268.2	49.79	0.058**
Seagrove Rd Observation	Waitemata Group – sandstones and mudstones	201	5.3	-0.163**

* = statistically significant

** = ‘meaningful’ (Kalbus et al. 2017)

2.4 Groundwater Chemistry and Groundwater Age

Typically, nitrate (commonly measured as nitrate-nitrogen concentrations) are elevated in Franklin District basalt aquifers (Petch et al. 1991; Cathcart 1995, Crowcroft and Smaill 2001, Close et al. 2001; Moreau et al. 2016; and Kalbus et al. 2017). For example, elevated nitrate concentrations in shallow wells are measured in AC’s monitoring wells located in basalt aquifers (Table 2.3). Nitrate concentrations have been measured above the maximum allowable value for drinking water in Glenbrook, Pukekohe, Bombay, and Drury wells (Meijer et al. 2016, Kalbus et al. 2017, Crowcroft and Smaill 2001). Nitrate concentrations are also elevated in Tauranga Group wells (Petch et al. 1991). Groundwater in the Kaawa shell aquifer shows very low nitrate-nitrogen concentrations (Meijer et al. 2016, Kalbus et al. 2017).

Land use is the main source of nitrate in groundwater in the area (Meijer et al. 2016 and Kalbus et al. 2017). In-groundwater chemical conditions have some effect on nitrate-nitrogen concentrations. For example, nitrate-nitrogen concentrations are reduced by deoxygenation in reducing conditions, as possibly demonstrated by nitrate-nitrogen concentrations in the Rifle Range Rd wells, i.e.:

- Rifle Range Rd Shallow well: median nitrate-nitrogen concentration 7.5 mg/L (Table 2.3) and median Dissolved Oxygen (DO) 69% saturation (Kalbus et al. 2017);
- Rifle Range Rd Deep well: median nitrate-nitrogen concentration 0.002 mg/L (Table 2.3) and median DO 1.15% saturation (Kalbus et al. 2017).

Table 2.3 Statistics of nitrate-nitrogen concentrations in AC monitoring wells 1998–2013 (Kalbus et al. 2017; Table 19).*

Well Name	Site Number	Formation	Depth (m)	Nitrate-nitrogen	Trend (mg/L/year)
				Median (mg/L)	
Ostrich Farm Rd Observation # 2	7418023	Kaawa Formation – shelly and carbonaceous sandstones	47.6	0.003	0.00
Ostrich Farm Rd Observation # 1	7418027	Kaawa Formation – shelly and carbonaceous sandstones	84	0.005	0.00
Fielding Rd – Sands	7419007	Pleistocene sediments – alluvial sediments	64	0.002	0.00
Fielding Rd – Volcanic	7419009	South Auckland Volcanics – basalt, scoria and tuff	46.7	0.005	0.00
BP Bombay	7419121	South Auckland Volcanics – basalt, scoria and tuff	79.4	9.2	0.21
Rifle Range Rd – Shallow	7428105	South Auckland Volcanics – basalt, scoria and tuff	42	7.5	0.57
Rifle Range Rd – Deep	7428103	South Auckland Volcanics – basalt, scoria and tuff	90	0.002	0.00
Douglas Rd Shell Bed	7429013	Kaawa Formation – shelly and carbonaceous sandstones	268.2	-	-
Seagrove Rd Observation	7417021	Waitemata Group – sandstones and mudstones	201	0.002	0.00

* Note that Kalbus et al. 2017 (Table 19) appears to contain typographical errors. Therefore, data in this table is taken from Kalbus et al. 2017 (page 56).

Saltwater intrusion has ‘occurred in the shell aquifer on the Glenbrook Peninsula’ and ‘pollution of the shell aquifer from overlying aquifers can occur due to poorly constructed bores.’ (Auckland Regional Water Board 1989). As a result, AC has enacted salinity monitoring as part of resource consent compliance monitoring requirements where saline intrusion is a risk to wells (Johnson 2019a).

Iron concentrations may exceed guidelines for aesthetic water quality in wells that take water from the volcanic aquifers and the Drury sand aquifer (Kalbus et al. 2017, Petch et al. 1991, Maggs 1991). Some Kaawa shell aquifer wells have iron and manganese concentrations above aesthetic guideline values (Kalbus et al. 2017). In addition, groundwater in wells taking water from the Tauranga Group demonstrate elevated levels of iron and manganese associated with peat layers and reducing conditions (Petch et al. 1991). Faecal coliforms have been recorded in groundwater from the Drury area and within WRC catchments (Auckland Regional Council 1991b; White et al. 2015).

Groundwater dating has included a recent study in the Pukekohe-Bombay area (van der Raaij 2015; Figure 2.7). ‘Nitrate concentrations show an inverse relationship’ with groundwater mean residence time (MRT) (van der Raaij 2015). For example, nitrate-nitrogen concentrations in the upper Pukekohe volcanic aquifer were greater than 13 mg/L and MRT was in the range 14–56 years (Table 2.4). In contrast, the nitrate-nitrogen concentration and MRT in the lower Pukekohe volcanic aquifer were 0.041 mg/L and 99 years, respectively.

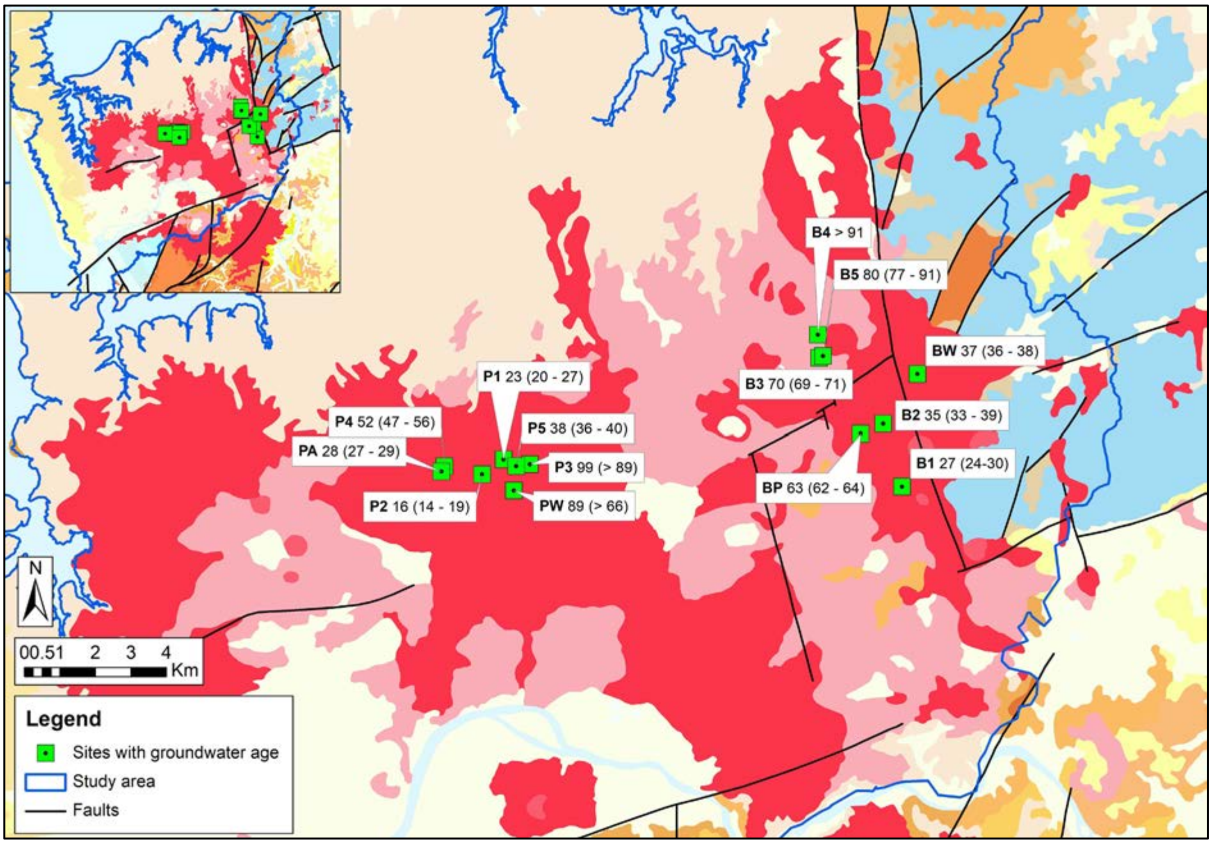

Figure 2.7 Location of groundwater dating measurements (van der Raaij 2015).

Table 2.4 MRT and nitrate-nitrogen concentrations in Pukekohe wells (van der Raaij 2015).

Sample ID	AC Well ID	Well Depth (m)	Nitrate-nitrogen (mg/L)	MRT (years)	Aquifer Lithology
P1	3598	37	13	23 (20–27)	Upper Pukekohe volcanic
P2	3573	40.4	22	16 (14–19)	Upper Pukekohe volcanic
P3	3623	72	0.041	99 (> 89)	Lower Pukekohe volcanic
P4	3512	28	28	52 (47–56)	Upper Pukekohe volcanic
P5	7428105	42	13	38 (36–40)	Upper Pukekohe volcanic

2.5 Groundwater Allocation and Use

Groundwater allocation has been a focus of science in the study area since the 1970s, e.g., 'In 1974, a letter from the Franklin County Council, sent jointly to the Auckland Regional Water Board and Waikato Valley Authority, expressed concern at the deterioration over the previous years of some bores within the County. This deterioration was indicated by bores drying up, and by water levels in bores falling.' (Auckland Regional Water Board and Waikato Valley Authority 1977). Since then, numerous reports by the Auckland Regional Water Board and Auckland Regional Council have assessed sustainable allocation limits, often provided by water budgets, and groundwater allocation has been shown to be larger than groundwater use (Table 2.5 and Table 2.6).

Current groundwater allocation by AC and WRC is based on allocation zones. AC assigns groundwater allocation limits, typically assessed for individual aquifers, within sub-regions for groundwater management purposes. For example, current AC Kaawa groundwater allocation is apportioned into six zones; the locations of these zones are based on inferred groundwater flow patterns (Viljevac et al. 2002). AC groundwater availability and consented groundwater allocation in two reporting areas: Awhitu and Franklin (Table 2.7). These areas include allocation to the main aquifers (volcanic and Kaawa, Figure 2.8 and Figure 2.9, respectively) and sand aquifers (Figure 2.10). WRC allocates groundwater in four zones (Figure 2.11 and Table 2.8). These zones sum allocation from all aquifers. Groundwater allocation limits for the Waitemata sediments was addressed by EarthTech (2018).

Table 2.5 Groundwater allocation limits calculated by Auckland Regional Water Board and Auckland Regional Council.

Item	Rate (m^3/year)	Area (km^2)	Notes	Reference
Kaawa Formation maximum allocation	10,862,400	298.5	Allocation apportioned to sub-areas	Auckland Regional Water Board (1989)
Pukekohe Volcanic Aquifer groundwater availability	2,345,750	56.63	Availability apportioned to sub-areas	Viljevac et al. (2002)
Kaawa shell aquifer groundwater availability	8,986,078	276.63	Availability apportioned to sub-areas	Viljevac et al. (2002)
Drury-Bombay groundwater availability	2,734,960	na	Availability apportioned to sub-areas	Auckland Regional Council (1991b)

Table 2.6 Groundwater allocation and groundwater use calculated by Auckland Regional Council (Crowcroft and Smaill 2001).

Groundwater Management Area	Groundwater Allocation (Million m^3/year)	Groundwater Use (Million m^3/year)
Pukekohe	1	0.6
Kaawa	6.2	4.7 (approximately)

Table 2.7 AC groundwater availability and consented groundwater allocation as of May 2017 (Johnson 2019b).

AC Reporting Area	AC Main Aquifer	AC Sub Aquifer 1	AC Sub Aquifer 2	Aquifer Area (km^2)	Groundwater Availability (m^3/year)	Consented Groundwater Allocation (m^3/year)
Awhitu	Awhitu Kaawa			226.8	2,235,000	659,270
	Awhitu Sand			226.8	1,890,000	95,000
Franklin	Franklin Kaawa	Bombay Drury Kaawa	Bombay-Drury Kaawa	30.2	718,000	298,624
			Papakura Kaawa	9.6	*	30,500
		Glenbrook Kaawa		85.2	2,863,000	1,399,595
		Pukekohe Kaawa		88.5	2,481,000	814,899
		Waiuku Kaawa		61.8	3,203,000	2,620,010
	Bombay Drury Sand			57.5	*	3,500
	Drury Sand			**	198,580	142,725
	Papakura Sand			23.3	133,000	18,380
	Franklin Volcanic	Bombay Volcanic		51.3	1,190,000	884,600
		Glenbrook Volcanic		37.1	1,205,000	126,750
		Pukekohe Volcanic	Pukekohe Central Volcanic	22.8	956,000	847,950
			Pukekohe North Volcanic	11.3	420,000	223,300
			Pukekohe West Volcanic	16.9	420,000	395,750
			Pukekohe South Volcanic	8.1	650,000	388,750
Sum				957	18,562,580	8,949,603

* currently, no groundwater availability is defined by AC.

** currently, no groundwater availability zone boundary is defined by AC.

Table 2.8 WRC groundwater availability and consented groundwater allocation (i.e., July 2019; Koh 2019).

WRC Management Zone	Area (km^2)	Management Level (m^3/year)	Consented Groundwater Allocation (m^3/year)
Waiuku – recharge zone	36.52	5,500,000	914,544
Waiuku – discharge zone	60.1	9,000,000	1,147,910
Pukekohe	79.25	12,000,000	3,213,518
Pukekawa	141.48	20,000,000	1,611,490
Sum	317.35	46,500,000	6,887,462

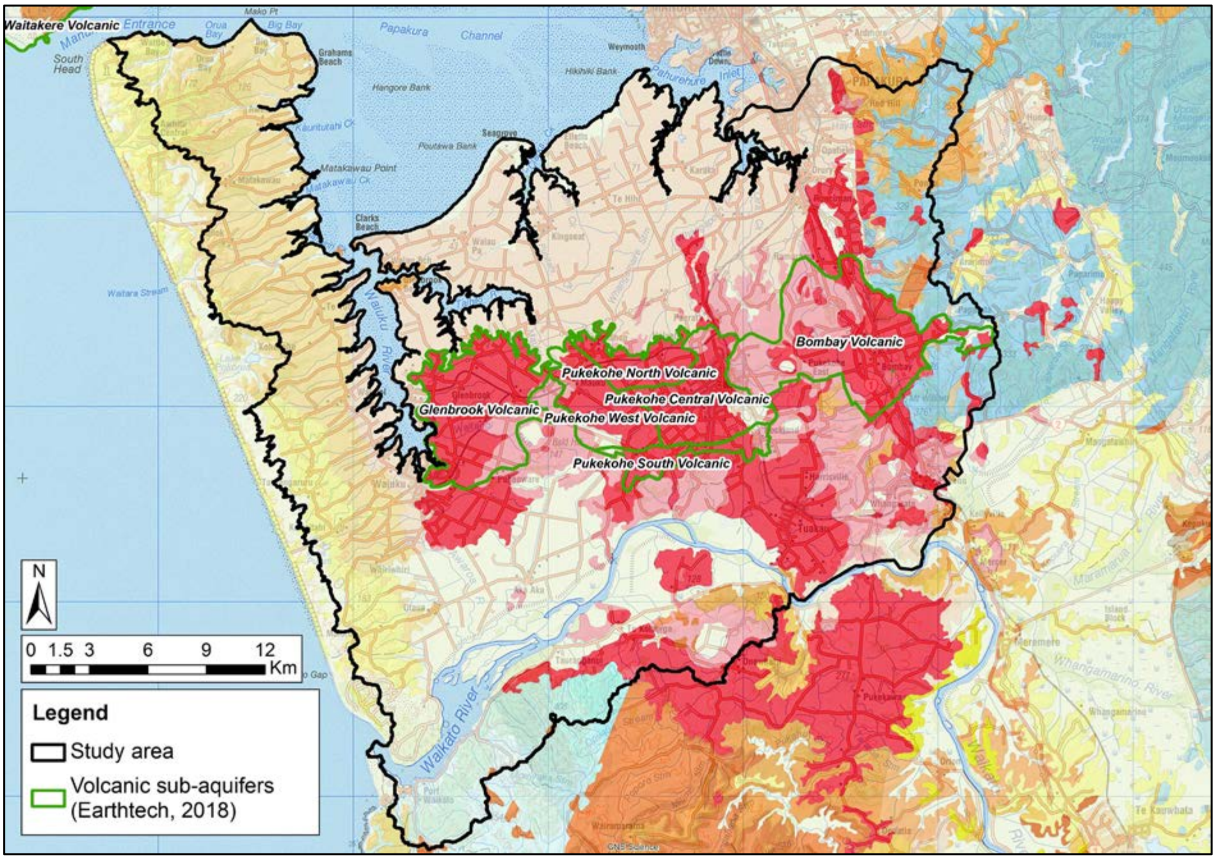

Figure 2.8 AC groundwater allocation zones for the volcanic aquifers (Earthtech 2018).

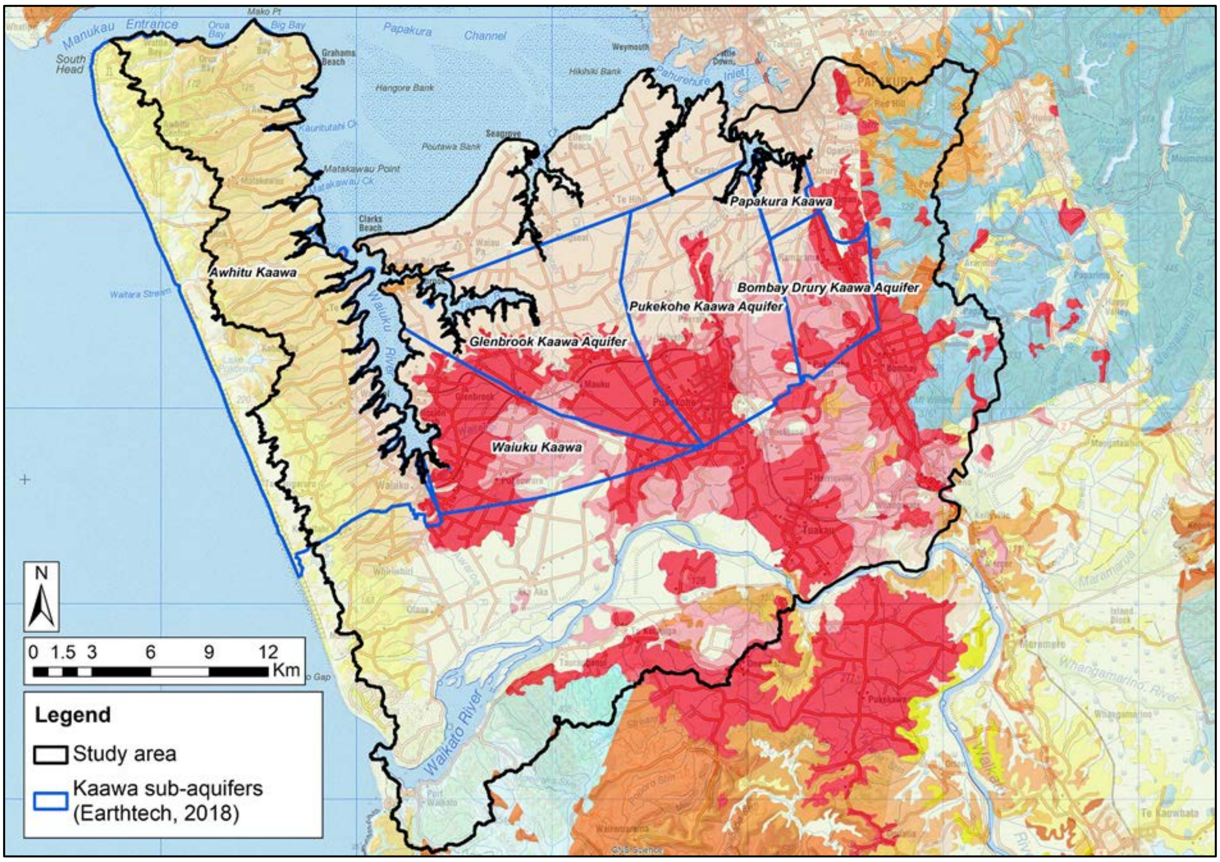

Figure 2.9 AC groundwater allocation zones for the Kaawa shell aquifers (Earthtech 2018).

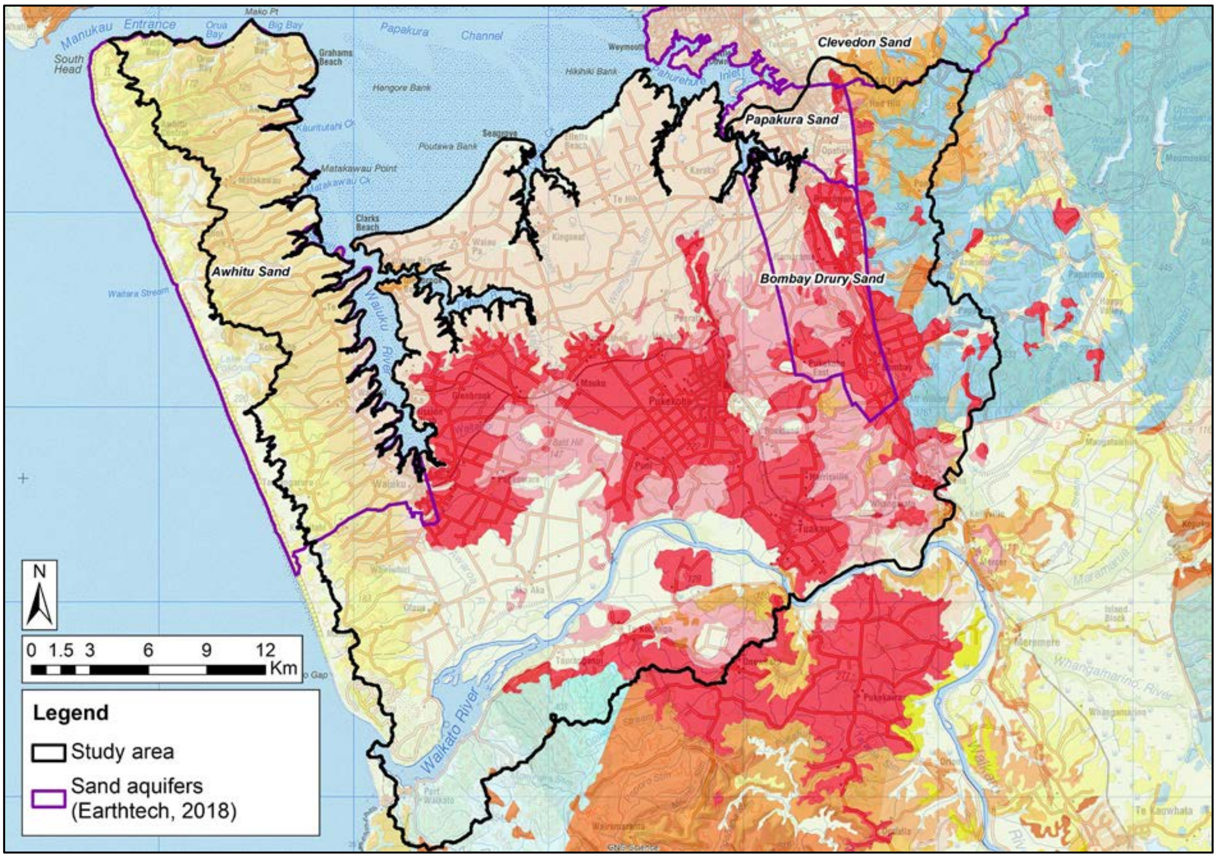

Figure 2.10 AC groundwater allocation zones for the sand aquifers (Earthtech 2018).

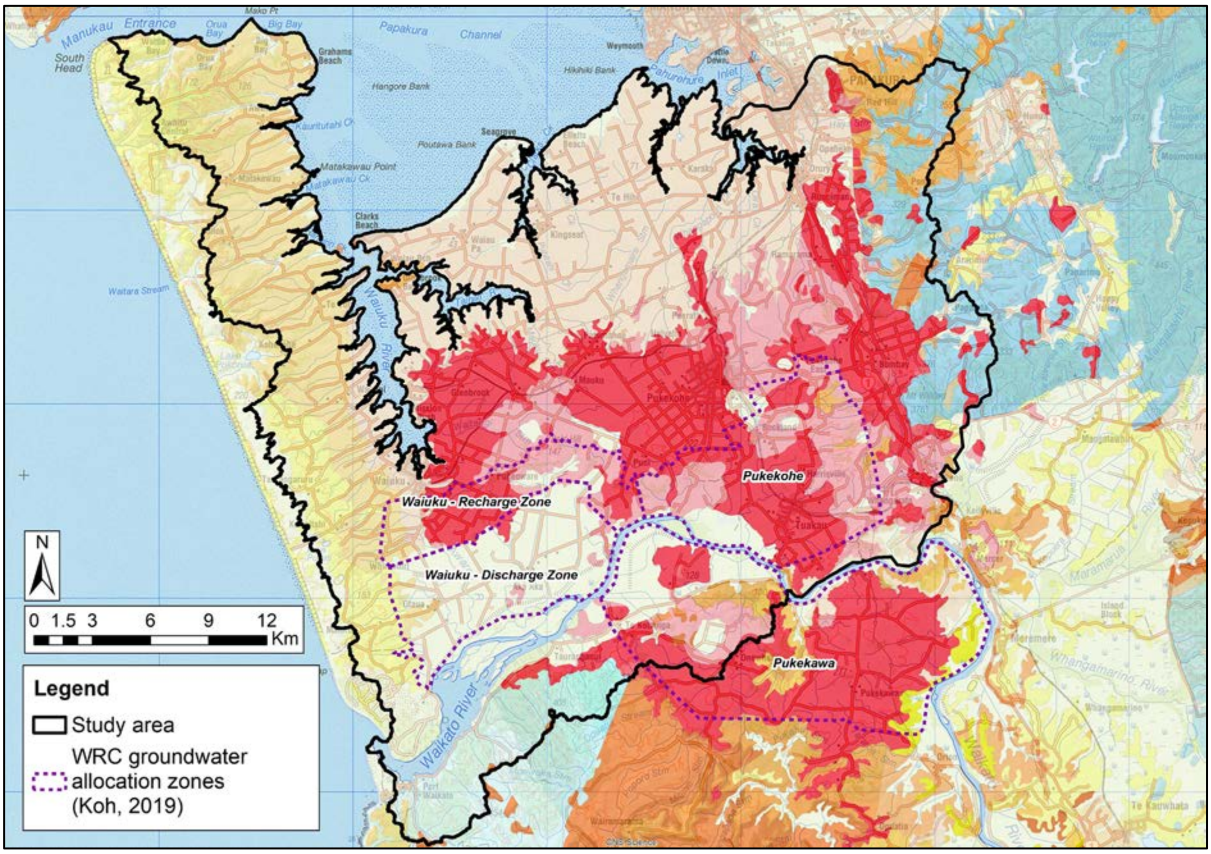

Figure 2.11 WRC groundwater allocation zones (Koh 2019).

2.6 Surface Water

The major streams of the northern part of the study area include Waitangi Stream, Mauku Stream, Whangapouri Stream, Whangamaire Stream, Oira Creek, Ngakoroa Stream and Hingaia Stream (Figure 2.12). These streams drain from Pukekohe and Bombay volcanic plateaux towards the Manukau Harbour and receive recharge from the volcanic aquifers (Viljevac et al. 2002). In the southern part of the study area, the main streams (i.e., Tutaenui Stream and Te Awaoa River) discharge from the Pukekohe and Glenbrook volcanic plateaux, respectively, into the Waikato River.

Streams in the study area receive baseflow from the groundwater system and have typically been considered in groundwater investigations. For example, the groundwater system provides monthly-average baseflow equivalent to 68–88 mm/year for a 1-in-5-year low flow in Tutaenui Stream (Petch et al. 1991). Annual stream flow from streams in the Pukekohe area was an equivalent of 554 mm/year and 524 mm/year (Petch et al. 1991, and White et al. 1996, respectively). Total baseflow from the Pukekohe volcanic aquifer to streams was estimated at approximately 26.1 M m^3/year, based on flow records from local streams (Viljevac et al. 2002). Springs in the area provide significant baseflow. For example, four springs on the Pukekohe Plateau flow at approximately 8.1 M m^3/year (Viljevac 1996).

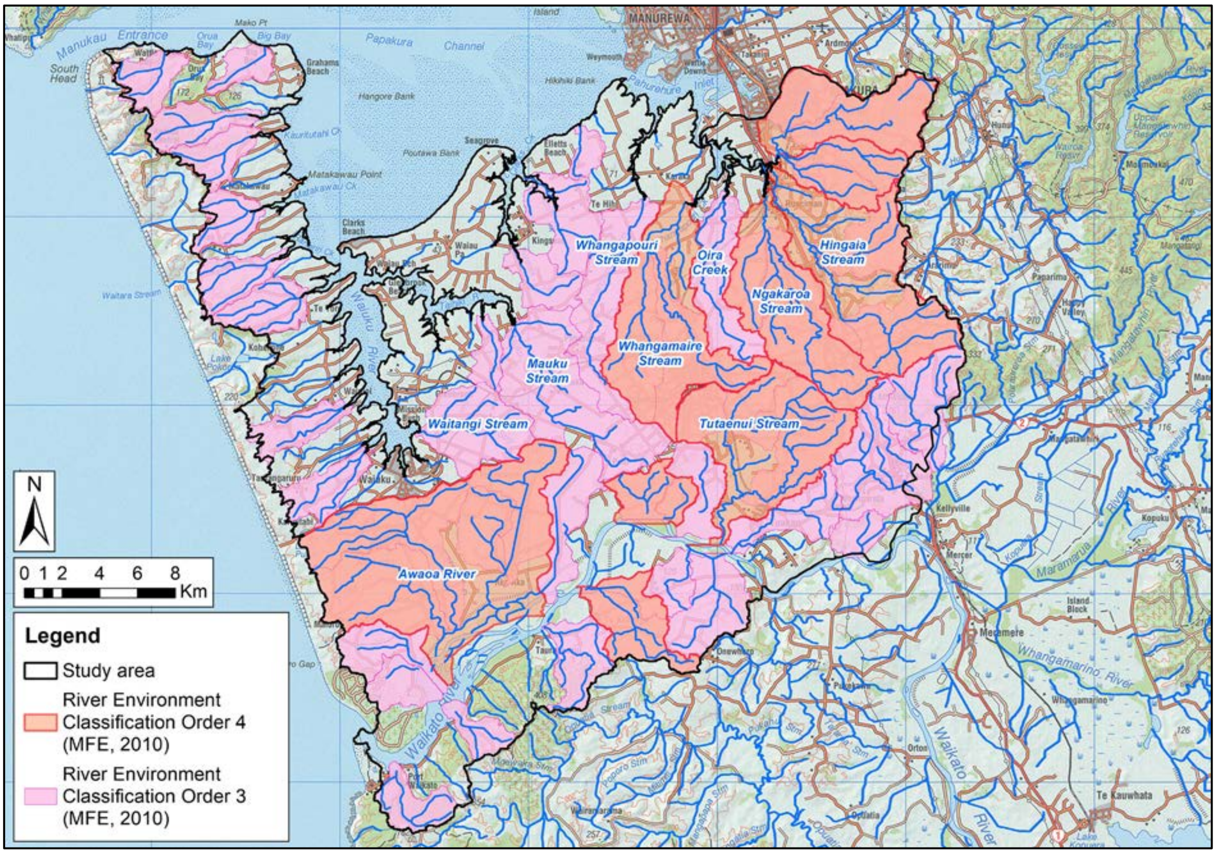

Figure 2.12 Major streams and related catchments located within the study area (River Environment Classification, Ministry for the Environment 2010).

3.0 METHODS

3.1 Digital Terrain Model

A digital terrain model (DTM) was created from two data sets:

- LiDAR data in the Auckland region provided by AC in New Zealand Transverse Mercator coordinates (NZTM), (Hill Forthcoming 2019);
- LiDAR data for the Lower-Middle Waikato region (including the Waikato River valley) calculated in New Zealand Map Grid (NZMG), described in White et al. (2015), and converted to NZTM.

The DTM was calculated by digitising the two data sets into points at a 100 m by 100 m interval, then merging, gridding and clipping to the study area.

3.2 Three-dimensional Geological Model

The 3D geological model was made using an archive of lithology information that was recorded in well logs that were drilled in the study area (Figure 3.1).

Lithological data for this project were sourced from a database that includes geological descriptions and geotechnical tests compiled for the purpose of 3D geological modelling that contains 34,733 geological records from 2,324 boreholes (Hill Forthcoming 2019). This data was obtained from the New Zealand Geotechnical Database (NZGD) and other sources including: GNS Science, AC, WRC and New Zealand Petroleum and Minerals data, mainly in the form of PDF format records of scanned paper borehole logs. Data compilation focused on descriptions of materials encountered during drilling. Lithological interval descriptions were entered verbatim from the logs and an interpretation of the geological formation was made from that description. A subjective ranking value was attached to each borehole record to signal the relative quality of the information so that confidence modelling can be applied to interpretations of the data. The database has been designed around GeoSciML (a data model and data transfer standard for geological information) and other data standards as well as formatting standards required by 3D modelling software.

The 3D model of the study area was developed to represent the distribution of key lithologies using ‘pseudo-logs’ with a method described by White and Reeves (1999) and White et al. (1996). In summary, the method uses well log descriptions to calculate three models each of three target lithologies, i.e.:

- basalt and associated deposits (such as scoria) of the South Auckland volcanics;
- peat and similar other deposits (e.g., timber) that indicate Puketoka Formation;
- shells that indicate the presence of the Kaawa Formation shell bed aquifer.

Well logs were ‘sampled’ at a 0.05 m interval to produce ‘pseudo-logs’, i.e., discretised representations of target lithologies with the target lithology assigned a value of 200 and other lithologies assigned a value of 100. Then, the ‘pseudo-logs’ are registered to ground elevation using the DTM. The 3D distributions of the three lithologies were calculated with a conformal (to the ground surface) 3D grid using the Earth Vision software. Then, the 3D grid was converted into a 3D property model where contours represent a proxy for the probability distribution of each lithology.

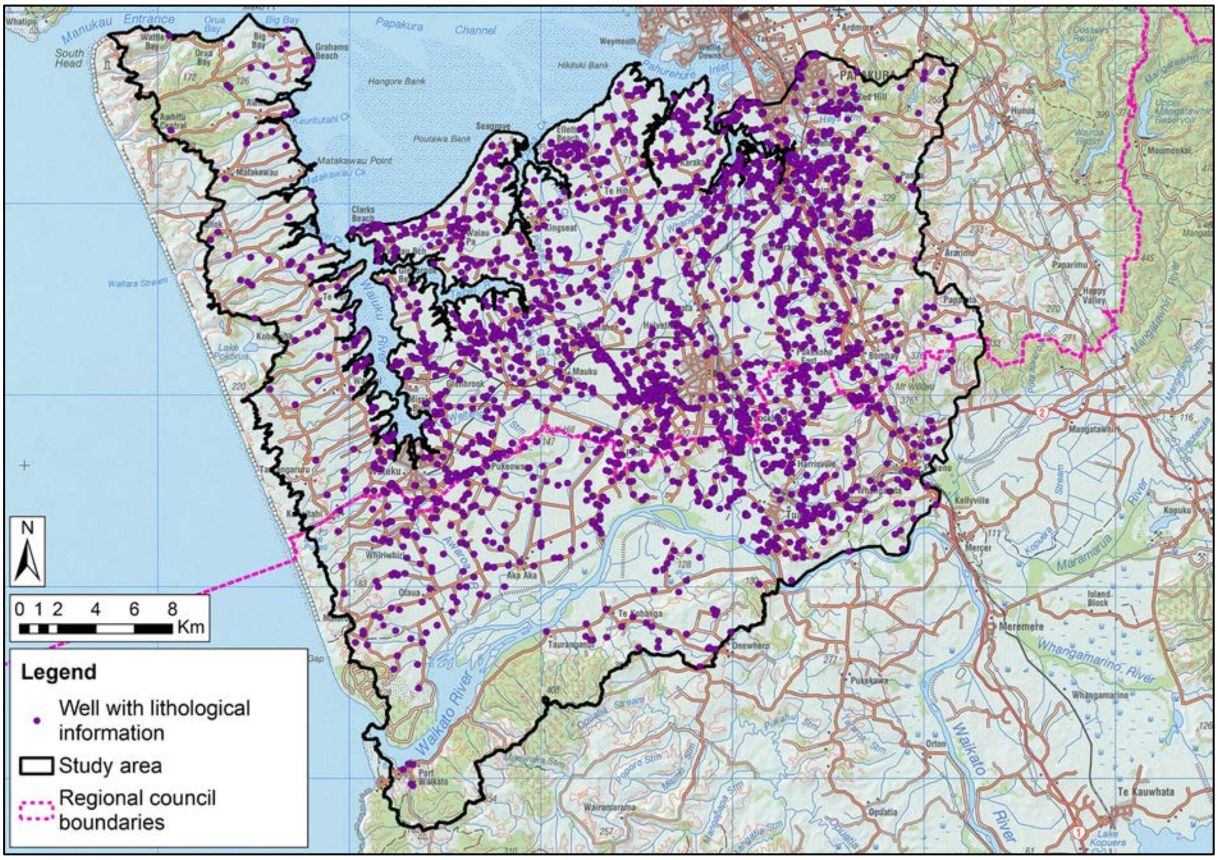

Figure 3.1 Location of wells with lithological information.

3.3 Groundwater Flow Budgets

Groundwater flow budgets aim to calculate the major components of groundwater flow in order to inform characterisation of the groundwater system and estimation of the volume of groundwater available for allocation.

3.3.1 Water Budgets

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).

$$\text{water inflow} = \text{water outflow} \tag{1}$$

i.e., $$P + Q_{IN} = AET + Q_{OUT} + \Delta S \tag{2}$$

P precipitation.

Q_{IN} water inflow, i.e., surface water (Q^{SW}_{IN}) and groundwater (Q^{GW}_{IN})

AET actual evapotranspiration

Q_{OUT} water outflow, i.e., surface water (Q^{SW}_{OUT}), groundwater (Q^{GW}_{OUT}) and water use (i.e., groundwater and surface water), Q^{USE}_{OUT}

ΔS change in water storage.

These budgets aim to represent catchment water flows over the long term and in natural conditions. Therefore, Q_{IN}, ΔS and Q^{USE}_{OUT} are assumed as zero, giving

$$P = AET + Q^{SW}_{OUT} + Q^{GW}_{OUT} \tag{3}$$

The assumption of zero Q_{IN} is consistent with our understanding of the hydrogeology of the study area, i.e., no large inflows to groundwater from water bodies outside the study area have been identified. The assumption of zero ΔS is reasonable over the period of the steady-state model. Evidence for relatively low groundwater levels reported in 1974, see above, may indicate that groundwater storage is declining over time. However, these low levels may have been caused by the 1973/1974 drought and may not be due to groundwater use (see Section 5). The assumption of zero Q^{USE}_{OUT} is consistent with one purpose of the model, i.e., to calculate natural groundwater inflows. However, the use of groundwater may impact on Q^{SW}_{OUT} as the groundwater system provides baseflow in streams.

Q^{GW}_{OUT} discharges across the catchment boundary. This outflow may travel to other groundwater catchments or across the coastal boundary. The route that this water takes could be via deep layers, so that Q^{GW}_{OUT} provides an estimates of recharge to: volcanic aquifers exclusive of the parts of these aquifers that provide baseflow; Kaawa shell aquifers, to surface waters in adjacent catchments; and to the ocean and estuaries.

Mean annual rainfall or precipitation (P) was estimated for each representative catchment with ArcGIS software and the nationwide National Institute of Water and Atmospheric Research (NIWA) precipitation dataset (Tait et al*.* 2006). This dataset is based on rainfall measurements at individual climate stations, interpolated throughout New Zealand and averaged for the period 1960–2006 (Tait et al*.* 2006). Similarly, mean AET was estimated for each representative catchment with ArcGIS software as AET from the land surface derived using a national-scale AET 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; Henderson 2019). This data was used because it calculates average rainfall and average AET over a long term that is very useful to the understanding of long-term average groundwater flow.

Long-term surface water outflow was assessed with calculations of median observed flow, taken to represent Q^{SW}_{OUT} and baseflow. Groundwater outflow was calculated to balance Equation 3. Water budgets were assessed with regard to the predominant geology in surface catchments, Section 3.3.4.

3.3.2 Surface Flow and Baseflow

Surface water flow is represented by baseflow (Q^{SW}_{BF}) and runoff or quick flow (Q^{SW}_{QF}) components:

$$Q^{SW}_{OUT} = Q^{SW}_{BF} + Q^{SW}_{QF} \tag{4}$$

The baseflow index (BFI) is represented with:

$$BFI = Q^{SW}_{BF} / Q^{SW}_{OUT} \tag{5}$$

Two approaches were used to calculate Q^{SW}_{BF} and Q^{SW}_{QF}. For the continuous-flow datasets, the estimated baseflow and quick flow time series were calculated by applying an Eckhardt 2-parameter digital baseflow filter (Eckhardt 2005) to the measured stream-flow time series. The Eckhardt (2005) baseflow filter parameters (“BFI_max” and “alpha”) were set at 0.8 and 0.98, respectively. While these values may vary between monitoring site locations, the values used are typical of reported literature values and also generally agree with the estimated filter parameter values for nearby gauging locations in the Hauraki Plains (e.g., Woodward and Stenger 2018).

For gauging data, this baseflow analysis is not appropriate. Gauging data is not typically measured regularly and the number of measurements at each site is quite variable. In addition, the timing of gauging measurements may show a bias toward low flows, as most gauging programmes have focused on this part of the hydrograph. In some instances, gaugings may have targeted flood flows. Therefore, two statistics are used to calculate two stream-flow components. The mean of gauged flows estimates Q^{SW}_{OUT} and the median of gauged flows estimates Q^{SW}_{BF}. Then, Q^{SW}_{QF} is calculated with Equation 4 and BFI is estimated with:

$$BFI = Q_{\text{Median gauging}} / Q_{\text{Mean gauging}} \tag{6}$$

3.3.3 Rainfall Recharge

Rainfall recharge (RR) to groundwater provides the water that becomes baseflow and groundwater outflow, i.e.:

$$RR = P - AET \text{ , and} \tag{7}$$

$$RR = Q^{SW}_{BF} + Q^{GW}_{OUT} \tag{8}$$

Long-term RR is calculated from Equation 7 using long-term estimates of P and AET. AC measurements of rainfall recharge at two sites in the study area (i.e., Karaka and Puni; Figure 3.2) can be used as a check on RR calculations. Each site includes three lysimeters and a ground-level rainfall gauge (Lovett 2016). Unfortunately, the duration of the Puni record is too short to be of use to this project (Johnson 2019c). Recording at the Karaka site commenced on 22/06/2016 (Table 3.1). These data were analysed by summing rainfall recharge measured in the lysimeters, and the rainfall site, for complete months of record. A large gap in the data record from 31/3/2017 was due to rain at the end of March 2017 that flooded the site (Lovett 2018).

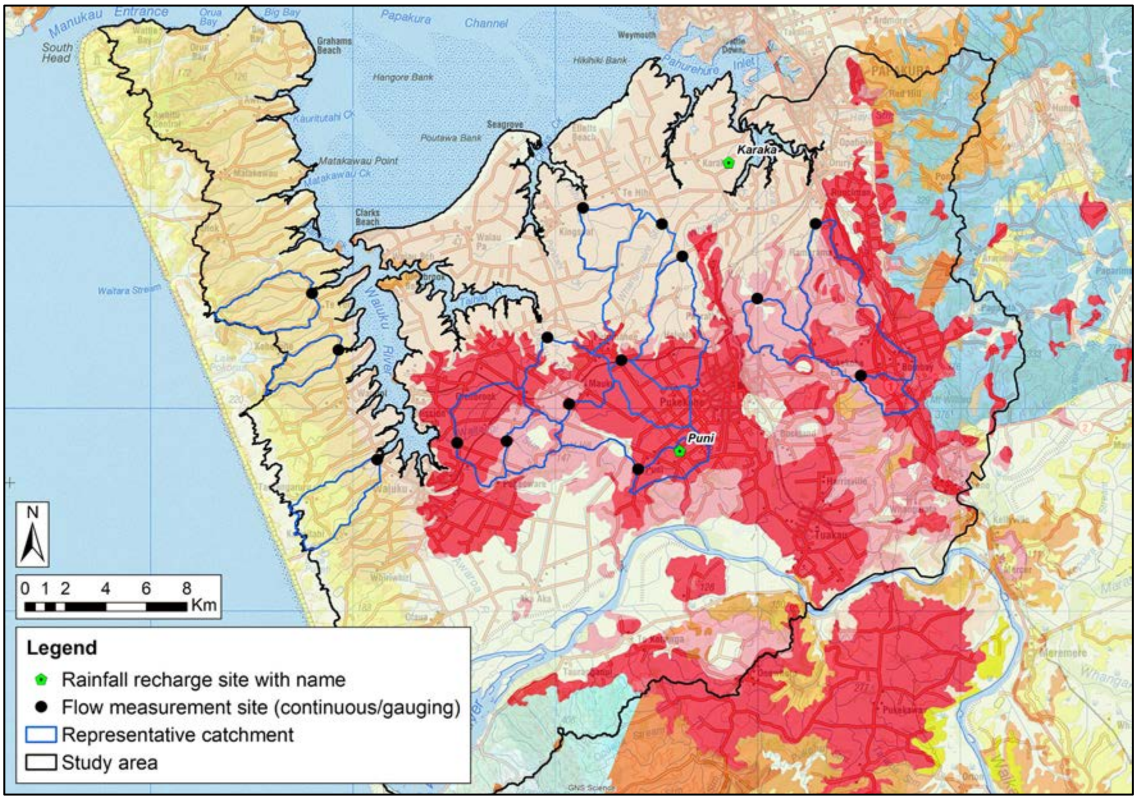

Figure 3.2 Location of the AC rainfall recharge sites (each site includes three lysimeters and a ground-level rainfall gauge) and the representative catchments with flow sites used in the water budget calculations.

Table 3.1 Summary of data recording periods at the Karaka rainfall recharge site.

Recording Period, Karaka Rainfall Recharge Site		**Note**
Start	**Finish**	
22/06/2016	3/04/2017	Lovett (2016)
3/05/2018	2/01/2019	End date of AC data query for this report

3.3.4 Surface Water Flow and Surface Catchments

Surface water flow data from the AC region includes historic gauging datasets and five continuous flow monitoring sites (Figure 3.3, Figure 3.4 and Appendix 1; Johnson 2019d). Gauging data from the Waikato region collated by White et al. (2015) included:

- WRC's historic gauging dataset (Jenkins 2015a);
- field measurements of surface water flows measured by WRC in 2015 for the Healthy River Project in the Lower to Middle Waikato zones (Hadfield 2015);
- surface flow measurements from stage recorders in the Waikato catchment, in particular mean and median flows in the period 1960 to 2006 (Jenkins 2015b).

The selection of 'representative catchments' aimed to characterise surface flows, particularly Q^{SW}_{BF} and Q^{SW}_{QF}, in predominant surficial geologies. It was also anticipated that the results gained for the representative catchments selected within the AC region can be extrapolated to the WRC catchments in the study area due to their similarities (i.e., climate, geology, land cover). The location of these catchments was based on:

- the location of AC and WRC flow measurements (Figure 3.3);
- predominant geology in the topographic catchments above flow-measurement sites with the aim of identifying features of long-term water budgets that are characteristic of these geologies (Figure 3.5 and Figure 3.6). Predominant geology was assessed from Qmap as: volcanic, sedimentary or mixed, Table 3.2; and
- the quality of the long-term flow record, i.e., identifying measurement sites with a large number of flow measurements because sites with a large number of flow measurements provided more reliable statistical calculations.

The sediments include two geological formations: 'sedimentary(A)', i.e., Pliocene Awhitu Group sediments on the Awhitu Peninsula comprised of 'cemented dune sane and associated facies' (Edbrooke 2001); and 'sedimentary(P)', i.e., Pliocene Puketoka Formation north of Pukekohe formed from 'pumiceous mud, sand, and gravel with muddy peat…' (Edbrooke 2001).

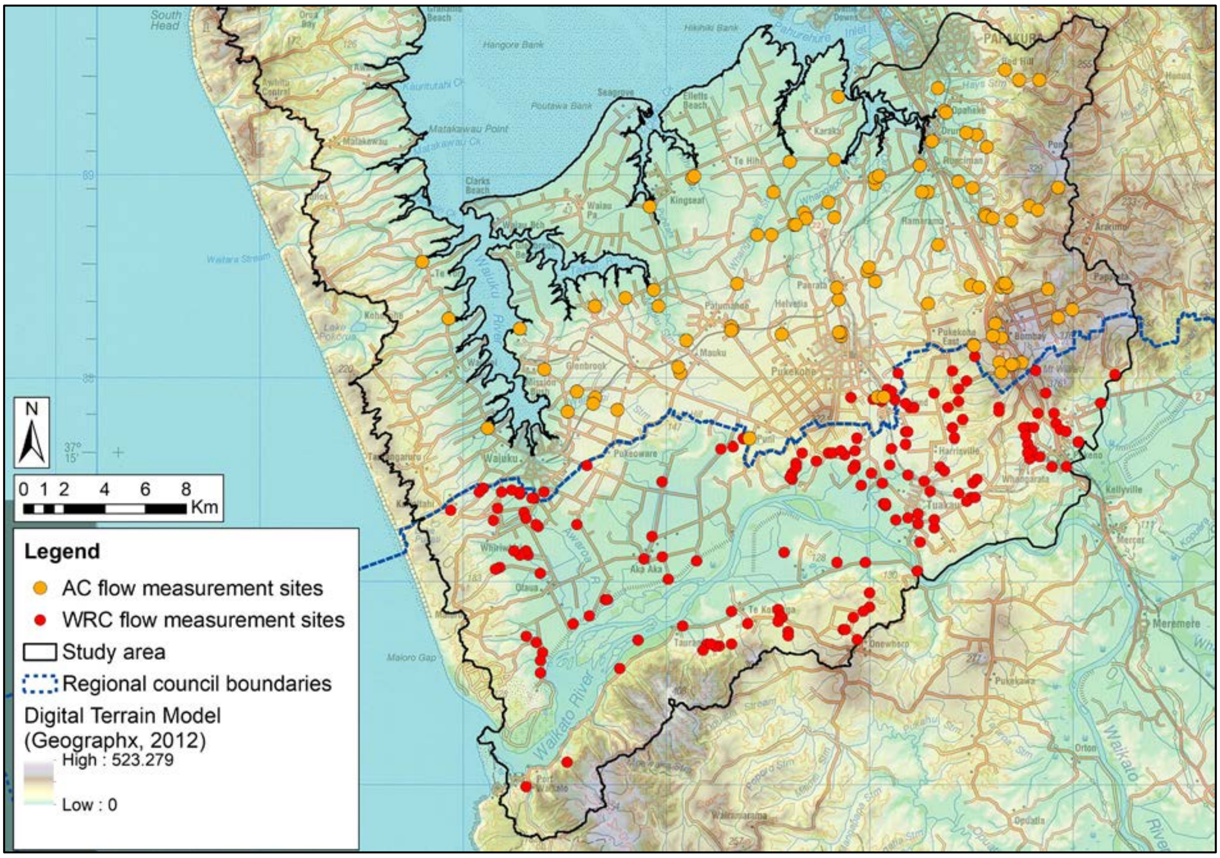

Figure 3.3 Flow measurements sites located within the study area (Johnson 2019d; White et al. 2015).

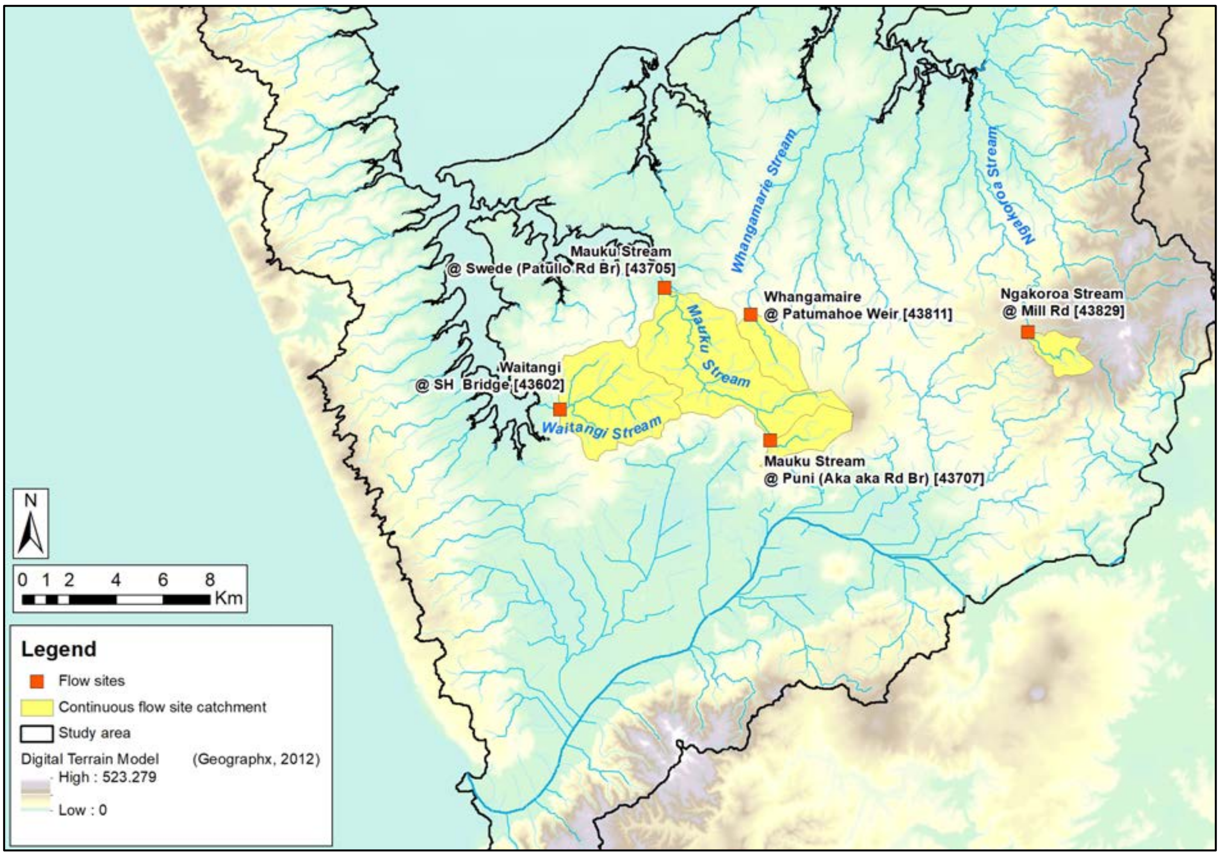

Figure 3.4 Locations of continuous surface flow measurements and the surface catchments of these sites.

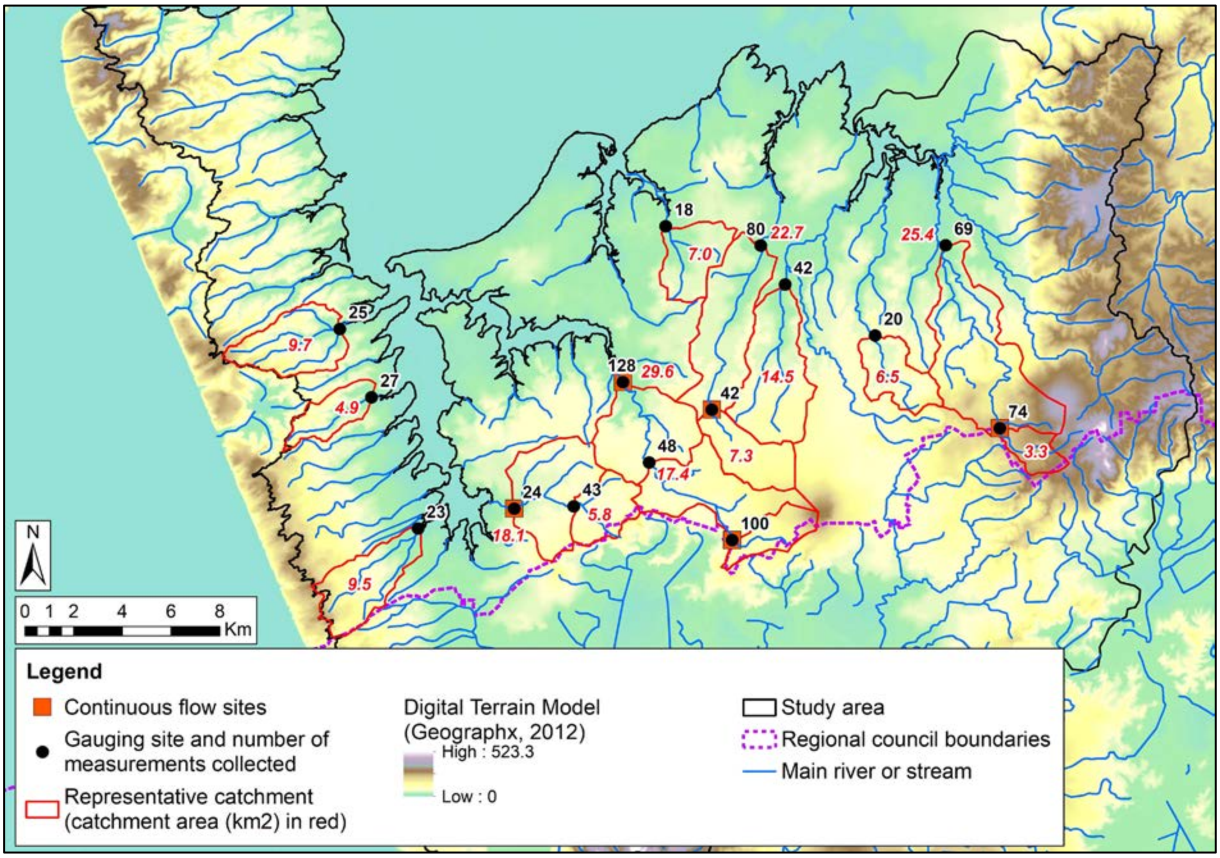

Figure 3.5 Representative catchments, catchment area and number of flow measurements at each gauging site.

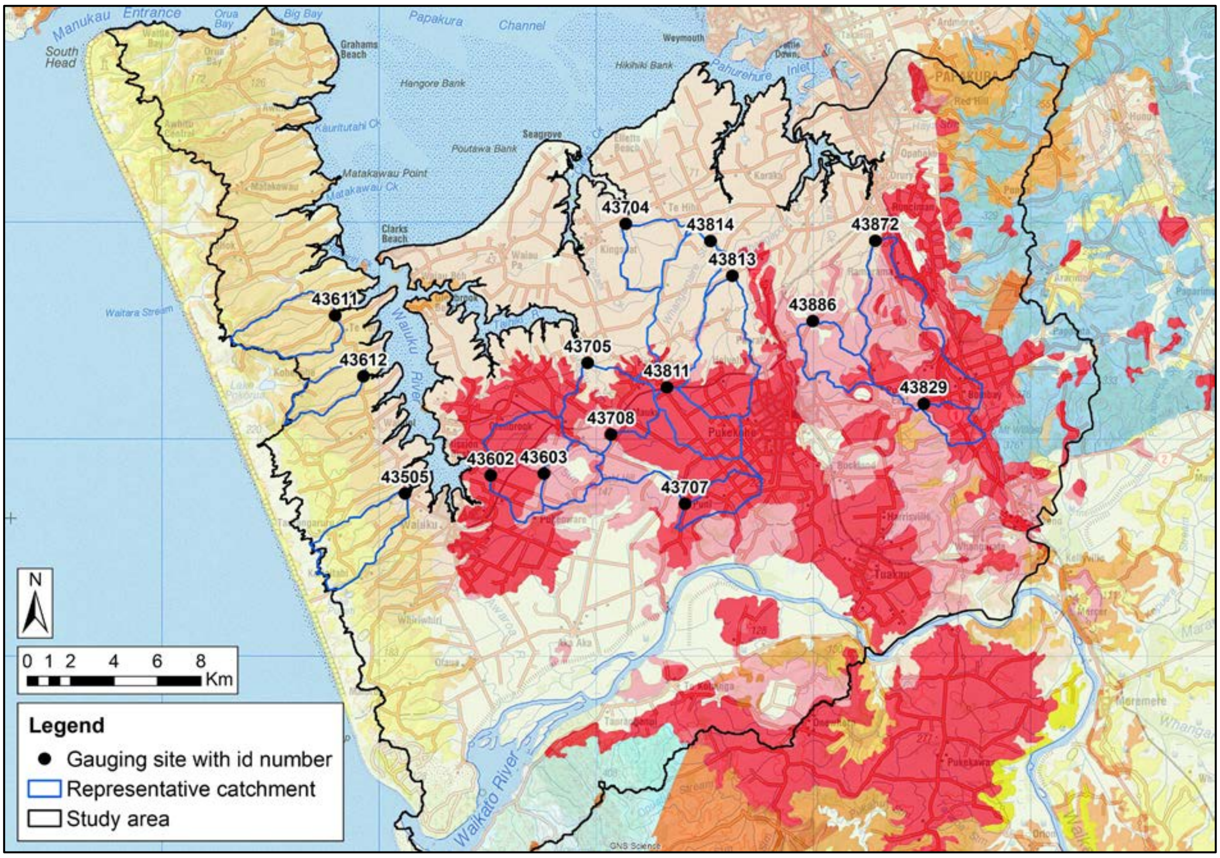

Figure 3.6 Representative catchments, gauging site numbers and surface geology.

Table 3.2 Predominant geology in representative catchments.

Surface Catchment Number	Catchment Area (km^2)	Predominant Geology	Surface Geology in the Catchment (Ratio)	
			Volcanic	Sedimentary
43505	9.5	Sedimentary(A)	0.00	1.00
43602	18.1	Volcanic	0.95	0.05
43603	5.8	Volcanic	0.85	0.15
43611	9.7	Sedimentary(A)	0.00	1.00
43612	4.9	Sedimentary(A)	0.00	1.00
43704	7.0	Sedimentary(P)	0.00	1.00
43705	29.6	Volcanic	0.90	0.10
43707	4.7	Volcanic	1.00	0.00
43708	17.4	Volcanic	0.95	0.05
43811	7.3	Volcanic	1.00	0.00
43813	14.5	Mixed	0.51	0.49
43814	22.7	Mixed	0.43	0.57
43829	3.3	Volcanic	1.00	0.00
43872	25.4	Volcanic	0.98	0.02
43886	6.5	Volcanic	1.00	0.00

3.4 Spring and Groundwater Quality

A water quality dataset was compiled using two information sources:

- water quality data collected at spring sites and from wells in the Auckland region during the period 4/12/1996 to 12/04/2018 (Johnson 2019e);
- groundwater data collected at monitoring sites, including eight State of the Environment sites to characterise groundwater resources in the Waikato River Catchment in the interval July 1987 to June 2014 (White et al. 2015). Many of these sites (42) had only a single analysis recorded; therefore, these sites were discarded from further analysis.

The combined dataset includes springs (3) and groundwater wells (28), Figure 3.7 and Appendix 2. Where known, well depths range from 5.2 m to 370.6 m below ground level. Groundwater chemistry measurements were assigned to aquifers using the distribution of aquifers assessed with the 3D geological model. Identified aquifers were: Basalt (16 sites), Basement (1 site), Drury sand (1 site), Holocene sediments (2 sites), Kaawa shell (2 sites), Kaawa sediments (4 sites) and Waitemata Sandstone (2 sites).

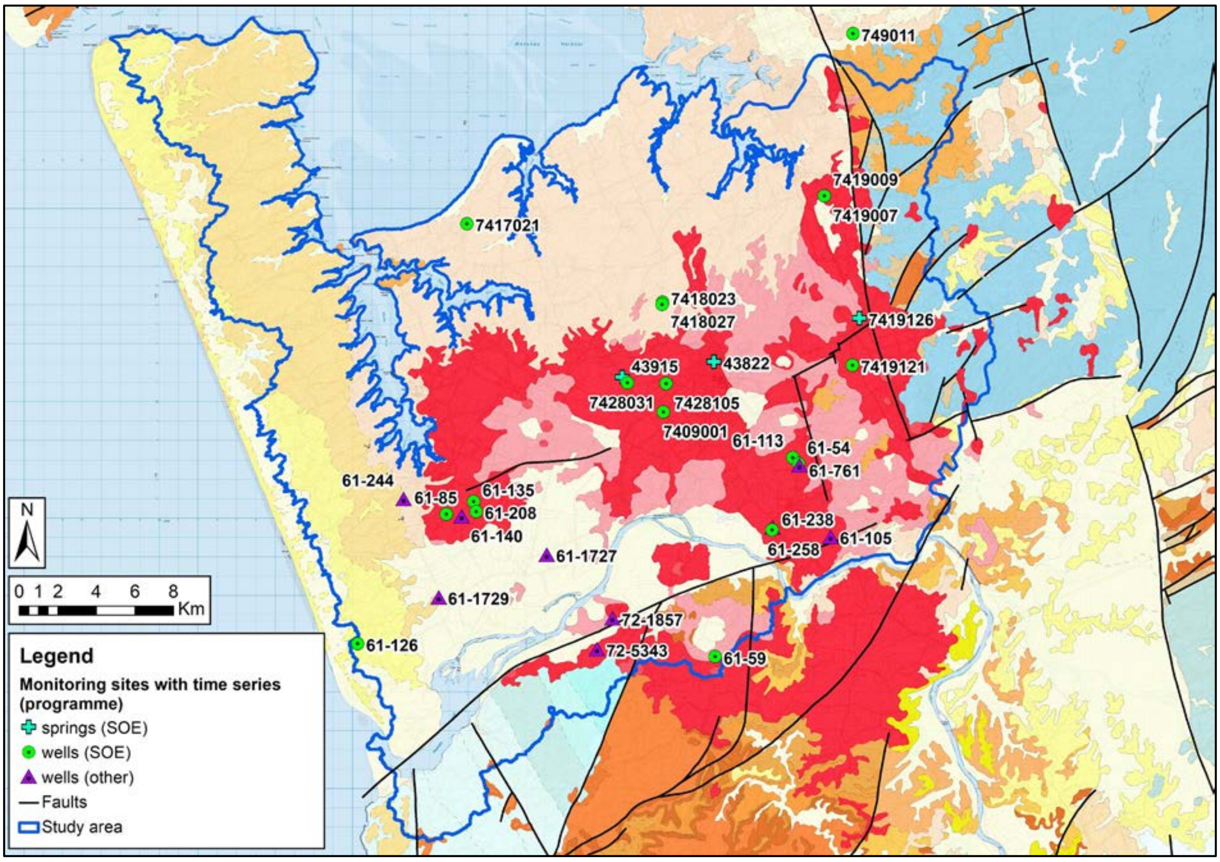

Figure 3.7 Location of groundwater and spring chemistry monitoring sites.

3.5 Trend Assessment

The Mann-Kendall test, seasonally adjusted where relevant, was used for trend assessment of environmental variables, i.e.: surface water flows at continuous flow sites (Figure 3.4); and 30 surface water quality (i.e., springs) and groundwater quality monitoring sites (Figure 3.7). Selected parameters for the state-and-trend assessment were: surface water flow, temperature (°C), conductivity (in units of mS/cm or µs/cm), chloride (Cl), total oxidised nitrogen (TON), nitrite-nitrogen (NO_2-N), nitrate-nitrogen (NO_3-N), ammonia-nitrogen (NH_4-N), dissolved iron (Fe), dissolved manganese (Mn) and dissolved reactive phosphorus (DRP).

The Mann-Kendall test has a long history of use in water quality studies in general (Helsel and Hirsch 2002) and has been applied in previous investigations of groundwater quality in New Zealand (Daughney and Randall 2009; Moreau and Daughney 2015). Seasonality was tested using the Kruskall-Wallis test, an equally widely used statistical test for environmental data analysis (Helsel and Hirsch 2002). Trend magnitudes are estimated using the Sen slope estimator, which robustly handles typical groundwater quality data, i.e., non-normally distributed time series containing missing and censored values (Snelder and Fraser 2018).

For this report, monitoring data was processed through the R software (Version 3.5.0) using the NADA (version 1.6-1) and LWP-Trends (version 1804) libraries. The NADA library implements the statistical methods to handle censored values. It is used here to calculate medians and median absolute deviations for time series with left-censored values. The LWP-Trends library was used to compute all statistical tests, on censored and uncensored time series that have been processed with NADA methods, however, it does not output either median or median absolute deviations. This library also provides new trend descriptors (Snelder and Fraser 2018):

- **Trend category**. The decreasing or increasing trend is assessed with a symmetric confidence interval. If this interval contains the zero value, the trend is described as "uncertain". If this interval does not contain the zero value, this interval is "established with confidence" and assigned either a "decreasing" or "increasing" descriptor. This method was recently developed and applied to river quality state-and-trend assessments (Larned et al. 2016; McBride Submitted 2018).
- **Trend direction**. This is a descriptive category based on the sign of the Sen slope. Possible values are: "increasing", "decreasing", "undetermined".
- **Percentage annual change in slope**. The annual change is calculated by dividing the Sen slope by the median. In this instance, the median is calculated over the same time period as the slope and is subject to the same minimum data requirement.
- **Lower and upper confidence interval bounds** for the Sen slope.
- **Sen slope probability**. In this report, the mean probability of all inter-observation slopes that are equal to zero. It informs on whether the true trend slope differs from zero.

To calculate meaningful state-and-trend metrics, minimum data point requirements were set as follows:

- Descriptive statistics (indicative of state over the selected time period): where more than half of the measurements are recorded below the detection limit (i.e., above a censoring level of 50%), median and trend metrics are reported as "non-determined". For censoring levels between 25% and 50% percentiles, the data is insufficient to derive these values with confidence and these values will be reported as "non-determined".
- Kruskall-Wallis test (includes seasonal, used for all time periods): two seasonality settings were used: one without any season and a second analysis with four seasons (Autumn, Winter, Spring and Summer), starting from the 60th Julian day (1st March); and a confidence interval of 95% was set. The annual time period commences on 1st March of the first year (start of Autumn). To enable seasonality state-and-trend assessments, all seasons must have at least one observation and individual seasons require at least two data points. The time period was adjusted at each site to cover the entire breath of record.
- Mann-Kendall test and Sen Slope estimator (includes seasonal, used for the two trend assessment time periods): the time series must contain at least eight data points, the maximum censored values must be smaller than the maximum observed values, and for each time series at least five unique observations must be required.

4.0 RESULTS

4.1 Digital Terrain Model and Well Log Location

The DTM in the study area shows relatively high ground in the Pukekohe-Waiuku-Drury area associated with volcanic deposits (Figure 4.1 and Figure 2.1). The Waikato River, and river mouth, are shown in the south. Elevations up to approximately 380 m in the east (i.e., the eastern Hunua Range). The elevation of Pukekohe Hill is approximately 200 m. Well logs are well- distributed throughout the study area (Figure 3.1).

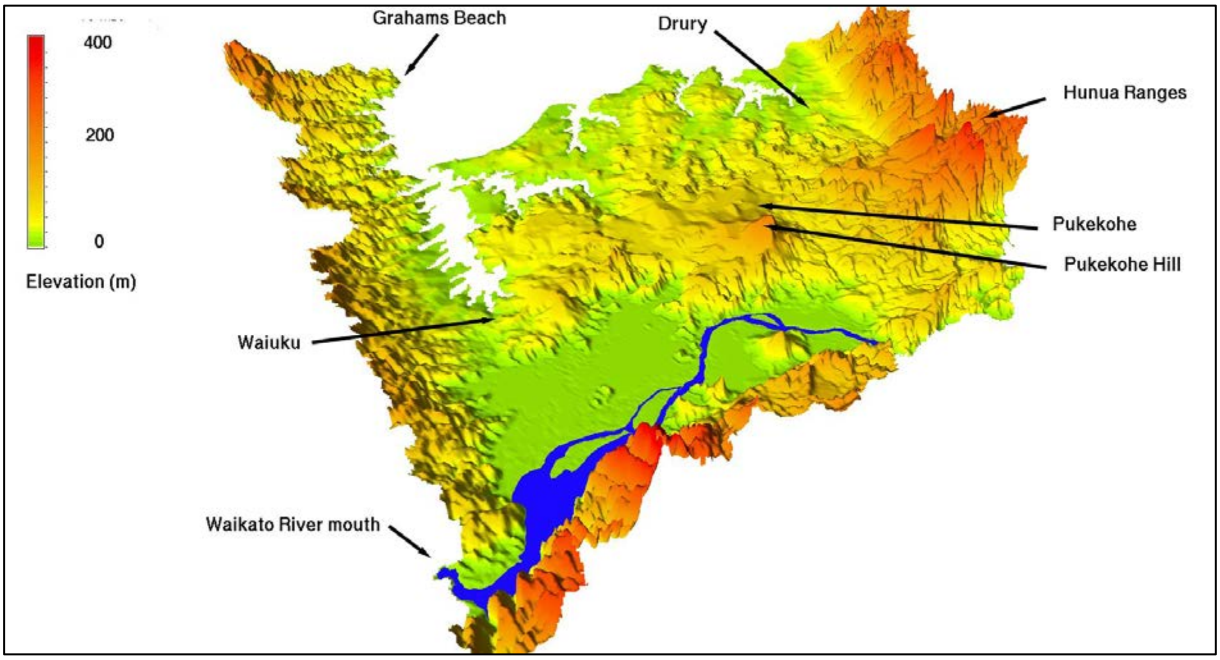

Figure 4.1 DTM of the study area showing the location of towns and the Waikato River.

4.2 Three-dimensional Geological Model

The 3D models of key lithologies, based on well logs in the study area, are represented with and without the DTM in Figure 4.2 and Figure 4.3, respectively. These views, and following model images, aim to show lateral continuity in target lithologies. Therefore, 3D model plots show model property values that were greater than 135, corresponding to an exceedance probability of 35%.

Few sub-surface volcanic lithologies are identified north of the ‘V1’ line, which is the approximate northern extent of mapped volcanic units (Figure 2.1). Subsurface volcanic units are located broadly in four south-southwest north-northwest trending groups: immediately east of Waiuku, Pukekohe, Bombay and the Hunua Range foothills.

The complexity of volcanic deposition is shown by the 3D geological model. For example, two major phases of Pukekohe volcanism are demonstrated by upper and lower volcanic units (Figure 4.4). Within the upper unit, multiple eruptive phases are possibly identified by volcanic units that come from Pukekohe Hill and dip to the south (i.e., ‘A’, ‘B’, ‘C’ and ‘D’). Peats, probably Puketoka Formation (Section 2.1), are typically located above shell units (Figure 4.5 and Figure 4.6).

Most shells are part of the Kaawa Formation. The shell model appears to identify multiple shell deposits including two Kaawa shell units (an upper and a lower) west of Waiuku (Figure 4.6). Holocene shell units are located in the study area and are differentiated from Kaawa shell units by their shallower depth (Figure 4.2 and Figure 4.3).

Six lithological cross sections, located on Figure 4.7, represent lithology in the study area (Figure 4.8 to Figure 4.13). These cross sections show the distribution of lithologies (i.e., Figure 4.3) on a grey background; features are noted on each cross section, for example:

- relatively thick volcanics are associated with volcanic hills, e.g., Pukekohe and Bombay (Figure 4.9 and Figure 4.13, respectively);
- the base of volcanic units is close to the top of shell units in the vicinity of Pukekohe Hill (Figure 4.9 and Figure 4.12);
- volcanic units are not common in the subsurface north of the 'V1' line (Figure 4.12);
- shell layers are relatively shallow in the north, and likely represent Holocene deposits distinct from Kaawa shells (Figure 4.8);
- shell layers generally dip towards the south. This dip can be continuous (Figure 4.6) or in a step-wise fashion (Figure 4.11, Figure 4.12 and Figure 4.13);
- multiple deep Kaawa shell layers are observed in most sections (e.g., Figure 4.9, Figure 4.11 and Figure 4.13);
- multiple Kaawa shell layers interspersed with peats possibly represent climatic cycles or fault-block offsets (Figure 4.13).

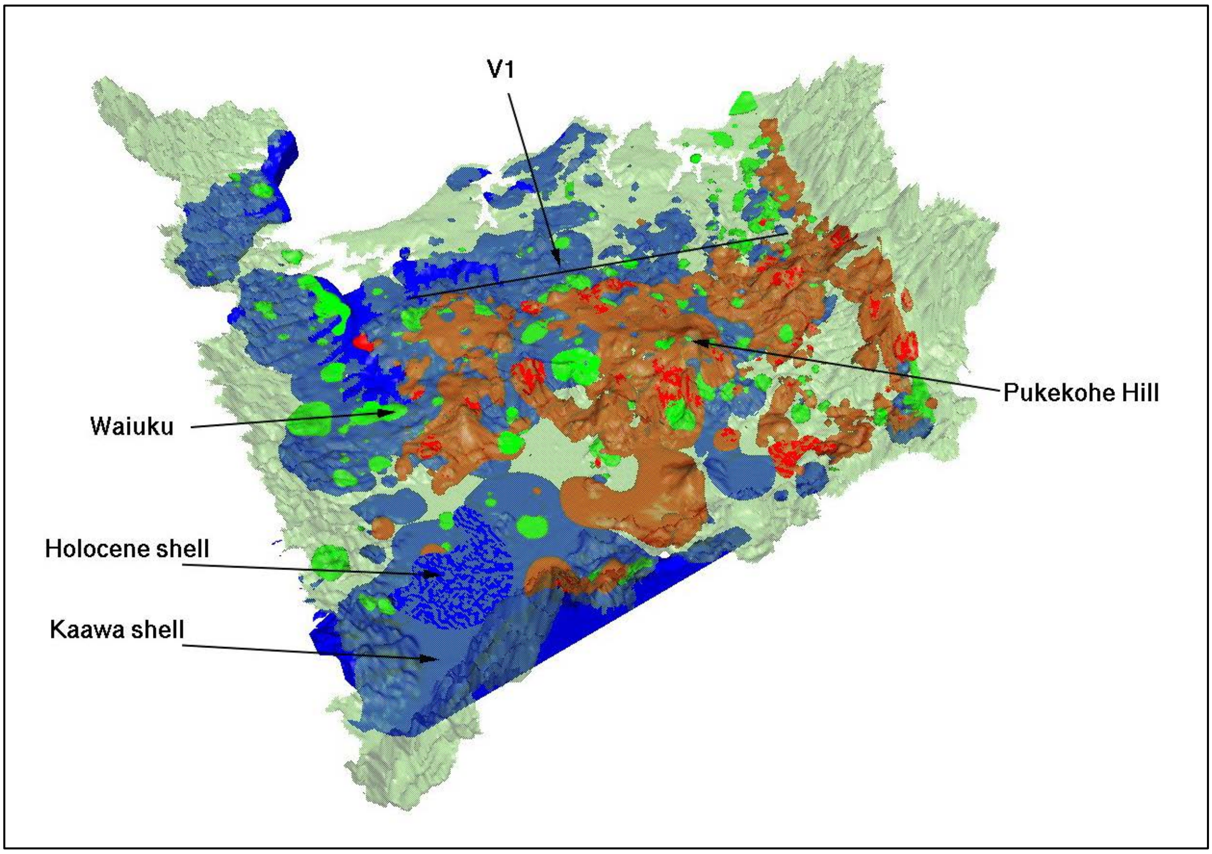

Figure 4.2 The DTM (plotted as semi-transparent) and the distribution of lithologies, perspective view above -200 m: volcanic (red/brown), peat (green) and shells (blue). The DTM is semi-transparent, therefore lithology colour differs in the sub-surface, e.g., sub-surface volcanic units are shown in a brown colour.

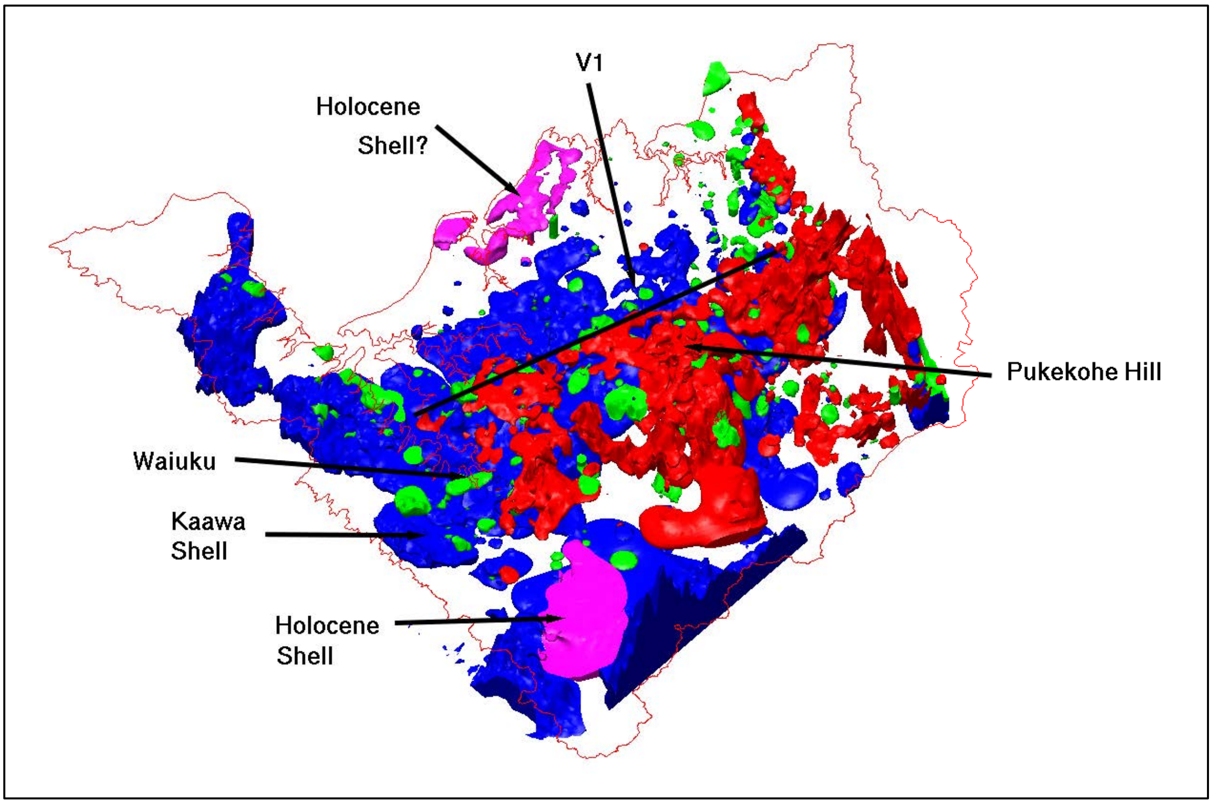

Figure 4.3 The distribution of lithologies, perspective view: volcanic (red), peat (green) and shells, i.e., possible Holocene shells (purple) and Kaawa shells (blue).

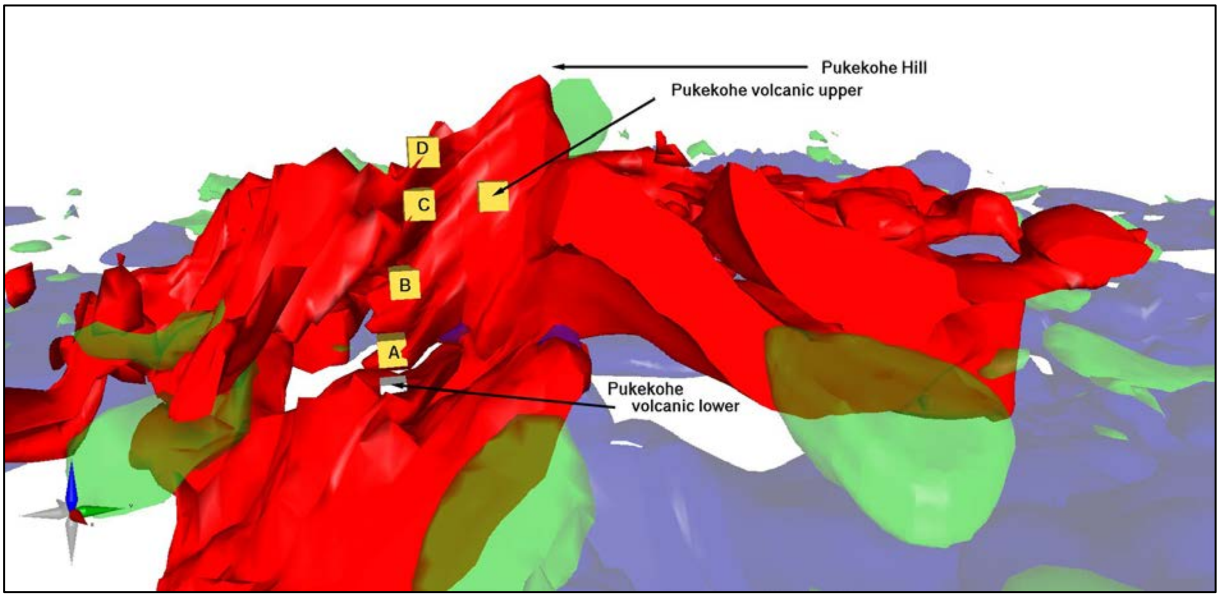

Figure 4.4 The distribution of volcanic lithologies in the vicinity of Pukekohe Hill, showing upper and lower volcanic units; viewed from the northeast. Multiple eruptive phases are possibly identified by volcanic units that come from Pukekohe Hill (i.e., markers ‘A’, ‘B’, ‘C’ and ‘D’).

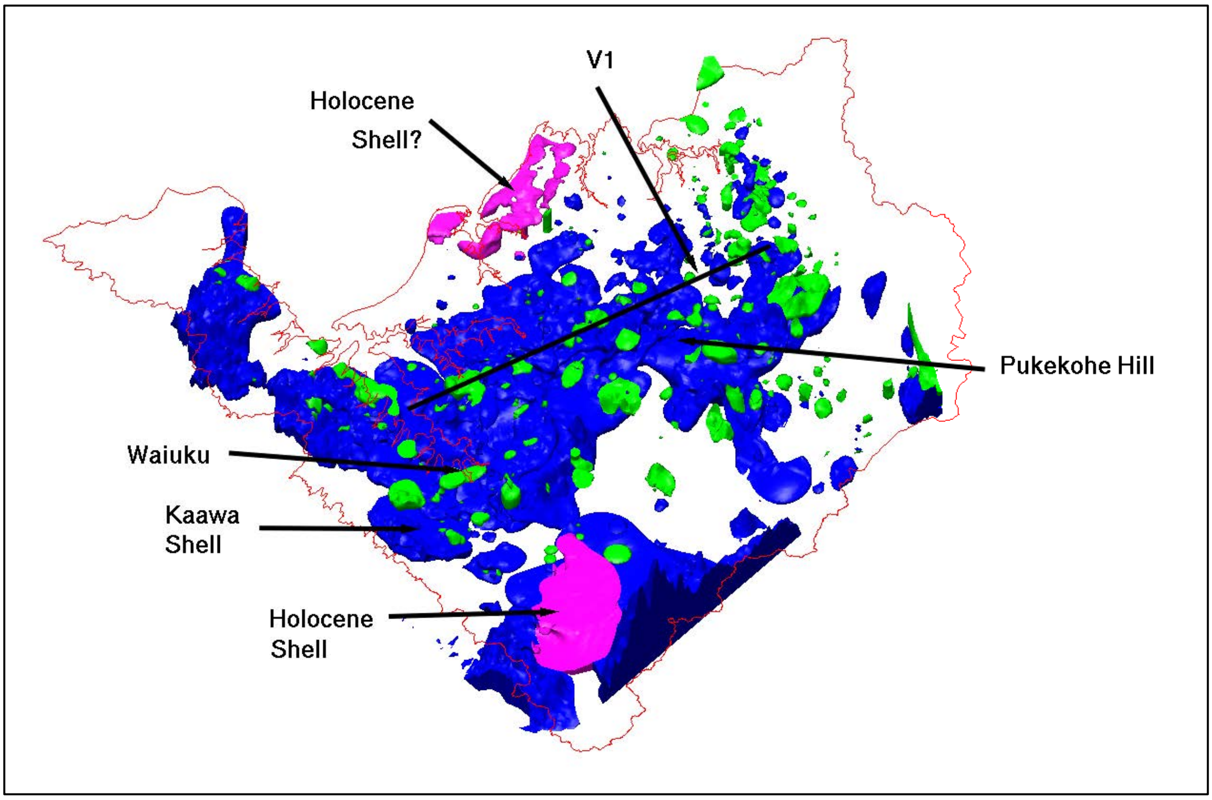

Figure 4.5 The distribution of lithologies peat (green) and shells, i.e., possible Holocene shells (purple) and Kaawa shells (blue).

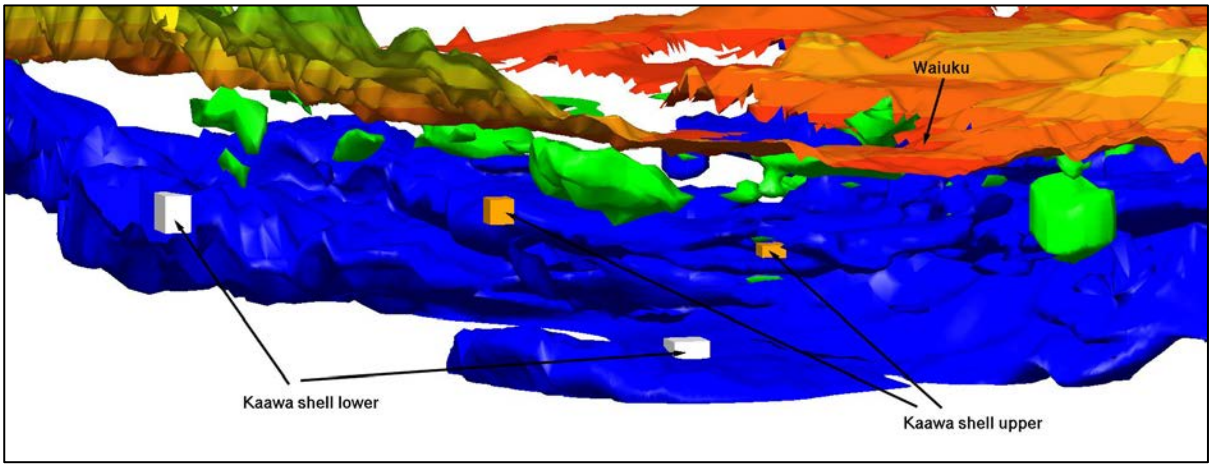

Figure 4.6 The distribution of shell lithologies (blue) and peat (green) lithologies in the vicinity of Waiuku, and the DTM (the orange-to-yellow coloured surface); viewed from the southwest. Shell units include shallow (yellow markers) and deep (white markers).

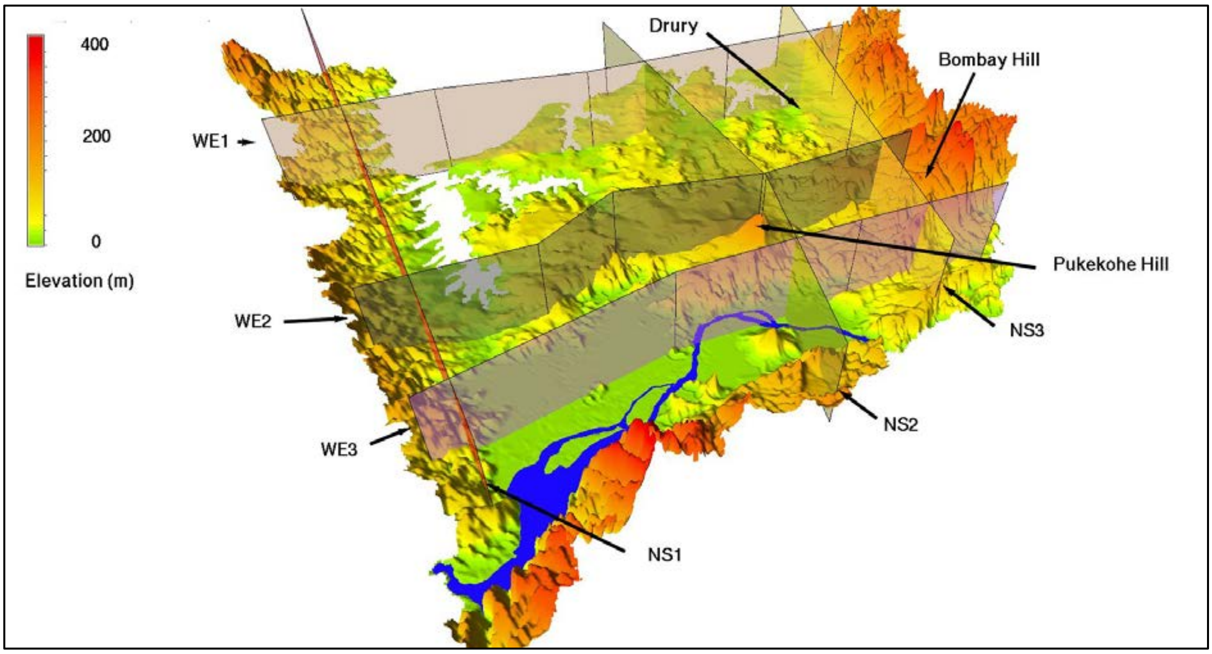

Figure 4.7 The DTM and the location of six lithological cross sections.

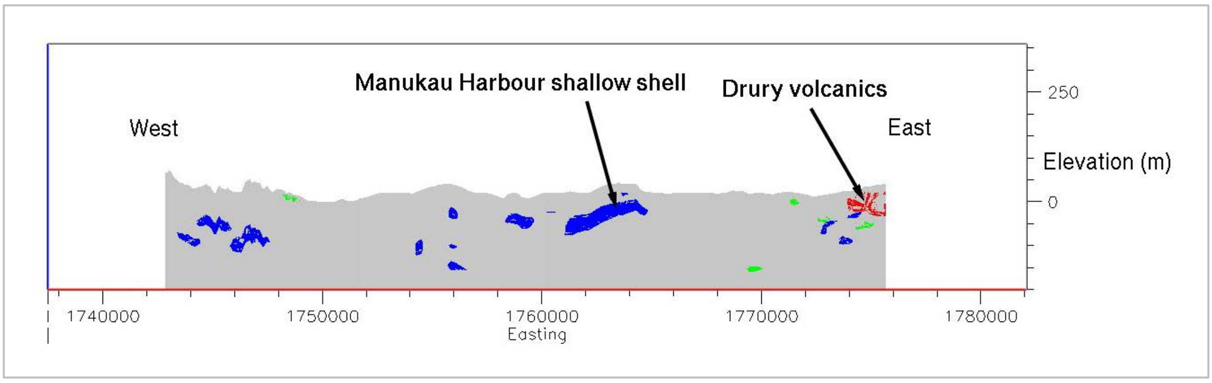

Figure 4.8 Cross section WE1: volcanics (red), peats (green) and shells (blue) above -200 m.

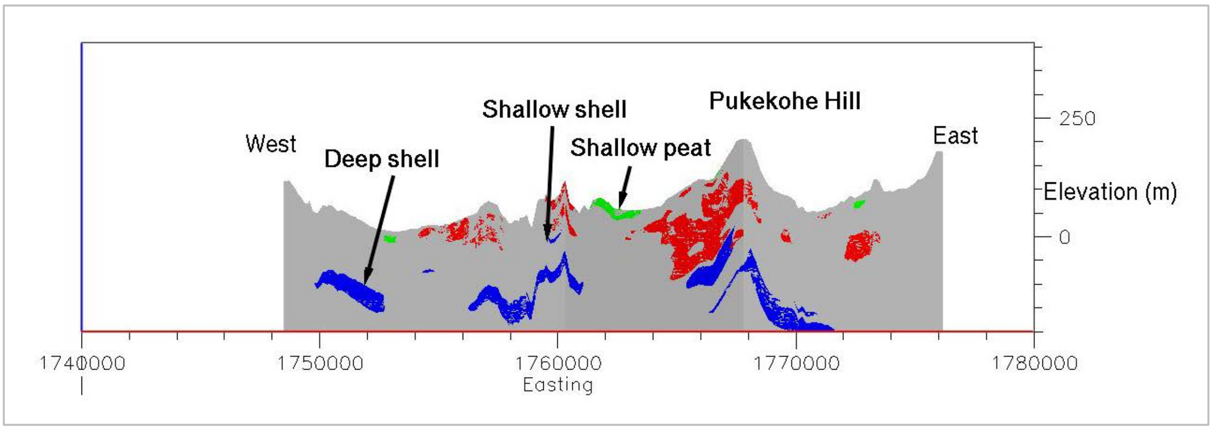

Figure 4.9 Cross section WE2: volcanics (red), peats (green) and shells (blue) above -200 m.

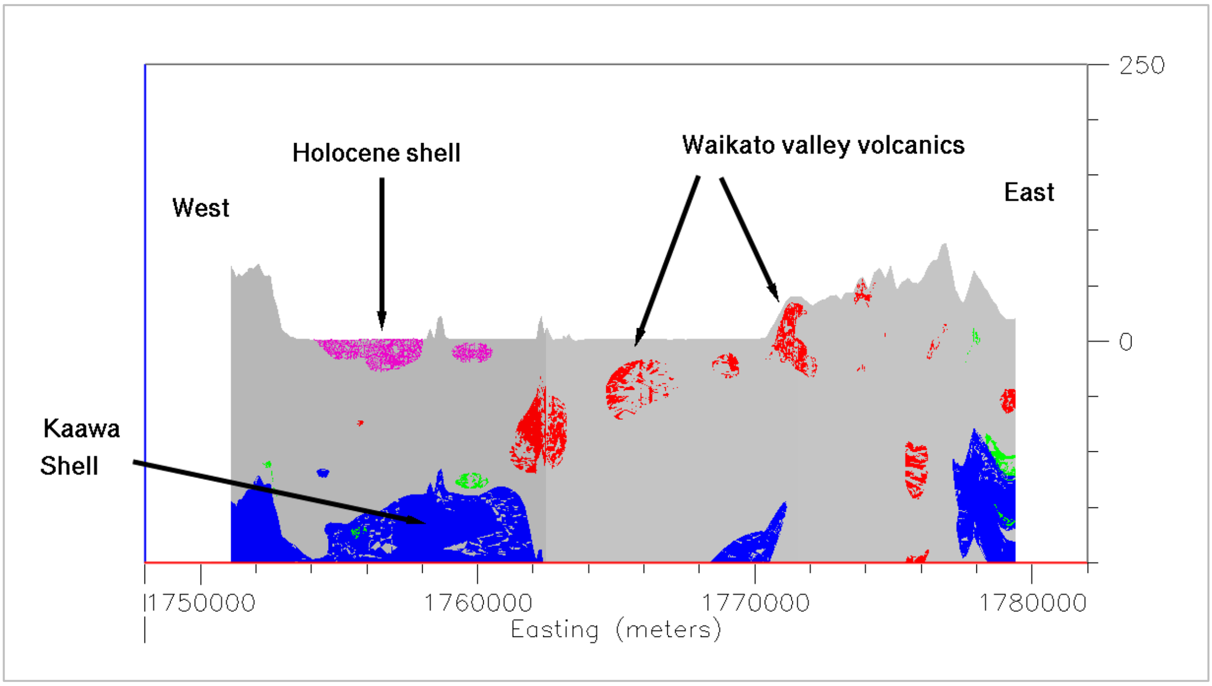

Figure 4.10 Cross section WE3: volcanics (red), peats (green) and shells (blue) above -200 m; with Holocene shells (purple) and Kaawa shells (blue).

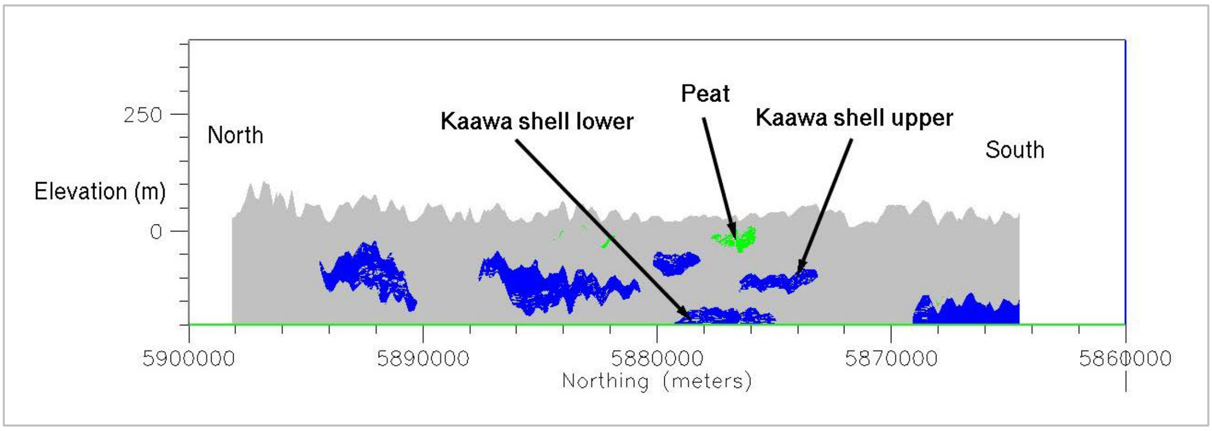

Figure 4.11 Cross section NS1: peats (green) and shells (blue) above -200 m.

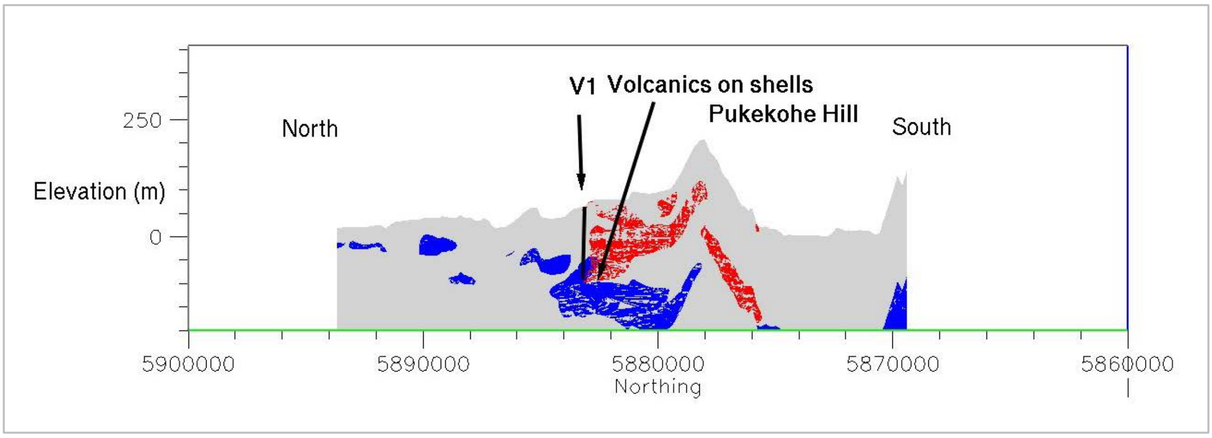

Figure 4.12 Cross section NS2: volcanics (red), peats (green) and shells (blue) above -200 m.

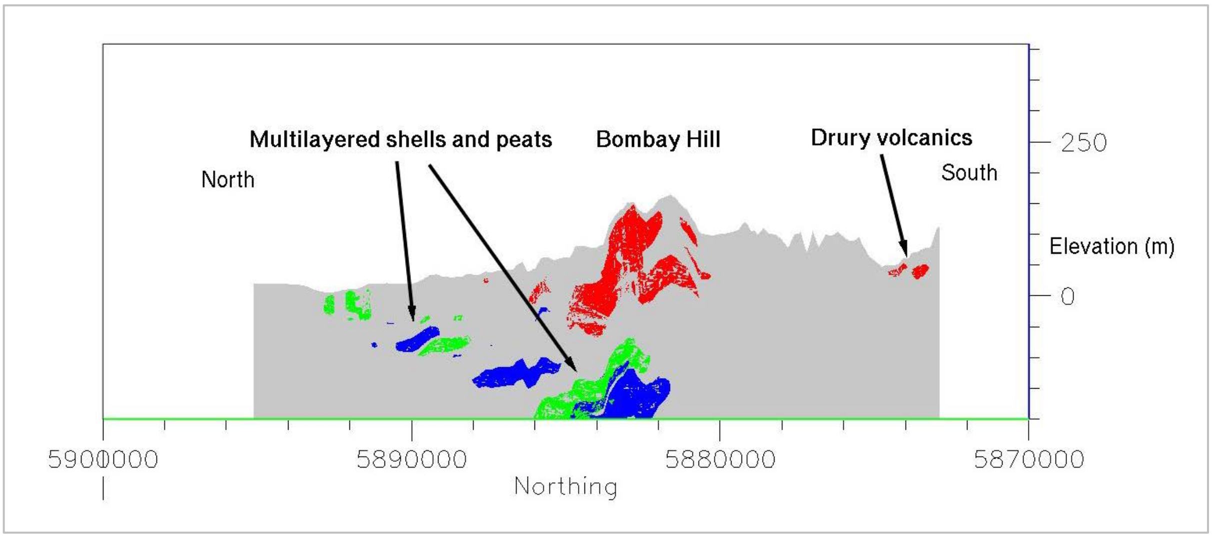

Figure 4.13 Cross section NS3: volcanics (red), peats (green) and shells (blue) above -200 m.

4.3 Water Budget

Water budgets demonstrate that Q^{GW}_{OUT} is relatively large, e.g., mean Q^{GW}_{OUT} is 273 mm/year (Table 4.1 and Table 4.2). Therefore, the budgets demonstrate that relatively large groundwater flows in the study area that do not travel to streams.

Preferred values of Q^{SW}_{OUT} are calculated from data measured at gauging sites and at continuous-flow sites (Table 4.1). Most commonly, Q^{SW}_{OUT} is calculated from gaugings because most flows are measured by gaugings. Q^{SW}_{OUT} is generally calculated from continuous-flow data, where this data is available (e.g., site 43602). However, site 43707 is an exception. Here, the preferred flow calculation was with data provided by gaugings because: the duration of the gauging data was longer than the duration of continuous-flow data set whilst the two methods provided similar Q^{SW}_{OUT} calculations.

Calculations of Q^{GW}_{OUT} were sometimes less than zero when Q^{SW}_{OUT} was calculated from gauging measurements. These values were not used in further calculations.

Predominant geology in a catchment is not a significant indicator of groundwater outflow (i.e., Q^{SW}_{OUT} and Q^{GW}_{OUT}). For example, standard deviations of Q^{GW}_{OUT} are large relative to the differences between mean Q^{GW}_{OUT} from volcanic and sedimentary lithologies (Table 4.3). This large variability may be due to data uncertainty, particularly to the estimates of baseflow, and to other factors, such as hydraulic properties of discrete depositional units, the topography, land cover, and degree of imperviousness may be relevant to the generation of groundwater outflow. However, Q^{GW}_{OUT} is similar in Awhitu Group sediments and Puketoka Formation sediments (i.e., ‘Sedimentary(A)’ and ‘Sedimentary(P)’ catchments, Table 4.2).

4.4 Rainfall Recharge

Long-term rainfall recharge in the representative catchments (calculated with Equation 7) averages 485 mm/year, or 37% of P, (Table 4.4). This estimate of long-term rainfall recharge is possibly an under-estimation of rainfall recharge in the study area because measured rainfall recharge was larger at the Karaka rainfall recharge site. For example, measured rainfall recharge at Karaka as a proportion of rainfall was in the range of 44% (lysimeter 3) to 50% (lysimeter 1), and annualised rainfall recharge was an average of 819 mm/year (Table 4.5 and Table 4.6). However, AC staff recognise that the Karaka lysimeter is located in a flat paddock site that is likely to express the maximum recharge for the area and may not be representative of larger parts of the Franklin area.

The record at Karaka has a short duration and measured rainfall recharge is highly seasonal, i.e., rainfall recharge is typically zero in the summer (Table 4.5). A likely seasonal bias in the measured rainfall recharge data at Karaka may result from a relatively short record, and the interruption of measurement at the site (see Section 3.3.3 and Recommendations).

Table 4.1 Water budget calculations for the representative catchments. Preferred values of Q^{SW}_{OUT} and Q^{GW}_{OUT} are shaded.

Surface Catchment Number	Catchment Area (km²)	Pre-dominant Geology	Inflow	Outflow					
			P (L/s) (1996–2006)	AET (L/s) (1996–2006)	Q^{SW}_{OUT} (L/s)	Q^{SW}_{OUT} Measurement Type*	Q^{SW}_{OUT} Monitoring Period	Q^{GW}_{OUT} (L/s)
43505	9.5	Sedimentary(A)	407	247	41	G	Jan 2003 – Feb 2006	119
43602	18.1	Volcanic	752	471	471	G	Jun 1980 – May 1985	-190
					124	C	Apr 1966 – Oct 2018	157
43603	5.8	Volcanic	240	149	28	G	Jul 1971 – Dec 2004	63
43611	9.7	Sedimentary(A)	389	259	31	G	Jan 2003 – Feb 2006	98
43612	4.9	Sedimentary(A)	201	131	24	G	Dec 2002 – Feb 2006	46
43704	7	Sedimentary(P)	279	188	17	G	Apr 1973 – Dec 1979	74
43705	29.6	Volcanic	1216	771	189	G	Feb 1970 – Feb 2005	256
					356	C	Feb 1977 – Apr 2007	89
43707	4.7	Volcanic	206	120	33	G	Jan 1976 – Feb 2005	53
					41	C	Oct 2004 – May 2007	45
43708	17.4	Volcanic	732	445	110	G	Jan 1976 – Feb 2005	177
43811	7.3	Volcanic	304	187	122	G	Jun 1976 – Mar 2014	-5
					103	C	Oct 1976 – Feb 2015	14
43813	14.5	Mixed	588	376	81	G	Jul 1971 – Feb 2002	130
43814	22.7	Mixed	920	593	173	G	Jul 1971 – Feb 2005	154
43829	3.3	Volcanic	144	85	61	G	Mar 1980 – Jun 2018	-2
					48	C	Mar 1980 – Aug 2018	11
43872	25.4	Volcanic	1037	662	132	G	Mar 1985 – Nov 2003	243
43886	6.5	Volcanic	263	170	10	G	Jan 1991 – Mar 2001	83

* C: continuous flow measurements, G: gauging measurements.

Table 4.2 Water budget calculations for the representative catchments with preferred values of Q^{GW}_{OUT} (Table 4.1) in units of mm/year.

Surface Catchment Number	Catchment Area (km^2)	Pre-dominant Geology	Inflow	Outflow				
			P (mm/year) (1996–2006)	AET (mm/year) (1996–2006)	Q^{SW}_{OUT} (mm/year)	Q^{SW}_{OUT} Measurement Type*	Q^{SW}_{OUT} Monitoring Period	Q^{GW}_{OUT} (mm/year)
43505	9.5	Sedimentary(A)	1351	820	136	G	Jan 2003 – Feb 2006	395
43602	18.1	Volcanic	1310	821	216	C	Apr 1966 – Oct 2018	274
43603	5.8	Volcanic	1305	810	152	G	Jul 1971 – Dec 2004	343
43611	9.7	Sedimentary(A)	1265	842	101	G	Jan 2003 – Feb 2006	319
43612	4.9	Sedimentary(A)	1294	843	154	G	Dec 2002 – Feb 2006	296
43704	7	Sedimentary(P)	1257	847	77	G	Apr 1973 – Dec 1979	333
43705	29.6	Volcanic	1296	821	379	C	Feb 1977 – Apr 2007	95
43707	4.7	Volcanic	1382	805	221	G	Jan 1976 – Feb 2005	356
43708	17.4	Volcanic	1327	807	199	G	Jan 1976 – Feb 2005	321
43811	7.3	Volcanic	1313	808	445	C	Oct 1976 – Feb 2015	60
43813	14.5	Mixed	1279	818	176	G	Jul 1971 – Feb 2002	283
43814	22.7	Mixed	1278	824	240	G	Jul 1971 – Feb 2005	214
43829	3.3	Volcanic	1376	812	459	C	Mar 1980 – Aug 2018	105
43872	25.4	Volcanic	1288	822	164	G	Mar 1985 – Nov 2003	302
43886	6.5	Volcanic	1276	825	49	G	Jan 1991 – Mar 2001	403
Mean			1306	822	211			273
Standard deviation			38	13	125			108

* Measurement Type: C (continuous); G (gaugings).

Table 4.3 Water budgets statistics by predominant geology for representative catchments.

Predominant Geology and Number of Catchments	P (mm/year)			AET (mm/year)			Q^{SW}_{OUT} (mm/year)			Q^{GW}_{OUT} (mm/year)		
	Mean	Median	SD*	Mean	Median	SD*	Mean	Median	SD*	Mean	Median	SD*
Volcanic (9)	1319	1310	37	815	812	8	254	216	142	251	302	129
Sedimentary (4)	1292	1280	43	838	843	12	117	119	35	336	326	42
Mixed (2)	1279	1279	1	821	821	4	208	208	45	249	249	49

* SD: standard deviation

Table 4.4 Estimate of long-term water budget components in representative catchments.

Surface Catchment Number	Catchment Area (km^2)	Pre-dominant Geology	P (mm/year) (1996–2006)	AET (mm/year) (1996–2006)	RR (Equation 7) (mm/year)	RR (%)
43505	9.5	Sedimentary(A)	1351	820	531	39
43602	18.1	Volcanic	1310	821	489	37
43603	5.8	Volcanic	1305	810	495	38
43611	9.7	Sedimentary(A)	1265	842	423	33
43612	4.9	Sedimentary(A)	1294	843	451	35
43704	7	Sedimentary(P)	1257	847	410	33
43705	29.6	Volcanic	1296	821	475	37
43707	4.7	Volcanic	1382	805	577	42
43708	17.4	Volcanic	1327	807	520	39
43811	7.3	Volcanic	1313	808	505	38
43813	14.5	Mixed	1279	818	461	36
43814	22.7	Mixed	1278	824	454	36
43829	3.3	Volcanic	1376	812	564	41
43872	25.4	Volcanic	1288	822	466	36
43886	6.5	Volcanic	1276	825	451	35
Average			1306	822	485	37
Standard deviation			38	13	48	3

Table 4.5 Summary of rainfall recharge, and ground-level rainfall measurements at the Karaka rainfall recharge site.

Year	Full Month	Month Sum (mm/month)			
		Lysimeter 1	Lysimeter 2	Lysimeter 3	Ground-level Rainfall
2016	July	98	143	132	171
2016	August	62	64	57	106
2016	September	67	75	62	169
2016	October	38	40	29	97
2016	November	26	22	24	111
2016	December	0	0	0	35
2017	January	0	0	0	41
2017	February	0	0	0	93
2017	March	193	225	22	408
Sum 2016/17 (mm)		484	569	326	1231
Sum 2016/17 (% of rainfall)		39%	46%	26%	na
2018	May	87	86	91	134
2018	June	148	150	161	201
2018	July	112	110	121	157
2018	August	71	63	75	119
2018	September	21	21	21	51
2018	October	0	0	0	79
2018	November	6	0	1	132
2018	December	154	9	151	52
Sum 2018 (mm)		599	430	621	925
Sum 2018 (% of rainfall)		65%	47%	67%	na
Sum all data (mm)		1083	1008	947	2156
Sum all data (% of rainfall)		50%	47%	44%	na

Table 4.6 Seasonal and annualised rainfall recharge at Karaka.

Rainfall Recharge	Season			
	Summer	Autumn	Winter	Spring
Lysimeter 1, mean (mm/month)	39	140	98	26
Lysimeter 2, mean (mm/month)	0	156	106	26
Lysimeter 3, mean (mm/month)	38	57	109	23
Mean, all lysimeters (mm/month)	26	118	104	25
Mean, all lysimeters (mm/season)	78	354	312	75
Number of months in season	4	2	5	6
Annualised, all lysimeters (mm/year)	819+/-121*			

* Mean and standard deviation of annualised estimates of mean seasonal rainfall recharge.

4.5 Surface Flows

Baseflow is the most significant component of stream flow at sites with continuous flow measurements, i.e., mean of 0.87, and volcanic lithologies are the predominant lithologies in the catchments of these sites (Table 4.7). Therefore, volcanic lithologies in the study area are characterised by large baseflows, as is common in New Zealand's volcanic lithologies (e.g., White et al. 2015).

BFI, calculated using Equation 5 with gauged data, is similar in Awhitu Group sediments and Puketoka Formation sediments (Table 4.8). BFI in volcanic lithologies (i.e., mean and standard deviations of 0.77 and 0.06, respectively) is larger than BFI in sedimentary lithologies (i.e., mean and standard deviations of 0.67 and 0.06, respectively), from Table 4.8. However, the difference between these two BFI calculations are possibly not significantly different.

A comparison of the two BFI calculation methods indicates that Eckhardt (2005), and continuous flow data, may provide better estimates of BFI than using Equation 5 with gauging measurements, Table 4.9. For example, Eckhardt (2005) estimates are more consistent than BFI (Equation 5), as demonstrated by the relatively large, and inconsistent, differences between the two estimates and the relatively low standard deviation of BFI (Eckhardt 2005). The relative inconsistency of BFI (Equation 5) is probably due to the relatively low number of gaugings recorded at each site.

Table 4.7 Summary of BFI estimated by the Eckhardt (2005) method for the five continuously-monitored streams.

Site Number	Site Name	Pre-dominant Geology	Start Date	End Date	Q^{SW}_{BF} (L/s)	Q^{SW}_{QF} (L/s)	Q^{SW}_{OUT} (L/s)	BFI (Eckhardt 2005)
43602	Waitangi @ S H Bridge	Volcanic	1/04/1966	2/10/2018	124	6	130	0.95
43707	Mauku Stream upstream @ Puni (Aka aka Rd Br)	Volcanic	14/10/2004	7/05/2007	41	9	50	0.82
43705	Mauku Stream downstream @ Swede (Patullo Rd Br)	Volcanic	9/02/1977	15/04/2007	356	80	436	0.82
43811	Whangamaire @ Patumahoe Weir	Volcanic	1/10/1976	27/02/2015	103	19	122	0.84
43829	Ngakoroa Stream @ Mill Rd	Volcanic	30/03/1980	16/08/2018	48	3	51	0.94
Mean								0.87
Standard deviation								0.07

Table 4.8 BFI estimated by Equation 5 for gauged streams[1].

Site Number	Site Name[2]	Pre-dominant Geology	Start Date	End Date	Number of Measurements	Q^{SW}_{OUT} (L/s)	Q^{SW}_{BF} (L/s)	BFI (Equation 5)
43886	Oira Trib @ Burtt Road Bridge	Volcanic	18/01/1991	14/03/2001	20	13	10	0.77
43829	Ngakoroa Stream upstream @ Mill Rd	Volcanic	28/03/1980	5/06/2018	66*	79	48	0.61
43872	Ngakoroa Stream downstream @ Runciman Rd Bridge	Volcanic	7/03/1985	26/11/2003	69	194	132	0.68
43811	Whangamaire upstream @ Patumahoe Weir	Volcanic	17/06/1976	5/03/2014	42	143	122	0.85
43814	Whangamaire downstream @ Fantail (Charles Rd)	Mixed	22/07/1971	17/02/2005	80	187	173	0.93
43813	Whangapouri Stream @ Effluent	Mixed	23/07/1971	19/02/2002	42	100	81	0.81
43707	Mauku Stream upstream @ Puni (Aka aka Rd Br)	Volcanic	22/01/1976	15/02/2005	100	43	33	0.77
43708	Mauku River middle @ Titi Road	Volcanic	22/01/1976	15/02/2005	48	153	110	0.72
43705	Mauku Stream downstream @ Swede (Patullo Rd Br)	Volcanic	20/02/1970	17/02/2005	128	336	189	0.56
43704	Te Hihi Stream @ Gumtree	Sedimentary(P)	16/04/1973	12/12/1979	14*	26	17	0.65
43612	Te Hakono Ck @ Awhitu Road	Sedimentary(A)	10/12/2002	14/02/2006	27	34	24	0.71
43611	Ohiku @ Lees Gully Road	Sedimentary(A)	10/01/2003	14/02/2006	25	52	31	0.60
43603	Waitangi Stream upstream @ Waiuku Rd Br.	Volcanic	21/07/1971	13/12/2004	43	34	28	0.82
43602	Waitangi Stream downstream @ S H Bridge	Volcanic	16/06/1980	23/05/1985	14*	27	30	0.90
43505	Kaurituahi @ Awhitu Road	Sedimentary(A)	10/01/2003	14/02/2006	23	57	41	0.72

1 Flow measurements during obvious flood events have been excluded.

2 Upstream / middle / downstream: indicate the relative position of each gauging site.

Table 4.9 Comparison of BFI estimates for the five continuously-monitored streams.

Site Number	Site Name	Pre-dominant Geology	BFI (Eckhardt 2005)	BFI (Equation 5)[1]
43602	Waitangi Stream downstream @ S H Bridge	Volcanic	0.95	0.90
43707	Mauku Stream upstream @ Puni (Aka aka Rd Br)	Volcanic	0.82	0.77
43705	Mauku Stream downstream @ Swede (Patullo Rd Br)	Volcanic	0.82	0.56
43811	Whangamaire upstream @ Patumahoe Weir	Volcanic	0.84	0.85
43829	Ngakoroa Stream upstream @ Mill Rd	Volcanic	0.94	0.49
Mean			0.87	0.75
Standard deviation			0.07	0.18

1 Flow measurements during obvious flood events have been excluded from these calculations.

4.6 Groundwater Chemistry: State

Typically, nitrate-nitrogen concentrations in springs and the basalt aquifer are relatively high (Table 4.10). This is not surprising as all springs rise in basalt lithologies. Nitrate-nitrogen concentrations and oxygen concentrations are significantly related in basalt aquifers (Table 4.11), as noted in Section 2.4. Therefore, land use is not the only control on nitrate-nitrogen concentrations in groundwater. Nitrate-nitrogen concentrations are relatively low in aquifers other than basalt. This could be due to wells in these lithologies being located in areas of less-intensive land use and/or having reducing conditions in groundwater, i.e., de-oxygenated groundwater (see Sections 4.7.2 and 5.8).

Table 4.10 Summary statistics for nitrate-nitrogen concentrations and iron in springs and groundwater. N is the number of median concentration values in the dataset (Appendix 2).

Item	Median NO_3-N			Median Fe		
	Mean (mg/L)	Std. dev. (mg/L)	N	Mean (mg/L)	Std. dev. (mg/L)	N
Springs	12.0	10.9	3	0.0003	NA	1
Basalt aquifer	6.8	4.1	16	0.02	0.02	13
Holocene sediments and Drury sand aquifers	2.2	3.7	3	0.14	0.19	3
Kaawa shell and sediment aquifers	1.3	2.7	7	0.7	1.4	5
Basement and Waitemata aquifers	0.009	0.014	3	0.6	0.5	2

Table 4.11 Summary statistics for nitrate-nitrogen concentrations and DO in groundwater (Appendix 2).

Regional Council	Type	Site	NO_3-N		DO	Aquifer
			Median (mg/L)	AnnualSenSlope.x (mg/L/year)	Median (mg/L)	
AC	Well	7428103	0.001	0.00	0.130	Basalt
AC	Well	7419009	0.002	0.00	0.140	Basalt
AC	Well	7428031	6.099	-0.06	8.360	Basalt
AC	Well	7428105	7.615	0.54	6.800	Basalt
AC	Well	7419121	9.200	0.18	7.865	Basalt

4.7 Trends Over Time

4.7.1 Surface Water Flow Trends

Trend analysis was completed for measured flow (i.e., Q^{SW}_{OUT}) at five continuous flow sites in the study area (Figure 4.14 and Figure 3.4). Clearly, the flow was seasonal with larger flow rates in winter and so seasonal adjustment was appropriate for the analysis. No statistically-significant trends over time were calculated for measured flow at four continuous flow sites in the study area; the period of record at one site (Mauku Stream @ Puni) was too short to undertake the trend analysis. (Table 4.12). Similarly, the trend analysis indicates no significant trends over time in calculated baseflow in four streams (Figure 4.15 and Table 4.13).

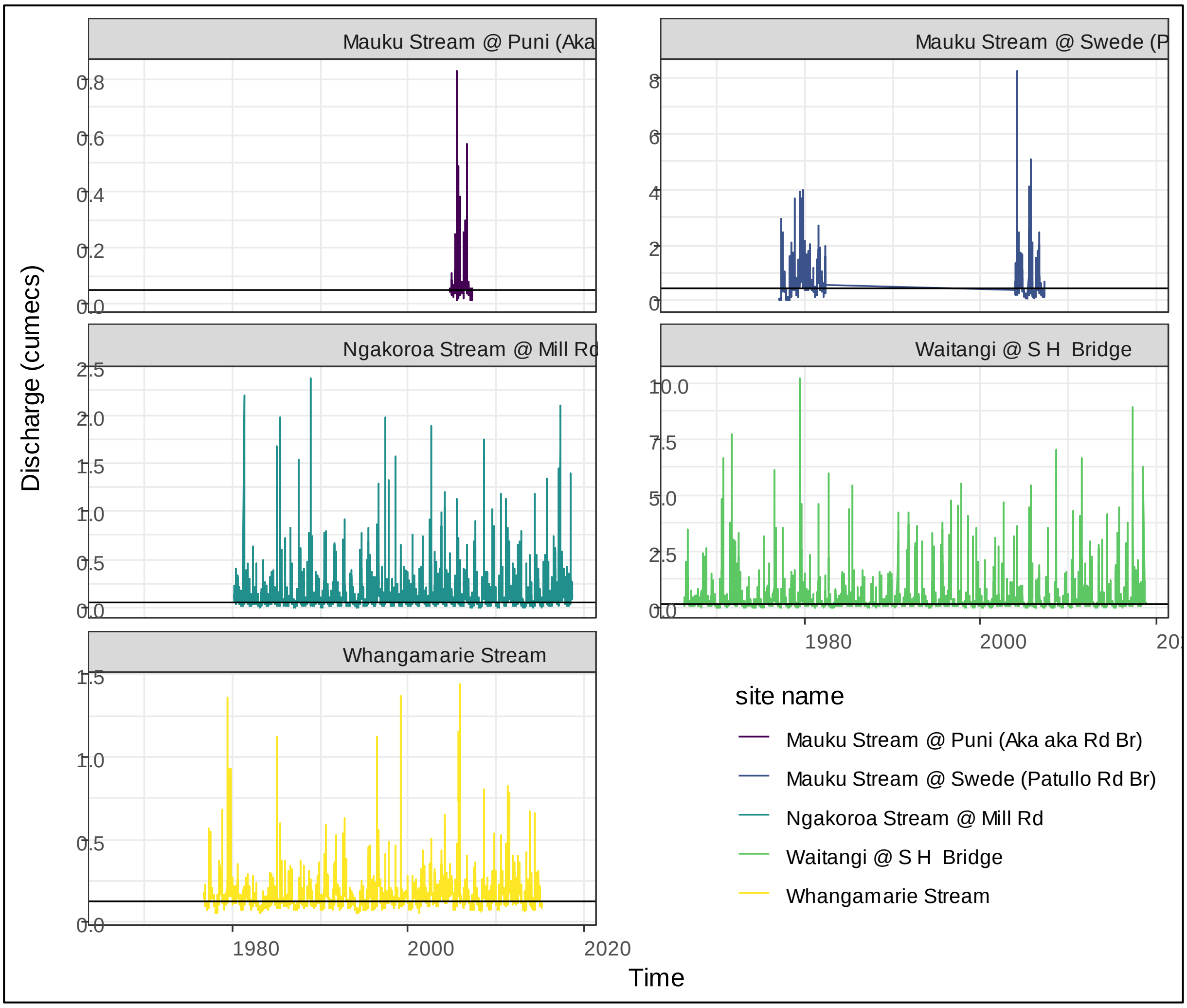

Figure 4.14 Q^{SW}_{OUT} at five continuous flow sites in the study area between 1966 and 2017 (Figure 3.4). Black lines are the medians of each time series.

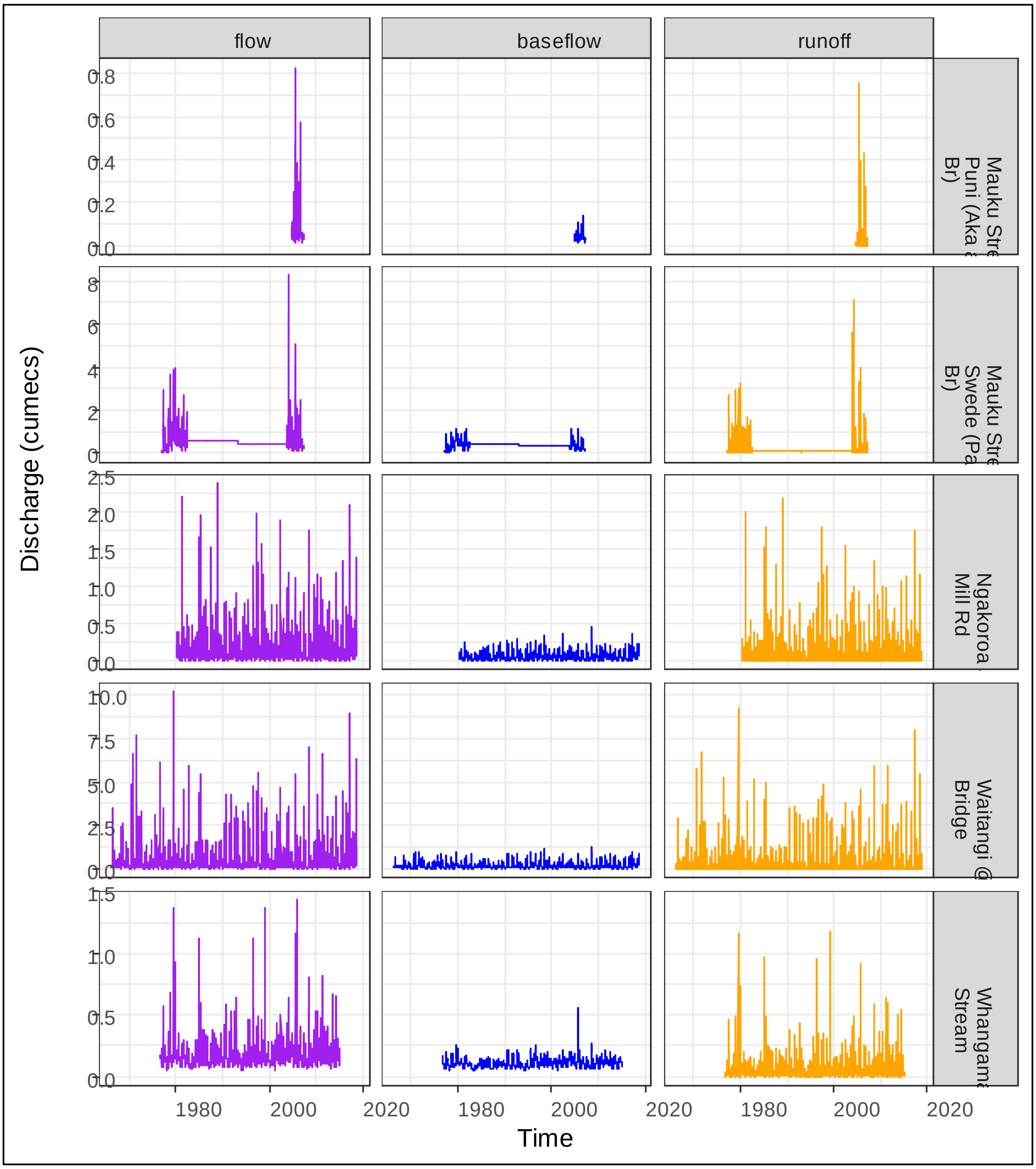

Figure 4.15 Q^{SW}_{OUT} ('flow') with Q^{SW}_{BF} ('baseflow') and Q^{SW}_{QF} ('runoff') calculated as Eckhardt (2005) at continuous flow sites in the 1966–2017 period.

Table 4.12 Trend summary statistics for entire record of streamflow data. No statistical monotonic trend is observed (i.e., Mann-Kendall p-value > 0.05).

Site Name	Site Number	Median (m^3/s/year)	Median Absolute Deviation (m^3/s/year)	# of Results	Trend Magnitude (Sen slope m^3/s/year)	P-value (Mann-Kendall test)	Comment
Mauku Stream @ Puni	43707	0.052	0.024	936	NA	NA	Insufficient data
Mauku Stream @ Swede	43705	0.420	0.296	11023	-0.0043	0.143	Seasonally-adjusted
Ngakoroa Stream @ Mill Rd	43829	0.058	0.053	14019	0.000061	0.621	Seasonally-adjusted
Waitangi @ S H Bridge	43602	0.147	0.131	19178	-0.00011	0.527	Seasonally-adjusted
Whangamaire @ Patumahoe Weir	43811	0.125	0.044	14029	0.00022	0.133	Seasonally-adjusted

Table 4.13 Trend summary statistics for baseflow data. No statistical trend is observed (Mann-Kendall p-value > 0.05).

Site Name	Site Number	Median ($m^3/s/year$)	Median Absolute Deviation ($m^3/s/year$)	# of Results	Trend Magnitude (Sen slope $m^3/s/year$)	P-value (Mann-Kendall test)	Comment
Mauku Stream @ Puni	43707	0.041	0.019	936	NA	NA	Insufficient data
Mauku Stream @ Swede	43705	0.356	0.162	11023	-0.00373	1	Seasonally-adjusted
Ngakoroa Stream @ Mill Rd	43829	0.048	0.041	14019	5.31E-05	0.301	Seasonally-adjusted
Waitangi @ S H Bridge	43602	0.124	0.105	19178	-6.00E-05	0.643	Seasonally-adjusted
Whangamaire @ Patumahoe Weir	43811	0.103	0.036	14029	0.000222	0.059	Seasonally-adjusted

4.7.2 Spring and Groundwater Chemistry Trends

Water chemistry indicators measured in springs and wells (Appendix 2) are plotted for:

- key indicators of nitrate-nitrogen (Figure 4.16 to Figure 4.18); iron (Figure 4.19 to Figure 4.21) and DO (Figure 4.22 to Figure 4.24); and
- other indicators, i.e., DRP, Mn, NH_3-N, Cl, electrical conductivity and temperature (Appendix 3).

The best groundwater-quality statistics come from basalt aquifers because much chemistry data is measured in this lithology (i.e., three springs and 16 wells). In contrast, groundwater-quality data in other lithologies was measured at less than four wells (Section 3.4).

Nitrate-nitrogen concentrations in springs and groundwater were commonly measured above the maximum allowable value for drinking water (i.e., 11.3 mg/L as NO_3-N, equivalent to 50 mg/L as NO_3; Ministry of Health 2008) in the data set since the mid-1990s, Figure 4.16 to Figure 4.18. In springs, these concentrations were commonly above 6.9 mg/L (i.e., the National Objectives Framework limit for nitrate toxicity values applicable to lakes and river environments; Ministry for the Environment 2017).

DO concentrations in basalt aquifers are ‘bimodal’ demonstrating oxic and anoxic conditions in wells (Figure 4.24, Table 4.11). Probably, nitrate-nitrogen concentrations in oxic basalt aquifers are more variable than in anoxic conditions. For example, the trend analysis demonstrated significant changes in nitrate-nitrogen concentrations, both increases and decreases, in groundwaters where median DO was greater than 6.8 mg/L (Table 4.11). Oxic conditions in basalt aquifers are indicated by low iron (Fe) concentrations (Figure 4.21). DO concentrations in springs are relatively high, consistent with oxygenated basalt aquifers as the source for spring flow (Figure 4.22).

Generally, nitrate-nitrogen concentrations in wells were increasing over time (Figure 4.18). It is possible that most of these wells take groundwater from the shallow, oxygenated, basalt aquifer because of the link between high nitrate-nitrogen concentrations and high DO concentrations (Table 4.11).However, DO was measured in only a few of these wells (Figure 4.17, Figure 4.18 and Figure 4.24).

Redox indicators (iron) have relatively high concentrations in Kaawa shell aquifer and in some basement/Waitemata sandstone groundwater, indicating anoxic conditions. High concentrations of iron may impart an unpleasant taste to drinking water (aesthetic guideline value of 0.2 mg/L; Ministry of Health 2008). High manganese concentrations in water results in the staining of laundry and whiteware (aesthetic guideline value of 0.04 mg/L; Ministry of Health 2008). Elevated manganese concentrations may also present toxicity to human health and ecosystems (maximum admissible value of 0.4 mg/L and trigger value or 1.9 mg/L; Ministry of Health 2008 and Australia and New Zealand Environment Conservation Council (ANZECC) 2000); see Appendix 3 for manganese concentrations in the study area.

In the Holocene sediments, nitrate-nitrogen concentrations at site 61-126 increased between 1995 and 2000, plateaued until 2010 with some values above 10 mg/L and then decreased until 2015 (Figure 4.16 and Figure 4.17). This is consistent with a decrease in electrical conductivity over the period of record (Appendix 3). The chemistry data collected at the sites sourced from the Kaawa sediments and the Drury sand are insufficient to report on trends.

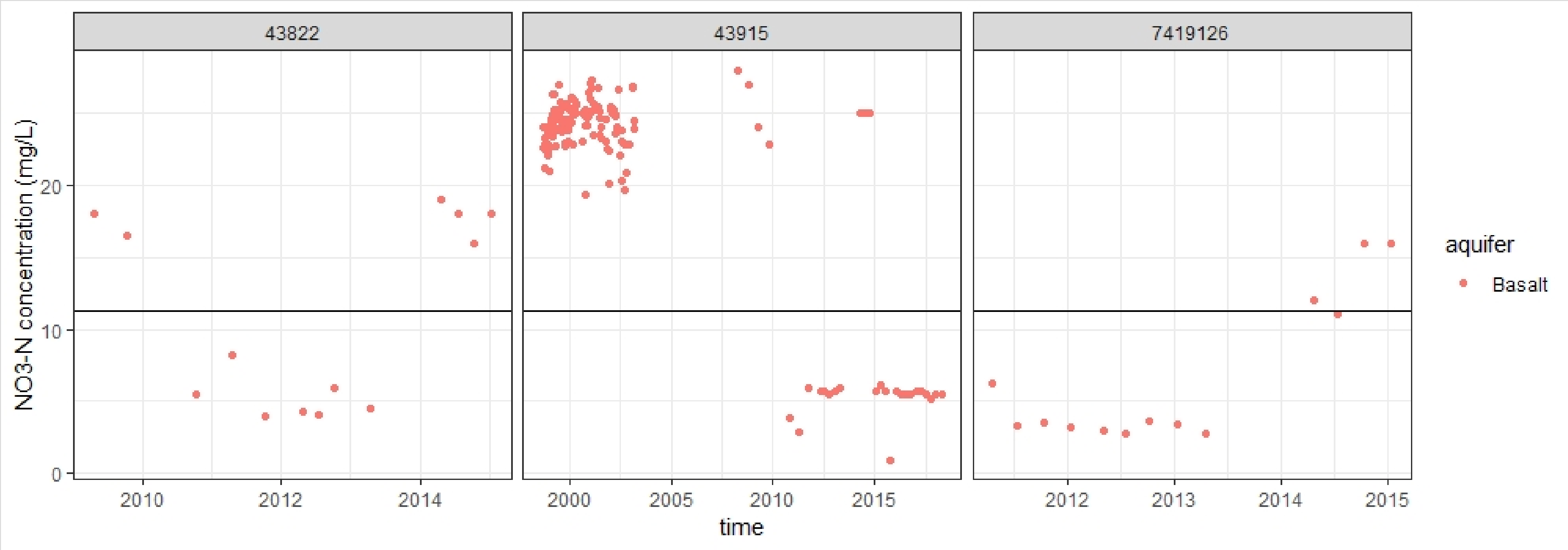

Figure 4.16 Nitrate-nitrogen time series at springs, all sourced from the basalt aquifer, in the period 2009–2018. The black line indicates the New Zealand drinking-water MAV for nitrate-nitrogen.

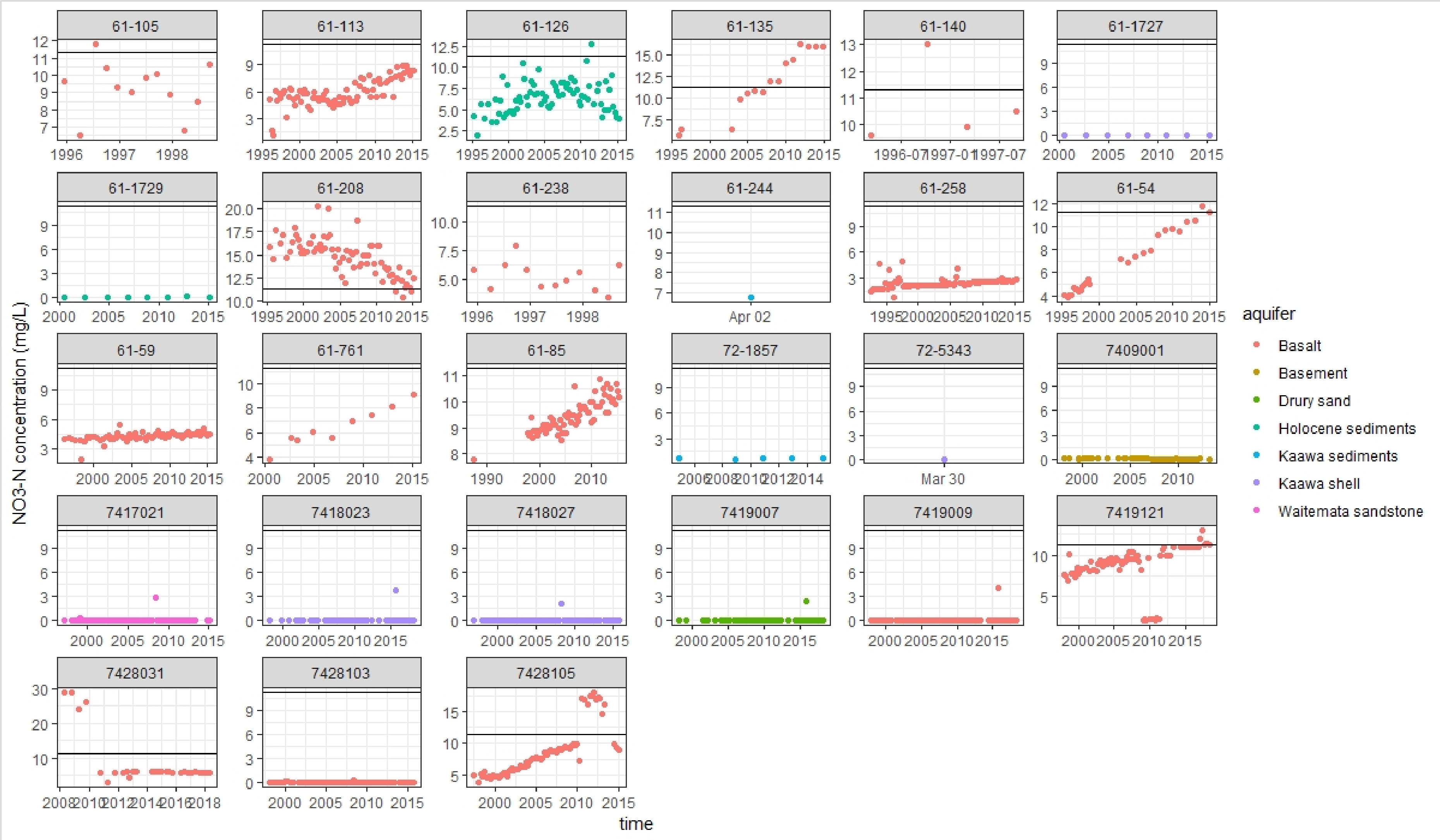

Figure 4.17 Nitrate-nitrogen time series at wells in the period 2009–2018 and aquifer type. The black line indicates the New Zealand drinking-water MAV for nitrate-nitrogen.

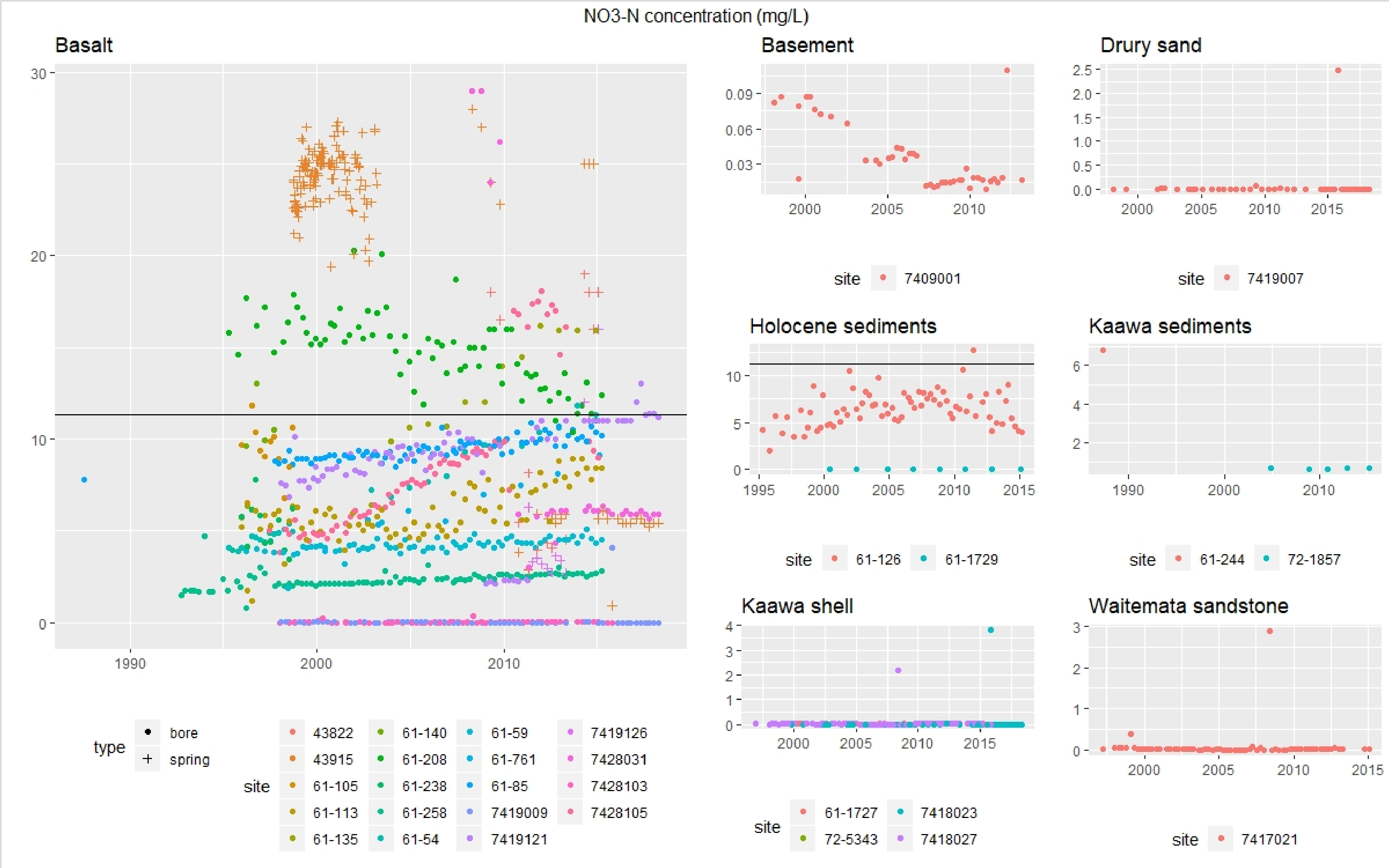

Figure 4.18 Nitrate-nitrogen time series at wells in the period 2009–2018 aggregated by aquifer type. The black line indicates the New Zealand drinking-water MAV for nitrate-nitrogen.

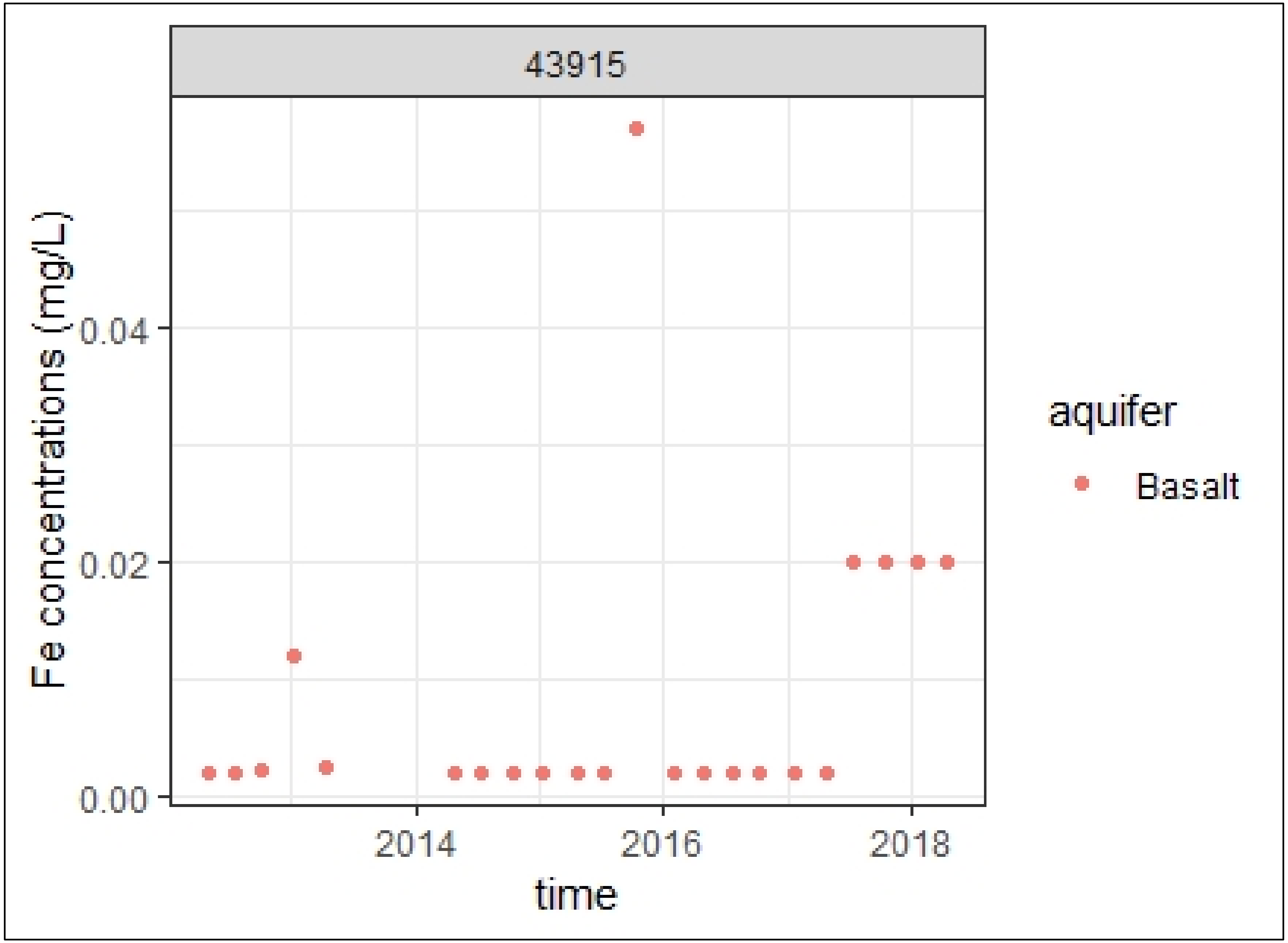

Figure 4.19 Fe time series at one spring, sourced from the basalt aquifer, in the period 2009–2018.

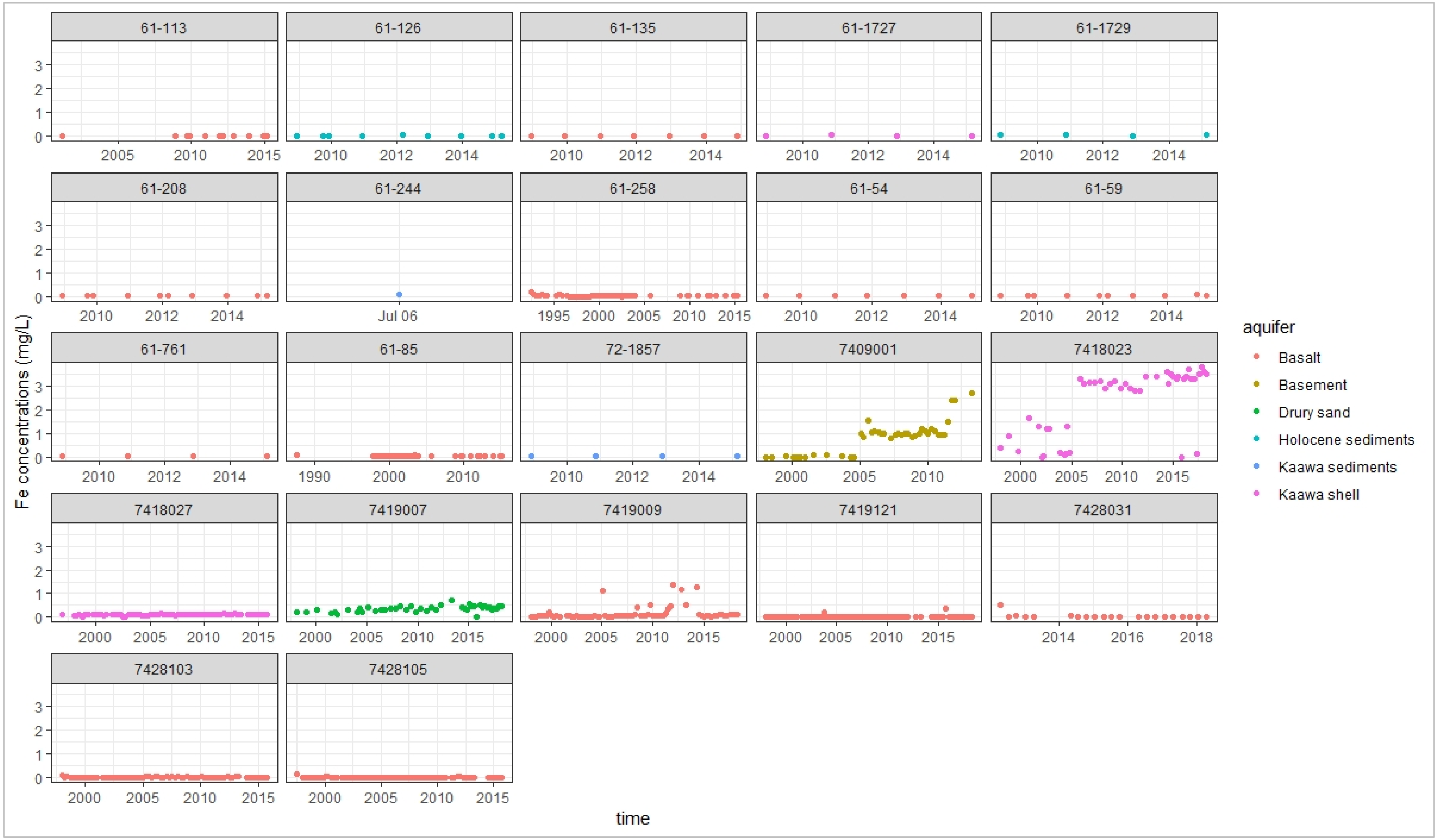

Figure 4.20 Fe time series at wells in the period 2009–2018 and aquifer type.

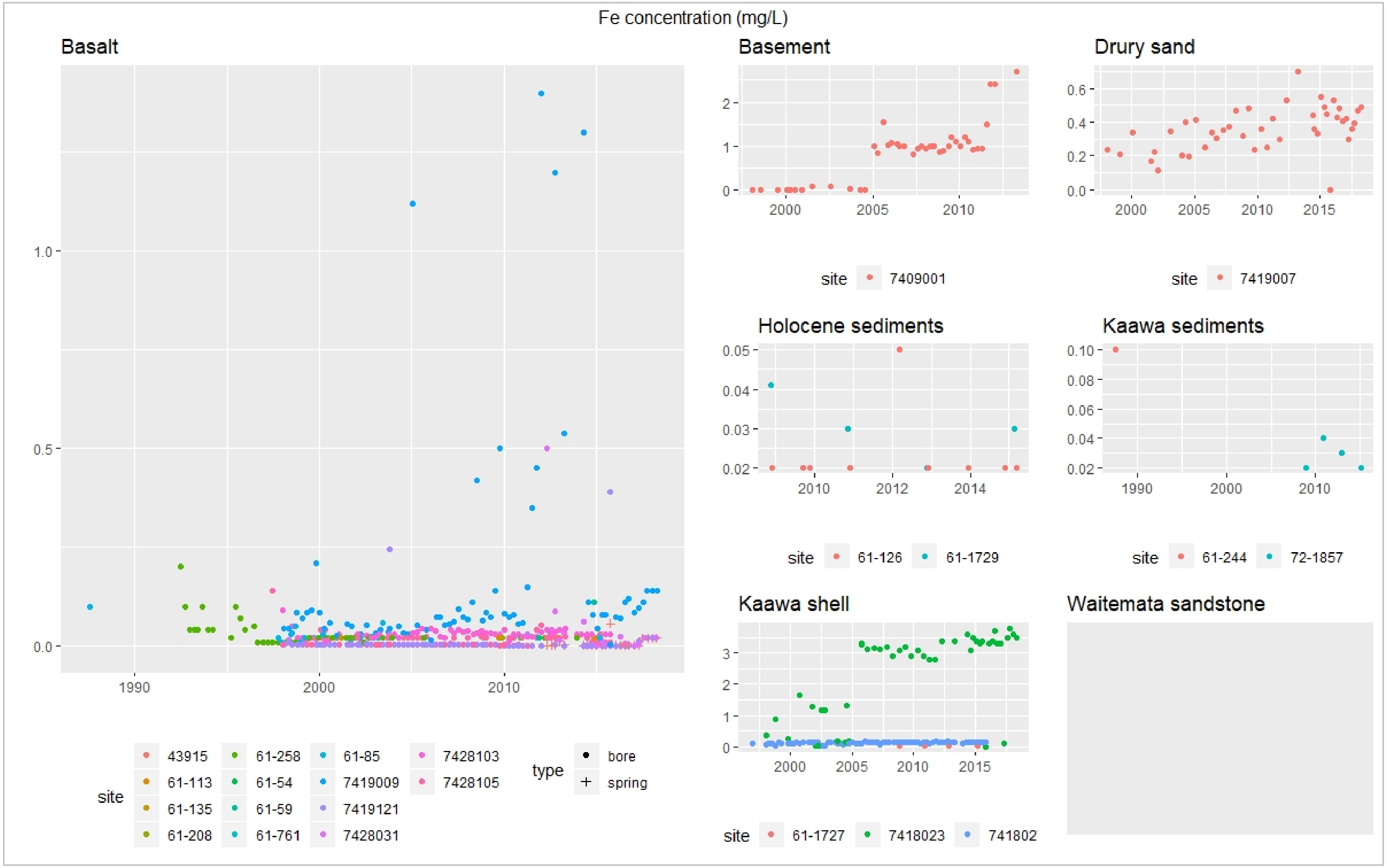

Figure 4.21 Fe time series at wells in the period 2009–2018 aggregated by aquifer type.

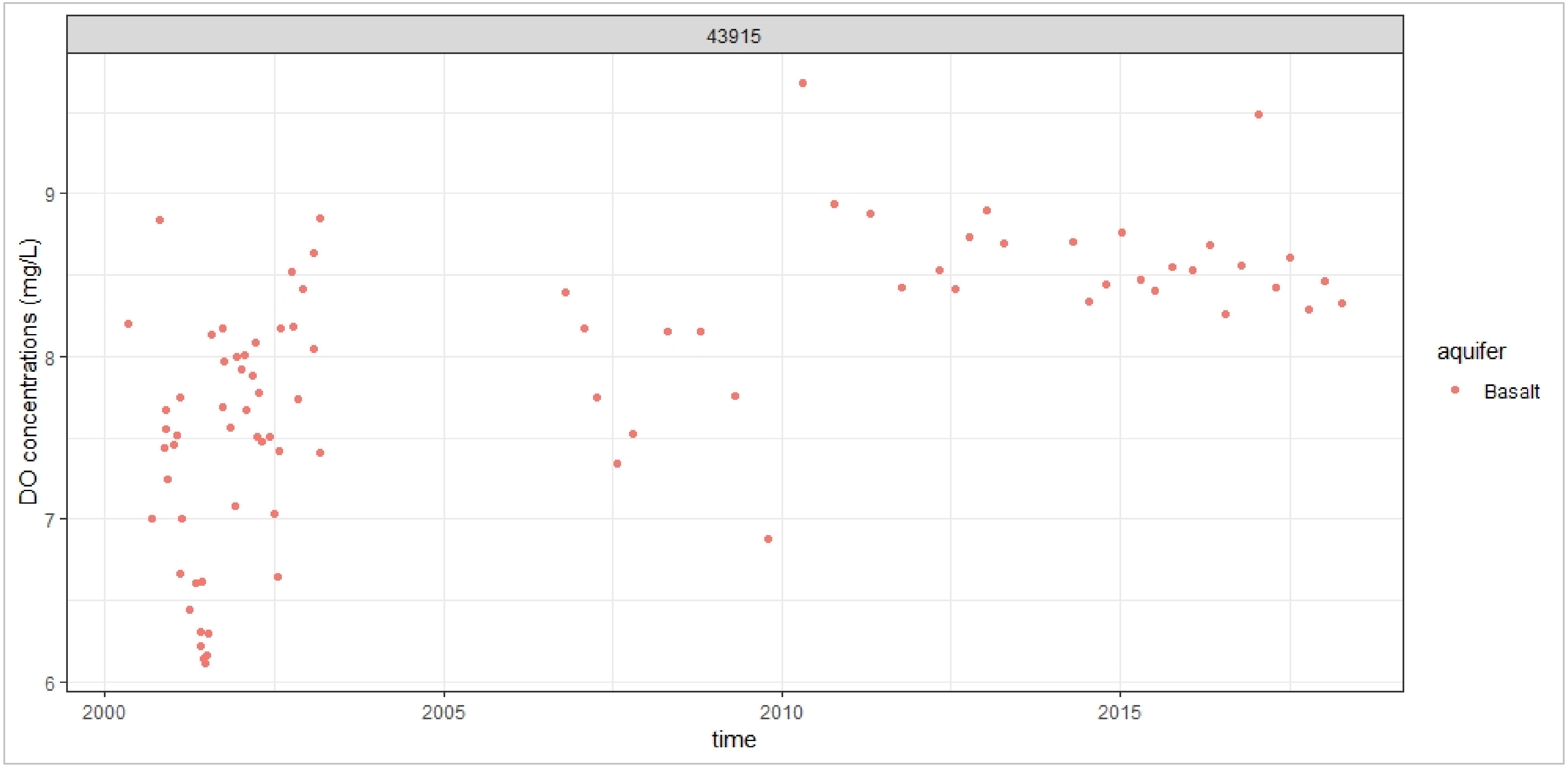

Figure 4.22 DO at one spring, sourced from the basalt aquifer, in the period 2009–2018.

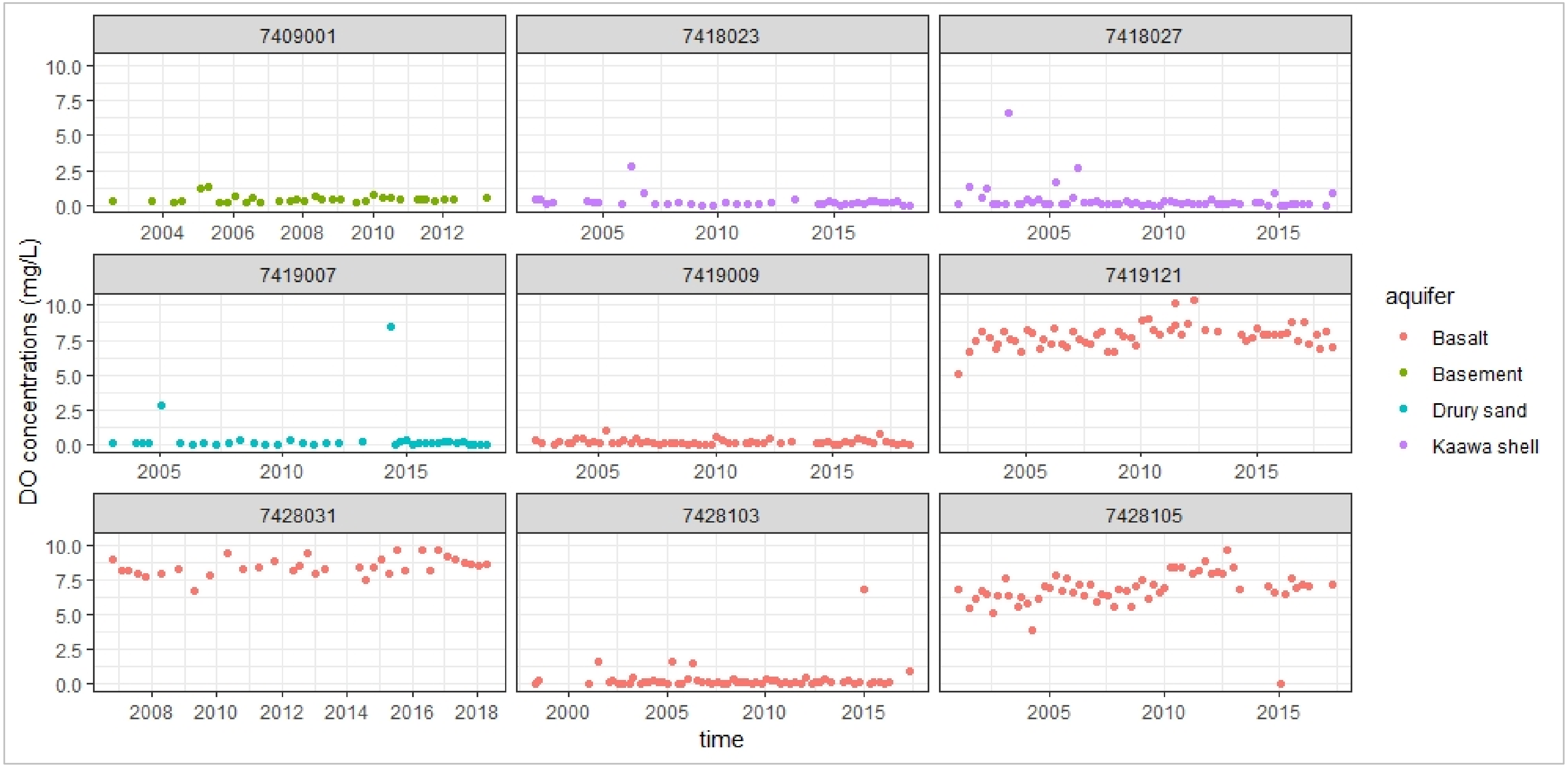

Figure 4.23 DO time series at wells in the period 2009–2018 and aquifer type.

Figure 4.24 DO time series at wells in the period 2009–2018 aggregated by aquifer type.

5.0 DISCUSSION

This report provides new insights (particularly geology, groundwater recharge, and water chemistry) that have implications for the understanding of the groundwater system of the study area.

5.1 Geology

Generally, the 3D model gives new information on the distribution of volcanic rocks and aquifers (e.g., Figure 4.4). Volcanic rocks seem separated into four groups: immediately east of Waiuku (with a possible residual crater in the Bald Hill area), Pukekohe, Bombay and the Hunua Range foothills. This grouping could be used as a basis for classification of the volcanic aquifers, including vertical separation of units, to further develop the current understanding of ‘upper’ and ‘lower’ volcanic aquifers in the Pukekohe volcanic system (e.g., Figure 4.4; Auckland Regional Water Board and Waikato Valley Authority 1977).

Shallow shell units are identified on the shores of Manukau Harbour and the Waikato River Valley by the 3D model (e.g., Figure 4.2 and Figure 4.3). These shells are possibly Holocene in age as their elevation range is approximately -17 m to -40 m; the maximum depth of these shells is consistent with the depth of many Holocene marine incursions located on the New Zealand coast (e.g., Wairau Plains, White et al. 2016). The addition of a shallow, Holocene shell aquifer management area may be justified if it is a source of irrigation water and is in demand.

The 3D shell model plots show some discontinuities, e.g., below Pukekohe Hill and parts of the Waikato River valley (Figure 4.5). However, Kaawa shells are probably continuous over the study area west of the Hunua Range. Multiple Kaawa-age shell sequences are identified in the 3D models (e.g., Figure 4.6 and Figure 4.11). Therefore, Kaawa shell, and associated sand, aquifers probably occur in discrete deposits. Multiple shell/peat sequences are potentially identified in the 3D models (e.g., Figure 4.13). These could be separated by movement on faults or could represent multiple climate phases.

A more detailed understanding of the continuity of discrete Kaawa shell deposits, and thus hydraulic connectivity, would aid the development of the most appropriate aquifer management regime, e.g., whether the Kaawa shell should be subdivided into upper and lower management areas. Therefore, further assessment of the 3D model and the distribution of key lithologies (volcanic, shells and peats) is recommended (Section 6.1). Interpretation of static hydraulic heads in wells is also relevant to the understanding of aquifer distribution and so is also recommended (Section 6.2).

5.2 Rainfall Recharge

Broadly, the rainfall recharge estimates in this report (Section 4.4) are similar to Viljevac et al. (2002). Rainfall recharge of 680 mm/year (Rosen et al. 2000) was used in the groundwater allocation regime for the volcanic and Kaawa shell aquifers (Viljevac et al. 2002). All three estimates of rainfall recharge (i.e., Rosen et al. 2000 and two estimates in this report), are reasonably similar (Table 5.1). The estimates are also similar to some estimates of rainfall recharge in the area, but not others, e.g., Auckland Regional Council (1991b) and Petch et al. (1991), respectively (Table 2.1).

The rainfall recharge calculation of Rosen et al. (2000) is similar to the range of rainfall recharge measured at the Karaka rainfall recharge site. This is significant because the two estimates were produced by different methods, although both were field-based. In addition, the two sites occupy different geographic positions, i.e., the work of Rosen et al. (2000) was near Pukekohe Hill and the Karaka site is near the coast; and different soil types.

However, rainfall recharge for the Karaka site was calculated from only two years of observations when records were discontinuous. Therefore, these observations do not represent a statistically-valid long-term, estimate of rainfall recharge. The observations do, however, clearly indicate that a significant volume of rainfall recharge enters the groundwater system in the study area. The observations also show the value of the rainfall recharge monitoring site in providing measurements of recharge – the value of data from this monitoring site can only increase as the length of record increases over time and further monitoring is recommended (Section 6.3).

Table 5.1 Summary of rainfall recharge (RR) calculations.

Item	RR (mm/year)	Method	Notes	Reference
Pukekohe volcanic aquifer	680	Soil moisture	Net of evaporation and runoff	Viljevac et al. (2002); Rosen et al. (1999, 2000). Table 2.1
Representative catchments	490 $^{+}/_{-}$ 50	Equation 7	Long-term mean and standard deviation, 15 representative catchments	This report: Table 4.4, rounded with the standard deviation of catchment estimates
Karaka rainfall recharge site	819 +/- 121[1]	Karaka rainfall recharge site	The range is from three lysimeters and two incomplete years of record	This report: Table 4.6, rounded

1 The range from three lysimeters.

5.3 Groundwater Outflow

Rainfall recharge provides for two outflow components in Equation 8: stream outflow (Q^{SW}_{OUT}) and groundwater outflow (Q^{GW}_{OUT}). An alternative form of Equations 4 and 8 is a groundwater budget, which considers, conceptually, the three-dimensionality of groundwater catchments and calculates two groundwater outflow terms, i.e.:

$$RR = Q^{SW}_{QF} + Q^{GW}_{S} + Q^{GW}_{D} \qquad (9)$$

Here, 'shallow' groundwater flow (Q^{GW}_{S}) is equal to Q^{SW}_{BF} (Equation 4) and 'deep' groundwater flow (Q^{GW}_{D}) is equal to Q^{GW}_{OUT} (Equation 8). Thus, baseflow flows from 'shallow' groundwater catchments and 'deep' groundwater flows to geolgical units below the shallow catchments. This conceptualistion was used to assess groundwater flows, and calculate groundwater available for allocation in the Bay of Plenty region under Plan Change 9 (PC9), White et al. (2008, 2018).

5.3.1 Stream Flow

The stream flow calculations are important because they determine the portion of RR that becomes 'deep' groundwater flow. Baseflow is the largest component of stream flow in the study area. For example, BFI was a mean of 0.87 in catchments dominated by volcanic lithologies as is common in New Zealand's volcanic lithologies (e.g., White et al. 2015). BFI was a mean of 0.67 in sediment-dominated catchments (Table 4.7 and Table 4.8, respectively). However, these mean values were derived by different methods, i.e., Eckhardt (2005) was used for continuous flow sites (all located in volcanic-dominated catchments) and Equation 5 was used for gauging data.

The importance of good surface water flow information is demonstrated by flow statistics (e.g., total flow, baseflow and quick flow) in the study area (Section 4.5). Here, BFI calculated with continuous flow measurements was shown to be of better quality than BFI calculated with gauged data. Continuous flow measurement sites are located solely in catchments where surface geology is dominated by volcanics (e.g., Table 4.7). Therefore, it is recommended that continuous flow measurements are made to assess flow statistics in catchments that are sediment-dominated (Section 6.4).

BFI (Equation 5), was similar in volcanic-dominated and sediment-dominated catchments (Table 4.8). Therefore, 'shallow' groundwater flow, which provides baseflow, is important in volcanic and sedimentary geologies.

5.3.2 Deep Groundwater Flow (Q^{GW}_{D})

The Q^{GW}_{D} estimates calculated in this report are similar to groundwater recharge values of Viljevac et al. (2002), Table 5.2. Viljevac et al. (2002) calculated a systematic difference between recharge to the Pukekohe volcanic aquifer and the Kaawa shell aquifer. However, this report calculated similar deep recharge in the geographic areas of the lithologies (e.g., Q^{GW}_{OUT}, Table 4.3).

Potentially, Q^{GW}_{D} may flow to any geological unit, and aquifer, in the study area, e.g.: shallow sedimentary aquifers; the volcanic aquifers; Puketoka Formation; Kaawa Formation sand and shell aquifers; and basement rocks. For example, Q^{GW}_{D} in the area of Pukekohe volcanics may flow to deeper layers, i.e., the volcanic aquifer below the catchments of spring-fed streams, the Puketoka Formation and the Kaawa Formation. Therefore, calculation of Q^{GW}_{D} is an important aim of science to support resource management because Q^{GW}_{D} provides an upper estimate of groundwater available for allocation in the deeper aquifers, whilst aiming to protect baseflow in streams, as with PC9 (White et al. 2018).

Table 5.2 Deep groundwater recharge (Q^{GW}_{D}). Note that the term 'Q^{GW}_{D}' (Equation 9) was not used by Viljevac et al. (2002).

Item	Q^{GW}_{D} (mm/year)	Method	Notes	Reference
Pukekohe volcanic aquifer	220	Water budget	Net of stream baseflow discharge	Viljevac et al. (2002)
Recharge to Kaawa shell aquifer (Pukekohe)	176	Water budget	Net of stream baseflow discharge	Viljevac et al. (2002)
Representative catchments	273 $^{+}/_{-}$ 110[1]	Water budget	Long-term average of 15 catchments	Table 4.2, rounded

[1] The mean and standard deviation from 15 catchments.

5.4 Mechanism of Recharge to Deep Aquifers

AC's current groundwater allocation regime in the area is based on Viljevac et al. (2002), Section 2.2. The conceptual model of Viljevac et al. (2002) has all Kaawa shell aquifer recharge coming from volcanic lithologies via volcanic feeder zones. However, this report points to several features of the Viljevac et al. (2002) conceptual model that may be incorrect.

Groundwater inflow to sediments is sourced from rainfall recharge on the sediments and from volcanic aquifers. Rainfall recharge to sediments is large, as demonstrated by measurements at Karaka, where rainfall recharge was in the range 44% to 50% of rainfall (Table 4.5). Deep groundwater outflow may provide groundwater inflow to sediments because Q^{GW}_{D} is relatively large in volcanic-dominated catchments (e.g., Table 4.3) In addition, Q^{GW}_{D} in sediment-dominated catchments may provide recharge to adjacent catchments.

Groundwater outflow is an indirect indication of groundwater inflow. For example, Q^{GW}_{S}, which provides surface baseflow, is the largest component of Q^{SW}_{OUT} because BFI is a mean of 0.67 in sedimentary catchments (Section 4.5).

The groundwater pathway from volcanic aquifers to Kaawa shell aquifer recharge is unlikely to be dominated by flow through volcanic feeder zones, because:

- volcanic rocks are adjacent to Kaawa shells in the subsurface (Figure 4.9 and Figure 4.12) and therefore volcanic aquifers may occur in close proximity to Kaawa shell aquifers;
- volcanic feeders probably occupy a small geographic area, relative to the surface area of the volcanic deposits.

The 3D geological model maps multiple shell layers within the Pliocene sediments, e.g., Figure 4.6 and Figure 4.9. Therefore, groundwater may enter Kaawa Formation shell aquifers through multiple shallow and deep pathways.

Together, these observations support a view that groundwater recharge to the Kaawa shell aquifer includes diffuse infiltration from overlying sedimentary strata as well as recharge from overlying volcanic aquifers, in contrast with Viljevac et al. (2002).

5.5 Groundwater Allocation Zones

AC and WRC have used different approaches to identify current groundwater allocation zone boundaries. Therefore, it is recommended that AC and WRC undertake a joint approach to the definition of a new set of groundwater allocation zone boundaries in the study area (Section 6.6).

AC separates groundwater allocation limits for three lithologies (i.e., volcanics, Kaawa shell aquifer and sand) whereas WRC has one groundwater allocation limit for all aquifers within a zone (Table 2.7 and Table 2.8, respectively). AC boundaries are inconsistent with WRC boundaries. For example, the southern boundaries of current AC volcanic groundwater allocation zones overlap with the northern boundaries of WRC zones in some places with some gaps between these boundaries (Figure 5.1).

Discrete shallow and deep volcanic aquifers were identified by bore logs, the 3D geological model, water chemistry data, and Viljevac (1996). However, AC allocation zones do not differentiate between shallow and deep volcanics. The AC management objectives for groundwater may not be fully realised in disparate volcanic aquifers if a single allocation regime is applied, although the water budget analysis indicates the current allocation regime is sustainable.

AC has defined the boundaries of volcanic-aquifer and Kaawa shell aquifer allocation zones using piezometric maps of groundwater elevation (Viljevac et al. 2002). By doing this, the allocation zone boundaries of each aquifer may not fall within consistent groundwater catchments, i.e. recharge zones may encompass areas larger than individual allocation zone boundaries and/or overlap zone boundaries. As such, a more appropriate management approach in the Pukekohe area may be to define allocation zones based on groundwater-surface water catchments (see Section 6.6).

AC Kaawa shell aquifer allocation zones do not extend as far north as the Manukau Harbour but shell beds are recorded in well logs near the Manukau Harbour coastline (Figure 5.2). These shell beds may have a Holocene age and are likely to have a limited connectivity with the upper and lower Kaawa shell beds, indicating the existing demarcation is sufficient to manage Kaawa shell water use. However, more detailed investigation of the connectivity of shell horizons may inform changes to the existing Kaawa shell aquifer management areas or the addition of new Holocene shell management areas. More information is needed to progress this, and recommendations have been made to that effect.

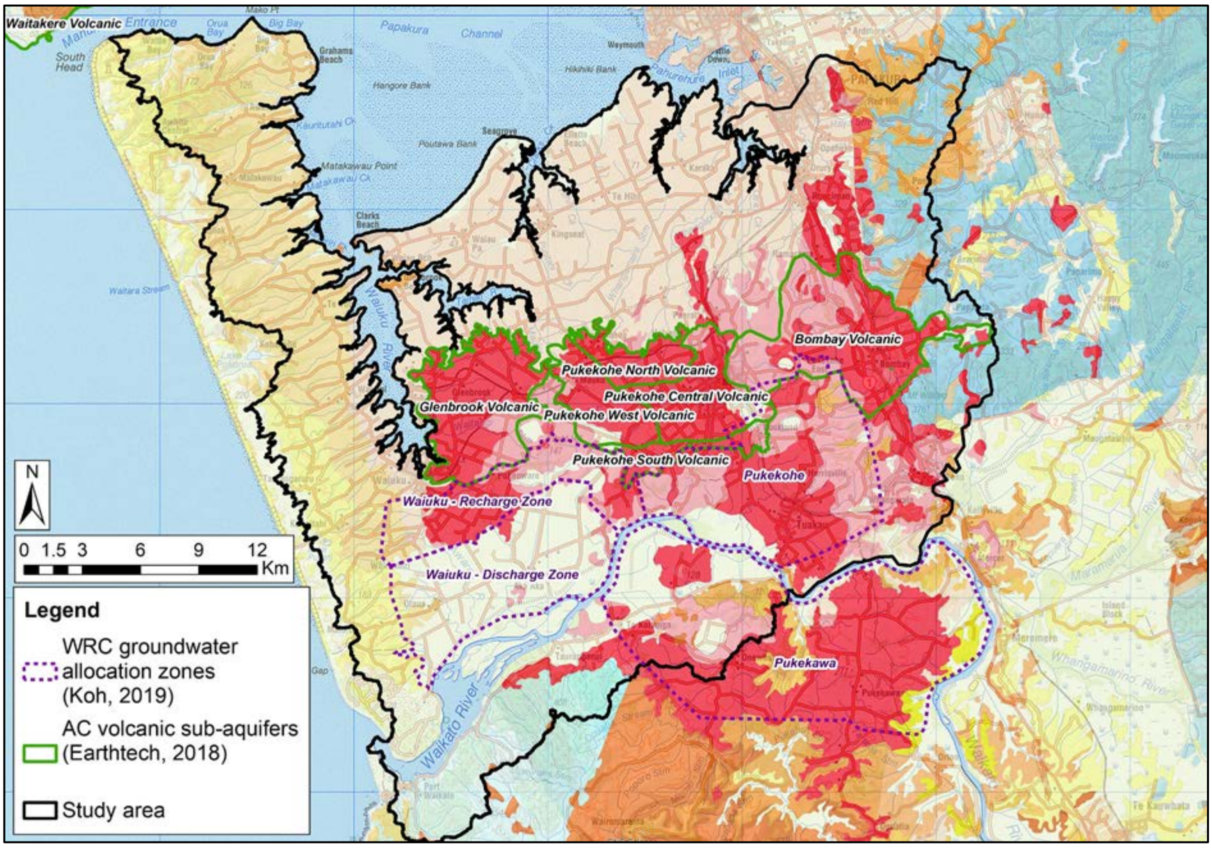

Figure 5.1 WRC groundwater allocation zone boundaries and AC groundwater allocation zone boundaries for the volcanic aquifers.

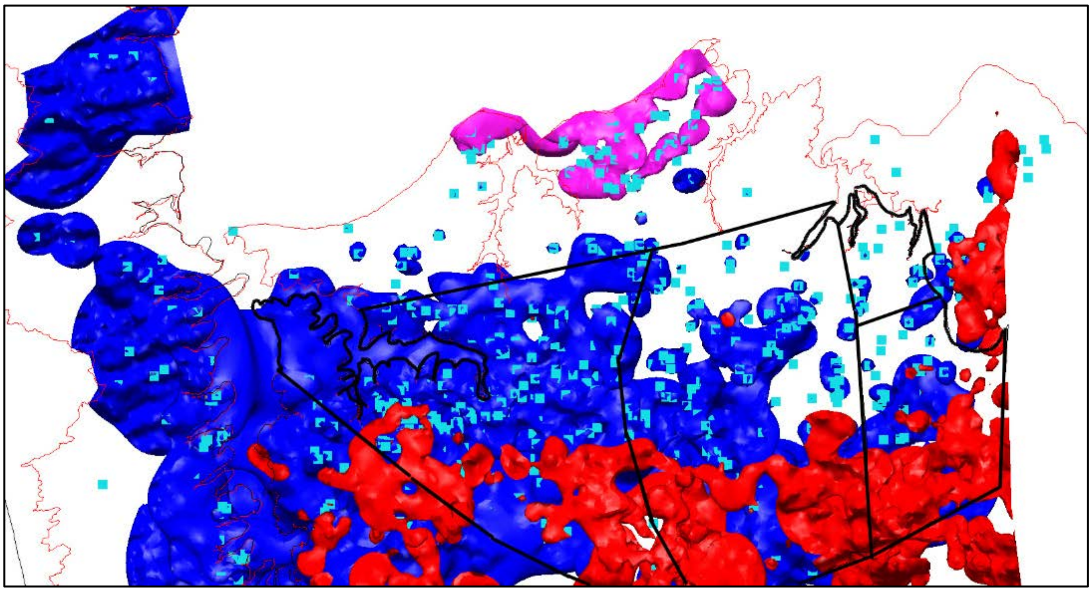

Figure 5.2 Contiguous shell deposits identified by the 3D model, including possible Holocene shell (purple) and Kaawa shell (dark blue). Also shown are the locations of shells identified in well logs (teal) and volcanics (red). The boundaries of AC Kaawa allocation bondaries (black) include: Waiuku, Glenbrook, Pukekohe, Papakura and Bombay-Durie (Figure 2.9).

5.6 Groundwater Allocation

5.6.1 Groundwater Allocation Limits and Currently-consented Groundwater Allocation

Groundwater availability (i.e., AC's current groundwater allocation limits and WRC's Management Level, Section 2.5) and currently-consented allocation are summarised as rates in units of mm/year (Table 5.3 and Table 5.4).The rates as mm/year were calculated by dividing rates as m^3/year and zone area as m^2 (Table 2.7 and Table 2.8) for the minor AC zones (i.e., Awhitu Kaawa, Papakura Kaawa, Bombay-Drury sand and Papakura Sand) and WRC zones.

The calculation of rates for the major AC allocation zones (i.e., basalt and Kaawa) required a different approach because these zones are overlapping (Figure 2.8 and Figure 2.9). Therefore, the aggregated average groundwater availability and consented groundwater allocation for the overlapping groundwater allocation zones were calculated by:

- aggregating the basalt allocation zones and the Kaawa allocation zones (i.e., Figure 5.3 and Figure 5.4, respectively). Note that the Papakura Kaawa allocation zone is not overlain by a volcanic allocation zone; therefore, the Papakura Kaawa allocation zone is not aggregated with other Kaawa allocation zones;
- aggregating the polygons in Figure 5.3 and Figure 5.4 (Figure 5.5);
- summing allocation limits and currently-consented allocation to volcanics and Kaawa, from Table 2.7, within the area of Figure 5.5;
- calculating allocation limits and currently-consented allocation in units of mm/year (Table 5.3).

The overlapping AC volcanic and AC Kaawa zones include the largest groundwater use in the study area (Table 5.3). In this area, groundwater availability was 40 mm/year. In comparison, average WRC Management Level averaged 147 mm/year (Table 5.4). Consented groundwater allocation was less than groundwater availability in all zones (Table 5.3 and Table 5.4).

Table 5.3 AC groundwater availability and consented groundwater allocation as mm/year.

Allocation Area	Figure Reference	Area (km^2)	Groundwater Availability (mm/year)	Consented Groundwater Allocation (mm/year)
Awhitu Kaawa	Figure 2.9	226.8	10	3
Papakura Kaawa	Figure 2.9	9.6	*	3
Awhitu Sand	Figure 2.10	226.8	8	0
Bombay-Drury Sand	Figure 2.10	57.5	*	0.1
Drury Sand	Na	**	**	**
Papakura Sand	Figure 2.10	23.3	6	1
AC volcanic zones	Figure 5.3	147.5	33	19
AC Kaawa zones (part)	Figure 5.4	265.7	35	19
AC volcanic zones and AC Kaawa zones (part)	Figure 5.5	295.6	48	27

* currently, no groundwater availability is defined by AC.

** currently, no groundwater availability zone boundary is defined by AC.

Table 5.4 WRC groundwater management level and consented groundwater allocation as mm/year (from Table 2.8).

WRC Management Zone	Area (km^2)	Management Level (mm/year)	Consented Groundwater Allocation (mm/year)
Waiuku – recharge zone	36.52	151	25
Waiuku – discharge zone	60.1	150	19
Pukekohe	79.25	151	41
Pukekawa	141.48	141	11
All area	317.35	147	22

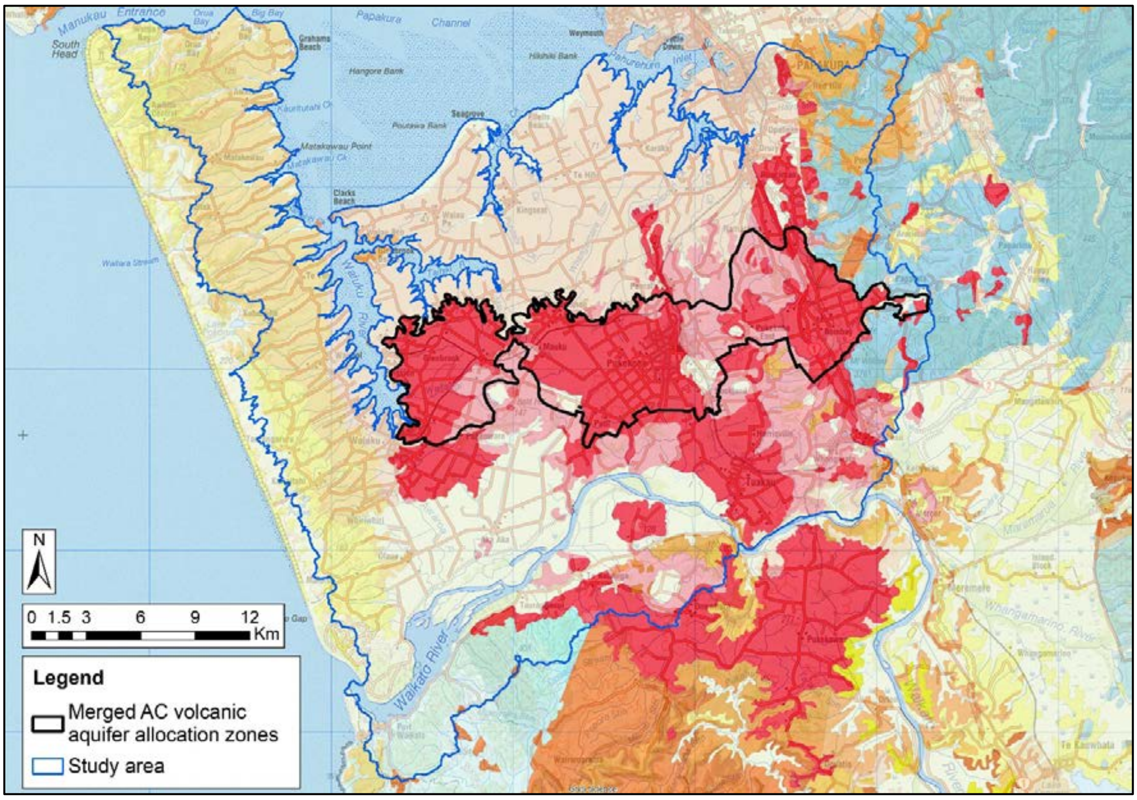

Figure 5.3 AC volcanic groundwater allocation zones (Figure 2.8) merged.

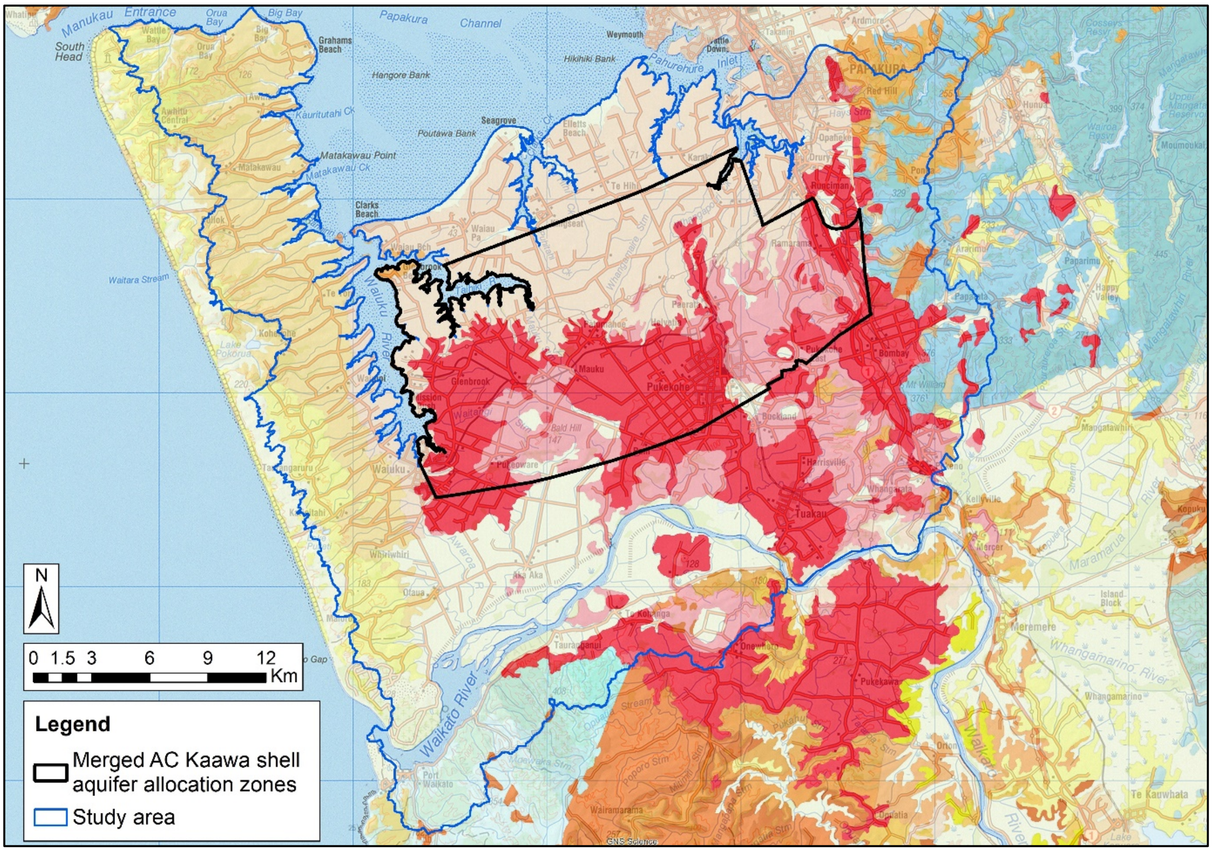

Figure 5.4 AC Kaawa groundwater allocation zones (Figure 2.9) merged. These are the Kaawa groundwater allocation zones that are vertically below the AC volcanic allocation zones (Figure 5.3).

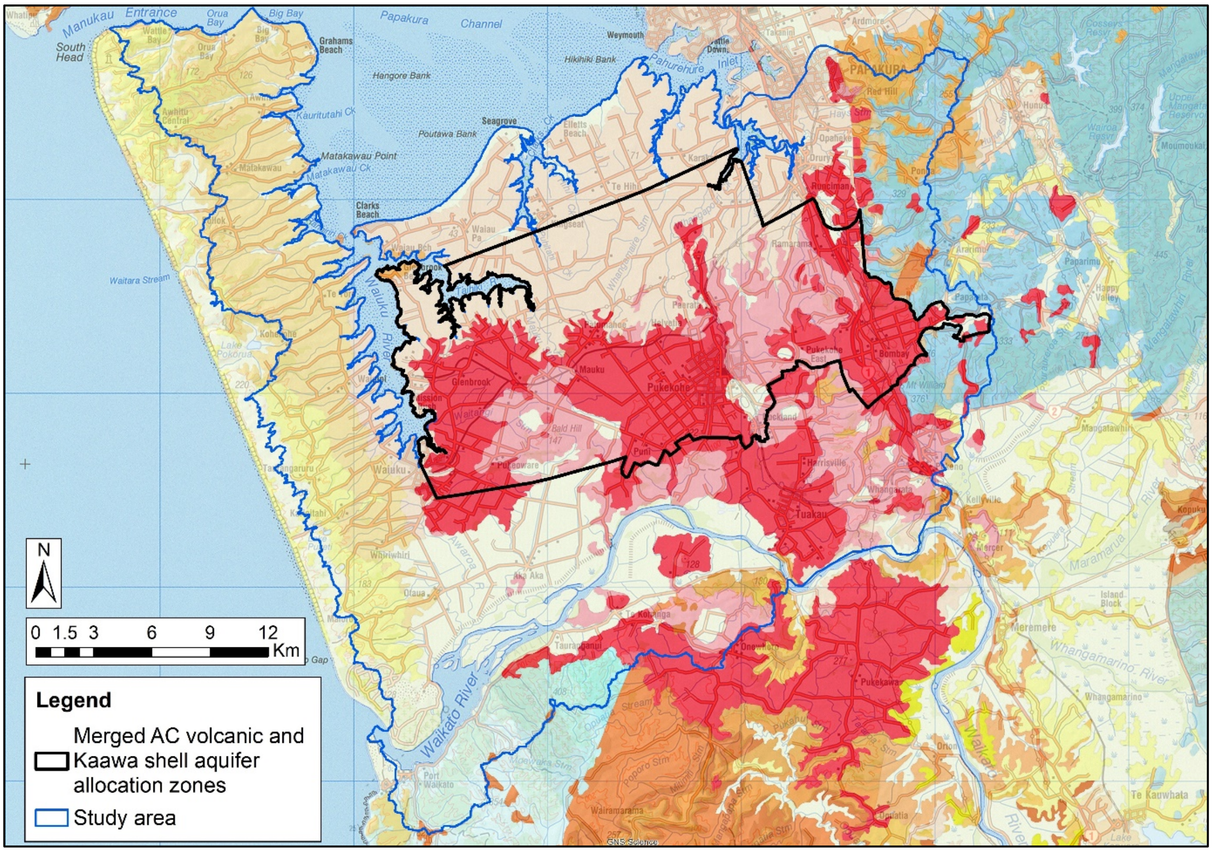

Figure 5.5 Extent of AC volcanic allocation zones and Kaawa groundwater allocation zones (part). This polygon is the union of Figure 5.3 and Figure 5.4.

5.6.2 Sustainability of Current Groundwater Allocation Limits and Currently-Consented Groundwater Allocation

Groundwater allocation in the study area appears sustainable at the scale of the allocation zones because:

- current AC and WRC groundwater allocation limits (Table 5.3 and Table 5.4) are less than average $Q^{GW}{}_{D}$, i.e., 273 +/- 108 mm/year (Table 5.2);
- current AC and WRC consented groundwater allocation (Table 5.3 and Table 5.4) are also less than average $Q^{GW}{}_{D}$, i.e., 273 +/- 108 mm/year (Table 5.2); and
- stream flow and stream baseflow shows no trends of decline over time (Section 4.7.1).

However, this report does not account for unconsented water takes as allowed under permitted activity rules or RMA s14(3)(b).

These findings indicate that AC groundwater allocation (i.e., groundwater availability and consented allocation) comprise less than 18% of average $Q^{GW}{}_{D}$ (from Table 5.3). Therefore, the AC groundwater allocation regime is conservative, because groundwater allocation is within the fractional allocation of $Q^{GW}{}_{D}$ (i.e., 50%) that was used in PC9 (Bay of Plenty Regional Council 2016); PC9 is viewed as having a conservative approach to groundwater allocation.

WRC's approach to groundwater allocation management in less conservative than that of AC, i.e., Management Levels are less than 55% of average $Q^{GW}{}_{D}$ (from Table 5.4).

5.7 Sustainability of Groundwater Use

Stream baseflow shows no trend of decline over time (Section 4.7.1). Therefore, stream baseflow is not impacted by any increase of groundwater use over the period of the stream-flow time series. Groundwater level trends for the period 2006 to 2016 were reported in Kalbus et. al. 2017 and show either positive or no discernible trends in all bores, with three exceptions. This indicates a sustainable water use regime for most of the Franklin groundwater resource. The three bores which show negative level trends are located in Waitemata geology in the Karaka and Waiau Pa Waitemata aquifer management areas. Previous work (Sinclair Knight Merz 2010) was unable to differentiate between climate and water use as the predominant drivers of water level declines.

Evidence for relatively low groundwater levels reported in 1974, see above, may indicate that groundwater storage is declining over time. However, these low levels may have been caused by the 1973/1974 drought and may not be due to groundwater use.

5.8 Groundwater Quality

Historically, nitrate-nitrogen concentrations in the volcanic aquifers have been high (Section 2.4). Today, concentrations in the basalt aquifers, and springs that discharge from basalt, typically remain high with most measurements showing significant increases in recent times (Section 4.6 and Section 4.7.2). Land use provides the high NO_3-N concentrations in the volcanic aquifers and spring-fed streams. The effect of land use on water quality (groundwater and springs) has been generally increasing over time, and in most cases this effect shows no sign of abating. However, nitrate-nitrogen concentrations decreased in one well that takes water from basalt (61–208), Figure 4.17. This decline in concentration may be caused by a decrease in land-use intensity over time in the groundwater catchment of the well.

Groundwater chemistry measurements by AC show a bi-modal distribution of nitrate-nitrogen. Here, high nitrate-nitrogen concentrations are associated with high DO concentrations, i.e., oxygenated basalt aquifers (Table 4.11). These aquifers are the source of spring flow, as demonstrated by high DO concentrations in springs. Low DO, and low nitrate-nitrogen, groundwaters are typical in deep groundwater (e.g., part of the basalt aquifer, the Kaawa Formation and basement; Table 4.11; Figure 4.24 and Figure 4.18). Therefore, redox processes in deep aquifers may mitigate high nitrate-nitrogen concentrations in recharging groundwater.

Down-stream effects of land use on surface water quality and stream ecology are possible, as the nitrate-nitrogen concentrations in springs are typically higher than 6.9 mg/L, i.e., higher than the National Objectives Framework for nitrate toxicity values in lakes and river environments (Ministry for the Environment 2017), Figure 4.16. Concentrations observed in the springs are much higher than concentrations in other surface water bodies in New Zealand that have led to environmental protection and restoration projects (e.g., Lake Taupo and Lake Rotorua, respectively).

Anoxic conditions were indicated by iron and oxygen concentrations in some wells that take water from basalt, Kaawa shell and basement/Waitemata sandstone (Sections 4.6 and 4.7.2; and Appendix 2). Therefore, groundwater chemistry does not have a simple relationship to land use in the study area and future assessments of land use and water quality must consider ambient groundwater chemical conditions.

5.9 Uncertainty

All environmental measurements have an element of uncertainty. An analysis of uncertainty of the water budget components can provide a useful context for decision-making associated with allocation; this analysis is recommended (Section 6.5). A conservative allocation regime is an appropriate way to build uncertainty into decisions that are based on environmental data. For example, the current AC regime is conservative (Section 5.6.2).

6.0 RECOMMENDATIONS

6.1 Geology

Further assessments of the 3D geological model will offer insights into the depositional history of volcanic and shell deposits in the study area (Section 5.1). Aims of this work could include a new classification of the volcanic aquifers that identifies:

- sources of volcanic deposits, combining the surface mapping of Taylor (2012, e.g., Figure 2.1) and the 3D geological model described in this report;
- vertical zonation of eruptive deposits, further developing the current understanding of volcanic sources, e.g., the ‘upper’ and ‘lower’ volcanic aquifers, with multiple eruptive phases, sourced from the Pukekohe volcanic centre (Figure 4.4); and
- refinement of the volcanic aquifer management areas.

Further assessment of the 3D distribution of shells is also recommended because multiple contiguous shell deposits were observed in the study area and these deposits may host separate aquifers. This assessment could focus on:

- layering of Pleistocene shells (e.g., Figure 4.11). The distribution of peat deposits is relevant to this analysis (Figure 4.13);
- assembling evidence for, or against, Holocene shell aquifers located on the south coast of Manukau Harbour and the Waikato River Valley (Figure 4.2 and Figure 4.3); and
- refinement of the shell aquifer management areas.

6.2 Groundwater Elevation Maps

Groundwater-level maps have multiple applications to groundwater investigations and to groundwater allocation, including:

- characterisation of the geographical location of aquifers;
- identification of vertical separation of aquifers and the hydraulic interaction between aquifers (Section 5.1);
- identification of groundwater flow directions relevant to assessment of groundwater-surface water interaction;
- identification of groundwater catchment boundaries, including groundwater divides with application to the definition of groundwater allocation zone boundaries.

The latest groundwater level maps are those of Viljevac, et al. (2002), Figure 2.4 and Figure 2.5. Revision of these maps using recent data is recommended. These revisions could consider:

- multiple volcanic aquifers. This report identified multiple deposits from volcanic eruptions (Figure 4.4). Multiple volcanic aquifers have been identified by Auckland Regional Water Board and Waikato Valley Authority (1977), Viljevac (1996) and White et al. (1996);
- Holocene shell aquifers that are hydrogeologically distinct from Kaawa shell aquifers;
- the findings from 3D geological modelling in this report which identified multiple Kawa shell aquifers.

As a first step, hydraulic heads in well could be attributed to lithology using well depths and the 3D model. Then, hydraulic heads in groups of wells could be interpreted in terms of potential distributions of aquifers. These maps could be used as part of the information that is relevant to the definition of groundwater zones, see following.

6.3 Rainfall Recharge Measurement

Importantly, the rainfall recharge observations at the Karaka recharge site indicate that measured rainfall recharge is larger than other rainfall recharge estimates (Table 6.1).

Long-term measurements are very important in the assessment of rainfall recharge (e.g., White et al. 2003). However, the Karaka rainfall recharge record is short and the site function has been interrupted by flooding (Section 3.3.3). The ongoing monitoring and compilation of a long-term dataset at the Puni rainfall recharge site is important as this site aims to measure rainfall recharge through soils derived from volcanic parent material.

Therefore, continued measurement of rainfall recharge at Karaka and Puni is recommended. Ideally, a 10-year record of rainfall recharge should be collected at these sites. This record will provide better statistics of long-term rainfall recharge, and ground-level rainfall that will be useful to water-resource investigations and water management including: the provision of better estimates of long-term rainfall recharge for water-allocation purposes; informing policies on council fractional allocation of Q^{GW}_{OUT}; calibration of water resources models in the area (see following); assessment of any long-term effects of climate change on rainfall recharge; and assessing water quality in rainfall recharge which is relevant to land use and water quality studies.

Table 6.1 Rainfall recharge (RR) estimates described in this report.

Method	**Predominant Geology in the Catchment of the Site**	**RR (mm/year)**	**Standard Deviation (mm/year)**	**Source**
Karaka site: annualised measured	Sedimentary	819	121	Table 4.6
Steady-state water budget	Mixed catchments	485	48	Table 4.4
Soil moisture measurements	Volcanics	680	na	Rosen et al. (2000), Table 2.1

6.4 Assembly of Time-series Data and Trend Analysis

Further trend analysis would be useful to the understanding of the groundwater-surface water system. With this aim, records of surface water flows, groundwater use and groundwater level could be assembled and analysed.

Continuous surface flow measurements in catchments that are sediment-dominated are recommended (Section 5.3). A purpose of these sites is to measure long-term flows and calculate better estimates of Q^{SW}_{QF} and Q^{SW}_{BF} than are currently available. Suggested locations for potential sites include:

- Awhitu Peninsula in Pliocene Awhitu Group sediments that are part of the Manukau Harbour Watershed (Figure 1.1);
- south of Waiuku in the Waikato River catchment;
- the vicinity of Karaka and the AC rainfall recording site at Karaka (Figure 3.2) in Pliocene Puketoka Formation (Edbrooke 2001; Section 3.3.4).

One site may be sufficient to represent flows in sediment-dominated catchments because key flow indicators (i.e., Q^{GW}_{OUT}, RR and BFI) are similar across Awhitu Group sediments and Puketoka Formation sediments (Table 4.2, Table 4.4 and Table 4.8, respectively). Ideally, the new site (or sites) should be located to minimise tidal influence on the stage record.

Records of water use (groundwater and surface water) could be assembled for time series analysis of flows in selected streams and analysis of groundwater level in wells. Criteria for selecting streams include: availability of continuous flow records; predominate catchment geology, with an aim to select a representative stream in volcanic-dominated and sedimentary-dominated; and region, with an aim to select representative streams in each region.

Selected wells could be representative of the various aquifer types, e.g.:

- shallow volcanic aquifers that discharge groundwater to surface water;
- deep volcanic aquifers that discharge groundwater to sedimentary aquifers;
- shallow Kaawa shell aquifer;
- deep Kaawa shell aquifer;
- AC region;
- WRC region;
- coastal aquifers, e.g., possible Holocene shell aquifer on the southern coast of Manukau Harbour (Figure 4.3).

Trend analysis could aim to assess the major stream flow components (i.e., Q^{SW}_{QF} and Q^{SW}_{QF}) and identify the relation between cause (e.g., groundwater use, surface water use and climate patterns) and effects on stream flow and groundwater level. In this regard, transient environmental data would be useful to characterise the drivers of groundwater system behaviour, see the following section.

6.5 Transient Environmental Data Sets

A transient model of recharge could be a useful next step in the characterisation of groundwater resources in the study area, following Viljevac (1996). This model could also be a key part of a transient groundwater flow model that would have multiple uses including assessment of:

- the boundaries of groundwater catchments;
- the interaction between groundwater and surface water;
- climatic trends over the long term and effects on groundwater recharge;
- the response of groundwater levels to seasonal variability of rainfall recharge;
- the response of surface flows to seasonal variability of rainfall recharge;
- effects of climate change on rainfall recharge and stream flow; and
- the uncertainty of model parameters and relations between parameter uncertainty and model predictions.

6.6 Groundwater Allocation Zone Boundaries

It is recommended that AC and WRC organise a joint approach to groundwater allocation in the study area to ensure a consistency of approach by the two councils (Section 5.4). Considerations for the location of allocation boundaries could include:

- current groundwater allocation and surface water allocation boundaries (e.g., Figure 5.1);
- boundaries of the regions and surface catchments, aiming to design zones that include surface waters and groundwaters;
- groundwater catchment boundaries identified with revised piezometric maps (Section 6.2);
- surface catchments defined from DTMs;
- groundwater-surface water catchments, i.e., consider the groundwater catchments of spring-fed streams and the surface catchments of streams;
- separate allocation zones for aquifers within the framework of groundwater-surface water catchments, e.g.: allocation to volcanic aquifers within zones that include recharge sources (i.e., rainfall) and discharge to spring-fed streams; and allocation to Kaawa shell aquifers within zones that include recharge sources (e.g., volcanic aquifers and rainfall recharge).
- the water budgets (including surface water flows) of groundwater-surface water catchments;
- 3D location of aquifers, and vertical zonation of aquifers as described in this report.

The sub-surface boundary between volcanics and sediments (‘V1’, Figure 6.1) provides evidence for a northern structural boundary between Pleistocene volcanics and sediments. This possible boundary may have relevance to the identification of allocation zone boundaries because it potentially marks a major lateral permeability gradation across potential allocation zones.

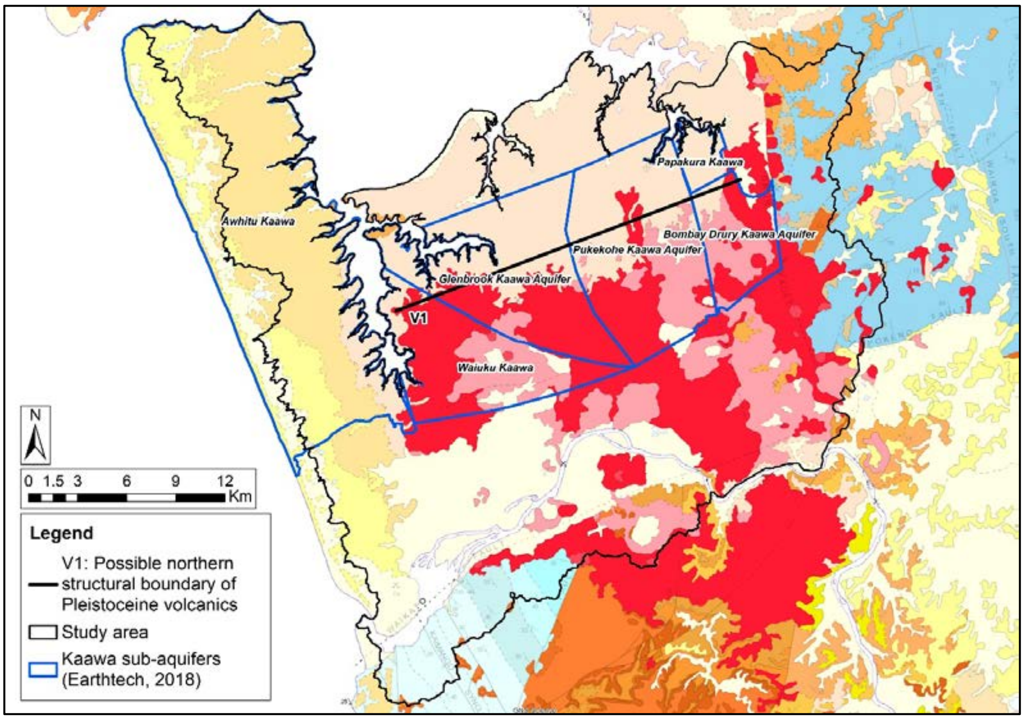

Figure 6.1 The V1 line, denoting the approximate northern boundary of Pleistocene Pukekohe volcanics and the northern extents of AC Kaawa shell aquifer groundwater allocation zones.

6.7 Groundwater Allocation

A groundwater allocation regime integrated across AC and WRC is the next logical step after the design of groundwater allocation zones across the two regions (Section 6.6). The needs for a new regime are not pressing, in regards of the water resource, because evidence suggests the groundwater resources in the area are being sustainably managed.

Considerations for the quantum of allocation include:

- the water budget calculations of measured rainfall, evapotranspiration, shallow groundwater flow and deep groundwater flow, as described in this report;
- provision for the preservation of baseflow, as per Bay of Plenty Regional Council's Plan Change 9 (Bay of Plenty Regional Council 2016);
- key policy decisions by the councils on the proportion of groundwater to allocate, e.g., the general approach of PC9 is to limit groundwater allocation to 50% of Q^{GW}_D (with provisos and provisions, e.g., prevention of sea water intrusion);
- surface water allocation;
- effects of climate change;
- the risks of salt water intrusion.

6.8 Water Chemistry and Land Use

DO is an important indicator of oxic and anoxic conditions in aquifers that has shown the potential to separate 'shallow' basalt aquifers from 'deep' basalt aquifers (Sections 4.6 and 4.7.2). However, few wells have good records of DO. Therefore, more DO measurements in groundwater are recommended in the study area to better characterise the groundwater circulation system.

Shallow and deep groundwater systems have been recognised in the basalt aquifers for many years. This report adds to this knowledge including: geological modelling, water budgets that separate shallow groundwater flows from deep flows; and water chemistry that identifies shallow, oxygenated water as the source for springs.

Further work on the characterisation of the shallow system with water chemistry is recommended to characterise the shallow and deep systems and better characterise the catchments of spring-fed streams. Specific tasks may include the compilation of water quality data and/or new groundwater chemistry testing of wells in the study area. This work is relevant to water allocation, by providing a better understanding of water budget components, and to the effects of land use on water quality by characterising the 3D catchments of springs.

Characterisation of the deep system (i.e., deep volcanics and Kaawa) using groundwater chemistry is also recommended. For the Kaawa, this characterisation may result in identification of separate circulation systems in Pleistocene shells and Holocene shells, and in the identification of separate aquifers with Kaawa shells (see also Section 6.1). This would include the compilation of historic data and addition of new chemistry data where required.

Nitrate-nitrogen concentrations remain high in the surface and groundwaters in the study area. It is recommended that technical work is undertaken that could lead to improvements to water quality in spring-fed streams, and the catchments of these streams. 3D catchment identification is the first step in making improvements to water quality. Then, land use could be identified in these catchments. Water and land policies could be developed to begin to reduce nitrate-nitrogen concentrations in groundwater and nitrate loading to springs.

6.9 Sustainability Studies

Sustainability studies could include regular monitoring of key sustainability indicators:

- water budget component trends over time: rainfall, rainfall recharge, evaporation, spring flow, and groundwater use;
- groundwater level trends over time. More work is required to investigate impacts on Waitemata aquifers where declining trends in groundwater level have been observed in the Papakura Kaawa allocation zone (Sinclair Knight Merz 2010), Section 5.7;
- groundwater chemistry – is the oxic/anoxic boundary stable over time and will the boundary prevent nitrate entering the deeper aquifers? – is groundwater salinity increasing near the coast?
- spring water chemistry;
- groundwater availability and consented groundwater allocation.

Land use and water quality studies are also relevant to the sustainability of the groundwater/fresh water system in the Franklin area, e.g.:

- one useful preliminary study could aim to identify causation of nitrate-nitrogen trends in groundwater over the long term, e.g., site 61-126 where nitrate-nitrogen concentrations have declined from high levels since 2010 (Section 4.7.2) and sites where nitrate-nitrogen concentrations have been increasing over time, e.g., 61-135, 61-54, 61-761, 61-85 and 7419121 (Figure 4.17);
- monitoring of nitrate-nitrogen and DO in groundwater and surface water;
- identifying trends in land use.

7.0 CONCLUSIONS

Auckland Council's (AC's) Natural Environment Strategy Unit, with staff from AC Regulatory Services, Healthy Waters, and the Research and Evaluation Unit, identified the future needs of groundwater in the region with groundwater scientists from GNS Science and Earthtech Consulting Ltd (Earthtech) in a May 2018 workshop. Subsequent discussions between AC and Waikato Regional Council (WRC) established that an assessment of groundwater availability in the Franklin area was a common interest of both councils.

Groundwater resource investigations from the 1970s by both regional councils, and antecedent organisations have developed much information about the groundwater system which principally consists of aquifers in volcanic (largely basaltic) and sedimentary (i.e., shells and sand) lithologies. For AC, this work culminated in Viljevac et al. (2002) which set the current groundwater allocation regime for the area. This regime, however, attracted some comment from Earthtech (2013) who recommended a recharge mechanism to deep aquifers that differed from that of Viljevac et al. (2002). For WRC, recent work in the area includes the Healthy Rivers Project, which summarised groundwater resource and groundwater quality in the area (White et al. 2015).

This report produces new interpretations of the geology and water budgets of the Franklin groundwater system by combining AC data, collected and collated since the work of Viljevac et al. (2002), with WRC data including White et al. (2015). This data includes the new digital terrain models (AC and WRC), a digital geology map (Heron 2014), a new well log database, national digital maps of long-term average rainfall and actual evaporation (Tait et al. 2006; Woods et al. 2006), measurements of rainfall recharge at AC's Karaka rainfall recharge site, stream-flow measurements (AC and WRC), and groundwater chemistry measurements (AC and WRC).

The three-dimensional distribution of three key lithologies (i.e., volcanic rocks, shells and organic-rich sediments) was calculated from the well log database. For example, volcanic lithologies occur in four major groupings (i.e., Bald Hill area, Pukekohe, Bombay and the base of the Hunua Range). Multiple shell bodies were modelled that corresponded to Kaawa aquifers (mainly) and possibly Holocene aquifers.

Groundwater flows were assessed with water budgets in representative catchments and measurements of rainfall recharge at an AC rainfall recharge site located at Karaka. Primarily, water budgets aimed to calculate rainfall recharge and estimate groundwater outflow that supports stream baseflow ('shallow' groundwater flow) and 'deep' groundwater flow that travels beyond the shallow circulation systems. Water budgets, calculated as long-term mean and median flow, were expressed in units of flow rate (e.g., m^3/s) and as specific discharge (i.e., mm/year averaged across the catchment).

Shallow groundwater flow was a mean of 211 mm/year in representative catchments (Table 4.2). This flow provided the most significant component of stream flow as demonstrated by a baseflow index that averaged 0.87 in streams with continuous flow measurements.

Deep groundwater flow was an average of 273 mm/year in representative catchments (Table 4.2) and is larger than AC's and WRC's groundwater allocation limits, which are larger than current allocation. This comparison indicates that current allocation is sustainable, which is in agreement with a time-series analysis that found no measurable long-term trend of declining stream baseflow over time.

High nitrate-nitrogen concentrations were measured in the basalt aquifer and in springs that discharge from this aquifer, which is consistent with observations of groundwater quality in the area noted from the 1990s. Two aquifers in basalt lithologies were identified, consistent with earlier research in the Pukekohe area:

- shallow, oxic groundwater with high nitrate-nitrogen concentrations that discharges to springs; and
- deep, anoxic groundwater that flows to the deeper Kaawa Formation.

Nitrate-nitrogen concentrations in shallow basaltic aquifers were generally increasing over time and concentrations were consistently higher than the drinking-water standard of 11.3 mg/L and an environmental standard of 6.9 mg/L. The deep aquifers (i.e., deep basalt, Kaawa and basement) were identified by anoxic groundwater and consequent low nitrate-nitrogen concentrations.

This study has presented several findings which are useful to direct further efforts in aquifer research for the Franklin area. The strong research management driver for this work can be addressed at a high level by noting conclusions regarding groundwater availabilities and management regimes:

- Groundwater allocation appears to be sustainable in shallow aquifers that support baseflow to streams due to a lack of significant declining trends in surface water flows and baseflow and the large proportion of deep groundwater recharge.
- Groundwater allocation also appears to be sustainable in deeper aquifers as the total amount of water allocated is less than the amount of water that contributes to deep recharge and is less than the 50% recharge limit applied by PC9.
- Geological data suggest that refinement of aquifer management area boundaries is warranted to reflect new understanding of the distribution of geological facies, particularly for shell units and the Pukekohe basalts.
- The respective management approaches applied by AC and WRC are incongruent and a consistent approach to management of the resource by the two regional councils is recommended.
- Discrete areas with declining groundwater trends like the Karaka and Waiau Pa Waitemata aquifer management areas require further analysis to isolate potential causes of the declines and may require management actions outside the generally sustainable approach that has been applied across the Franklin area.
- Elevated nitrate-nitrogen in shallow volcanic aquifers remains an issue. With no change in land use practices, high concentrations of nitrate-nitrogen in streams will remain due to the high baseflow component of streamflow. Nitrate contamination is independent of water quantity management.
- Ongoing measurement of rainfall recharge at AC lysimeter sites is important to build knowledge of groundwater recharge and inform further refinement of the allocation regime

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APPENDICES

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APPENDIX 1 STATISTICS FOR THE AC GAUGING SITES

Site ID	Site	NZTM E	NZTM N	Start Date	End Date	Number of Measurements	Mean Flow (m^3/s)	Median Flow (m^3/s)	Standard Deviation	BFI (Equation 5)
43505	Kaurituтahi @ Awhitu Road	1751247	5877494	10/01/2003	14/02/2006	23	0.057	0.041	0.062	0.72
43602	Waitangi @ S H Bridge	1755195	5878315	16/06/1980	23/05/1985	24	1.672	0.471	1.853	0.3
43603	Waitangi Stream @ Waiuku Rd Br.	1757645	5878405	21/07/1971	13/12/2004	43	0.034	0.028	0.033	0.8
43604	Waitangi Stream @ Neil Morley Road Culvert	1755644	5879302	21/07/1971	30/01/2001	39	0.028	0.027	0.025	1.0
43605	Ruakohua @ Mission Bush Rd	1754042	5880399	22/12/1999	15/02/2005	38	0.020	0.014	0.019	0.7
43606	Waitangi Trib @ Glenbrook Vintage Railway Totara	1756544	5879003	23/12/1999	15/02/2005	32	0.033	0.025	0.032	0.8
43607	Waitangi @ Glenbrook Vintage Railway Culvert	1756445	5878703	23/12/1999	15/02/2005	30	0.051	0.034	0.055	0.7
43611	Ohiku @ Lees Gully Road	1748033	5885687	10/01/2003	14/02/2006	25	0.052	0.031	0.071	0.6
43612	Te Hakono Ck @ Awhitu Road	1749338	5882890	10/12/2002	14/02/2006	27	0.034	0.024	0.038	0.7
43703	Te Hihi Stream @ Raupo	1761324	5889812	6/03/1970	10/07/1973	18	0.034	0.021	0.027	0.6
43704	Te Hihi Stream @ Gumtree	1761424	5889912	16/04/1973	12/12/1979	18	0.054	0.017	0.063	0.3
43705	Mauku Stream @ Swede (Patullo Rd Br)	1759660	5883507	20/02/1970	17/02/2005	128	0.336	0.189	0.392	0.6
43706	Mauku Stream @ Days Road	1761039	5881812	22/01/1976	11/12/1979	24	0.024	0.019	0.021	0.8
43707	Mauku Stream @ Puni (Aka aka Rd Br)	1764148	5877017	22/01/1976	15/02/2005	100	0.043	0.033	0.036	0.8
43708	Mauku River @ Titi Road	1760742	5880211	22/01/1976	15/02/2005	48	0.153	0.110	0.181	0.7
43709	Mauku Tributary @ Gravestone	1759434	5884309	2/02/1977	30/03/1978	22	0.037	0.014	0.053	0.4
43712	Taihikiki Stream @ Wymers Road	1756536	5883503	22/03/1983	22/03/1983	1	0.001	Insufficient data available		
43713	Mauku Trib @ Pilgram Road.	1760641	5880511	28/02/1996	28/02/1996	1	0.086	Insufficient data available		
43714	Puhitahi Stream @ Kingseat Road	1759227	5888408	11/12/2001	20/02/2002	4	0.074	0.037	0.062	0.5
43715	Speedy Stream @ Glenbrook Road	1758035	5883906	6/12/2001	20/02/2002	5	0.038	0.032	0.018	0.8
43806	Hingaia Stream @ Ingrams Road	1775434	5884438	13/03/1959	1/03/1962	4	0.069	0.069	0.029	1.0
43810	Maketu Stream @ Rimu Stand	1777028	5887741	14/11/1969	26/09/1974	37	0.124	0.057	0.202	0.5
43811	Whangamaire @ Patumahoe Weir	1763321	5882374	17/06/1976	5/03/2014	42	0.143	0.122	0.074	0.9
43812	Whangapouri Stream @ Pines	1768026	5888625	23/07/1971	15/03/2001	37	0.036	0.022	0.043	0.6
43813	Whangapouri Stream @ Effluent	1766328	5887521	23/07/1971	19/02/2002	42	0.100	0.081	0.097	0.8
43814	Whangamaire @ Fantail (Charles Rd)	1765325	5889119	22/07/1971	17/02/2005	80	0.187	0.173	0.102	0.9
43815	Oira Stream @ Swing Bridge	1770325	5889529	23/07/1971	30/03/1978	15	0.104	0.040	0.112	0.4
43816	Maketu Stream @ Peach Hill	1777927	5888443	25/10/1972	17/09/1991	11	0.031	0.025	0.025	0.8
43817	Maketu Stream @ Lambrecht	1778327	5888244	25/10/1972	18/01/1974	12	0.024	0.023	0.012	1.0
43818	Ngakoroa Stream @ Weedy.	1772523	5890433	14/11/1969	20/02/1970	4	0.056	0.041	0.047	0.7
43819	Whangapouri Stream @ Railway Bridge	1768535	5883825	14/07/1982	2/02/1983	6	0.203	0.214	0.04	1.1
43821	Whangapouri Stream U/S Hickeys Spring	1768639	5882026	20/01/1976	15/03/1977	9	0.010	0.012	0.004	1.2
43822	Whangapouri Stream @ Hickey Spring	1768638	5882226	8/01/1976	20/03/2003	21	0.091	0.077	0.064	0.8
43823	Ngakoroa Stream @ S H 1	1776441	5880740	10/11/1976	4/05/1979	7	0.017	0.008	0.018	0.5
43824	Hingaia Stream @ Stones Road.	1776534	5884440	8/02/1983	11/02/1998	17	0.063	0.048	0.086	0.8
43825	Whangapouri Stream @ Gun Club Road	1765738	5882120	20/01/1976	16/05/1986	7	0.016	0.012	0.012	0.8
43826	Oira Stream Sth S.H.22 @ Karaka	1770324	5889829	9/10/1978	25/11/1997	15	0.069	0.036	0.065	0.5
43827	Ngakoroa Stream @ Razorback Road	1777541	5880742	14/03/1978	14/03/1978	1	0.004	Insufficient data available		
43828	Ngakoroa Stream @ Beaver Road.	1777141	5880641	14/03/1978	4/05/1979	3	0.010	0.011	0.006	1.1
43829	Ngakoroa Stream @ Mill Rd	1775153	5881619	28/03/1980	5/06/2018	74	0.124	0.061	0.151	0.5
43830	Ngakoroa Stream G No 1 Beaver Road	1776542	5880240	14/03/1978	14/03/1978	1	0.000	Insufficient data available		
43831	Ngakoroa Stream @ No 2 Beaver Road.	1777041	5880641	14/03/1978	14/03/1978	1	0.001	Insufficient data available		
43832	Whangapouri Stream 230ft U/S Spring	1768638	5882226	3/02/1976	11/12/1979	2	0.099	Insufficient data available		
43833	Whangapouri Stream 500FT U/S Spring.	1768538	5882225	3/02/1976	11/12/1979	2	0.104	0.104	0.113	1.0
43835	Oira Stream @ Bluff Hill Road	1769933	5885228	17/02/1972	11/12/1979	5	0.022	0.007	0.022	0.3
43836	Ngakoroa Stream @ Masters Fence.	1776539	5881940	13/02/1979	10/04/1992	4	0.006	0.002	0.009	0.3
43837	Ngakoroa @ Raventhorpe	1775034	5884538	7/03/1979	5/01/1998	7	0.081	0.055	0.044	0.7
43838	Ngakoroa Stream @ Kerns Road.	1773430	5886535	4/05/1979	28/03/2008	29	0.111	0.095	0.062	0.9

Site ID	Site	NZTM E	NZTM N	Start Date	End Date	Number of Measurements	Mean Flow (m^3/s)	Median Flow (m^3/s)	Standard Deviation	BFI (Equation 5)
43839	Ngakoroa Stream @ Mill Rd No 1	1752838	5882397	4/05/1979	4/05/1979	1	0.001	Insufficient data available		
43840	Whangapouri Creek @ Blackbridge road.	1768322	5890725	27/06/1979	27/06/1979	1	0.733	Insufficient data available		
43841	Hingaia Stream @ Gt Sth Rd	1773121	5891634	27/06/1979	29/01/2002	18	0.397	0.318	0.256	0.8
43842	Hays Stream @ Ponga Road Opaheke	1773416	5894235	27/06/1979	27/06/1979	1	0.207	Insufficient data available		
43843	Symonds Stream @ Suttons Rd	1773718	5893135	27/06/1979	27/06/1979	1	0.115	Insufficient data available		
43844	Hingaia Stream @ Log	1776634	5884641	16/01/1973	23/02/1998	15	0.071	0.058	0.037	0.8
43845	Hayes Stream @ Ford	1776714	5895141	25/10/1972	17/01/1974	10	0.040	0.023	0.045	0.6
43846	Hingaia Stream @ Bridge	1775434	5884438	6/03/1974	6/03/1974	1	0.174	Insufficient data available		
43847	Oira Stream @ S.H.22 Bridge	1770524	5889929	17/08/1955	8/03/2000	17	0.032	0.020	0.048	0.6
43848	Oira Stream @ Postles	1770334	5884729	17/02/1972	17/02/1972	1	0.016	Insufficient data available		
43851	Hingaia Stream @ Quarry Road	1774425	5889637	8/02/1983	23/02/1998	15	0.305	0.216	0.219	0.7
43852	Whangamaire Stream @ Ostrich Road	1763534	5884616	5/11/1982	18/02/1998	16	0.114	0.138	0.06	1.2
43854	Drury Creek @ Hingaia Bridge	1768516	5893826	27/06/1979	27/06/1979	301	0.163	0.174	0.087	1.1
43855	Whangapouri Stream @ Sandstone Bed	1766827	5888122	10/10/1980	17/02/2005	39	0.288	0.279	0.117	1.0
43859	Maketu Stream @ Ramarama Road Bridge	1775728	5888039	8/02/1983	26/01/1984	3	0.057	0.023	0.061	0.4
43861	Whangamaire Stream @ Hunters Road.	1763238	5882516	3/03/1983	3/03/1983	1	0.084	Insufficient data available		
43862	Whangamaire Stream @ Mansells	1766123	5890621	3/03/1983	14/02/1984	3	0.107	0.112	0.012	1.0
43863	Whangamaire Trib @ Glenbrook Road	1764529	5887018	16/02/1982	17/03/1983	5	0.110	0.117	0.07	1.1
43864	Hingaia Stream @ Youngs Pond.	1776834	5884441	24/02/1983	18/02/1997	4	0.330	0.231	0.352	0.7
43865	Hingaia Stream @ Trib Junction	1775125	5889338	1/03/1983	1/03/1983	1	0.018	Insufficient data available		
43869	Ngakoroa Trib @ Great South Road	1776238	5882640	28/02/1983	28/02/1983	1	0.000	Insufficient data available		
43870	Ngakoroa Trib @ Hoods	1772936	5883634	28/02/1983	28/02/1983	1	0.003	Insufficient data available		
43871	Whangamaire Trib @ Glenbrook Road.	1765229	5887019	8/11/1982	8/11/1982	1	0.000	Insufficient data available		
43872	Ngakoroa Stream @ Runciman Rd Bridge	1772926	5889133	7/03/1985	26/11/2003	69	0.194	0.132	0.181	0.7
43873	Ngakoroa Stream @ Ross Dear Farm Junction	1772625	5889133	7/03/1985	1/12/1997	2	0.118	Insufficient data available		
43878	Hayes Stream @ Waterfall Above Quarry	1778415	5894645	5/03/1990	5/03/1990	1	0.004	Insufficient data available		
43879	Hayes Stream @ Winstones Quarry	1777415	5894643	5/03/1990	5/03/1990	1	0.007	Insufficient data available		
43880	Maketu trib @ Peach Hill Rd	1775784	5887939	13/11/1991	14/08/1992	3	0.059	0.028	0.069	0.5
43883	Hingaia @ Stone Road #2 (main & spring)	1776734	5884641	17/12/1991	26/03/2008	30	0.153	0.128	0.115	0.8
43884	Hingaia Trib @ Sawyer Road	1779337	5889346	17/12/1991	4/03/1996	9	0.045	0.043	0.019	1.0
43885	Hingaia Trib @ Paparata Road	1779337	5882946	10/09/1991	23/02/1998	19	0.046	0.034	0.043	0.7
43886	Oira Trib @ Burtt Road Bridge	1770032	5885428	18/01/1991	14/03/2001	20	0.013	0.010	0.013	0.8
43889	Hingaia Trib @ Cascades Road	1778835	5884345	6/04/1993	11/01/1998	4	0.049	0.051	0.018	1.0
43890	Whangapouri @ Paerata Falls	1768434	5884425	28/03/1994	11/05/1994	2	0.119	Insufficient data available		
43891	Waihoihoi Trib @ Cossey RD	1775320	5891938	11/05/1994	11/05/1994	1	0.006	Insufficient data available		
43892	Waihoihoi Trib @ Drury Hills Road	1775821	5891339	29/03/1994	29/03/1994	1	0.030	Insufficient data available		
43893	Hingaia Trib @ Farr Road	1780037	5883346	16/12/1991	17/03/1994	2	0.008	Insufficient data available		
43895	Whangapouri Stream @ Glenbrook Rd Bridge	1766928	5887822	5/02/2003	20/03/2003	3	0.208	Insufficient data available		
43896	Whangapouri Stream @ Glenbrook Road	1766428	5887522	5/02/1991	1/03/1994	4	0.249	0.238	0.113	1.0
43897	Sutherlands Trib @ Gt Sth Rd Culvert	1776117	5882041	10/02/1994	10/02/1994	1	0.002	Insufficient data available		
43898	Maketu trib @ Davis Road	1776128	5887840	24/09/1991	24/09/1991	1	0.004	Insufficient data available		
43968	Whangapouri @ Paerata Rise	1768327	5887871	19/09/2018	11/12/2018	5	0.018	0.010	0.019	0.6
434111	Tutaenui Trib at Buckland Road	1770444	5879029	6/12/2001	19/02/2002	6	0.055	0.055	0.023	1.0
434112	Tutaenui Trib at Railway	1770744	5879029	6/12/2001	19/02/2002	7	0.094	0.072	0.058	0.8
1043803	Waihoihoi @ Appleby Rd	1774820	5892038	16/12/1999	28/03/2008	31	0.028	0.015	0.038	0.5
1043804	Waihoihoi @ Sutton Rd	1773818	5893036	16/12/1999	28/03/2008	12	0.081	0.056	0.084	0.7
43811G	Whangamaire @ Patumahoe Railway Culvert	1763238	5882316	20/01/1976	26/03/1976	6	0.121	0.113	0.047	0.9
43829G	Ngakoroa Stream @ Mill Rd	1775199	5881562	14/03/1978	4/05/1979	3	0.037	0.042	0.028	1.1

APPENDIX 2 WATER CHEMISTRY STATISTICS IN SPRINGS AND WELLS INCLUDING TREND ANALYSIS

Time intervals for the data are:

- Auckland region: 4/12/1996 to 12/04/2018
- Waikato region: 2/04/1987 to 17/03/2015

This table includes the results of the trend analysis (e.g., AnnualSenSlope.x and Intercept.x).

Regional Council	Type	Site	Parameter	Median	MAD	Censoring	#res	Kw p-value	AnnualSenSlope.x	Intercept.x	Mk p-value	Aquifer
AC	Spring	43822	NH_3Nagg	0.011	0.006	0.00	9	NA	0.00	0.01	0.38	Basalt
AC	Spring	43822	NO_3N	8.155	6.229	0.00	13	NA	0.26	7.77	0.54	Basalt
AC	Spring	43822	EC	306.000	7.413	0.00	11	NA	12.76	290.05	0.01	Basalt
AC	Spring	43822	Cl	22.500	0.741	0.00	4	NA	NA	NA	NA	Basalt
AC	Spring	43822	DRPagg	0.019	0.005	0.00	8	NA	0.00	0.02	0.39	Basalt
AC	Spring	43915	DRPagg	0.023	0.011	0.00	22	0.74	0.00	0.01	0.01	Basalt
AC	Spring	43915	Fe	0.000	0.000	0.73	22	0.68	0.00	0.00	0.10	Basalt
AC	Spring	43915	DO_F	8.030	0.749	0.00	84	<0.05	0.06	8.01	0.00	Basalt
AC	Spring	43915	NH_3Nagg	0.006	0.002	0.59	51	0.32	0.00	0.01	0.09	Basalt
AC	Spring	43915	Temp	15.100	0.148	0.00	117	<0.05	0.00	15.08	0.63	Basalt
AC	Spring	43915	Mn	0.001	0.000	1.00	12	NA	NA	NA	NA	Basalt
AC	Spring	43915	EC	300.600	33.210	0.00	84	0.35	3.11	340.39	0.00	Basalt
AC	Spring	43915	NO_3N	24.300	1.631	0.00	159	<0.05	-1.07	29.18	0.00	Basalt
AC	Spring	43915	Cl	28.000	0.000	0.00	3	NA	NA	NA	NA	Basalt
WRC	Well	61-105	NO_3N	9.505	1.112	0.00	12	0.08	-0.40	10.06	0.63	Basalt
WRC	Well	61-113	NH_3Nagg	0.010	0.000	0.81	37	0.26	0.00	0.01	0.00	Basalt
WRC	Well	61-113	Fe	0.020	0.000	1.00	11	NA	NA	NA	NA	Basalt
WRC	Well	61-113	DRPagg	0.004	0.000	0.50	2	NA	NA	NA	NA	Basalt
WRC	Well	61-113	Cl	18.200	1.483	0.10	42	0.40	0.11	17.65	0.27	Basalt
WRC	Well	61-113	Temp	15.500	0.593	0.00	62	<0.05	0.03	15.30	0.04	Basalt
WRC	Well	61-113	EC	134.500	16.309	0.00	68	0.43	1.45	122.37	0.00	Basalt
WRC	Well	61-113	NO_3N	5.775	1.112	0.00	78	0.31	0.17	4.27	0.00	Basalt
WRC	Well	61-113	Mn	0.049	0.019	0.00	11	NA	0.00	0.05	0.79	Basalt
WRC	Well	61-126	Mn	0.016	0.008	0.00	10	NA	0.00	0.01	0.39	Holocene sediments
WRC	Well	61-126	Temp	15.500	1.038	0.00	63	<0.05	0.01	15.47	0.47	Holocene sediments
WRC	Well	61-126	NO_3N	6.450	1.950	0.00	74	0.07	0.12	5.48	0.01	Holocene sediments
WRC	Well	61-126	NH_3Nagg	0.012	0.003	0.32	34	0.15	0.00	0.01	0.96	Holocene sediments
WRC	Well	61-126	Cl	60.600	5.930	0.07	42	0.10	1.57	52.83	0.00	Holocene sediments
WRC	Well	61-126	Fe	0.020	0.000	0.89	9	NA	NA	NA	NA	Holocene sediments
WRC	Well	61-126	EC	356.000	32.617	0.00	65	0.39	5.94	303.99	0.00	Holocene sediments
WRC	Well	61-126	DRPagg	0.009	0.007	0.00	3	NA	NA	NA	NA	Holocene sediments
WRC	Well	61-135	Fe	0.020	0.000	1.00	7	NA	NA	NA	NA	Basalt
WRC	Well	61-135	Temp	16.300	0.297	0.00	9	NA	0.01	16.29	0.92	Basalt
WRC	Well	61-135	EC	229.000	43.737	0.00	12	NA	6.44	217.20	0.00	Basalt
WRC	Well	61-135	DRPagg	0.012	0.000	0.00	1	NA	NA	NA	NA	Basalt
WRC	Well	61-135	NO_3N	12.000	3.707	0.00	15	NA	0.60	10.59	0.00	Basalt
WRC	Well	61-135	NH_3Nagg	0.010	0.000	0.91	11	NA	NA	NA	NA	Basalt
WRC	Well	61-135	Cl	16.100	4.300	0.43	7	NA	NA	NA	NA	Basalt
WRC	Well	61-135	Mn	0.001	0.000	1.00	8	NA	NA	NA	NA	Basalt
WRC	Well	61-140	NO_3N	10.215	0.667	0.00	4	NA	NA	NA	NA	Basalt
WRC	Well	61-1727	DRPagg	0.074	0.000	0.00	1	NA	NA	NA	NA	Kaawa shell
WRC	Well	61-1727	NO_3N	0.050	0.000	1.00	8	NA	NA	NA	NA	Kaawa shell
WRC	Well	61-1727	NH_3Nagg	0.320	0.000	0.00	7	NA	0.00	0.32	0.32	Kaawa shell
WRC	Well	61-1727	Fe	0.015	0.000	0.50	4	NA	NA	NA	NA	Kaawa shell
WRC	Well	61-1727	Mn	0.023	0.002	0.00	5	NA	0.00	0.02	1.00	Kaawa shell
WRC	Well	61-1729	Fe	0.030	0.007	0.25	4	NA	NA	NA	NA	Holocene sediments
WRC	Well	61-1729	DRPagg	0.082	0.000	0.00	1	NA	NA	NA	NA	Holocene sediments
WRC	Well	61-1729	NH_3Nagg	0.026	0.010	0.00	7	NA	0.00	0.03	0.05	Holocene sediments
WRC	Well	61-1729	NO_3N	0.050	0.000	0.88	8	NA	NA	NA	NA	Holocene sediments

Regional Council	Type	Site	Parameter	Median	MAD	Censoring	#res	Kw p-value	AnnualSenSlope.x	Intercept.x	Mk p-value	Aquifer
WRC	Well	61-1729	Mn	0.099	0.001	0.00	5	NA	0.00	0.10	1.00	Holocene sediments
WRC	Well	61-208	Temp	15.900	0.890	0.00	64	<0.05	0.06	15.45	0.00	Basalt
WRC	Well	61-208	Cl	56.800	5.041	0.09	43	0.26	-0.44	58.49	0.10	Basalt
WRC	Well	61-208	NH_3Nagg	0.010	0.000	0.80	35	0.61	0.00	0.01	0.27	Basalt
WRC	Well	61-208	NO_3N	15.100	1.779	0.00	75	0.66	-0.24	17.31	0.00	Basalt
WRC	Well	61-208	EC	410.500	24.463	0.00	66	0.53	-1.16	419.32	0.13	Basalt
WRC	Well	61-208	Fe	0.020	0.000	0.80	10	NA	NA	NA	NA	Basalt
WRC	Well	61-208	DRPagg	0.052	0.025	0.00	3	NA	NA	NA	NA	Basalt
WRC	Well	61-208	Mn	0.003	0.001	0.00	11	NA	0.00	0.00	0.17	Basalt
WRC	Well	61-238	NO_3N	5.225	1.364	0.00	12	0.11	-0.46	5.86	0.45	Basalt
WRC	Well	61-244	NO_3N	6.784	0.000	0.00	1	NA	NA	NA	NA	Kaawa sediments
WRC	Well	61-244	Fe	0.100	0.000	1.00	1	NA	NA	NA	NA	Kaawa sediments
WRC	Well	61-244	DRPagg	0.077	0.000	0.00	1	NA	NA	NA	NA	Kaawa sediments
WRC	Well	61-244	NH_3Nagg	0.030	0.000	0.00	1	NA	NA	NA	NA	Kaawa sediments
WRC	Well	61-258	NO_3N	2.400	0.311	0.00	92	0.89	0.04	1.94	0.00	Basalt
WRC	Well	61-258	NH_3Nagg	0.010	0.000	0.83	65	0.23	0.00	0.01	0.00	Basalt
WRC	Well	61-258	Fe	0.020	0.000	0.91	54	0.95	0.00	0.01	0.10	Basalt
WRC	Well	61-258	Temp	15.000	0.445	0.00	85	<0.05	0.04	14.57	0.00	Basalt
WRC	Well	61-258	Mn	0.005	0.007	0.92	51	0.35	NA	NA	NA	Basalt
WRC	Well	61-258	Cl	21.000	0.000	0.00	91	0.12	0.00	21.00	0.08	Basalt
WRC	Well	61-258	DRPagg	0.075	0.012	0.08	25	0.80	0.00	0.07	0.81	Basalt
WRC	Well	61-258	EC	230.000	14.826	0.00	87	0.45	0.00	230.00	0.66	Basalt
WRC	Well	61-54	DRPagg	0.004	0.001	1.00	2	NA	NA	NA	NA	Basalt
WRC	Well	61-54	Cl	12.900	1.038	0.00	11	NA	0.18	12.67	0.04	Basalt
WRC	Well	61-54	Temp	15.150	1.038	0.00	18	NA	0.13	14.87	0.01	Basalt
WRC	Well	61-54	EC	109.500	17.791	0.00	22	0.23	3.88	99.30	0.00	Basalt
WRC	Well	61-54	Fe	0.020	0.000	1.00	7	NA	NA	NA	NA	Basalt
WRC	Well	61-54	Mn	0.003	0.000	0.00	8	NA	0.00	0.00	0.04	Basalt
WRC	Well	61-54	NO_3N	5.400	2.135	0.00	27	<0.05	0.40	4.11	0.00	Basalt
WRC	Well	61-54	NH_3Nagg	0.010	0.000	0.91	11	NA	NA	NA	NA	Basalt
WRC	Well	61-59	Temp	15.050	0.519	0.00	60	<0.05	0.04	14.71	0.00	Basalt
WRC	Well	61-59	EC	122.000	2.965	0.00	62	0.54	0.07	121.52	0.35	Basalt
WRC	Well	61-59	NH_3Nagg	0.010	0.000	0.92	37	0.23	NA	NA	NA	Basalt
WRC	Well	61-59	NO_3N	4.200	0.297	0.00	72	0.61	0.04	3.89	0.00	Basalt
WRC	Well	61-59	Fe	0.020	0.000	0.80	10	NA	NA	NA	NA	Basalt
WRC	Well	61-59	Mn	0.005	0.001	0.00	11	NA	0.00	0.01	0.20	Basalt
WRC	Well	61-59	DRPagg	0.004	0.000	1.00	2	NA	NA	NA	NA	Basalt
WRC	Well	61-59	Cl	18.000	1.483	0.10	41	0.34	-0.05	18.21	0.19	Basalt
WRC	Well	61-761	Mn	0.001	0.000	0.40	5	NA	NA	NA	NA	Basalt
WRC	Well	61-761	Fe	0.020	0.000	1.00	4	NA	NA	NA	NA	Basalt
WRC	Well	61-761	NH_3Nagg	0.010	0.000	0.88	8	NA	NA	NA	NA	Basalt
WRC	Well	61-761	NO_3N	6.060	1.394	0.00	9	NA	0.29	5.77	0.00	Basalt
WRC	Well	61-761	DRPagg	0.004	0.000	1.00	1	NA	NA	NA	NA	Basalt
WRC	Well	61-85	Temp	15.800	0.445	0.00	66	0.07	0.04	15.51	0.00	Basalt
WRC	Well	61-85	Mn	0.005	0.002	0.71	38	0.47	0.00	0.00	0.92	Basalt
WRC	Well	61-85	NH_3Nagg	0.010	0.000	0.91	65	0.97	0.00	0.01	0.01	Basalt
WRC	Well	61-85	EC	240.000	11.861	0.00	64	0.68	0.72	234.78	0.00	Basalt
WRC	Well	61-85	Fe	0.020	0.000	0.82	38	0.35	0.00	0.01	0.14	Basalt
WRC	Well	61-85	Cl	31.000	0.000	0.00	71	0.89	0.00	31.00	0.62	Basalt
WRC	Well	61-85	NO_3N	9.400	0.593	0.00	74	0.90	0.09	8.66	0.00	Basalt
WRC	Well	61-85	DRPagg	0.040	0.042	0.64	28	<0.05	0.00	0.02	0.61	Basalt
WRC	Well	72-1857	Mn	0.001	0.000	0.00	4	NA	NA	NA	NA	Kaawa sediments
WRC	Well	72-1857	NH_3Nagg	0.010	0.000	0.80	5	NA	NA	NA	NA	Kaawa sediments
WRC	Well	72-1857	DRPagg	0.088	0.000	0.00	1	NA	NA	NA	NA	Kaawa sediments
WRC	Well	72-1857	NO_3N	0.660	0.044	0.00	5	NA	0.01	0.65	0.81	Kaawa sediments

Regional Council	Type	Site	Parameter	Median	MAD	Censoring	#res	Kw p-value	AnnualSenSlope.x	Intercept.x	Mk p-value	Aquifer
WRC	Well	72-1857	Fe	0.024	0.007	0.50	4	NA	NA	NA	NA	Kaawa sediments
WRC	Well	72-5343	NH_3Nagg	0.280	0.000	0.00	1	NA	NA	NA	NA	Kaawa shell
WRC	Well	72-5343	NO_3N	0.050	0.000	1.00	1	NA	NA	NA	NA	Kaawa shell
AC	Well	7409001	Cl	23.850	0.890	0.00	20	0.93	-0.13	24.15	0.18	Basement
AC	Well	7409001	DO_F	0.360	0.133	0.00	33	0.13	0.02	0.28	0.05	Basement
AC	Well	7409001	DRPagg	0.003	0.001	0.68	41	0.78	0.00	0.00	0.40	Basement
AC	Well	7409001	EC	537.500	49.667	0.00	38	0.11	5.94	508.29	0.00	Basement
AC	Well	7409001	Fe	0.950	0.222	0.20	41	0.97	0.11	0.40	0.00	Basement
AC	Well	7409001	Mn	0.010	0.002	0.00	40	0.99	0.00	0.01	0.00	Basement
AC	Well	7409001	NH_3Nagg	0.006	0.000	0.68	41	0.60	0.00	0.01	0.20	Basement
AC	Well	7409001	NO_3N	0.026	0.017	0.00	43	0.62	0.00	0.05	0.00	Basement
AC	Well	7409001	Temp	16.300	0.208	0.00	43	<0.05	0.00	16.28	0.33	Basement
AC	Well	7409011	Cl	21.000	0.371	0.00	16	NA	0.02	20.95	0.65	Waitemata sandstone
AC	Well	7409011	DO_F	0.120	0.089	0.00	19	0.78	0.01	0.11	0.55	Waitemata sandstone
AC	Well	7409011	DRPagg	0.090	0.010	0.00	27	0.20	0.00	0.09	0.49	Waitemata sandstone
AC	Well	7409011	EC	450.600	21.201	0.00	23	0.78	2.06	444.90	0.11	Waitemata sandstone
AC	Well	7409011	Fe	0.260	0.282	0.04	27	<0.05	0.01	0.24	0.17	Waitemata sandstone
AC	Well	7409011	Mn	0.083	0.030	0.00	26	<0.05	0.00	0.08	0.50	Waitemata sandstone
AC	Well	7409011	NH_3Nagg	0.530	0.110	0.00	27	<0.05	-0.01	0.58	0.02	Waitemata sandstone
AC	Well	7409011	NO_3N	0.001	0.002	0.54	28	0.34	0.00	0.00	0.01	Waitemata sandstone
AC	Well	7409011	Temp	18.000	0.445	0.00	28	<0.05	0.00	18.00	0.89	Waitemata sandstone
AC	Well	7417021	Cl	34.000	1.483	0.00	65	0.81	0.04	33.72	0.05	Waitemata sandstone
AC	Well	7417021	DRPagg	0.043	0.009	0.45	31	0.94	0.00	0.04	0.05	Waitemata sandstone
AC	Well	7417021	EC	420.500	14.085	0.00	58	0.23	-0.36	423.53	0.45	Waitemata sandstone
AC	Well	7417021	NH_3Nagg	0.240	0.030	0.02	57	0.70	0.00	0.24	0.69	Waitemata sandstone
AC	Well	7417021	NO_3N	0.001	0.015	0.75	65	0.20	0.00	0.02	0.38	Waitemata sandstone
AC	Well	7417021	Temp	18.140	0.237	0.00	61	<0.05	-0.02	18.27	0.00	Waitemata sandstone
AC	Well	7418023	Cl	20.000	0.000	0.00	3	NA	NA	NA	NA	Kaawa shell
AC	Well	7418023	DO_F	0.150	0.133	0.00	39	0.97	0.00	0.17	0.36	Kaawa shell
AC	Well	7418023	DRPagg	0.019	0.015	0.14	44	0.46	0.00	0.02	0.24	Kaawa shell
AC	Well	7418023	EC	300.000	8.896	0.00	43	<0.05	1.99	289.57	0.00	Kaawa shell
AC	Well	7418023	Fe	3.100	0.445	0.04	47	0.67	0.11	2.48	0.00	Kaawa shell
AC	Well	7418023	Mn	0.134	0.035	0.00	36	<0.05	-0.01	0.15	0.00	Kaawa shell
AC	Well	7418023	NH_3Nagg	0.191	0.079	0.00	47	0.75	-0.01	0.26	0.00	Kaawa shell
AC	Well	7418023	NO_3N	0.001	0.000	0.40	45	0.88	0.00	0.00	0.12	Kaawa shell
AC	Well	7418023	Temp	17.235	0.245	0.00	45	0.12	0.00	17.25	0.60	Kaawa shell
AC	Well	7418027	Cl	22.000	0.000	0.00	61	0.24	0.00	22.00	0.00	Kaawa shell
AC	Well	7418027	DO_F	0.120	0.089	0.00	60	0.25	-0.01	0.18	0.03	Kaawa shell
AC	Well	7418027	DRPagg	0.121	0.036	0.09	34	0.10	0.00	0.11	0.11	Kaawa shell
AC	Well	7418027	EC	310.000	12.454	0.00	74	0.26	1.60	296.37	0.00	Kaawa shell
AC	Well	7418027	Fe	0.120	0.015	0.00	69	0.71	0.00	0.11	0.00	Kaawa shell
AC	Well	7418027	Mn	0.060	0.000	0.01	70	0.37	0.00	0.06	0.06	Kaawa shell
AC	Well	7418027	NH_3Nagg	0.191	0.016	0.01	69	0.73	0.00	0.18	0.01	Kaawa shell
AC	Well	7418027	NO_3N	0.001	0.012	0.76	74	0.38	0.00	0.01	0.68	Kaawa shell
AC	Well	7418027	Temp	17.589	0.132	0.00	75	<0.05	0.01	17.53	0.11	Kaawa shell
AC	Well	7419007	Cl	19.000	0.297	0.00	17	0.37	0.02	18.96	0.31	Drury sand
AC	Well	7419007	DO_F	0.090	0.089	0.00	37	0.79	0.00	0.10	0.58	Drury sand
AC	Well	7419007	DRPagg	0.186	0.024	0.00	42	<0.05	0.00	0.19	0.88	Drury sand
AC	Well	7419007	EC	359.100	14.529	0.00	42	0.14	1.20	353.01	0.06	Drury sand
AC	Well	7419007	Fe	0.360	0.133	0.02	43	<0.05	0.01	0.31	0.00	Drury sand
AC	Well	7419007	Mn	0.038	0.007	0.00	32	<0.05	0.00	0.04	0.72	Drury sand
AC	Well	7419007	NH_3Nagg	0.688	0.094	0.00	43	0.24	-0.01	0.73	0.02	Drury sand
AC	Well	7419007	NO_3N	0.000	0.001	0.48	42	0.94	0.00	0.00	0.08	Drury sand
AC	Well	7419007	Temp	17.500	0.165	0.00	43	<0.05	0.00	17.48	0.46	Drury sand
AC	Well	7419009	Cl	20.600	0.667	0.00	38	0.36	0.03	20.44	0.13	Basalt

Regional Council	Type	Site	Parameter	Median	MAD	Censoring	#res	Kw p-value	AnnualSenSlope.x	Intercept.x	Mk p-value	Aquifer
AC	Well	7419009	DO_F	0.140	0.104	0.00	59	0.24	0.00	0.16	0.41	Basalt
AC	Well	7419009	DRPagg	0.038	0.007	0.00	74	0.20	0.00	0.04	0.05	Basalt
AC	Well	7419009	EC	321.700	9.711	0.00	66	0.68	1.57	309.24	0.00	Basalt
AC	Well	7419009	Fe	0.073	0.042	0.00	74	0.66	0.00	0.04	0.00	Basalt
AC	Well	7419009	Mn	0.020	0.006	0.00	62	0.66	0.00	0.03	0.00	Basalt
AC	Well	7419009	NH_3Nagg	0.046	0.022	0.00	75	0.35	0.00	0.08	0.00	Basalt
AC	Well	7419009	NO_3N	0.002	0.002	0.08	76	0.51	0.00	0.00	0.00	Basalt
AC	Well	7419009	Temp	17.100	0.297	0.00	75	<0.05	0.01	17.01	0.31	Basalt
AC	Well	7419121	Cl	20.000	0.741	0.00	40	0.45	0.05	19.78	0.10	Basalt
AC	Well	7419121	DO_F	7.865	0.615	0.00	60	<0.05	0.04	7.61	0.05	Basalt
AC	Well	7419121	DRPagg	0.100	0.013	0.00	76	0.64	0.00	0.10	0.17	Basalt
AC	Well	7419121	EC	272.450	13.269	0.00	66	0.18	2.42	253.84	0.00	Basalt
AC	Well	7419121	Fe	0.005	0.000	0.87	76	0.68	0.00	0.00	0.65	Basalt
AC	Well	7419121	Mn	0.001	0.000	0.89	64	0.88	0.00	0.00	0.25	Basalt
AC	Well	7419121	NH_3Nagg	0.008	0.000	0.57	77	0.67	0.00	0.01	0.10	Basalt
AC	Well	7419121	NO_3N	9.200	1.735	0.00	77	0.95	0.18	7.57	0.00	Basalt
AC	Well	7419121	Temp	14.560	0.237	0.00	75	<0.05	0.00	14.56	0.74	Basalt
AC	Spring	7419126	Cl	20.000	1.483	0.00	4	NA	NA	NA	NA	Basalt
AC	Spring	7419126	DRPagg	0.051	0.006	0.00	11	NA	0.00	0.05	0.03	Basalt
AC	Spring	7419126	EC	278.500	22.239	0.00	14	<0.05	-3.84	284.74	0.03	Basalt
AC	Spring	7419126	NH_3Nagg	0.005	0.000	0.00	7	NA	0.00	0.00	0.13	Basalt
AC	Spring	7419126	NO_3N	3.501	1.172	0.00	13	0.65	2.23	0.16	0.16	Basalt
AC	Well	7428031	DO_F	8.360	0.593	0.00	34	0.95	0.06	8.13	0.02	Basalt
AC	Well	7428031	DRPagg	0.023	0.010	0.00	21	0.59	0.00	0.02	0.17	Basalt
AC	Well	7428031	EC	376.650	12.824	0.00	34	0.68	1.81	369.19	0.12	Basalt
AC	Well	7428031	Fe	0.005	0.016	0.38	21	0.27	0.00	0.02	0.01	Basalt
AC	Well	7428031	Mn	0.001	0.000	0.25	12	NA	0.00	0.00	0.78	Basalt
AC	Well	7428031	NH_3Nagg	0.006	0.004	0.54	28	0.77	0.00	0.01	0.72	Basalt
AC	Well	7428031	NO_3N	6.099	0.335	0.00	28	0.67	-0.06	6.29	0.02	Basalt
AC	Well	7428031	Temp	15.408	0.185	0.00	34	0.27	0.02	15.35	0.22	Basalt
AC	Well	7428103	Cl	24.000	1.186	0.00	67	0.50	0.00	24.00	0.51	Basalt
AC	Well	7428103	DO_F	0.130	0.119	0.00	61	0.22	0.00	0.12	0.72	Basalt
AC	Well	7428103	DRPagg	0.225	0.027	0.00	60	0.92	0.00	0.24	0.08	Basalt
AC	Well	7428103	EC	270.500	14.085	0.00	72	0.45	0.32	267.91	0.32	Basalt
AC	Well	7428103	Fe	0.030	0.009	0.07	69	0.18	0.00	0.02	0.00	Basalt
AC	Well	7428103	Mn	0.022	0.003	0.00	69	0.98	0.00	0.02	0.91	Basalt
AC	Well	7428103	NH_3Nagg	0.180	0.016	0.05	66	0.25	0.00	0.18	0.32	Basalt
AC	Well	7428103	NO_3N	0.001	0.012	0.65	71	0.10	0.00	0.01	0.85	Basalt
AC	Well	7428103	Temp	14.600	0.163	0.00	73	<0.05	0.01	14.55	0.17	Basalt
AC	Well	7428105	Cl	17.100	0.593	0.00	65	0.74	-0.06	17.43	0.00	Basalt
AC	Well	7428105	DO_F	6.800	0.741	0.00	57	0.78	0.10	6.13	0.00	Basalt
AC	Well	7428105	DRPagg	0.060	0.012	0.12	59	0.61	0.00	0.06	0.04	Basalt
AC	Well	7428105	EC	212.200	18.977	0.00	66	0.71	3.35	186.54	0.00	Basalt
AC	Well	7428105	Fe	0.003	0.010	0.66	71	0.87	0.00	0.01	0.45	Basalt
AC	Well	7428105	Mn	0.001	0.002	0.51	71	0.34	0.00	0.00	0.00	Basalt
AC	Well	7428105	NH_3Nagg	0.010	0.000	0.72	68	0.75	0.00	0.01	0.31	Basalt
AC	Well	7428105	NO_3N	7.615	2.795	0.00	66	0.95	0.54	3.43	0.00	Basalt
AC	Well	7428105	Temp	15.400	0.445	0.00	70	<0.05	0.03	15.11	0.00	Basalt

APPENDIX 3 WATER CHEMISTRY PLOTS

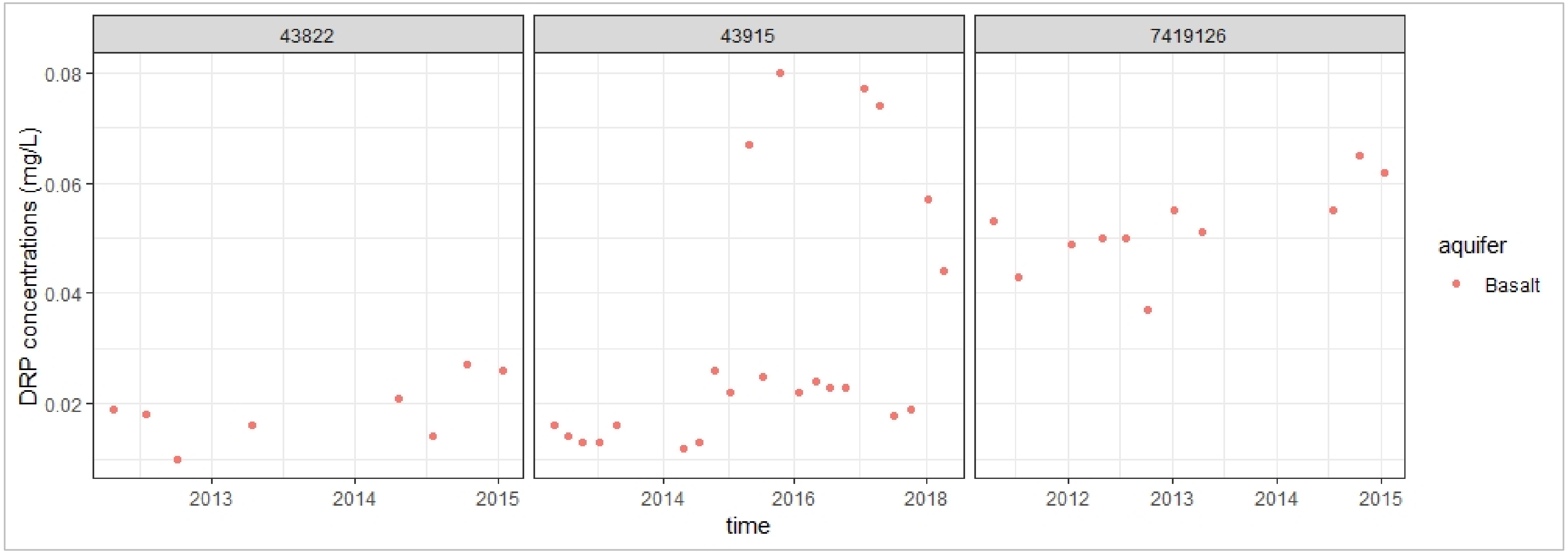

Figure A3.1 DRP measured in springs (AC).

Figure A3.2 DRP measured in wells.

Figure A3.3 DRP measured in aquifers.

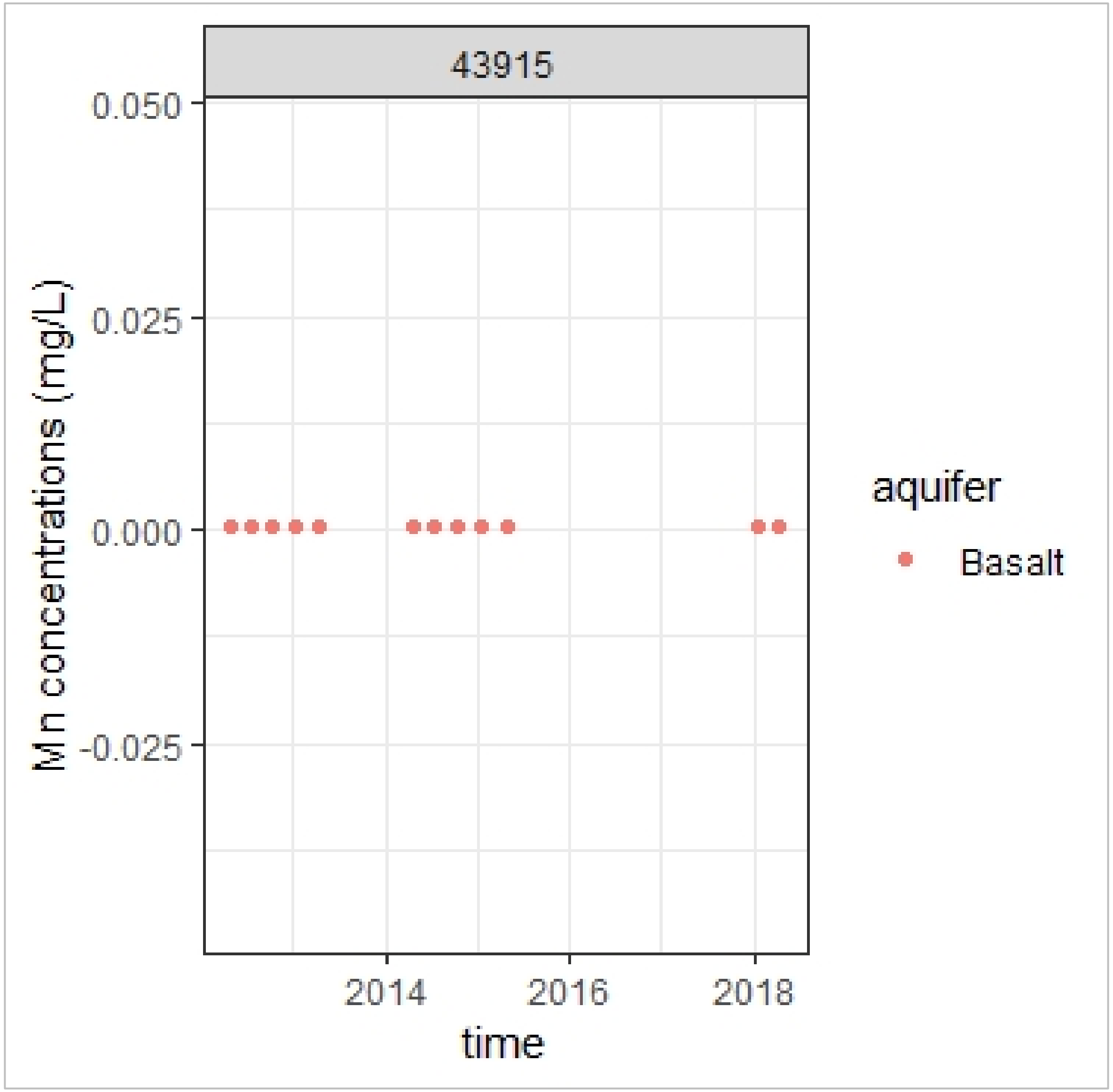

Figure A3.4 Mn measured in a spring (AC).

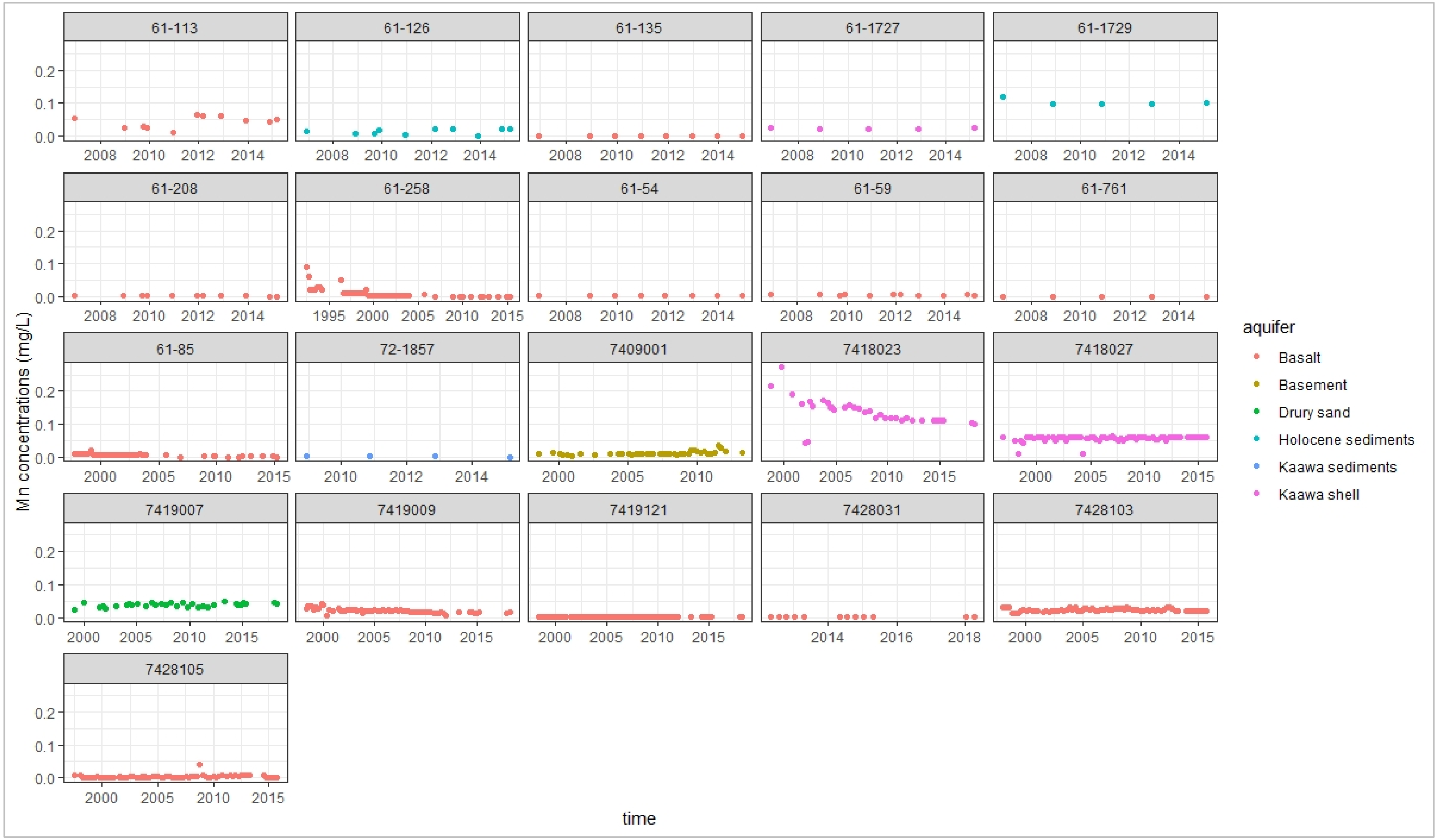

Figure A3.5 Mn measured in wells.

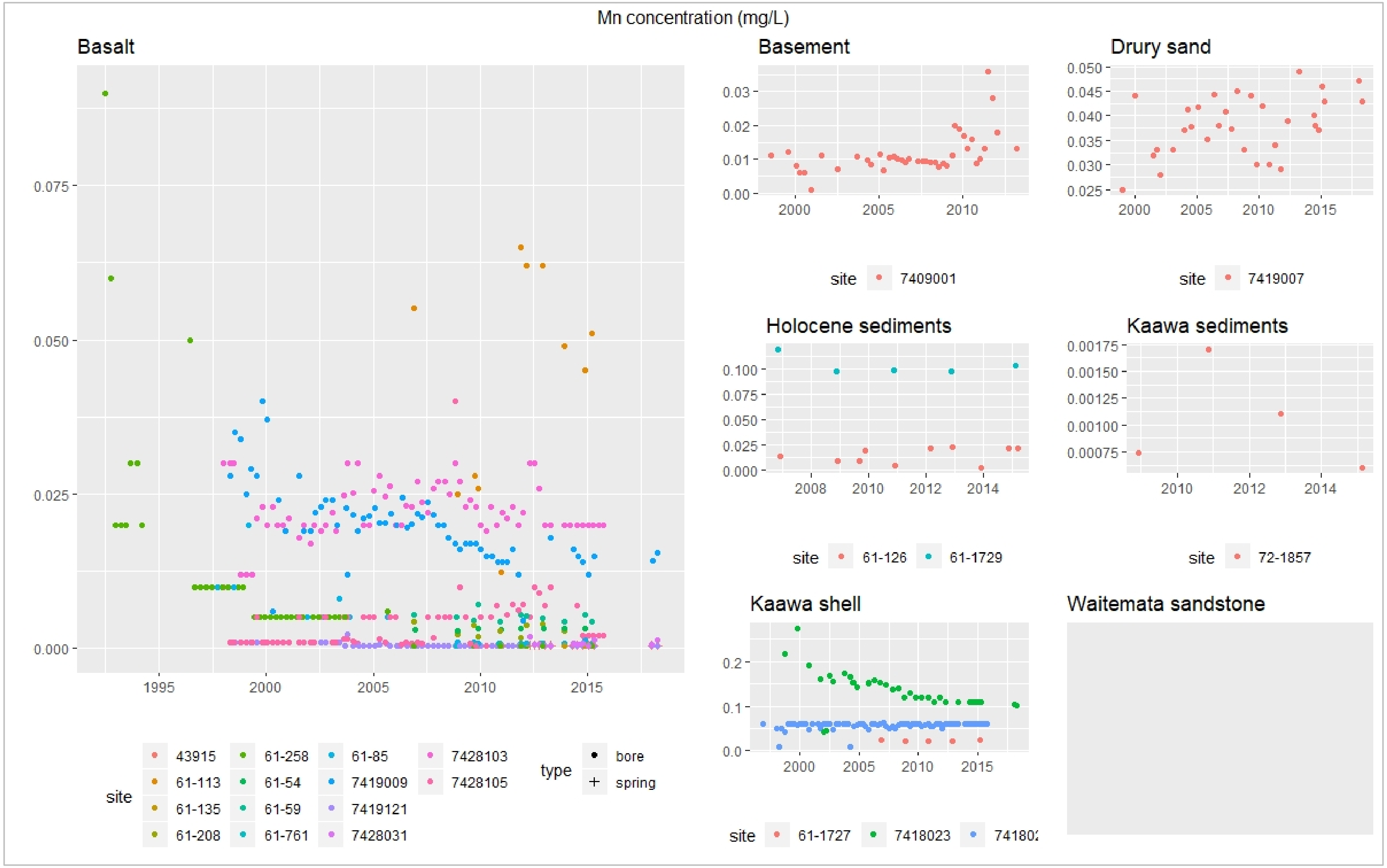

Figure A3.6 Mn measured in aquifers.

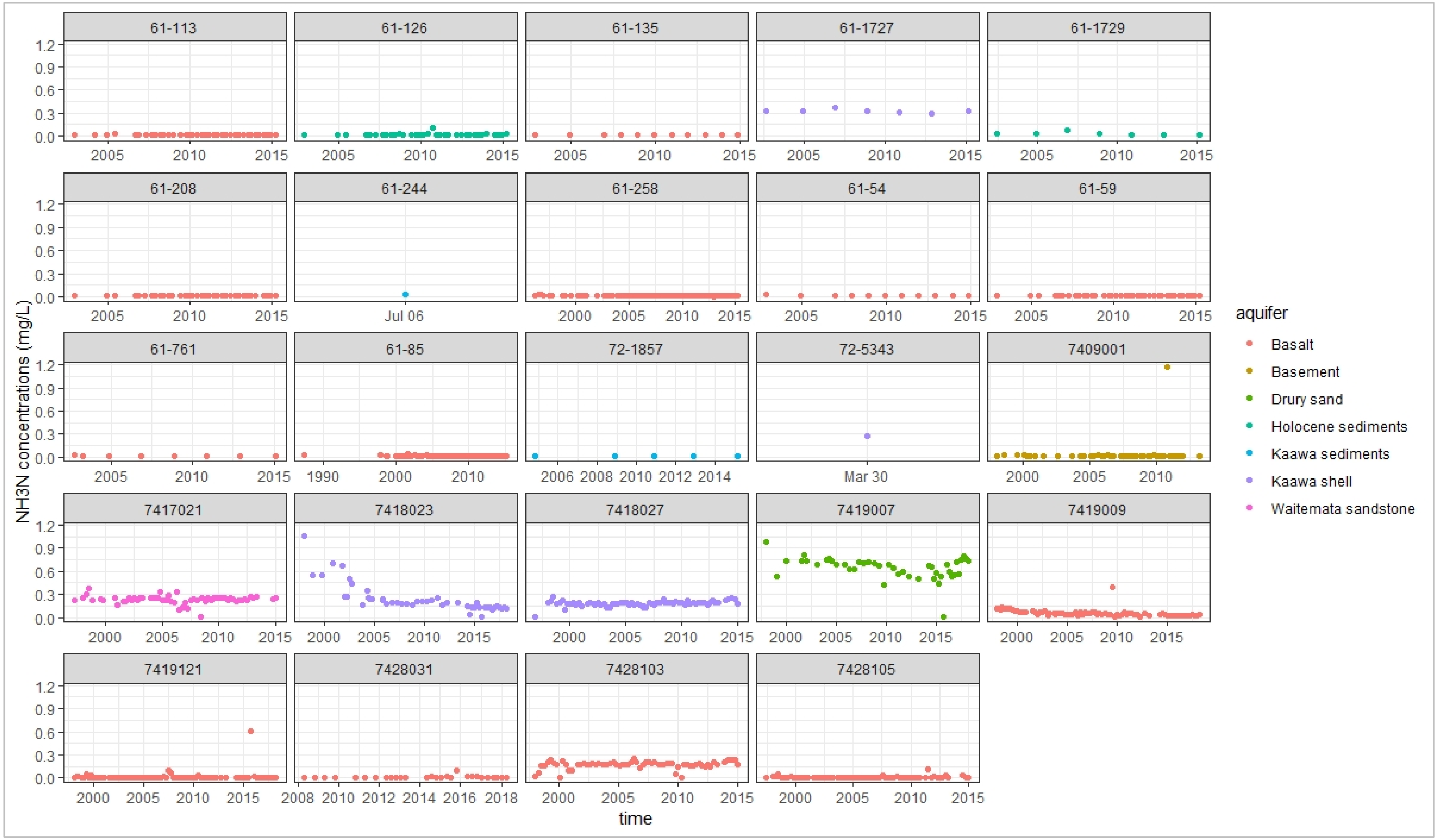

Figure A3.7 NH_3-N measured in wells.

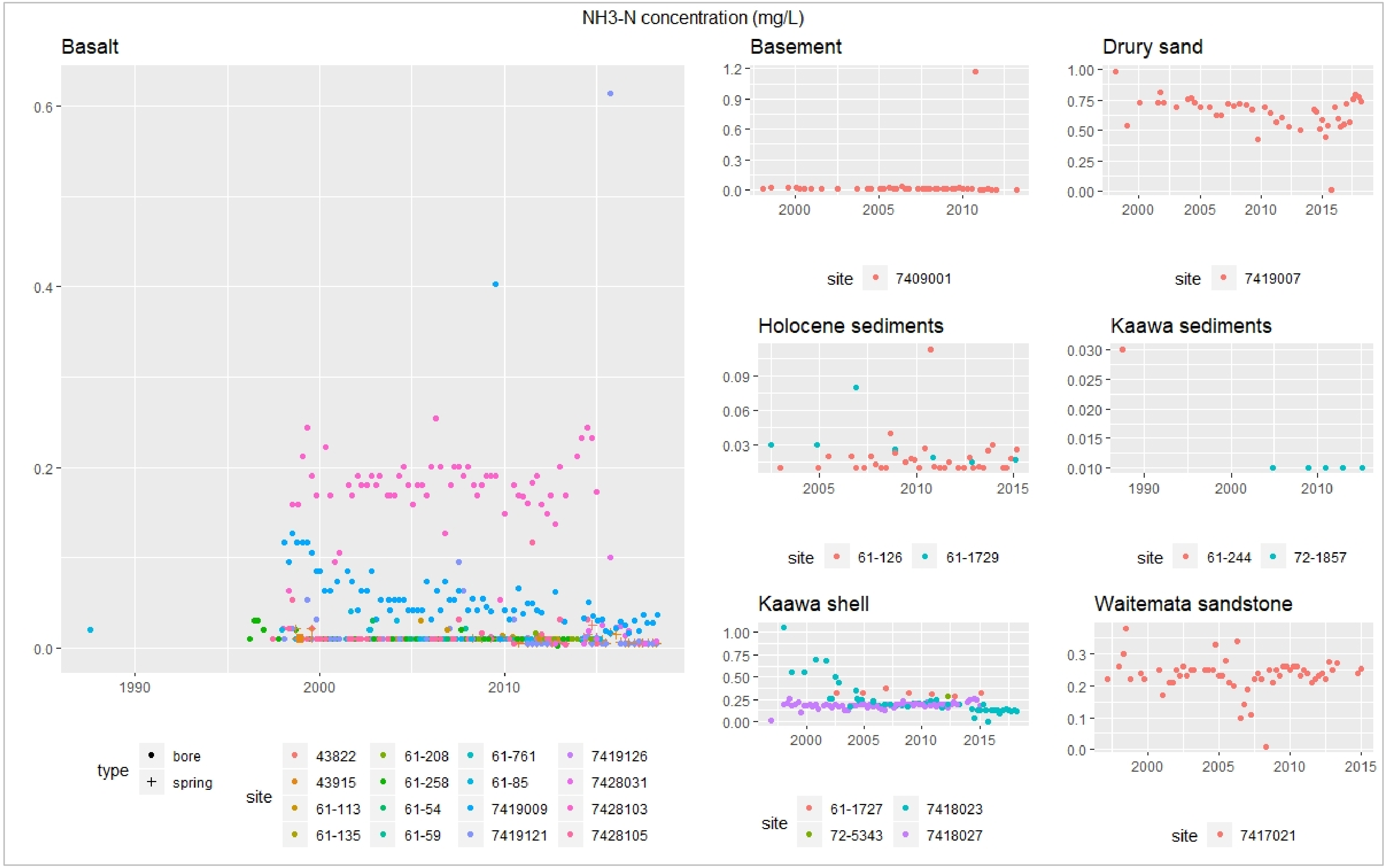

Figure A3.8 NH$_3$-N measured in aquifers.

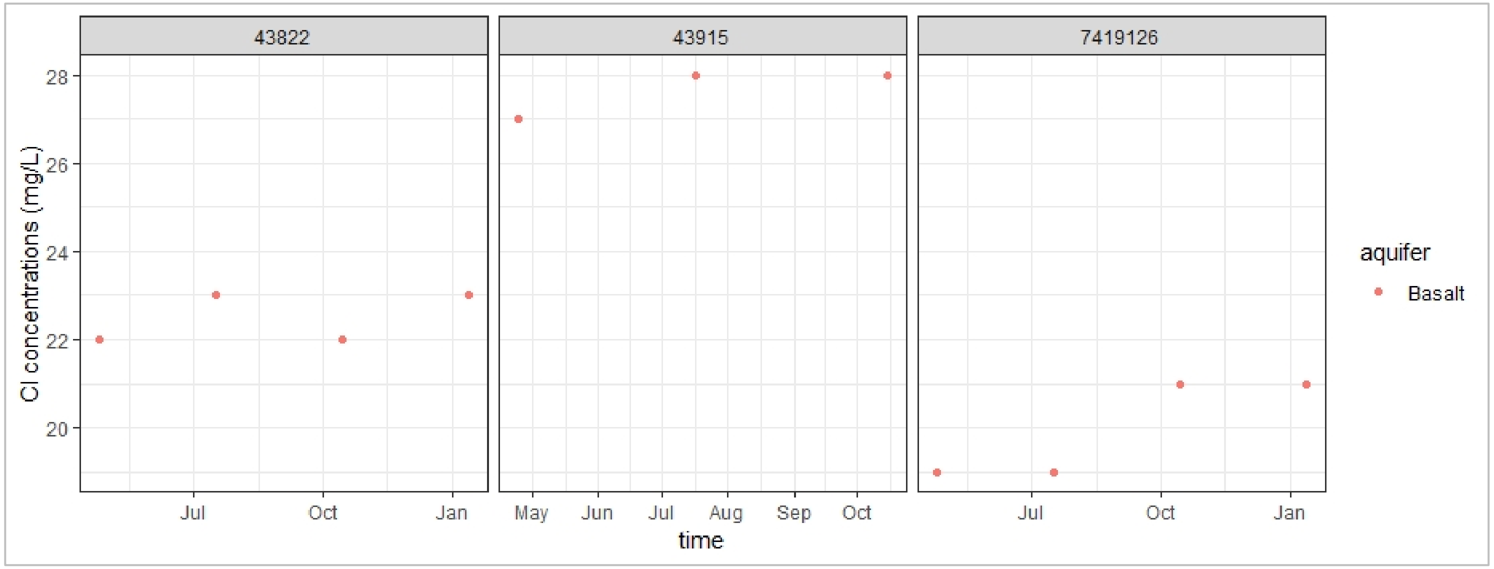

Figure A3.9 Cl measured in springs (AC).

Figure A3.10 Cl measured in wells.

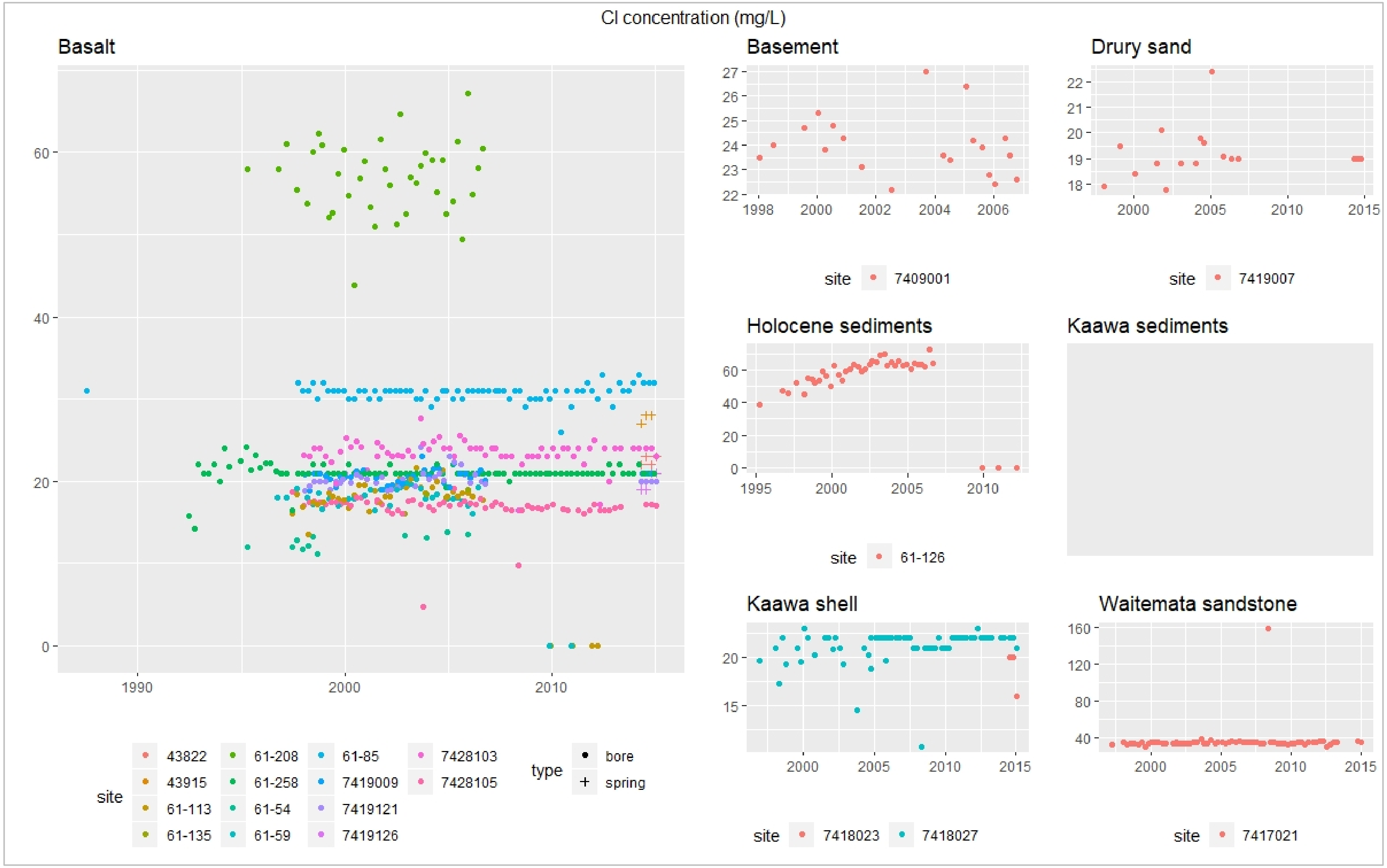

Figure A3.11 Cl measured in aquifers.

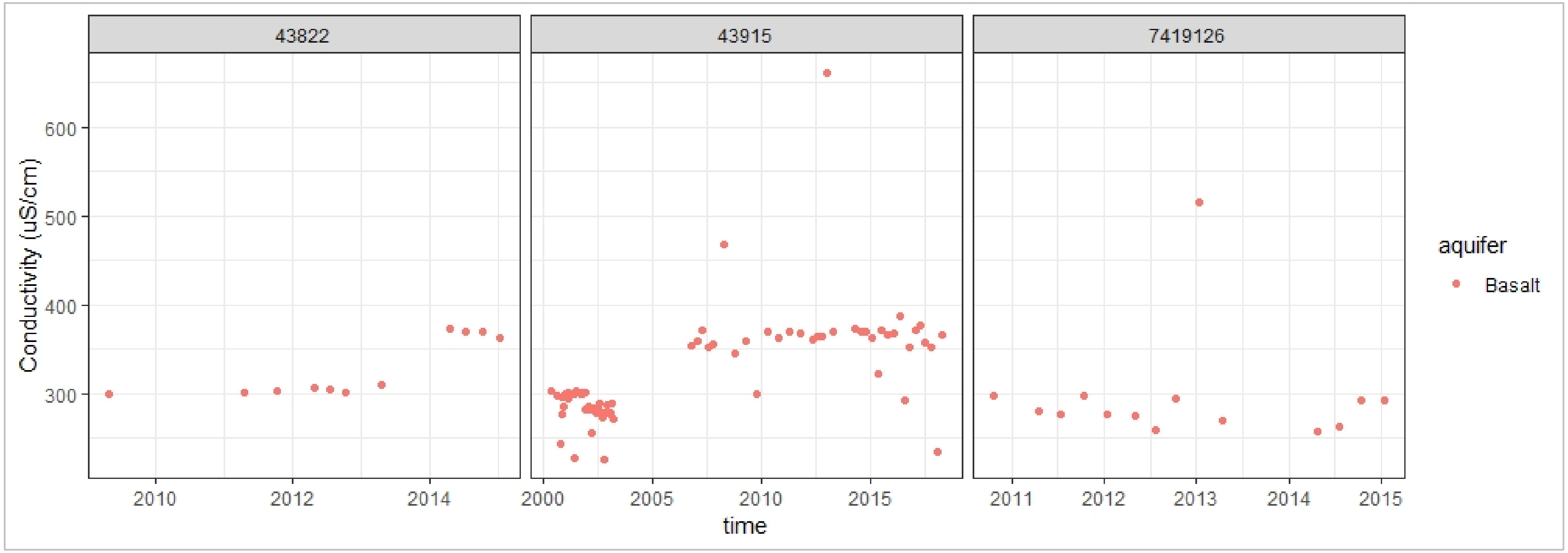

Figure A3.12 Electrical conductivity measured in springs (AC).

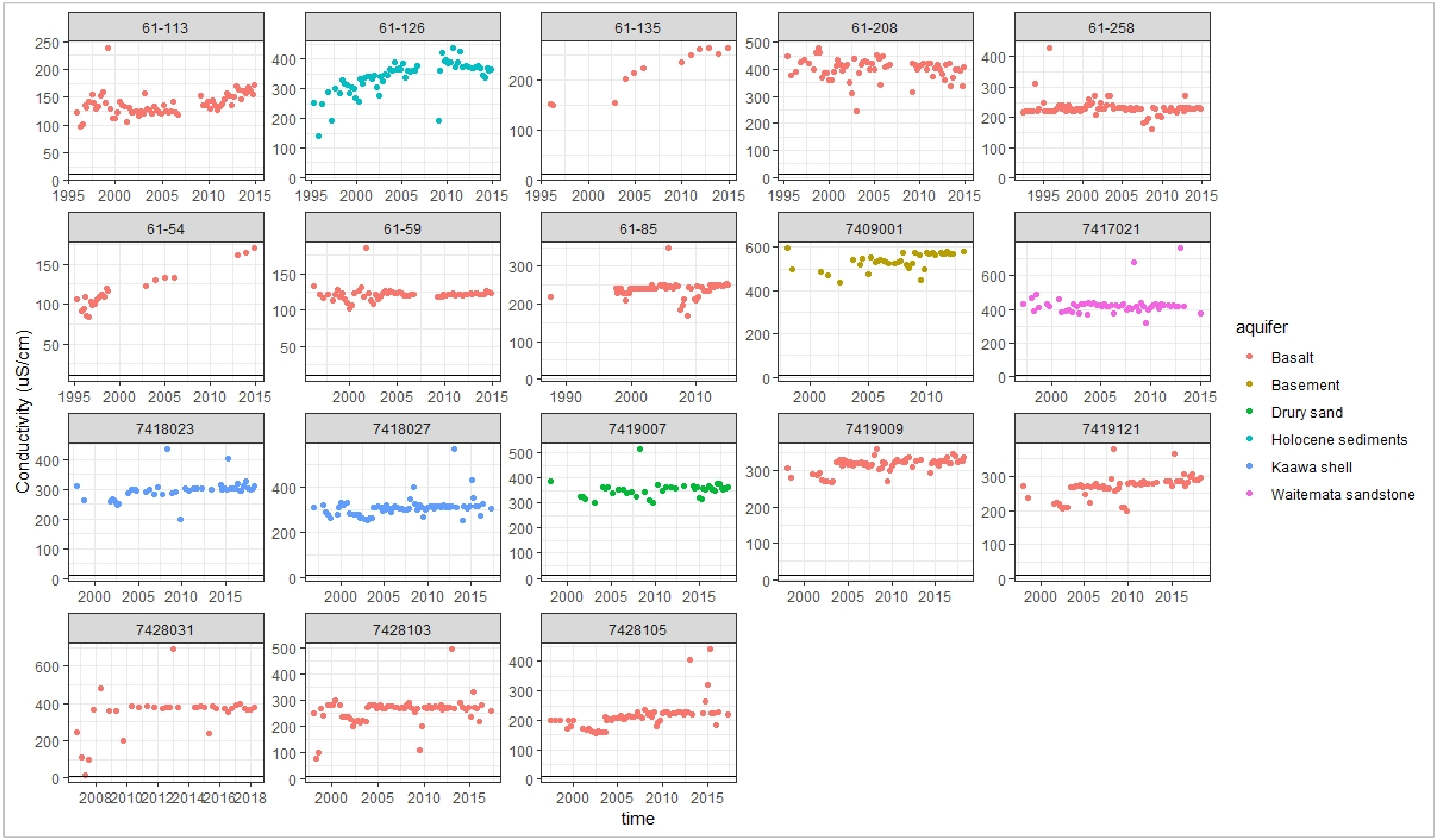

Figure A3.13 Electrical conductivity measured in wells.

Figure A3.14 Electrical conductivity measured in aquifers.

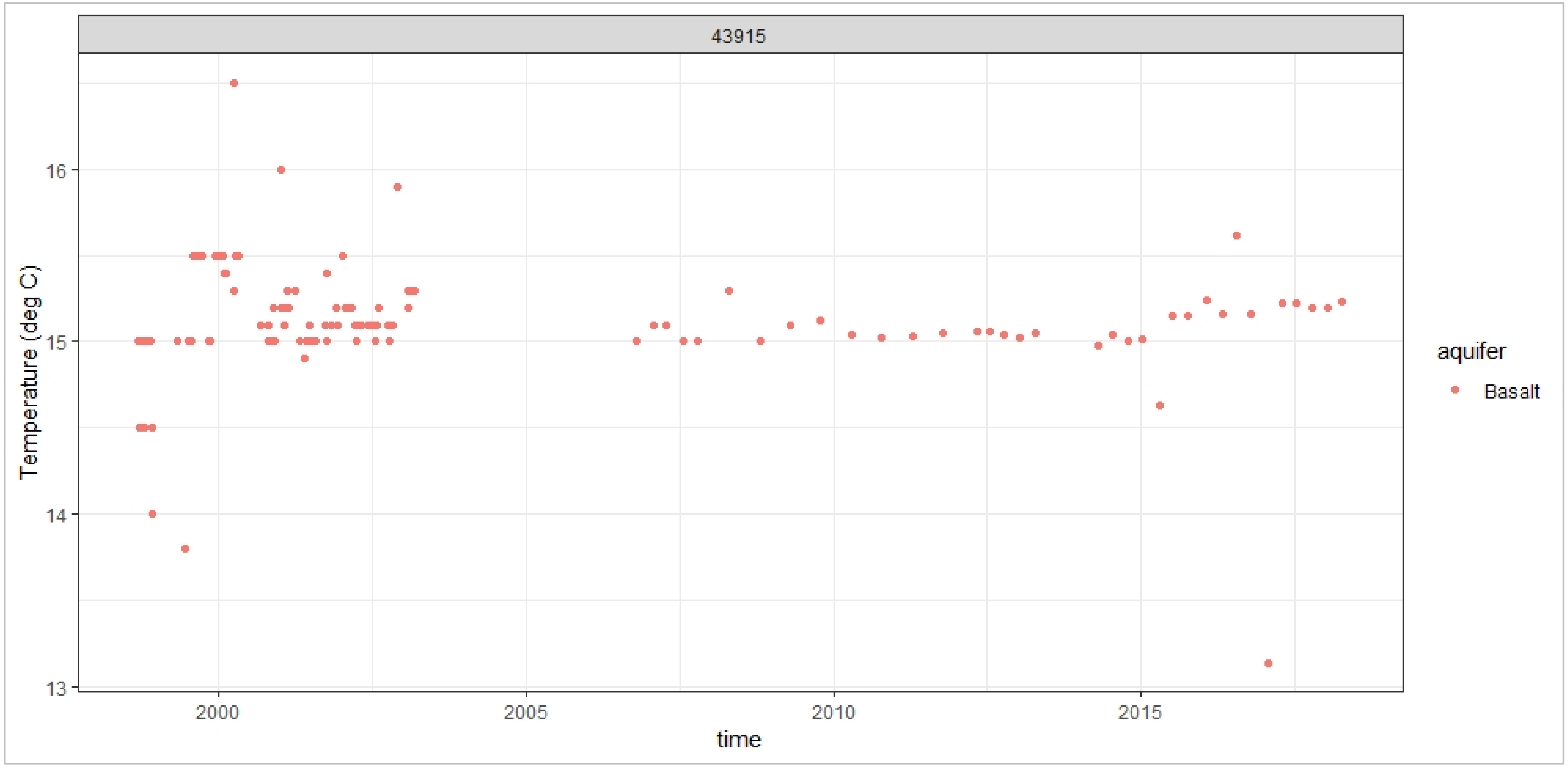

Figure A3.15 Temperatures measured in a spring (AC).

Figure A3.16 Temperatures measured in wells.

Figure A3.17 Temperature in aquifers.

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Principal Location

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