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Geological model and water budget of the Hauraki Plains, Waikato region, 2016

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EXECUTIVE SUMMARY

GNS Science was commissioned by Waikato Regional Council to assess the Hauraki Plains geology, identify aquifers in a three-dimensional model and develop water budgets of the Hauraki Plains with an aim of assisting an assessment of groundwater sustainability in the Hauraki Plains area.

A geological model of the Hauraki Plains identified hydrogeological layers that are relevant to groundwater flow. Key units for groundwater flow included: Holocene sediments that are approximately 30 m thick at the coast and generally thin towards the south; Pleistocene Hinuera Formation, which includes volcaniclastic alluvium that provides most of the infill in the Hauraki Plains and is extensively exposed in the south of the Plains; Mamaku Plateau Formation ignimbrite, which forms the headwater catchments of the Waihou River catchment; Waiteariki Ignimbrite, which is located on the Kaimai Range north of Mamaku Plateau and is located below sediments in the vicinity of Matamata; and basement, which includes greywacke and Coromandel volcanics.

Water budgets generally calculated the major inflows (rainfall, surface flow and groundwater flow) and outflows (actual evapotranspiration, surface flow and groundwater flow) of catchments and zones. The total surface water outflow from the Hauraki Plains area was an estimated mean of 73.9 m^3/s from three major catchments at the coast (i.e., the Waihou River catchment, the Piako River catchment and the Hauraki north-west area of 53.8 m^3/s, 18.5 m^3/s and 1.6 m^3/s, respectively); estimated groundwater outflow at the coast from the area was small compared to surface flow, i.e., 1.9 m^3/s.

Water budgets of the Waihou River catchment did not include groundwater inflows and groundwater outflows because relatively large negative residual flows were consistently calculated for sub-catchments and zones and some long-term average surface flow estimates in the Waihou River appear inconsistent. Therefore, the estimates were considered as unreliable and improved estimates of water budget components are required in this catchment.

The boundary between relatively permeable Pleistocene sediments and relatively impermeable Holocene sediments has an important role in controlling groundwater flow in the Hauraki Plains. Most groundwater flow in the southern Hauraki Plains comes to the ground surface in this area, as demonstrated by groundwater outflows from sub-catchments. For example, groundwater outflows were 67% and 21% of total outflow from the Waihekau Stream sub-catchment (located south of this boundary) and the Waitoa River 1249_22 sub-catchment (located near this boundary), respectively. In addition, the base flow index (BFI) tends to increase towards the boundary. For example, BFI increased from 0.53 to 0.63 between Waitoa River 1249_38 sub-catchment and Waitoa River 1249_18 sub-catchment, respectively.

Recommendations in this report include a revision of the rainfall model, particularly in the area of the Mamaku Plateau and the Kaimai Range. In addition, surface water flow estimates could be improved with a field programme of gaugings to measure surface flows in the Hauraki Plains.

1.0 INTRODUCTION

Groundwater resources in the Waikato region, including the Hauraki Plains, are increasingly under pressure as land use and population numbers intensify. These pressures have resulted in the development of policies by Waikato Regional Council (WRC) to manage groundwater sustainably. The three key WRC policies relevant to groundwater resources are: the co-management of groundwater and surface water; the management of land and water quality; and the management of geothermal systems. Co-management of groundwater and surface water is effected by WRC's "Variation 6", now included in the regional plan (Waikato Regional Council 2016). Management of land and water quality, including groundwater and surface water, in the Lake Taupo catchment is operative (Environment Court 2011) and WRC also aims to protect some geothermal features from the effects of groundwater use.

Groundwater resources in the Hauraki Plains area (Figure 1.1) are important because:

- groundwater is a water supply that is coming under increasing usage pressure in New Zealand and the Waikato region (Hadfield 2001);
- groundwater discharge supports baseflow in most of the streams in the Hauraki Plains area and, therefore, management of the groundwater system is important to the sustainability of surface water flow and quality, e.g., the Piako River catchment (White and Tschritter 2014).

GNS Science was commissioned by WRC to assess the Hauraki Plains geology, identify aquifers and represent these aquifers in a three-dimensional model of geology using available data. WRC also commissioned GNS Science to develop water budgets of the Piako River catchment to assess groundwater-surface-water interaction, following an initial report (White and Tschritter 2014). In addition, groundwater interaction between the Piako River catchment and the Waihou River catchment was assessed with the development of water budgets for the Waihou River catchment.

This report assembles a summary of relevant geology as a three-dimensional model. The three-dimensional geological model is used to develop a conceptual model of the groundwater system, including a model of the water budget for the Hauraki Plains. Together, these two models will provide WRC with information to begin an assessment of groundwater sustainability in the Hauraki Plains area. The report also includes a discussion of water budget components and recommendations for further development of the 3D geological model and future assessment of water budget components for use with a proposed groundwater flow model.

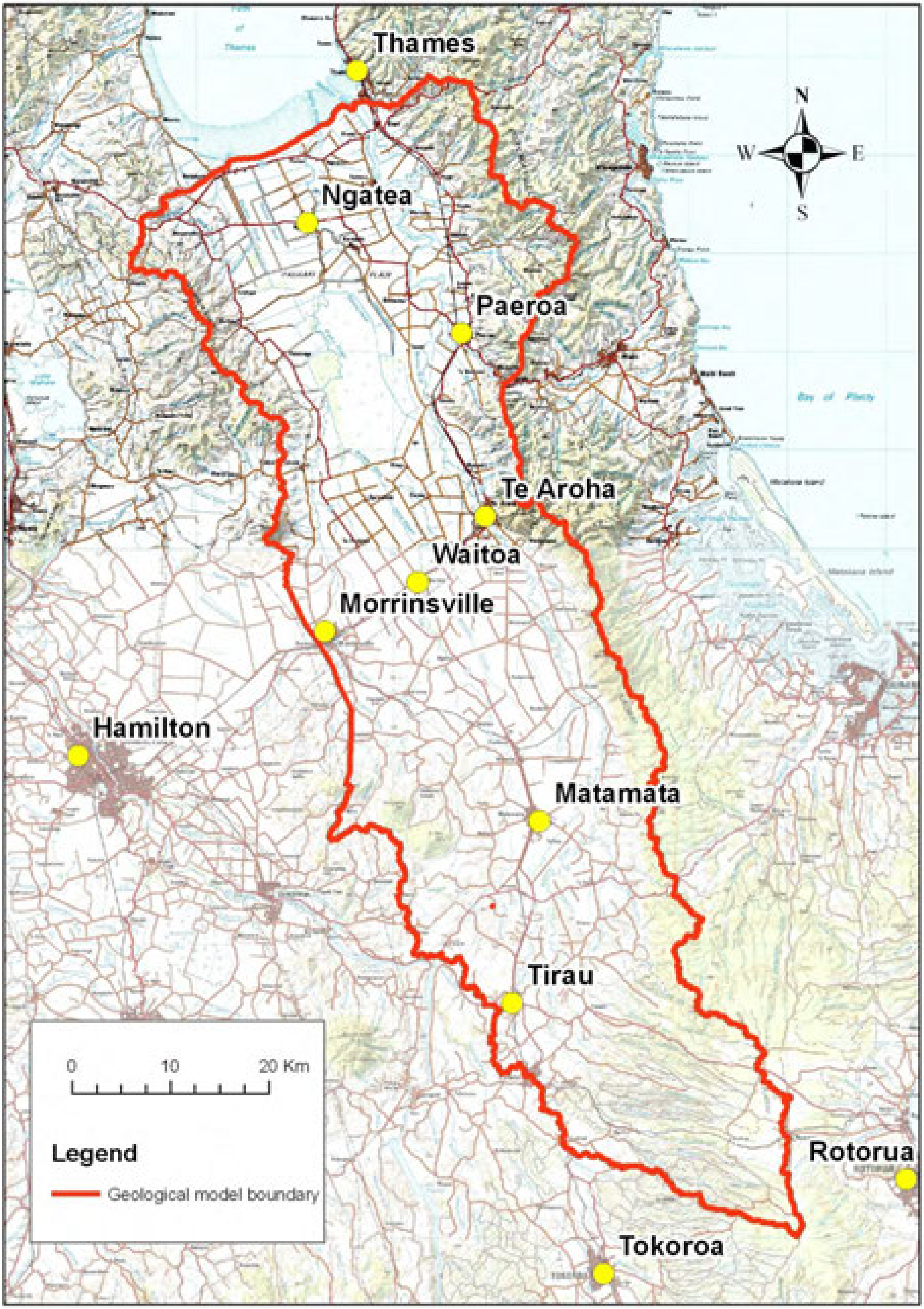

Figure 1.1 Location of the Hauraki Pains area with the boundary of the Hauraki geological model developed in this report.

2.0 REVIEW OF THE GEOLOGY AND HYDROGEOLOGY OF THE HAURAKI PLAINS

The Hauraki Plains are bounded to the east by Tertiary – Quaternary age predominantly andesitic and rhyolitic rocks of the Coromandel Range, Kaimai Range and Mamaku Plateau (Figure 2.1). To the west, the plains are bounded by the low-permeability Jurassic age metagreywacke basement rocks of the Hapuakohe and Pakaroa ranges, which are part of the Torlesse Group. The plains were formed within the Hauraki Rift, a continental rift structure with a large thickness of sediments (Hochstein and Hunt 1980), Figure 2.2. Sources of sediment to the Hauraki Rift include volcanic eruptions in the Taupo Volcanic Zone (TVZ) and marine incursions. Ignimbrites derived from the Kaimai Range and Mamaku Plateau are also observed in the Hauraki Rift.

The plains area occupies the southern part of a c. 25-30 km wide continental rift zone that developed as a back-arc rift during the Kaimai tectonic event (5-2.5 Ma; Hodder 1984). The Hauraki Rift extends for c. 300 km, including the Hauraki Gulf to the north. In the south, the Hauraki Rift is buried by Pleistocene ignimbrite sheets of the TVZ (Skinner 1986).

The Hauraki Rift acted as a structural repository for pyroclastics derived from the Coromandel Peninsula. The ancestral Waikato River often flowed into the Hauraki Gulf, and over time, the Hauraki Rift filled with pumice, mud and gravel until the Late Plesitocene (Manville and Wilson 2004). The Hauraki Plains are thus filled by a large thickness of predominantly Tauranga Group sediments deposited by ancient Waikato River channels (Hadfield 2001). More recently, the alluvial deposits of the Hauraki Plains have been built up by sediments transported by the Piako River and the Waihou River, which flow north to reach the sea at the Firth of Thames.

Land in the Hauraki Plains is flat, peat-heavy and partly swampy, with dairy farming an important local industry. The Hauraki Plains between the Firth of Thames and Waitoa are a flood plain only a few meters above sea level where peat deposits (e.g., Kopuatai Peat Dome) are common and drainage ditches are used to maintain farm land. South of Waitoa, the Hauraki Plains increase in elevation and comprise Pleistocene depositional surfaces partly covered by distal flows of Pleistocene ignimbrite sheets (Hochstein and Hunt 1980).

The general horizontal groundwater flow direction is towards the north in the Hauraki Plains (Hadfield 2001). Confining groundwater conditions are observed on the plains, and springs (some warm) are common. Total water use is a small proportion of available groundwater (Hadfield 2001).

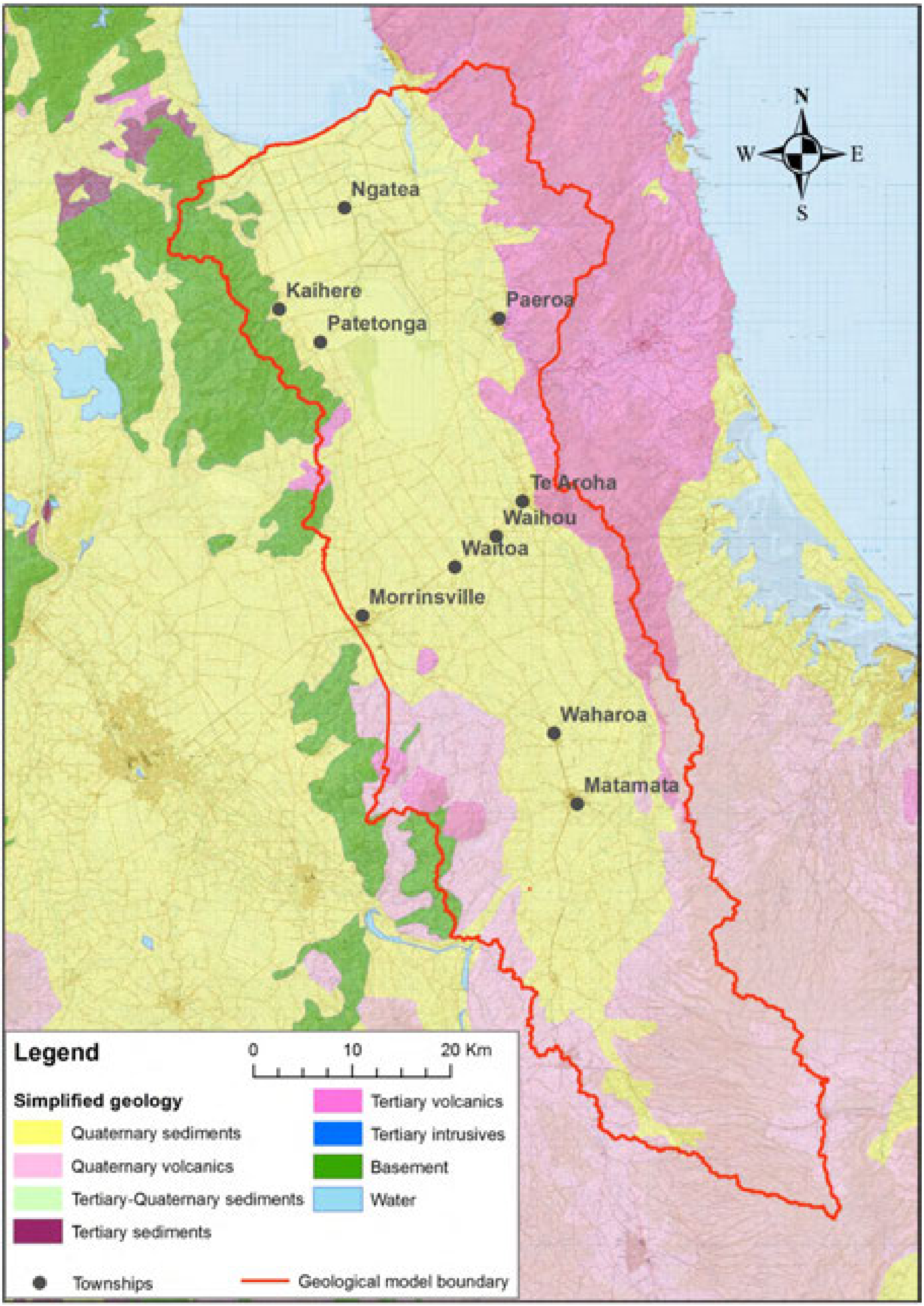

Figure 2.1 Summary geological map of the study area, after Leonard et al. (2010) and Edbrooke (2001).

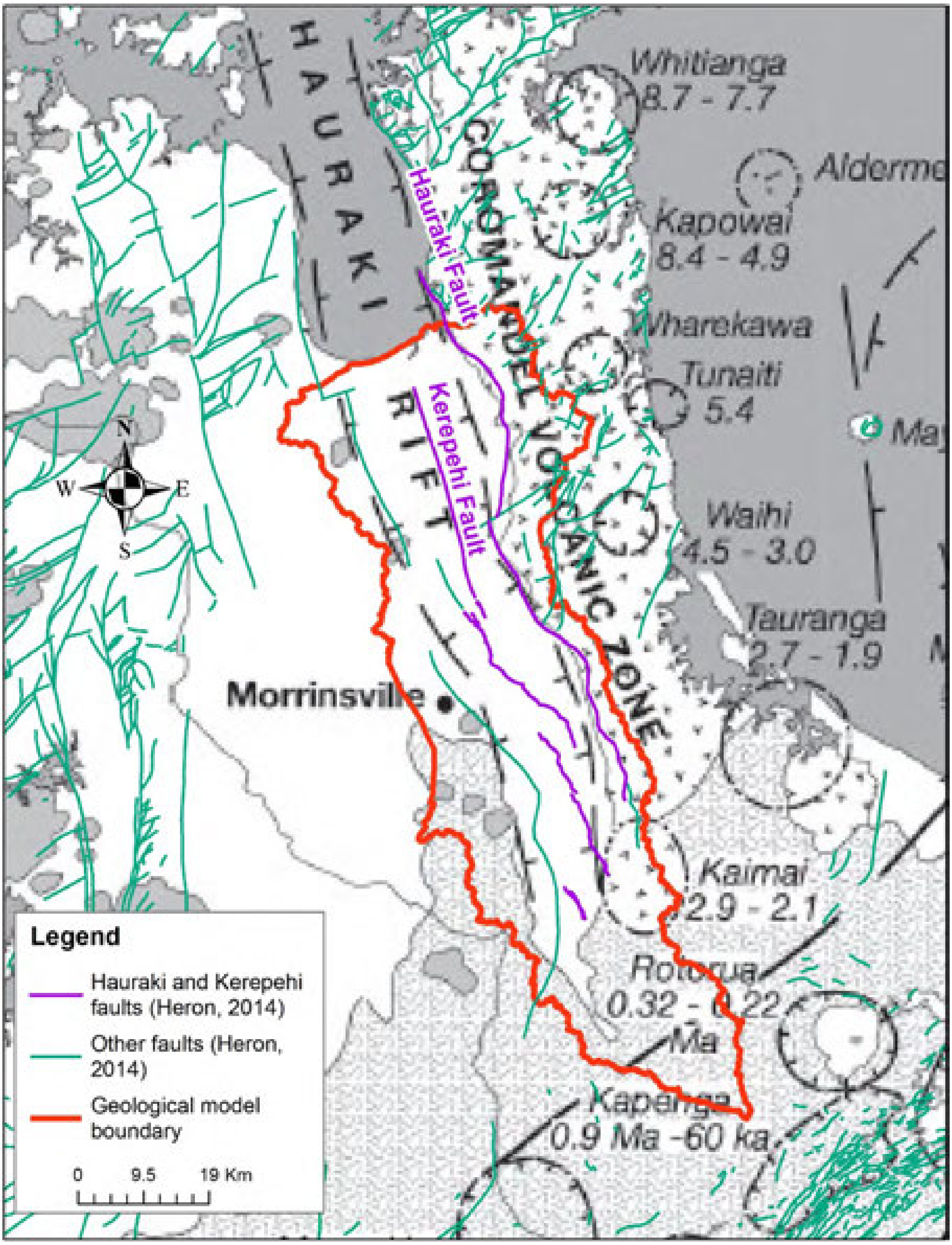

Figure 2.2 Location of Hauraki and Kerepehi faults within the geological model area (base map after Briggs et al. (2005)).

2.1 Geological Structure

The Hauraki Rift, west of the Coromandel Peninsula, is defined by currently-active faults striking at approximately 340° azimuth (Chick et al. 2001), Figure 2.2. The Hauraki Fault forms the eastern boundary of the rift against tertiary volcanic rocks of the Coromandel Peninsula. The Kerepehi Fault is also an important structural feature. It runs parallel with the Hauraki Rift and lies buried beneath the alluvial cover, displacing greywacke basement rocks (de Lange and Lowe 1990). Geophysical sections across the Hauraki Rift (Figures 2.3 and 2.4) show that the rift consists of three structural elements: 1) a fault-angle depression to the west, 2) a central horst, and 3) a graben to the east. This composite rift structure is filled with Tertiary and Quaternary terrestrial sediments to a maximum thickness of 3 km (Hochstein and Balance 1993).

To the south, the rift extends as far as the Ohakuri Volcanic Centre (Hochstein and Hunt 1980) and south of Matamata it is infilled by non-volcanic sediments, suggesting that the Hauraki Rift development commenced prior to development of the TVZ in the early Pleistocene (Hochstein and Hunt 1980). According to geophysical modelling of Hochstein and Balance (1993), sediments infilling the Hauraki Rift can be divided into older consolidated Tertiary sediments that become thicker to the south and unconsolidated Quaternary sediments that become thicker to the north (Figures 2.3 and 2.4).

Pleistocene volcanic rocks, including Mamaku Plateau Formation ignimbrite, cover most of the Hauraki Rift south of Matamata. South of the Hauraki Plains, the Hauraki Rift is buried beneath ignimbrite, and other deposits of volcanic origin from the Rotorua Caldera (Milner et al. 2003). Unconsolidated sediments are an estimated 500 m thick near the Firth of Thames and a central horst ridge (i.e., Section A, Figure 2.4) is continuous along the axis of the Hauraki Rift (Hochstein and Balance 1993). The thickness of unconsolidated sediments decreases to about 300 m at the southern end of the Hauraki Plains near Matamata (i.e., Section C, Figure 2.4). The horst structure that divides the rift zone into an eastern and western graben at the northern end of the Hauraki Plains disappears towards the south. South of Matamata the Hauraki Rift widens and merges with the TVZ (Hochstein and Balance 1993).

The geological structure of the southern Hauraki Plains (Figures 2.5 and 2.6) is summarised by Houghton and Cuthbertson (1989) and Cuthbertson (1981), including:

- Basement greywacke;
- Tertiary sediments and volcanics;
- Quaternary sediments, including Pleistocene – Holocene age Tauranga Group sediments and Holocene Piako Swamp.

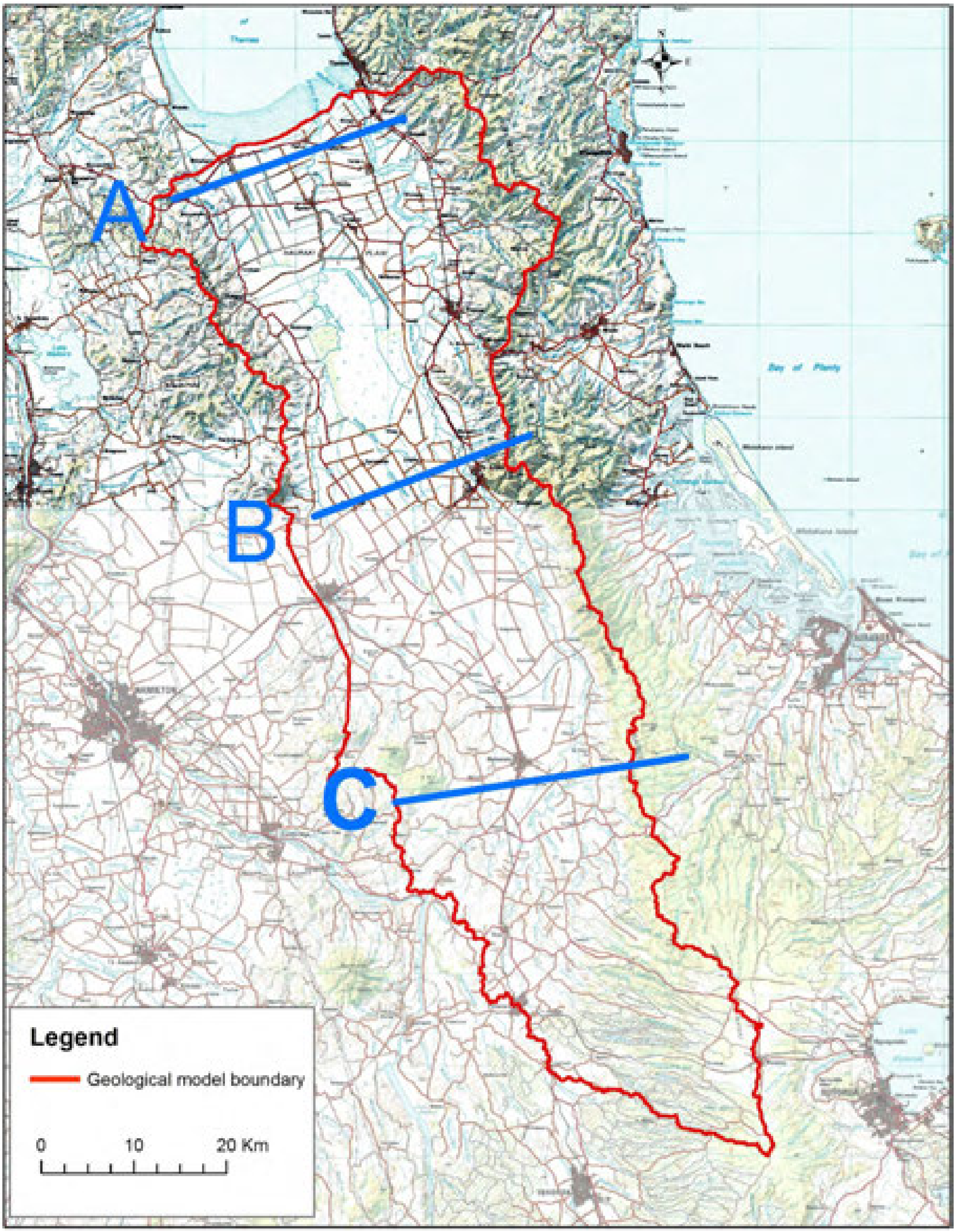

Figure 2.3 Location of geophysical survey sections across Hauraki Rift after Hochstein et al. (1986) and Hochstein and Balance (1993). Profile A: Northern end of Hauraki Plains, B: middle south of Kopuatai Peat Dome and C: southern end of Hauraki Plains.

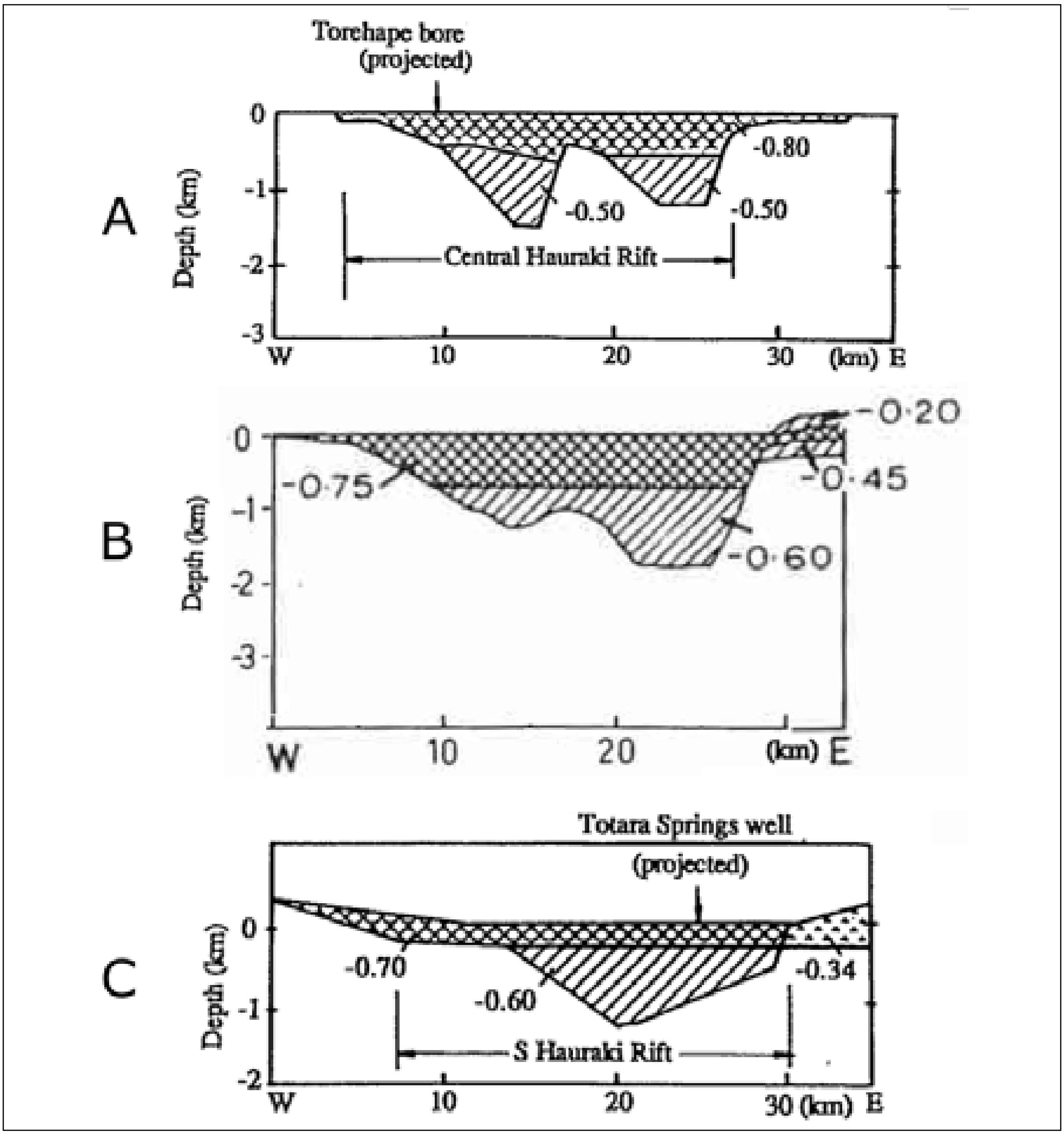

Figure 2.4 Interpretation of geophysical (gravimetry) survey sections across Hauraki Rift (Figure 2.3), after Hochstein et al*.* (1986) and Hochstein and Balance (1993). Numbers describe the density contrast (in 10^3 kg/m^3) used for modelling the sediments compared to that used for modelling the basement (shown in white; 2.65 x 10^3 kg/m^3). Note the decrease in the thickness of younger unconsolidated sediments (crossed pattern) towards the south and the increase in the thickness of the older consolidated Tertiary sediments (diagonal line pattern) towards the south. The dotted unit represents Tertiary Coromandel volcanics (Profile C).

Figure 2.5 Location of geological block model in the southern Hauraki Plains (Figure 2.6).

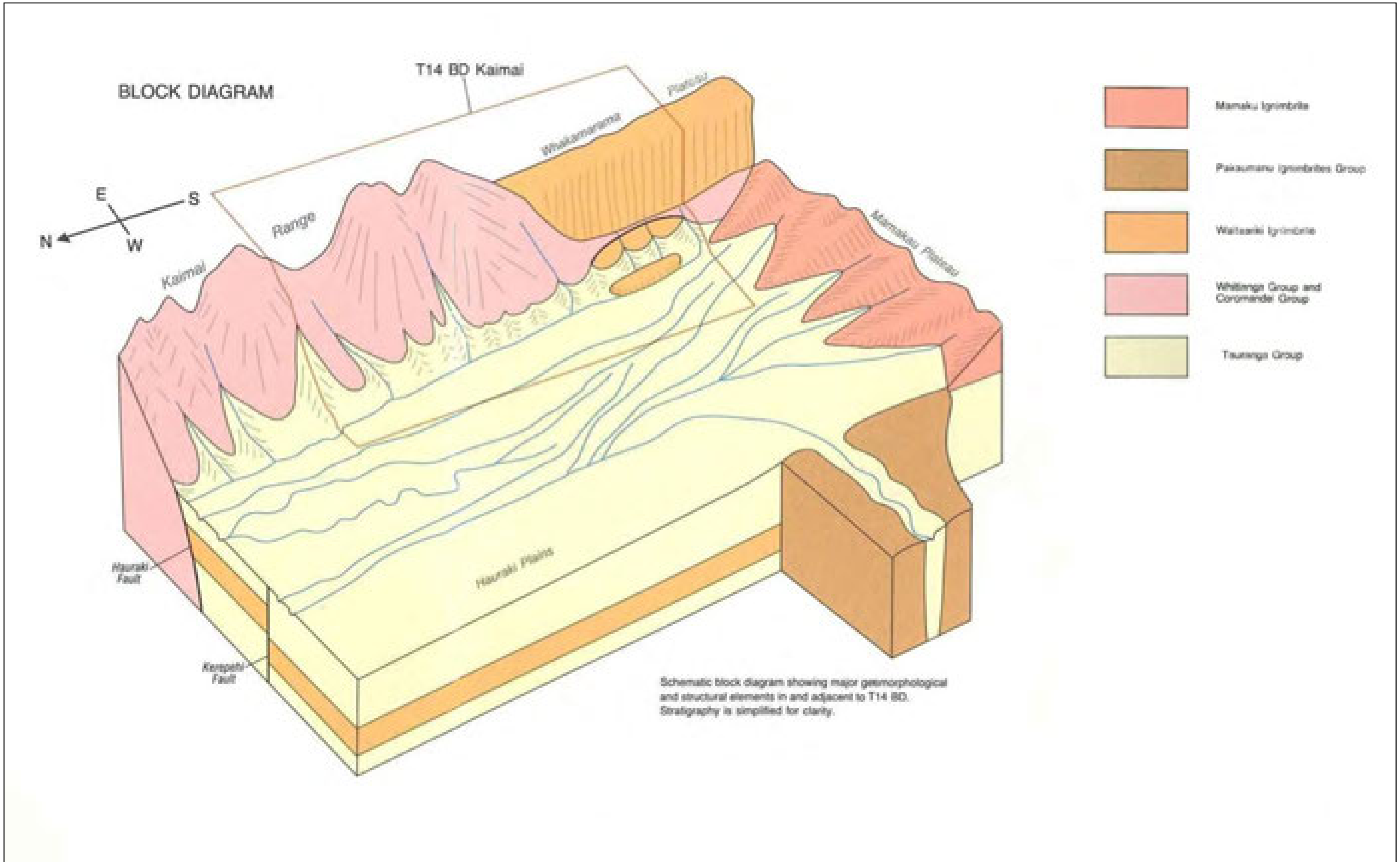

Figure 2.6 Geological block model in the southern Hauraki Plains (after Houghton and Cuthbertson 1989). The location of this model is shown in Figure 2.5. Note that the sediments located below Waiteariki Ignimbrite are probably Tertiary in age because Briggs et al. (2005) identify a Pliocene age for the Ignimbrite.

2.2 Major Geological Units

2.2.1 Basement Greywacke

The basement is made up of Jurassic greywacke (Torlesse Group) rocks (Figure 2.1). Jurassic greywacke rocks are exposed along the western margin of the study area, on the Hapuakohe Range. The eastern side of the study area is bounded by Tertiary volcanic rocks of the Coromandel Range. Geophysical modelling indicates that the region is mostly underlain by down-faulted greywacke rocks (Hochstein and Hunt 1980; Hochstein et al. 1986) and greywacke is assumed to occur at depth on the eastern side of Hauraki Plains (Houghton and Cuthbertson 1989).

Basement rocks generally are not productive aquifers in New Zealand due to restricted pore space. However, their permeability is predominantly controlled by fractures in the rocks (Yang et al. 2001) and fractured zones do typically provide a limited groundwater resource. In the Hamilton Basin, which is located west of the Hauraki Plains, typical yields of 0.3-0.4 L/s have been reported from basement rocks, and maximum yields of 2.15 L/s (Marshall and Petch 1985).

2.2.2 Tertiary Sediments and Volcanics

Basement rocks are overlain by Tertiary sediments to a maximum thickness of about 2-3 km (de Lange and Lowe 1990; Hochstein et al. 1986). The thickness of consolidated Tertiary sediments increases towards the south on the Hauraki Plains (Hochstein and Hunt 1980).

Tertiary volcanic rocks occur along the north-eastern side of the Hauraki Plains in the Coromandel Range; east of Matamata these rocks comprise mostly dacitic ignimbrites including the Waiteariki Ignimbrite. Further to the north, towards Thames, rocks consist of Upper Miocene to Pliocene andesites and dacites of the Coromandel Group (Skinner 1986). Waiteariki Ignimbrite is interbedded with Tauranga Group sediments in the southern Hauraki Plains. Hydrothermal alteration and mineralisation is widespread throughout the Coromandel Peninsula (Skinner 1986).

Tertiary volcanic rocks are also present to the west of the study area and include Miocene to Pliocene rocks of the Kiwitahi Andesites (Skinner 1986). These rocks are remnant outliers of dissected andesitic volcanoes and lava flows.

2.2.3 Quaternary Sediments

Quaternary sediments, of the Pleistocene – Holocene age Tauranga Group, in the Hauraki Plains include:

- pre-Hinuera Formation fluvial deposits including those derived from the TVZ (i.e., mQ and eQ; Leonard et al. (2010));
- Hinuera Formation fluvial deposits (i.e., Q3a; Leonard et al. (2010));
- Holocene fluvial deposits (i.e., Q1; Leonard et al. (2010)); and
- Holocene-age Piako Swamp deposits, including the Kopuatai Peat Dome, that were deposited in the current interglacial period.

Fluvial Tauranga Group sediments form common aquifers in the Waikato River catchment. The deposits are quite heterogeneous and include gravel, sand, silt, mud and peat of fluvial, lacustrine and volcanogenic sediments. Therefore, their hydraulic properties vary greatly. For example, yields in Hinuera Formation deposits may exceed more than 28 L/s (Marshall and Petch 1985), whereas interbedded paleosols, peat, tephra and loess layers may form aquitards.

2.2.3.1 Pleistocene pre-Hinuera Formation

Pre-Hinuera Formation Tauranga Group 'early Quaternary' alluvium derived from the TVZ, includes Karapiro Formation (Edbrooke 2001). Karapiro Formation is exposed west of Matamata in 'an extensive set of fluvial terraces' (Stanley 1994). The formation is described by Stanley (1994) as the following facies in outcrop at Kirk Rd (Figure 2.5):

- 'gravel, stratified' about 2 m thick at the top of the formation, above;
- 'massive or crudely bedded gravel' about 2 m thick, above;
- 'sand, medium to coarse' about 1 m thick, above;
- 'massive or crudely bedded gravel' about 2 m thick, above;
- 'sand, very fine to coarse' that is relatively thin, above;
- 'silt', less than 1 m thick, above;
- 'sand, medium to coarse' about 2 m thick at the base of the Formation.

The age range for this formation is 1.23 Ma to 0.33 Ma (Stanley 1994), with age estimates provided from the ages of an overlying tephra and an underlying ignimbrite. Stanley (1994) proposes that Karapiro Formation 'originally in-filled' the Hauraki Rift before being buried and then overlain by Hinuera Formation. Gravels are common in the Karapiro Formation and these gravels could be an important marker for geological correlation in the Hauraki Rift. Drill holes identify a significant thickness of Pleistocene sediments below Hauraki Plains. However, the thickness of pre-Hinuera Formation alluvium is unknown because the boundary between Pre-Hinuera Formation and Hinuera Formation is unknown. Pre-Hinuera Formation Tauranga Group sediments are identified below Waiteariki Ignimbrite (Figure 2.6 and Briggs et al. 2005).

2.2.3.2 Pleistocene Hinuera Formation

Hinuera Formation sediments, present in Hauraki Plains and the Hamilton Basin, comprise mainly infilling near-surface Tauranga Group volcaniclastic alluvium (Figures 2.6 and 2.7). These terrestrial sediments were mostly deposited after the Oruanui caldera eruption from the Lake Taupo area 26,500 years ago (Manville and Wilson 2004), when the sea level was approximately 100 m lower (Hochstein and Balance 1993).

Hinuera Formation surface exposure in the Hauraki Plains extends north from the foothills of the Mamaku Plateau (Schofield (1965); McGlone et al. (1978); Cuthbertson (1981)) to the Te Aroha – Morrinsville area (Figure 1.1). Hinuera Formation comprises mainly cross-bedded sand and gravels interbedded with silt and some peat; these sediments are composed of mainly rhyolitic and pumiceous materials (Cuthbertson 1981). Manville and Wilson (2004), Figure 2.8, identified four phases of deposition of the Hinuera Formation in Hauraki Plains:

- Hinuera A deposited after the 220 ka Mamaku eruption and before the Oruanui eruption from the Lake Taupo area 26,500 years ago when the Waikato River flowed into the Hauraki Plains (Figure 2.9);
- Hinuera B deposited between approximately 26,500 and 24,000 years ago before the Waikato River moved to its present course;

- Hinuera C deposited by the break-out flood from Lake Taupo after the Oruanui eruption and forms 'much of the surface development of the Hinuera Formation in the Hauraki Plains' Manville and Wilson (2004). Palaeochannel systems (Figure 2.10) are observed on the ground surface 'one corresponding to the ancestral Waikato River and a more easterly system corresponding to the Waihou River' (Manville and Wilson 2004);
- Hinuera D where 'the Waihou River became entrenched in its course throughout Hauraki Plains' (Manville and Wilson 2004).

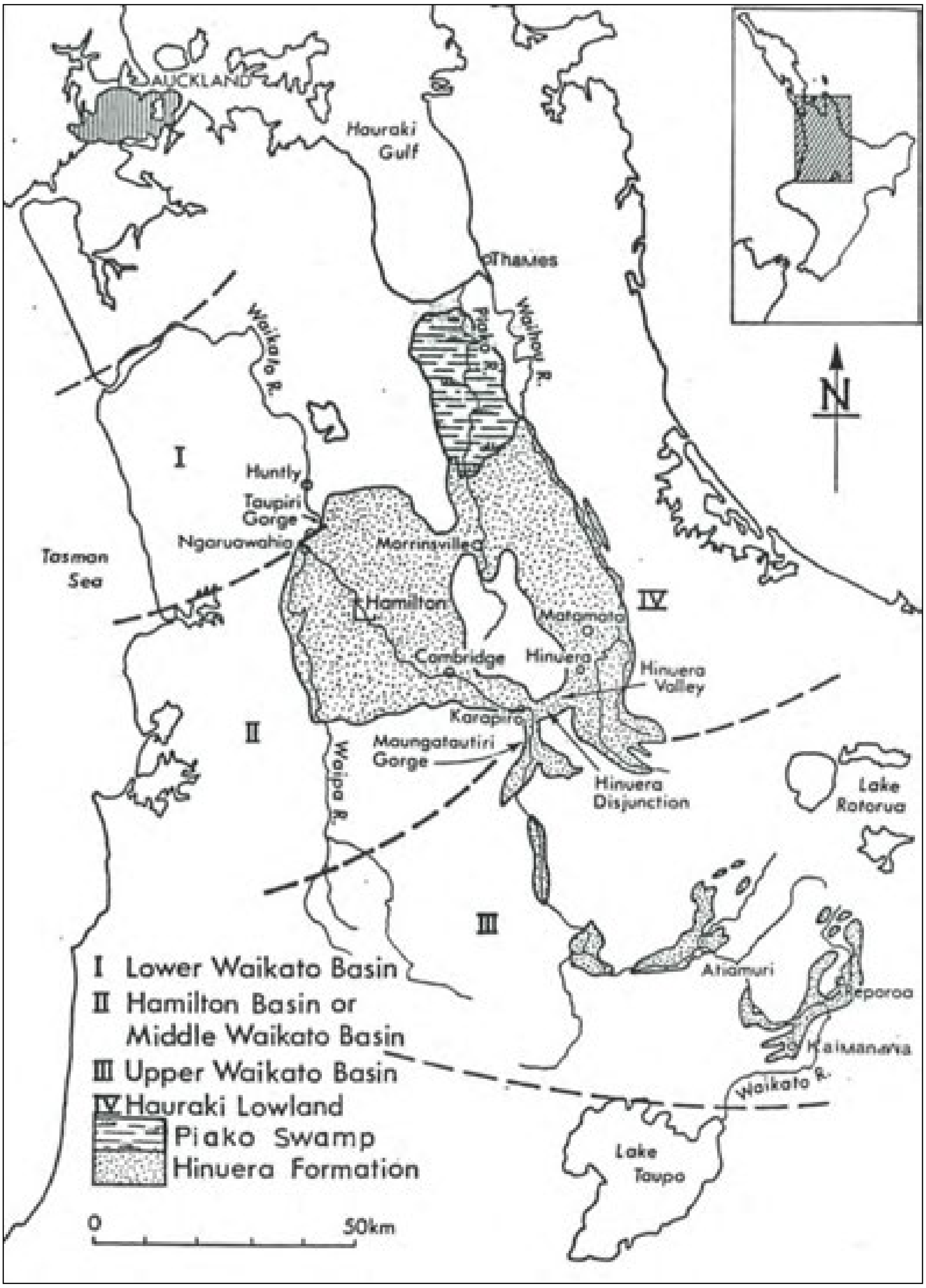

Figure 2.7 Location of the Hinuera Formation in Hauraki Plains and Hamilton Basin and location of Piako Swamp (after Cuthbertson 1981).

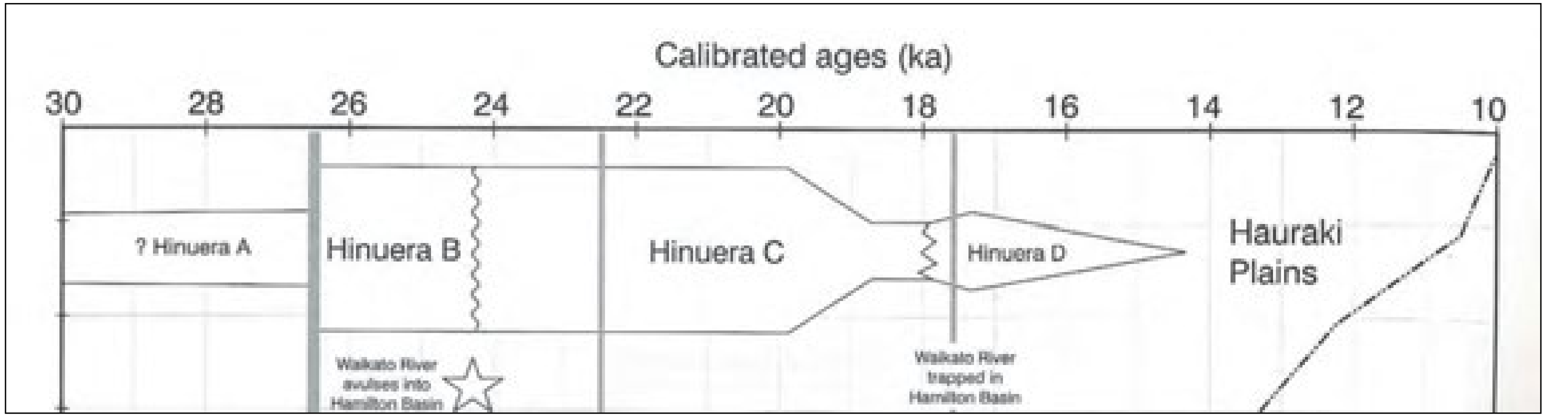

Figure 2.8 Hinuera Formation development in Hauraki Plains (after Manville and Wilson 2004).

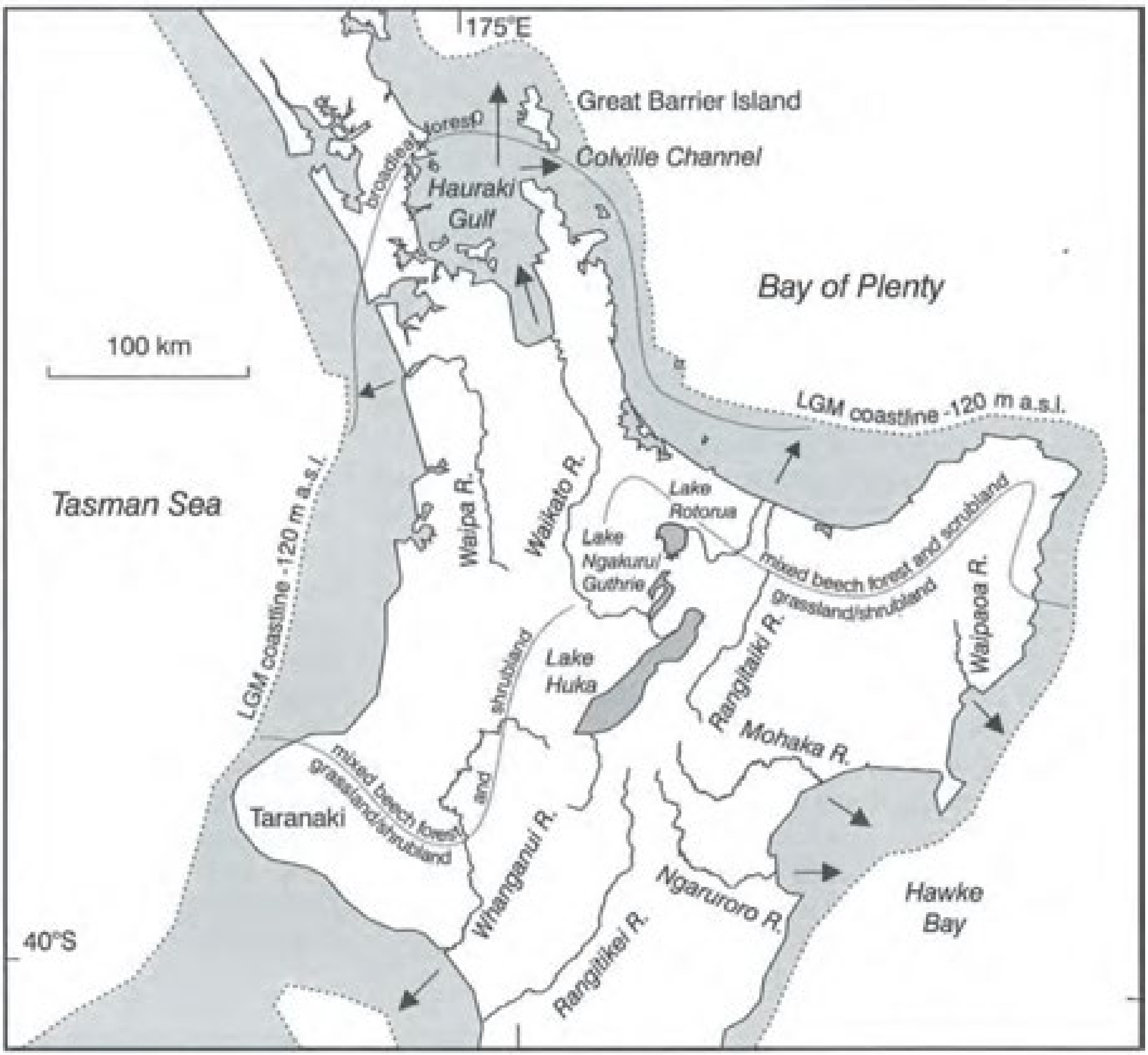

Figure 2.9 The Waikato River flowed into Hauraki Plains immediately before the 26,500 Oruanui eruption (Manville and Wilson 2004).

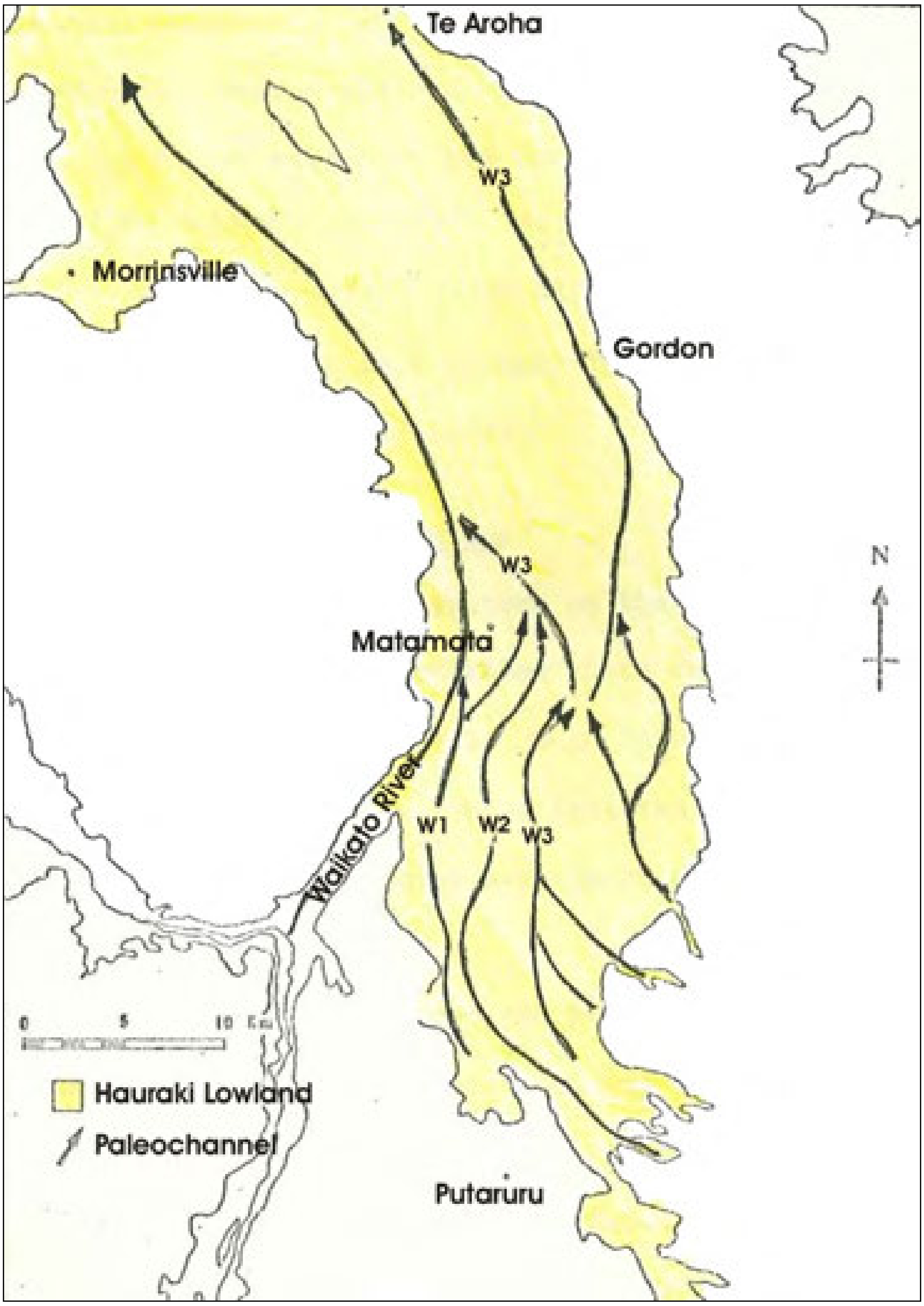

Figure 2.10 Schematic of Waikato River and Waihou River channel features on the surface of Hinuera Formation (after Cuthbertson 1981).

2.2.3.3 Holocene Alluvial Deposits

Holocene alluvial deposits include 'reworked Hinuera Formation material since the end of Hinuera deposition' (Cuthbertson 1981) of the Waitoa Formation (Houghton and Cuthbertson 1989). These deposits are associated with modern river courses and palaeochannels of modern rivers and streams.

2.2.3.4 Holocene Piako Swamp and Kopuatai Peat Dome

Pleistocene sediments at the ground surface were partly drowned with a rise in sea level in the Holocene period. Following the post-glacial sea level rise the Hinuera Formation became overlain by thin marine and estuarine muds, river sediments and peat deposits of the Piako Swamp (Figure 2.7), which includes the Kopuatai Peat Dome (de Lange and Lowe 1990).

The Kopuatai Peat Dome is the largest raised peat bog in New Zealand and is unique as it contains records of up to thirteen tephra layers within peat sediments (de Lange 1989; Newnham et al. 1995). The bog formed on the paleo-channel of the ancient Waikato River (Newnham et al. 1995). The development and evolution of the Kopuatai Peat Dome is described in detail by Newnham et al. (1995) and Shearer (1997). In summary, peat first developed in the south at Piako Swamp and later became covered by a marine transgression around 6,000 years ago. The areal extent of the bog decreased around 4,000 years ago in association with warm and dry climates, followed by contraction to its current position.

As the Kopuatai Peat Dome is situated above a fault zone (Kerepehi Fault), progressive offsets of the tephra horizons with time have shown that vertical fault movement (downthrown to the west) has been occurring for the past c. 10,700 years (Newnham et al. 1995) thus providing evidence that the Hauraki Plains remains an active rift zone.

2.2.4 Quaternary Volcanics

2.2.4.1 Waiteariki Ignimbrite

Waiteariki Ignimbrite is mapped on the Kaimai Range north of Mamaku Plateau (Houghton and Cuthbertson 1989). This ignimbrite is a welded and possibly sourced from the Kaimai Volcanic Centre (Briggs et al. 2005). Waiteariki Ignimbrite is Pliocene, with a measured age of approximately 2.09 Ma (Leonard et al. 2010; Briggs et al. 2005). The thickness of Waiteariki Ignimbrite below outcrop is an estimated 300 m in the Kaimai Range (White et al. 2008); the unit is also identified below the Hauraki Plains (Houghton and Cuthbertson 1989), Figure 2.6.

2.2.4.2 Pakaumanu Group

Pakaumanu Group ignimbrite forms outcrops over a wide area in the southwest of the Hauraki Plains west of Matamata. The Pakaumanu Group ignimbrite, with an inferred age of approximately 1.68 to 1.0 Ma, comprises a series of welded and non-welded ignimbrite deposits (Edbrooke 2005).

2.2.4.3 Mamaku Plateau Formation

Mamaku Plateau Formation ignimbrite sheets, erupted from the Rotorua Caldera around 240 ka ago (Shane et al. (1994); Leonard (2003)), cover the Hauraki Rift in the south and form the Mamaku–Kaimai Plateau (White et al. 2004). The surface of this plateau dips gently to the northwest and the ignimbrite thins westwards towards the Hauraki Rift (Milner et al. 2003). The ignimbrite consists of three main subunits (Milner et al. 2003) with thicknesses estimated by

White et al. (2007): upper, non-welded and a median thickness of 5 m; middle, strongly welded with cooling joints and a median thickness of 60 m; lower, non-welded and a median thickness of 45 m. The ignimbrite units overlie a basal tephra sequence. Studies by Gravley et al. (2006, 2007) indicate a close temporal and spatial proximity of the eruption of the Mamaku Ignimbrite and the eruption of the Ohakuri Formation.

Rosen et al*.* (1998) consider the lower and upper units of Mamaku Plateau Formation ignimbrite as permeable and the middle section as impermeable. Morgenstern et al*.* (2004), however, suggest that the middle section is an aquifer due to the existence of fractures in this sheet. The basal tephra sequence, on the other hand, is likely to be an aquitard: Crafar (1974); Morgenstern et al*.* (2004); White et al*.* (2007).

A transmissivity of 600 m^2/day was calculated for Mamaku Plateau Formation from a pumping test conducted in a bore northwest of Lake Rotorua. Hydraulic conductivity was calculated as ca. 6 m/d (~0.007 cm/s) for an assumed formation thickness of 100 m Reeves et al*.* (2005). A transmissivity value of 4,280 m^2/day and a hydraulic conductivity value of 717 m/day for Mamaku Plateau Formation ignimbrite have been calculated from a pumping test in the Lake Tarawera catchment (Thorstad et al*.* 2011).

2.2.5 Some Published Lithological Observations from Drill Holes

Shallow core logs drilled at the Firth of Thames contain at least 10 m of Holocene volcanic mud, similar in composition to that of the Hauraki Plains, mainly prograding silicic pyroclastic and volcaniclastic mud deposits (Naish et al. 1993). Coring of the Kopuatai Peat Dome show peat sediments, which include tephra horizons (de Lange and Lowe 1990), of up to 14 m thickness.

Bore holes located near Ngatea were comprised of unconsolidated sediment to depths of 350 m, which is consistent with Pleistocene sediment thicknesses in bores near Thames of 340 m (Hochstein and Balance 1993). At Torehape, in the northern Hauraki Plains, a 310 m deep groundwater well intersects unconsolidated volcaniclastic sediments and marine clays, silts and river gravels; volcaniclastic sediments comprise about 30% of the sequence and therefore volcaniclastic sediments do not dominate deposition in this part of the Hauraki Plains (Hochstein and Balance 1993). Gravels are encountered in the ‘Torehape number 1’ groundwater well in three depth intervals (White 1981; Dewhurst 1983):

- approximately 166 m to 180 m, gravel, sand;
- approximately 251 m to 255 m, gravel;
- approximately 288 m to 293 m, gravel.

In addition, the well encountered ‘clay, weathered greywacke becoming hard’ at depths of approximately 300 m to 310 m, possibly indicating the proximity of greywacke basement at these depths.

In the southern Hauraki Plains, volcaniclastic sediments and ignimbrites are common in drill holes. For example, a 320 m drill hole at Totara Springs consists mostly of pyroclastic flows and volcaniclastic sediments with only minor alluvial sediments (Hochstein and Balance 1993). At 100 m depth this well intersects Waiteariki Ignimbrite and underlying alluvial sediments.

Kear and Tolley (1957) assessed lithology in a drill hole at Morrinsville approximately 287 m deep, where they identified (Figure 2.11):

- 'mainly acid volcanic detritus' Kear and Tolley (1957) to a depth of approximately 274 m including 'beds' A, B, C, D, E and F;
- brown sand, with well-rounded grains of Mesozoic rocks, between approximately 274 m and approximately 287 m including 'bed' G.

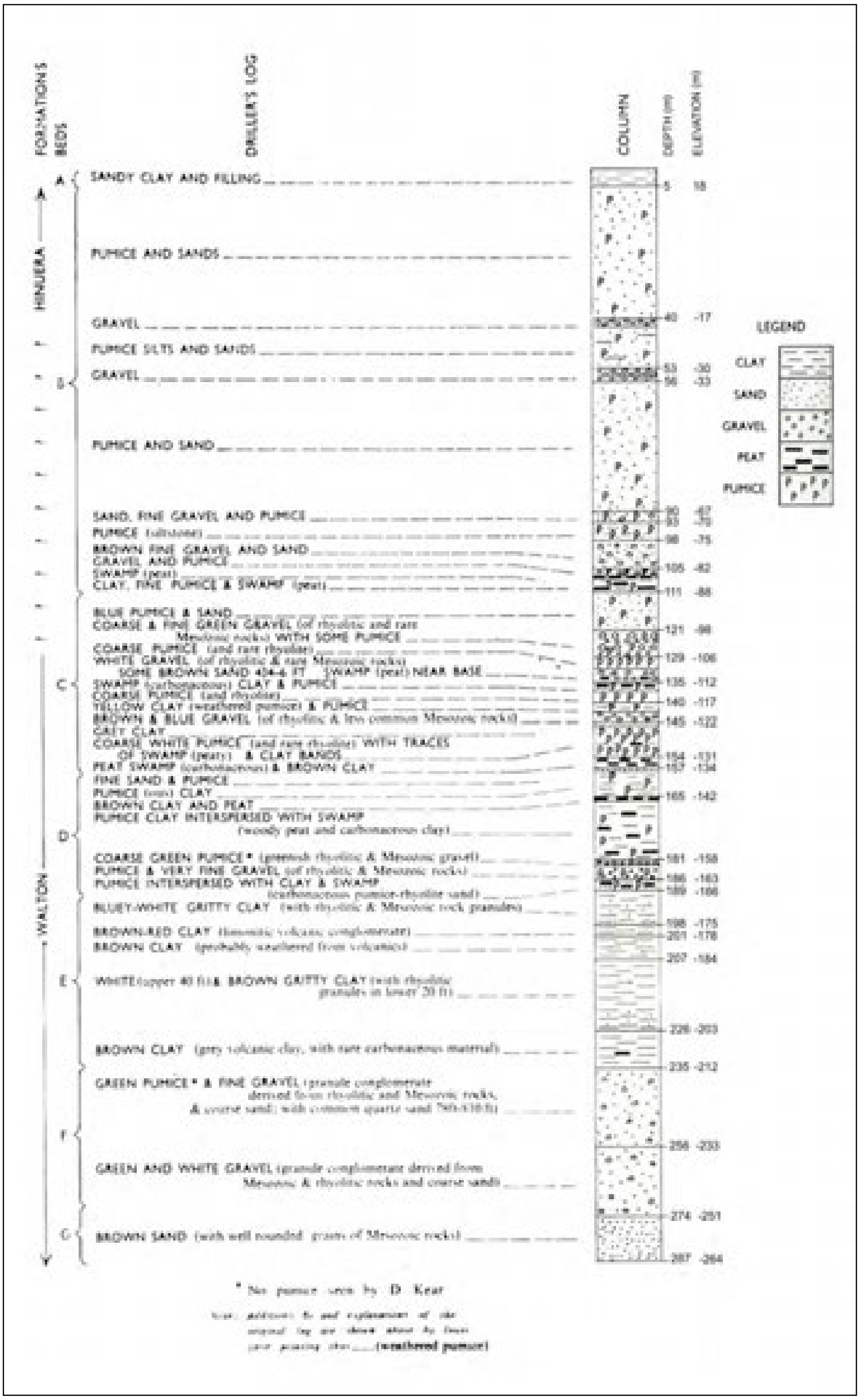

Figure 2.11 Lithological log of the approximately 287 m deep drill hole near Morrinsville (Kear and Tolley 1957).

Kear and Tolley (1957) correlate beds A and B, to a depth of approximately 111 m, with Hinuera Formation (in part) and older Pleistocene sediments (in part) with an unknown contact between Hinuera Formation and older Pleistocene sediments. Pleistocene plant microfossils are observed in beds C and D in the depth range approximately 135 m to approximately 189 m of Nukumaruan stage (part of the Late Pliocene Period of the Tertiary), or approximately 2.4 Ma to 1.63 Ma. Beds E and F, to approximately 274 m, are ‘probably Nukumaruan in age’ (Kear and Tolley 1957). Gravels, derived from acid volcanics and from Mesozoic rocks, are observed in bed F. However, the Tertiary age of these sediments proposed by Kear and Tolley (1957) appears contradicted by Stanley (1994) who suggests these sediments are Pleistocene in age and part of Tauranga Group (Karapiro Formation) sediments.

Gravel was also observed in approximately nine layers in the Morrinsville drill hole; these gravels are:

- commonly composed of rhyolitic and Mesozoic clasts;
- commonly interbedded with swamp deposits, suggesting a sequence of sedimentary deposition in a relatively high-energy environment (gravel) and deposition in a relatively low-energy environment (swamp), e.g., possibly representing an alternating glacial/interglacial sequence.

Gravels are also observed in wells located near Matamata (e.g., Zemansky and Wall 2007). For example, gravels were identified in a well drilled for water supply near Matamata in the following depth intervals (Zemansky and Meilhac 2007):

- approximately 8.8 m to 11.9 m, very coarse sand and gravel;
- approximately 19.4 m to 20 m, gravel;
- 41 m to approximately 49.4 m gravels, sands and clay;
- approximately 82.7 m to 84.6 m very coarse sand and gravel.

Gravel was also observed in a 212.4 m drill hole near Matamata but this hole did not intersect thick gravel horizons (Meilhac and Zemansky 2007). Gravel occurs with sands and silts in the depth intervals:

- 12 m to 23 m, sandy silt with gravel;
- approximately 66 m to 74 m, sands and gravels;
- 153 m to 156 m ‘small’ gravels and silt;
- 168 m to 174 m ‘small’ gravels and sand;
- 191 m to 193 m ‘small’ gravels and silt.

Meilhac and Zemansky (2007) suggest that this drill hole intersected the Hinuera Formation but did not reach the Karapiro Formation.

2.3 Geothermal Features and Hot Springs

The hydrological setting of Hauraki Plains hot springs is summarised in Figure 2.12 from Hochstein and Nixon (1979). Meteoric flows derived from the western and eastern ranges flows into the rift depression to depths of up to 6 km. This groundwater is heated at depth to temperatures of up to 250-300 °C and then flows towards the surface as hot springs along faults (Hochstein and Hunt 1980).

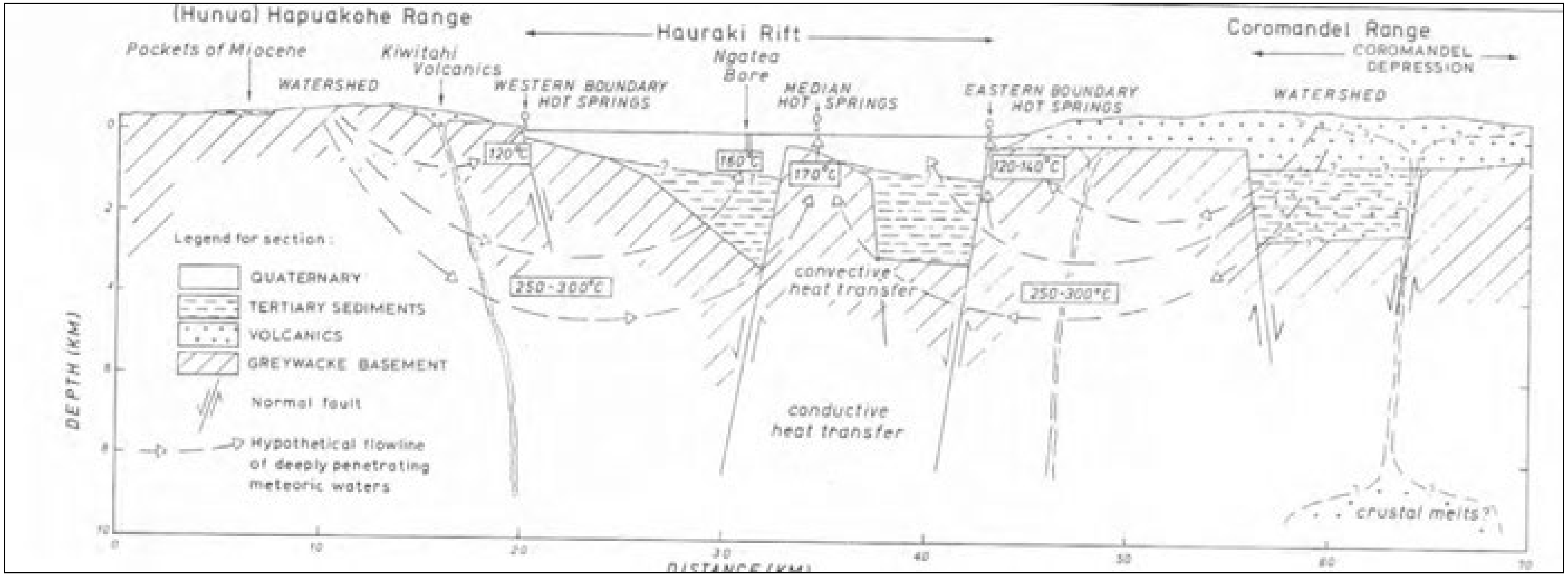

Figure 2.12 Simplified hydrological setting of Hauraki Plains (after Hochstein and Nixon 1979).

3.0 METHODOLOGY

3.1 3D Geological Model

The Hauraki Plains 3D model was assembled as a layer model, and a volume model using EarthVision 8.1 3D modelling software (Dynamic Graphics, Inc.). The horizontal model resolution was set to 100 m by 100 m with an elevation range of approximately +1000 m to -1500 m relative to mean sea level.

3.1.1 Introduction

A 3D geological model is generally composed of a series of geological layers that are assembled by taking into account their relative chronology and structural relationships. The model developed in this report is built from a sequence of simplified geological layers, hereafter referred to as the ‘model units’, which correspond to an aggregation of individual geological formations and groups of formations. These aggregations are based on the hydrogeological characteristics of units and the data available for modelling. This definition of the units to be modelled is a key step in the modelling process. Once defined, the contact surfaces between units are modelled and their relative chronology established to allow the generation of representative volumes.

Faults can also be represented in the model. Generally, they are indicated through the behaviour of the surfaces and volumes, but they can be made more explicit, if necessary, e.g., to simplify modelling between two fault blocks with hugely different geological units present. For the Hauraki Plains model, the explicit integration of faults is not required within the scope of the model as a conceptual model of the groundwater system.

Data sets available to create the Hauraki Plains geological model include topographic data, geological maps, geological cross sections, and well logs. The geological maps and geological sub-surface information available are used to identify geological formations in the area and to group all relevant geological formations and groups into key model units. Then, the geological map (QMAP; Heron et al. 2012) polygons for all geological formations are assembled and merged into model unit polygons in ArcGIS (Esri Geographic Information System).

These polygons are used to identify topographic data points for the areas where these units are mapped at the ground surface. This surface exposure data is then combined in EarthVision with sub-surface data that are derived from other data sources (Section 3.1.2), and the contact surfaces for each model unit are constructed through interpolation between all available scattered data points for a unit. Several types of contact surfaces exist within EarthVision to best represent the underlying geological processes: erosion, deposition and unconformity. Local manual edits (control points) can be added by the modellers to constrain the contact surfaces in areas with little input data. The modeller then defines the surface chronology in a so-called “sequence file”; and surfaces are assembled to produce a stratigraphic 3D volume model.

Uncertainty in the geological model is strongly dependent on the datasets used for the modelling. For example, uncertainties in the horizontal location of layer boundaries are comparatively small for layers exposed, and mapped, at the ground surface. However, for layers below the ground surface, uncertainties in observations and interpretation will lead to larger uncertainties. The amount of input information available for a layer provides constraints on the possible ranges of the layer spatial extent (lateral and vertical). A layer can be well constrained if, for example, a high density of wells are available that penetrate this layer and underlying units, or poorly constrained due to lack of wells or other information.

3.1.2 Model Data Sources

3.1.2.1 Topographic Data

Topographic data (Figure 3.1) are used to estimate the land surface elevation across the study area. The topographic datasets were used to develop a digital terrain model (DTM), which interpolates ground elevation between points at which measurements have been made. The DTM used for the geological modelling is a 5 m resolution DTM provided by WRC (Braybrook 2014). This DTM was used to define the top surface (i.e., ground elevation) of the 3D geological model, including the elevations of geological units and faults that are mapped at the ground surface. The DTM was also used to estimate the elevations of well heads, allowing conversion of depths measured by bore logs into elevations relative to mean sea level.

3.1.2.2 Geological Maps

Surface geology (Figure 2.1) in the Hauraki Plains has been compiled from the 1:250,000 scale Rotorua and Auckland ArcGIS maps (Leonard et al*.* 2010; Edbrooke 2001; Heron et al. 2012). The geological boundaries were used in ArcGIS to define the ground surface exposures of geological units that were then used in the 3D model.

3.1.2.3 Cross Sections

Cross sections relevant to the Hauraki Plains geological model are those derived from gravity measurements (Figure 2.4). These are particularly relevant to the estimation of the thickness of unconsolidated sediments in the Hauraki Plains. The interpretation of structure in the southern Hauraki Plains is also relevant to the model development (Figure 2.6) as are the geological cross sections of Houghton and Cuthbertson (1989).

3.1.2.4 Well Log Data

WRC records the locations of bores within the Hauraki geological model area; these bores may include lithological information (Figure 3.2). Most bores are located within quaternary sediments of the Hauraki Plains, between the Kopuatai Peat Dome and Tirau.

The depth range of bores with lithological information within the Hauraki model area is shown in Figure 3.3. This includes a total of 1442 wells with:

- 925 bores drilled up to 50 m depth;
- 430 bores drilled from 50 m to 130 m depth; and
- 87 bores drilled from 130 m to 360 m depth.

3.1.2.5 Loss of Lithological Information in the WRC Lithology Database

WRC's database of lithology includes a summary of lithology recorded by drillers. WRC summarises lithological identifications in well logs as 'dominant fraction' and 'secondary fraction' of lithology. Typically, more lithological information is recorded in the original well logs than in WRC's database. For example:

- The lithological log of the Morrinsville well (Figure 2.11) records lithological information such as sediment type and some details on the sample, including provenance (e.g., 'brown sand' and 'well rounded grains of Mesozoic rocks' at the base of the well).

Information on 'well rounded grains' and 'grains of Mesozoic rocks' is very useful to geological model development as it indicates the depositional environment of sediments.

- WRC's database has, for the lithology at the base of the well, 'sands brown'. This conveys much less information than is available, and therefore information is lost in the WRC lithology database for this well.

It is recommended (Section 6) that WRC record full lithological descriptions, as noted by the driller, on its database of lithology. This will give full information on lithology, including lithology markers, available for geological modelling.

3.1.3 Grouping of Formations into Model Units

The Hauraki Plains 3D geological model was constructed to represent major formations between the ground surface and the basement. However, the model does not represent all units mapped at the ground surface in the area (Leonard et al. 2010; Edbrooke 2001) and formations are grouped to simplify the model.

Formations are grouped into model units depending on lithology, geographic extent, age range and/or data availability, with regard to the purpose of the model. Each geological map polygon is grouped with similar map polygons. The polygon grouping is based on the stratigraphical unit of the polygon and its description. In some cases, polygons of limited extent are aggregated with the surrounding model layer.

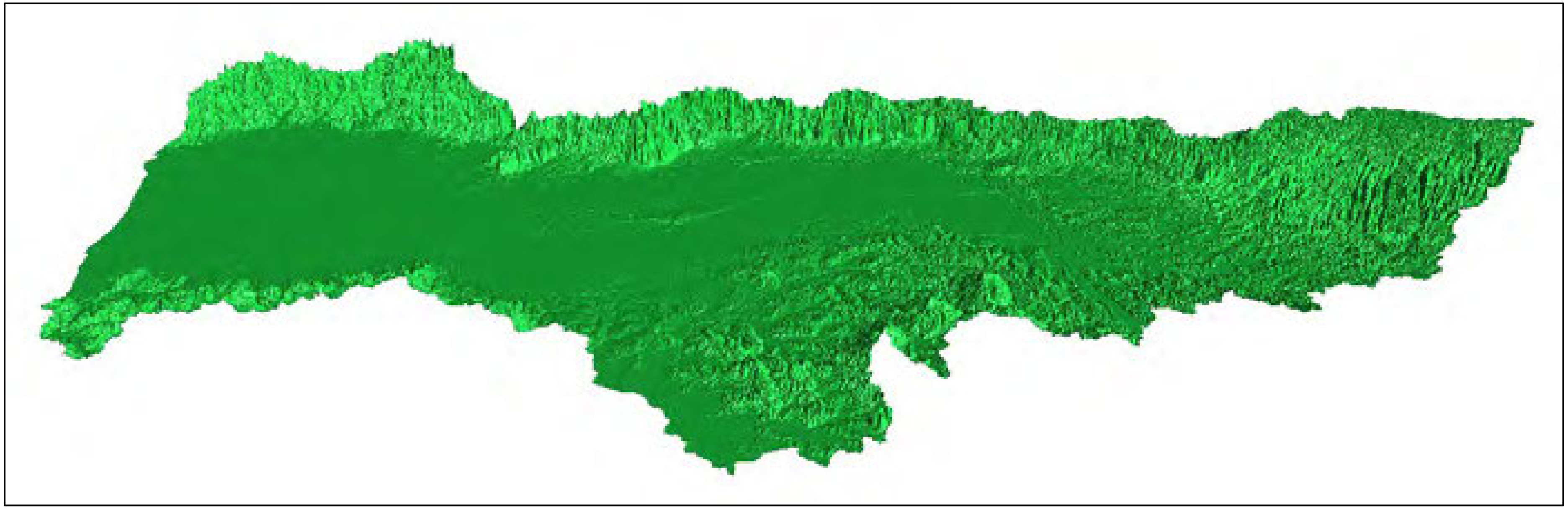

Figure 3.1 DTM of the study area, viewed from the west; vertical exaggeration 5.

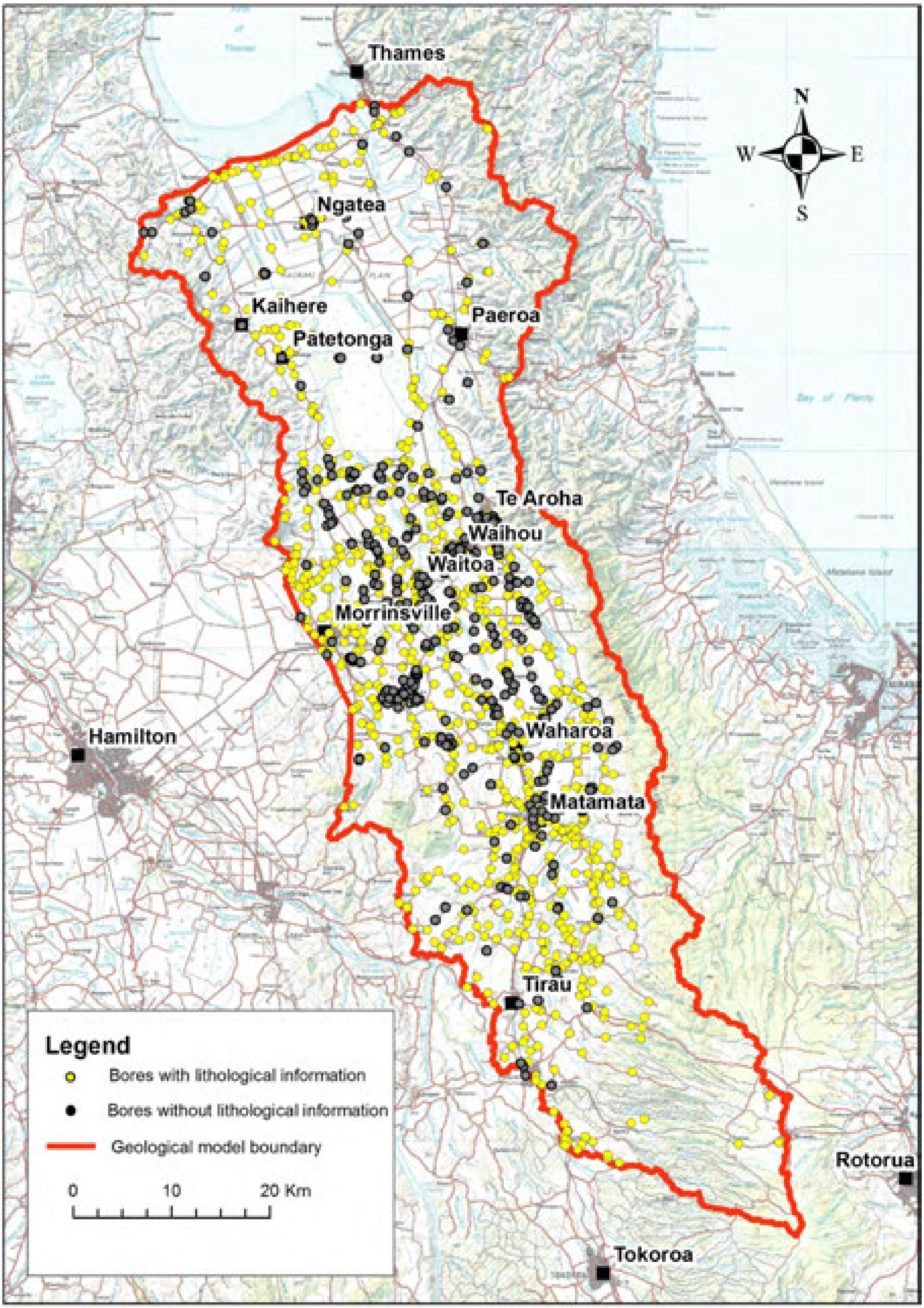

Figure 3.2 Location of bores from Environment Waikato records with and without lithological information in the Hauraki geological model area.

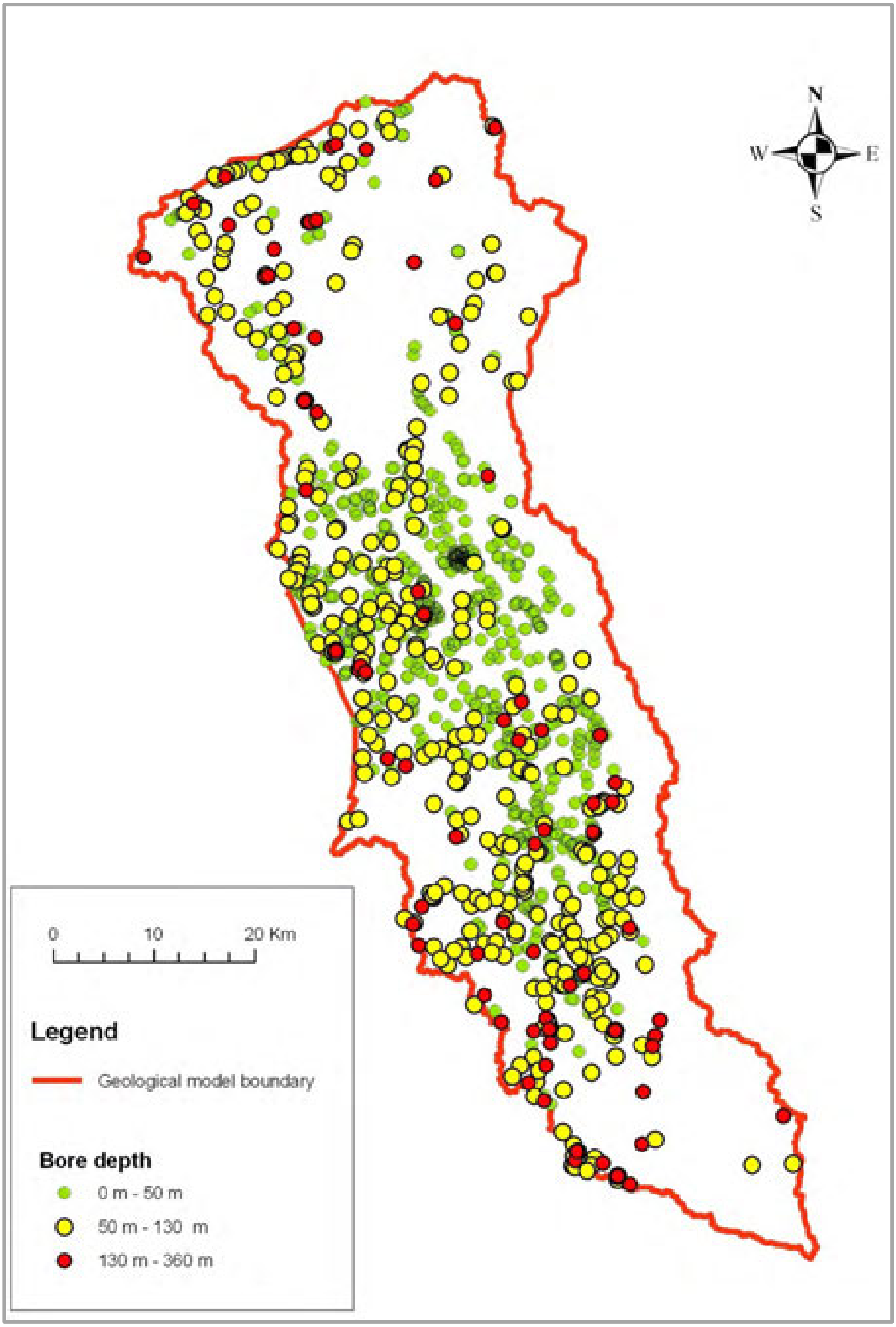

Figure 3.3 Depths of bores in the Hauraki geological model area with lithological information.

3.1.4 Model Units Description

The following text summarises the distribution of eight model layers that are represented in the Hauraki Plains geological model. These layers are outlined from oldest to youngest.

3.1.4.1 Basement

The basement layer of the model includes three lithological units: Jurassic greywacke, Tertiary Coromandel Group volcanics and Tertiary sediments. The “basement” of the North Island is conventionally accepted as low-grade metamorphosed Permian to Jurassic sedimentary terranes (i.e., greywacke) (Adams et al. 2009), however, it is known or inferred that these terranes also include much younger buried volcanic (e.g., andesite) and plutonic bodies (Stratford and Stern 2008; Sherburn et al. 2003; Arehart et al. 2002). Basement in the Hauraki Plains geological model includes mapped units that crop out (Leonard et al. 2010; Edbrooke 2001) that are chosen for their similar hydraulic characteristics.

Jurassic greywacke is exposed in the Hapuakohe Ranges to the east of Hauraki Plains. Greywacke is also identified in some drill holes. Where a greywacke gravel fan covers greywacke basement in the Hapuakohe Ranges, the base of the gravel fan is assumed as the top of the greywacke basement. Tertiary Coromandel Group volcanics crop out east of the Hauraki Plains. These volcanics are above greywacke in the eastern ranges. The geophysical model of Hochstein and Balance (1993) shows that the thickness of these volcanics may be approximately 200 m above the Jurassic basement (Figure 2.4).

Tertiary sediments are included in basement because these sediments are not mapped at the ground surface in the area and there is no information on the depth of Tertiary sediments in the Hauraki Plains area assessable from WRC drill hole data.

3.1.4.2 Tertiary Waiteariki Ignimbrite

Waiteariki Ignimbrite occurs on the Kaimai Range and beneath the southern Hauraki Plains. Waiteariki Ignimbrite crops out east of Matamata and has been identified in drill holes to 150 below sea level in the area. For example, ignimbrite was identified in well 64_593, northeast of Matamata, to the base of the well to a depth of 352 m (corresponding to an elevation of approximately 300 m below sea level).

3.1.4.3 Pleistocene Pakaumanu Group Ignimbrite

The Pakaumanu Group ignimbrites occupy the southern Hauraki Plains. They crop out west of Matamata and area deeper than 150 m below sea level in the subsurface northwest of Matamata.

3.1.4.4 Early Quaternary Tauranga Group Sediments

This unit crops out in the southwest of the Hauraki Plains (Leonard et al. 2010) and may represent Pleistocene Karapiro Formation (Stanley 1994), which was proposed as Tertiary by Kear and Tolley (1957). Gravel layers may mark chronological breaks in sedimentary deposition, for example:

- Stanley (1994) observed approximately 6 m of gravel at the top of Karapiro Formation, Section 2.2.3.1. Therefore gravel layers may mark the top of Karapiro Formation in the Hauraki Rift;
- Kear and Tolley (1957) observe gravel interbedded with swamp deposits (Section 2.2.5). Therefore, the gravel may indicate a chronological transition between deposition in a

relatively high-energy environment (gravel) and deposition in a relatively low-energy environment (swamp), e.g., possibly representing an alternating glacial/interglacial sequence.

Deposition of these sediments occurred later than Waiteariki Ignimbrite and probably mostly later than Pakaumanu Group ignimbrite. Therefore, the top surface of Tauranga Group eQ sediments is assumed to occur above Pakaumanu Group ignimbrite, where these two units are buried.

3.1.4.5 Pleistocene Mamaku Plateau Formation Ignimbrite

Mamaku Plateau Formation ignimbrite crops out in the southeast of the Hauraki Plains and overlies the southern extension of the Hauraki Rift. This ignimbrite has an elevation range of approximately 100 m to more than 600 m and is up to 200 m thick.

3.1.4.6 Greywacke Gravel from Hapuakohe Range

Greywacke gravel sourced from the greywacke Hapuakohe Range forms an extensive greywacke gravel fan in the north-western Hauraki Plains. This fan is exposed at the ground surface in the Hapuakohe Ranges (Section 3.1.4.1), and gravel lithologies recorded in well logs show that extensive gravel lenses radiate away from the Range. The top of the greywacke gravel fan is modelled from approximately 100 m above sea level, (i.e., gravel is exposed in the Hapuakohe Ranges) and occurs to approximately 150 m below sea level in the subsurface. Therefore, the base of the gravel fan is assumed as Early Quaternary Tauranga Group sediments.

3.1.4.7 Pleistocene Hinuera Formation

Hinuera Formation (i.e., Tauranga Group Q3a; Leonard et al. (2010)) Q3 includes Pleistocene sediments exposed at the ground level south of the Morrinsville – Te Aroha road. Where the Hinuera Formation outcrops, the ground surface obtained from a DTM represents the top of the layer. Gravel deposits in the Hinuera Formation possibly form marker beds. For example, gravels in the Holocene marine-estuarine geographical area form small and isolated, widely scattered deposits, possibly reflecting a decrease of the fluvial energy associated with the shift of the course of the ancestral Waikato River. In the subsurface of this area, the gravel layers probably reflect the lateral continuation of the greywacke gravel fan from the Hapuakohe Range because gravel clasts are mostly greywacke, indicating they were probably not deposited by a river system such as the ancestral Waikato River.

3.1.4.8 Holocene Coastal Sediments

This unit includes Holocene swamp and alluvial sediments mapped at the ground surface (Edbrooke 2001) with marine sediments (as evidenced by shells in wells) at depth. The top of these sediments is represented in the model by a DTM (Section 3.1.2.1) of the Holocene outcrop. As evident from the DTM, a change in topographic gradient occurs approximately in line with the Te Aroha – Morrinsville road, with lower elevations towards the north. Higher elevated areas south of the Te Aroha – Morrinsville road probably restricted the transgression of the sea during the Holocene, and thus inhibited the deposition of marine-estuarine sediments in the southern Hauraki Plains.

Scattered deposits of Holocene terrestrial sediments may occur to the south of this topographic boundary in river channels. However, these are not represented in the model as a separate layer due to their limited extent and the general lack of information on their distribution.

3.2 Water Budgets

A general water budget equation is used to describe the relationships between water inflow, water outflow and water storage within a defined area of a catchment (Figure 3.4). The following text introduces water budget equations and components.

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

i.e.,

$$P + Q_{IN} = AET + Q_{OUT} + \Delta S \tag{2}$$

Water inflows include:

P precipitation,

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

Q^{SW}_{IN} surface water inflow

Q^{GW}_{IN} groundwater inflow

Water outflows include:

AET actual evapotranspiration

Q_{OUT} surface water and groundwater flow out from the area

ΔS change in water storage.

These water outflows include:

$Q_{OUT} = Q^{SW}_{OUT} + Q^{GW}_{OUT}$

$Q^{SW}_{OUT} = Q^{SW}_{QF} + Q^{SW}_{BF} + U^{SW}$

$Q^{GW}_{OUT} = Q^{GW}_{COUT} + U^{GW}$

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

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

U^{SW} consumptive surface water use

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

Expanding Equation 2 for surface water and groundwater terms, with the assumptions that: ΔS is zero (meaning that all flows are the same over time, so that the budget represents long-term average flow); surface quick flow and baseflow terms are not separated; and U^{SW} and U^{GW} are equal to zero (i.e., the budgets aim to represent natural flows) has:

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

Surface flow statistics were calculated from flow measurements made by WRC at stage recorder sites and gauging sites. Mean, median and baseflow at stage recorder sites were calculated by Jenkins (2015). Mean flow and median flow at gauging sites were estimated from available flow measurements. Base flow index (BFI) was calculated as:

$$BFI = \text{baseflow/mean flow} \tag{4}$$

The groundwater outflow terms were estimated with the water budget and with the Darcy flow equation at the coast, i.e.:

$$Q = \frac{dh}{dl} K A \tag{5}$$

where

Q is the total groundwater discharge (m^3/s),

K is the hydraulic conductivity of the aquifer (m/s),

dh/dl is the hydraulic gradient (unitless), and

A is the cross-sectional area through which the groundwater is flowing (m^2).

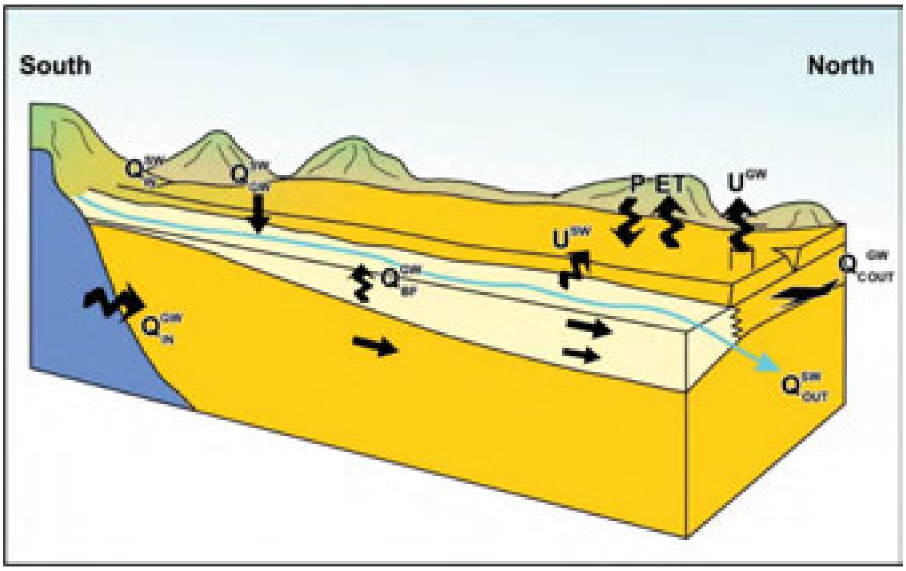

Figure 3.4 Schematic of groundwater budget components.

3.3 Model Data

Mean annual rainfall (P) was estimated using ArcGIS and the nationwide National Institute of Water and Atmospheric Research (NIWA) Virtual Climate Station Network dataset. This dataset is based on rainfall measurements at individual climate stations, interpolated throughout New Zealand by NIWA and averaged for the period 1960 to 2006 (Tait et al*.* 2006). Mean annual AET was estimated using ArcGIS and a national-scale AET map developed by NIWA for the period 1960 to 2006 that does not have specific consideration for land use, land cover, soil type or groundwater recharge (Woods et al*.* 2006).

Surface water flows have been assessed in each water model area (i.e., catchments, sub-catchments and zones). Surface flow measurements from stage recorders in the Hauraki Plains catchments were used to estimate flows, in particular mean and median flows in the period 1960 to 2006 (Jenkins 2015); this was the period of rainfall and AET estimates that was used by Tait et al*.* (2006) and Woods et al*.* (2006), respectively. In addition, WRC's historic gauging data set was used to estimate surface flows (Jenkins 2015) and individual spot gauging measurements estimated flows in catchments draining the Mamaku Plateau (Dell 1982), Figure 3.5. All flow estimates in the water budget (Equation 3) were rounded to the nearest 0.1 m^3/s.

K was estimated for Holocene sediments as the equivalent of 2 m/day from tests of Holocene sands in the Christchurch Formation (Thorpe 1991); K in Hauraki Plains Pleistocene sediments was estimated from an analysis of local pump tests. The width of the cross section of groundwater flow is that of the catchments at the coast. The thicknesses of formations are estimated from suitable well logs that are nearest the coast. For example, the thickness of Pleistocene sediments, for the purposes of the Darcy flow calculation, is approximately 280 m in the Torehape 1 well drilled near Ngatea.

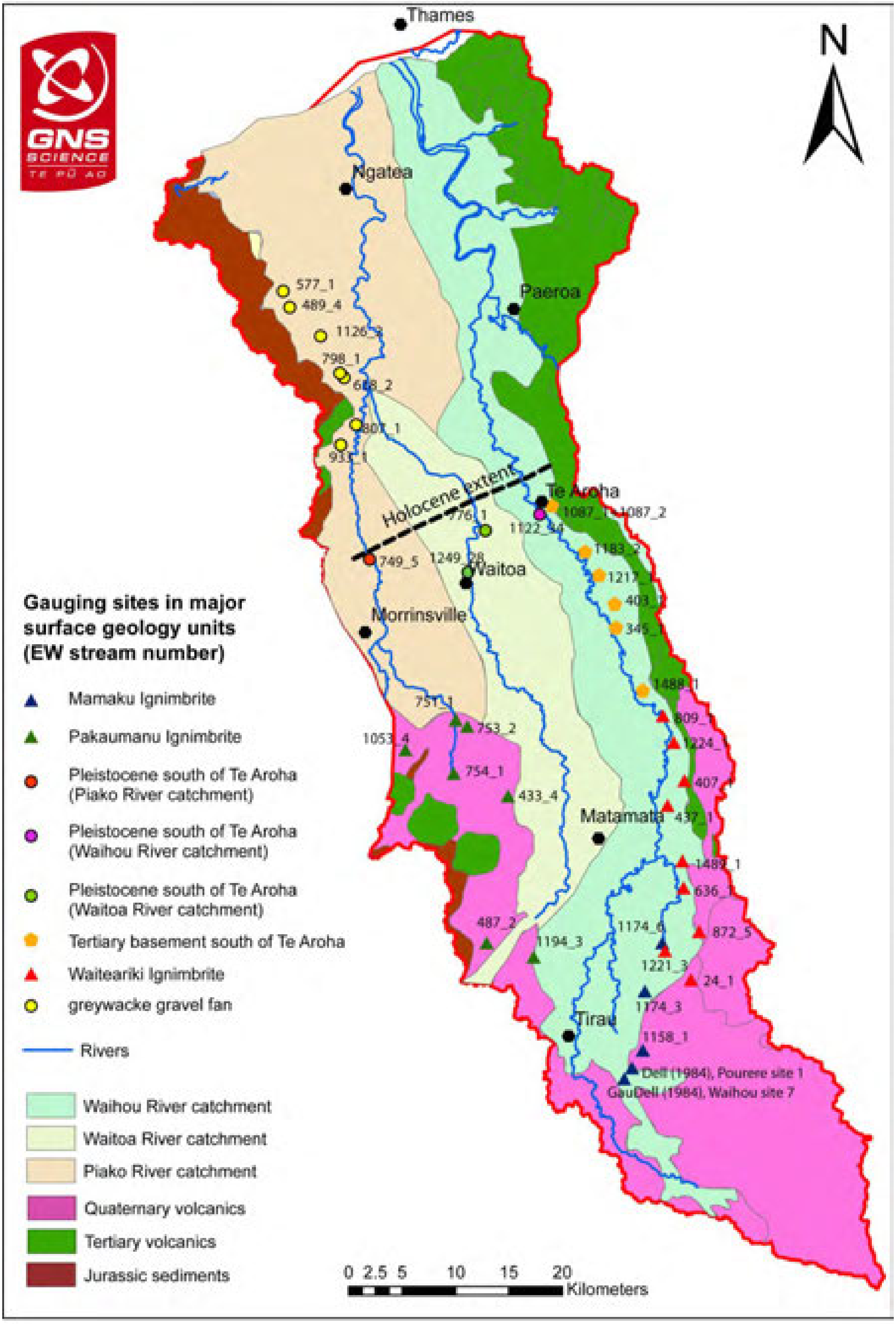

Figure 3.5 Gauging sites representing surface water discharge from surface geological units in the Hauraki Plain.

3.4 Water Budget Calculation

Water budgets were developed in the Hauraki Plains catchments (i.e.: Waihou River, Piako River, including the Waitoa River catchment, and Hauraki north-west, Figure 3.6) with the catchment flow routing schemes shown schematically in Figures 3.7 and 3.8. Three sets of water budgets were developed, i.e.:

- the three full catchments;
- sub-catchments above the recorder sites or localities (Figures 3.9, 3.10, 3.11). For example, the “Piako River 749_15” catchment includes the land area of the “Piako River 749_10” sub-catchment (Figure 3.10);
- zones between recorder sites or localities (Figures 3.9, 3.10, 3.11). For example, the “Piako River 749_15” zone excludes the land area of the “Piako River 749_10” sub-catchment (Figure 3.10).

These budgets were used to calculate some flow components. Surface flows were not measured in rivers and drains at the coast. Therefore, surface flows at the coast were calculated to balance inflows and groundwater flow across the coastal boundary (Equation 5).

Groundwater outflows from, or inflows to, catchments and zones were calculated by assuming that the water budget was balanced, i.e., the total inflow equals the total outflow in each catchment. This approach relies, in part, on good-quality estimates of P, AET and mean stream flow. However, these estimates are inconsistent with a balanced water budget in some model areas. Therefore, residual flows (i.e., the net inflow, or outflow) required to balance the water budget was calculated in some model areas; the implications of these flows on the water budget are considered in the Discussion. In addition, the potential for groundwater flow to travel between the major catchments (i.e., between the Waihou River catchment and the Piako River catchment) is addressed in the Discussion. The Discussion also considers data quality with regard to residual flows as a background to recommendations for new field measurements associated with water budget components.

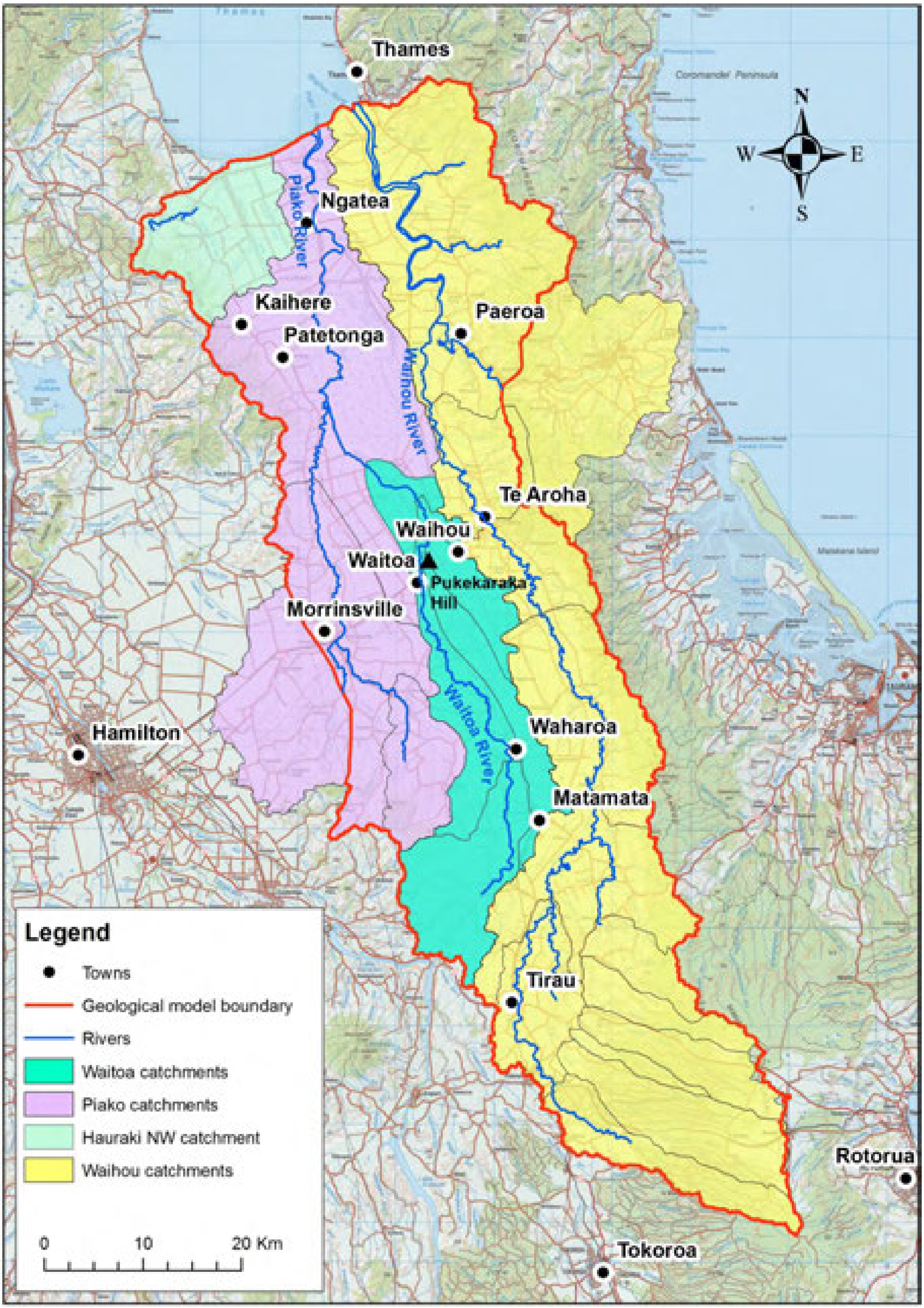

Figure 3.6 Major surface water catchments of the study area (Piako River, Waitoa River and Waihou River).

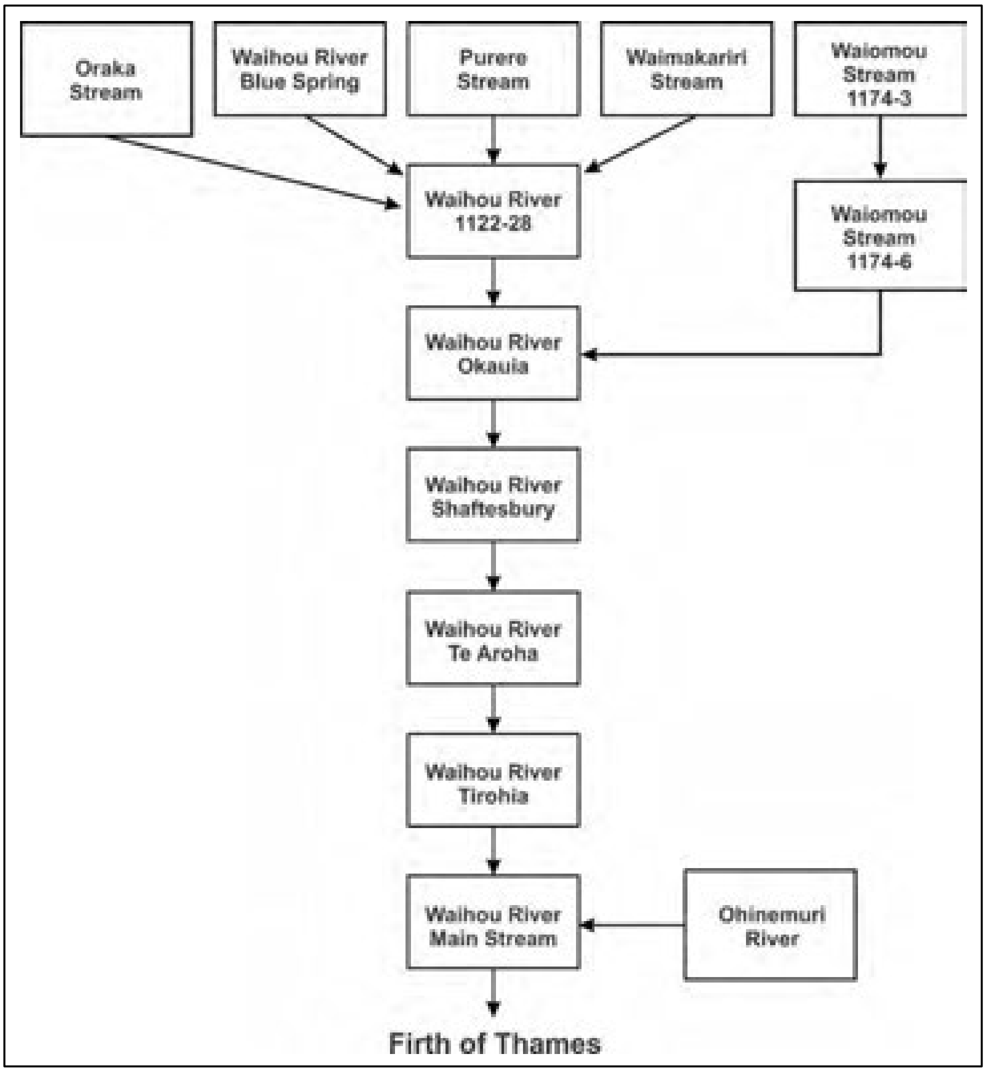

Figure 3.7 Catchment routing scheme for the Waihou River catchment.

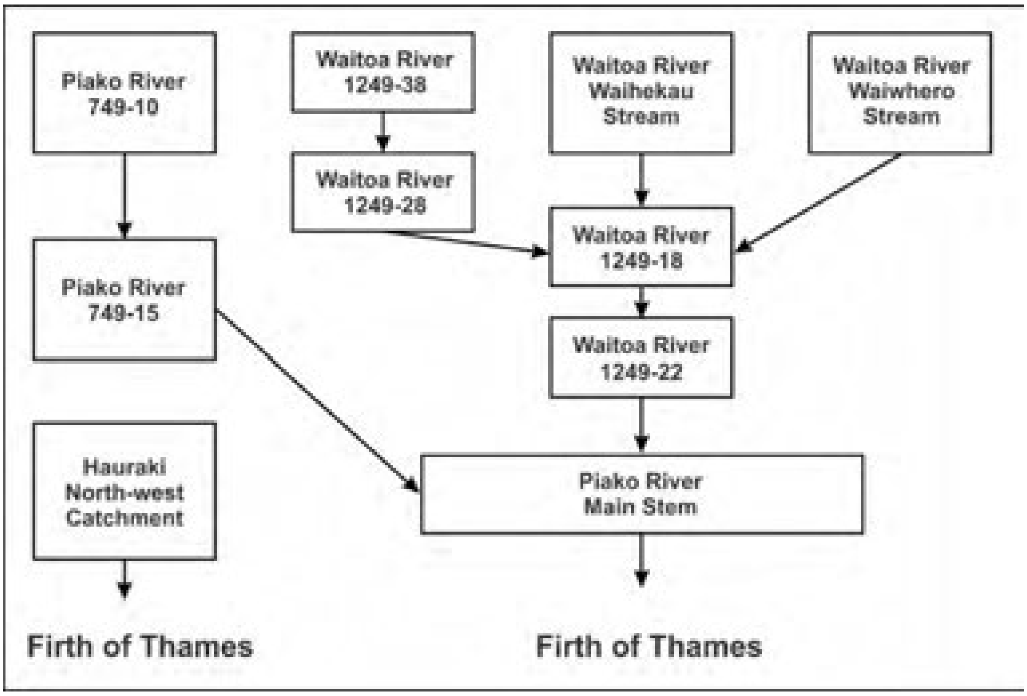

Figure 3.8 Catchment routing scheme for the Piako River catchment, including the Waitoa River catchment.

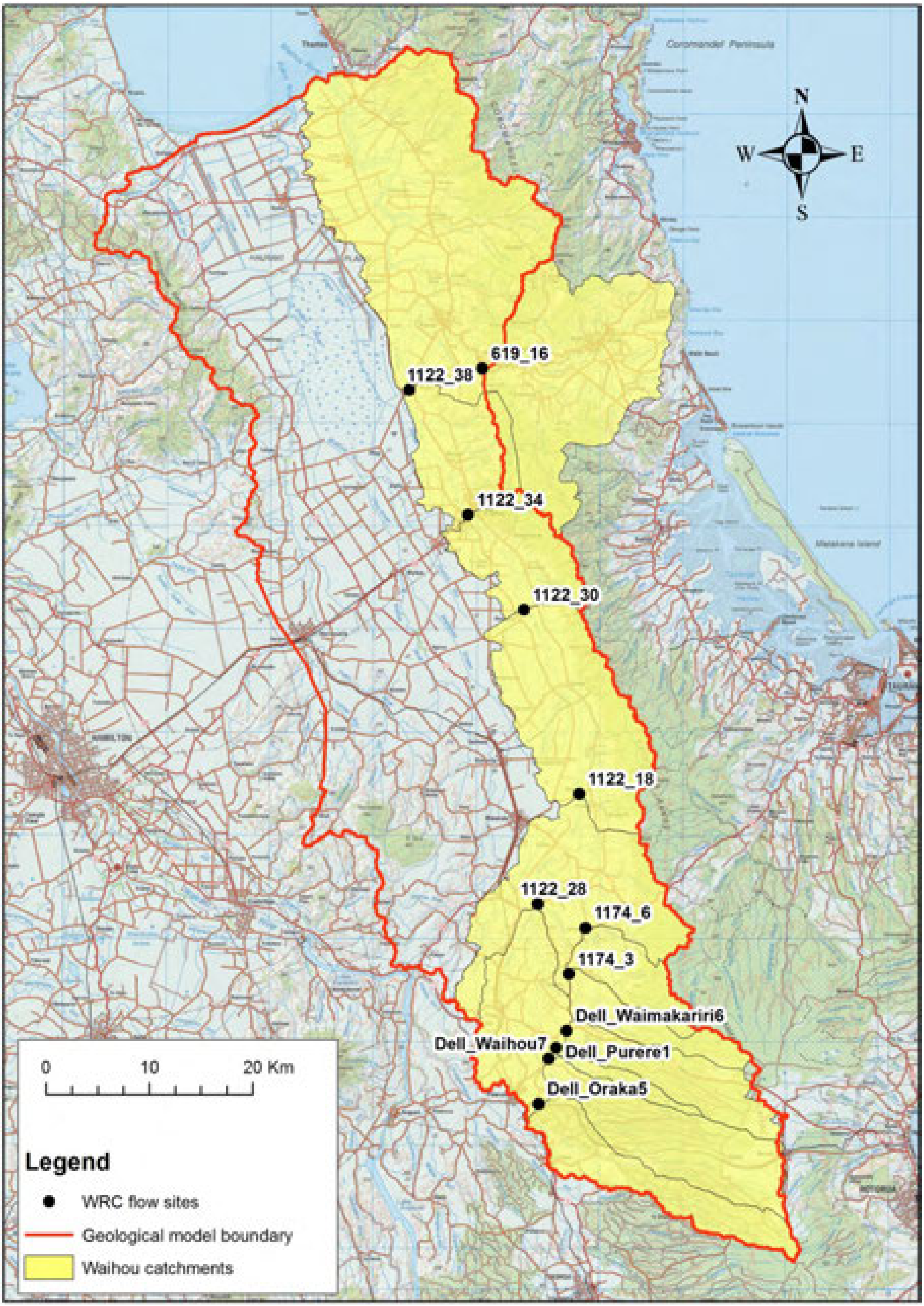

Figure 3.9 Surface catchment polygons in the Waihou River catchment.

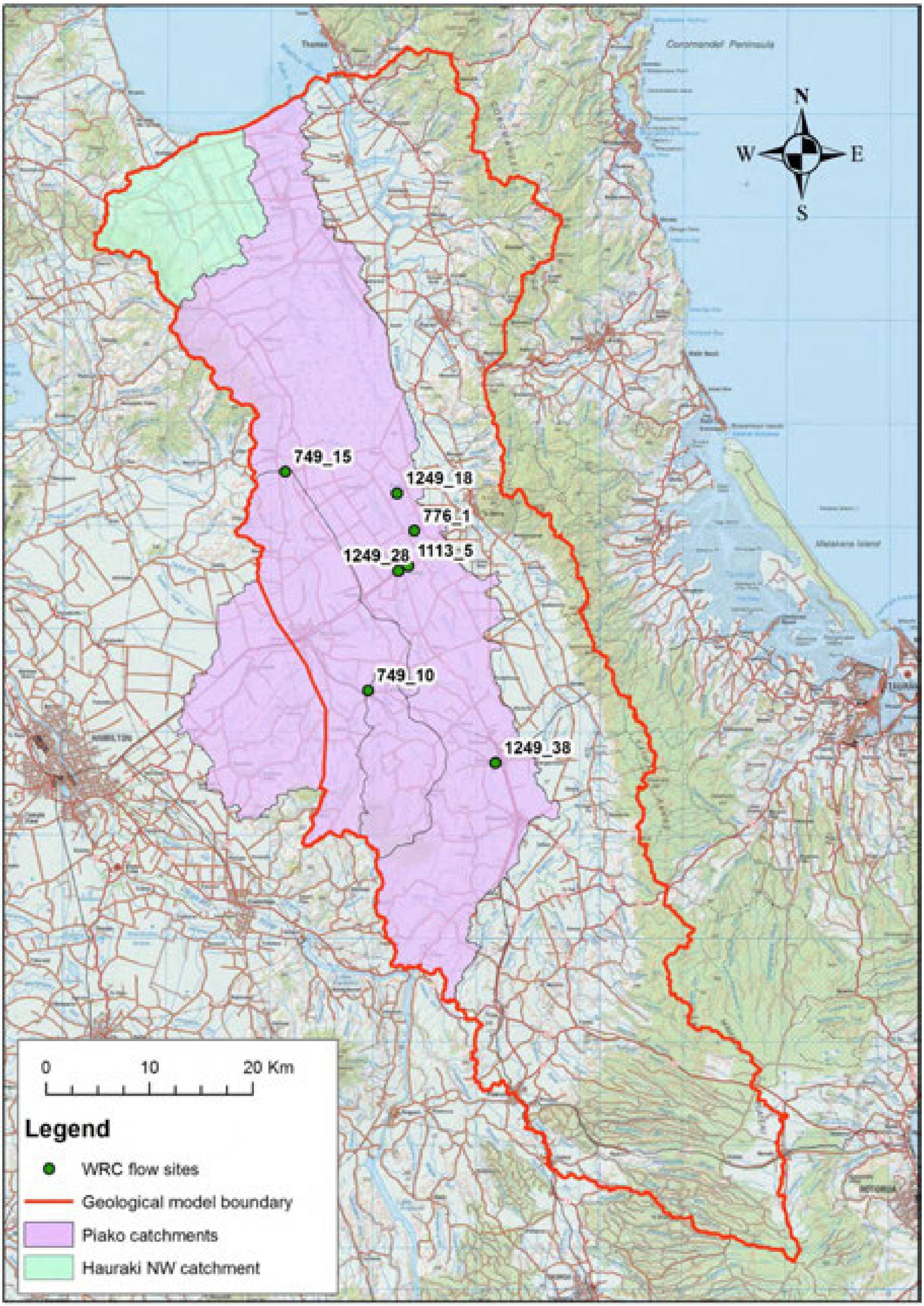

Figure 3.10 Surface catchment polygons in the Piako River catchment.

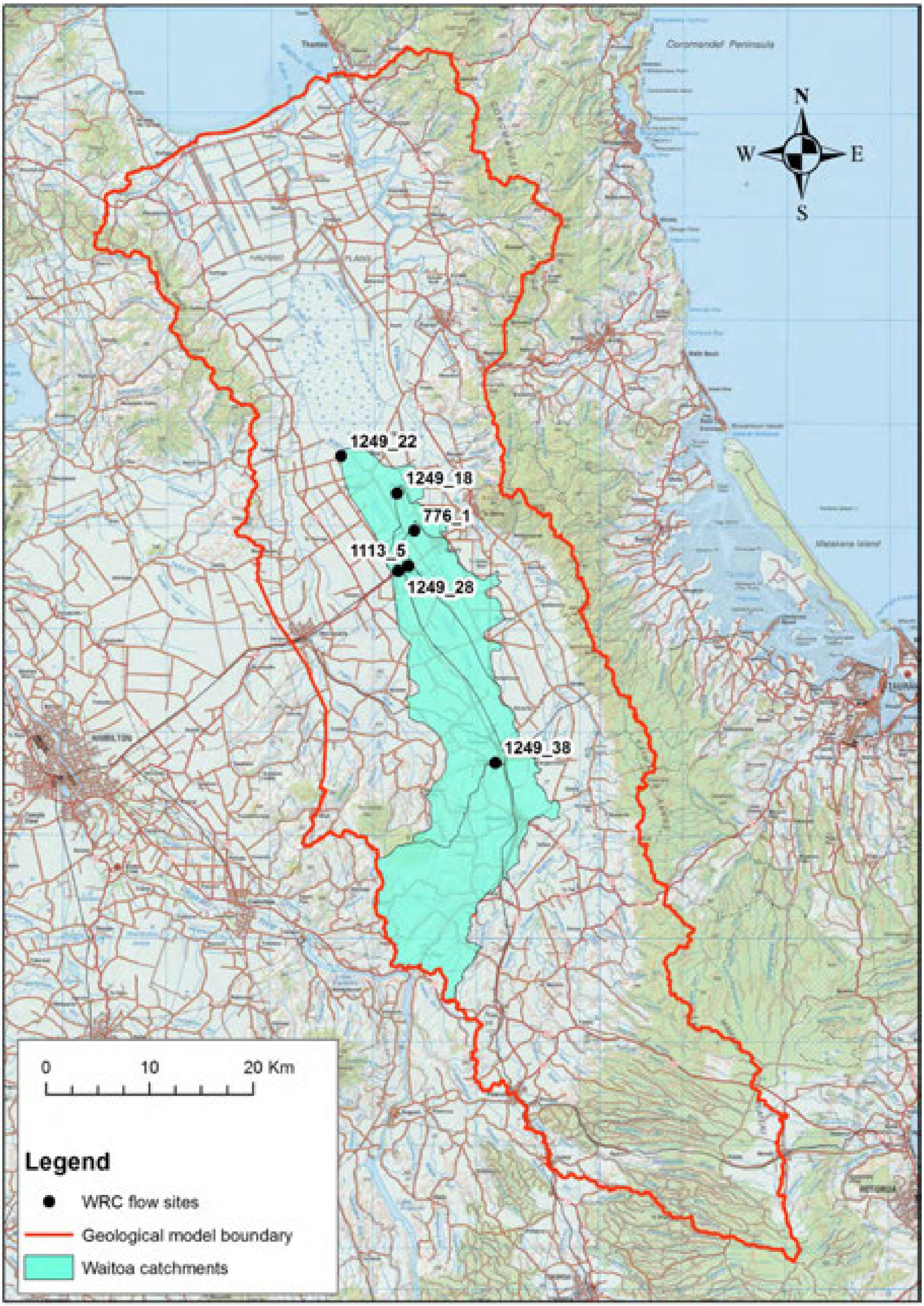

Figure 3.11 Surface catchment polygons in the Waitoa River catchment.

4.0 RESULTS

4.1 Digital Terrain Model and the Southern Limits of the Holocene Marine Incursion

The location of the Paeroa Tahuna Road marks the approximate boundary of the transition between Kopuatai Peat Dome (in the north) with sediments predominantly deposited in a terrestrial environment to the south (Figure 4.1). Pukekaraka Hill is a control on drainage in the middle of the Hauraki Plains. Streams in the Piako River catchment, including Waitoa River are typically incised into Hauraki Plains near the hill (Figures 4.1 and 3.6).

4.2 Hauraki 3D Geological Model

Hinuera Formation fills the southern Hauraki Plains above the Waiteariki Ignimbrite near Matamata and Waharoa (Figures 4.2 and 4.3). East of Matamata, Waiteariki Ignimbrite crops out in the Kaimai Range. Basement and Pakaumanu Ignimbrite crop out west of Matamata and Waharoa. The boundary between Holocene sediments and Hinuera Formation is located west of Te Aroha (Figure 4.4). Here, the Hinuera Formation has a maximum thickness of approximately 150 m and sits above early Pleistocene sediments. Elevated basement in the middle of the Hauraki Plains represents the northern extension of Pukekaraka Hill (e.g., cross section A, Figure 2.4). Elevated basement also continues to the north (Figure 4.5). In the section west of Paeroa, the Quaternary sequence is represented by Holocene sediments, with a maximum thickness of approximately 30 m, above Hinuera Formation and early Pleistocene sediments.

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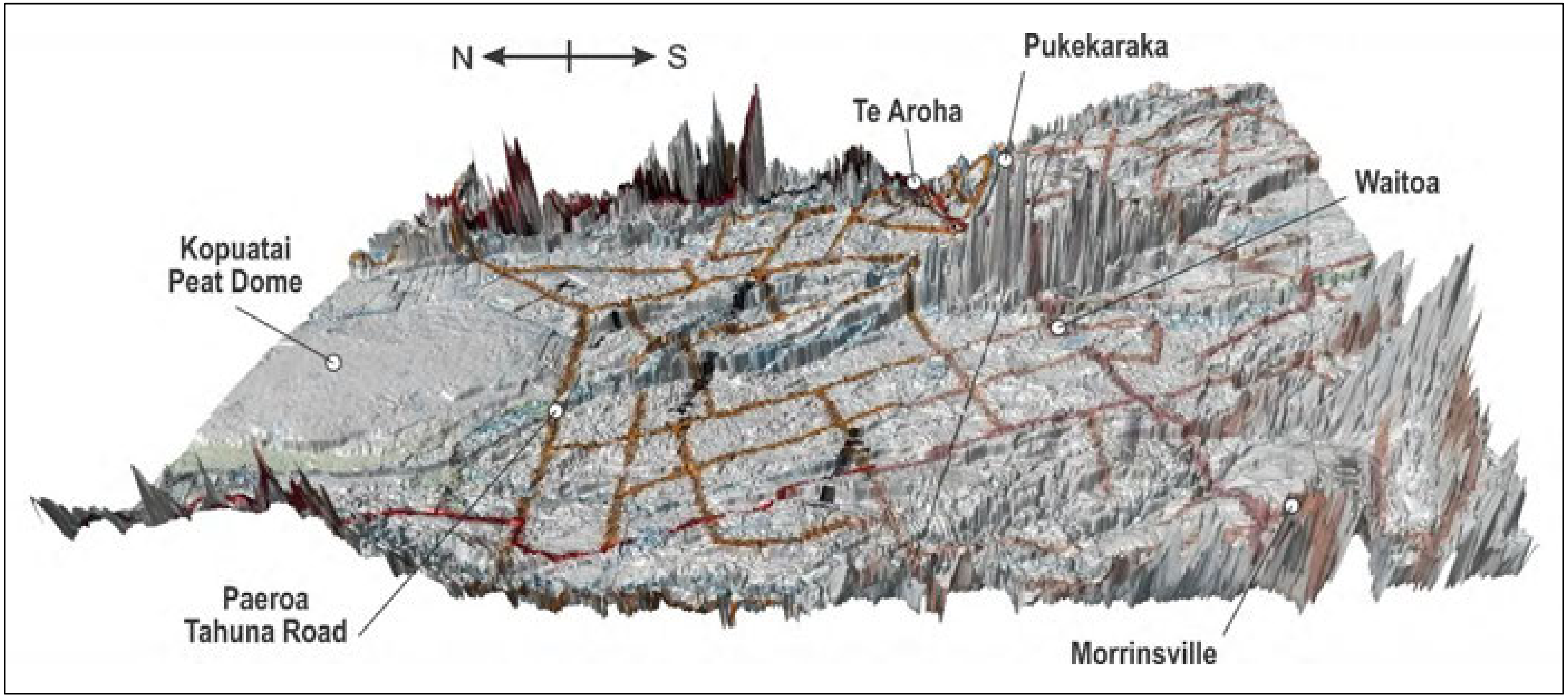

Figure 4.1 DTM of the middle Hauraki Plains, between approximately Kopuatai Peat Dome and Waitoa, viewed from the west; vertical exaggeration approximately 100.

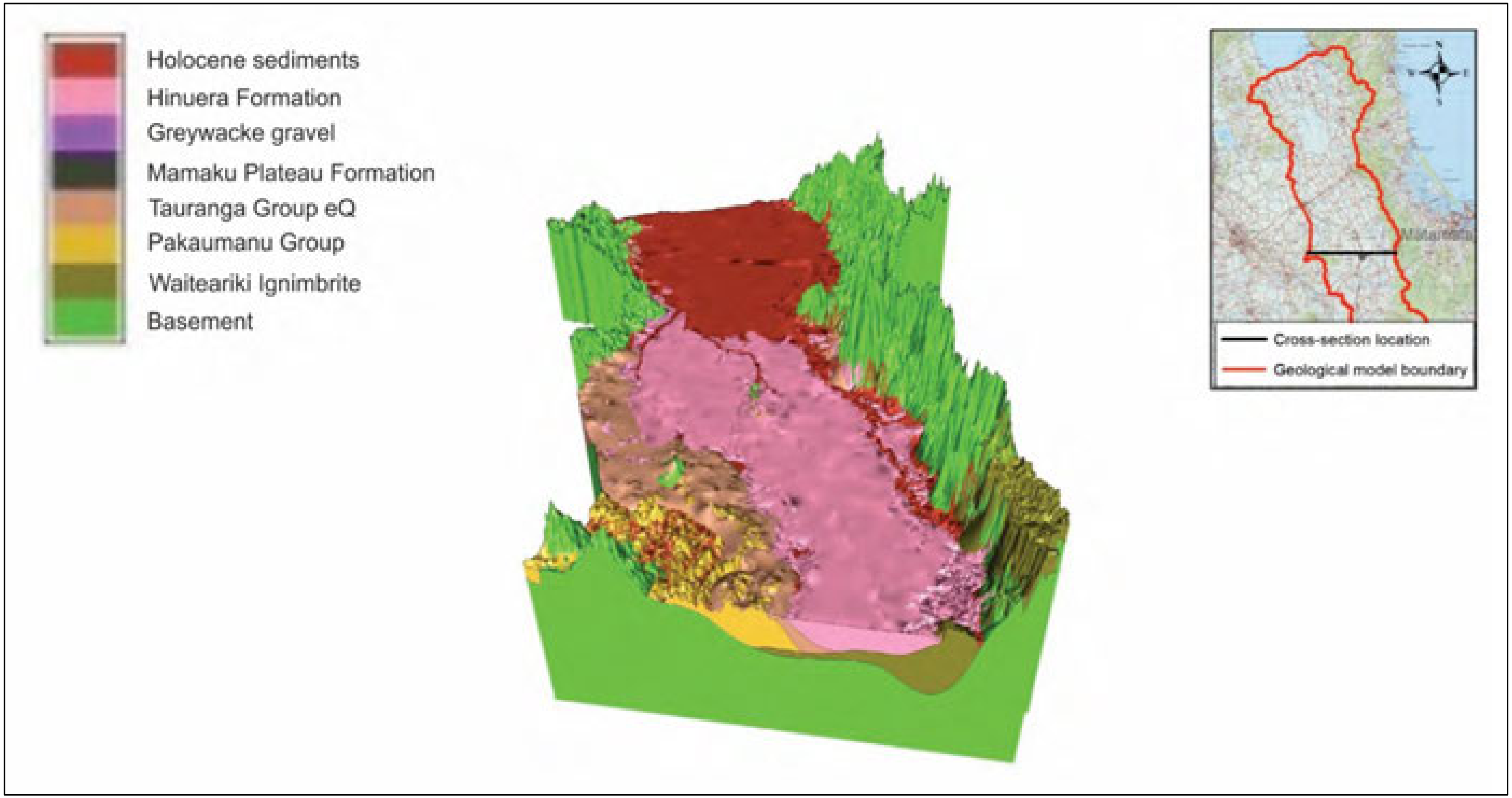

Figure 4.2 Cross section of the geological model in the southern Hauraki Plains near Matamata.

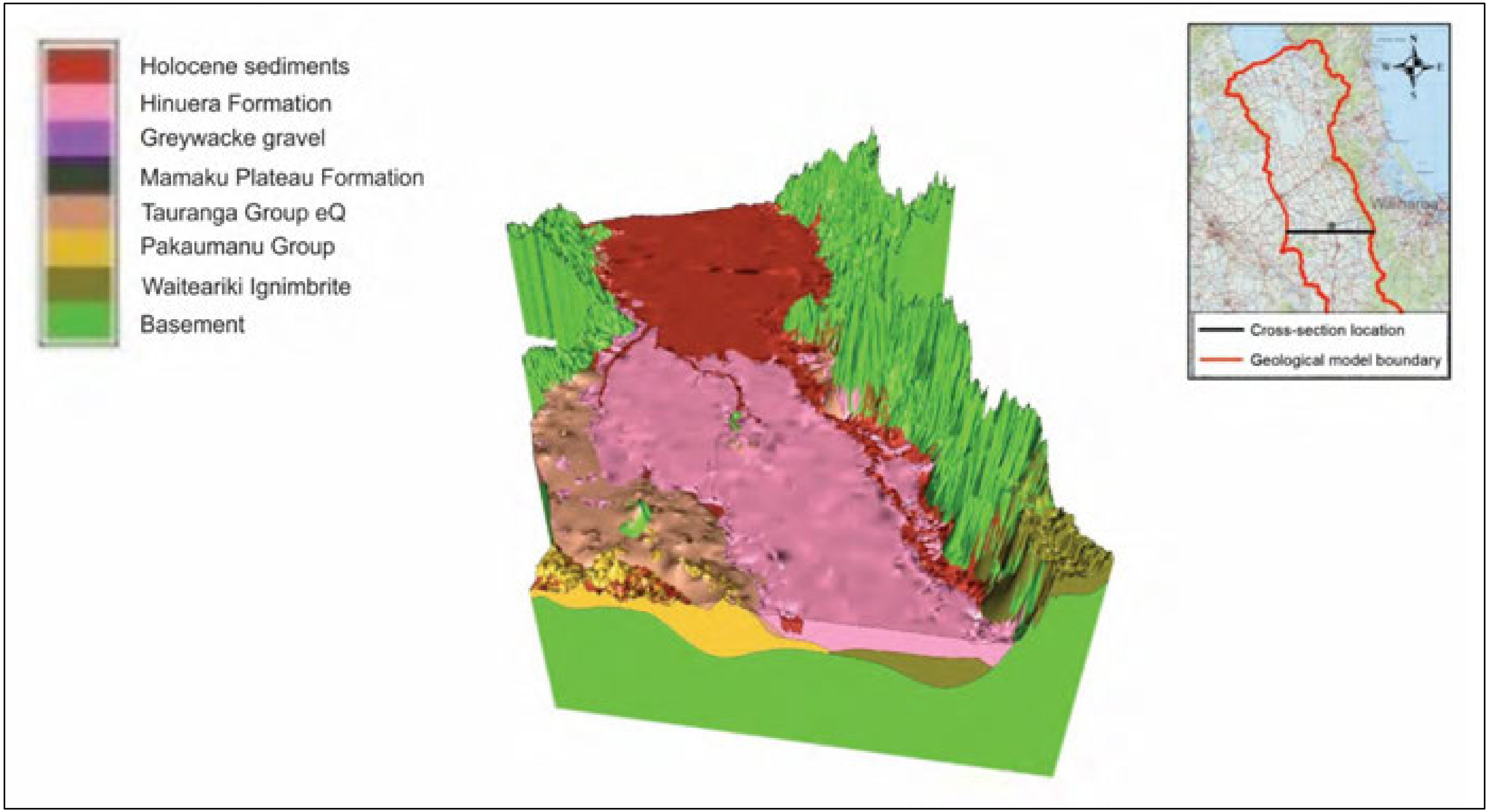

Figure 4.3 Cross section of the geological model in the southern Hauraki Plains near Waharoa.

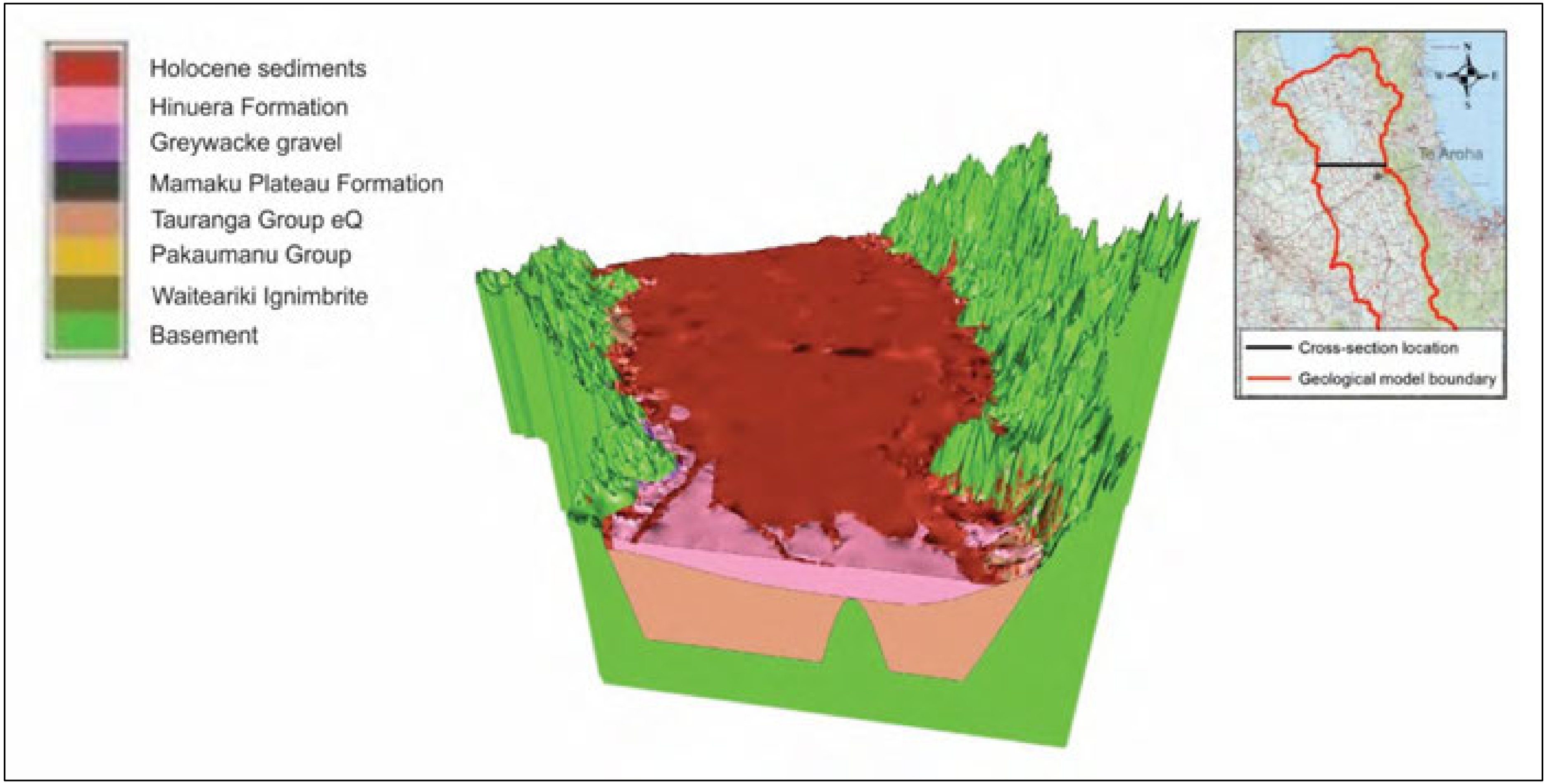

Figure 4.4 Cross section of the geological model in the middle Hauraki Plains near Te Aroha.

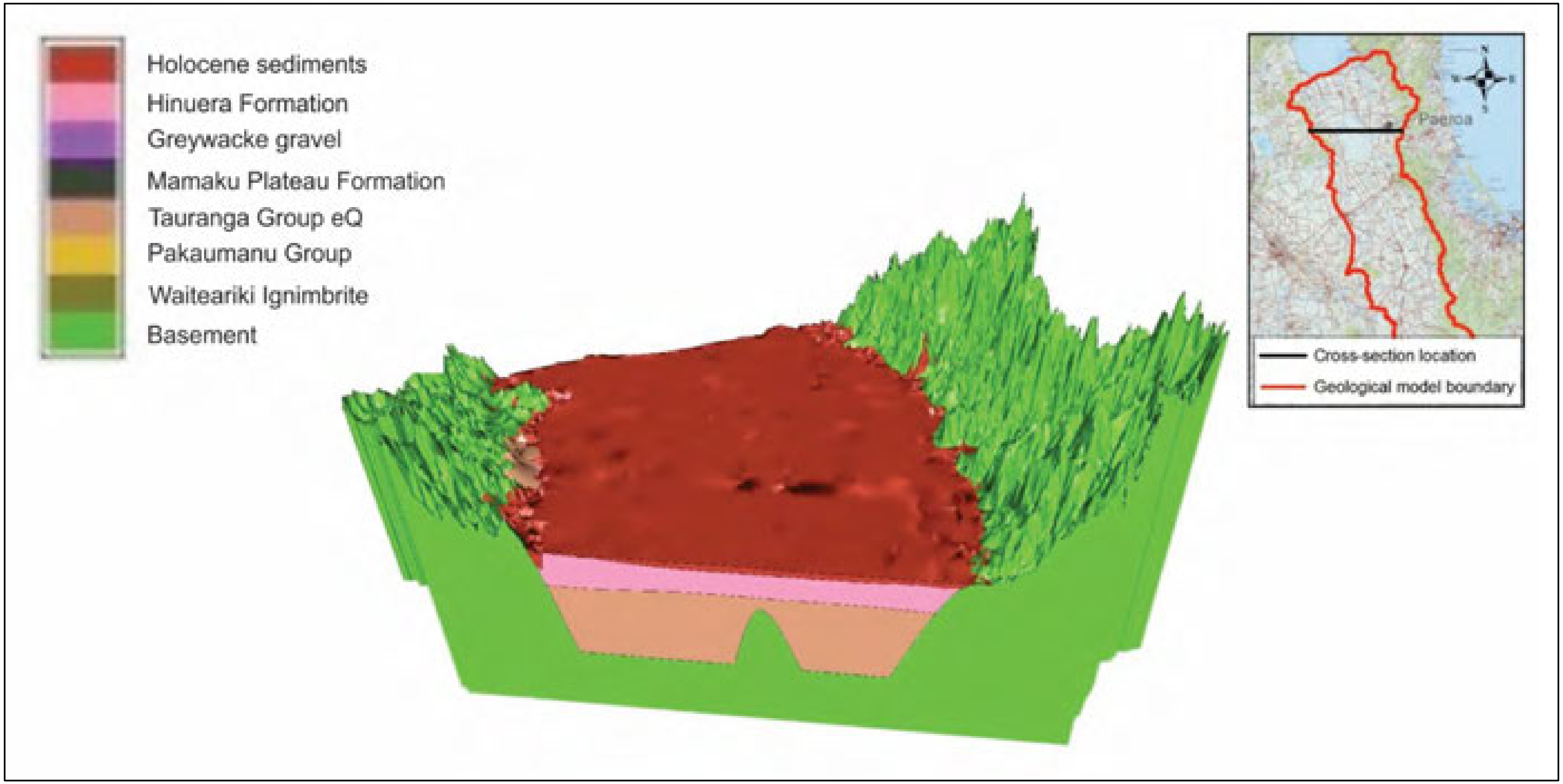

Figure 4.5 Cross section of the geological model in the northern Hauraki Plains near Paeroa.

4.3 Water Budgets

The total land area of the three Hauraki Plains catchments is approximately 3623 km^2 (Table 4.1; Figure 3.6). Surface water outflow from this area is an estimated mean of 73.9 m^3/s; estimated groundwater outflow at the coast from the area is a small proportion of surface flow, i.e., 1.9 m^3/s (Tables 4.1 and 4.2). The Waihou River catchment has the largest area and has the largest surface flow at the coast. However, groundwater flow at the coast is largest from the Piako River catchment area because this catchment has the largest width at the coast. These budgets assume that no groundwater flows between the Waihou River catchment and the Piako River catchment, see the Discussion (Section 5.5). Average rainfall in the Waihou River catchment is significantly less than average rainfall in the Piako River catchment.

The water budget of the Waihou River sub-catchments and zones do not calculate Q^{GW}_{IN} and Q^{GW}_{OUT} (Tables 4.3 and 4.4). This is because: negative residual flows were consistently calculated for headwaters sub-catchments and zones, residual flows were typically a relatively large proportion of Q^{SW}_{OUT}, and some long-term average flow estimates in the Waihou River appear inconsistent. Together, these observations suggest that improvements in estimates of water budget components are required in the Waihou River catchment (see Discussion).

Negative residual flows were calculated for headwaters areas, i.e., Waihou River (Blue Springs), Purere Stream, Waimakariri Stream and Waiomou Stream 1174_3. For example, a residual flow in the Waihou River (Blue Springs) catchment was -0.8 m^3/s as inflows and outflows were 7.6 m^3/s and 8.4 m^3/s, respectively. The negative residual flows may indicate that groundwater flows from adjacent catchments. However, the eastern boundary of these catchments on the Mamaku Plateau has been defined with consideration of the water budgets in Lake Rotorua catchments (White et al. 2014). Groundwater inflow to headwaters catchments is most unlikely from Waihou River catchments located to the west. Negative residual flows are common, and residual flows that are relatively large proportion of Q^{SW}_{OUT}, suggesting that uncertainties in water budget components are consistent and that unreasonable values of Q^{GW}_{OUT} could be calculated if it is assumed that Q^{GW}_{OUT} equals residual flow.

Long-term average flow estimates in the Waihou River appear inconsistent at the Tirohia and Te Aroha sites, i.e., average flow at Tirohia is less than average flow at Te Aroha (Tables 4.3 and 4.4). Therefore, a large negative residual flow in the Waihou River Te Aroha zone (i.e., -12.5 m^3/s; Table 4.3) is probably associated with uncertainty in the estimate of flow at the Te Aroha site (see Discussion).

Water budget components in the Piako River sub-catchments are probably a more reasonable estimate of mean flows in the water budget components than estimates in the Waihou River catchment. This is because residual flows in the Piako River sub-catchments are generally low, and residual flows are generally positive, unlike the Waihou River sub-catchments (Table 4.5).

Due to the above, residual flows in the Piako River zones are assumed to generally represent Q^{GW}_{OUT} (Table 4.6). Residual flow from the Piako River 749_10 sub-catchment (0.1 m^3/s) was not assigned to Q^{GW}_{IN} because this low flow could represent rounding error. Generally, the groundwater outflows from main-stem Piako River catchments are small relative to the total catchment outflow from surface water and groundwater. For example, groundwater outflows were less than 20% and 4% of total catchment outflow in the Piako River 749_10 and Piako River 749_15 catchments, respectively (Table 4.6). This indicates that most rainfall recharge has returned to the river upstream of the recorder site.

Groundwater outflows from Waitoa River catchments located south of the boundary between Holocene and Pleistocene sediments were large relative to total catchment outflow. For example, groundwater outflows were 67% and 75% of total catchment outflow in the Waihekau Stream 1113_5 and Waiowhero Stream 776_1 catchments, respectively. Importantly, this percentage tends to decrease towards the boundary of Holocene and Pleistocene sediments, e.g., groundwater outflow from the Waitoa River 1249_22 catchment is 21% of total outflow. This indicates the role of the boundary between Holocene and Pleistocene sediments in controlling groundwater flow (White and Tschritter 2014).

In the Waihou River catchment, BFI is probably near 1 at the base of the Mamaku Plateau as baseflow probably dominates surface water flow, in common with catchments that drain the Mamaku Plateau to the Lake Rotorua catchment (White et al. 2014). However, BFI cannot be computed at the base of the Mamaku Plateau because only spot gaugings are measured in this area (see Discussion). BFI possibly decreases down the Waihou River catchment, indicating that the importance of baseflow decreases away from the Mamaku Plateau. For example, BFI is 0.88 and 0.79 at sites 1122_18 and 1122_38, respectively (Table 4.7). BFI in the Paiko River catchment generally increases in a downstream direction. For example, BFI at sites 749_10, 1249_38 and 1249_18 are 0.44, 0.53 and 0.63, respectively. This indicates the increasing influence of groundwater inflows to river flows with distance down the river.

Table 4.1 Water budgets of full catchments: Hauraki north-west, Piako River and Waihou River (Figure 3.6).

Catchment name	Area (km^2)	Inflow mean (m^3/s)			Outflow mean (m^3/s)		
		P	Q^{SW}_{IN}	Q^{GW}_{IN}	AET	Q^{SW}_{OUT}	Q^{GW}_{COUT}
Waihou River at the coast	1976	106.3	0	0	51.8	53.8	0.7
Piako River at the coast	1480.8	57.6	0	0	38.3	18.5	0.8
Hauraki north-west	166.1	6.4	0	0	4.4	1.6	0.4
Total	3622.9	170.3	0	0	94.5	73.9	1.9

Table 4.2 Estimates of groundwater flow across the coastal boundary (Equation 8).

Catchment	Unit	Thickness (m)	Width (m)	Cross-sectional area A (m^2)	Hydraulic conductivity (m/s)	i	Q^{GW}_{COUT} (m^3/s)
Waihou	Holocene	40	6000	240000	0.00002	0.0017	<0.05
	Pleistocene	280	6000	1680000	0.00023	0.0017	0.7
Piako	Holocene	40	7000	280000	0.00002	0.0017	<0.05
	Pleistocene	280	7000	1960000	0.00023	0.0017	0.8
Hauraki north-west	Holocene	40	4000	160000	0.00002	0.0017	<0.05
	Pleistocene	280	4000	1120000	0.00023	0.0017	0.4

Table 4.3 Water budgets for Waihou River sub-catchments (Figures 3.7and 3.9).

Sub-catchment name	Flow site and locations	Area (km^2)	Inflow mean (m^3/s)			Outflow mean (m^3/s)			Residual (m^3/s)
			P	Q^{SW}_{IN}	Q^{GW}_{IN}	AET	Q^{SW}_{OUT}	Q^{GW}_{COUT}	
Oraka Stream	Dell_Oraka5	106	5.4	0	0	2.6	2.3	0	0.5
Waihou River (Blue Springs)	Dell_Waihou7	139.8	7.6	0	0	3.4	5	0	-0.8
Purere Stream	Dell_Purere1	20.2	1	0	0	0.5	0.8	0	-0.3
Waimakariri Stream	Dell_Waimakariri6	84.3	4.8	0	0	2.1	4.7	0	-2.0
Waiomou Stream 1174_3	1174_3	55	3	0	0	1.4	2.7	0	-1.1
Waiomou Stream 1174_6	1174_6	112.6	6	0	0	2.9	2.8	0	0.3
Waihou River 1122_28	1122_28	469.6	23.9	0	0	11.7	16.4	0	-4.2
Waihou River Okauia	1122_18	783.1	40.2	0	0	20	26.8	0	-6.6
Waihou River Shaftsbury	1122_30	1000	51.8	0	0	25.8	29.5	0	-3.5
Waihou River Te Aroha	1122_34	1096.2	57.1	0	0	28.4	41.2	0	-12.5
Waihou River Tirohia	1122_38	1204.5	62.3	0	0	31.2	39.8	0	-8.7
Ohinemuri River	619_16	270.3	17.8	0	0	7.1	12.5	0	-1.8
Waihou River at coast	Waihou River at coast (no flow site)	1976	106.3	0	0	51.8	53.8	0.7	0.0

Table 4.4 Water budgets for Waihou River zones (Figures 3.7 and 3.9).

Zone name	Flow site and locations	Area (km^2)	Inflow, mean annual (m^3/s)			Outflow, mean annual (m^3/s)			Residual (m^3/s)
			P	Q^{SW}_{IN}	Q^{GW}_{IN}	AET	Q^{SW}_{OUT}	Q^{GW}_{COUT}	
Oraka Stream	Dell_Oraka5	106	5.4	0	0	2.6	2.3	0	0.5
Waihou River (Blue Springs)	Dell_Waihou7	139.8	7.6	0	0	3.4	5	0	-0.8
Purere Stream	Dell_Purere1	20.2	1	0	0	0.5	0.8	0	-0.3
Waimakariri Stream	Dell_Waimakariri6	84.3	4.8	0	0	2.1	4.7	0	-2
Waiomou Stream 1174_3	1174_3	55	3	0	0	1.4	2.7	0	-1.1
Waiomou Stream 1174_6	1174_6	57.6	3	2.7	0	1.5	2.8	0	1.4
Waihou River 1122_28	1122_28	119.3	5.1	12.8	0	3.1	16.4	0	-1.6
Waihou River Okauia 1122_18	1122_18	200.9	10.3	19.2	0	5.4	26.8	0	-2.7
Waihou River Shaftsbury 1122_30	1122_30	216.9	11.6	26.8	0	5.8	29.5	0	3.1
Waihou River Te Aroha 1122_34	1122_34	96.2	5.3	29.5	0	2.6	41.2	0	-9
Waihou River Tirohia 1122_38	1122_38	108.3	5.2	41.2	0	2.8	39.8	0	3.8
Ohinemuri River 619_16	619_16	270.3	17.8	0	0	7.1	12.5	0	-1.8
Waihou River at coast	Waihou River at coast (no flow site)	501.2	26.2	52.3	0	13.5	53.8	0.7	10.5

Table 4.5 Water budgets for Piako River sub-catchments (Figures 3.8, 3.10 and 3.11).

Sub-catchment name	Flow site and locations	Area (km^2)	Inflow mean (m^3/s)			Outflow mean (m^3/s)			Residual (m^3/s)
			P	Q^{SW}_{IN}	Q^{GW}_{IN}	AET	Q^{SW}_{OUT}	Q^{GW}_{COUT}	
Piako River 749_10	749_10	99.2	4.1	0	0	2.6	1.6	0	-0.1
Piako River 749_15	749_15	542.4	20.8	0	0	13.8	6.8	0	0.2
Waitoa River 1249_38	1249_38	153.1	6	0	0	3.9	1.5	0	0.6
Waitoa River 1249_28	1249_28	258.9	10.2	0	0	6.7	3.2	0	0.3
Waihekau Stream	1113_5	78.6	3.3	0	0	2.1	0.4	0	0.8
Waiowhero Stream	776_1	52.8	2.2	0	0	1.4	0.2	0	0.6
Waitoa River 1249_18	1249_18	408.8	16.3	0	0	10.7	4.9	0	0.7
Waitoa River 1249_22	1249_22	450	17.9	0	0	11.7	4.9	0	1.3
Piako River at coast	Piako River at coast (no flow site)	1480.8	57.6	0	0	38.3	18.5	0.8	0

Table 4.6 Water budgets for Piako River zones (Figures 3.8, 3.10 and 3.11).

Zone name	Flow site and locations	Area (km^2)	Inflow mean (m^3/s)			Outflow mean (m^3/s)			Residual (m^3/s)
			P	Q^{SW}_{IN}	Q^{GW}_{IN}	AET	Q^{SW}_{OUT}	Q^{GW}_{COUT}	
Piako River 749_10	749_10	99.2	4.1	0	0	2.6	1.6	0	-0.1
Piako River 749_15	749_15	443.2	16.7	1.6	0	11.2	6.8	0.3	0
Waitoa River 1249_38	1249_38	153.1	6	0	0	3.9	1.5	0.6	0
Waitoa River 1249_28	1249_28	105.8	4.2	1.5	0.6	2.8	3.2	0.3	0
Waihekau Stream	1113_5	78.6	3.3	0	0	2.1	0.4	0.8	0
Waiowhero Stream	776_1	52.8	2.2	0	0	1.4	0.2	0.6	0
Waitoa River 1249_18	1249_18	18.5	0.6	3.8	1.7	0.5	4.9	0.7	0
Waitoa River 1249_22	1249_22	41.2	1.6	4.9	0.7	1	4.9	1.3	0
Piako River at coast	Piako River at coast (no flow site)	488.4	18.9	11.7	1.6	12.8	18.6[1]	0.8	0

[1] Q^{SW}_{OUT} differs from Table 4.5, due to rounding.

Table 4.7 Calculated flows and BFI at zone boundaries in the Waihou River and Piako River catchments in the period 1960 to 2006.

Site number	River name	Site name	Mean flow (m^3/s)	Median flow (m^3/s)	Baseflow (m^3/s)	BFI	Averaging period (start date)	Averaging period (end date)	N (gaugings)
1174-3	Waiomou Stream	1174-3	2.7	2	na	na	22/07/1976	26/01/1988	22
1174-6	Waiomou Stream	1174-6	2.8	2.8	na	na	1/03/1973	14/04/1987	8
1122_28	Waihou River	1122_28	16.4	14.2	na	na	17/03/1959	4/02/1988	56
1122_18	Waihou River	Okauia	26.8	24	23.7	0.88	23/03/1982	31/12/2006	na
1122_30	Waihou River	Shaftesbury	29.5	26	27.7	0.94	10/03/1982	31/12/2006	na
1122_34	Waihou River	Te Aroha	41.2	33.1	31	0.75	11/01/1965	31/12/2006	na
1122_38	Waihou River	Tirohia	39.8	33.1	31.5	0.79	1/01/1970	31/12/2006	na
619_16	Ohinemuri River	Karangahake	12.5	6.5	5.3	0.42	1/01/1960	31/12/2006	na
749_10	Piako River	Kiwitahi	1.6	0.8	0.7	0.44	23/04/1980	31/12/2006	na
749_15	Piako River	Paeroa-Tahuna Rd Br	6.8	3	2.9	0.43	3/07/1972	31/12/2006	na
1249_38	Waitoa River	Waharoa Control	1.5	0.8	0.8	0.53	18/05/1984	31/12/2006	na
1249_28	Waitoa River	SH26 Br Waitoa	3.2	1.9	1.8	0.56	21/03/1990	31/12/2006	na
1113_5	Waihekau Stream	Waihekau Stream	0.4	0.3	na	na	26/02/1973	11/04/2008	22
776_1	Waiowhero Stream	Waiowhero Stream	0.2	0.2	na	na	20/11/1969	4/04/2000	18
1249_18	Waitoa River	Mellon Rd Recorder	4.9	3.1	3.1	0.63	2/05/1986	31/12/2006	na
1249_22	Waitoa River	Paeroa-Tahuna Rd	4.9	2.7	6.8	1.39	22/06/1972	14/07/1998	na

5.0 DISCUSSION

5.1 Water Budget Components

The water budget of the Waihou River catchment did not calculate Q^{GW}_{IN} and Q^{GW}_{OUT} (Section 4.3). This was principally because residual flows were consistently negative and residual flows were typically a relatively large proportion of $Q^{SW}_{OUT,}$ suggesting the estimates were unreliable. Therefore, improvements in estimates of water budget components are required, particularly for this catchment (Section 6.2).

One possible reason for the unreliable estimates, is that the long-term average rainfall of Tait et al. (2006) too low across the Mamaku Plateau and the Kaimai Range, which are located in the Waihou River catchment. On the Mamaku Plateau, this would explain some of the negative residual flow calculated for Waihou River headwaters sub-catchments and zones, i.e., Waihou River (Blue Springs), Purere Stream, Waimakariri Stream and Waiomou Stream 1174_3. The large negative residual flow in the Waihou River at Te Aroha catchment may also be explained by low rainfall in the Tait et al. (2006) model.

AET is typically the second-largest water budget component after rainfall (e.g., Table 4.1) and typically has a high uncertainty. Therefore, any reassessment of rainfall in the Hauraki Plains area should also be associated with a reconsideration of AET calculated by Woods et al. (2006).

Typically, flow measurements at continuous flow sites were used to assess surface outflows from sub-catchments and zones; flow statistics were calculated from gauging measurements, only, at four zones at the base of the Mamaku Plateau and five zones in the Waihou River and Piako River catchments (Tables 4.4 and 4.7). Flow estimates in the four zones at the base of the Mamaku Plateau were generally derived from single-gauging measurements (Dell 1982) and therefore the quality of the estimate of long-term average flow is unknown and surface flow components cannot be separated into baseflow and quick flow; however the estimate of steady-state flow may be reasonable because flows at these sites are most probably dominated by baseflow. Surface outflows were estimated from multiple gauging measurements in five Waihou River and Piako River catchments (Table 4.7). However, an assessment of the quality of the flow statistics at these sites was beyond the scope of this project.

Lastly, groundwater outflow estimates were calculated to balance the water budget. This assumption could be tested with further work, including development of a groundwater flow model of the Hauraki Plains.

5.2 Long-term Average Flow Estimates

Water budget estimates of long-term average flows has some apparent inconsistencies. For example, the average flow at the downstream site in the Waihou River catchment (Tirohia) is less than average flow at the upstream site (Te Aroha); and average flow at Waitoa River site 1249_18 is within 0.1 m^3/s of flow at Waitoa River site 1249_22 (Table 4.7). These inconsistencies could result from the use of different time intervals for averaging which generally differs between sites. The time interval for long-term averaging of flows measured by continuous flow recorders was data collected within the period 1960 to 2006, i.e., the period of the average rainfall and AET estimates (Tait et al. (2006) and Woods et al. (2006), respectively).

Average surface water flow at Waitoa River site 1249_18 is within 0.1 m^3/s of flow at Waitoa River site 1249_22 (Table 4.7). However, the average flow in the Waitoa River decreases between these sites if assessed with a precision of the average flow at less than 0.1 m^3/s, i.e., average flow was 4.918 m^3/s (site 1249_18) and 4.876 m^3/s (site 1249_22). Flow at site 1249_22 should be larger than flow at site 1249_18 because P-AET was 0.6 m^3/s in the zone of site 1249_22 (Table 4.6). The calculation of baseflow at site 1249_22 indicates a possible error in the calculation of average flow at site 1249_22; baseflow was 6.8 m^3/s at this site, which was much larger than average flow and median flow at the site (Table 4.7).

Therefore, further statistical assessment of flows is recommended, including selection of a common period for averaging and uncertainty (Section 6.3 and Section 6.4, respectively).

5.3 Sub-catchment Boundaries

Negative residual water flow, e.g., residual flow into the Waimakariri Stream of 2 m^3/s (Table 4.4), are possibly explained by groundwater catchment boundaries that differ from surface catchment boundaries. Larger catchment areas in the Waihou River zones on the Mamaku Plateau could provide inflow to balance the water budgets. However, relatively large land areas are required to balance the water budgets because residual flows are a large proportion of surface water outflow. For example, residual flow is 42% of Q^{SW}_{OUT} in the Waimakariri Stream zone (Table 4.4), i.e., the land area in this zone could be 42% larger, for the same rainfall, than the current zone area to balance the water budget.

Larger zones on the Mamaku Plateau could include land to the east, i.e., the Lake Rotorua groundwater catchment, or to the north and south of the current zone boundaries. It is unlikely that all the residual flow, which is a total of 3.7 m^3/s from the five Mamaku Plateau zones (Table 4.4) could be provided from the Lake Rotorua groundwater catchment because this flow would be ‘taken’ from Lake Rotorua spring-fed streams (i.e., Hamurana Springs, Awahou Stream and Waiteti Stream). This flow would require a large land area which would be ‘removed’ from the catchments of these streams resulting in a significant impact on groundwater outflow to the springs. It is also unlikely that the boundaries of the zones could move significantly in a north-south direction.

Currently, zone boundaries are set with a DTM and a loose best-fit to Q^{SW}_{OUT} and are coincident with boundaries of adjacent zones (White et al. 2014; Figure 3.9). Revision of boundaries will require relatively large land areas north and south of the five Mamaku Plateau zones, which is probably unreasonable with regard to the directions of flow for groundwater and surface water runoff. Similarly, an inflow of 9 m^3/s is required to balance the water budget of the Waihou River Te Aroha zone, and this will require a large land area. Therefore, negative residual flows are best explained by an average rainfall that is too low, which supports a recommendation to revise the long-term rainfall estimates of Tait et al. (2006), Section 6.2.

5.4 Uncertainties in Water Budget Components

The use of mean values for water budget components in this report does not include the uncertainty in model components. This uncertainty probably accounts for part, possibly most, of the residual flows. Therefore, an analysis of uncertainty of model inflows and outflows would add considerably to the interpretation of Q^{GW}_{OUT} calculations. An analysis of uncertainty is best completed after a consideration of water budget components (Section 6.4).

5.5 Potential for Groundwater Flow Between the Major Catchments

Water budgets developed in this report assume that there is no transfer of groundwater between the major catchments, i.e., between the Waihou River catchment and the Piako River catchment. Groundwater transfers are possible between adjacent zones (Figures 3.9 and 3.11). However, the water budgets of Waihou River zones are probably subject to significant uncertainty in rainfall (Section 5.1) and the water budgets do not identify a consistent pattern, and consistent quantum, of losses and gains between adjacent zones (Table 5.1). Therefore, groundwater flow between the major catchments cannot be assessed with these water budgets.

Table 5.1 Residual flows and Q^{GW}_{COUT} in adjacent zones mapped in Figures 3.9 and 3.11.

Waihou River zone			Paiko River zone		
Zone name	Flow site	Residual[1] (m^3/s)	Zone name	Flow site	Q^{GW}_{COUT}[1] (m^3/s)
Waihou River Okauia 1122_18	1122_18	2.7	Waitoa River 1249_38	1249_38	-0.6
Waihou River Shaftsbury 1122_30	1122_30	-3.1	Waiowhero Stream	776_1	-0.6
Waihou River Te Aroha 1122_34	1122_34	9	Waitoa River 1249_18	1249_18	-0.7

1 Here, the zone gains are represented as positive numbers and the zone losses are represented as negative numbers; therefore the sign of the numbers differs from the zone water budget.

5.6 Piako River Catchment: Comparison of Water Budgets

The water budgets for the Piako catchment calculated in this report were similar to those calculated by White and Tschritter (2014). This was because the same rainfall and AET maps were used in both reports and surface flows estimated in this report are similar to the flows calculated in White and Tschritter (2014), Table 5.2. Therefore, the conclusions of White and Tschritter (2014) are valid with the water budget calculations in this report. For example, most groundwater recharge in the Piako Pleistocene unit of White and Tschritter (2014), which is approximately equivalent to the sum of two sub-catchments (i.e., Piako River 749_15 and Waitoa River 1249_18), flows to the surface in the Piako River catchment.

Table 5.2 Piako River catchment surface flow calculations in this report and in White and Tschritter (2014).

Surface flow (Table 4.7)			Surface flow (White and Tschritter 2014)		
Site name	Mean flow (m^3/s)	Median flow (m^3/s)	Site name	Mean flow (m^3/s)	Median flow (m^3/s)
Paeroa-Tahuna Rd Br	6.8	3	Piako2	6.8	2.9
Mellon Rd Recorder	4.9	3.1	Waitoa2	4.9	2.9
Paeroa-Tahuna Rd	4.9	2.7	Waitoa4	5.5	2.7

6.0 RECOMMENDATIONS

6.1 Well Logs

WRC's database of lithology includes a summary of lithology recorded by drillers. This summary typically contains lithological identifications 'dominant fraction' and 'secondary fraction' of lithology (Section 3.1.2.4). Therefore, the database contains much less information than is available on well logs. Hence, it is recommended that WRC record full lithological descriptions, as noted by the driller, on its lithology database.

6.2 Geological Model

The 3D geological model described in this report was developed as a conceptual model that aimed to represent the key Hauraki Plains formations relevant to groundwater flow. However, more work on the layer grids is recommended as part of the groundwater flow modelling project, including representation of Tertiary sediments and consideration of faults. The layer grids described in this report provide a very useful starting point for this work.

6.3 Water Budget Components and Zone Boundaries

It is recommended that the rainfall model is revised, particularly in the area of the Mamaku Plateau and the Kaimai Range (Section 5.1). Remodelled rainfall on the Mamaku Plateau (noted in White et al. 2014) will be of relevance to a re-assessment of rainfall in the Waihou River catchment. In parallel, the AET estimates of Woods et al. (2006) could be revised including the new rainfall estimates.

Surface water flow estimates that were used in the water budget should be revised (Section 5.2 and Section 5.4). A field programme should measure more surface flows in the Hauraki Plains area. Priority sites are those that measure zone outflows in the Hauraki Plains where flows are currently estimated by gaugings (Tables 4.3 and 4.7). These measurements should aim to provide improved estimates of average flows, baseflows and quick flows.

Groundwater inflows to zones, and outflows from zones, could be calculated with a steady-state groundwater flow model, should this be developed. The groundwater flow model could also inform calculation of new zone boundaries, e.g., groundwater catchments on the Mamaku Plateau.

6.4 Long-term Flow Estimates

The time interval for averaging of continuous surface flows generally differs between flow recorder sites (Section 5.2). Therefore, revision of flow estimates (i.e., average, median and baseflow) is recommended with a common period for flow calculation.

6.5 Uncertainty

Estimates of the uncertainty in steady state water budget components (i.e., rainfall, AET, rainfall recharge, surface flows and groundwater flows) would be useful to the assessment of flows in Hauraki Plains (Section 5.4). An assessment of uncertainty is recommended after consideration of revisions to water budget components (Section 5.1, Section 5.2 and Section 6.2). An assessment of the uncertainties in surface flows could follow the approach of Rutherford and Palliser (2014) in the Lake Rotorua catchment.

7.0 CONCLUSIONS

A geological model of the Hauraki Plains identified eight hydrogeological layers that are relevant to groundwater flow. Holocene sediments are approximately 30 m thick at the coast and generally thin towards the south. This unit includes alluvial, swamp and marine deposits. Pleistocene Hinuera Formation included volcaniclastic alluvium, which provided most of the infill in the Hauraki Plains and is extensively exposed in the south of Hauraki Plains. These sediments include greywacke gravel, which may form a fan deposit with an origin in the northwest of the Hauraki Plains. Mamaku Plateau Formation ignimbrite forms the headwater catchments of the Waihou River. Tauranga Group (including early Pleistocene sediments) crop out in the west of Hauraki Plains in fluvial terraces. Pakaumanu Group ignimbrite formed outcrops over a wide area in the southwest of the Hauraki Plains west of Matamata. Waiteariki Ignimbrite was located on the Kaimai Range north of Mamaku Plateau and is located below sediments in the vicinity of Matamata. Basement rocks include greywacke and Coromandel volcanics.

The total surface water outflow from the Hauraki Plains area was an estimated mean of 73.9 m^3/s in three major catchments; estimated groundwater outflow at the coast from the area is a small proportion of surface flow, i.e., 1.9 m^3/s. Estimated surface water outflows at the coast from the Waihou River catchment, the Piako River catchment and the Hauraki north-west were 53.8 m^3/s, 18.5 m^3/s and 1.6 m^3/s, respectively.

Water budgets calculated the major inflows (rainfall, surface flow and groundwater flow) and outflows (actual evapotranspiration, surface flow and groundwater flow) of catchments and zones. However, water budgets of the Waihou River did not calculate groundwater inflows and groundwater outflows because negative residual flows were commonly calculated for headwaters sub-catchments and zones, suggesting that improved estimates of water budget components are required in the Waihou River catchment. In addition, long-term average flow estimates in the Waihou River were inconsistent at the Tirohia and Te Aroha sites, i.e., average flow at the downstream site (Tirohia) was less than average flow at the upstream site (Te Aroha).

Water budget components in the Piako River sub-catchments were probably more reasonable estimates of mean flows than water budget components in the Waihou River catchment. This is because residual flows in the Piako River sub-catchments were generally low, and residual flows were generally positive. Therefore, residual flows in the Piako River zones were assumed to generally represent groundwater outflow.

The boundary between relatively permeable Pleistocene sediments and relatively impermeable Holocene sediments have an important role in controlling groundwater flow, i.e., most groundwater flow in the southern Hauraki Plains comes to the ground surface in this area. Groundwater outflows from Waitoa River catchments located south of the boundary between Holocene and Pleistocene sediments were large relative to total catchment outflow. For example, groundwater outflows were 67% and 75% of total sub-catchment outflow in Waihekau Stream and Waiowhero Stream, respectively. Importantly, this percentage tends to decrease towards the boundary of Pleistocene and Holocene sediments, e.g., groundwater outflow at this boundary from the Waitoa River 1249_22 sub-catchment was 21% of total outflow. In addition, the BFI tends to increase towards the boundary. For example, BFI increased from 0.53 to 0.63 between Waitoa River 1249_38 sub-catchment and Waitoa River 1249_18 sub-catchment.

Recommendations in this report include a revision of the rainfall model, particularly in the area of the Mamaku Plateau and the Kaimai Range. In addition, surface water flow estimates that were used in the water budget should be revised and a field programme is recommended to measure surface flows in the Hauraki Plains. The sites that use gaugings to measure outflows from Hauraki Plains zones are a priority for further assessments of flows.

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