Healthy Rivers | Wai Ora
PLAN FOR CHANGE | HE RAUTAKI WHAKAPAIPA

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Groundwater resource characterisation in the Waikato River catchment for Healthy Rivers Project

This report was commissioned by the Technical Leaders Group for the Healthy Rivers Wai Ora Project

The Technical Leaders Group approves the release of this report to Project Partners and the Collaborative Stakeholder Group for the Healthy Rivers Wai Ora Project.

Signed by:

Date: 2 December 2015

Groundwater resource characterisation in the Waikato River catchment for the Healthy Rivers Project

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EXECUTIVE SUMMARY

The “Healthy Rivers Project” (Wai Ora: He Rautaki Whakapaipai) aims to improve water quality in the Waikato River and Waipa River and their catchments, including groundwater, by improving key water indicators (e.g., nitrogen, phosphorus, bacteria and sediment) in the project area. A science team has been engaged by the Healthy Rivers Project (HRP) to provide information on water resources in these catchments. This report describes the models of geology and water budgets that were developed by GNS Science and were used, with groundwater chemistry data, to characterise the HRP groundwater systems.

Geology in the Upper Waikato River catchment (UW) zone of the HRP area is dominated by Pleistocene volcanic rocks associated with the Taupo Volcanic Zone. Aquifers in this area include ignimbrite, rhyolite and volcanoclastic sediments. Water budgets of the HRP catchments in the UW show that rainfall recharge is relatively large, in common with other areas in the TVZ (i.e., the Lake Rotorua catchment); coincidently, surface quick flow is relatively small. Therefore, most of the water that enters UW catchments (typically more than 90%) flows into the groundwater system. Surface flow is dominated by baseflow; this is water that discharges from the groundwater system. In addition, groundwater outflow from HRP catchments may discharge to the Waikato River. Nitrate-nitrogen concentrations in UW groundwater are commonly relatively high, i.e., above ½ of the Maximum Allowable Value set for community water supplies (Ministry of Health, 2008). This clearly shows that land use is impacting on groundwater quality.

Important aquifers in the Waipa River catchment zone include Miocene sediments (and limestones associated with Waitomo caves), Alexandra Group volcanics and thick Quaternary Tauranga Group sediments of the Hamilton Basin. Baseflow is typically 60% to 80% of river flow and, as a result, a considerable portion of the net rainfall enters the groundwater system. Groundwater outflow from HRP catchments particularly that from Miocene sediments southwest of Otorohanga, is also important to the catchment water budgets. Relatively high median nitrate-nitrogen concentrations occur in the Waipa River catchment, but they are as not as common as in the UW area.

The Lower-Middle Waikato River catchment zone occupies the Hamilton Basin and the Lower Waikato Basin. Groundwater recharge in the Hamilton Basin travels toward the Waikato River to enter the river above Taupiri where greywacke basement in the ranges provides a barrier to lateral groundwater flow. Tauranga Group sediments are relatively shallow in the Lower Waikato Basin. Here, swamps are common and, therefore, groundwater is at, or close to, the ground surface in large areas around the Waikato River between Huntly and the coast. Relatively high median nitrate-nitrogen concentrations, and E coli counts above community drinking water standards, are the most common in the Lower-Middle Waikato River catchment.

In addition, this report describes the hydrogeological characteristics of each of the 74 HRP catchments, including geology, water budgets and groundwater chemistry. Groundwater information developed in this report is intended to be used, with other environmental information provided by the team, by the community as they move towards consideration of options to improve water quality. Therefore, this report also includes a general description of groundwater in each catchment, and images of the catchments, to assist in the general understanding of the HRP catchments.

Recommendations for future work related to the groundwater resource in the HRP area follow a review of science information in the HRP area, including that developed in this

report. These recommendations include: improvements to the quality of the WRC well log database; the building of steady-state groundwater flow models for the Waipa and LMW zones so that the HRP can assess the water quality effects of land-use options; and improvements to the groundwater quality database to allow monitoring of the effects of land use on surface and groundwater quality. A monitoring plan for field measurements is also proposed. The main elements of this plan include: surface flow and surface chemistry measurements; groundwater chemistry; and the definition of sampling intervals that are appropriate to monitor the changes in water quality associated with community actions through the Healthy Rivers Project.

1.0 INTRODUCTION

The “Healthy Rivers Project” has come out of the settlement for Waikato River and Waipa River iwi. This project (Healthy Rivers: Plan for Change/Wai Ora: He Rautaki Whakapaipai) has been set out in settlement legislation and is co-managed by iwi and the Waikato Regional Council. The project aims to improve water quality in the Waikato River catchment, including groundwater, between Lake Taupo and the sea (Figure 1.1) by controlling key water indicators (e.g., nitrogen, phosphorus, bacteria and sediment) within acceptable limits and thereby secure the future of the land and water resources in the catchment that are of crucial economic and environmental value to the Waikato Region and to New Zealand.

In 2014, a science team was assembled to provide summaries of current information on the water resource in the Waikato River catchment. This team included scientists located at Waikato Regional Council (WRC), National Institute of Water and Atmospheric Research (NIWA), GNS Science, Lincoln Agritech, Aqualinc, ESR and others. They were also tasked to identify immediate information needs, to be completed before approximately April 2015, that could contribute to a broad-scale assessment of land use and water quality in the catchment.

The role of GNS Science in the project has been to characterise the groundwater resources in the Waikato River catchment within 74 Healthy River Project (HRP) catchments (Figure 1.2 Figure 1.3, and Figure 1.4). This has included geological modelling of three catchment zones (Upper Waikato, Waipa and Lower-Middle Waikato), Figure 1.1. The Upper Waikato River (“UW”) catchment is characterised by large areas of volcanic deposits produced by the Taupo Volcanic zone (TVZ). The lower to middle Waikato River (“LMW”) and Waipa River (“Waipa”) catchments include two sedimentary basins that are intensively farmed and contain most of the human population of the Waikato Region.

These models are used to develop the framework for understanding groundwater resources, for example to identify key aquifers in the region. Water budgets of the HRP catchments aim to estimate inflows to the groundwater system, for example rainfall, and outflows from the groundwater system, including baseflow to streams as groundwater has been demonstrated as a key source of surface water in the catchment (White, 2010). Water budgets are used to identify outflows to adjacent catchments as these outflows are relevant to the residence time of water in catchments. GNS Science has also developed maps of groundwater elevations in the three zones, which identify the directions of groundwater flow in catchments; these are relevant to the characterisation of catchments and the environments that receive nutrients from land use.

This report includes a synthesis, by zone, of the results of the assessment of the groundwater resources in 74 HRP catchments, including summaries of the:

- general distribution of aquifers and aquicludes, via geological models of the three zones;
- main aquifer and aquifer thicknesses in HRP catchments;
- hydraulic properties of aquifers;
- catchment water budgets, including groundwater inflows and outflows;
- stream flow components, i.e., base flow, which is sourced from the groundwater system, and quick flow; and
- groundwater chemistry.

Summaries of the groundwater-related properties of HRP catchments are included in Appendix 1 (general descriptions of groundwater in each catchment) and in the “HRP Template”. Data in the template is presented in the report under three general categories:

- geology and aquifer properties (Appendix 2)
- water budgets (Appendix 3)
- groundwater chemistry (Appendix 4).

This information, together with that of other providers, is intended to be used in a public information system that will be used by the HRP in their consultation with land owners in the catchment, and the public. This consultation aims to identify future options for management of the water and land resources to meet the aims of the HRP.

In addition, this report includes an analysis of areas where the information base could be further developed to improve future understanding of the groundwater resource, and the linked surface water flow systems, in the Waikato River catchment.

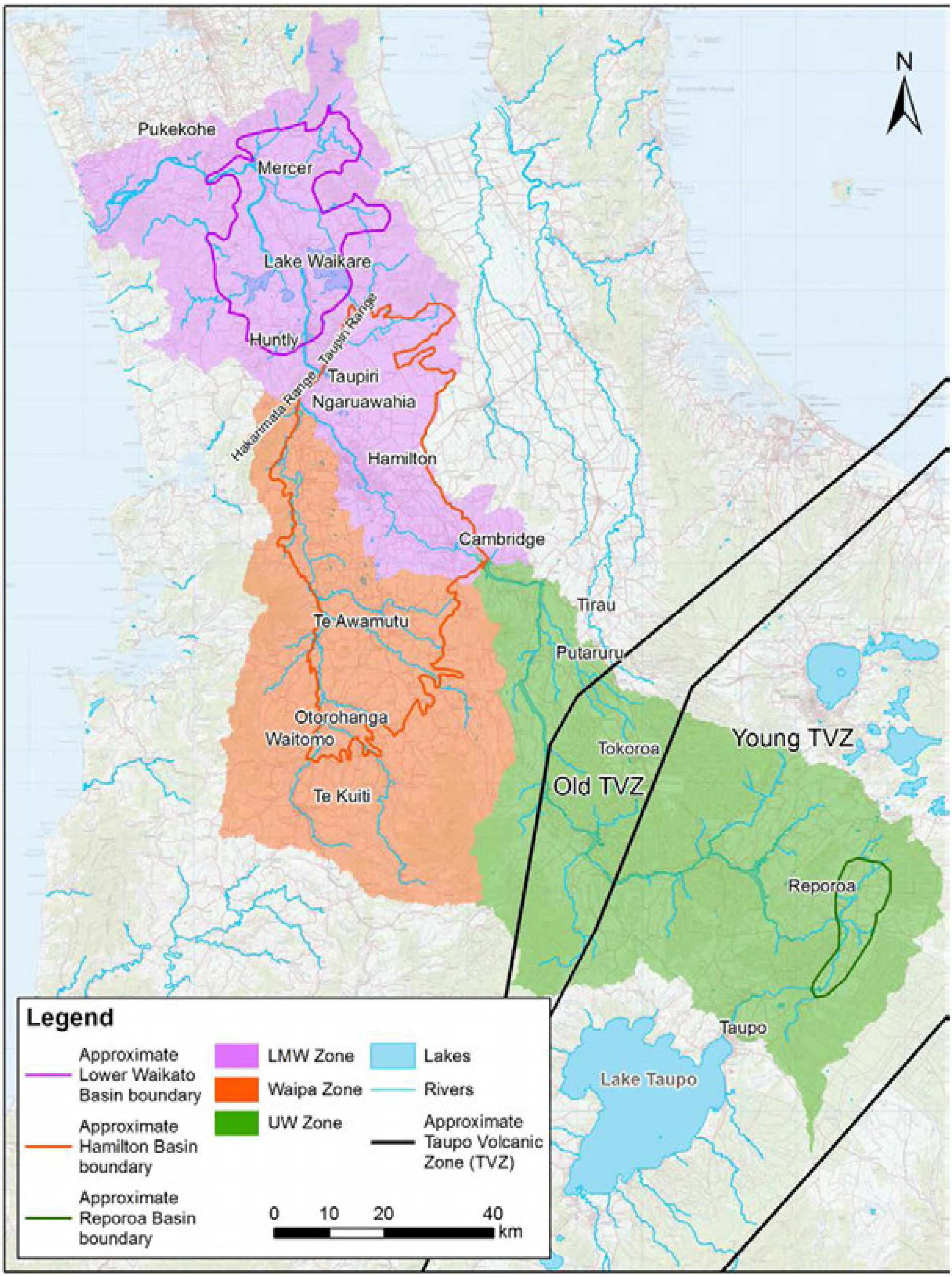

Figure 1.1 The Waikato River catchment and the three Healthy River Project zones.

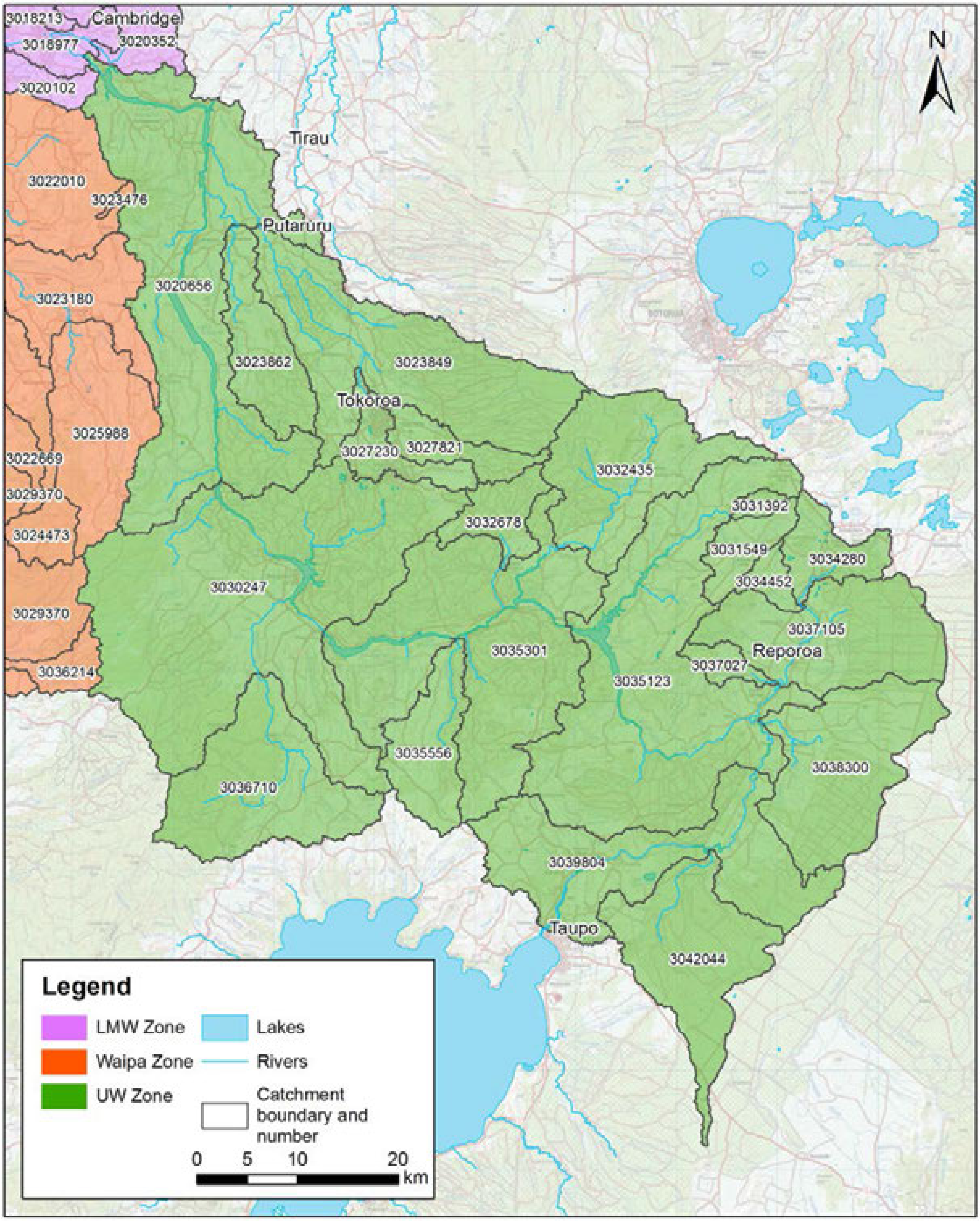

Figure 1.2 HRP catchments in the Upper Waikato zone.

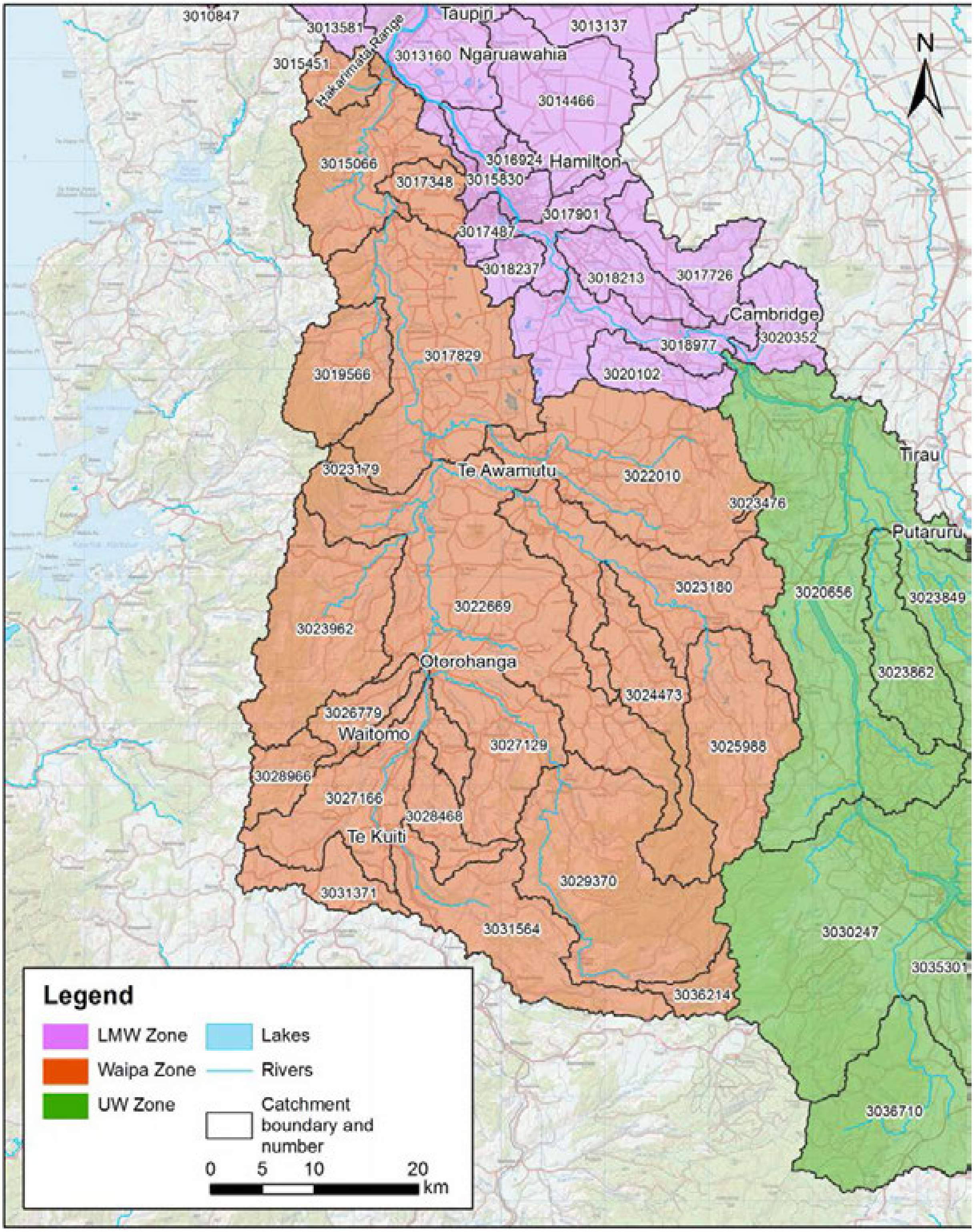

Figure 1.3 HRP catchments in the Waipa zone.

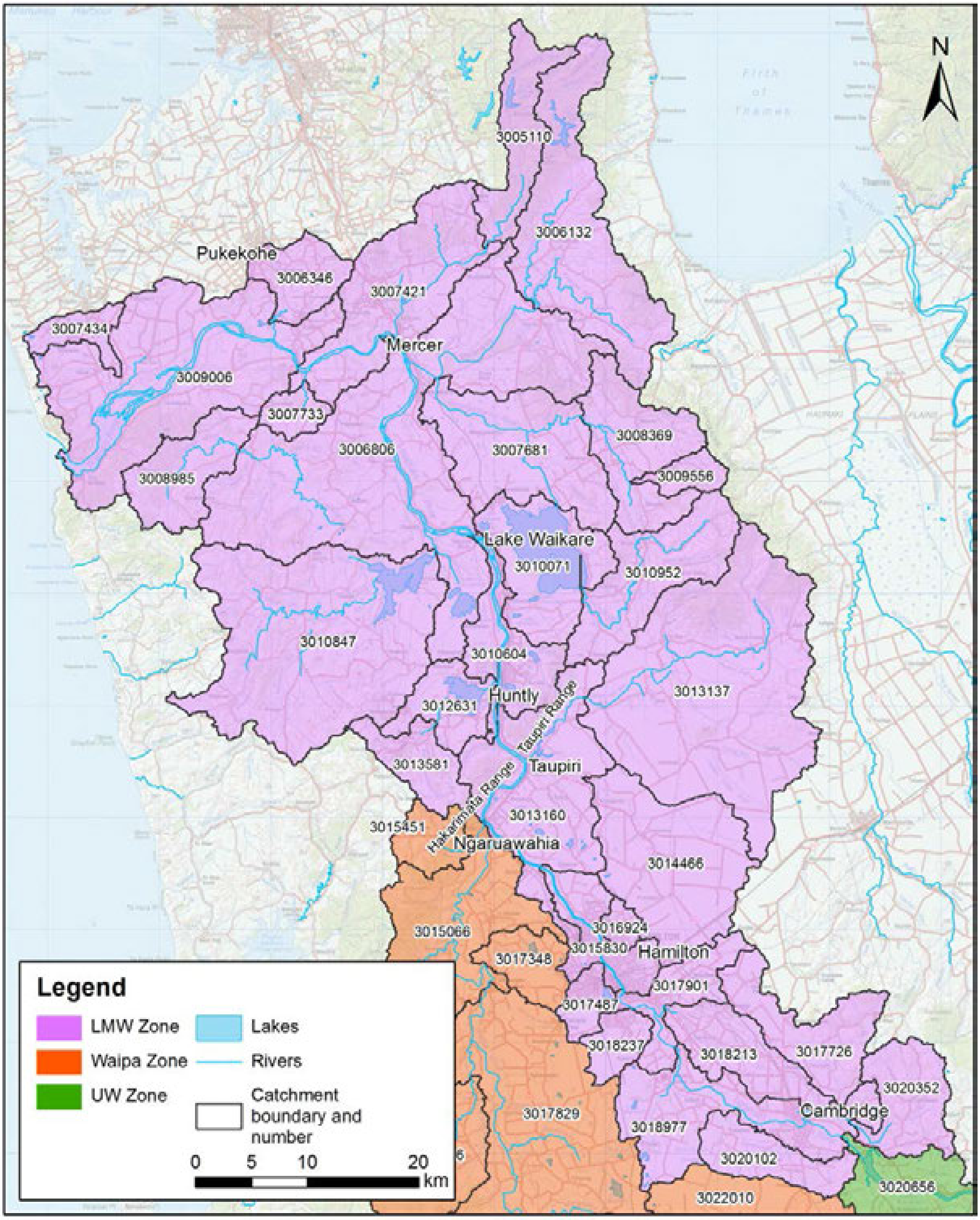

Figure 1.4 HRP catchments in the Lower-middle Waikato zone.

2.0 REVIEW OF THE GEOLOGY OF THE WAIKATO RIVER CATCHMENT

The geology of the Waikato River catchment is summarised for the LMW, Waipa and UW zones in Figure 2.1, Figure 2.2 and Figure 2.3, respectively. These maps, and the geological formation nomenclature that is used in this report, are generally that of three relevant digital QMAP geological maps at a 1:250,000 scale that cover the catchment: i.e., Auckland (Edbrooke, 2001), Waikato (Edbrooke, 2005) and Rotorua (Leonard *et al.,* 2010).

2.1 GEOLOGICAL HISTORY AND STRUCTURE

The geological history of the Waikato River catchment is outlined for the Cretaceous and for post-Cretaceous deposits in two parts, i.e., firstly for the LMW and Waipa zones and secondly for the UW zone. This is because the geological history of the Waikato River catchment was similar in both parts during the Cretaceous (i.e., the approximate age range 140 million years to 65 million years ago) but markedly different after this period. During the Cretaceous, basement greywacke, typically older than approximately 140 million years (Ma) was uplifted and then subjected to prolonged erosion and deep weathering. These processes produced a New Zealand-wide Cretaceous unconformity, i.e., a depositional time gap, of approximately 35 Ma.

Following the Cretaceous, thick sedimentary deposits formed in two basins in the LMW and Waipa zones (Figure 1.1) and a long period of proximity to the coast gave rise to iconic local landforms such as Waitomo Caves. In contrast, geology in the UW zone was dominated by Pleistocene volcanism since the Taupo Volcanic Zone (TVZ) began to form about 2 Ma years ago.

2.1.1 Lower-Middle Waikato and Waipa

Regional subsidence in the late Paleogene Period (i.e., approximately 65 Ma to 23 Ma) initiated deposition of the sedimentary cover sequence within the LMW and Waipa zones above the Cretaceous unconformity. The oldest rocks in this sequence are Late Eocene to Oligocene sedimentary rocks of the Te Kuiti Group. This group includes basal coal measures overlain by marginal marine to outer shelf sediments. Te Kuiti Group deposition continued to the end of the Oligocene when the tectonic setting changed to one of variable compression as the active plate margin propagated through northern New Zealand. The sequence was uplifted, gently tilted and eroded to varying degrees, mainly in the east. This was quickly followed by deposition of terrestrial-dominated sediments in a rapidly subsiding basin. The sediments of this Early Miocene depositional phase are included within the Waitemata Group near to the coast (north and west). Extensive erosion of Waitemata Group formations occurred after Early Miocene uplift, and mainly westward titling, particularly in the east, and in some areas the group has been completely removed. However, thick Waitemata Group sequences are preserved in the Hamilton Basin, where there was little uplift.

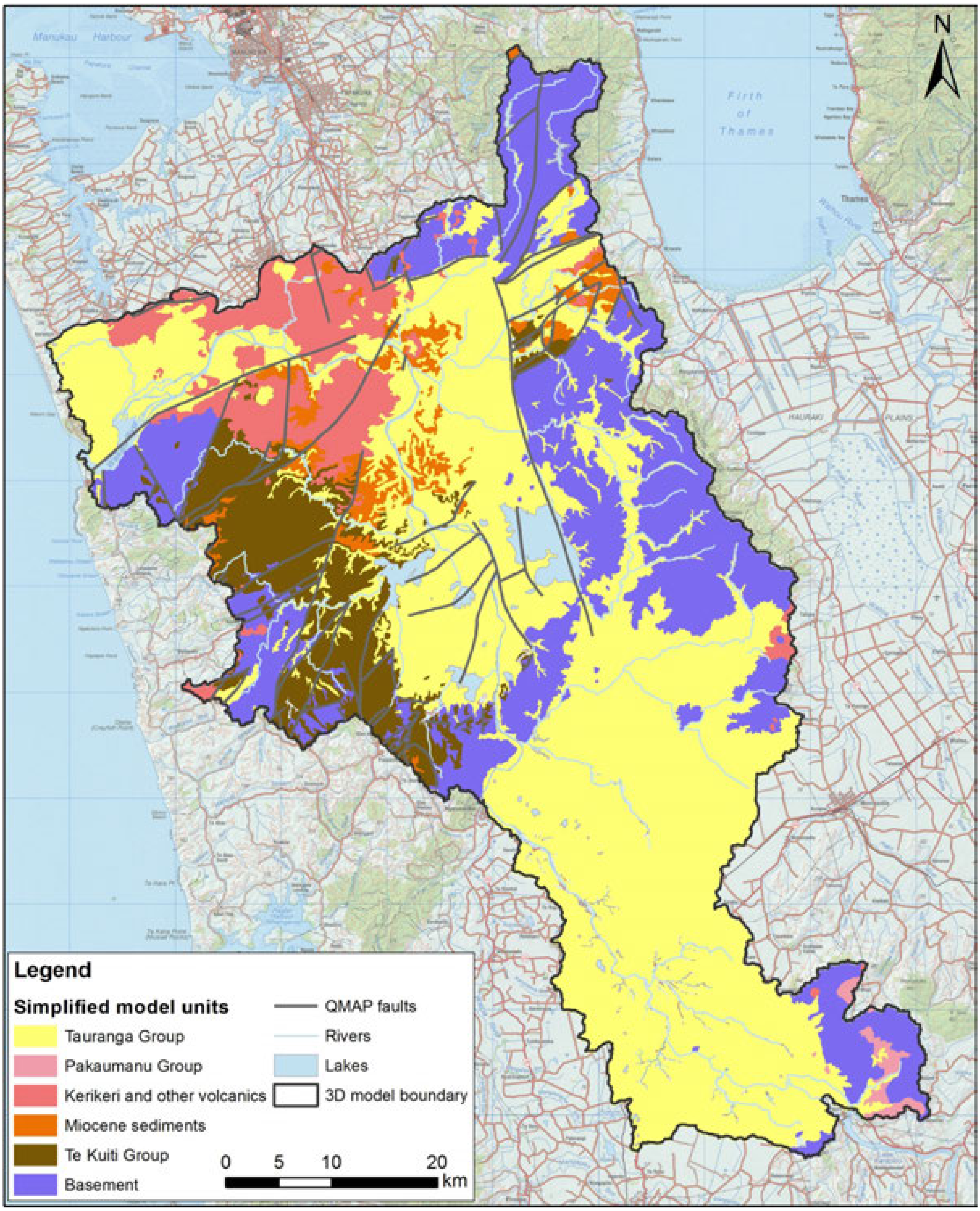

Figure 2.1 Summary geological map of the LMW area.

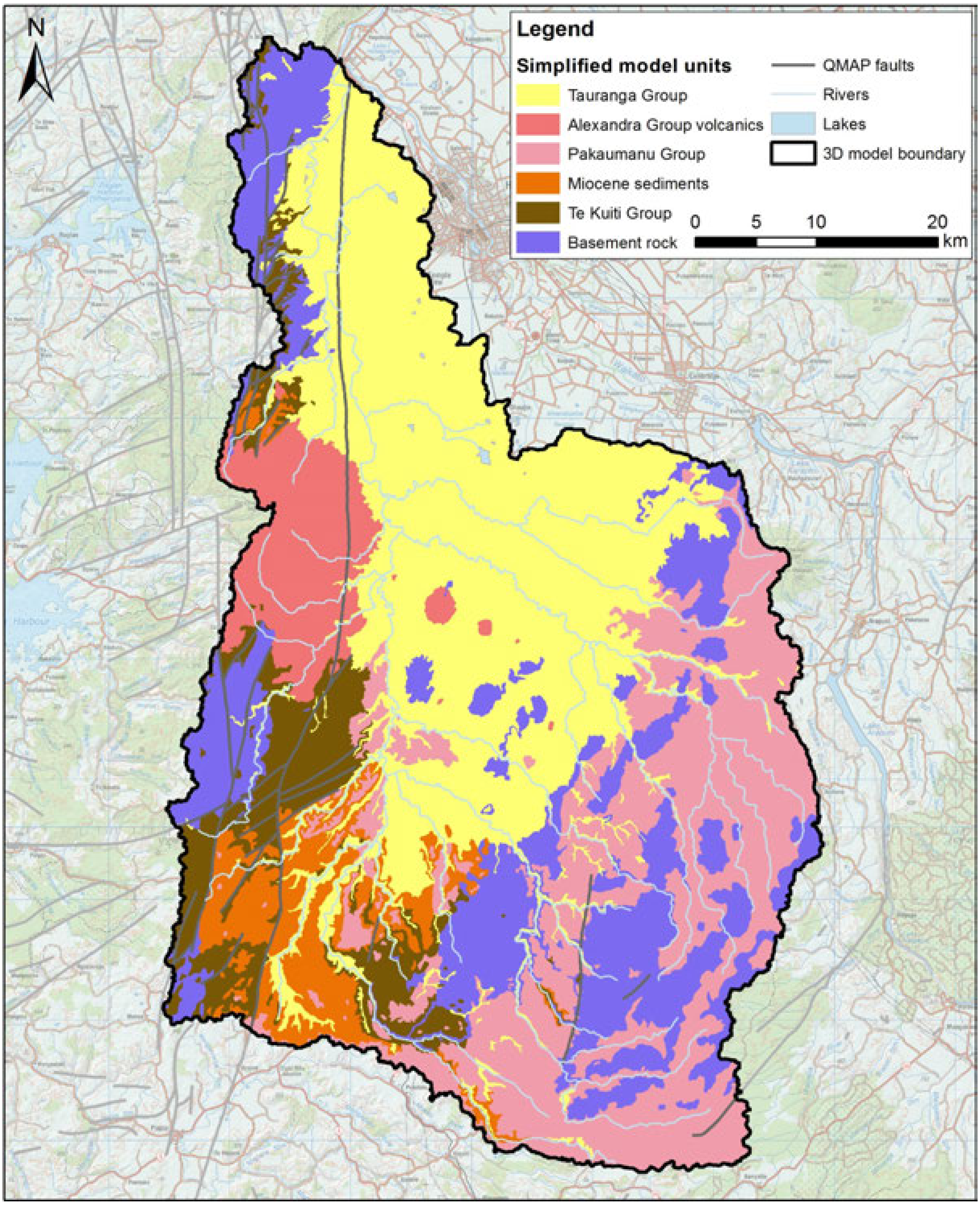

Figure 2.2 Summary geological map of the Waipa area.

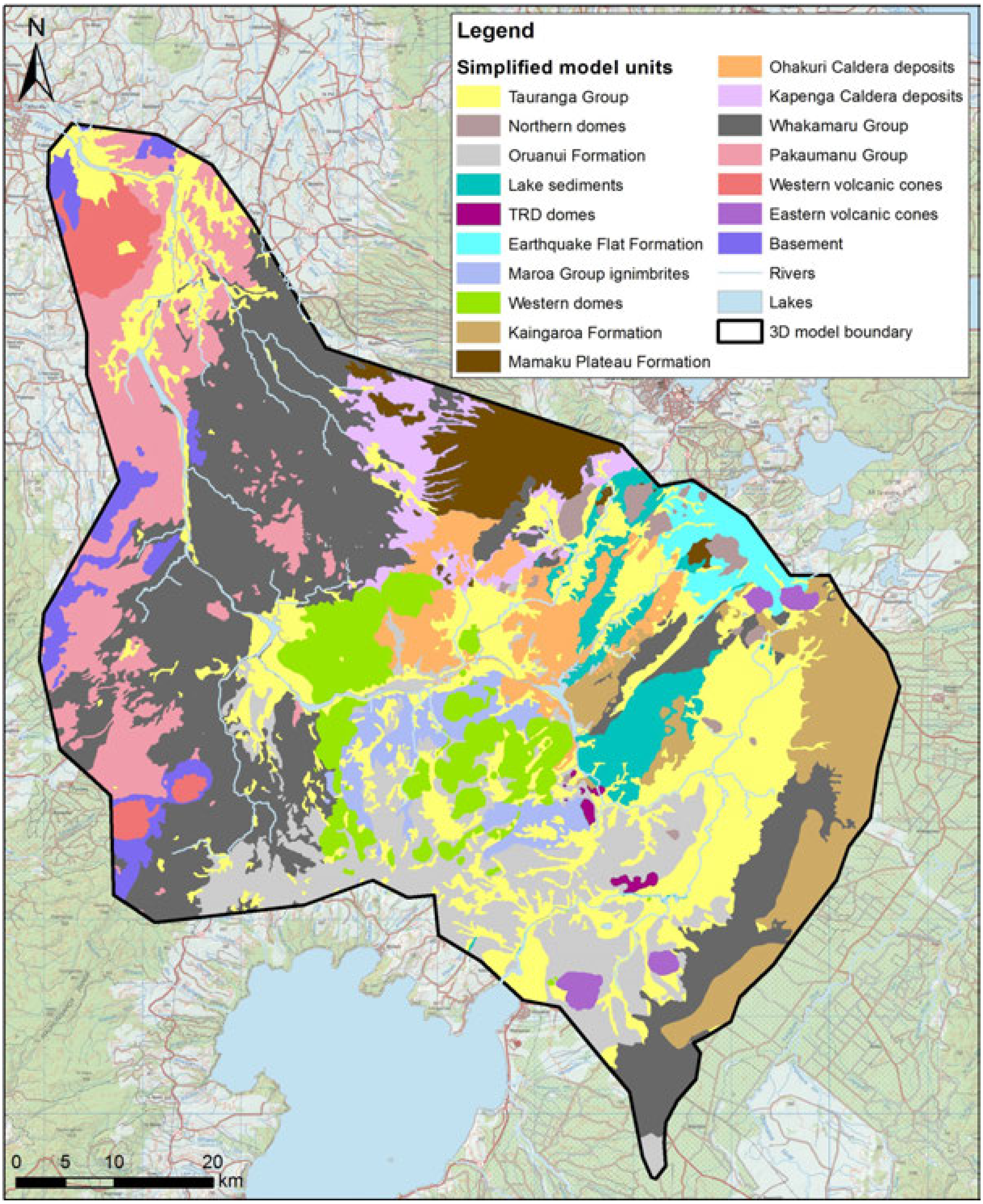

Figure 2.3 Summary geological map of the UW area.

Since Miocene uplift, predominantly non-marine sediments have been deposited in the lower and middle Waikato and Waipa areas. These late Miocene to Holocene deposits are included in the Tauranga Group, which consists of gravel, sands, silts, muds and peats of fluvial, lacustrine and distal ignimbrite origin. In addition, Pliocene Kaawa Formation marine sediments were deposited in the South Auckland area. The oldest remnants of volcanoes in LMW are small, Middle to Late Miocene, subaerial andesite volcanoes (i.e., Kiwitahi Volcanic Group) along the eastern margin of the LMW. Kerikeri Volcanic Group includes Pleistocene basaltic volcanoes of the South Auckland Volcanic Field. Late Pliocene to earliest Pleistocene back-arc volcanism produced the Alexandra Group volcanics, consisting of several low-angle cones, including Pirongia, Te Kawa and Kakepuku within the Waipa catchment. The Mangakino Volcanic Centre (located within the older Taupo Volcanic Zone) produced the Pleistocene Pakaumanu Group, which covers most of the southeast of the Waipa catchment, but has only been mapped at the ground surface throughout a small area in the south east of the Lower to Middle Waikato catchment.

Predominantly normal faults displace all pre-Late Miocene rocks and dominant N-to-NNW faults intersect with subsidiary NE-to-ENE trending faults to produce the block-faulted landscape of today. Many faults have no surface expression as their scarps were buried by Tauranga Group sediments, or volcanic rocks, after most movement had ceased. The N to NW faults are not as numerous but tend to be longer and have larger displacements, typically up to 500 m. Faults of this type include Wairoa, Drury, Kimihia, Maungaroa, Karaka, Oraki and Waipa faults (Edbrooke *et al.,* 1994).

2.1.2 Upper Waikato

The geology of the Upper Waikato area is dominated by Pleistocene TVZ volcanic units, with associated volcanoclastic sediments, and basement greywacke. Extensive volcanism in the TVZ is divided into three periods by Wilson *et al*. (1995), Figure 1.1:

- old TVZ where the commencement of volcanic activity in the TVZ is indicated by eruptions that formed the Mangakino Caldera, with at least nine eruptions in the interval 1.6 Ma to 0.95 Ma (Wilson *et al*., 2009);
- young TVZ in the period between the onset of eruptions from the Whakamaru Caldera (approximately 300 ka) and deposition of Rotoiti Pyroclastics from the Okataina Caldera at approximately 61 ka (Wilson *et al*., 2007, 2009). This period includes formation of calderas including Maroa, Reporoa, Rotorua, Okataina and Taupo; and
- modern TVZ, from the eruption of Rotoiti Formation to the present day, including volcanic activity associated with the Taupo and Okataina calderas and the formation of Lake Taupo.

Calderas and faults are key structural elements of the TVZ (Wilson *et al*., 1995; Spinks *et al*., 2005) that are associated with considerable displacement of the basement. For example, the basement under the TVZ is as much as 7 km below sea level, approximately 3 km below sea level under the Reporoa Basin and approximately 1 km below sea level at Lake Ohakuri (Leonard *et al*., 2010). Basement greywacke elevation measurements are provided by drilling in the geothermal fields including Rotokawa, Ngatamariki and Ohaaki.

Lakes often form in calderas; for example, Lake Huka occupied the Reporoa Caldera, and part of the present Lake Taupo area, before the Oruanui eruption, Figure 2.4, Manville and Wilson (2004).Caldera-forming eruptions can have significant effects on river flows. For example, the Waikato River flowed to the Hauraki Gulf before the Oruanui eruption (Figure 2.4). After this eruption, the river flowed to the Hamilton Basin and deposited large volumes of volcanogenic sediments, derived from the Oruanui eruption, in the basin.

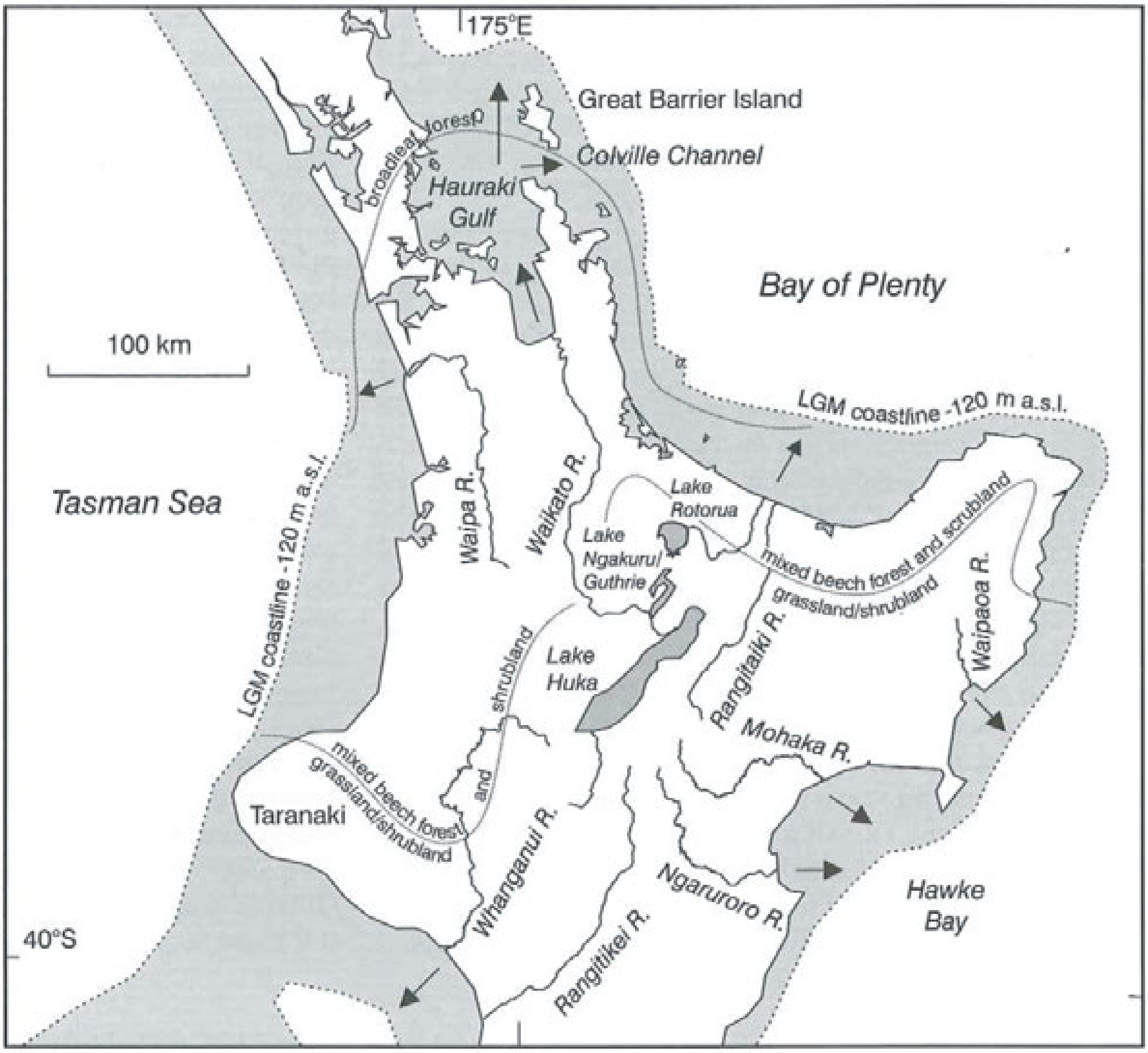

Figure 2.4 Major Late Quaternary hydrological features of the North Island. Of significance to groundwater in the Waikato River catchment are the Waikato River's flow into the Hauraki Gulf and the presence of Lake Huka (Manville and Wilson, 2004) in the Reporoa Basin before the Oruanui eruption. The LGM coastline represents the coastline at the Last Glacial Maximum (21 – 18 ka).

The Taupo Fault Belt is a broadly NE-SW oriented band of intense, late Quaternary, dominantly normal faulting. Some of the faults within this belt have cumulative displacements of several hundred metres and have split the TVZ into a series of tilted blocks. In the west of the area, the Paeroa Block, bounded by the Paeroa Fault, is an example of such structural units. The Paeroa Fault (Grindley, 1959) is a normal fault, downthrown to the northwest in a prominent scarp that is parallel to the main faults in the TVZ (Risk *et al*., 1994). In the east, the Kaingaroa Fault is associated with the eastern margin of the TVZ (Risk *et al*., 1994). The fault has a 200 m scarp that separates the Kaingaroa Plateau from the Reporoa Basin. This prominent feature of the landscape runs the full length of the eastern side of the basin.

2.2 GEOLOGICAL FORMATIONS AND PROPERTIES

Geological units in the Waikato River catchment that are important to groundwater flow are represented in the geological models (see Figure 2.2, Figure 2.3, Figure 2.4 and Table 2.1). These units include aquifers and aquicludes. The following text summarises some of the features of these units including their origins and their properties with regard to groundwater resources.

Table 2.1 Geological units in the Waikato River catchment that are represented in the Waikato River catchment geological models.

Geological unit	Age	Upper Waikato catchment	Waipa River catchment	Lower-middle Waikato River catchment
Tauranga Group	Holocene and Pleistocene (0 to 2 Ma)	✓	✓	✓
Oruanui Formation	Pleistocene (27 ka)	✓		
Earthquake Flat Formation	Pleistocene (61 ka)	✓		
Upper Waikato lake sediments	Pleistocene (less than approximately 320 ka)	✓		
Maroa Group ignimbrites	Pleistocene (196 – 283 ka)	✓		
Rhyolite lava domes	Pleistocene (post-date the Whakamaru Group, to approximately 80 ka)	✓		
Kaingaroa Formation	Pleistocene (230 ka)	✓		
Ohakuri Caldera deposits	Pleistocene (240 ka)	✓		
Mamaku Plateau Formation	Pleistocene (240 ka)	✓		
Kapenga Caldera deposits	Pleistocene (275 ka)	✓		
Eastern volcanic cones	middle Pleistocene	✓		
Whakamaru Group	Pleistocene (320 - 340 ka)	✓		
Pre- Whakamaru Group volcanics	Pleistocene	✓		
Mangakino volcanics	Pleistocene (1.68 to 0.95 Ma)	✓		
Western UW volcanic cones	Pliocene-Pleistocene	✓		
Kerikeri Volcanics	Pleistocene Late Pliocene to Early Quaternary			✓
Kaawa Formation	Early to Late Pleistocene			✓
Alexandra Group volcanics	Late Pliocene to earliest Pleistocene		✓	
Pakaumanu Group	Late Pliocene to earliest Pleistocene		✓	✓
Miocene sediments	Miocene		✓	✓
Te Kuiti Group	Late Eocene to Early Miocene		✓	✓
Basement greywacke	Various units (> ~140 Ma)	✓	✓	✓

2.2.1 Tauranga Group

Tauranga Group sediments form common aquifers in the Waikato River catchment. These sediments underlie the Hamilton and lower Waikato lowlands, and elsewhere are present as areas of valley-confined alluvium. The deposits are quite heterogeneous and include gravel, sand, silt, mud and peat of fluvial, lacustrine and volcanogenic sediments. Thickness is highly variable, typically in the range 5 – 80 m, but thicknesses of up to 600 m are known in the Hamilton Basin (Katz, 1968). The older, Pliocene to Middle Quaternary sediments comprise a sequence of laterally interfingering lenses and tongues of pumiceous gravel, sand and silt with interbedded peat, diatomaceous mud and ignimbrite tephra.

Tauranga Group sediments and associated volcanics include Pleistocene Hinuera Formation around Mangakino (Healy *et al*., 1964) and Holocene deposits. Hinuera Formation deposition

(Manville, 2002; Manville and Wilson, 2004) includes sediments deposited in the Hamilton Basin by the break-out flood from Lake Taupo after the Oruanui eruption. Holocene deposits, partly formed as a result of the post-Taupo eruption break-out flood (Manville *et al*., 2009), include ignimbrite and primary volcanic ash beds mixed with recent pumiceous sands and gravels. These sediments are usually unconsolidated with layered paleosols and loess.

Tauranga Group includes two subgroups in the Hamilton Basin. The Walton Subgroup (Late Pliocene to Middle Quaternary) covers large expanses of the surface geology. In this area, the group is dominated by primary and re-worked, non-welded ignimbrite and tephra, and comprises a sequence of interfingering lenses of pumiceous fine-grained sand and silt with interbedded peat, pumiceous gravelly sand and mud. The Piako Subgroup has two characteristic deposits: the Late Pleistocene Formation, deposited by the braided river systems of the ancestral Waikato River, and constituting fluvial, pumiceous and rhyolitic gravel, sand and silt with minor peat beds; and Holocene swamp deposits that form muddy peat-dominated areas. The Walton Subgroup typically provides large volumes of good quality water, whilst the Piako Subgroup provides water of variable quality and yields (Edbrooke, 2005). The Hinuera Formation (Piako Subgroup) and the Walton Subgroup are the most important of the Tauranga Group for groundwater resources. Bores in these groups may yield greater than 28 L/s (Marshall and Petch, 1983).

2.2.2 Oruanui Formation

The Oruanui eruption produced the caldera now filled by Lake Taupo (Wilson, 1993; Wilson, 2001). The Oruanui event is radiocarbon dated at 22,590±230 yrs. B.P. (Wilson *et al*., 1988), which is equivalent to about 27.1 calendar years (Lowe, 2011). This unit is a composite of pumice-dominated flow (ignimbrite) and air fall deposits that both formed and mantled the landscape (Wilson, 1991). This unit is characterised by an almost complete lack of jointing, but, in comparison with the Taupo Ignimbrite, is somewhat finer grained and somewhat less permeable (Hadfield *et al*., 2001). The thickness of Oruanui Formation was between 50 and 240 metres in the Lake Taupo catchment when it was deposited, but a large volume of the deposits have been removed by erosion.

2.2.3 Earthquake Flat Formation

Earthquake Flat Formation is exposed in the northwestern part of the study area between Kapenga and Rainbow Mountain. The Formation is sourced from six main eruptive vents close to the boundary of the Kapenga Caldera (Nairn, 2002) and covers an area of ~110 km^2. It comprises non-welded pyroclastic flow and air fall deposits up to 120 m thick (Nairn, 2002) that erupted approximately 61 thousand years ago (Wilson *et al*., 2007).

2.2.4 Upper Waikato Lake sediments

This group comprises Huka Group as well as mid-Quaternary lake sediments associated with the Kapenga Caldera and the Reporoa Basin. The Huka Group (including the Huka Falls Formation), as defined from Wairakei drill cores, consists of well-bedded lacustrine siltstone, diatomite, fluviatile conglomerate, sandstone, pumice breccia and tuff (Grindley, 1960), and is approximately 140 m thick at the Kaiapo Fault scarp in Mapara Valley near Taupo.

The Huka Falls Formation is an important feature of the hydrological system associated with several TVZ geothermal fields because its predominantly fine-grained, lacustrine sediments typically form a cap rock to geothermal aquifers. The primary permeability of these sediments is typically low because of the fine grain size. The rhyolitic detrital lithology is predisposed to hydrothermal alteration to clay, and silica cementation is common near surface; both contribute to its aquitard nature. Jointing is sparsely present in the finer units, but is unlikely to make a significant contribution to overall permeability (Hadfield *et al*., 2001).

2.2.5 Maroa Group Ignimbrites

The Maroa Group ignimbrites include the following pyroclastic units are mapped in the UW: Mokai Formation, Atiamuri Formation, Pukeahua Formation and Orakanui Formation (Leonard *et al*., 2010). The pyroclastic deposits include non-welded and welded ignimbrites, dated at 283 ka to 196 ka (Leonard, 2003).

2.2.6 Rhyolite Lava Domes

A group of rhyolite lava domes located near the Kapenga Volcanic Centre are all likely to have typical rhyolite lava fabric including flow-banding, spherulitic and vesicular textures, and brecciated zones. A widely spaced (but variable) columnar and a blocky joint pattern is typical. The western dome grouping includes rhyolite lava domes of the Maroa Volcanic Centre. Many of the domes are coalesced and form small steep-sided massifs of dense, jointed lava. Most of the Maroa domes erupted within only 29 ka starting from approximately 251 ka to approximately 80 ka (Leonard, 2003). Rhyolite lava domes in the Taupo-Reporoa Depression (TRD), e.g. Oruahineawe-Kaimanawa, are mapped as middle Pleistocene in age (Leonard *et al.,* 2010) and post-date the Whakamaru Group ignimbrites. Rhyolite domes are commonly identified in the subsurface in TRD geothermal fields. However these domes are not represented in the 3D model due to limited information on the horizontal distribution of these domes from drill holes.

2.2.7 Kaingaroa Formation

Kaingaroa Formation ignimbrite is the product of the only major eruption from the Reporoa Caldera (Nairn *et al.*, 1994; Houghton *et al*., 1995). It extends radially 20 – 30 km from its inferred source and underlies an 800 km^2 area mainly to the east and southeast of the caldera, where it the caps the Rangitaiki Ignimbrite to form the Kaingaroa Plateau. The formation is subdivided into a basal tephra sequence, coarse source-proximal breccias and three ignimbrite units; total formation thickness is in the range 30 – 80 m (Beresford and Cole, 2000b).

2.2.8 Ohakuri Caldera Deposits

The Ohakuri Formation comprises non-welded pyroclastic units, namely ignimbrites and pumice and ash fall deposits (Leonard *et al.*, 2010). Typically these are tens of metres thick, and occur north and west of Atiamuri, around the Ohakuri Caldera (Gravley *et al.*, 2006; Gravley *et al*., 2007).

2.2.9 Mamaku Plateau Formation

The ignimbrite sheets of Mamaku Ignimbrite, 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 Mamaku 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.

2.2.10 Kapenga Caldera Deposits

For the purpose of this study, these deposits include Pokai Formation and Chimp Formation that possibly originated from the Kapenga Caldera (Karhunen, 1993). The Pokai Formation is exposed west and east of the Mamaku Plateau. Its maximum observed thickness is >80 m and the formation consists mostly of ignimbrite flow units (Karhunen, 1993). The main ignimbrite deposits are typically more than 20 m thick and generally non-welded near the base. The Chimp Formation is exposed along the western and northern edges of the Mamaku Plateau. It comprises mostly non-welded, poorly consolidated rhyolitic ignimbrite up to 20 m thick. The age of this formation is constrained by the overlying 275 ka (Leonard, 2003; Gravely *et al*., 2007) Pokai Formation and underlying Whakamaru Group ignimbrites (Karhunen, 1993; Beresford and Cole, 2000a).

2.2.11 Eastern Volcanic Cones

This grouping includes dacite cones and lavas of middle Pleistocene age (Maungaongaonga and Maungakakaramea/Rainbow Mountain), Nairn (2002), near the intersection of State Highways 5 and 38. Mt Tauhara dacite and Rolles Peak andesite near Taupo are also included in this group on the basis of broadly similar rock composition, ages and inferred hydrological properties. Maungaongaonga and Maungakakaramea are dacite cones that overlie Rangitaiki Ignimbrite (Nairn, 1981) and are stratigraphically located below Earthquake Flat Breccia (Nairn, 2002). Thus an age between 61 and 320 ka is assumed for Maungakakaramea. Maungaongaonga has been dated at 160 ka and 180 ka (Nairn, 2002).

2.2.12 Whakamaru Group

Whakamaru Group consists of widespread plateau-forming ignimbrite sheets, erupted between 320 ka and 340 ka (Houghton *et al*., 1995) from the Whakamaru Caldera in the TVZ (Wilson *et al*., 1986). The thickest and most extensive sheets are the Whakamaru Ignimbrite (generally in the west of TVZ) and the Rangitaiki Ignimbrite (generally in the east). Paeroa subgroup ignimbrites are included in this Group. Whakamaru Group ignimbrites are variably welded and reach a maximum thickness of approximately 1 km (Wilson *et al*., 1986; Rosenberg *et al*., 2009). Bulk permeability is intrinsically low, but widely spaced sub-vertical joints are characteristic and allow dominantly fracture-controlled flow.

2.2.13 Pakaumanu Group

Welded and non-welded ignimbrites of the Pakaumanu Group cover a large area of the western UW and southeast of the Waipa catchment. These ignimbrites represent the early phase of TVZ development as they were sourced from the Mangakino Volcanic Centre, located within the older Taupo Volcanic Zone (Houghton *et al.,* 1995). In the LMW, Pakaumanu Group ignimbrite deposits rest on the basement hills and are intercalated with Tauranga Group deposits. The Pakaumanu Group ignimbrites form a significant aquifer unit. Within the Pakaumanu Group ignimbrites, typically an upper porous layer overlies a welded and fractured zone (Marshall and Petch, 1983). These ignimbrites are exposed to the west of Waikato River between Arapuni (Healy *et al*., 1964) and west of Lake Taupo (Grindley, 1960) and between Putaruru and Karapiro to the east of the Waikato River.

Marshall Ignimbrite, exposed south and west of Tokoroa, forms, with older ignimbrites, a desiccated plateau north of the Waikato River (Briggs *et al*., 1993).The greatest thickness of the unit is approximately 110 m. Widely spaced, mostly sub-vertical, fractures occur in the basal unit. However, few wells take water from the Marshall Ignimbrite as groundwater yields are low (measured hydraulic conductivity 0.2 m/day; Waikato Valley Authority, 1987).

2.2.14 Western UW Volcanic Cones

This group comprises three Pliocene-Pleistocene volcanic cones associated with basement rocks in the west of the UW area. These are the eroded andesitic strato-cones of Mt Pureora and Mt Titiraupenga (Titiraupenga Andesite; Grindley, 1960), and Mt Maungatautari (Briggs, 1986); they include both rubbly and strongly jointed lava flows and associated lahar deposits. Titiraupenga and Pureora, in the southwest of the study area, are aligned northeast-southwest, broadly coincidental with the structural grain of the basement.

2.2.15 Alexandra Group Volcanics

Late Pliocene to earliest Pleistocene back-arc volcanism produced the Alexandra Group volcanics in the Waipa area; with the Alexandra Group volcanics consisting of several low-angle cones, including Pirongia, Te Kawa and Kakepuku within the Waipa catchment. The Alexandra Group volcanics in this area are basalt and basaltic andesite lava dominated, usually 10 – 20 m thick (Marshall and Petch, 1983), with minor scoria and tuff.

The Alexandra Group volcanics are likely to be a significant aquifer due to the lava flows being well-jointed. For example, a highly fractured andesite aquifer has been located at 110 m depth near to Waikeria and interpreted as 100 m thick (Mayhew and Caldwell, 1984).

2.2.16 Kerikeri Volcanics

Late Pliocene to Early Quaternary basalts of the Kerikeri Volcanics are located in Ngatutura, and the South Auckland Volcanic fields are present in the north and west of the catchment area. The fields contain numerous, small-volume volcanoes that produced lava flows, scoria cones and explosion craters. Pukekohe is one example. Basalts associated with this volcano are an important source of groundwater. In addition, Kiwitahi Volcanic Group, located in the southeast of the LMW, includes deeply-weathered lavas, breccias and dikes.

2.2.17 Kaawa Formation

Pliocene marine sediments were deposited in the south Auckland area, mainly north of Waikato Fault, and are included in the *Kaawa Formation*. The formation is up to 150 m thick, unconformably overlies Waitemata or Te Kuiti Group and is disconformably overlain by Tauranga Group. It underlies much of the Manukau lowland area and consists of muddy and shelly sandstone, mudstone and conglomerate, deposited in shallow marine and estuarine environments and is an important source of groundwater (Hollis, 1986; Greig *et al*., 1989). The transmissivity of the formation is in the range 14 m^2/day to 500 m^2/day (Viljevac *et al*., 2002).

2.2.18 Miocene Sediments

Overlying the Te Kuiti Group is a terrigenous-dominated Miocene sedimentation sequence. This sequence includes the Waitemata Group near to the coast (north and west), the Mahoenui Group further inland (south and east), and the Mokau Group south of Waitomo. The Waitemata Group is dominated by fine- to medium-grained sandstone and sandy siltstone and lies at a depth of 0.5–1.5 km in the north of the Waipa Catchment. In the southwest of the Waipa Catchment, the Mahoenui Group outcrops as the mudstone dominated (with minor limestone) Taumatamaire Formation. This formation is up to 800 m thick, with bioclastic limestone beds up to 25 m thick in this locality (west of Te Kuiti). The Mokau Group consists of shallow marine sandstone and mudstones, including coal measures. Coal exploration drillholes have found subsurface thicknesses greater than 500 m. The Middle to Late Miocene Whangamomona Group is found in outcrops immediately south of the Waipa Catchment and conformably overlies the Mokau Group and Mahoenui Group.

To the north of the Waipa Catchment (South Auckland), the Waitemata Group is generally regarded as hydrogeologic basement, but can yield small groundwater supplies (Hadfield, 2001). For hydrogeological purposes, the Mahoenui Group, Mokau Group and Waitemata Group can be considered as one hydrogeologic unit: Miocene sediments. These Miocene sediments are fine-grained and have low permeability. Although limestone beds may provide small groundwater supplies, their existence in a mudstone (aquiclude) dominated lithology suggests that these supplies are likely to be separate and distinct. Associated springs can also provide a source of good quality water. Additionally, Mercer Sandstone is a medium grained subgroup that may contain water resources (Marshall and Petch, 1983).

2.2.19 Te Kuiti Group

Unconformably overlying Waipapa terrane is the Eocene to Oligocene Te Kuiti Group. The group represents a predominantly transgressive sequence from basal coal measures through overlying marginal marine to outer shelf and upper bathyal calcareous mudstone, calcareous sandstone and limestone. The Te Kuiti Group is up to 500 m thick and is present in both the Hamilton Basin and lower Waikato Valley, although it is generally thinner and locally absent in the Hamilton Basin (Edbrooke, 2001, 2005).

The lower part is subdivided into five formations dominated by mixed clastic and carbonate sediments. The basal Waikato Coal Measures consist of up to 200 m of carbonaceous mudstone with coal seams and minor muddy sandstone and conglomerate deposited in a non-marine, fluvial plain setting (Edbrooke *et al.,* 1995). The coal measures are well developed in the lower Waikato valley but are thin or absent in Hamilton Basin. The coal measures grade up into the marginal to shallow marine Mangakotuku Formation that is dominated by mudstone with some muddy, glauconitic sandstone horizons. It is up to 200 m thick in the north and thins to the south. Three formations (Glen Massey Formation, Whaingaroa Formation and Aotea Formation) occur above the Mangakotuku Formation. These include massive, calcareous sandstone and siltstones with calcareous sediments and bioclastic limestone. The upper part of the Te Kuiti Group is characterised by carbonate sediments including massive calcareous mudstone and sandy to pure bioclastic limestone that are included in Te Akatea and Orahiri formations. Deposition occurred in shelf to upper bathyal depths in the Late Oligocene.

The Te Kuiti Group is well known in the lower Waikato valley from both outcrops and numerous coal exploration drillholes, but is not well known in the Hamilton Basin because of its depth (commonly >800 m), lack of outcrop and relatively few sufficiently deep drillholes. Available information indicates the Te Kuiti Group in the Hamilton Basin is up to 200 m thick and dominated by mudstone with some sandstone and limestone beds. The group is thickest in the west and thins to the east.

The Te Kuiti Group has three formations with aquifer potential: Pukemiro Sandstone, Elgood Limestone and Glen Massey Sandstone (Marshall and Petch, 1983). The Pukemiro Sandstone has seeps and springs associated with outcrops. The Elgood Limestone has the potential to supply groundwater where solution cavities are located. The Glen Massey Sandstone has crevices and minor solution cavities associated with calcareous deposits. An artesian flow of >55 L/s has been obtained from the Elgood Limestone (Marshall and Petch, 1983).

2.2.20 Basement

The “basement” of the North Island is conventionally accepted as low-grade metamorphosed Permian to Jurassic (Adams *et al.,* 2009) sedimentary terranes (i.e. greywacke). These basement rocks are typically “massive to poorly bedded, fine - to medium-grained sandstone” (Edbrooke, 2005) including thin-bedded alternating sandstone and mudstone (Grindley, 1960). Basement rocks belonging to the Murihiku Terrane occur in the west with Waipapa Terrane in the east. The boundary of these terranes marked by the Waipa Fault Zone, trends north to northwest roughly through the centre of the Hamilton and Lower Waikato basins (Mortimer, 2004). The Murihiku terrane is predominantly fossiliferous siltstone with minor sandstone, conglomerate and shell beds. Basement outcrops in the Waipa Catchment west of the Waipa Fault Zone consist of thin-bedded to massive siltstone and fine- to coarse-grained sandstone with thin conglomerate beds.

Basement outcrop is located in the west of TVZ through to the Hauraki Gulf and between the Hamilton Basin and the Lower Waikato Basin.

Mineralised intergranular cement results in very low values of porosity and permeability in Basement rocks, such that intergranular fluid storage is typically non-existent. Jointing and shearing provide discrete locations of high secondary permeability, with associated water storage capacities. The typically limited extents and discrete nature of these resources, however, result in restricted productive groundwater storage volumes. Typical yields of 0.3 – 0.4 L/s have been reported, and up to 2.15 L/s (Marshall and Petch, 1983).

3.0 METHODS

3.1 GEOLOGICAL MODELS

Three 3D geological models have been developed for the Waikato River catchment zones for WRC, HRP and GNS Science research projects: an Upper Waikato River catchment (UW) model described in White and Tschritter (2015); a Waipa River catchment (Waipa) model described in Rawlinson (2014); and a Lower to Middle Waikato River (LMW) catchment model. The theory and methodology behind the development of the LMW 3D geological model is described in detail below. The UW and Waipa models generally follow the same process of geological model development; for details see White and Tschritter (2015) and Rawlinson (2014).

The UW model has been developed in New Zealand Map Grid projection (NZMG) in EarthVision software; The Waipa model has been developed in New Zealand Transverse Mercator projection (NZTM2000) in Leapfrog Geothermal 2.8; and the LMW model has been developed in NZTM2000 in Leapfrog Geo 2.2. The software and projection choices have been at the preference of WRC. All models have a vertical extent that allows for the representation of the basement across their respective entire model areas.

3.1.1 LMW Geological Model

The geological model extends over an area of 3,521 km^2, and the modelling resolution is 200 m by 200 m. The vertical extent of the model is between -1,500 m and 1500 m RL.

3.1.1.1 Theory

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. These aggregations are decided by the modellers and the decisions are based on both geological characteristics and the available data 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. However, each fault splits the model into separate fault blocks, and each fault block forms a distinct geological model. Hence, the integration of faults increases the complexity of the model and its development time. For the LMW model, the explicit integration of faults is not required within the scope of the model as a conceptual geological model, and additionally, is hindered by the limited timeframe available.

Data sets available to create the LMW geological model include topographic data, geological maps, geological cross-sections, well logs, and interpreted geophysical data. The QMAP geological maps (Edbrooke, 2001, 2005; Leonard *et al.,* 2010) 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, using the digital seamless version of the QMAP geological map, the polygons for all geological formations are assembled and merged into model unit polygons in ArcGIS.

These polygons are then 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 Leapfrog with sub-surface data that are derived from other data sources (discussed in Section 3.1.1.4), and the contact surfaces for each model unit are constructed through interpolation between all available scattered data points for a unit. The interpolation method used by Leapfrog Geo is based on Radial Basis Functions (RBFs), which is equivalent to Dual Kriging. Several types of contact surfaces exist to best represent the underlying geological processes: erosion, deposition and intrusion. User defined directional trends are used to constrain the interpolation to create representative geological surfaces. Local manual edits (control lines) can be added by the modellers to constrain the contact surfaces in areas with little input data. The modeller then defines the surfaces chronology; and surfaces are assembled to produce a stratigraphic 3D volume model.

The uncertainty the geological model is subject to 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. The spatial distribution of data is an important contributor to model uncertainty; another contributor is the uncertainty of the model input data itself. Additional uncertainty may be introduced through the interpolation algorithm used to interpolate the layer surfaces and the resolution chosen for the model surfaces. A surface that is created through one interpolation method can differ immensely if another interpolation method is used. The surfaces with directional trends that guide the interpolation within Leapfrog Geo require significant testing and adjustment by the modeller(s), to create interpolation surfaces that honour the data locations whilst remaining geologically reasonable. The more input data points that are available, the lower the uncertainty resulting from the interpolation method. The data sources, and the resulting model uncertainties involved with these data, are discussed in more details below.

3.1.1.2 Data sources

Topographic data

Topographic data is 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 in this report is a 5 m resolution DTM provided by WRC. 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.

Geological maps

The surface geology in the study area has been mapped at a 1:250,000 scale as part of the following three QMAP maps: Auckland (Edbrooke, 2001), Waikato (Edbrooke, 2005) and Rotorua (Leonard *et al*., 2010*).*These QMAPs are represented in the GNS Science QMAP Seamless Database that has been used to extract the surficial boundaries between units to be modelled. The digital map has 49 distinct map units covering the study area and these have been aggregated into seven modelled units in the 3D model (Section 3.1.1.3). The QMAP data is accurate at a 1:250 000 scale. The spatial accuracy of the data is estimated to be no better than +/- 250 m for accurately located geological features. Additionally, geologic units might not be shown in a map if a unit is disperse and their thickness is less than 5 to 10 m. QMAP, for instance, generally will not display a unit unless it is at least 10 m thick or geologically significant (GNS Science, 2015). This can result in unit boundaries that are quite different than the actual boundary.

Cross-sections

The published QMAP geological maps include interpretative subsurface geological cross-sections. Cross-sections that lie within, or near to, the model area were used as guidelines to establish the boundaries between modelled units. Relevant cross-sections area the QMAP Auckland cross-section (Edbrooke, 2001) and the QMAP Waikato cross-section (Edbrooke, 2005). These cross-sections extend to a depth of 7.8 km and 5 km, respectively. Therefore, the Quaternary sediments are often too shallow to be depicted, or the uncertainty of the very shallow depicted line would introduce too much of a large uncertainty to use this information (e.g. width of the line comparable to the depth of the Quaternary).

Bore log data

Three different bore log datasets were used to constrain the subsurface distribution of geological formations. These datasets were:

a) bores from the WRC bore database,

b) bores from coal exploration National Coal Resources Survey (NCRS) drillholes (Ministry of Business Innovation and Employment, 2014; Ministry of Business Innovation and Employment, 2015), and

c) bores from petroleum exploration (Ministry of Economic Development, 2015).

Some of the bores are listed in both the WRC and the NCRS database. The following sections describe characteristics, processing and limitations of these bore datasets.

Bores from the WRC database

Lithological bore log data in the Waikato River catchments was provided by WRC in the form of Excel spreadsheets on 16/12/2014. The dataset comprised 3522 individual bore logs that are reasonably well distributed throughout the model area (Figure 3.1). The datasets included a dominant lithology, secondary lithology, description, and formation column. The first two columns are summarising descriptors of the description column. For example, the description ‘brown sandy clay’ would have clay as the dominant lithology and sand as secondary lithology. The secondary lithology column was often left blank and also the description column was left blank for a few intervals. The dominant lithology column is completely filled, the description column is only missing a few intervals. The secondary lithology column and, in particular, the formation column are rarely filled.

The usability of these bores for the construction of the 3D geological model is limited. Approximately 85% of WRC bores are less than 100 m deep and, therefore, cannot be used to identify deeper geological conditions. Another factor that restricts the usability of these bores is the questionable quality of the lithological log descriptions. Generally, the lithologies were logged by drillers and not by qualified geologists. As a result, they vary with the driller, and drilling method, and are not subjected to any quality control.

Another disadvantage of these lithological logs is that the interval descriptions generally do not include an interpreted geological formation. A 3D geological model is developed from boundaries between geological formations. Therefore, these boundaries have to be inferred from the lithological logs in the WRC bore dataset, where possible, before this bore data can be used for the modelling. This can be done manually or in an automated way. Due to the high number of bores and lithological descriptions, and the nature of the model as a 'conceptual' model, only an automated method was applied based on the dominant lithology column. For example, the descriptors 'basement rocks' and 'greywacke' were used to identify the top surface of basement rocks ('basement contacts') in Leapfrog.

Coal exploration bores

Geological logs from 2169 NCRS coal exploration bores in the study area were received as digital datasets Ministry of Economic Development (2014) (Figure 3.1). The vast majority of these bores are clustered in two areas: north of Huntly and in the vicinity of Maramarua. Of these 2169 bores, 1838 have been drilled into basement rock. These exploration bores are essential input datasets for 3D geological modelling as they have been described and assigned geological formations by qualified geologists and, therefore, provide the most accurate geological subsurface information.

However, the main limitation of this dataset is its clustered distribution. While the bore density in the two cluster areas, north of Huntly and near Maramarua, is very advantageous for 3D geological modelling in these exact areas, resulting in very low local model uncertainties, the lack of deep, well described bores throughout the remaining model area, results in high uncertainties in those parts of the 3D model. Another disadvantage of this dataset, for future model refinement for groundwater applications, is that there is no stratigraphic or lithological differentiation between Quaternary sediments and these are aggregated as 'Undifferentiated Quaternary' in the database.

Petroleum exploration bores

Petroleum exploration bore data from the Ministry Of Economic Development (Ministry of Economic Development, 2015) was searched to extract reports on petroleum bores in the model area (Figure 3.1). Relevant well logs were digitised from the reports obtained. Petroleum bore logs, like coal exploration bore logs, have been recorded by geologists and include geological formations. These kinds of logs are, as mentioned before, are essential for geological 3D modelling. Throughout the model area, 35 petroleum bores that were of interest for the modelling were identified and used to constrain subsurface extents of model units. The depth of these bores ranged between 182 and 1207m. Advantages and disadvantages of these bores are the same as of the coal exploration bores. The latter are also aggravated by the limited number of petroleum bores available throughout the model area.

Other data sources

Aside from the data sources described above, there are many other information sources that contribute to the development of a 3D geological model, including: published geological investigations, cross sections and maps. Key information sources used in this study include the contour maps. For the northernmost part of the LMW model area, contours for the top surfaces of Kaawa Formation and Waitemata Group have been derived by Viljevac *et al.,* (2002), from the interpretation of borelogs in the area.

3.1.1.3 Grouping of formations

The actual geological modelling process starts with the grouping of geological formations within the study area that are mapped at the ground surface, or have been logged at depth, into model units. Grouping of geological units is generally required when it is not feasible to model all geological formations due to constraints like geological complexity, data availability and quality, size of the model area, and time available to build the model. The project objectives must also be taken into account, if the geology is only one aspect of the greater scope of the model, like for example, if the purpose of the model is to be used for geotechnical or hydrogeological applications. The purpose of the LMW geological model is to provide a conceptual geological model for the groundwater assessment at a sub-regional scale. As such, the scope of the model does not require or allow for the modelling of all geological formations in high detail. Additionally, the spatially limited availability of higher quality sub-surface data (the geological logs of the coal and petroleum exploration bores, see previous section) would not support the modelling of formations in detail throughout the entire model area.

The groups were decided based on the formations occurring in the QMAP geological data, the geological logs of the coal and petroleum exploration bores, and the grouping of formations in the adjacent geological models (Rawlinson, 2014; White and Tschritter, 2015).

As a result, the following model units are represented in the LMW 3D model, from youngest to oldest:

- Tauranga Group
- Pakaumanu Group
- Kerikeri and other volcanics
- Kaawa Formation
- Miocene sediments (Waitemata Group)
- Te Kuiti Group
- Basement

All of these model units, aside of Kerikeri and other volcanics and Kaawa Formation, are based solely on a higher level stratigraphic classification for each formation. However, Kerikeri and other volcanics is an artificial group consisting of the Kerikeri Volcanics and the Kiwitahi Volcanics, based on their similar lithology (see Section 2.4). Kaawa Formation, while part of Tauranga Group, has been separated out due to its high aquifer potential.

3.1.1.4 Model unit surface development

Generally, surfaces were developed to represent the top of each model unit. The bottom of each model unit is then automatically represented by the top surfaces of the units underneath it. The top surfaces are constructed using a combination of mapped surficial geology (QMAP data) and subsurface geological data, e.g. bore logs, etc., Section 3.1.1.2. The data used for the subsurface extents for each model unit surface is described in Table 3.1. Due to the nature of the model as a regional conceptual geological model, manual fine tuning of surfaces has only been performed when the edits that have been carried out had a significant impact over larger areas.

Table 3.1 Data sets used for the development of the LMW model unit top surfaces.

Model unit	Surface data	Subsurface data
Tauranga Group	QMAP	N/A
Pakaumanu Group	QMAP	N/A
Kerikeri and other volcanics	QMAP	Interpretation from WRC bore logs;
Kaawa Formation	Not mapped in QMAP	Interpretation from WRC bore logs; Surface contours from (Viljevac *et al.,*2002); Re-interpretation of Otaua-1 exploration bore (Edbrooke *et al.,* 2009);
Waitemata Group	QMAP	Logs of coal and petroleum exploration bores; Surface contours from Viljevac *et al.,* (2002); Re-interpretation of Otaua-1 exploration bore (Edbrooke *et al.,* 2009); QMAP cross-sections;
Te Kuiti Group	QMAP	Logs of coal and petroleum exploration bores; Interpretation of WRC bore logs; QMAP cross-sections; Waipa model data at model boundary (Rawlinson, 2014)
Basement	QMAP	Logs of coal and petroleum exploration bores; Logs of WRC bores; QMAP cross-sections; Waipa model data at model boundary (Rawlinson, 2014); Upper Waikato model data at the model boundary (White and Tschritter, 2015).

3.1.1.5 HRP template: Geological Properties

The HRP template (Appendix 2) includes geology and aquifer properties .These features (in bold), and methods that were used to define the features, are as follows:

- **geomorphology** is a short description of key landforms in the catchment**;**
- **predominant surface geology** was identified from the Qmap geological map as the surface geology in the area from which most groundwater is taken;
- **geology (water table aquifer)** was identified as the geology of the shallow water table. Generally, this is the same as the predominant surface geology;
- **geology (principal aquifer)** is the aquifer that provides most groundwater in a catchment which was identified from well locations and general well depths with the assistance of the geological models;
- **water table aquifer transmissivity** (T) was identified from the geological unit of the water table and "standard" T values for these units, which were based on field measurements and published values (Tschritter et al., 2014);
- **principal transmissivity** (T) was identified from the geological unit of the principle aquifer and "standard" T values for these units, which were based on field measurements and published values;
- **groundwater gradient** (i) is estimated as the topographic gradient in the area of the principal aquifer;
- **water table aquifer and principal aquifer: groundwater velocity** Darcy velocity in the aquifer (V_D) was calculated as V_D = ki where k = T/t, t is the effective aquifer thickness;
- **average aquifer thickness** equal to the average aquifer thickness, estimated from a 3D geological model;
- **effective aquifer thickness** equal to the average aquifer thickness, to a maximum of 100 m, i.e., groundwater flow is assumed to flow only through a 100 m thickness of aquifer where the average aquifer thickness is greater than 100 m.

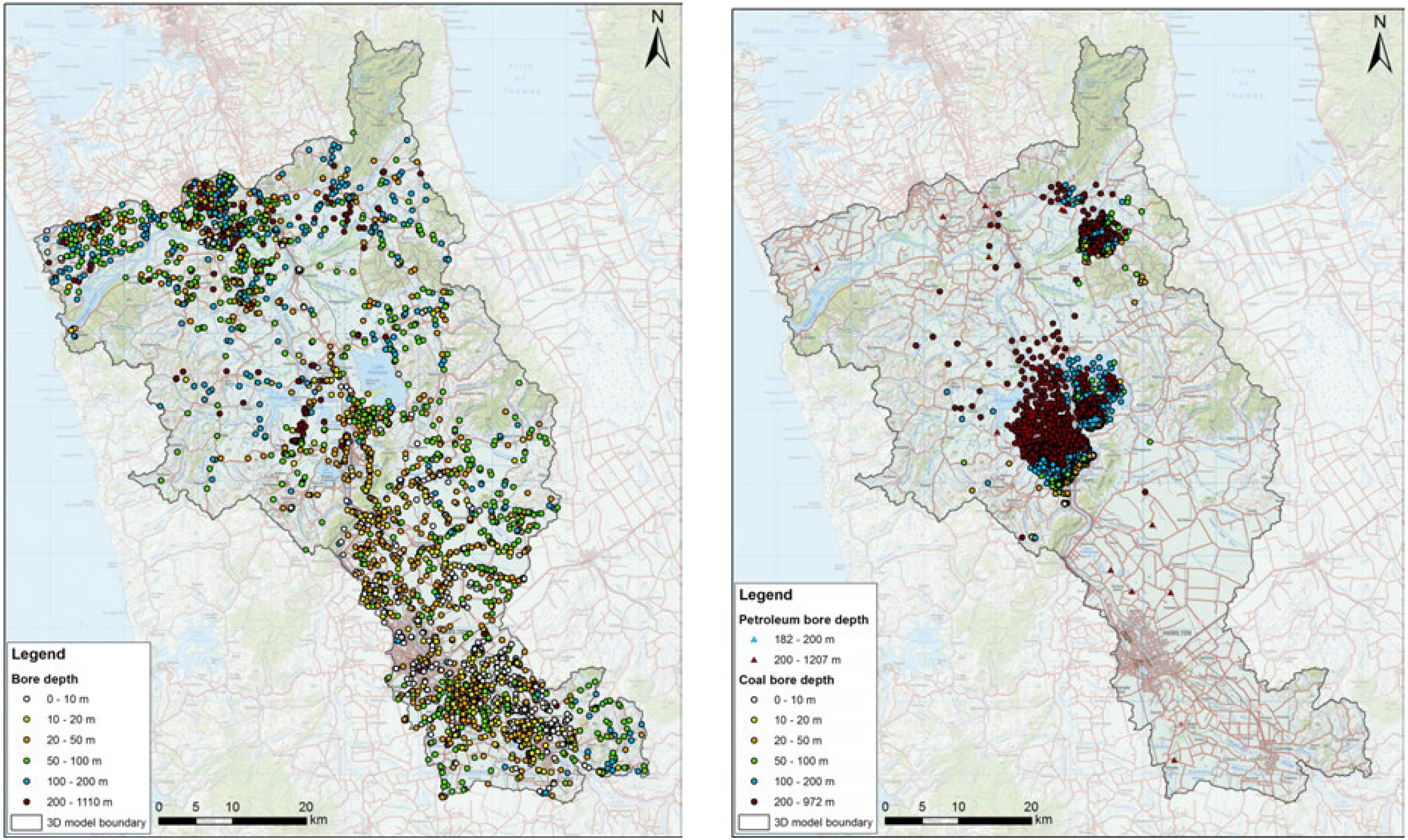

Figure 3.1 Spatial distribution of bores in the model area : (left) bores with lithological logs from the WRC bore database; and (right) petroleum and coal exploration bores with geological logs.

3.2 WATER BUDGET AND GROUNDWATER FLOWS

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 (Scanlon *et al.,* 2002; Scanlon, 2012), Figure 3.2.

water inflow = water outflow (1)

i.e. $P + Q_{IN} = ET + Q_{OUT} + \Delta S$ (2)

Water inflows include:

P precipitation,

$Q_{IN} = Q^{SW}_{IN} + Q^{GW}_{IN}$ (3)

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

Q^{GW}_{IN} groundwater inflow

Water outflows include:

ET evapotranspiration

Q_{OUT} water flow out from the area

ΔS change in water storage.

With:

$Q_{OUT} = Q^{SW}_{OUT} + Q^{GW}_{OUT}$ (4)

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

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

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

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

U^{SW} consumptive surface water use

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

Expanding Equation 2 for surface water and groundwater terms, with the assumption that ΔS is zero, meaning that all flows are the same over time, has:

$P + Q^{SW}_{IN} + Q^{GW}_{IN} = ET + Q^{SW}_{IN} + Q^{SW}_{BF} + Q^{SW}_{QF} + U^{SW} + U^{GW} + Q^{GW}_{COUT}$ (5)

In addition, the quick flow and base flow components of surface flows can be identified, i.e.,

Q^{SW}_{IN} = quick flow (Q^{SW}_{INBF}) + base flow (Q^{SW}_{INQF}) (6)

$Q^{SW}_{IN} = Q^{SW}_{OBF} + Q^{SW}_{OQF}$ (7)

Q^{SW}_{OBF} surface water base flow outflow, i.e., base flow inflow plus baseflow generated in the area (i.e., discharge to surface water from the saturated portion of the groundwater system) and Q^{SW}_{OQF} is surface water quick flow outflow (i.e., quick flow inflow plus quick flow generated in the area which is interflow and runoff).

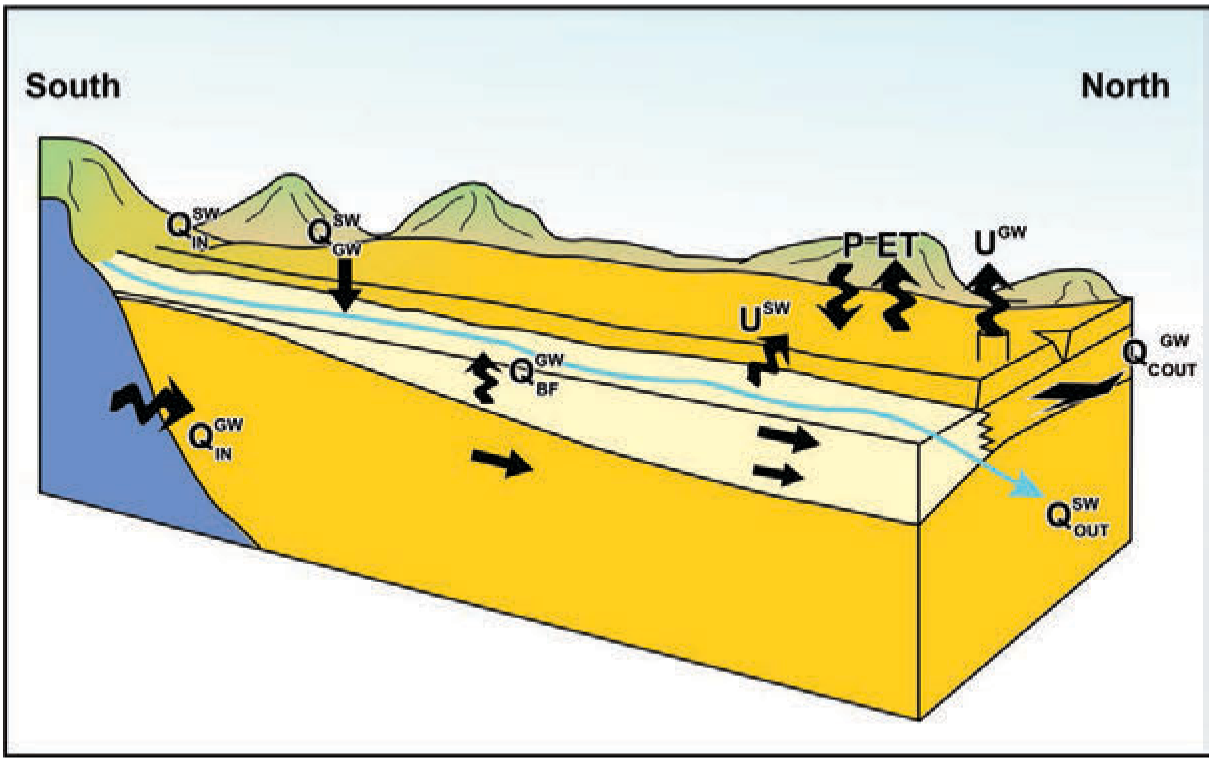

Figure 3.2 Schematic of groundwater budget components.

The following text discusses each of the components, and simplifying assumptions, in this equation for the Waikato River catchment.

3.2.1 Rainfall and evapotranspiration

Mean annual rainfall (P) was estimated by GIS from the nationwide National Institute of Water and Atmospheric Research (NIWA) dataset based on the rainfall measurements at individual climate stations, interpolated throughout New Zealand by NIWA and averaged for the period 1960 – 2006 (Tait *et al.,* 2006). Mean annual AET was estimated by GIS with a national-scale map developed by NIWA for the period 1960 – 2006 without specific consideration of land use, land cover, soil type or groundwater recharge (Woods *et al.,* 2005).

3.2.2 Surface water flows

Surface water flows and groundwater flows to each zone have been assessed with the groundwater budget including gauging measurements (i.e., WRC's historic gauging data set; Jenkins, 2015a; and field measurements of surface water flows measured by WRC in 2015 for the HRP in the Waipa and LMW zones; Hadfield, 2015). Surface flow measurements from stage recorders in the Waikato catchment were also used to estimate flows, in particular mean and median flows in the period 1960 to 2006 (Jenkins, 2015b; Payne, 2015); this was the period of rainfall and AET estimates that was used by Tait *et al.,* (2006) and Woods *et al.,* (2006), respectively. Note that flow estimates by stage recorders were used in the water budgets as a priority over gauging measurements where both types of data occur.

3.2.3 Surface water flow: base flow and quick flow

Surface water flow is represented by base flow and quick flow components.

In this report, base flow was assumed to be represented by median flow estimates, and quick flow as the difference between mean and median flow estimates, at the locations of gauging sites and continuous flow sites. Hence, the baseflow index (BFI) is represented with mean and median flow estimates, i.e.:

$$Q_T = Q^{SW}{}_{OBF} + Q^{SW}{}_{OQF} \quad (8)$$

$$BFI = Q^{SW}{}_{OBF} / Q_{OT} \quad (9)$$

With $Q^{SW}{}_{OBF}$ = median outflow and Q_{OT} = mean outflow (as an estimate of total outflow), then:

$$BFI = Q_{Median} / Q_{Mean} \quad (10)$$

Baseflow could be calculated with a baseflow analysis (e.g., White *et al*., 2012; White, 2010). This analysis was completed on flow records at stage recorder sites in the Waikato catchment for period the 1960 to 2006. However, the baseflow analysis is generally not appropriate for gauging measurements because they highly variable in number of measurements at each site and sampling is often biased (e.g., measurements may be collected to measure floods. Therefore, baseflow is assumed as median flow in this report.

3.2.4 Water use

Consumptive uses of groundwater and surface water in the Waikato region includes: irrigation, drinking water, and industrial applications. The budgets aim to represent natural flows. (i.e., U^{SW} and U^{GW} are equal to zero, Equation 7).

3.2.5 Water budgets

Water budgets were developed for HRP catchments to estimate surface water and groundwater flow components. These budgets (Equation 5) included estimates of land area, P, AET and surface flows with water outflow at zone boundaries set to balance the water budget. Groundwater outflow from zones was calculated with the groundwater budget.

The catchment flow scheme that was used to develop budgets is summarised for the UW (Figure 3.3), Waipa (Figure 3.4) and LMW (Figure 3.5) zones. Generally, the water budgets aim to represent means of observed flows at the locations of stage recorders in the Waikato River and Waipa River which are located at the outlets of HRP catchments named in Figure 3.3, Figure 3.4 and Figure 3.5. Means of observed flows in the Upper Waikato (Figure 3.3) are those of Payne (2015) and those of Jenkins (2015b) in the other catchments.

Generally, estimates of river flow calculated by the water budget follow the means of observed flows (see Section 3.2.6). However, the estimates of river flow were systematically less than observed mean flows in the Waipa River catchment. Therefore, HRP catchment rainfalls were adjusted by a constant factor (i.e., a uniform increase of 7%) in this catchment so that river flow calculated by the water budget was similar to observed mean flow at Whatawhata. Other minor adjustments to mean rainfall were also used to balance water budgets (see Section 3.2.6).

3.2.6 HRP Template: Water budgets

Water budget components are summarised in three zones for each HRP catchment including inter-catchment water flows described in the following:

- UW zone, according to Figure 3.3.
- Waipa zone, according to Figure 3.4.
- LMW zone, according to Figure 3.5.

Cells coloured yellow in each summary are the estimated flows in the main stems of the Waikato River and Waipa River (Figure 3.3, Figure 3.4 and Figure 3.5). For example, the outflow of HRP catchment 3035123 is coloured yellow as this estimates the flow in the Waikato River at Ohukuri Dam (Figure 3.3).

The following water flow statistics are reported for the HRP catchments (Appendix 3):

- HRP water budgets, i.e., inflows (rainfall, surface water and groundwater) and outflows (AET, surface water and groundwater);
- Estimates of BFI from the land in each HRP catchment with reference to WRC flow recorder sites (i.e. gauging sites and stage recorder sites);
- Estimates of baseflow and quick flow for surface water outflow from the catchment based on the water budget outflow and BFI estimates.

The unit of flow is $m^{3/}s$.

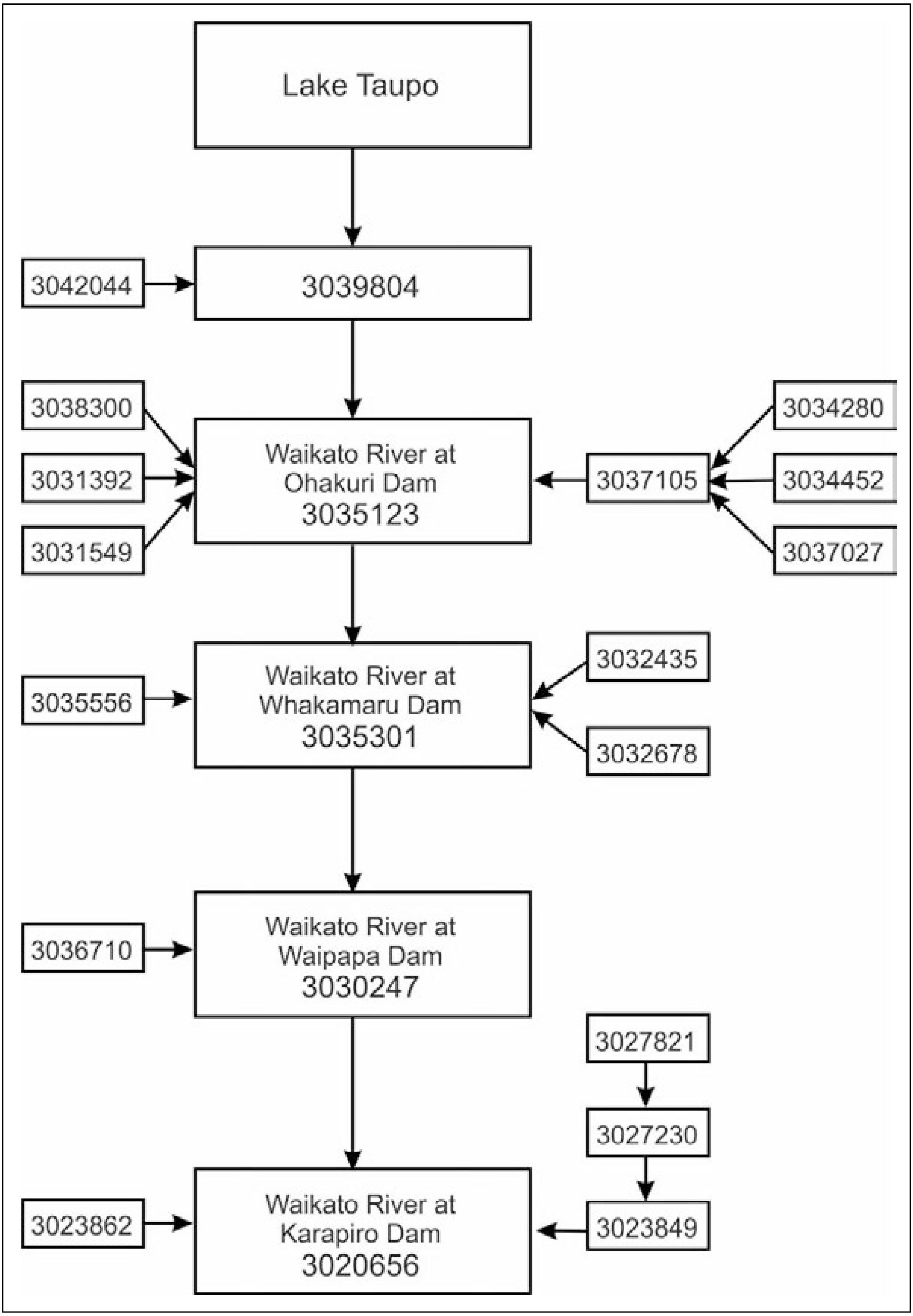

Figure 3.3 Catchment flow scheme for the UW zone.

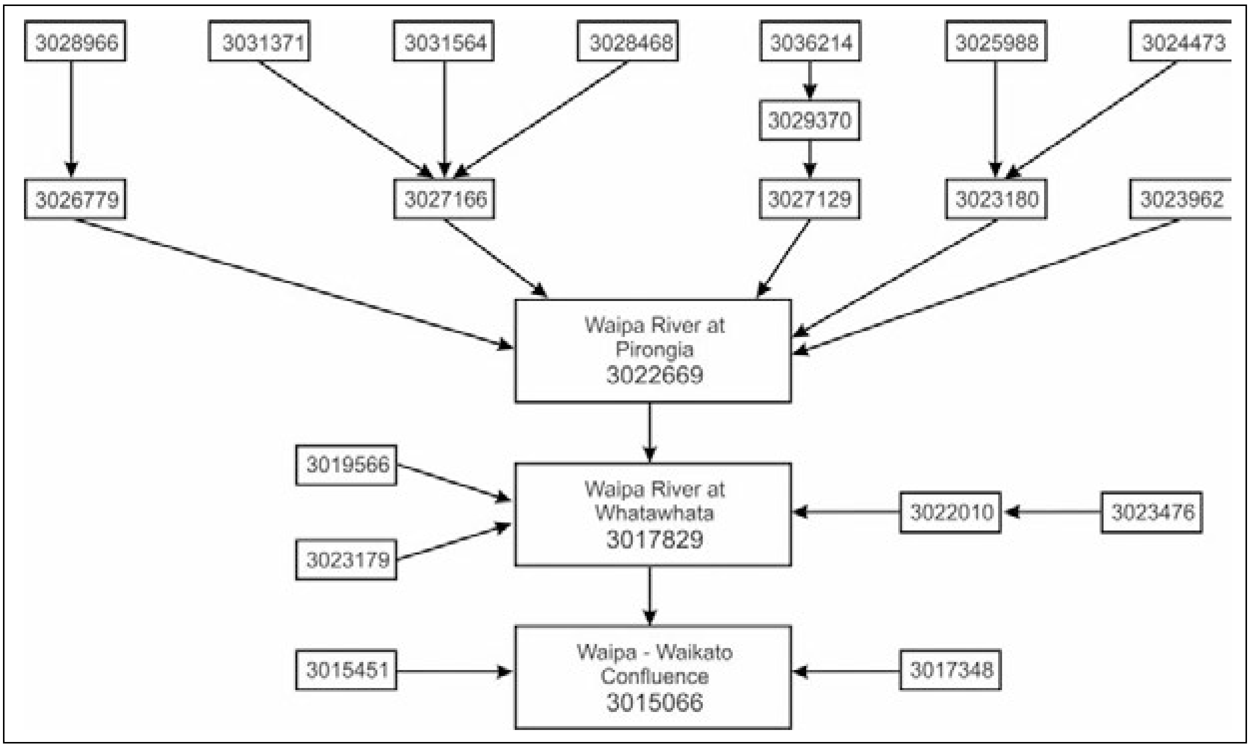

Figure 3.4 Catchment flow scheme for the Waipa zone.

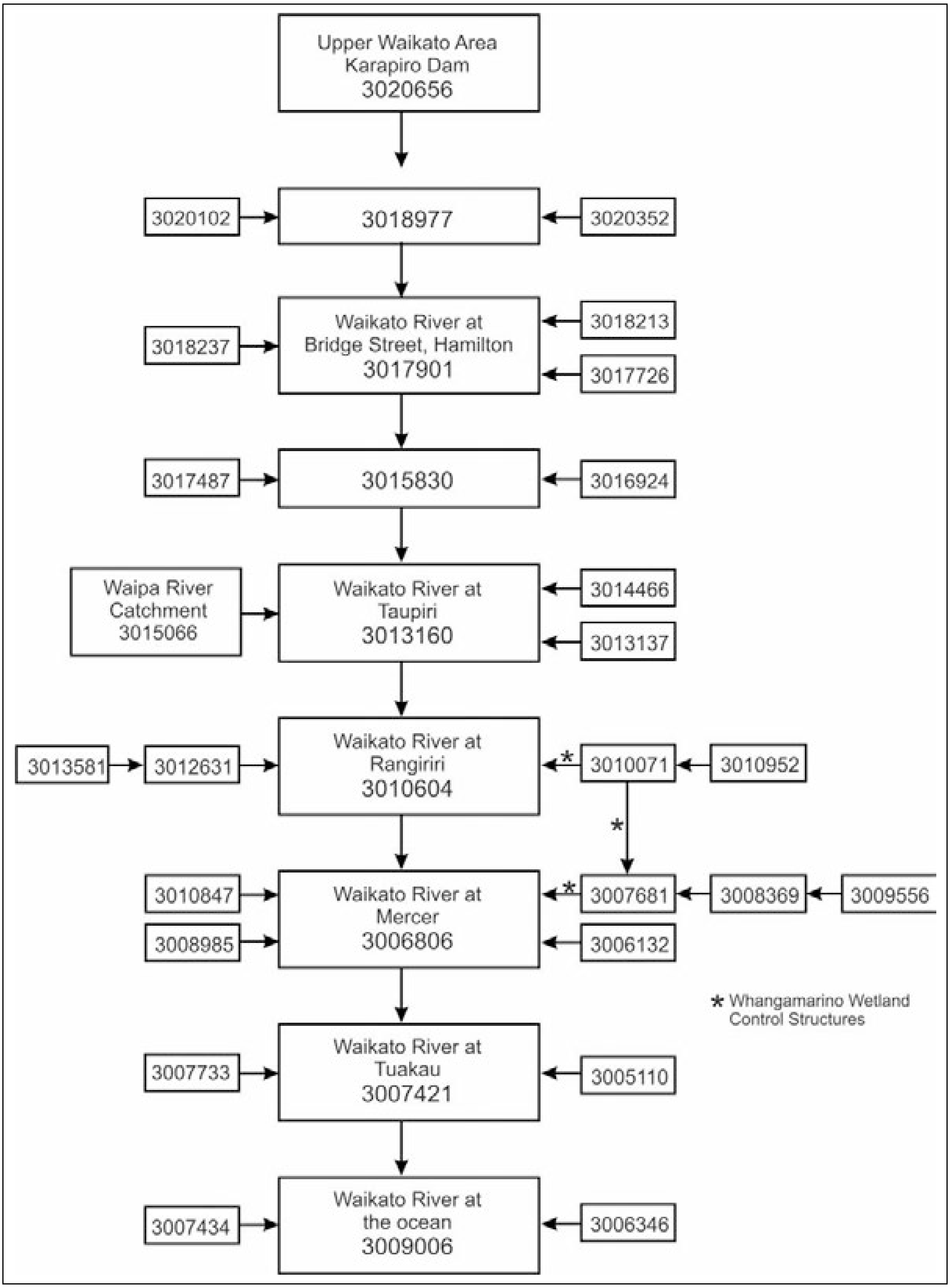

Figure 3.5 Catchment flow scheme for the LMW zone.

3.3 PIEZOMETRIC MAPS

Piezometric maps aim to represent static groundwater elevation in the three zones. These were estimated in each zone using multiple information, including measurements of groundwater depth in wells recorded by WRC (Jenkins, 2015a) and the results of the 2015 field programme in the Waipa catchment (Rawlinson *et al*, 2015). Potentially, the depth of groundwater in wells is impacted by pumping, particularly pumping of the well where groundwater depth is measured. Therefore, depth measurements recorded by WRC with only one depth measurement are removed from the dataset. Procedures to measure groundwater depth in the Waipa catchment ensured that static water levels were recorded.

The relation between ground elevation and groundwater elevation was developed for HRP catchments and groups of catchments. Groundwater elevation was calculated as ground elevation at well locations, as calculated from the DTM, minus groundwater depths. Piezometric elevations were then calculated with the addition of fixed-elevation cells. Fixed-elevation cells included lakes and permanently-flowing rivers and streams, where elevations were estimated with the DTM. The locations of permanently flowing rivers and streams were identified by synoptic surveys by the summer 2015 field programme in the Waipa and LMW zones (Hadfield, 2015) and by other gauging data held by WRC.

Piezometric elevations were then calculated on a 100 m by 100 m grid. These elevations were then compared with published groundwater level maps. These maps include areas around: Pukekohe (Waikato Regional Council, 1991), Ohinewai (Waikato Valley Authority, 1986), Tokoroa (Waikato Valley Authority, 1987), Reporoa (Piper, 2005) and Wairakei (Bromley, *et al*. 2000).

3.4 GROUNDWATER CHEMISTRY

Groundwater quality data from the WRC monitoring programme was provided to GNS Science. This included, but was not limited to, data from the Groundwater National Monitoring Programme (NGMP), which is a collaboration between GNS Science and WRC), and WRC's State of the Environment monitoring programme (SOE). NGMP and SOE data (up to 2008) was obtained from the Geothermal and Groundwater database (GNS Science, 2015). Quality coded, recent SOE data and data from other monitoring programmes were provided by WRC (three individual files received; Hadfield, 2015).

Data was aggregated and checked for duplicates and anomalous values (e.g. concentrations recorded as "0"). The raw datasets, covering the Waikato region, consisted of 5,498 samples analysed for 83 analytical parameters collected at 585 wells. A subset of the data was obtained for the Waikato and Waipa river catchments using well selection (ArcGIS analysis) and parameter selection. Only environmental indicators representative of total dissolved solids content (electrical conductivity); aquifer oxidation status (iron, manganese), microbiological indicators (E. coli) and nutrients (dissolved reactive phosphorus, nitrogen species) were used for trend analysis. The final dataset consisted of 4,841 analyses collected at 531 wells (Figure 3.6).

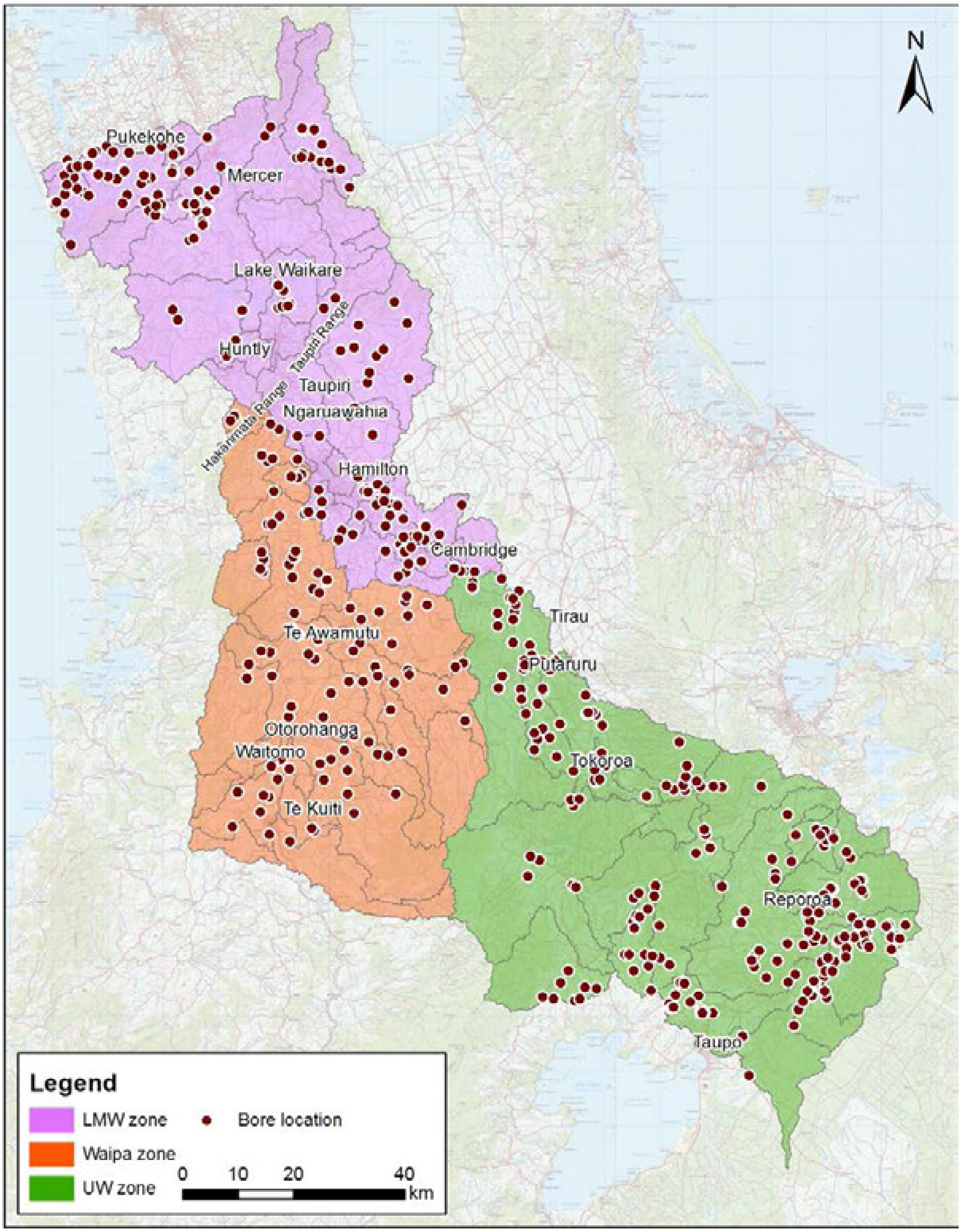

Figure 3.6 Location of bores with groundwater chemistry measurements in the HRP area.

3.4.1 Trend analysis

Mann-Kendall seasonally adjusted trend tests, and Kruskal-Wallis seasonality tests, were performed on the aggregated WRC groundwater datasets using the Calculator Spreadsheet (Daughney, 2007 and 2010). Absolute trends (units per year) were estimated using the seasonal Kendall Sen slope estimator and linear regression (Daughney 2007 and 2010). For median and median absolute deviation calculation, log-probability regression was used on censored values, below 80% censoring (Daughney, 2007 and 2010). For parameters for which censoring was above 80%, trend analysis was not undertaken. Censored values were replaced by one-half the highest detection limit for the purpose of trend testing (Daughney and Reeves 2006; Daughney, 2007 and 2010).

Trend analysis was run for the entire record length at each well. In some cases, there was only one analysis for a given well (e.g. well 61-12). The longest record was for the 1987 to 2015 period (well 69-2187). Outliers were excluded for trend analysis (outlier threshold: four times the median absolute deviation); the seasonality test was defined for four seasons, starting from the 60th Julian day (1st March); and a confidence interval of 95% was set. Non-statistically significant trend magnitudes were not reported (Mann-Kendall p-value>0.05). A minimum of ten data points was used for meaningful trend test detection in groundwater.

The following groundwater quality statistics are reported for each catchment:

- median range: the median is a measure of central tendency. It is a more resistant measure than mean values because it is not affected by outliers (Helsel and Hirsch, 2002)
- trend magnitudes: the rate of change in each parameter. In this report, the trend magnitudes are based on Sen's slope estimator, which is commonly used for environmental reporting (Helsel and Hirsch, 2002)
- Mann-Kendall statistical test p-values: data-calculated probability value (p-value) to compare with an acceptable error rate (arbitrarily set) to reject or accept the hypothesis being tested (Helsel and Hirsch, 2002).

Individual well statistics were grouped per catchment using GIS, and descriptive statistics, for instance, the median nitrate-nitrogen concentration for a given catchment is the median value of individual median concentration for that parameter.

3.4.2 HRP Template: Groundwater Chemistry

The following groundwater quality statistics are reported for the HRP catchments that have groundwater quality data (Appendix 4):

- median range: the median is a measure of central tendency. It is a more resistant measure than mean values because it is not affected by outliers (Helsel and Hirsch, 2002)
- trend magnitudes: the rate of change in each parameter. In this report, the trend magnitudes are based on Sen's slope estimator, which is commonly used for environmental reporting (Helsel and Hirsch, 2002)
- Mann-Kendall statistical test p-values: data-calculated probability value (p-value) to compare with an acceptable error rate (arbitrarily set) to reject or accept the hypothesis being tested (Helsel and Hirsch, 2002).

Individual well statistics were grouped per catchment using GIS, and descriptive statistics, for instance the median nitrate-nitrogen concentration for a given catchment is the median value of individual median concentration for that parameter.

3.5 GAP ANALYSIS

An understanding of groundwater resources in the HRP area requires:

- measurements, e.g., field measurements;
- science data bases; and
- models, e.g., models that would be useful to meet HRP aims in regards of the management of groundwater and surface water. Here the term “models’ is used in the wider sense than just “computer models”. Therefore, models includes conceptual models (e.g. Figure 3.2) and the results of research that links cause and effect (e.g., land use and water quality).
- A simple summary of the current state of these was completed for the HRP area. This analysis is completed for each of the major components of the HRP Template, i.e., “geology”, “water budget” and “groundwater chemistry”. For each, the summary includes a short comment on the various items within each category.

Then, the gaps are identified and the work required to fill the gaps is described. The analysis, completed by HRP zone, is based on the opinions of the authors of this report that were formed during the project, and were formed on other projects in the HRP area. Recommendations that build on the gap analysis may include reference to specific HRP catchments (Section 6).

4.0 RESULTS

This section summarises the groundwater systems in the three HRP zones. The appendix includes further information specific to each catchment, including: catchment images and descriptions of the groundwater system (Appendix 1), geology (Appendix 2), water budgets (Appendix 3) and groundwater chemistry (Appendix 4).

The description of groundwater in the zones begins with a summary of the geology, as this provides the fundamental framework of the groundwater system, and a description of aquifers. Then, water budgets are summarised including the key issues for nutrient transport such as baseflow, quick flow and groundwater outflow from catchment. The groundwater level (or piezometric level) is also an important facet of groundwater systems as it informs assessment of groundwater-surface water interaction. Therefore, the key trends in groundwater levels will be described using the piezometric maps derived in this report. Lastly, groundwater chemistry in each zone will be summarised including the state and trends of nutrients, E. coli, and indicators of reducing conditions.

4.1 UPPER WAIKATO

4.1.1 Geology

The elevation of the top surface of the basement model unit (Figure 4.1) varies considerably in the Upper Waikato model area. Large basement offsets have occurred as the TVZ developed, and, therefore, basement geology dominates the cross-section of the model (Figure 4.2). The basement top surface has been separated into distinct fault blocks with the main structural elements represented by the cross section:

- basement exposure and shallow basement in the west (‘A’, Figure 4.2);
- Whakamaru and Ohakuri calderas in the vicinity of ‘B’;
- Reporoa Basin with basement elevation approximately -3000 m (between ‘B’ and ‘C’); and
- relatively shallow basement under the Kaingaroa Plateau (‘C’).

The 3D geological model summarises the distribution of: basement including the large basement offsets associated with faults and calderas (Figure 4.1A); Whakamaru Group ignimbrites, which are important aquifers, and older formations (Figure 4.1B); lake sediments and older formations (Figure 4.1C); Oruanui Formation Figure 4.1D); and the modern-day surface lithology including Tauranga Group sediments, which supplies many households with groundwater (Figure 4.1E).

Western volcanics including Mt Maungatautari, Mt Titiraupenga and Mt Pureora, are associated with greywacke on the western margins of the TVZ. Pakaumanu Group ignimbrites are exposed at the ground surface around Mangakino Caldera and are assumed to fill the Hauraki Rift extension and the base of the TVZ rift. Eruptions from the Whakamaru Caldera deposited large volumes of Whakamaru Group ignimbrites within, and outside, the TVZ rift (Figure 4.1B).

Deposits sourced from the Ohakuri Caldera are located in the central and northern central part of the model area. Mamaku Plateau Formation is exposed at the ground surface in the northern central part of the model area. This formation is a very important aquifer because it is the source of groundwater for many users and also provides flow to many large springs, and also provides baseflow to many significant streams around the Mamaku Plateau, including Pokaiwhenua Stream near Tokoroa.

Western domes are associated with the Maroa Volcanic Centre. Maroa Group ignimbrites are distributed between the Western domes at, and below, the ground surface in the southern central model area. Eastern volcanic cones, e.g. Mt Tauhara and Maungakakaramea (Rainbow Mountain), are assumed to have their base on the top surface of Whakamaru Group ignimbrites. Lake sediments are widely distributed throughout the eastern part of the model area, particularly in the Reporoa Basin, associated with Lake Huka (Figure 2.4) and the Kapenga Caldera (Figure 4.1C). These sediments provide an important aquiclude.

Earthquake Flat Formation, which is used for groundwater supply, is exposed at the ground surface in the northeastern part of the model area. Its horizontal subsurface distribution is assumed to be limited mostly to the areas of surface exposure (Figure 2.3). Oruanui Formation is exposed widely throughout the central and eastern parts of the model area and is overlain only by Tauranga Group deposits. Tauranga Group sediments, including associated volcanics, and the Waikato River bed, are also widely distributed in the model area (Figure 4.1E).

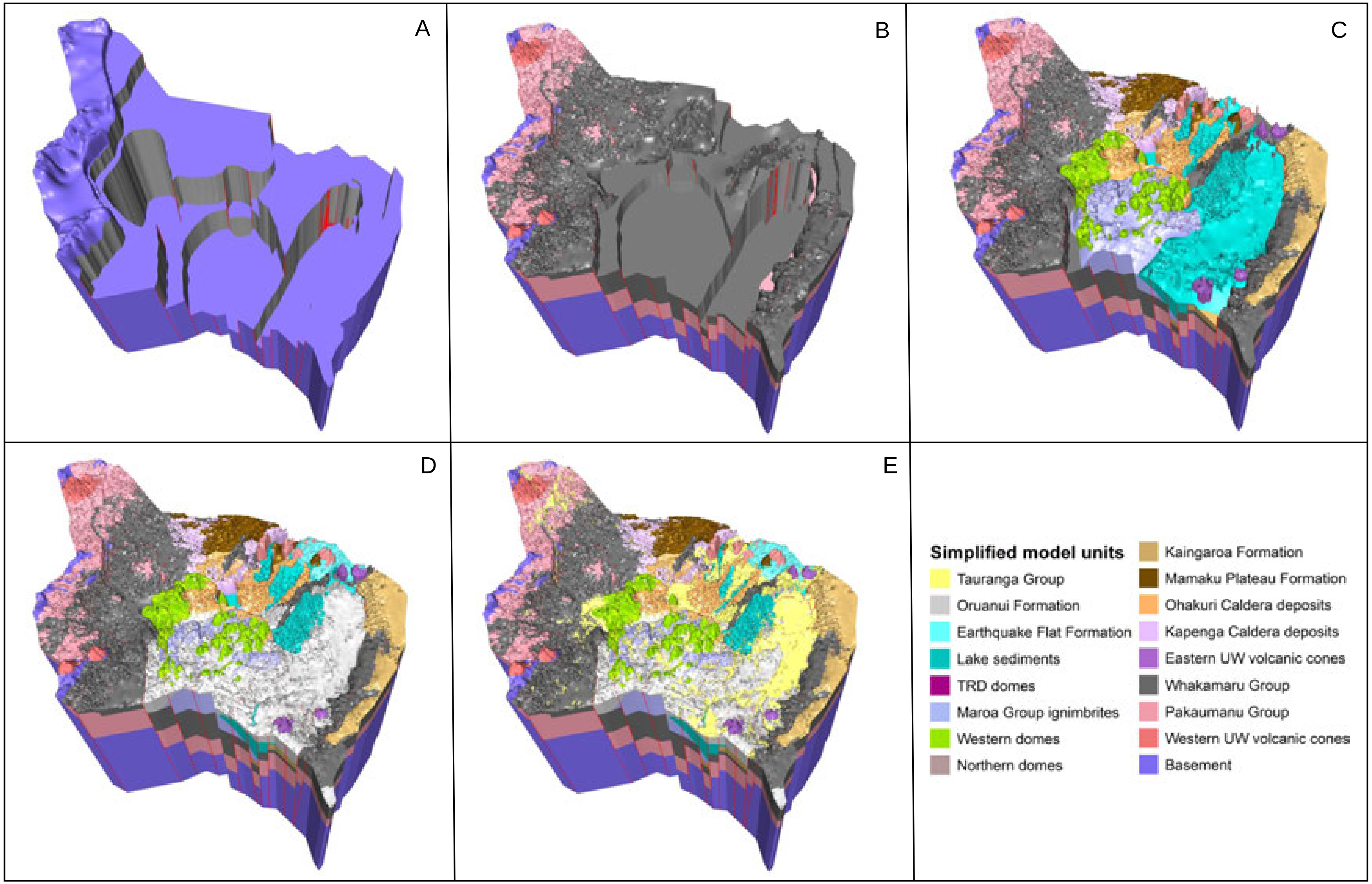

Figure 4.1 Views of the UW 3D geological model from the oldest to the youngest model unit. The view direction is from south to north.

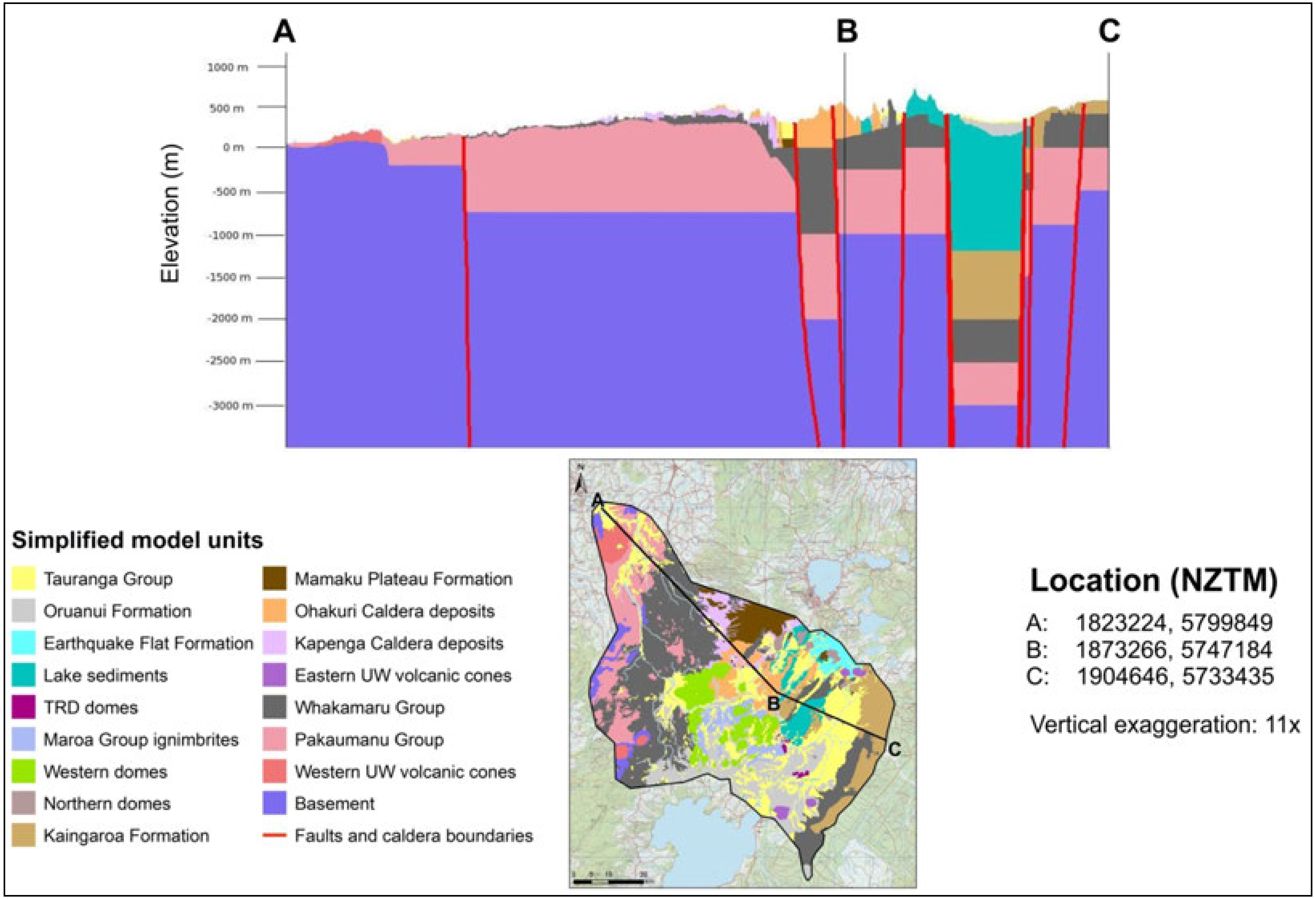

Figure 4.2 North-south cross-section through the UW geological model.

4.1.2 Water Budget

Waikato River flow estimated with the water budget (Appendix 3) is generally similar to calculated long-term flows in the Waikato River (Table 4.1). This budget is suitable for the description of general features in groundwater flow in the Upper Waikato catchment. Amendments to water budget components would produce better estimates of Waikato River flow. However, these amendments would have little implication for the understanding of the groundwater system.

Table 4.1 Waikato River flows: average of observed long-term (i.e., 1960 – 2006) flow and flows estimated with the water budget.

Catchment name	Catchment number	Observed flow site	Observed flow mean 1960 – 2006 (m^3/s)	Source of observed flow estimate	Water budget flow (m^3/s)
Lake Taupo	na	Reids Farm	151.2	Payne (2015)	151 (assumed)
Waikato at Ohakuri	3035123	Ohakuri Dam	175.1	Payne (2015)	183.1
Waikato at Whakamaru	3035301	Whakamaru Dam	189.5	Payne (2015)	201.9
Waikato at Waipapa	3030247	Waipapa Dam	212.8	Payne (2015)	226.4
Waikato at Karapiro	3020656	Karapiro Dam	238.8	Payne (2015)	251.1

These budgets, and associated estimates of baseflow and quick flow (Appendix 3), show that the groundwater system is hugely important to the hydrology of the Upper Waikato. This is because most rainfall recharge (i.e., P-AET) in the area flows to groundwater, which is typical of the TVZ. Estimated BFI in Upper Waikato catchments is an average of 0.94 in these catchments and that means that an average of 94% of rainfall recharge will go to the groundwater systems and then reappear in streams and rivers. This is not a new conclusion in regards of TVZ hydrology and hydrogeology because it has been observed before, by workers including: Hutchinson (1983); *White et al.,* (2007) and White, (2010).

Relatively high baseflow is also consistent with high rates of rainfall recharge, which is observed in the TVZ. For example, a rainfall recharge of approximately 50% of rainfall was observed at the Kaharoa rainfall recharge site, near Rotorua (White *et al.,* 2007). High rates of rainfall recharge explain a notable feature of hydrology in the TVZ, i.e. stream beds are general dry in the upper reaches of catchments. For example, no permanent flowing streams are observed on the tops of rhyolite domes and ignimbrite sheets (e.g. the Kaingaroa Plateau).

The water budget indicates where groundwater outflow may occur from a catchment. In the Upper Waikato, most catchments have a zero, or low groundwater outflow. This indicates that most outflow from catchments occurs via surface water, which mostly comes from the groundwater system (see above). Groundwater outflow is calculated for five catchments (i.e., 3034452, 3037027, 3037105, 3031392 and 3031392. Four of these (i.e., all except 3037105) are headwaters catchments Therefore, most groundwater outflow flows to downstream catchments and then to the Waikato River. Groundwater outflow from these catchments is relatively low, i.e., below 0.4 $m^{3/}s$, and this may be within the uncertainty range in water budget components, which may mean that no groundwater outflow occurs. The exception (i.e., 3037105 which is the Waiotapu at Homestead catchment) borders the Waikato River and is located at the western boundary of the Reporoa Basin. Therefore, it is most likely that groundwater outflow from this catchment flows to the Waikato River.

4.1.3 Piezometric Levels

The piezometric surface in the Upper Waikato has the appearance of the DTM because groundwater elevation is a function of ground elevation, and fixed-head points constrain the surface, e.g., along the Waikato River (Figure 4.3). This map, which compares reasonably with published piezometric maps from Waikato Valley Authority (1987) and Bromley *et al.,* (2000), demonstrates that groundwater will move in a down-topographic gradient towards the Waikato River in the Upper Waikato. In comparison with water budgets, this shows that catchment boundaries are most probably the locations of groundwater divides, i.e., groundwater recharge within HRP catchments will most probably stay in that catchment until it discharges, either mostly to the Waikato River or out of headwaters catchments to down-stream catchments (see above).

Therefore, the definition of the catchment boundary is crucial to link land units with their receiving waters. Generally, the topographic catchment boundary is the same as the groundwater divide. However, the definition of these boundaries may not be clear-cut where the topographic boundary crosses relatively planar features, e.g. the Kaingaroa Plateau. In these circumstances, further analysis may improve the definition of the boundary (e.g., White *et al*., 2014).

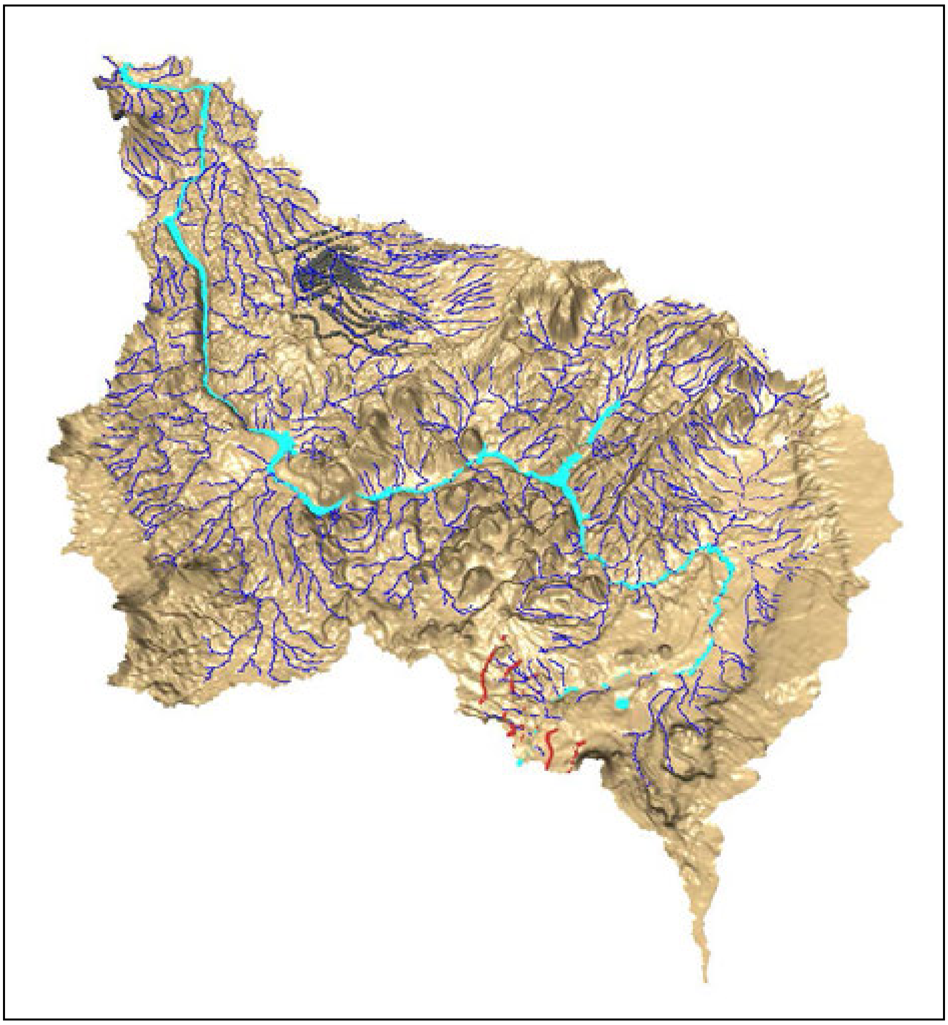

Figure 4.3 Piezometric surface of the UW zone at 10x elevation exaggeration. The following datasets have been added for comparison purposes: piezometric contours in purple (Waikato Regional Council, 1991); piezometric contours in grey (Waikato Valley Authority, 1987); piezometric contours in red (Bromley *et al.,* 2000); fixed-head cells in light blue for Lake Rotokawa and the Waikato River; and fixed-head cells representing streams in dark blue. The view direction is towards the north.

4.1.4 Groundwater Chemistry

Groundwater chemistry in the Upper Waikato in measured in 21 wells by WRC (Table 4.2). A summary of these measurements by catchments indicates that nitrate-nitrogen is commonly higher then MAV (i.e., higher than 11.3 mg/L) and between ½ of MAV and MAV. This indicates that relatively high nitrogen concentrations are common in Upper Waikato groundwater and that land use is impacting on groundwater quality. In addition, nitrate-nitrogen concentrations are not increasing over time, possibly indicating that any recent land use intensification has not yet impacted further on groundwater quality. However, the summary of nitrogen in Table 4.2 does not represent whole catchments, but the maximum median concentration within a catchment. It is possible that, in the same catchment, other wells have lower concentrations (Appendix 4).

Commonly MN is greater than MAV and Fe is greater than guideline concentrations. Elevated concentrations of these elements indicate anoxic conditions in groundwater. Therefore, anoxic conditions are probably common in Upper Waikato groundwater.

Table 4.2 Summary of groundwater chemistry in the Upper Waikato (Appendix 4).See Ministry of Health (2008) for MAVs and water quality guidelines.

Item	Number of Upper Waikato catchments
Median N measured that is greater than MAV for NN	6
Median N between 1/2 of MAV and MAV for NN	7
N increasing at least 0.1 mg/L/decade	0
EC trend is an increase	2
E. coli counts are greater than MAV	1
Mn greater than MAV	6
Fe greater than guideline	12
Few wells	4
Number of catchments with no groundwater chemistry data	7
Number of catchments	21

4.2 WAIPA

4.2.1 Geology

A preliminary 3D hydrogeological model of the Waipa has been developed (Rawlinson, 2014; Figure 1.1, Figure 4.5) that consists of the following lumped geological units, in chronological order from youngest to oldest:

1) Holocene sediments and Tauranga Group – the main Waipa aquifer unit.
2) Pakaumanu Group – both a fractured and porous aquifer.
3) Alexandra Group volcanics – which provides groundwater from fractured aquifers.
4) Miocene sediments – hydrogeological basement of the main Waipa aquifer, with discrete limestone water sources.
5) Te Kuiti Group – with limited discrete fractured and limestone water sources.
6) Basement rock – generally not regarded as aquifer, but may have limited discrete fractured water sources.

Of the faults in the area, only the Waipa Fault Zone extends across the entire catchment and is of broad significance. Therefore, only this fault zone has been used within the model. There is no available dip information, therefore a dip of 90° has been used, which allows a reasonable match of the 3D fault surface to fault lines depicted in the QMAP cross sections.

The Hamilton Basin is structurally defined by a graben bounded by upthrown ranges of Mesozoic basement rock (Figure 4.4A, Figure 4.5). Basement rock lies at a depth of approximately 2 km in the centre of the graben in the north of the Waipa. Normal faulting has upthrown basement in steps progressively to the east, while to the west the Waipa Fault Zone has upthrown basement rock almost to the surface. Basement rock is significantly shallower approximately 50 km south, where basement rock lies at approximately 150 m deep. In the southeast, close to Te Kawa, there are both small and large ranges of outcropping basement rock between which basement rock has been estimated at a depth of 500 m from magnetic and resistivity surveys (Marshall and Petch, 1983; Mayhew and Caldwell, 1984), suggesting a complicated faulted basement structure in this area. The Te Kuiti Group lies at a depth of 1 – 2 km in the north of the Waipa (where it is up to 500 m thick) and outcrops in the southwest of the catchment (Figure 4.4B). Miocene sediments lie to a depth of approximately 1400 m in the north of the Waipa area and crop out in the southwest of the catchment (Figure 4.5).

Alexandra Group volcanics exist on the western-central portion of the Waipa and consist of several low-angle cones, including Pirongia, Te Kawa and Kakepuku Figure 4.4C). Pakaumanu Group covers basement in the southeast of the Waipa, across the Rangitoto Range (Figure 4.4D). The Tauranga Group has a thickness of up to 600 m in the Hamilton Basin and gradually thins to the south where thicknesses are typically approximately 5 m (Figure 4.4E). Using the existing data, uncertainties in model unit thickness and extents are high within the Waipa River Plains to the south of Mt Pirongia.

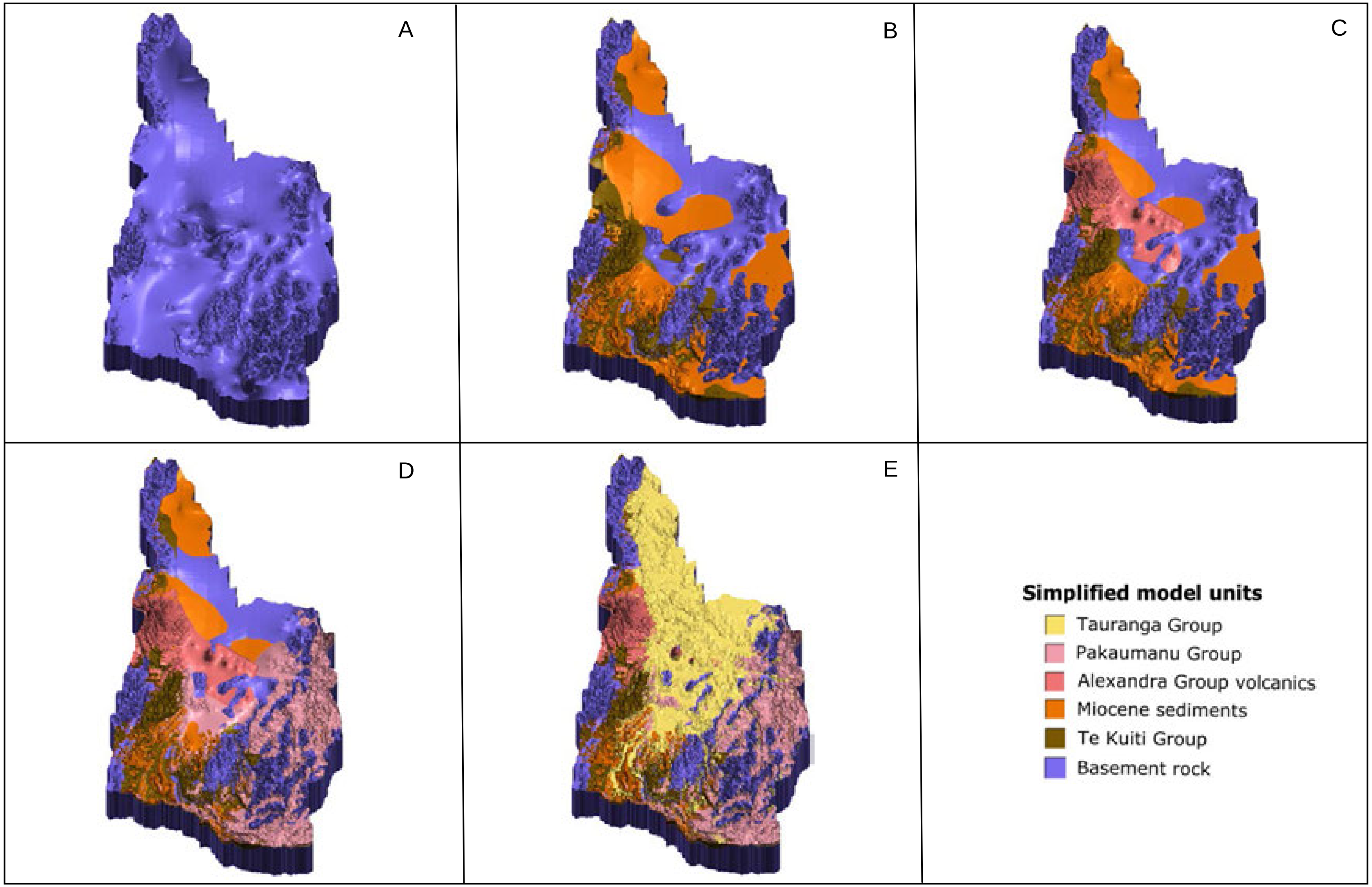

Figure 4.4 Views of the Waipa 3D geological model from the oldest to the youngest model unit. The view direction is from south to north.

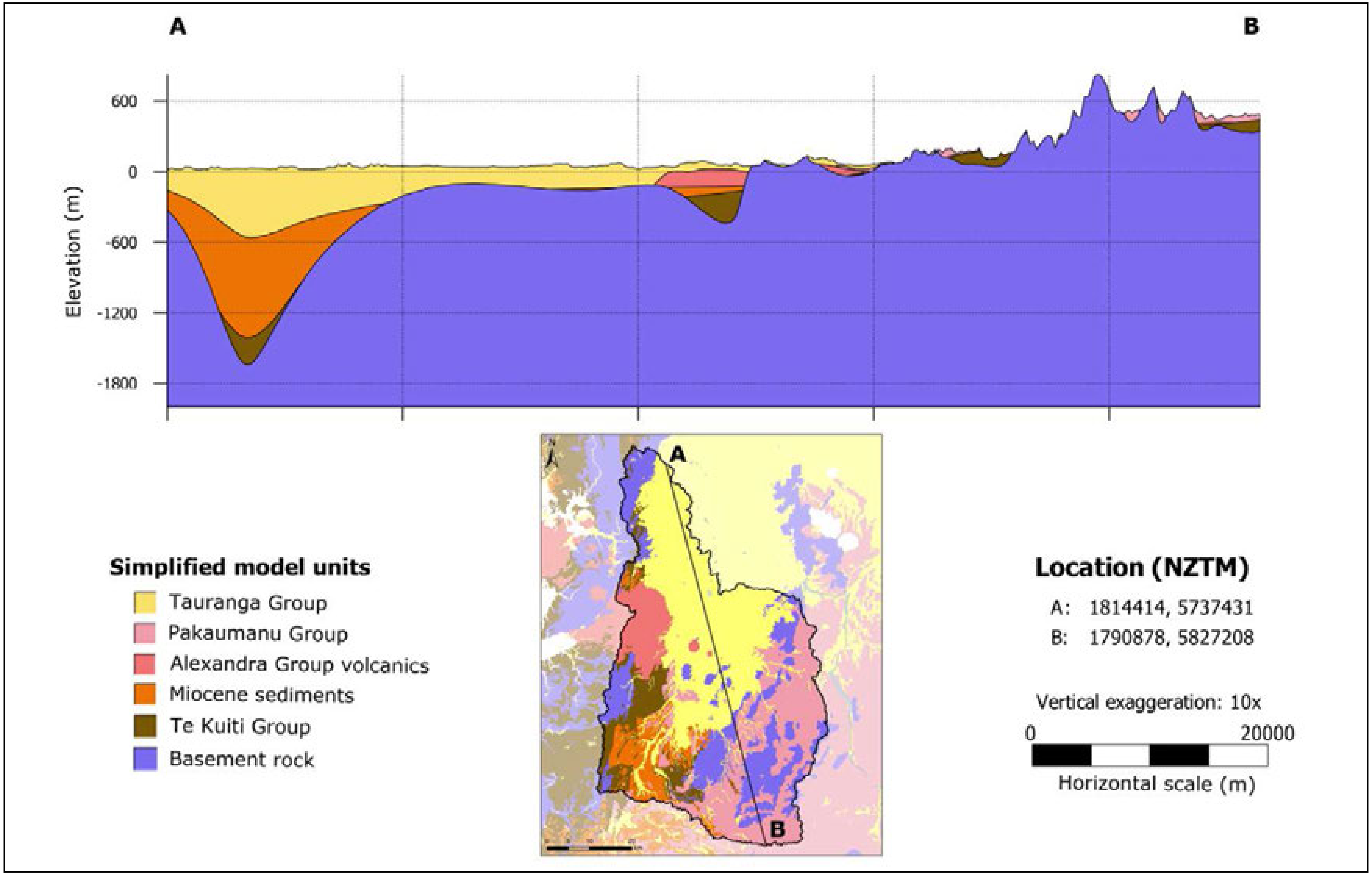

Figure 4.5 North-south cross-section through the Waipa geological model.

4.2.2 Water Budget

Waipa River flow estimated with the water budget (Appendix 3) is similar to calculated long-term flows in the river (Table 4.3). This is because the rainfall estimates of Tait *et al.* (2006) were adjusted by approximately + 7% so that water budget flow matched observed flow at the Whatawhata site. The water budget estimates a 96.5 m^3/s outflow of the Waipa River catchment at Waingaro Rd bridge to the Waikato River with this adjustment.

Table 4.3 Waipa River flows: average of observed long-term (i.e., 1960 – 2006) flow and flows estimated with the water budget.

Catchment name	Catchment number	Observed flow site	Observed flow mean 1960 – 2006 (m^3/s)	Source of observed flow estimate	Water budget flow (m^3/s)
Waipa at Pirongia-Ngutunui Rd bridge	3022669	Waipa at Pirongia-Ngutunui Rd bridge	74.5	Jenkins (2015b)	74.5
Waipa at SH23 bridge Whatawhata	3017829	Waipa at SH23 bridge Whatawhata	87.7	Jenkins (2015b)	87.7
Waipa at Waingaro Rd bridge	3015066	na	na	na	96.5

Water budgets of catchments demonstrate the importance of groundwater in the hydrology of the zone. For example, the average of estimated BFI (Appendix 3, Table A3.5) is 0.77, which means that most surface water has come from the groundwater system. Baseflow-dominated catchments are typically in the headwaters catchments. For example, base-flow dominated catchments are above Otorohanga (3026779, 3027166 and 3031371), reflecting the importance of groundwater flow into the Te Kuiti Group formations. The BFI is typically in the range 0.6 +/- 0.1 in catchments in the Hamilton Basin. Therefore, baseflow and quick flow are both important in this area.

Commonly, groundwater outflow is estimated, and these outflows are largest for the headwaters catchments. In particular, the group of catchments above Otorohanga demonstrate some of the largest groundwater outflows in the Waipa. For example, the water budget calculates that groundwater outflow is approximately 2.8 m^3/s from catchment 3026779, which is one of this group. Most probably, groundwater from headwaters catchments flows out of the groundwater system through springs or seeps in the area where the headwaters catchments meet the relatively flat ground, and relatively low-permeability sediments in the Hamilton Basin.

4.2.3 Piezometric Levels

Groundwater elevations follow the topography and are relatively flat in the Hamilton Basin (Figure 4.6). In addition, many small streams occupy the basin. Therefore, the relatively low BFI in the Hamilton Basin is explained by low groundwater flow rates and a large network of streams to carry quick flow. In addition, the substrate is typically silty, and as a result the rainfall recharge rate will be lower than on more permeable soils.

However, relatively few streams are in the northern area of the catchment. This is probably because this area includes significant areas of Hinuera Formation that were deposited by the Waikato River after the Oruanui eruption. This area has a sand substrate and so rainfall recharge is likely to be greater than in other areas of the basin. In addition, peaty soils occur in this area. These are likely to impede drainage.

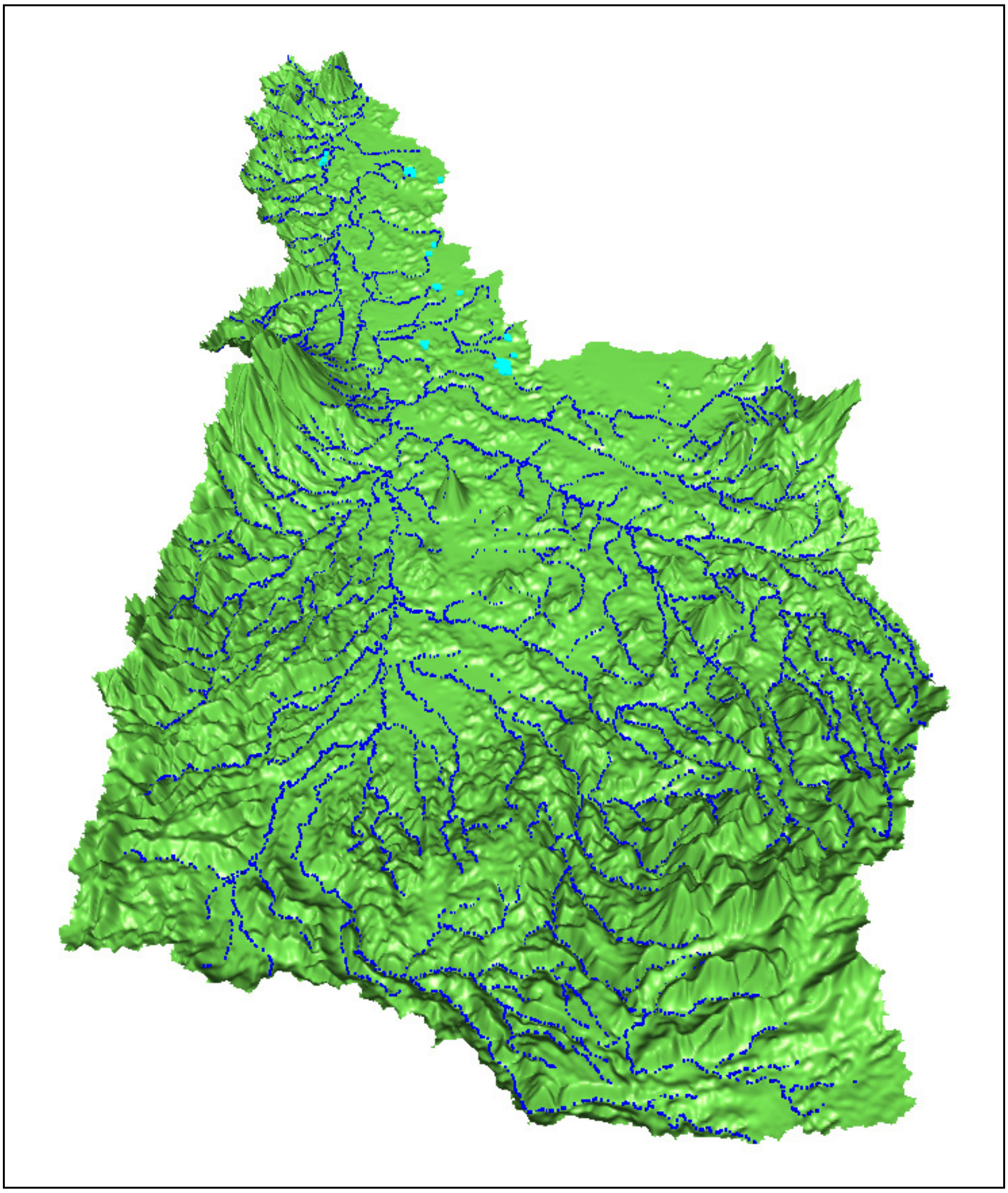

Figure 4.6 Piezometric surface of the Waipa zone at 10x elevation exaggeration. The following datasets have been added for comparison purposes: fixed head cells of lakes and the Waikato River – in light blue; and fixed head cells of streams – in dark blue. The view direction is towards the north.

4.2.4 Groundwater Chemistry

Groundwater chemistry in the Waipa is measured in 22 wells by WRC (Appendix 4), Table 4.4. Nitrate-nitrogen is sometimes higher than MAV (i.e., higher than 11.3 mg/L) and between ½ of MAV and MAV. Therefore, relatively high nitrogen concentrations are somewhat common in Waipa groundwater. Nitrate-nitrogen concentrations are increasing over time in some wells, which is additional information that land use is impacting on groundwater quality in this zone.

Mn and Fe are greater than MAV and guideline concentrations in some wells. Therefore, anoxic conditions occur in the Waipa zone. However, elevated concentrations of these elements are less common than in the Upper Waikato zone.

Table 4.4 Summary of groundwater chemistry in the Waipa zone (Appendix 4). See Ministry of Health (2008) for MAVs and water quality guidelines.

Item	Number of Waipa catchments
Median N is greater than MAV for NN	2
Median N between 1/2 of MAV and MAV for NN	3
N increasing at least 0.1 mg/L/decade	2
EC trend is an increase	0
E. coli counts are greater than MAV	3
Mn greater than MAV	4
Fe greater than guideline	3
Poor data	13
Number of catchments with no groundwater chemistry data	7
Number of catchments	31

4.3 LOWER MIDDLE WAIKATO

4.3.1 Geology

A combination of GIS (ESRI ArcGIS 10.1) and 3D geological modelling software (Leapfrog Geo 2.2) has been used to construct the conceptual geological model for the Lower to Middle Waikato zone (Figure 4.7, Figure 4.8).

The model has been constructed using the New Zealand Transverse Mercator projection (NZTM2000). The surface area covered by the model is 3,521 km^2, the model extends to a depth of 1.5 km, to provide a continuous basement surface (Figure 4.7A), and the resolution of the model is set to 200 m. The complex geology of the region has been simplified into the following seven key model units based on available data:

1) Tauranga Group – important aquifer, but heterogeneous composition and hydrogeological behaviour.
2) Pakaumanu Group – both a fractured and porous aquifer.
3) Kerikeri Volcanic Group (including Kiwitahi Group) – both a fractured and porous aquifer.
4) Kaawa Formation – important aquifer (porous and fractured, with highly variable hydraulic properties).
5) Miocene sediments – with limited discrete fractured and limestone water sources.
6) Te Kuiti Group – with limited discrete fractured and limestone water sources.
7) Basement – generally not regarded as aquifer, but may have limited discrete fractured water sources.

Faults are indicated in the model by the behaviour of the model units (Figure 4.8).

The deepest basement in the LMW catchment is located in the Hamilton Basin (Figure 4.7A, Figure 4.8). In this graben structure it reaches a maximum depth of approximately -1300 m ASL. However, there are only very few deep bores in this area, and, therefore, the basement model unit is not very well constrained in the basin. Basement is also particularly deep (approximately -800 m ASL) between Pukekohe and the Waikato River mouth. However, there is only one bore (Otaua-1), which constrains the basement in this area, and that results in a very high uncertainty of the basement structure. In the Lower Waikato Basin, the maximum basement depth is approximately -700 m ASL. Deep bores are scarce in the deepest parts of the basin; however, in the shallower parts of the basin, in the south and northeast, a high density of well described coal exploration bores provides a comprehensive and more accurate picture of the basement structure. These two areas in the Lower Waikato Basin are the parts of the 3D model with the lowest uncertainty of the vertical and lateral distribution of the model units represented at these sites.

Te Kuiti Group (Figure 4.7B) is most prominent in the northern part of the LMW model, filling wide parts of the Lower Waikato Basin with a thickness of up to 700 m. In the Hamilton Basin, deposits of this group only reach a maximum thickness of up to 200 m.

Miocene sediments (Figure 4.7C), with a thickness of more than 800 m, are modelled in the Hamilton Basin. In the northern part of the Lower Waikato Basin, the model shows a thickness of up to 500 m for these sediments. However, not many deep bores are located in both of these areas, which increases the uncertainty of the result.

Kaawa Formation is a very localised model unit in the northwestern part of the LMW model (Figure 4.7C). Although this model unit is generally limited to north of the Waikato Fault, a small number of bores, with deposits that are potentially equivalent to this formation, extend this model unit further to the south, where remnants of it underlie Kerikeri volcanics south of Mercer. Kaawa Formation reaches a maximum thickness of 434 m in the model; however, this is mostly constrained by the log of one oil exploration bore near Port Waikato. All other bores used to constrain this model unit have been logged by commercial drillers and the top of the unit was interpreted from the, quite often ambiguous, log descriptions. Therefore, there is a high uncertainty of the exact top and bottom elevations of this formation.

Kerikeri volcanics are predominantly located in the northernmost part of the LMW model (Figure 4.7). Here they reach a maximum thickness of 200 m and overlie Kaawa Formation, Miocene sediments, Te Kuiti Group, or basement directly in places.

Pakaumanu Group deposits are mapped at the ground surface in a small area in the southeastern part of the LMW zone (Figure 4.7). As there is no subsurface data for this unit, it has been limited to this part of the model area. Deposits of this model unit have a maximum thickness of 127 m in the LMW model.

Tauranga Group deposits cover large parts of the LMW model (Figure 4.7). The thickest Tauranga Group deposits are located in the Hamilton Basin. Here these deposits have a maximum thickness of more than 700 m in the LMW area. In most other parts of the LMW model, that are covered by Tauranga Group, this model unit only has a thickness of less than 100 m, but locally it can be up to 200 m thick.

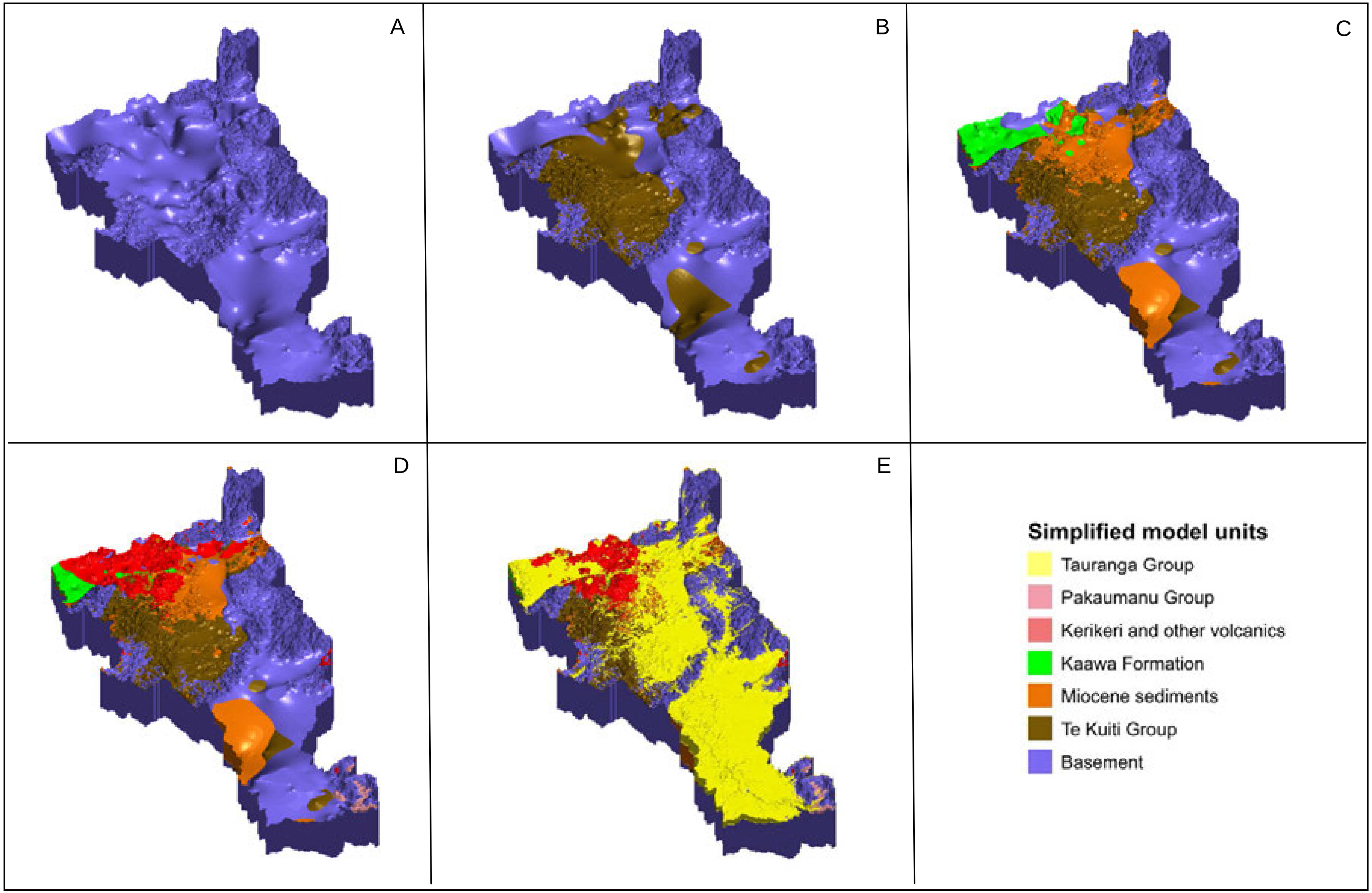

Figure 4.7 Views of the LMW 3D geological model from the oldest to the youngest model unit. The view direction is from south to north.

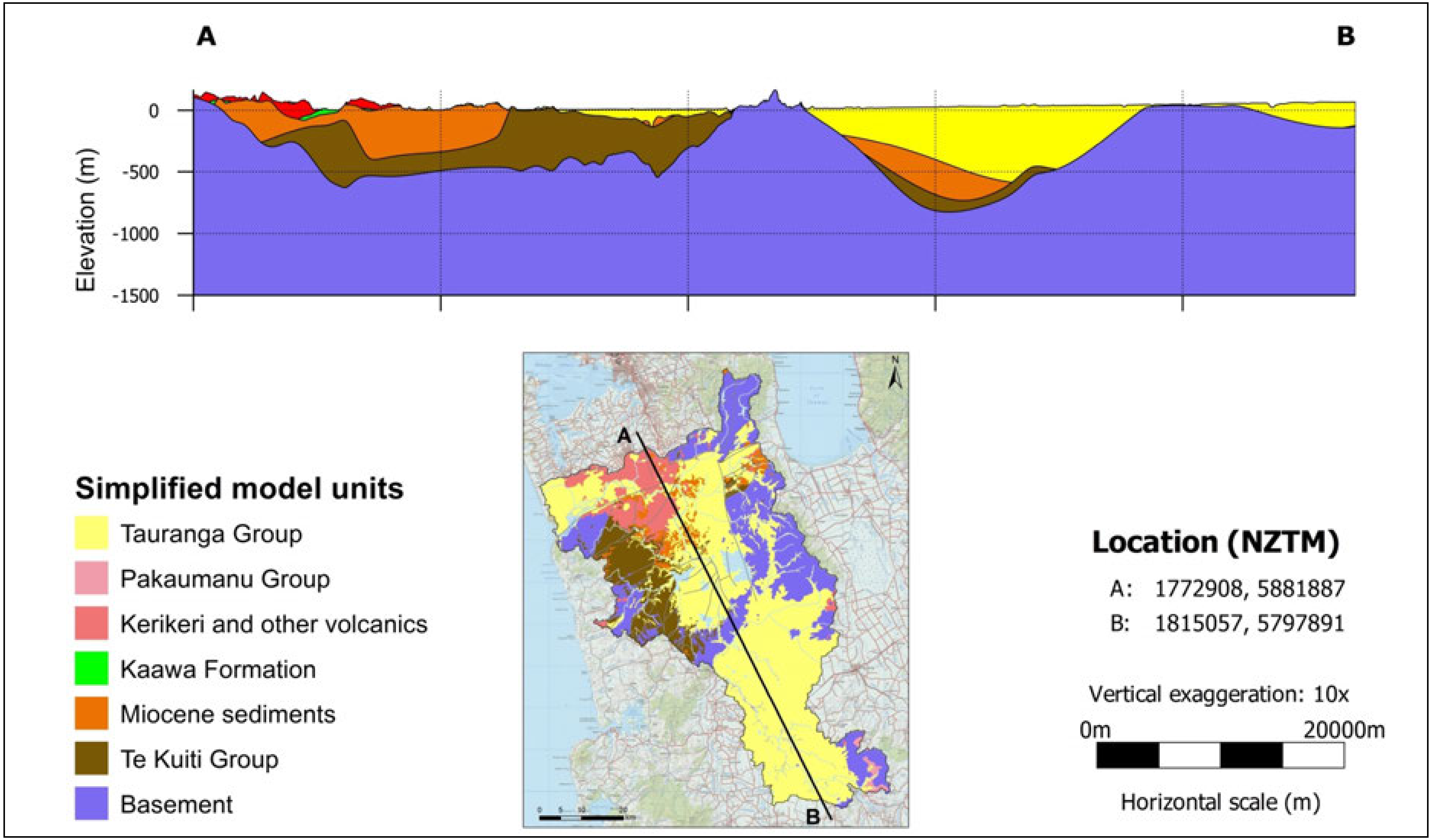

Figure 4.8 North-south cross-section through the LMW geological model.

4.3.2 Water Budget

Lower-middle Waikato River flows estimated with the water budget approximate the flows estimated from WRC recorder sites (Table 4.5). LMW River flow estimated with the water budget (Appendix 3) is similar to calculated long-term flows in the river (Table 4.2). This is because the rainfall estimates of Tait *et al.* (2006) were adjusted by approximately + 7% so that flows are matched at the Whatawhata site. The water budget estimates a 96.5 m^3/s outflow of the Waipa River to the Waikato River.

Table 4.5 LMW flows: average of observed long-term (i.e., 1960-2006) flow and flows estimated with the water budget.

Catchment name	Catchment number	Observed flow site	Observed flow mean 1960 –2006 (m^3/s)	Source of observed flow estimate	Water budget flow (m^3/s)
Waikato at Bridge St bridge	3017901	Hamilton Traffic bridge	260.9	Jenkins (2015b)	257.4
Waikato at Huntly-Tainui bridge	3013160	Ngaruawahia Cableway	338.5	Jenkins (2015b)	365.7
Waikato at Rangiriri	3010604	Rangiriri Bridge	369.2	Jenkins (2015b)	369.9
Waikato at Mercer Bridge	3006806	Mercer Bridge	410	Jenkins (2015b)	394.7
Waikato at Tuakau Bridge	3007421	na	na	na	401.9
Waikato at Port Waikato	3007421	na	na	na	408.6

Groundwater flow is important in the providing baseflow in LMW streams and rivers. A wide range of estimated BFI occurs in the LMW. Base-flow dominated surface flows (i.e., BFI is greater than 0.8) are common in the Lower-middle Waikato. For example, estimated BFI is typically high in the main stem of the Waikato River (e.g., BFI at the Huntly-Tainui Bridge is 0.86). Estimated BFI is also high for lake outlets; for example, BFI at the outlet of Lake Waikare is 0.99, although this value is probably influenced by lake control structures. Control structures on the lower Waikato Waipa control scheme probably also influence the BFI estimate. For example, mean and median flow on the outlet of the Whangamarino wetland (catchment 3007681 at WRC gauging site 1293_15) are 5.0 m^3/s and 0 m^3/s, respectively.

Commonly, groundwater outflow is calculated for LMW catchments. Estimated groundwater outflows are typically in the range 0 to 0.3 m^3/s for catchments in the Hamilton Basin and this would generally flow directly to the Waikato River. Relatively large groundwater outflows are calculated for the catchments 3008369 and 3007681, that are associated with the Whangamarino wetland, of 1.7 m^3/s and 1.4 m^3/s, respectively.

4.3.3 Piezometric Levels

Groundwater levels in the Hamilton Basin typically follow topography (Figure 4.9). This means that groundwater recharge in the Hamilton Basin will flow towards the Waikato and into the river upstream of Taupiri. Groundwater recharge in the vicinity of Hamilton will generally flow to the nearby Waikato River.

Drainage problems are common in the Lower Waikato Basin in the vicinity of the Waikato River. This is because water tables are shallow, as groundwater from headwaters catchments discharges to the river. In addition, groundwater levels are at the ground surface through the Whangamarino wetland. Horizontal groundwater gradients are low in the vicinity but are relatively high in the headwaters catchments. For example, high horizontal gradients were measured between Pukekohe Hill and the Waikato River (Waikato Regional Council, 1991), whereas the horizontal groundwater gradients will be approximately zero in the section of river below the hill.

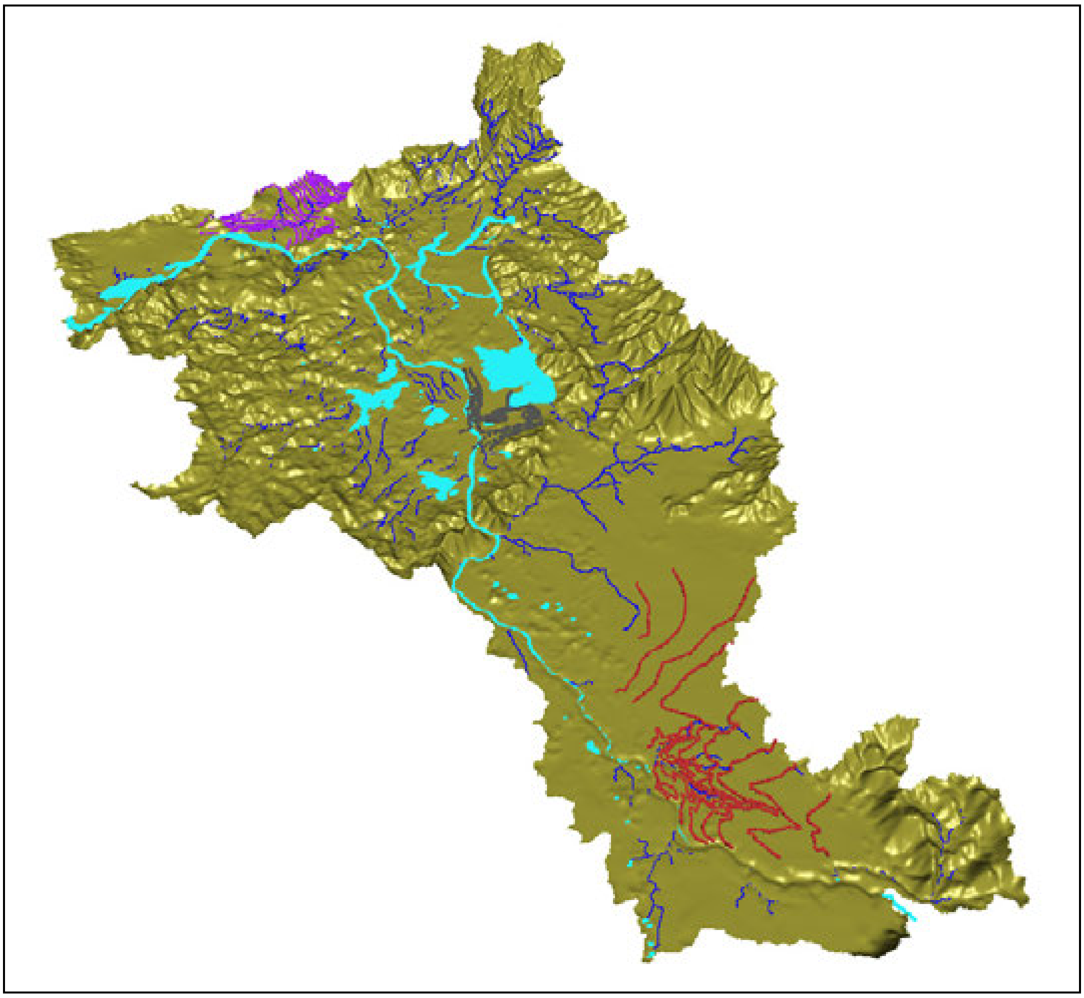

Figure 4.9 Piezometric surface of the LMW zone at 10x elevation exaggeration. The following datasets have been added for comparison purposes: piezometric contours from Waikato Regional Council (1991) – in purple; piezometric contours from Waikato Valley Authority (1986) – in grey; piezometric contours from Marshall and Petch, (1983) – in red; fixed head cells of lakes and the Waikato River – in light blue; and fixed head cells of streams – in dark blue. The view direction is towards the north.

4.3.4 Groundwater Chemistry

Groundwater chemistry in the Lower-Middle Waikato is measured in 29 wells by WRC (Appendix 4), Table 4.6. Groundwater chemistry information indicates that land use is clearly impacting on groundwater quality in the zone. Nitrate-nitrogen is commonly higher than MAV (i.e., higher than 11.3 mg/L) and commonly between ½ of MAV and MAV. Nitrate-nitrogen concentrations are increasing over time in some wells. In addition, this zone also has the most catchments, of the HRP zones, where biological indicators in groundwater are greater than the MAV and the most catchments with an increasing E. coli trend.

This conclusion is not new. Relatively high nitrogen concentrations have been observed under Pukekohe Hill for decades (e.g., Waikato Regional Council, 1991) and this is observed in data summaries of Appendix 4. For example, median nitrate-nitrogen concentrations in catchment 3006346, which includes Pukekohe Hill, are in the range <0.05 to 9.8 mg/L and are increasing at rate between 0.27 and 0.42 mg/L/decade. However, the demonstration that high nitrate concentrations are common in the LWM zone points to some of the information needs to meet the aims of the HRP project.

Table 4.6 Summary of groundwater chemistry in the Lower-middle Waikato zone (Appendix 4). See Ministry of Health (2008) for MAVs and water quality guidelines.

Item	Number of Lower-middle Waikato catchments
Median N is greater than MAV for NN	10
Median N between 1/2 of MAV and MAV for NN	4
N increasing at least 0.1 mg/L/decade	5
EC trend is an increase	6
E. coli counts are greater than MAV	11
Mn greater than MAV	3
Fe greater than guideline	9
Few wells	17
Number of catchments with no groundwater chemistry data	8
Number of catchments	29

5.0 GAP ANALYSIS

An assessment of the current state of the scientific information that supports the understanding of groundwater resources in the HRP area (Section 3.5) includes work completed in this report (Table 5.1). For example, this report developed conceptual models of geology and water flow in the three HRP zones (Section 4).

The items "graded" with a code, in regards of the suitability of current information to address the aims of the HRP in regards of groundwater and surface water, with a high degree of certainty, i.e.:

- 1 (suitable for purpose);
- 2 (mostly suitable for purpose); and
- 3 (not suitable for purpose, or not available).

Table 5.1 The current state of scientific information on groundwater resources in the HRP area.

HRP Template group	Component	Item	HRP zone			Comments
			UW	Waipa	LMW	
Geology	Measurements	Well logs	2	2	2	Data coverage is poor in many areas, e.g., in the deeper sections of the Tauranga Group (i.e., Hamilton Basin north and west of Te Awamutu; Lower Waikato Basin and Reporoa Basin).
		Pump tests	2	2	2	Generally, pump tests done by drillers and have extremely variable quality. Therefore, more properly constructed pump test are required.
		Surface geology	1	1	1	Qmap maps are available.
		Surface geophysics	3	3	3	Data coverage is very poor. Data has been collected in the UW but not analysed for groundwater properties.
	Science data base	Well logs	3	3	3	The well log summary on the WRDC data base is too generic and does not allow property modelling (i.e., lithological variability) of aquifers in the Tauranga Group.
		Pump tests	2	2	2	Generally, pump test records are of those done by drillers and have extremely variable quality.
		DTM	1	1	1	The WRC DTM appears suitable.
	Models	Conceptual model	2	2	2	Conceptual models completed in this report (Section 4). These models could be improved with more detailed layer structures.
		Property models	3	3	3	Property models (e.g. permeability, chemistry) could be completed where data is suitable.
Water budget	Measurements	Conceptual model	2	2	2	Conceptual model completed in this report (Section 4).
		Stage recorder sites	1	1	1	Long-term stage recorder sites provide important data sets.
		Gauging sites	2	2	2	The distribution of low-flow measurements could be improved. The measurement of synoptic surveys of summer low flows is very important.
		HRP monitoring plan	3	3	3	A monitoring plan could aim to measure outflows (water and chemistry) from every HRP catchment and assess progress of the HRP.
	Science data base	Flow records	1	1	1	Data is easily available.
		Water budget component (rainfall)	1	1	1	Rainfall maps are available, including a Waikato specific map that wasn't used in this project.
		Water budget component (AET)	2	2	2	AET is somewhat understood but these estimates could be improved.
		Water budget component (runoff)	3	3	3	Runoff (i.e., quick flow) is somewhat understood but these estimates could be improved.
	Models	Flow model (steady state)	1	3	3	A steady-state groundwater flow model of each zone would be very useful.
		Groundwater quality	1	3	3	A steady-state groundwater flow model, including chemical transport, of each zone would be very useful.
		Flow model (transient)	1	3	3	A groundwater flow model capable of transient calculations of each zone would be useful.
		Management scenarios	1	3	3	Assessment of management options can be completed with a model.

HRP Template group	Component	Item	HRP zone			Comments
			UW	Waipa	LMW	
Groundwater chemistry	Measurements	Catchment coverage	2	2	2	Many catchments have no, or poor, data coverage (Section 4).
		Indicator suite	2	2	2	Many catchments lack measurements for the full suite of indicators (Appendix 4).
		E. coli measurements	3	3	3	Few wells have this data but E. coli observations are common (Appendix 4).
	Science data base	Chemistry database	1	1	1	Data is easily available.
		HRP monitoring plan	3	3	3	A monitoring plan could aim to assess progress under the HRP; this plan could identify suitable existing wells and future possible well locations.
		Trend analysis	2	2	2	Relatively few wells have suitable data for trend analysis (Appendix 4).
		Analysis of chemistry data	3	3	3	Analysis of data has not generally been completed (e.g.: groundwater quality and land use; and groundwater quality and well depth).
		Capture zones	3	3	3	Capture zones of wells have not been identified, but groundwater catchments are probably the surface catchment boundary.

1. Suitable for purpose.
2. Mostly suitable for purpose.
3. Not suitable for purpose, or not available.

6.0 RECOMMENDATIONS

The following recommendations build on the summary of current science information related to the HRP (Section 5):

1) Improvements in the quality of the WRC well log data base so that “properties” (e.g., lithology) of sediments can be modelled. This is because much of the information recorded by drillers is not available for geological model development through the WRC database, which heavily summarises lithological identifications in well logs.
2) Generally, pump test records are of those done by drillers and have extremely variable quality. Therefore, properly constructed pump tests, and analysis of these tests, would reduce the uncertainty of layer hydraulic properties in the HRP area.
3) The distribution of low-flow measurements could be improved, ideally with measurements at the HRP catchment outflows, largely at existing WRC sites. In addition, synoptic surveys of summer low flows are very important, e.g. the work completed by WRC in summer 2014/2015. This work could be planned as part of the monitoring plan, see following.
4) Improve HRP catchment water budgets. This could include improvements to: the rainfall map (e.g., with the ‘new’ Waikato regional rainfall map; Jenkins, 2015b); low-flow (i.e., baseflow) outflows including new gauging measurements (see above); improved AET and runoff estimates; and improved calibration to HRP catchment outflows (i.e., baseflow and quick flows).
5) Steady-state groundwater flow models of the Waipa and LMW zones should be built, which supplement the UW model, as a basis for groundwater studies.
6) A steady-state groundwater flow model should include chemical transport (e.g., nitrate-nitrogen).
7) The steady-state groundwater flow model and transport model should be used with scenarios that may include land-use options to assess the effects, e.g., on groundwater and surface water quality.
8) Many catchments have no, or poor, data chemistry coverage. Therefore, purpose-built monitoring wells should be considered for monitoring groundwater chemistry. These wells should be properly constructed and pump tested (see recommendation 2).
9) Existing groundwater chemistry data should be analysed, including: groundwater quality and land use; and groundwater quality and well depth.
10) Many catchments lack measurements for the full suite of groundwater chemistry indicators. Therefore, selected existing monitoring wells could be resampled for the full suite of indicators. In particular, few wells have E. coli data and this issue should be addressed with more sampling.

A monitoring plan for field measurements is recommended. The main elements of this plan should include:

- surface flow and surface chemistry measurements that aim to monitor HRP catchments.
- groundwater chemistry, which aims to monitor the full suite of groundwater indicators at the recharge and discharge areas to HRP catchments, or representative HRP catchments.
- selection of appropriate intervals between measurements and the criteria for event-based monitoring.
- any new sampling is to supplement existing monitoring by WRC and NIWA.

In particular, these recommendations aim to develop and improve key data sets and models so that they are suitable for HRP purposes. These recommendations are a sub-set of the gaps (Section 5), because some data sets and models are more important to the HRP project than others.

7.0 SUMMARY

The “Healthy Rivers Project” (Wai Ora: He Rautaki Whakapaipai) aims to improve water quality in the Waikato River catchment, including groundwater, between Lake Taupo and Port Waikato by controlling key water quality indicators (e.g., nitrogen, phosphorus, bacteria and sediment) within acceptable limits. In 2014, a science team was assembled to provide summaries of current information on water resources in the Waikato River catchment. GNS Science was tasked to describe the current knowledge of groundwater resources in 74 Healthy River Project (HRP) catchments and to identify immediate information needs that could contribute to a broad-scale assessment of land use and water quality in the catchment.

Three catchment zones (Upper Waikato, Waipa and Lower-Middle Waikato) were defined in the project area. This project summarised the geology and aquifers of these zones with 3D geological models. Water flows, including groundwater, were estimated in the HRP catchments with a water budget model and groundwater chemistry observations were used to indicate the effects of land use on water quality. Together, these models and observations show the importance of the groundwater system to hydrology and water quality in the HRP area.

The Upper Waikato zone is characterised by large areas of volcanic deposits produced by the Taupo Volcanic Zone (TVZ). Geology in the zone is dominated by Pleistocene volcanic rocks which form important aquifers including ignimbrite and rhyolite. Water budgets show that baseflow is a very important component of stream flow, i.e., baseflow is greater than 80% of total stream flow. In addition, rainfall recharge is relatively high, in common with other areas in the TVZ. Most rainfall in HRP catchments has the following pathway: 1) groundwater recharge, 2) flow in the groundwater system, as interflow or groundwater, and 3) outflow to surface water. This pathway indicates that most water that leaves the land area of HRP catchments has done so after passing through soil layers and has the potential to transport nutrients from the soil into the hydrological system. Clearly, land use is impacting on groundwater quality in the Upper Waikato zone. Nitrate-nitrogen concentrations in groundwater are commonly relatively high, i.e., above ½ of the Maximum Admissible Value set for community water supplies (Ministry of Health, 2008).

In the Waipa zone, important aquifers include Miocene sediments and limestones associated with Waitomo caves, Alexandra Group volcanics and thick Quaternary Tauranga Group sediments of the Hamilton Basin. Baseflow is typically 60% to 80% of river flow and a considerable portion of the net rainfall enters the groundwater system. Groundwater has a relatively high median nitrate-nitrogen concentration in the Waipa River catchment. However, the occurrence of high nitrate-nitrogen concentrations in groundwater is less common than in the Upper Waikato zone, probably because the groundwater system transports a lesser proportion of rainfall to surface water.

The Lower-Middle Waikato zone includes Tauranga Group sediments that are relatively shallow in the Lower Waikato Basin. Here, swamps are common and, therefore, groundwater is at, or close to, the ground surface in large areas around the Waikato River between Huntly and the coast. Generally, groundwater is shallow in the Lower Waikato Basin outside the swampy areas and groundwater quality is impacted by land use. For example, relatively high median nitrate-nitrogen concentrations, and E. coli counts above community drinking water standards, are the most common in the Lower-Middle Waikato zone.

The Waipa and Lower-Middle Waikato zones occupy the Hamilton Basin which is an important agricultural area and the main population centre in the Waikato region.

Groundwater recharge in the Hamilton Basin travels toward the Waikato River to enter the river above Taupiri where greywacke basement in the ranges provides a barrier to lateral groundwater flow.

Recommendations for future work to improve characterisation of the groundwater system and assist with monitoring changes in water quality associated with community actions through the HRP include: improvements to the WRC well log database; the building of steady-state groundwater flow models that the HRP can use to assess the water quality effects of land-use options; and improvements to the groundwater quality database. A monitoring plan for field measurements is also suggested. The main elements of this plan include: surface flow and surface chemistry measurements; and groundwater chemistry.

8.0 ACKNOWLEDGEMENTS

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APPENDICES

APPENDIX 1: HEALTHY RIVERS PROJECT CATCHMENTS: IMAGES SHOWING CATCHMENT LOCATIONS AND DESCRIPTIONS OF GROUNDWATER SYSTEMS.

The location of each Healthy Rivers Project catchment is shown by a relief-shaded image. The description of the groundwater system in each catchment includes a summary of geology, water budget, groundwater-surface water interaction, piezometric levels and groundwater chemistry that are based on the data sets developed in this report. An additional commentary summarises other relevant features of the catchments such as springs and geothermal systems.

The range in median estimates of groundwater chemistry measured in wells is calculated in Appendix 4. The text in Appendix 1 summarises nitrate-nitrogen concentrations (only) because it is associated with land use. The following classification of nitrate-nitrogen concentrations in Healthy Rivers Project catchments:

- Median nitrate concentrations in groundwater can be greater than MAV, i.e., median nitrate-nitrogen concentrations is greater than 11.3 mg/L;

- Median nitrate concentration in groundwater is be greater than MAV (only one well sampled), i.e., median nitrate-nitrogen concentration in the well is greater than 11.3 mg/L;

- Median nitrate concentrations in groundwater can be greater than 1/2 MAV, i.e., median nitrate-nitrogen concentrations can be greater than 5.7 mg/L but less than 11.3 mg/L;

- Median nitrate concentrations are elevated, up to 1/2 MAV, i.e., maximum median nitrate-nitrogen concentrations is between 2 mg/L and 5.7 mg/L;

- Median nitrate concentrations in groundwater are low in this catchment, i.e., median nitrate-nitrogen concentrations are less than 2 mg/L;

- No groundwater nitrate-nitrogen chemistry data is available in this catchment, i.e., groundwater chemistry is measured in the catchment, but nitrate is not measured;

- No wells measure groundwater chemistry in this catchment.

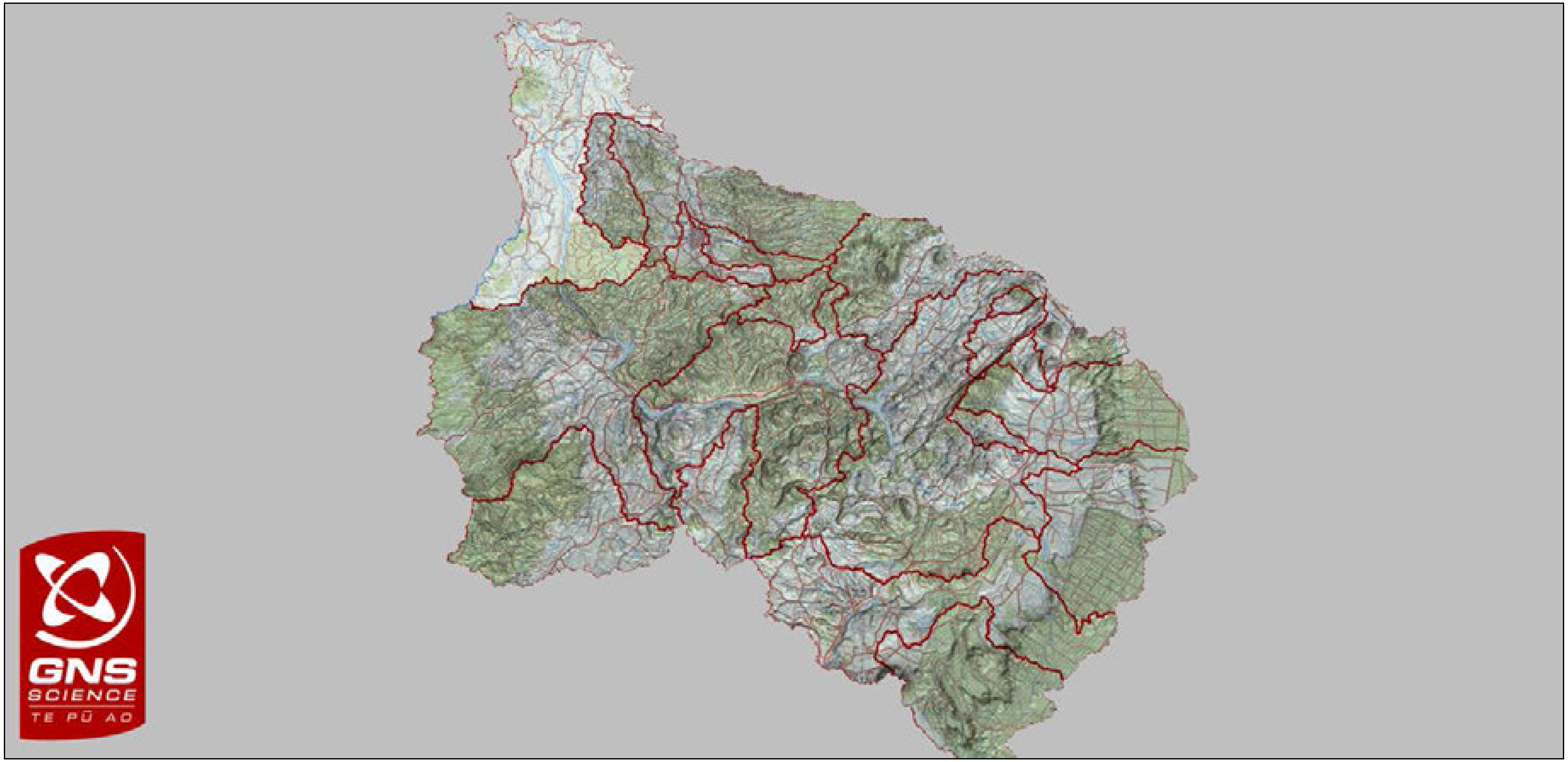

Figure A1.1: Zone: Upper Waikato River. Catchment: Waikato at Karapiro, 3020656.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is unlikely. The water table is typically in the Pakaumanu Group. Water tables are typically deeper than 3 m. Many small streams flow to the Waikato River and its lakes. However, generally, stream valleys are dry above lake level to the east of the river. Median nitrate concentrations in groundwater can be greater than MAV.

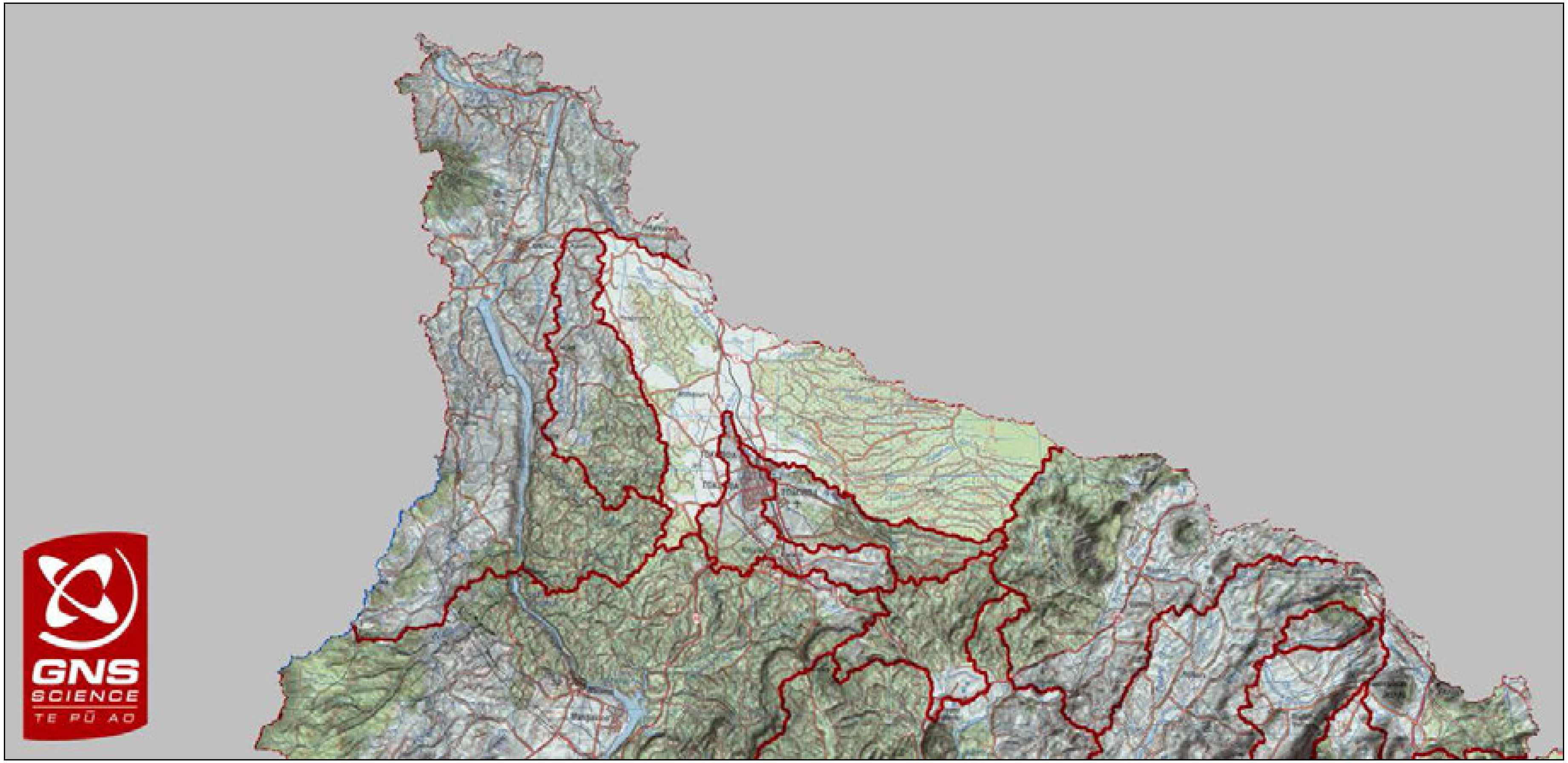

Figure A1.2: Zone: Upper Waikato River. Catchment: Pokaiwhenua, 3023849.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Whakamaru Group. Water tables are typically deeper than 3 m. Spring-fed streams drain the Mamaku Plateau across the catchment. Median nitrate concentrations in groundwater can be greater than 1/2 MAV.

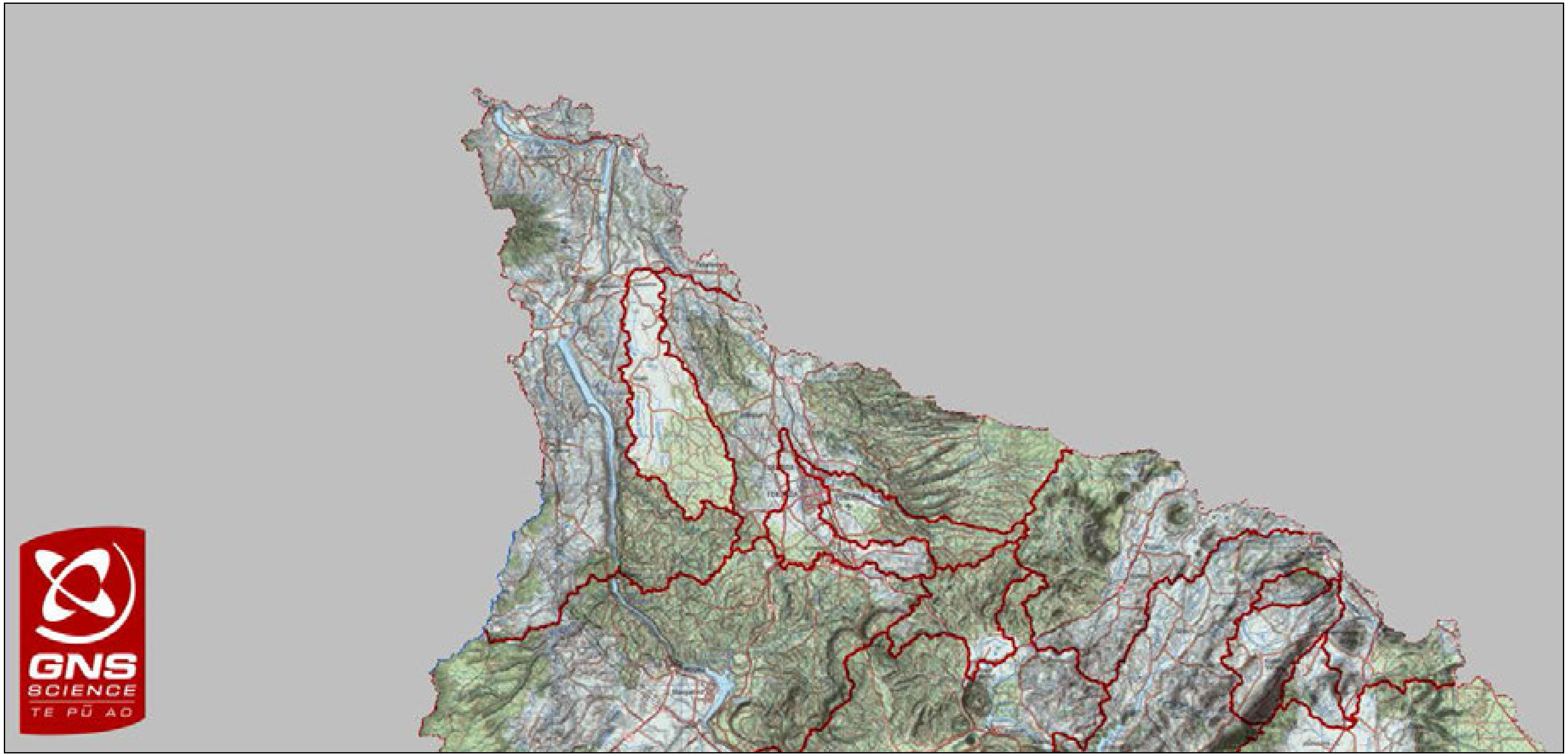

Figure A1.3: Zone: Upper Waikato River. Catchment: Little Waipa, 3023862.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Whakamaru Group. Water tables are typically deeper than 3 m. Groundwater outflow from the catchment may flow to the Waikato River as springs were observed at river level before the construction of the hydro-electric power dam. Median nitrate concentrations in groundwater can be greater than 1/2 MAV.

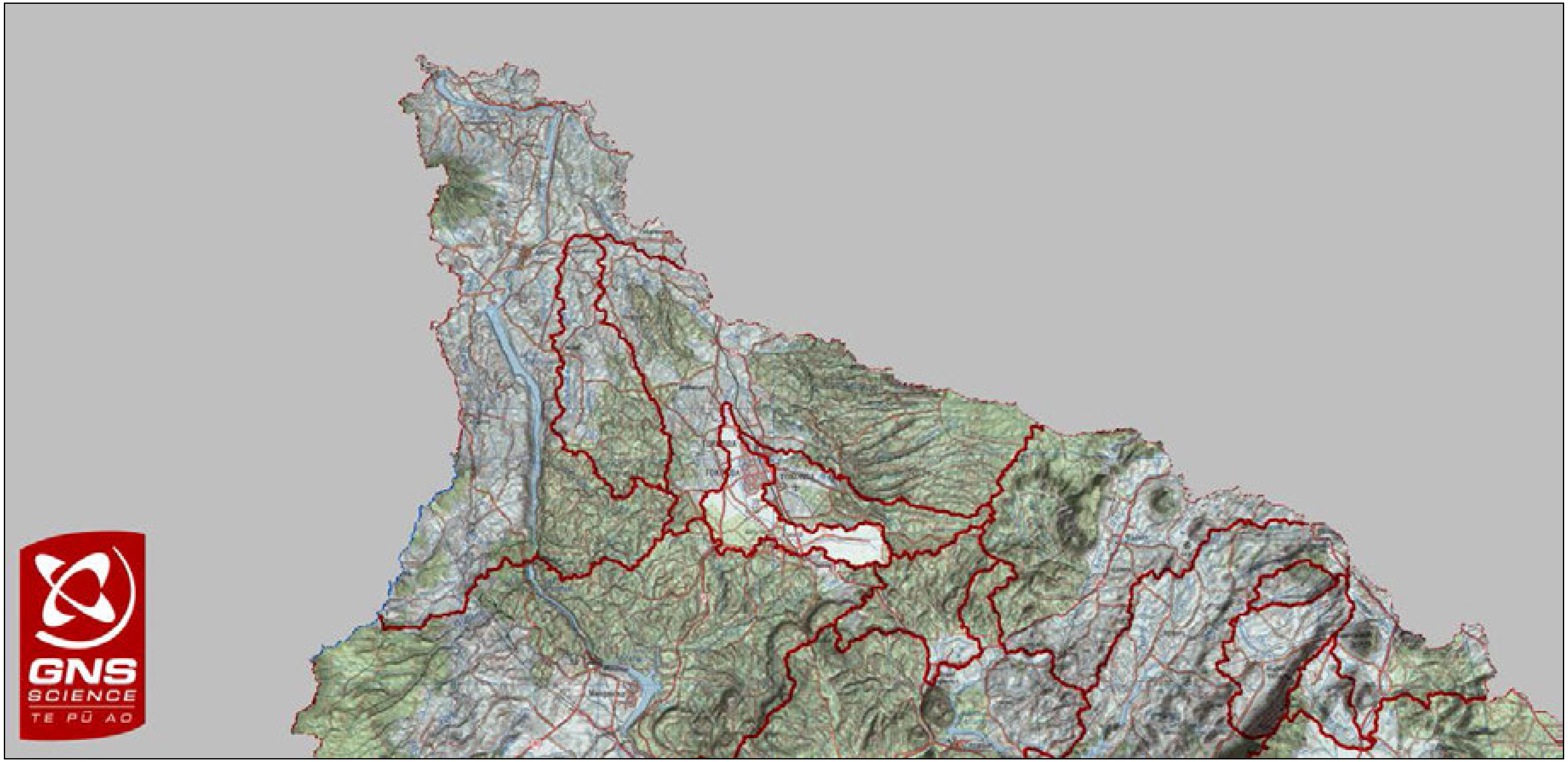

Figure A1.4: Zone: Upper Waikato River. Catchment: Mangamingi, 3027230.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Whakamaru Group. Water tables are typically deeper than 3 m. Spring-fed streams cross the catchment but generally the stream beds are dry. Median nitrate concentrations in groundwater can be greater than MAV.

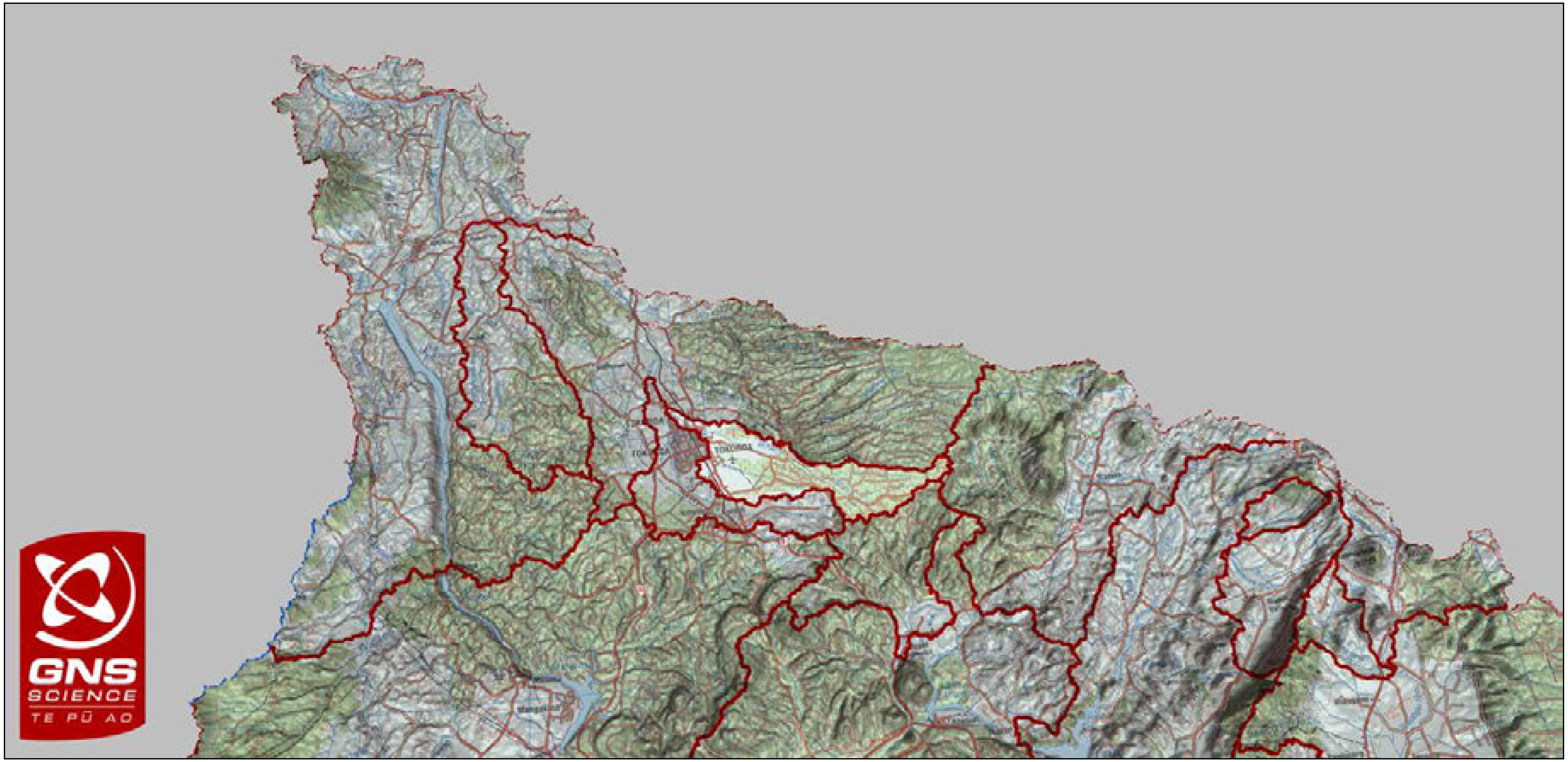

Figure A1.5: Zone: Upper Waikato River. Catchment: Whakauru, 3027821.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Whakamaru Group. Water tables are typically deeper than 3 m. Spring-fed streams cross the catchment but generally the stream beds are dry. Median nitrate concentrations in groundwater are low in this catchment.

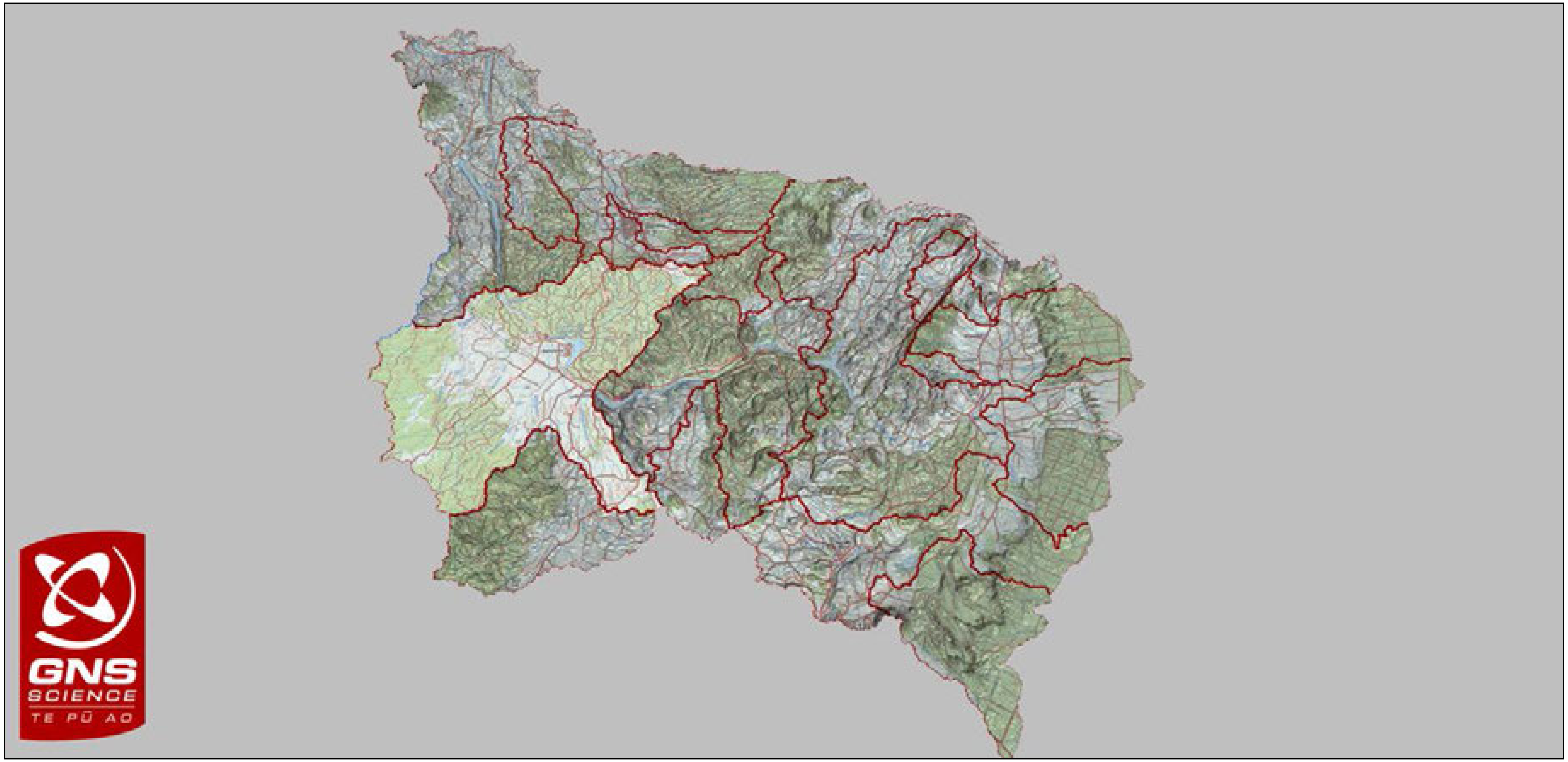

Figure A1.6: Zone: Upper Waikato River. Catchment: Waikato at Waipapa, 3030247.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is unlikely. The water table is typically in the Whakamaru Group. Water tables are typically deeper than 3 m. Many small streams flow to the Waikato River and its lakes. Generally, stream valleys are dry to the east of the river. Median nitrate concentrations in groundwater can be greater than 1/2 MAV.

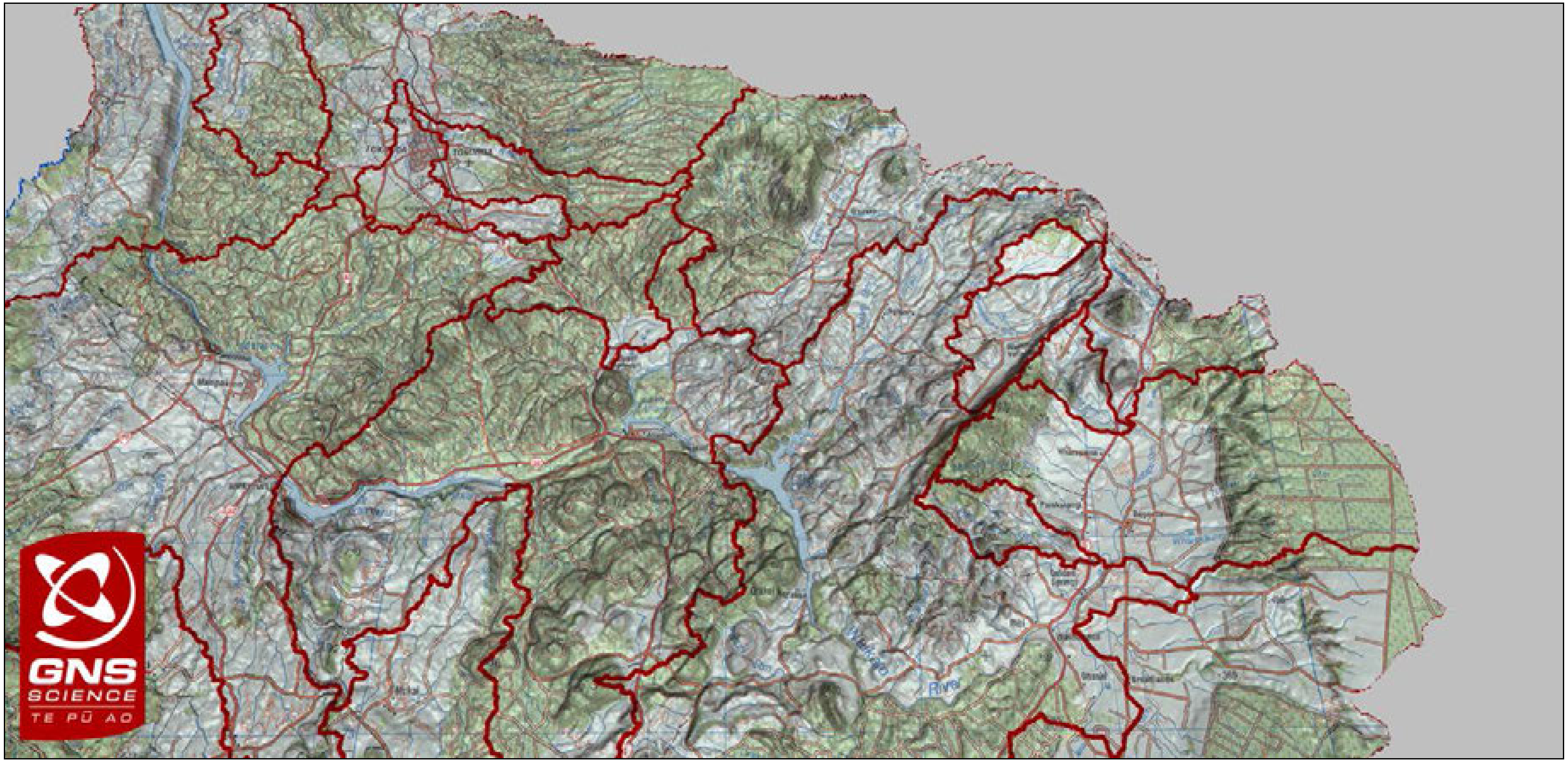

Figure A1.7: Zone: Upper Waikato River. Catchment: Whirinaki, 3031392.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is unlikely. The water table is typically in the Rotoiti Formation. Water tables are typically deeper than 3 m. The catchment drains Rotoiti Formation and Whakamaru ignimbrite. The Waikiti geothermal field is within this catchment. Median nitrate concentrations in groundwater can be greater than MAV.

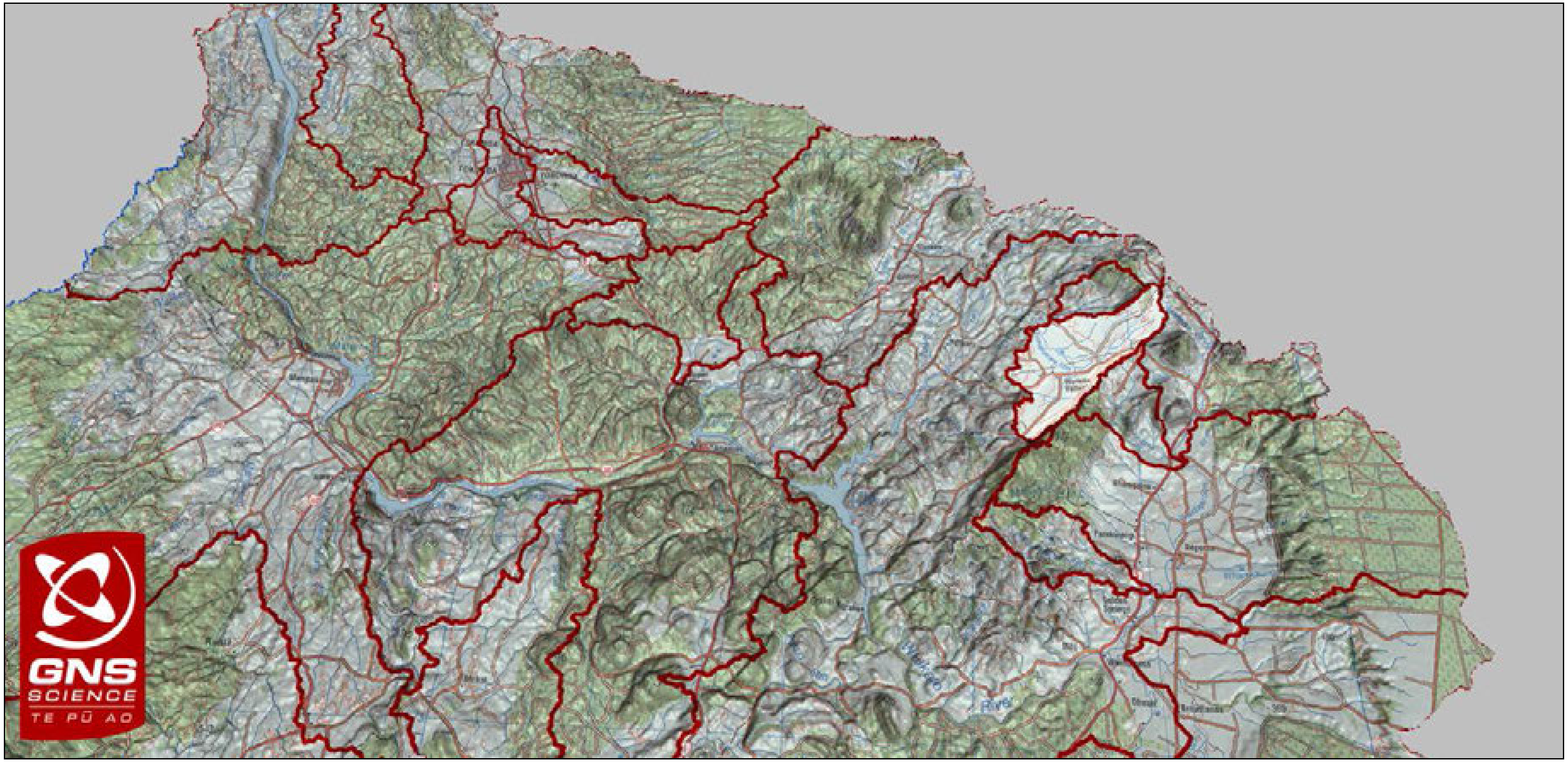

Figure A1.8: Zone: Upper Waikato River. Catchment: Otamakokore, 3031549.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is unlikely. The water table is typically in the Rotoiti Formation. Water tables are typically deeper than 3 m. The catchment drains Rotoiti Formation and Whakamaru ignimbrite. The Waikiti geothermal field is within this catchment. Median nitrate concentrations in groundwater can be greater than MAV.

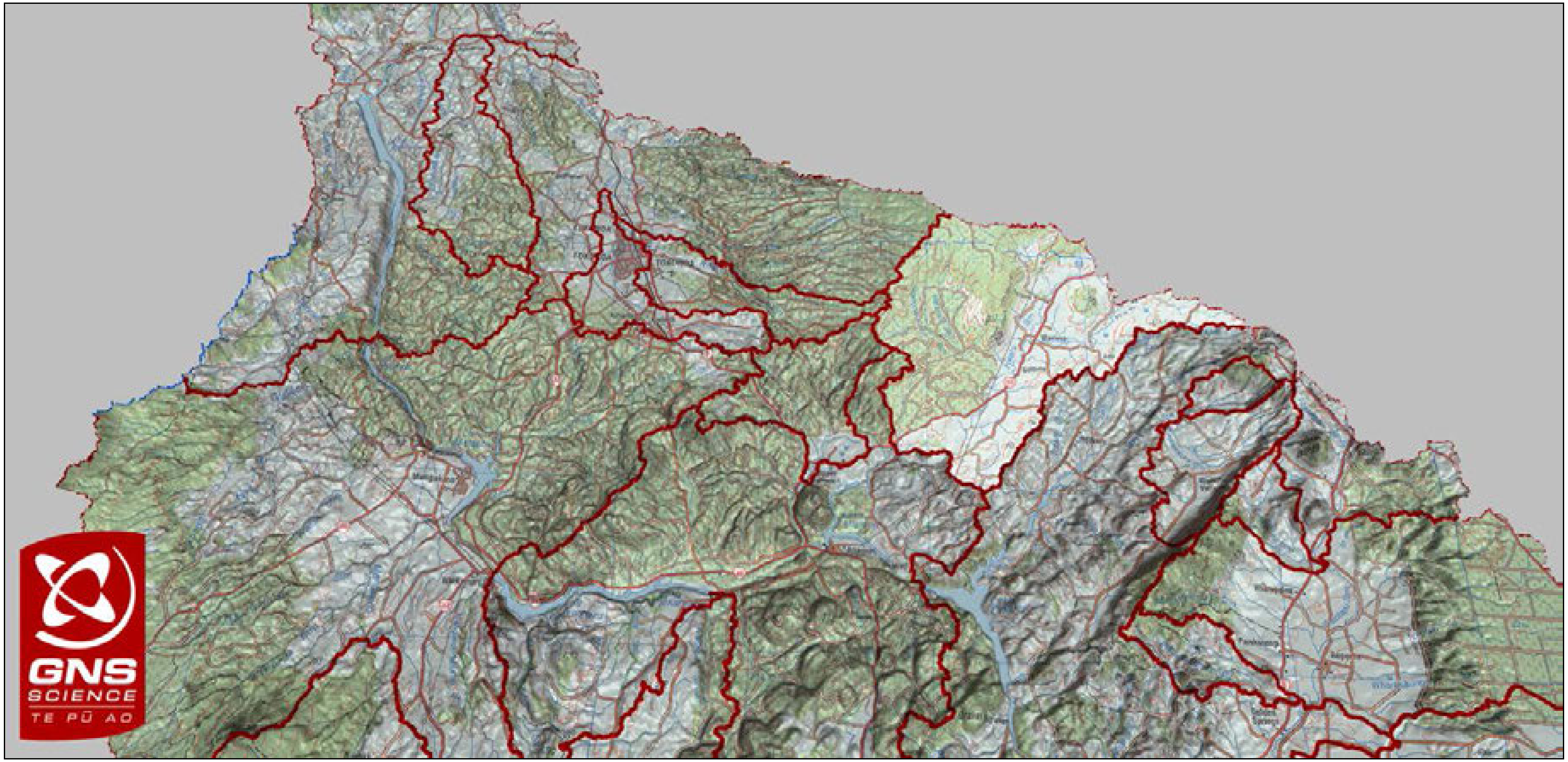

Figure A1.9: Zone: Upper Waikato River. Catchment: Tahunaatara, 3032435.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Aquifers in this catchment drains from the Mamaku Plateau, including Horohoro. Many small valleys are dry above the Waikato River. Median nitrate concentrations in groundwater are low in this catchment.

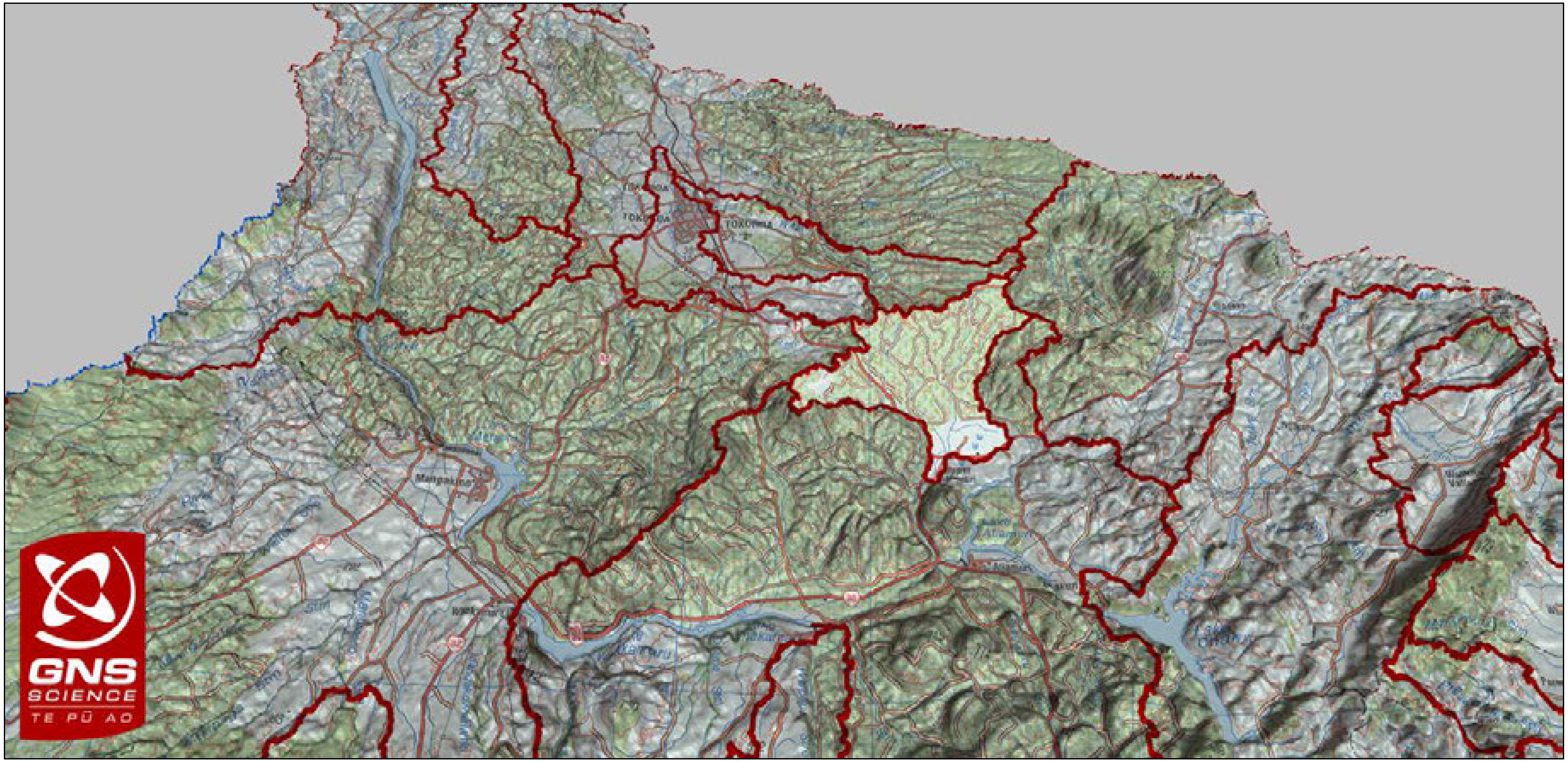

Figure A1.10: Zone: Upper Waikato River. Catchment: Mangaharakeke, 3032678.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Ohakuri Formation. Water tables are typically deeper than 3 m. This catchment drains from the southern end of the Mamaku Plateau. Many small valleys are dry in the catchment. No wells measure groundwater chemistry in this catchment.

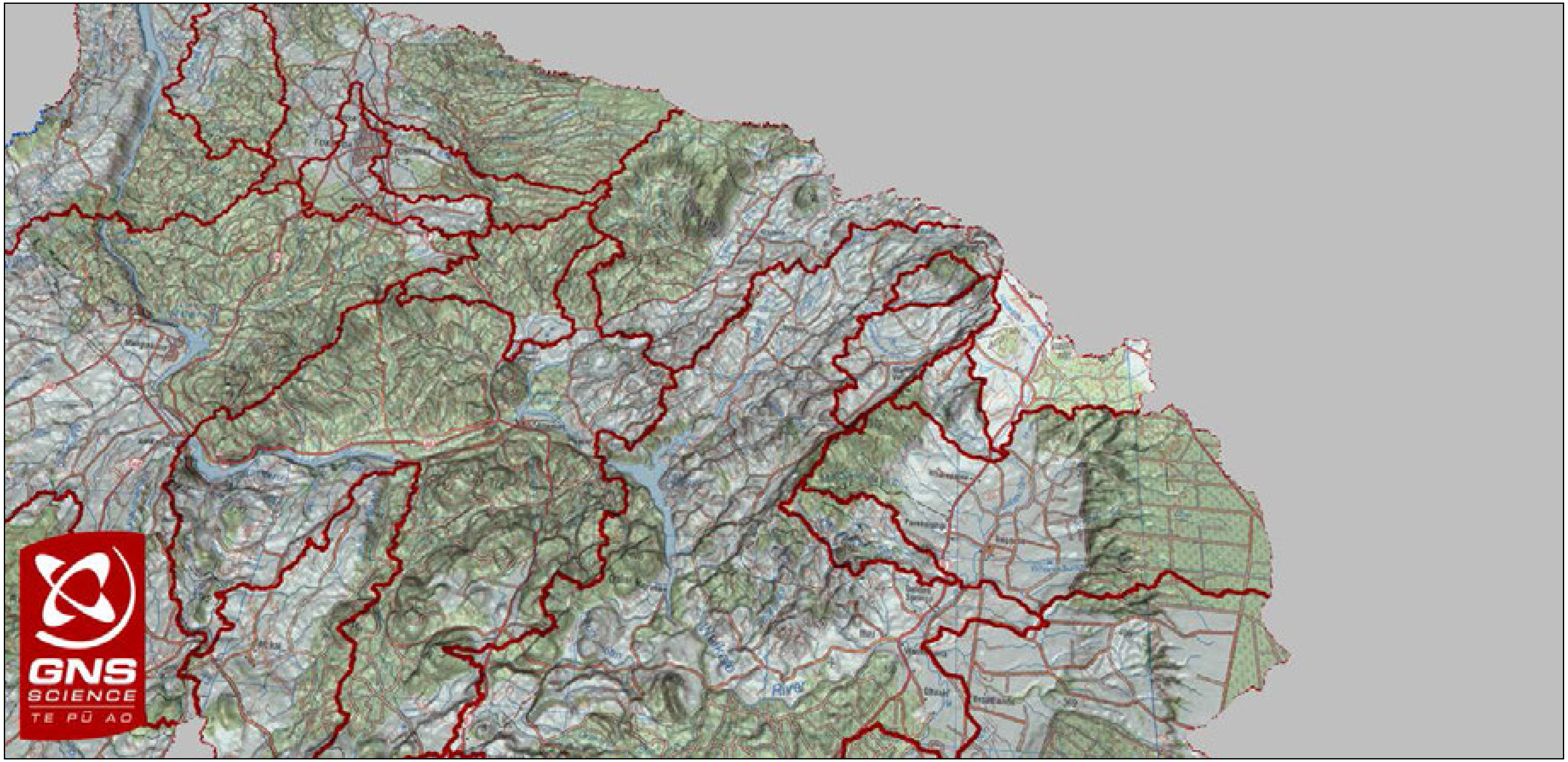

Figure A1.11: Zone: Upper Waikato River. Catchment: Waiotapu at Campbell, 3034280.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is unlikely. The water table is typically in the Rotoiti Formation. Water tables are typically deeper than 3 m. The catchment drains relatively young in the north and the Kaingaroa Plateau (in the east). The Waiotapu Geothermal field is located in the catchment. Groundwater velocities will be low across the Reporoa Basin. Median nitrate concentrations in groundwater are low in this catchment.

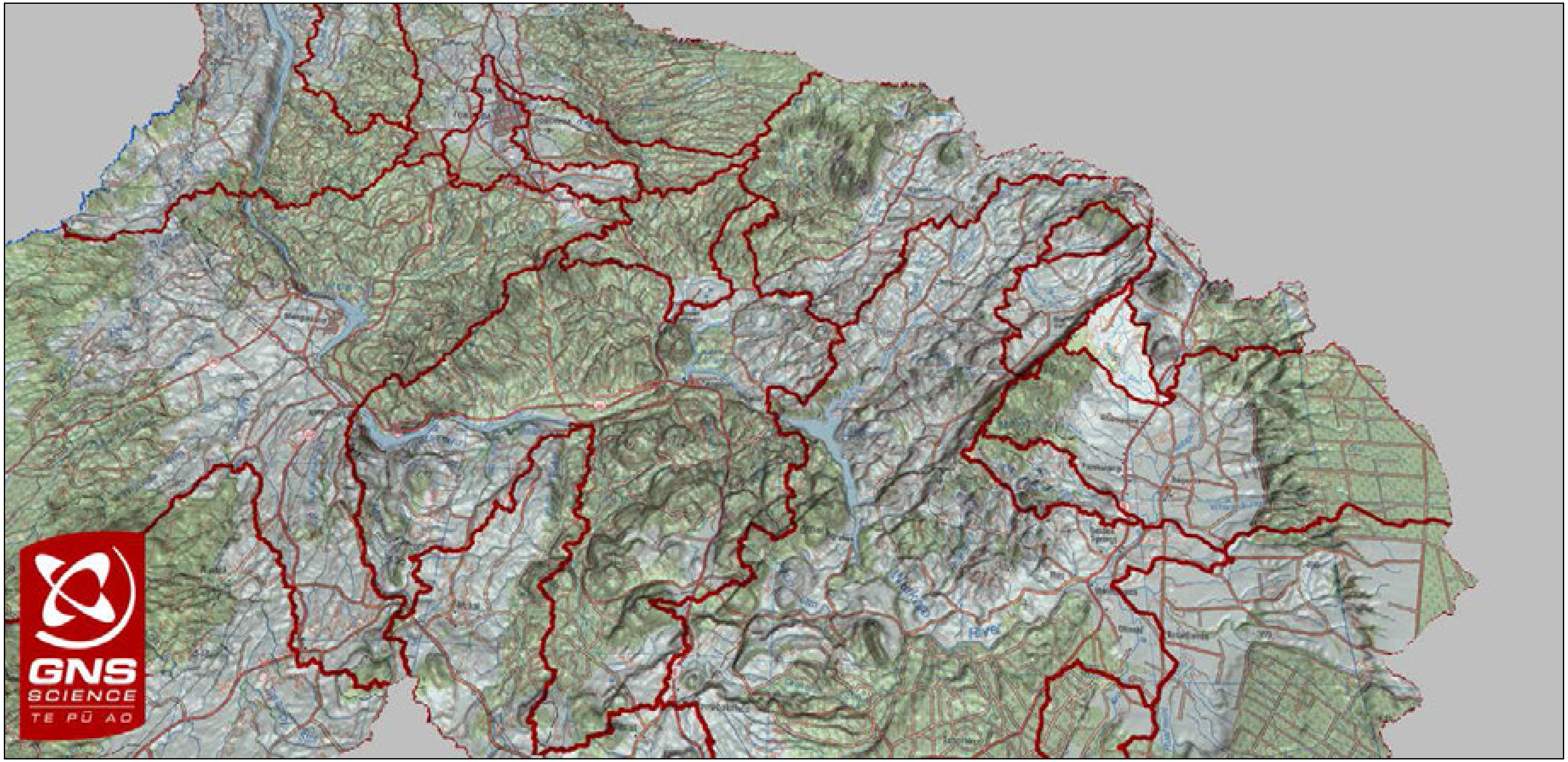

Figure A1.12: Zone: Upper Waikato River. Catchment: Kawaunui, 3034452.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. The catchment drains from the Paeroa Range to the Reporoa Basin. Median nitrate concentrations in groundwater are low in this catchment.

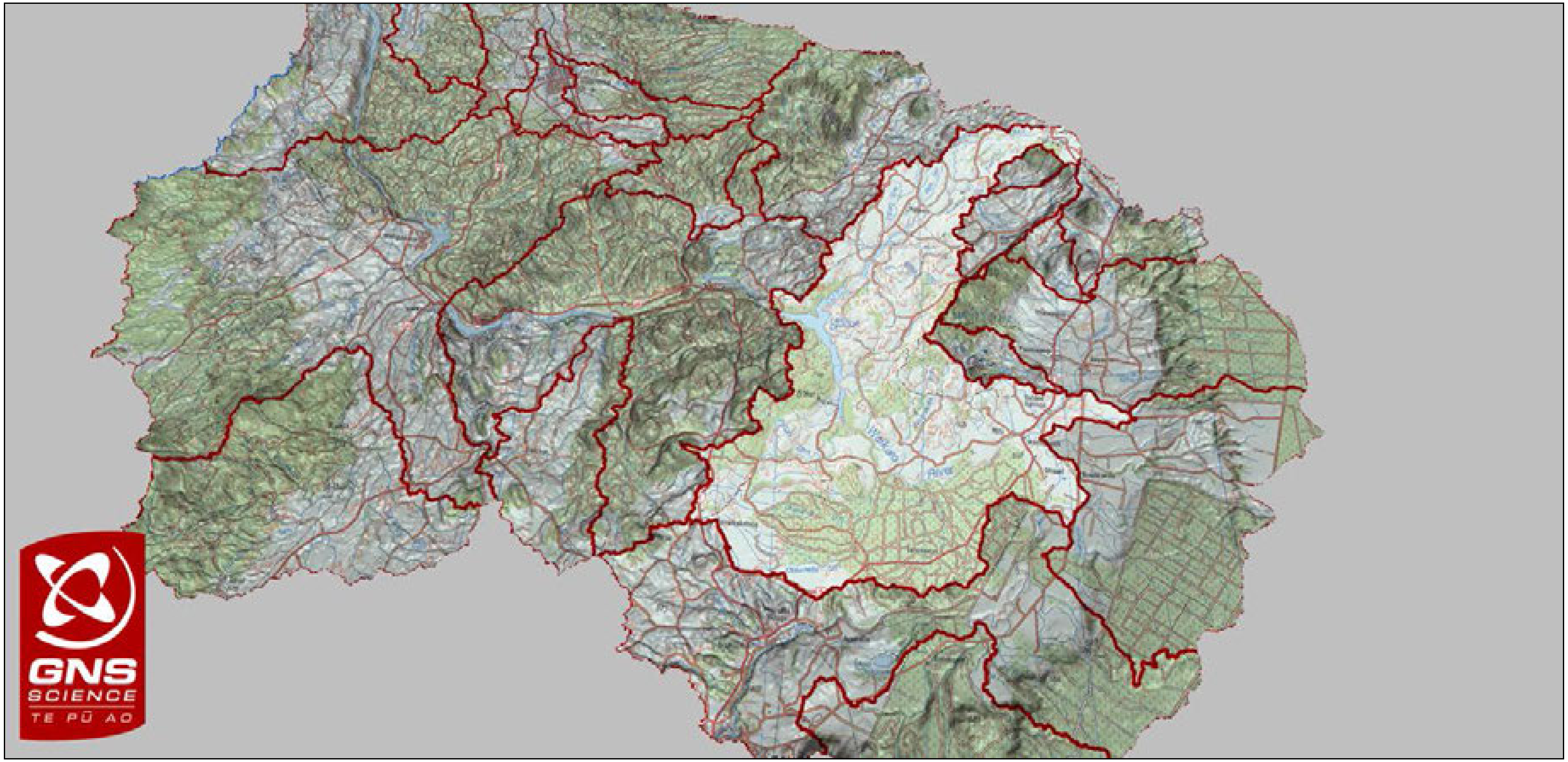

Figure A1.13: Zone: Upper Waikato River. Catchment: Waikato at Ohakuri, 3035123.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is unlikely. The water table is typically in the Tauranga Group and volcanic lithologies. Water tables are typically deeper than 3 m. Many small streams flow into the Waikato River. Many small valleys are dry above the Waikato River. The catchment includes geothermal fields (Orakei Korako and Ngatamariki). Median nitrate concentrations in groundwater can be greater than 1/2 MAV.

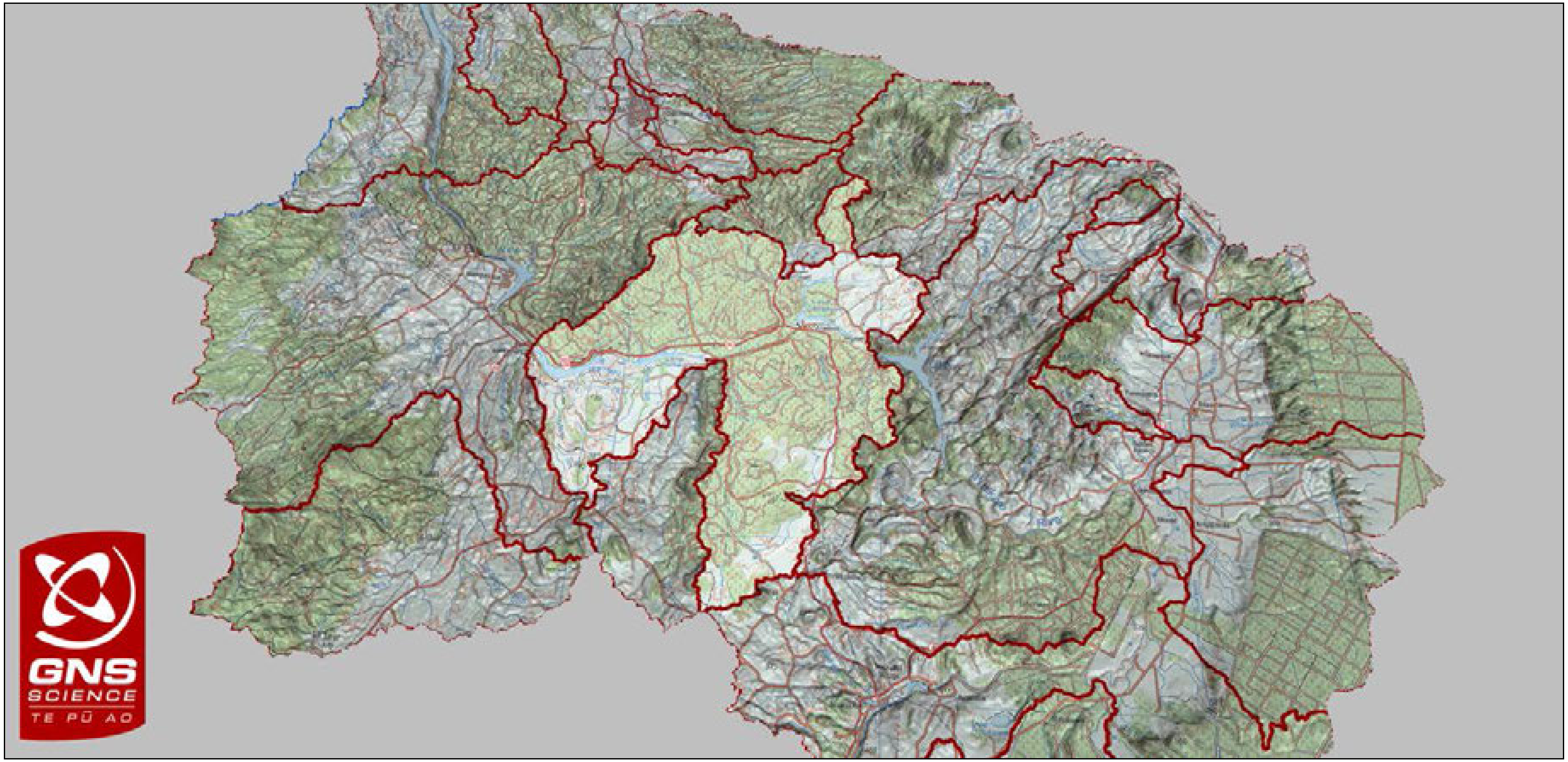

Figure A1.14: Zone: Upper Waikato River. Catchment: Waikato at Whakamaru, 3035301.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is unlikely. The water table is typically in the ignimbrite. Water tables are typically deeper than 3 m. Many small stream valleys are dry above the Waikato River. The catchment includes many domes of the Maroa Volcanic Centre. Median nitrate concentrations in groundwater can be greater than 1/2 MAV.

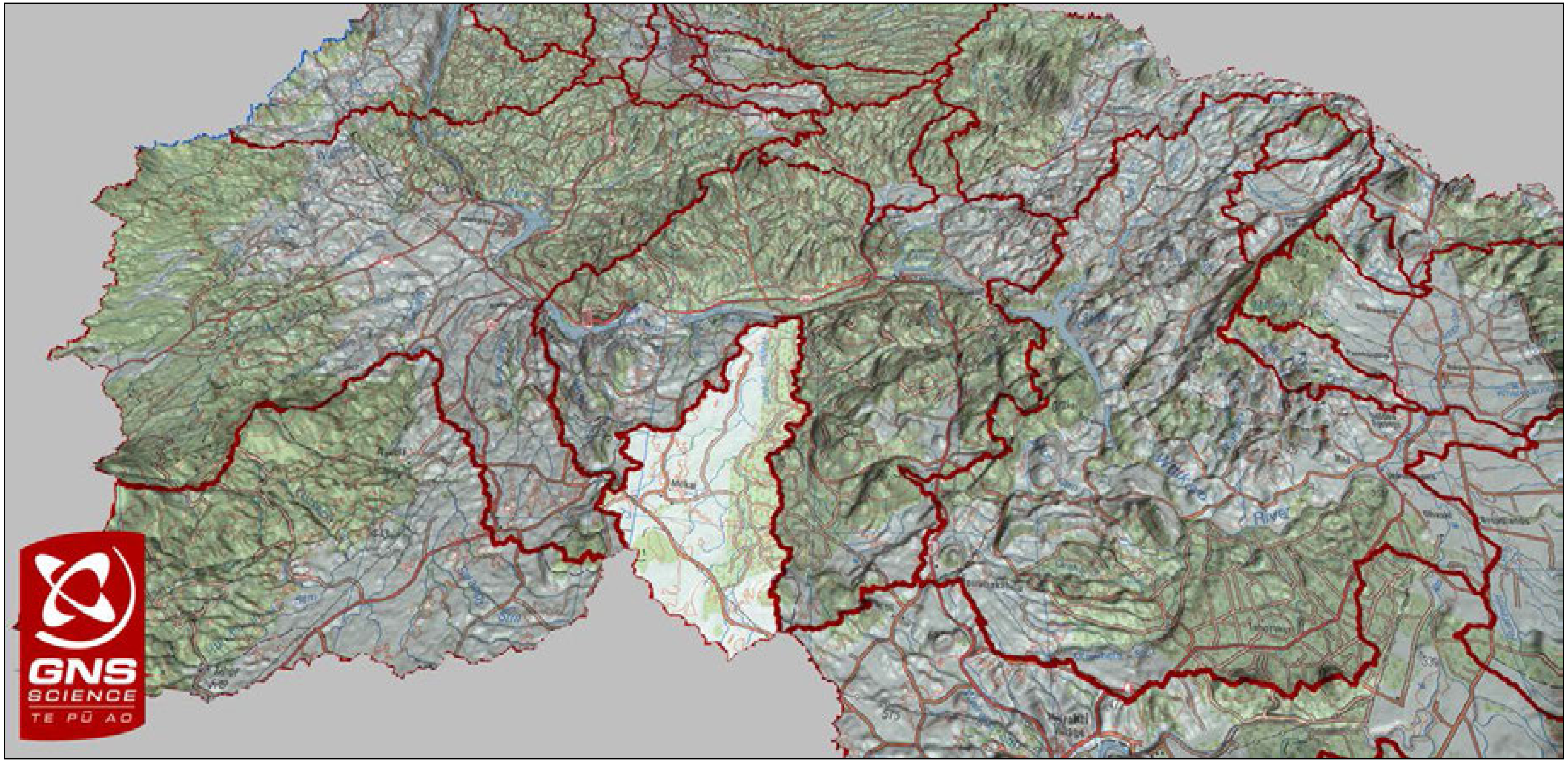

Figure A1.15: Zone: Upper Waikato River. Catchment: Waipapa, 3035556.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Mokai Formation. Water tables are typically deeper than 3 m. Many small stream valleys are dry above approximately the elevation of Mokai. The catchment includes the Mokai geothermal field. Median nitrate concentrations are elevated, up to 1/2 MAV.

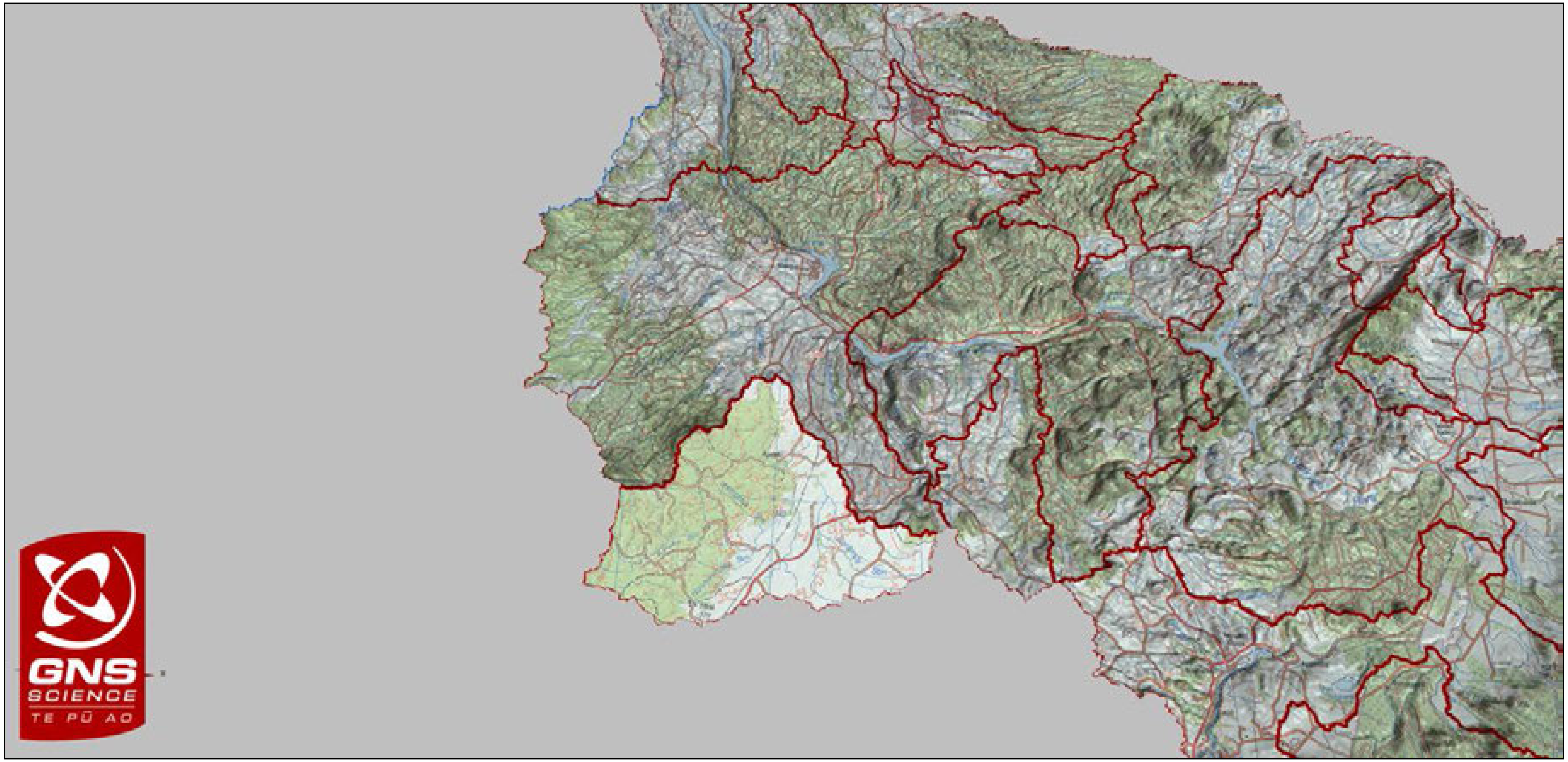

Figure A1.16: Zone: Upper Waikato River. Catchment: Mangakino, 3036710.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Whakamaru Group. Water tables are typically deeper than 3 m. Stream beds are typically dry in their upper reaches. Median nitrate concentrations in groundwater can be greater than 1/2 MAV.

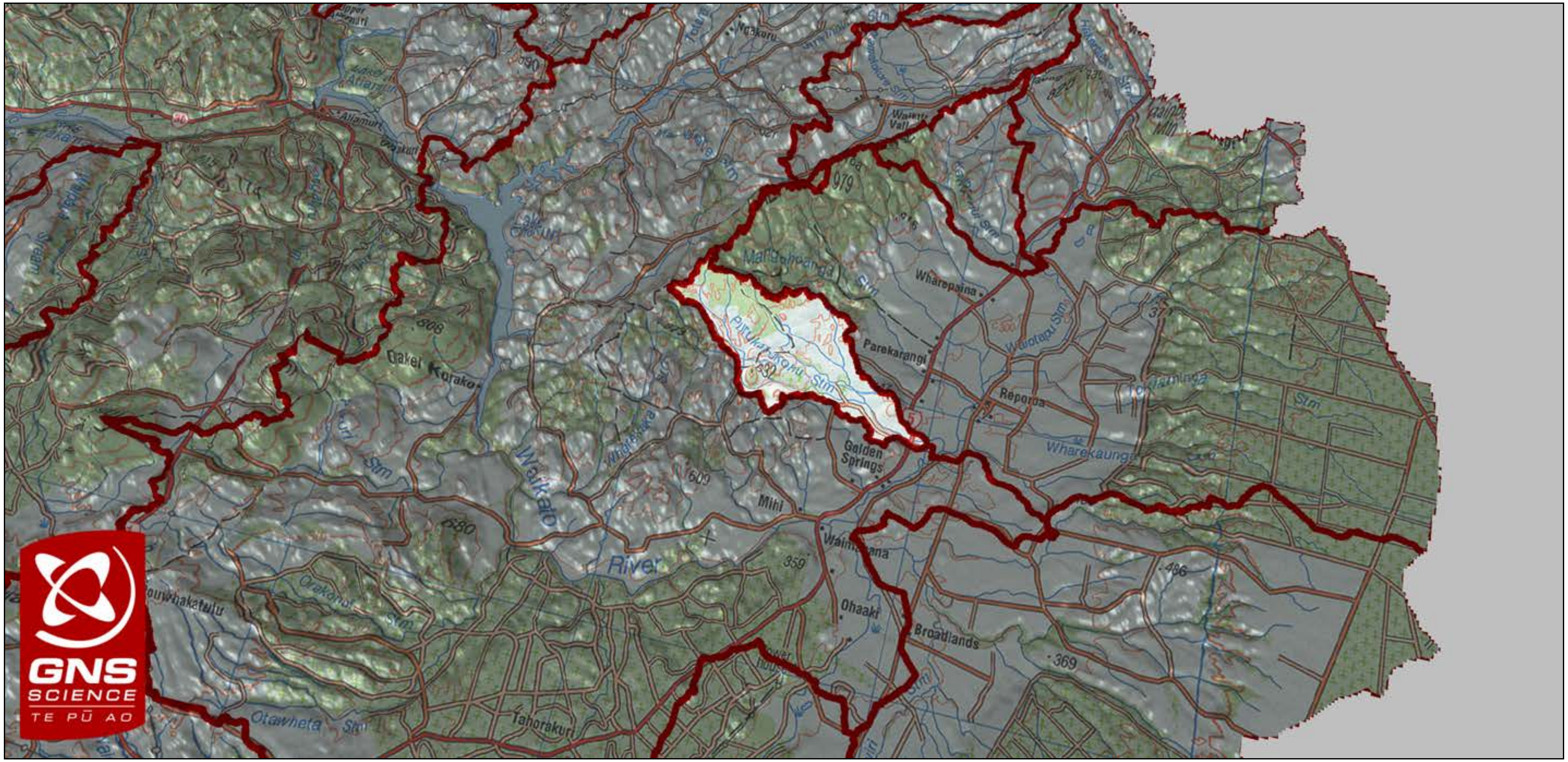

Figure A1.17: Zone: Upper Waikato River. Catchment: Mangakara, 3037027.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely towards Reporoa Stream. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. The catchment drains from the Paeroa Range to the Reporoa Basin. Median nitrate concentrations in groundwater can be greater than 1/2 MAV.

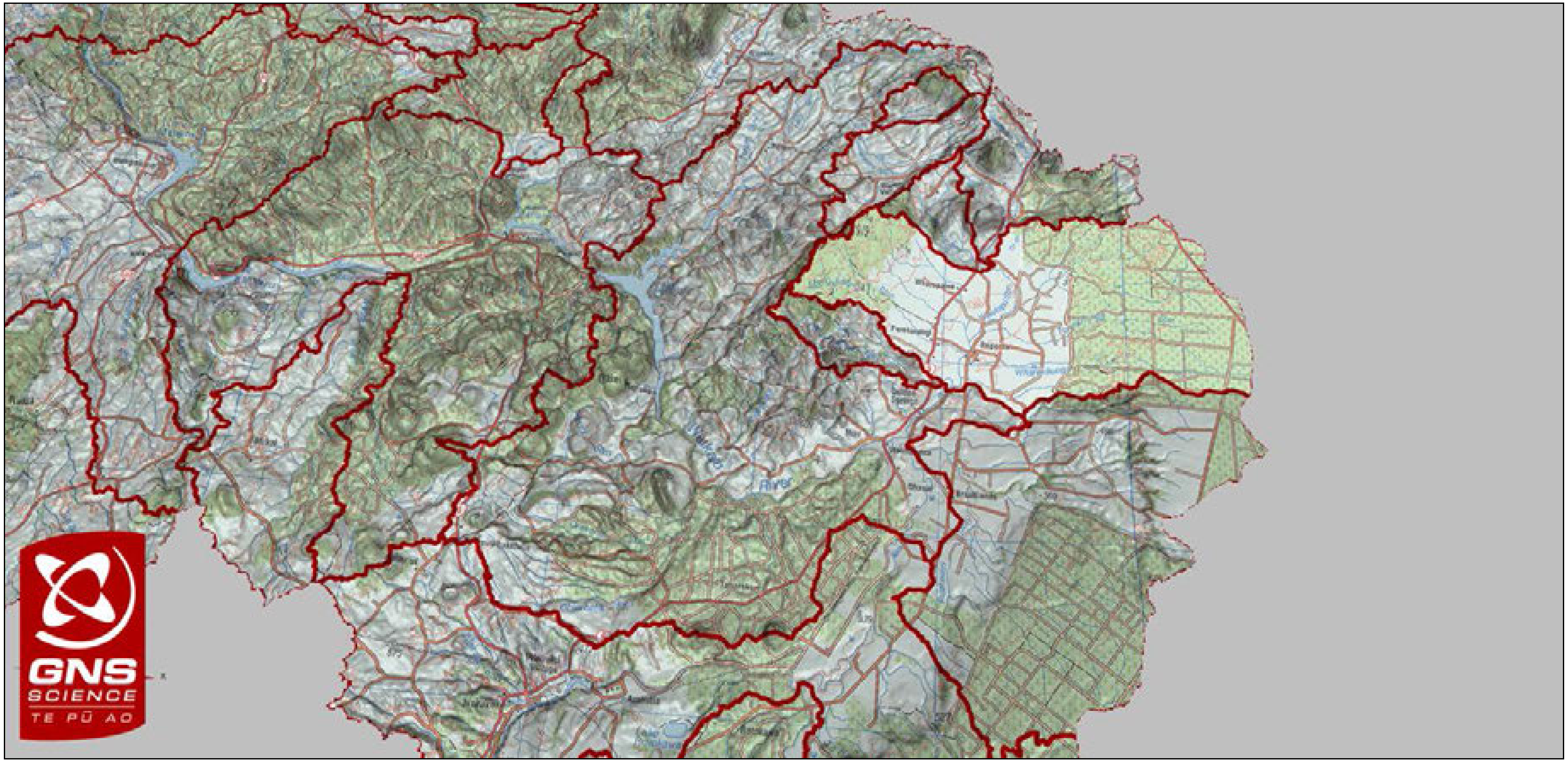

Figure A1.18: Zone: Upper Waikato River. Catchment: Waiotapu at Homestead, 3037105.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Aquifers drain the Kaingaroa Plateau to the east and the Paeroa Range to the west. Spring-fed streams cross the Reporoa Basin. Groundwater velocities will be low across the Reporoa Basin to the Waikato River.
Median nitrate concentrations in groundwater can be greater than 1/2 MAV.

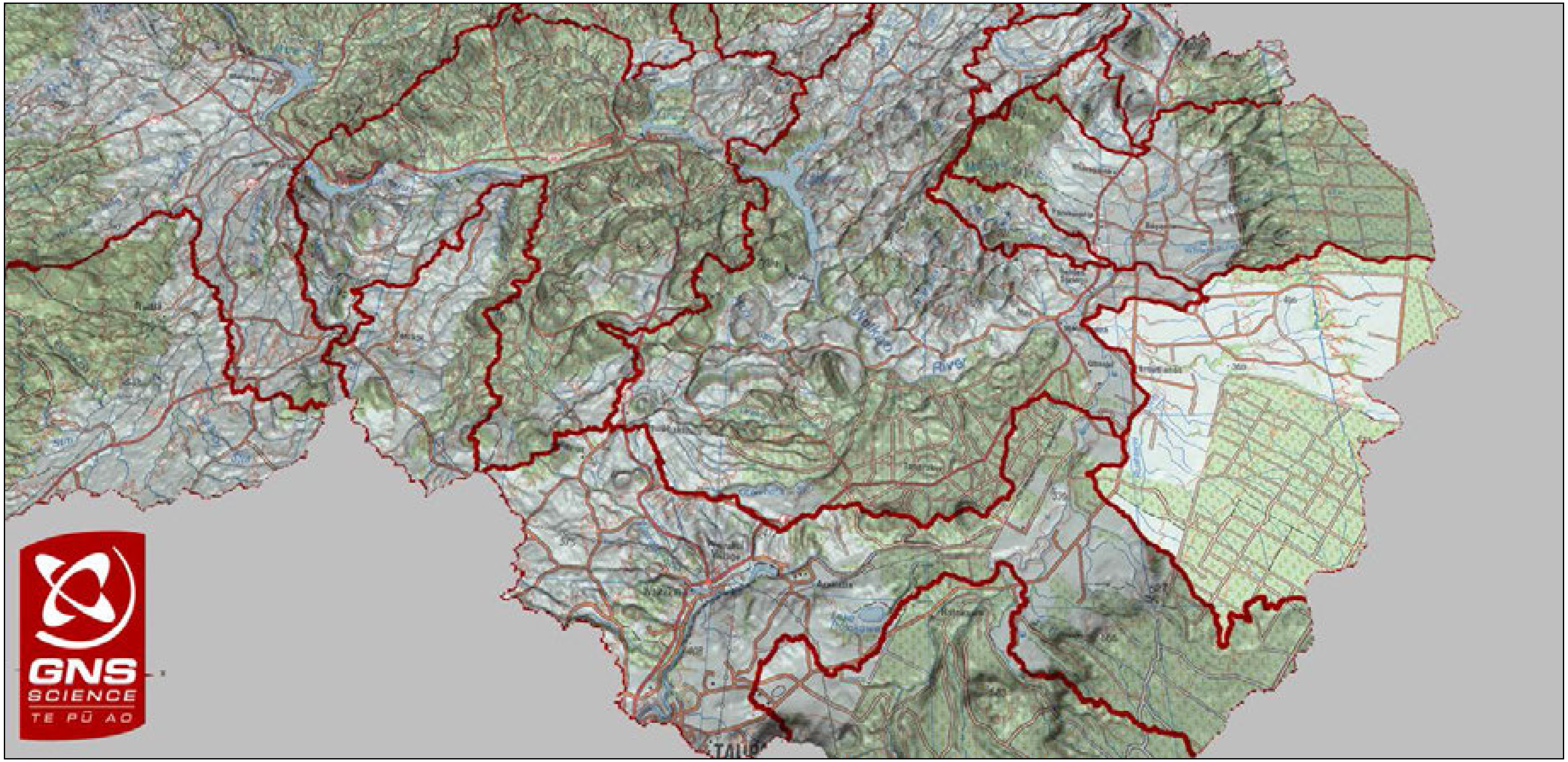

Figure A1.19: Zone: Upper Waikato River. Catchment: Torepatutahi, 3038300.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is unlikely. The water table is typically in the Whakamaru Group. Water tables are typically deeper than 3 m. Many small valleys are dry above the Reporoa Basin. Aquifers drain the Kaingaroa Plateau and spring-fed streams cross the Basin. Groundwater velocities will be low across the Reporoa Basin to the Waikato River. Median nitrate concentrations in groundwater can be greater than MAV.

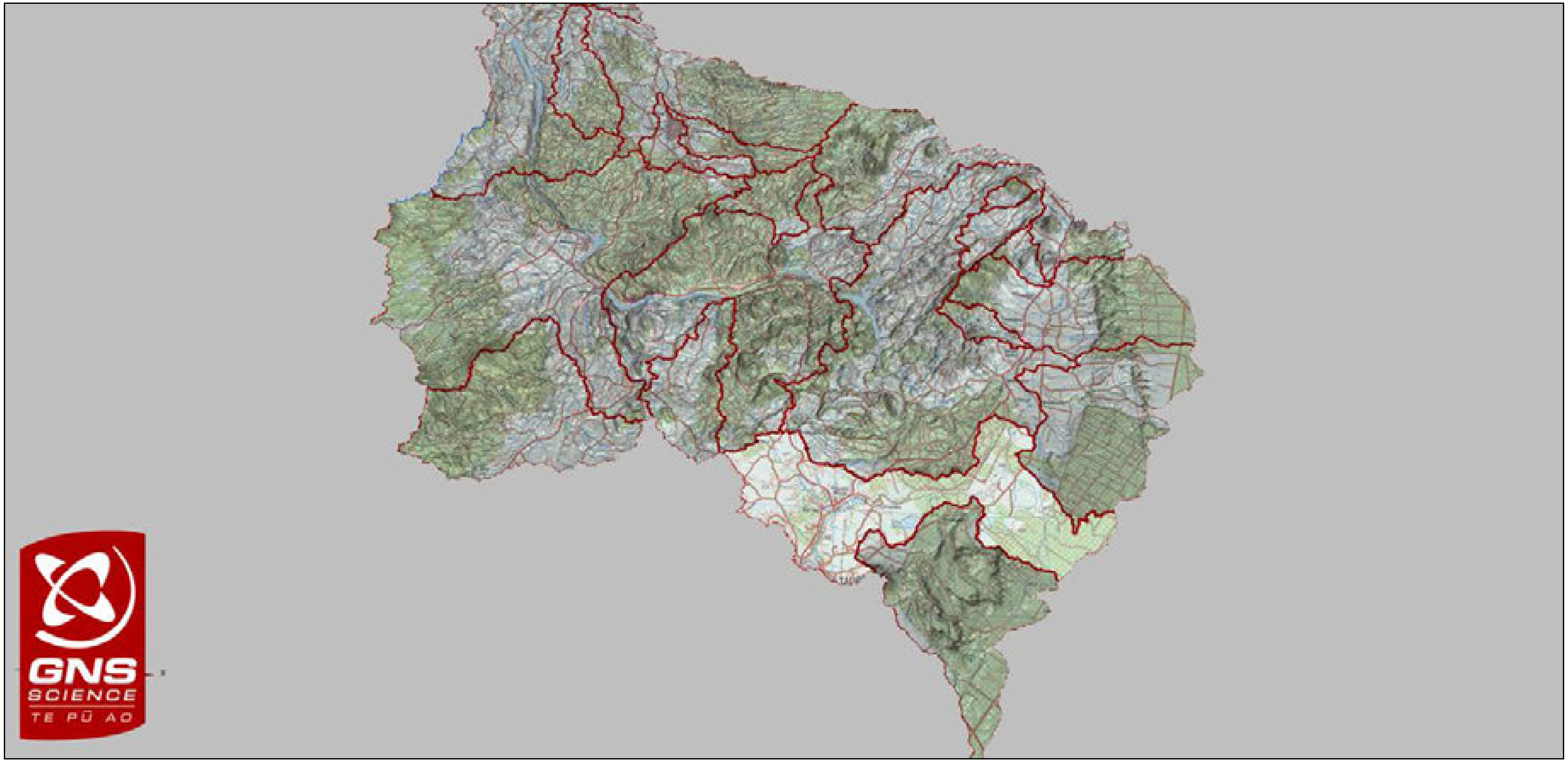

Figure A1.20: Zone: Upper Waikato River. Catchment: Waikato at Ohaaki, 3039804.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is unlikely. The water table is typically in the Oruanui Formation. Water tables are typically deeper than 3 m. Many small valleys are dry above the Waikato River. The catchment includes geothermal fields (Wairakei, Taupo and Rotokawa). Median nitrate concentrations in groundwater can be greater than MAV.

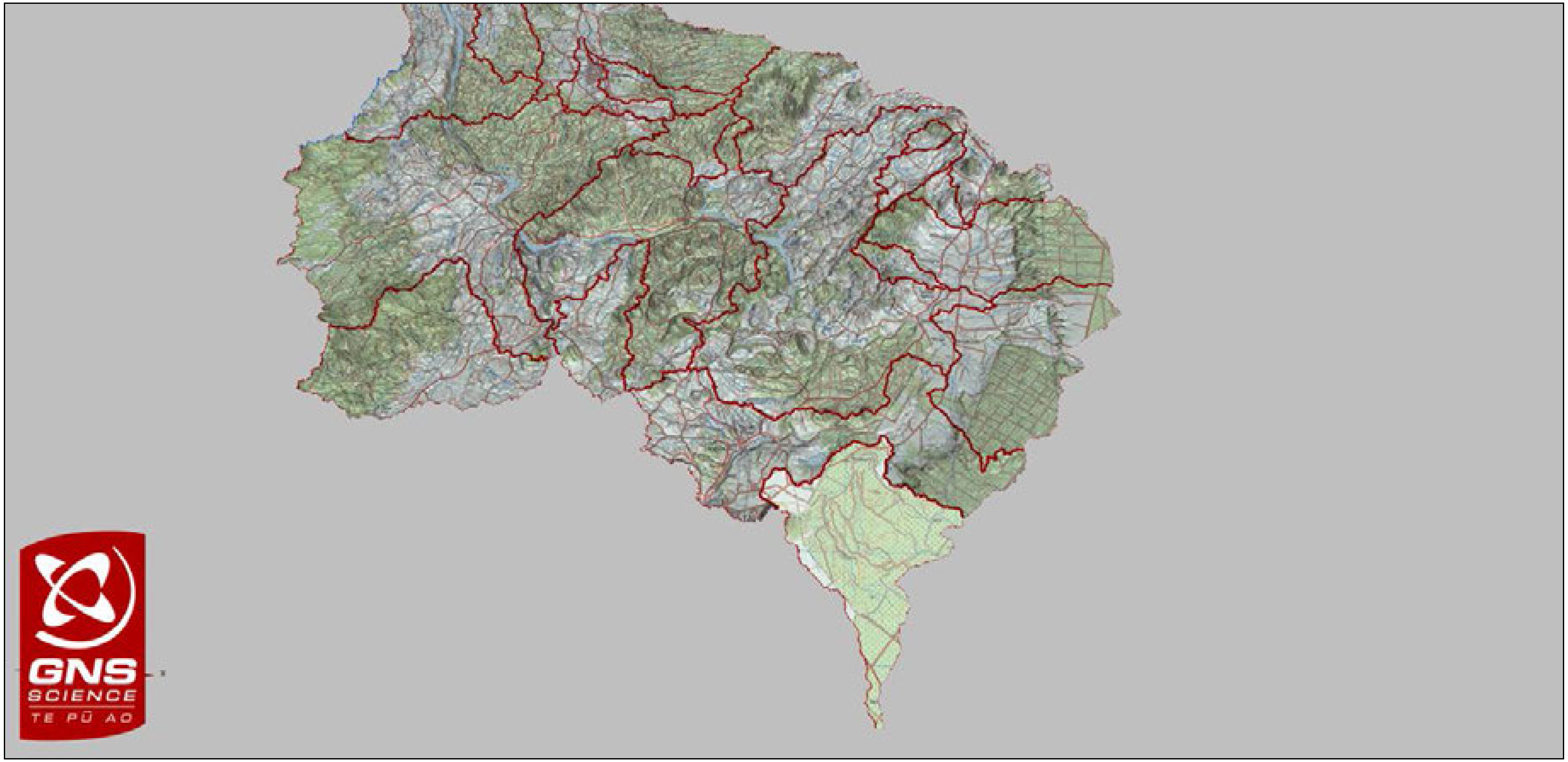

Figure A1.21: Zone: Upper Waikato River. Catchment: Pueto, 3042044.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is unlikely. The water table is typically in the Oruanui Formation. Water tables are typically deeper than 3 m. Aquifers drain the Kaingaroa Plateau and this recharge flows to Pueto Stream. Groundwater velocities will be low across the Broadlands valley to the Waikato River Median nitrate concentrations in groundwater can be greater than 1/2 MAV.

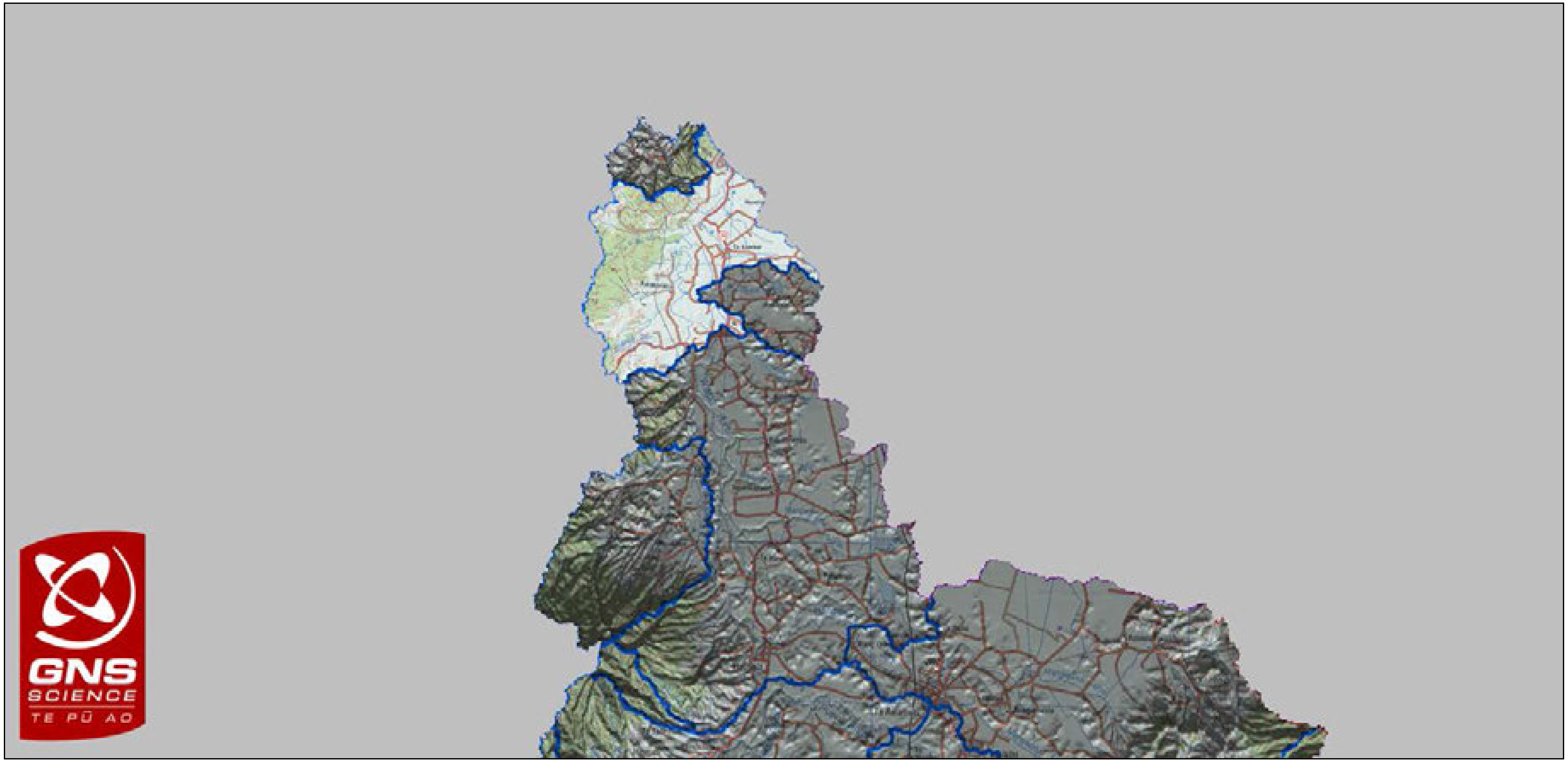

Figure A1.22: Zone: Waipa River. Catchment: Waipa at Waingaro Rd Br, 3015066.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is unlikely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Tauranga Group sediments include sands where infiltration is moderate and drained peats to the east, where infiltration is slow. Median nitrate concentrations in groundwater can be greater than 1/2 MAV.

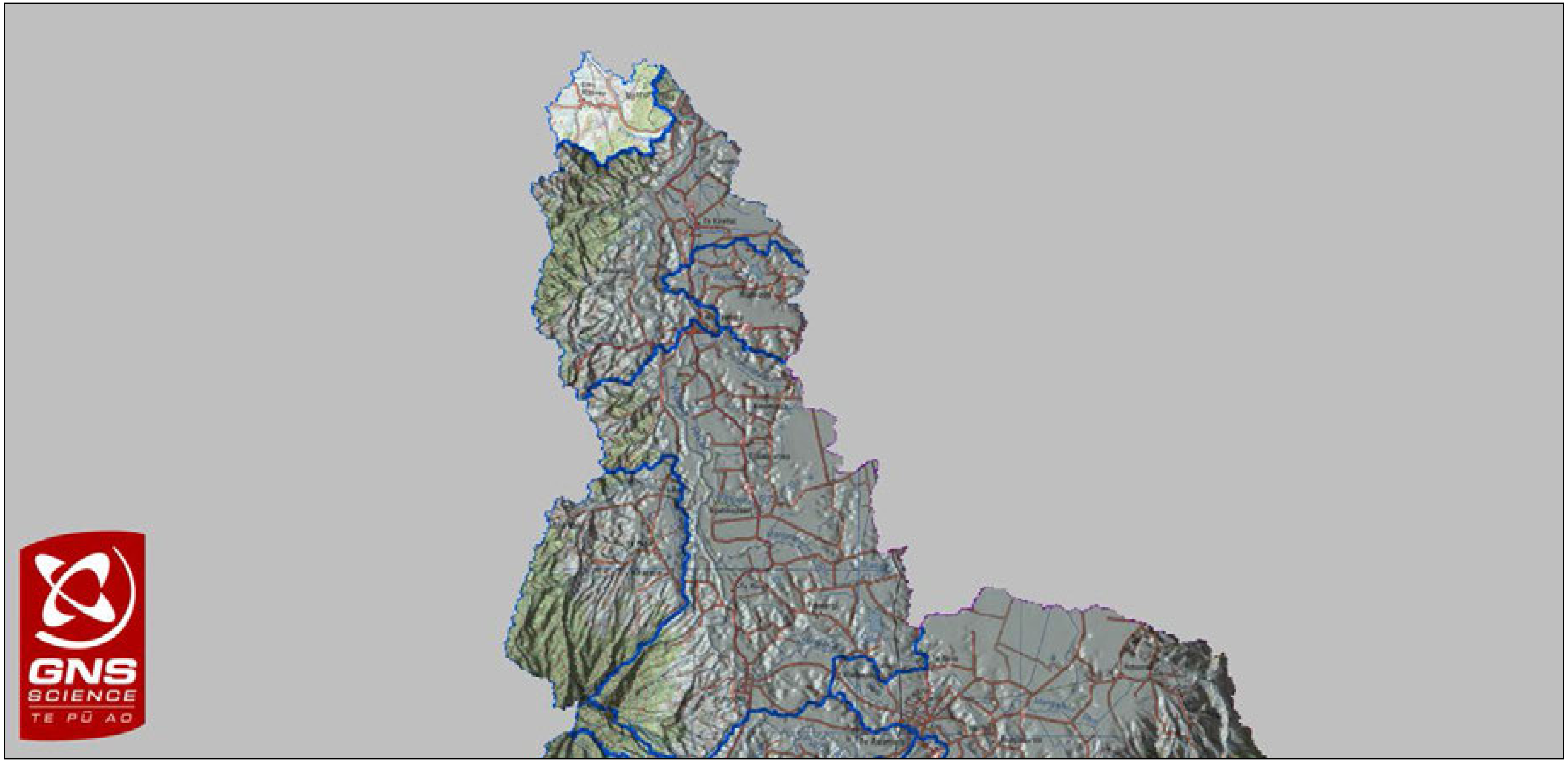

Figure A1.23: Zone: Waipa River. Catchment: Firewood, 3015451.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Basement (Murihiku terrane). Water tables are typically deeper than 3 m. Drainage is rapid as topographic gradients are high. Median nitrate concentrations in groundwater are low in this catchment.

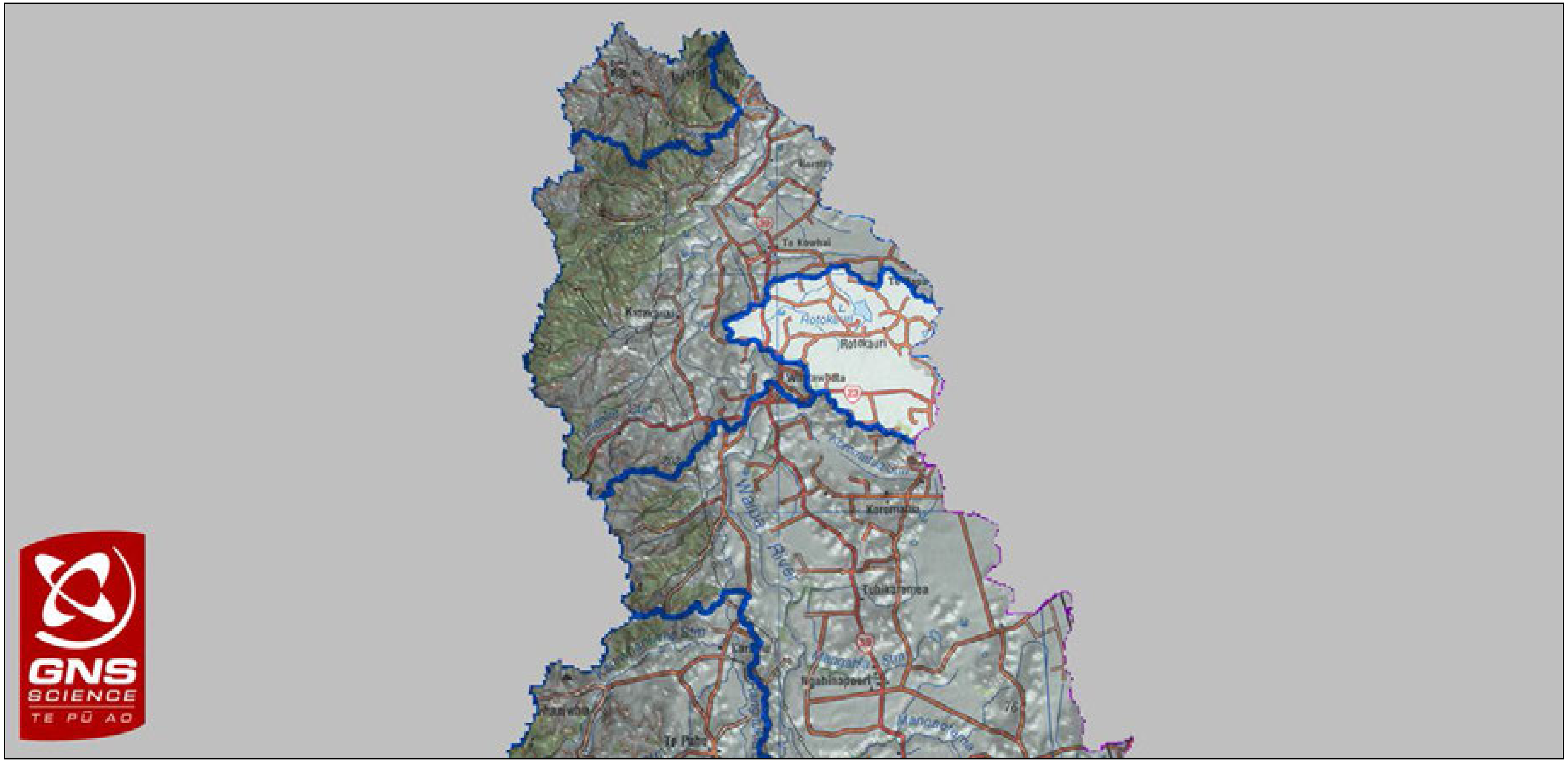

Figure A1.24: Zone: Waipa River. Catchment: Ohote, 3017348.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Tauranga Group sediments include volcanogenic sands where infiltration is moderate and drained peats, where infiltration is slow. Median nitrate concentrations in groundwater are low in this catchment.

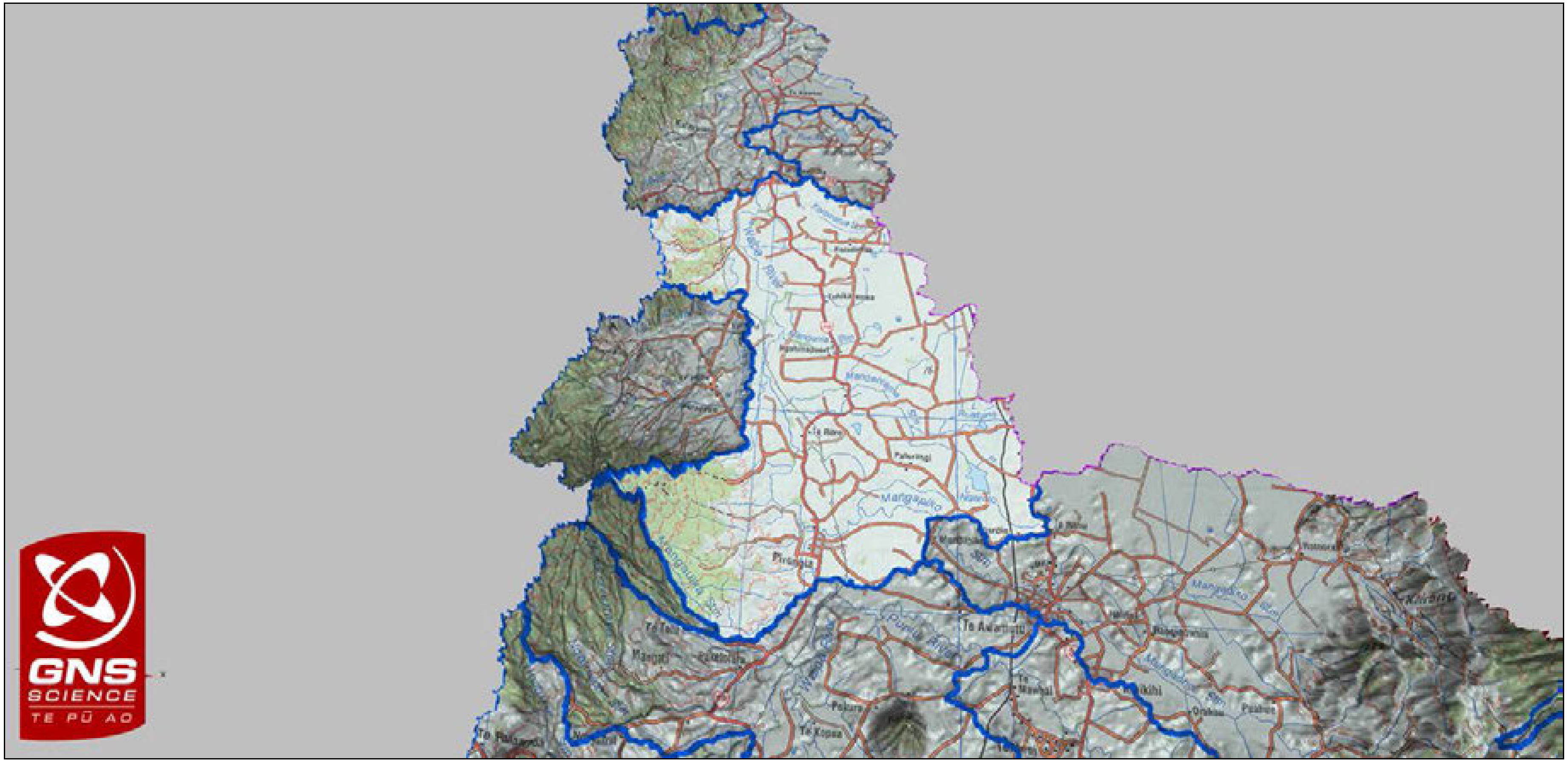

Figure A1.25: Zone: Waipa River. Catchment: Waipa at SH23 Br Whatawhata, 3017829.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is unlikely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Tauranga Group sediments include Hinuera Formation where infiltration is relatively rapid and drained peats, where infiltration is slow. Median nitrate concentrations in groundwater can be greater than MAV.

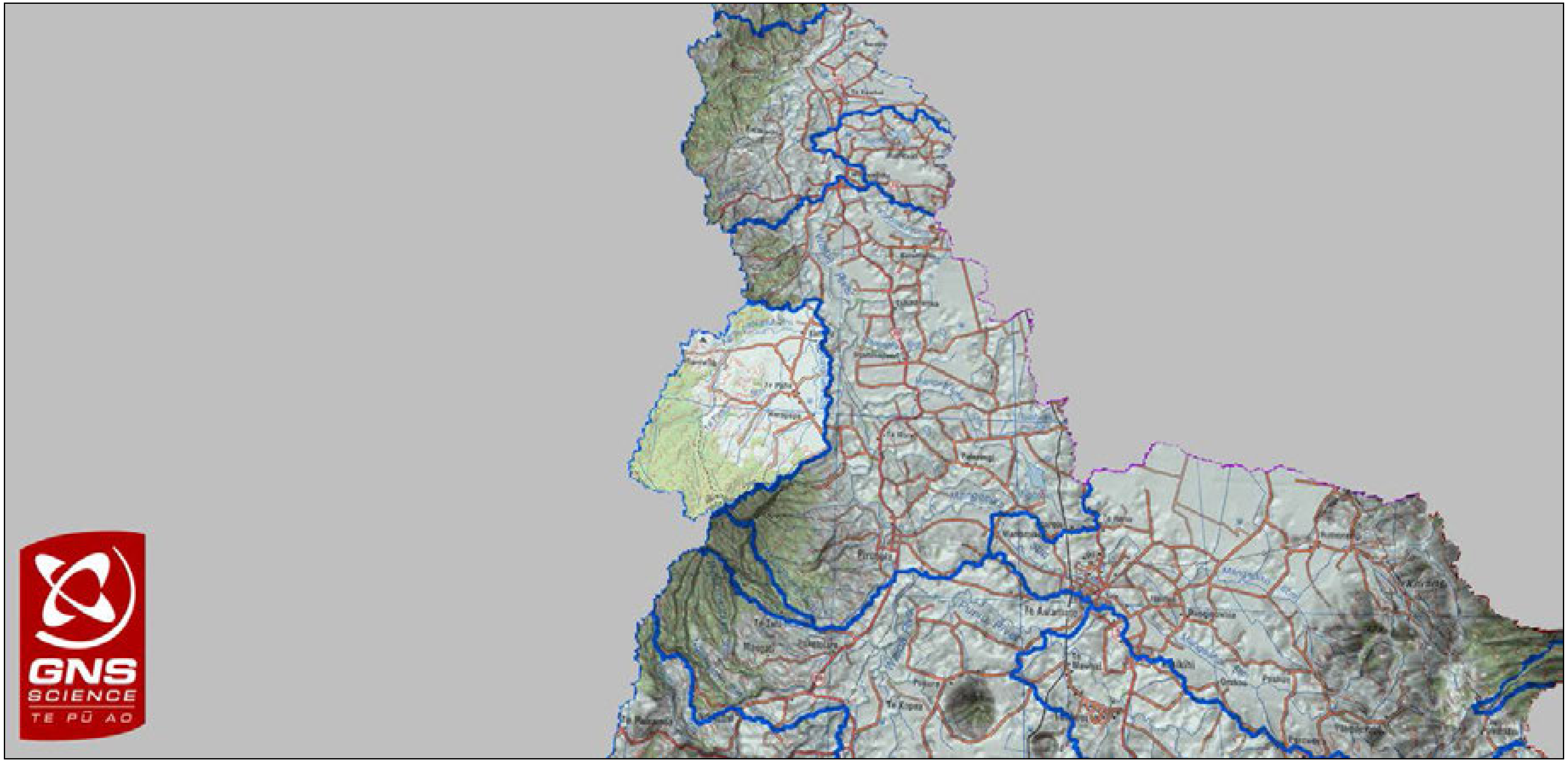

Figure A1.26: Zone: Waipa River. Catchment: Kaniwhaniwha, 3019566.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Steep gradients on Pirongia mean rapid runoff, however baseflow is a significant component of surface water outflow. Wells are typically located in Tauranga Group sediments at the bottom of the catchment. Median nitrate concentrations in groundwater are low in this catchment.

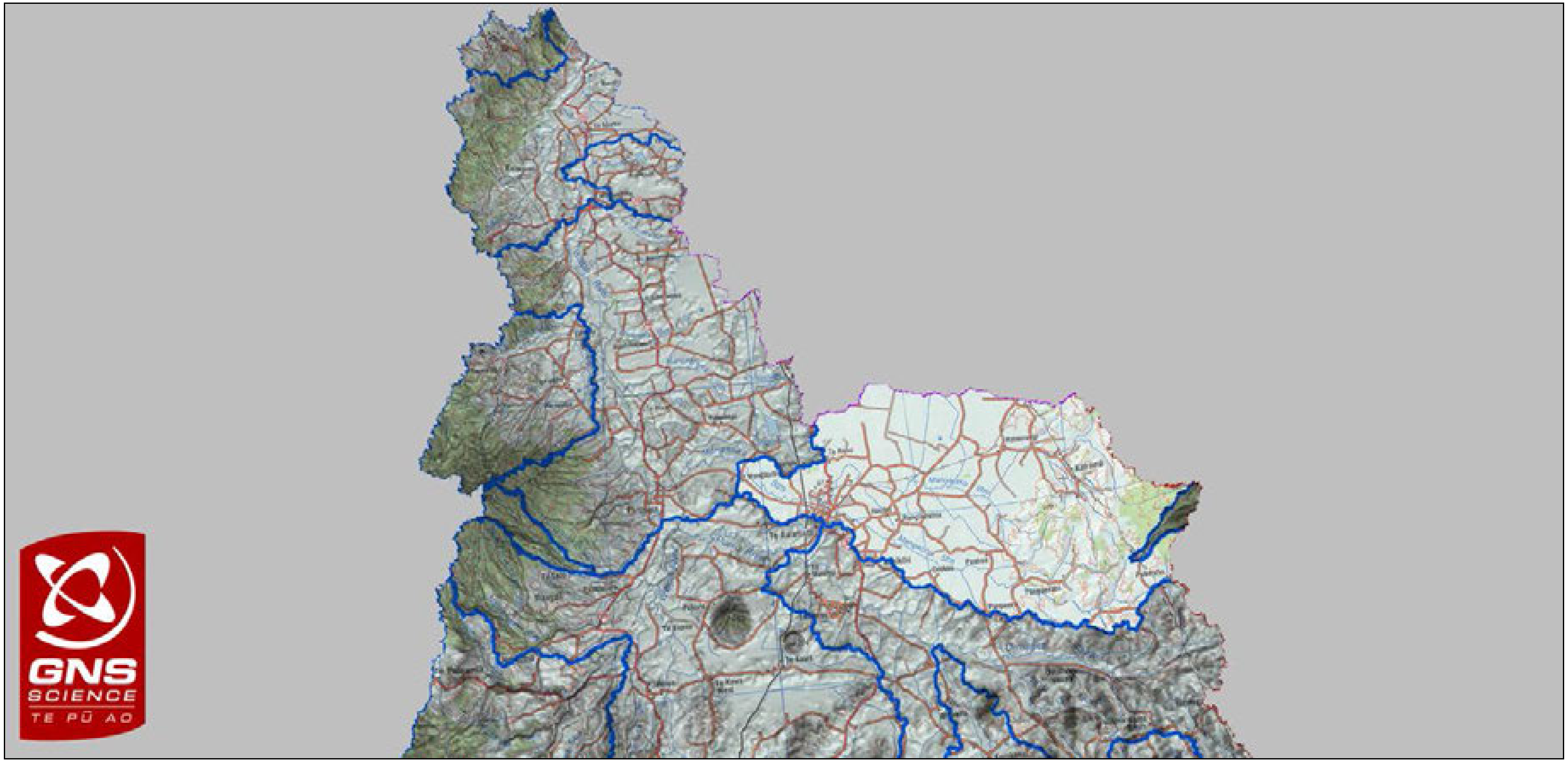

Figure A1.27: Zone: Waipa River. Catchment: Mangapiko, 3022010.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Tauranga Group sediments include Hinuera Formation where infiltration is relatively rapid and drained peats, where infiltration is slow. Median nitrate concentrations in groundwater can be greater than 1/2 MAV.

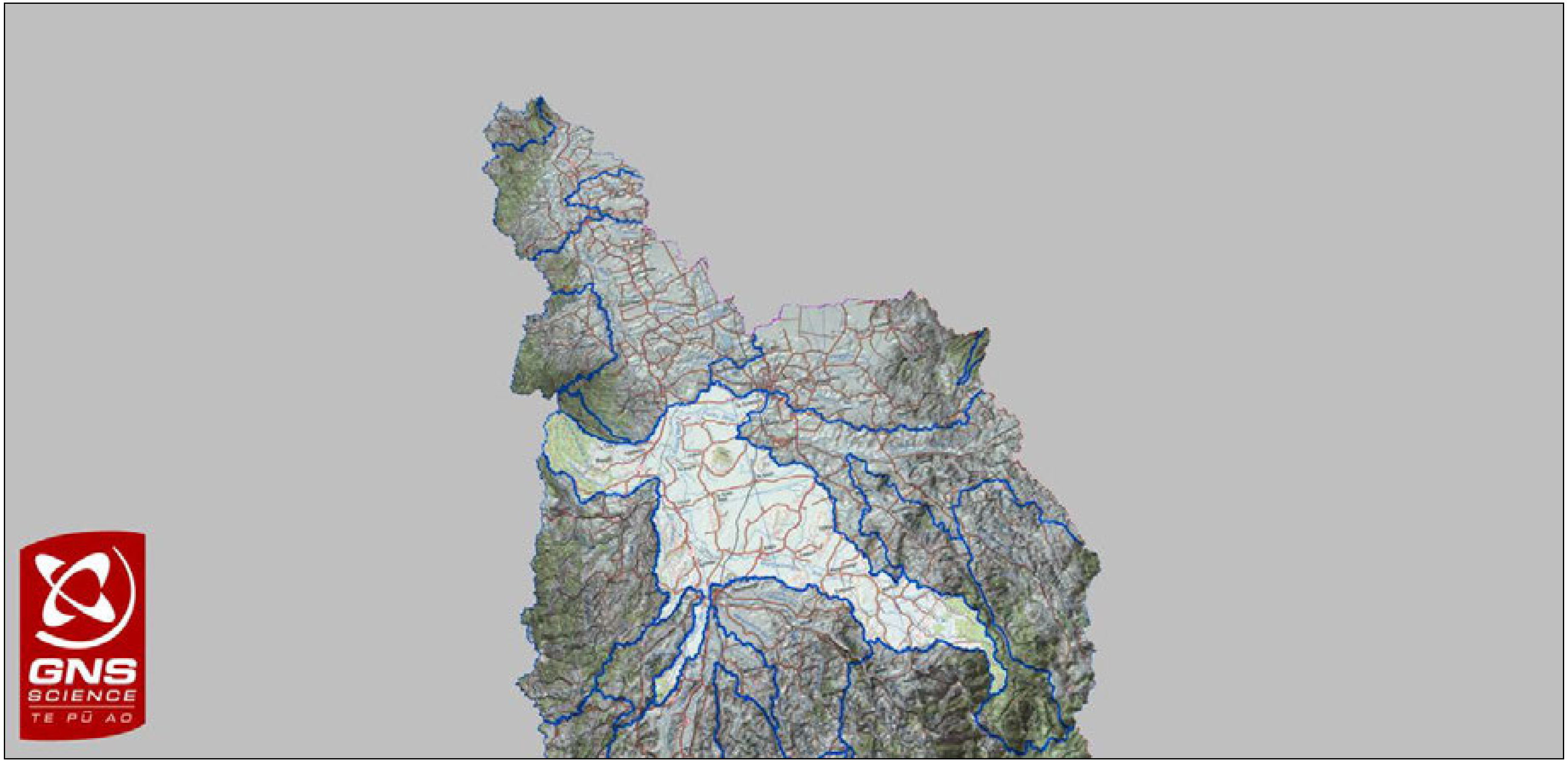

Figure A1.28: Zone: Waipa River. Catchment: Waipa at Pirongia-Ngutunui Rd Br, 3022669.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is unlikely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Volcanogenic sediments, silts and drained peats dominate in the lower reaches. Median nitrate concentrations are elevated, up to 1/2 MAV.

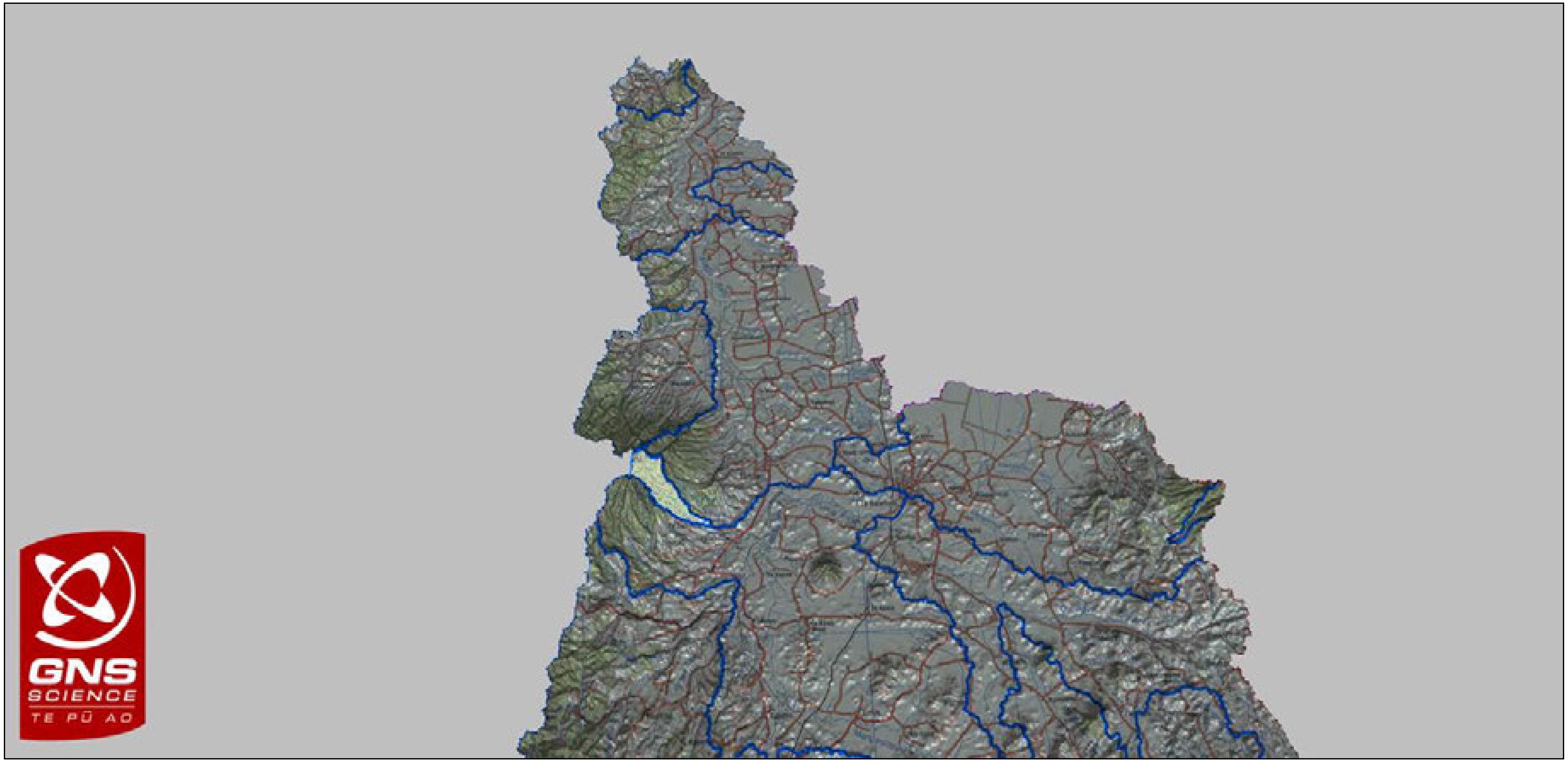

Figure A1.29: Zone: Waipa River. Catchment Mangauika, 3023179.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is unlikely. The water table is typically in the Alexandra Group volcanics. Water tables are typically deeper than 3 m. Steep gradients on Pirongia mean rapid runoff, however baseflow is a significant component of surface water outflow. No wells measure groundwater chemistry in this catchment.

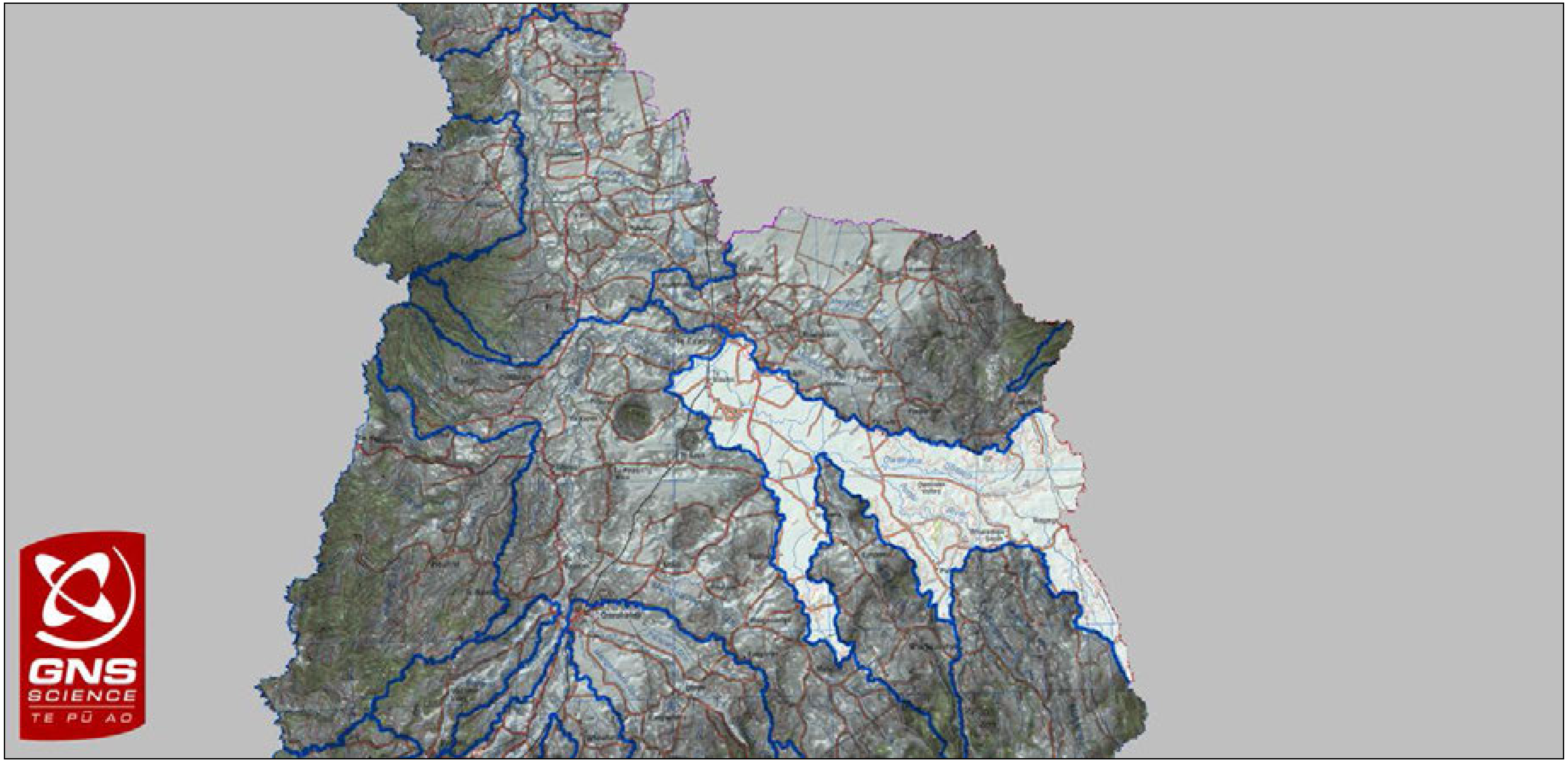

Figure A1.30: Zone: Waipa River. Catchment: Puniu at Bartons Corner Rd Br, 3023180.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is unlikely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Volcanogenic sediments and silts dominate in the middle and lower reaches. Median nitrate concentrations are elevated, up to 1/2 MAV.

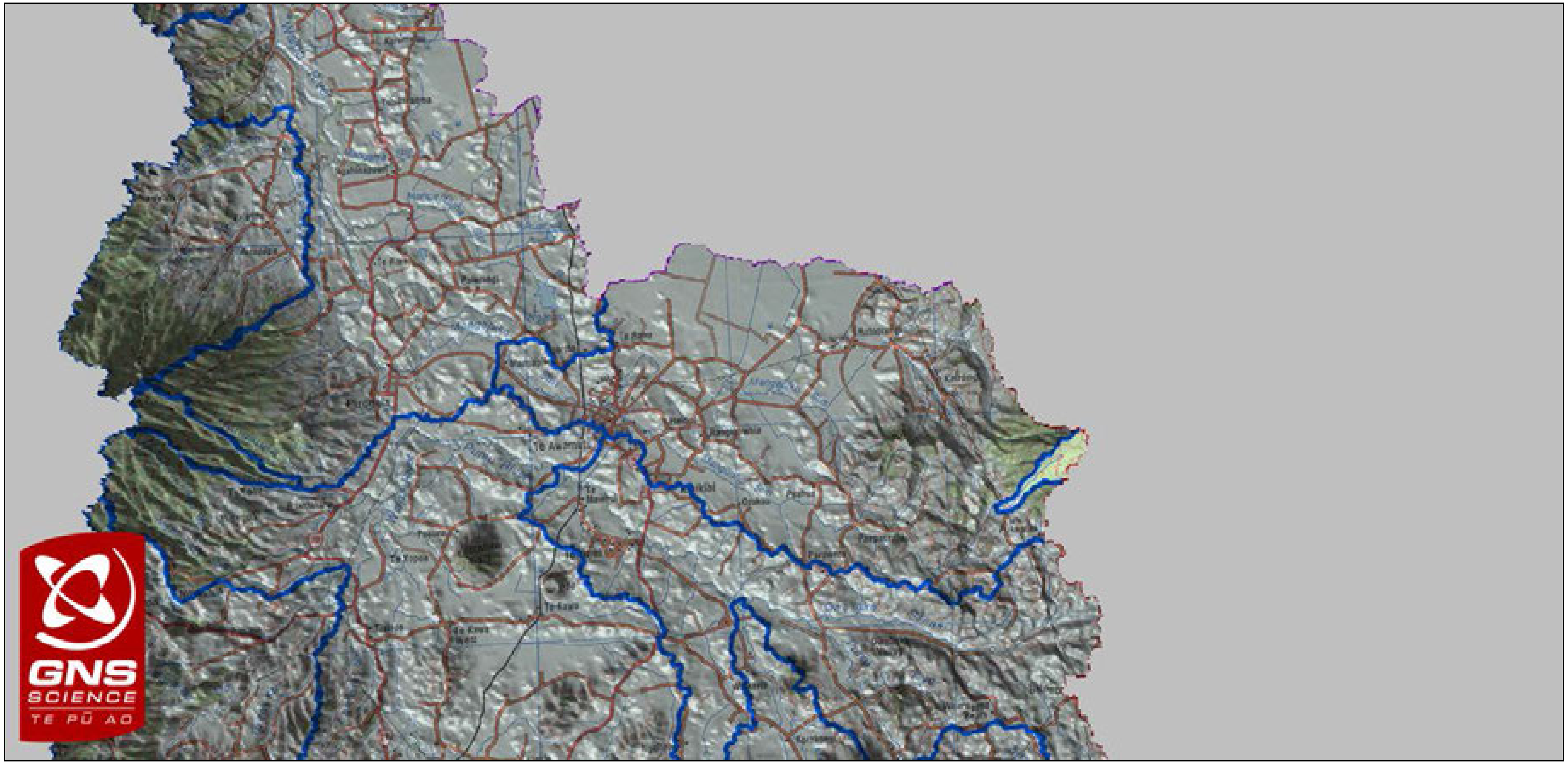

Figure A1.31: Zone: Waipa River. Catchment: Mangaohoi, 3023476.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is unlikely. The water table is typically in the Maungatautari Formation. Water tables are typically deeper than 3 m. Steep gradients on Maungatauteri mean rapid runoff, however baseflow is a significant component of surface water outflow. No wells measure groundwater chemistry in this catchment.

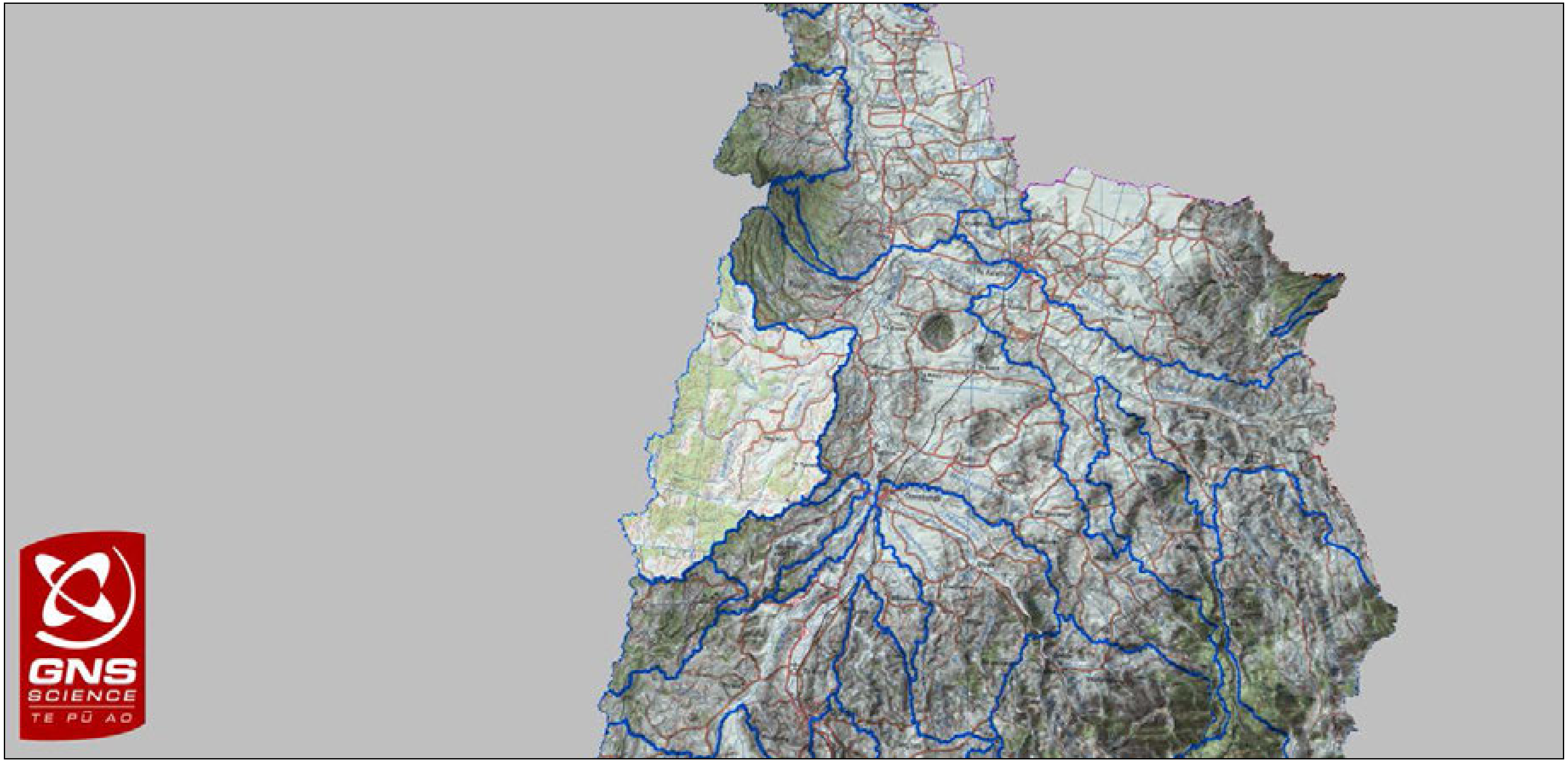

Figure A1.32: Zone: Waipa River. Catchment: Moakurarua, 3023962.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Alexandra Group volcanics. Water tables are typically deeper than 3 m. Wells are typically located in the western hills. Median nitrate concentrations in groundwater can be greater than 1/2 MAV.

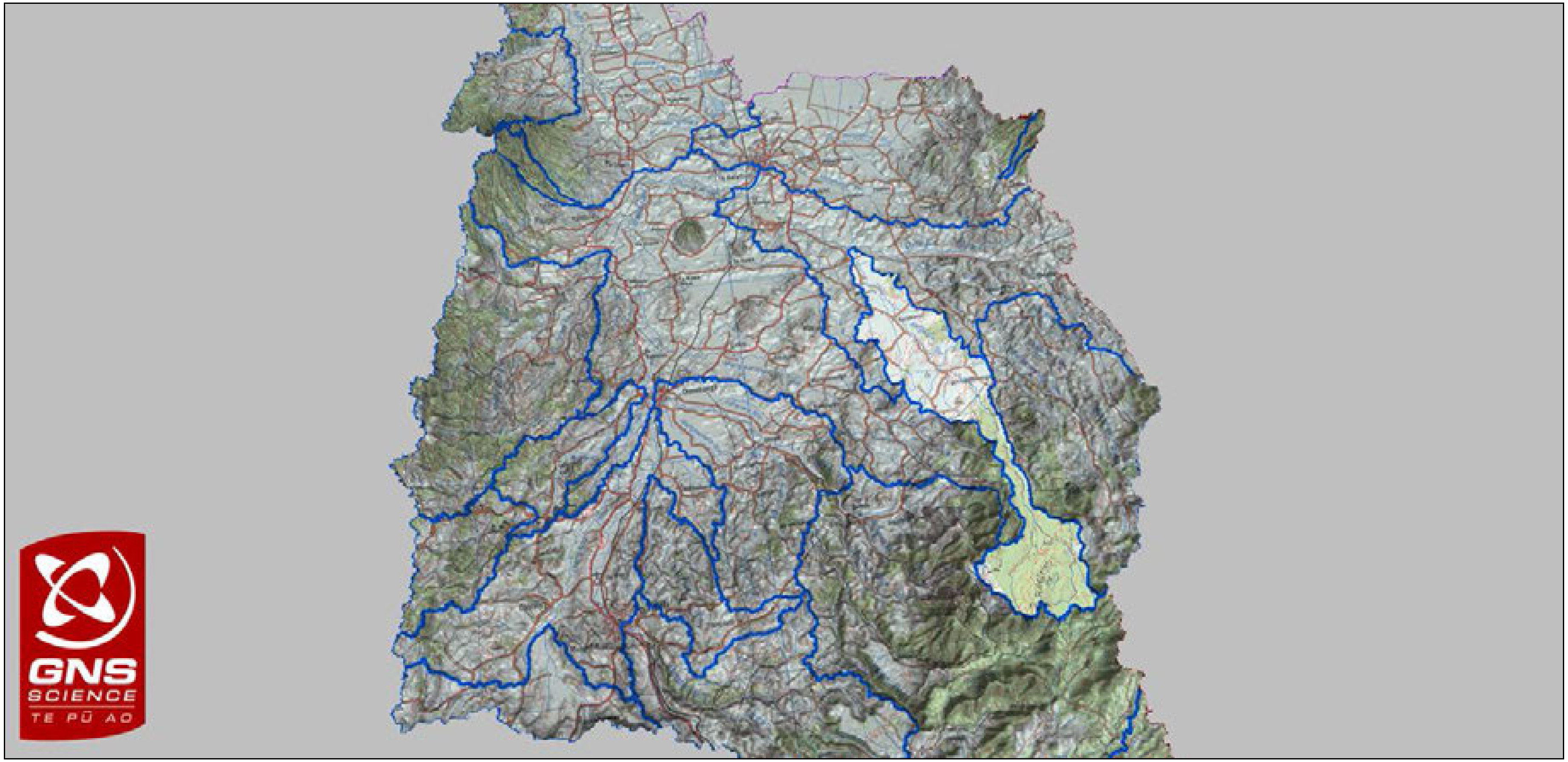

Figure A1.33: Zone: Waipa River. Catchment: Mangatutu, 3024473.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is unlikely. The water table is typically in the Pakaumanu Group. Water tables are typically deeper than 3 m. Valleys are generally dry as ignimbrite is prominent. Median nitrate concentrations are elevated, up to 1/2 MAV.

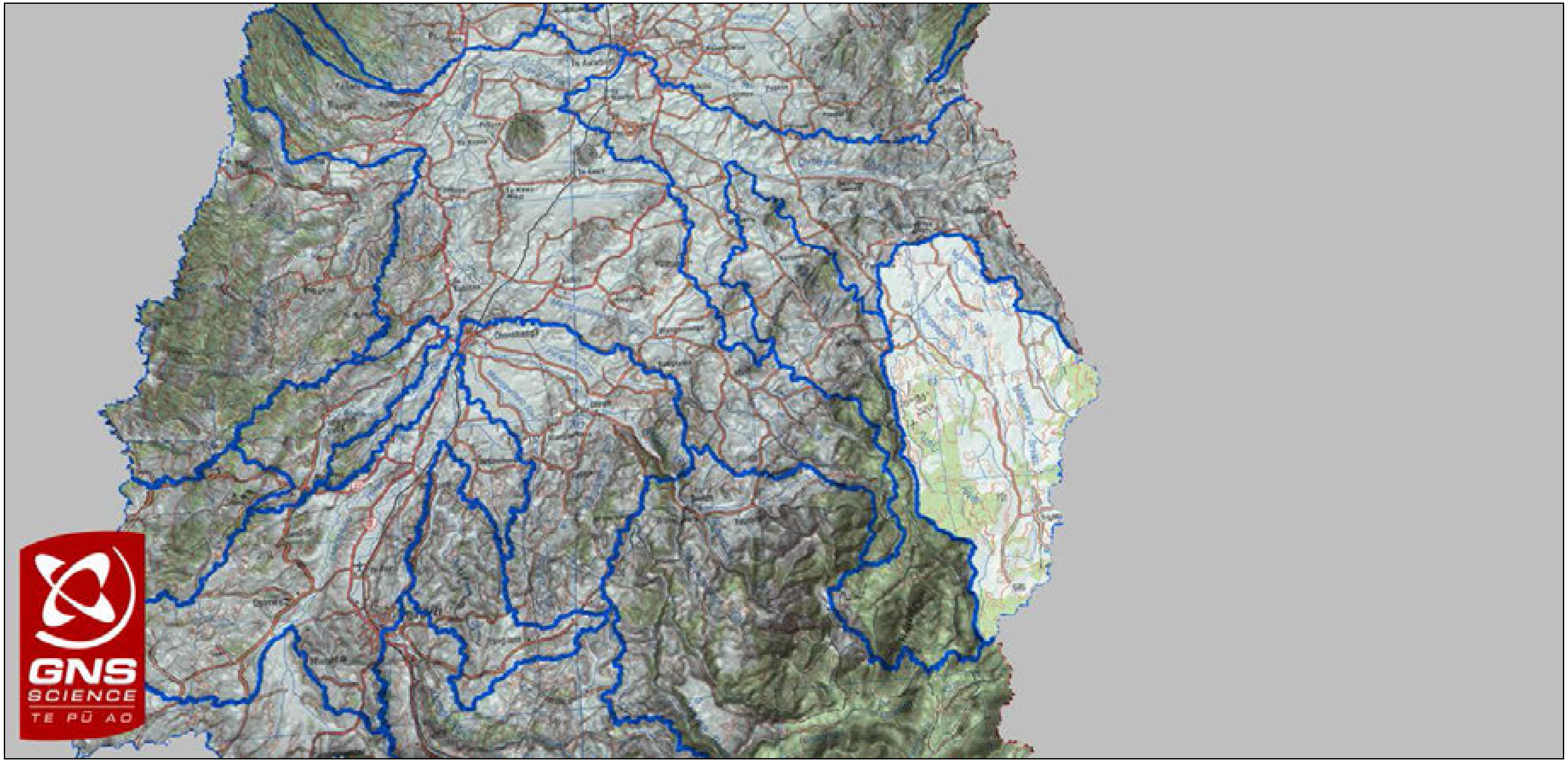

Figure A1.34: Zone: Waipa River. Catchment: Puniu at Wharepapa, 3025988.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is likely. The water table is typically in the Pakaumanu Group. Water tables are typically deeper than 3 m. Valleys are generally dry as ignimbrite is prominent. No wells measure groundwater chemistry in this catchment.

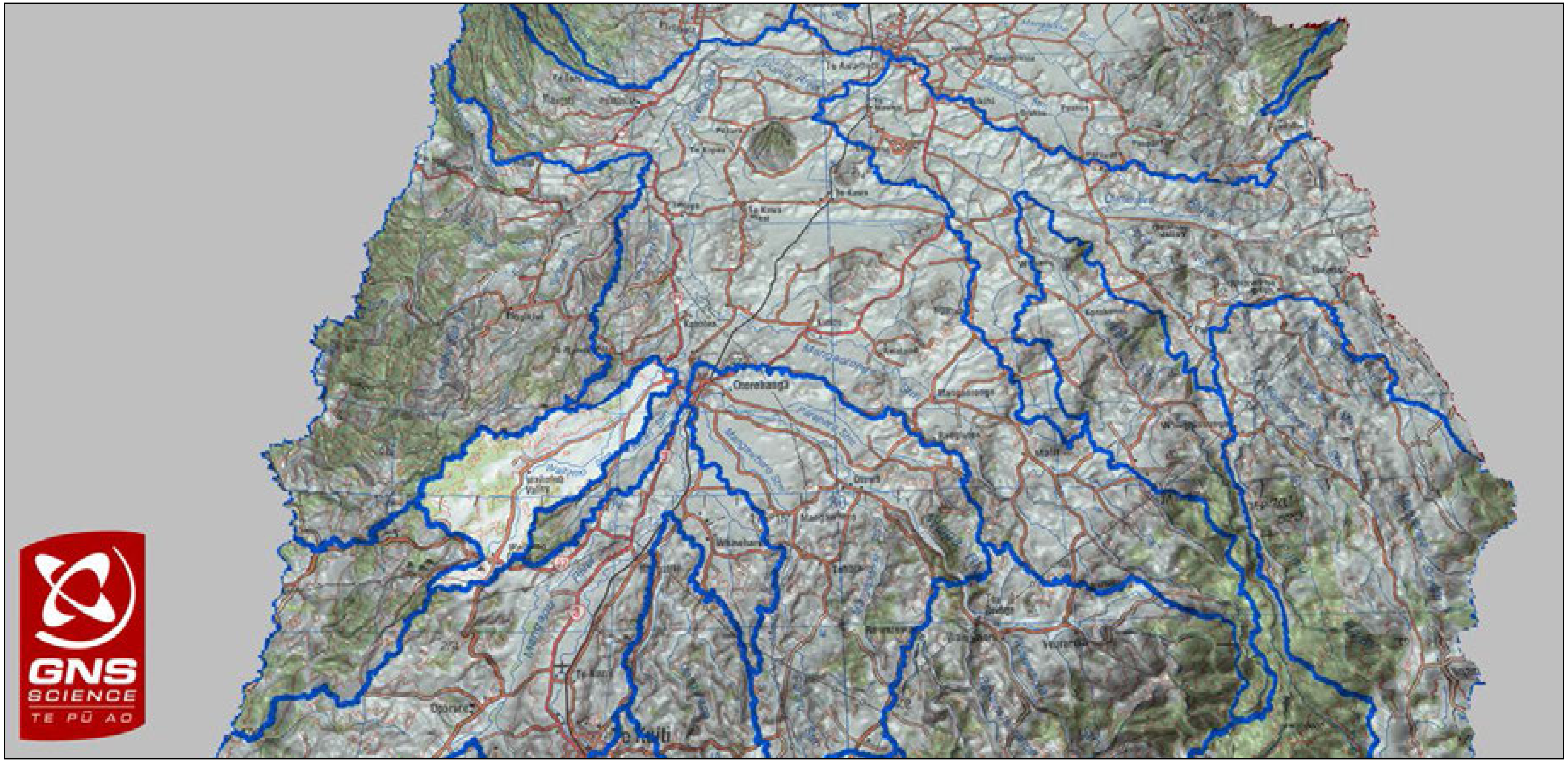

Figure A1.35: Zone: Waipa River. Catchment: Waitomo at SH31 Otorohanga, 3026779.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Mahoenui Group. Water tables are typically deeper than 3 m. Waitomo caves and karst conditions are common. No wells measure groundwater chemistry in this catchment.

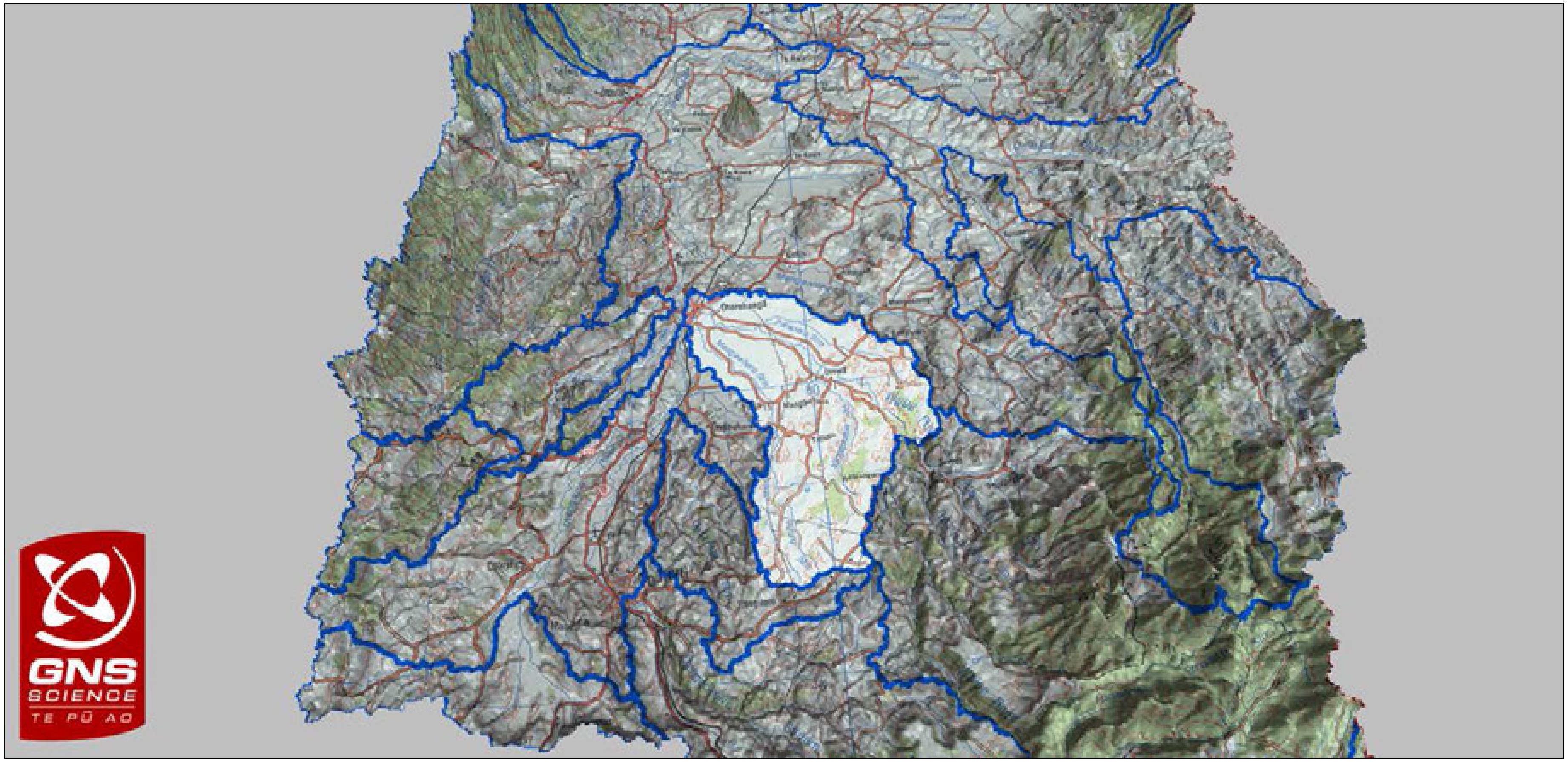

Figure A1.36: Zone: Waipa River. Catchment: Waipa at Otorohanga, 3027129.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is unlikely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Wells are typically located in relatively permeable Tauranga Group sediments at the bottom of the catchment. Median nitrate concentrations in groundwater can be greater than MAV.

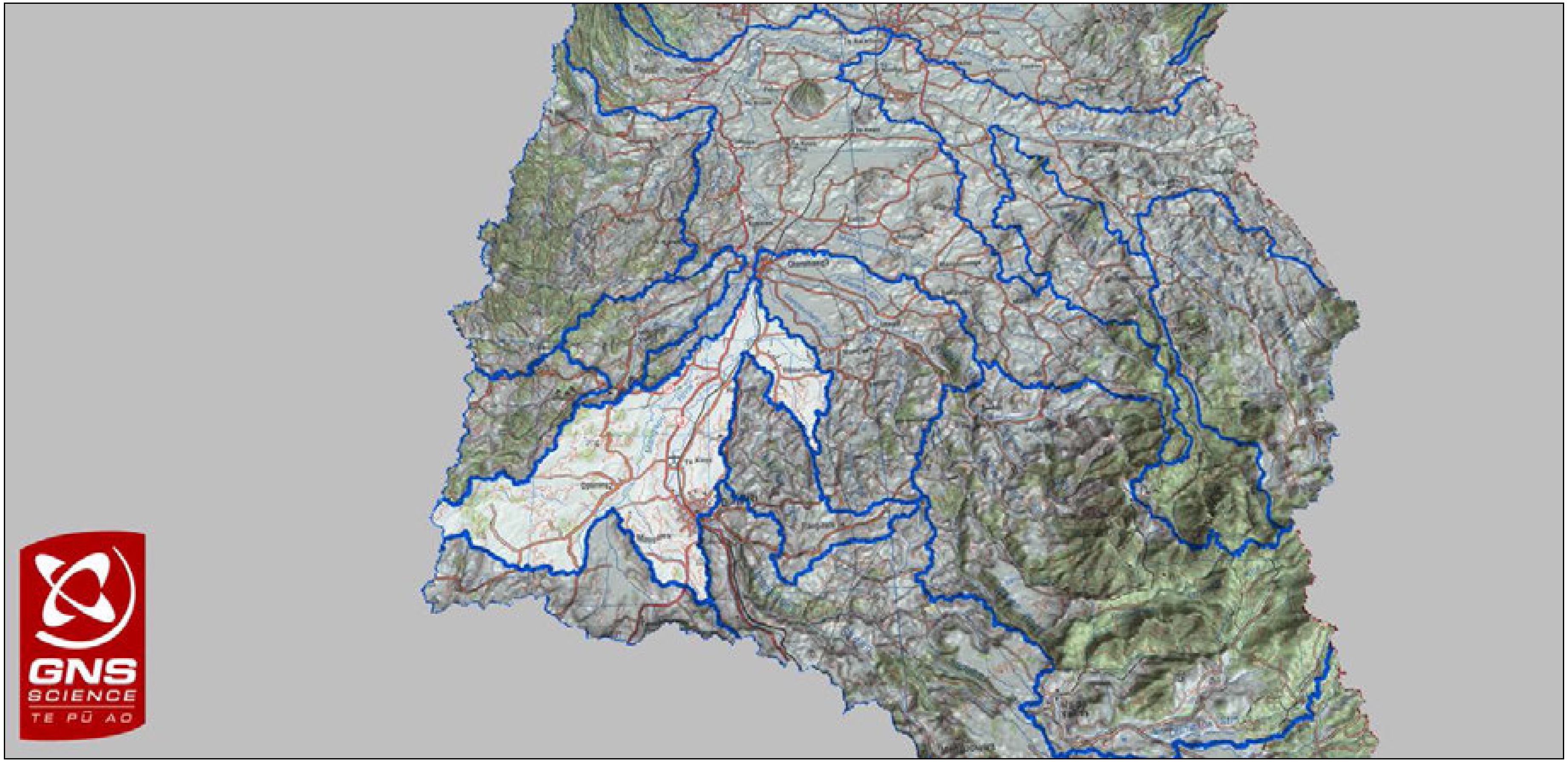

Figure A1.37: Zone: Waipa River. Catchment: Mangapu, 3027166.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is likely. The water table is typically in the Holocene sediments. Water tables are typically deeper than 3 m. Shallow wells in valleys are typical. Median nitrate concentrations in groundwater can be greater than 1/2 MAV.

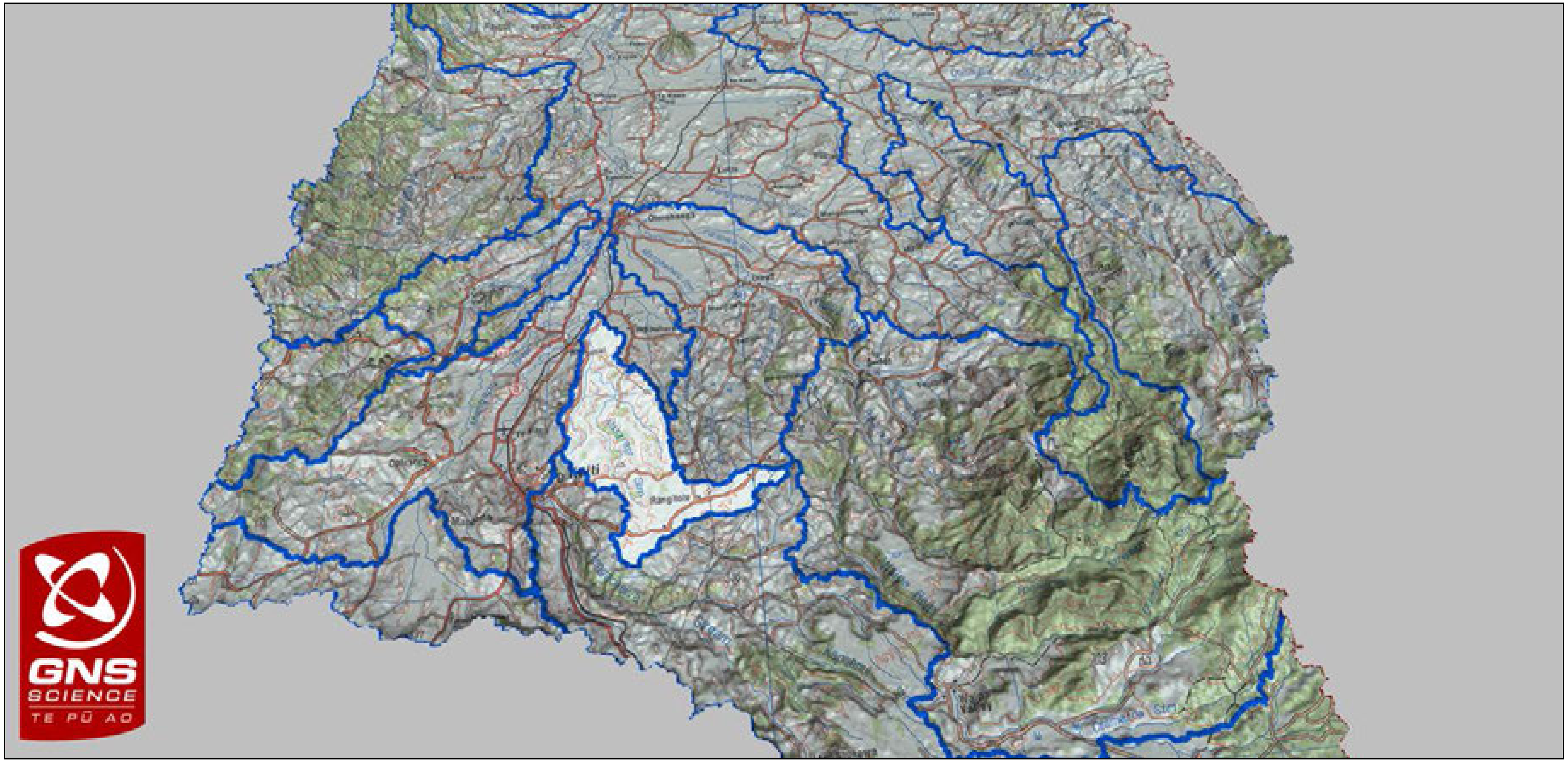

Figure A1.38: Zone: Waipa River. Catchment: Mangarapa, 3028468.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Wells are typically located in Tauranga Group sediments at the bottom of the catchment. Median nitrate concentrations in groundwater are low in this catchment.

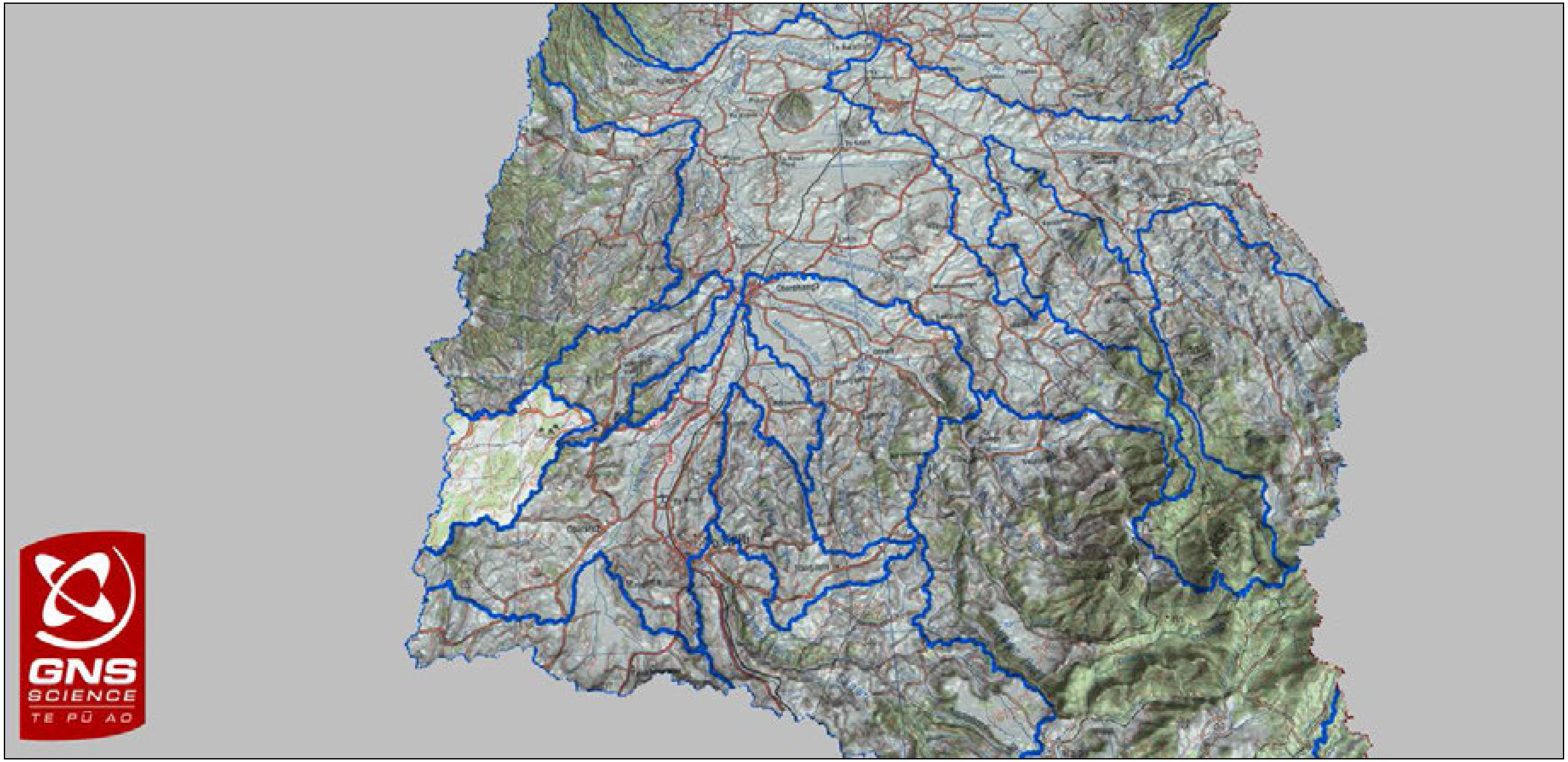

Figure A1.39: Zone: Waipa River. Catchment: Waitomo at Tumutumu Rd, 3028966.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is likely. The water table is typically in the Mahoenui Group. Water tables are typically deeper than 3 m. Karst conditions are common. No wells measure groundwater chemistry in this catchment.

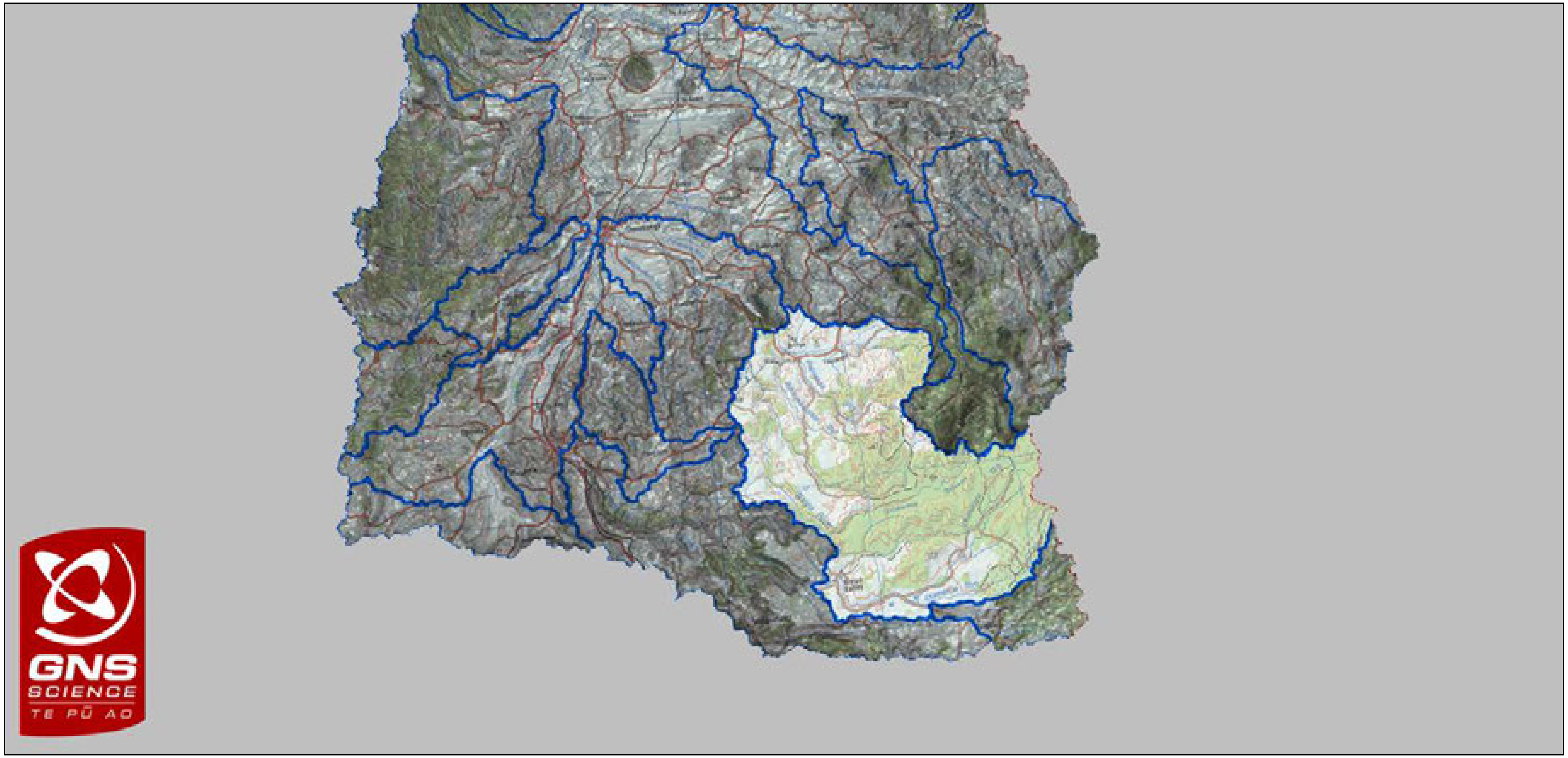

Figure A1.40: Zone: Waipa River. Catchment: Waipa at Otewa, 3029370.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is unlikely. The water table is typically in the Pakaumanu Group. Water tables are typically deeper than 3 m. Significant flow gains in the lower reaches, elsewhere flows are low. Median nitrate concentrations in groundwater are low in this catchment.

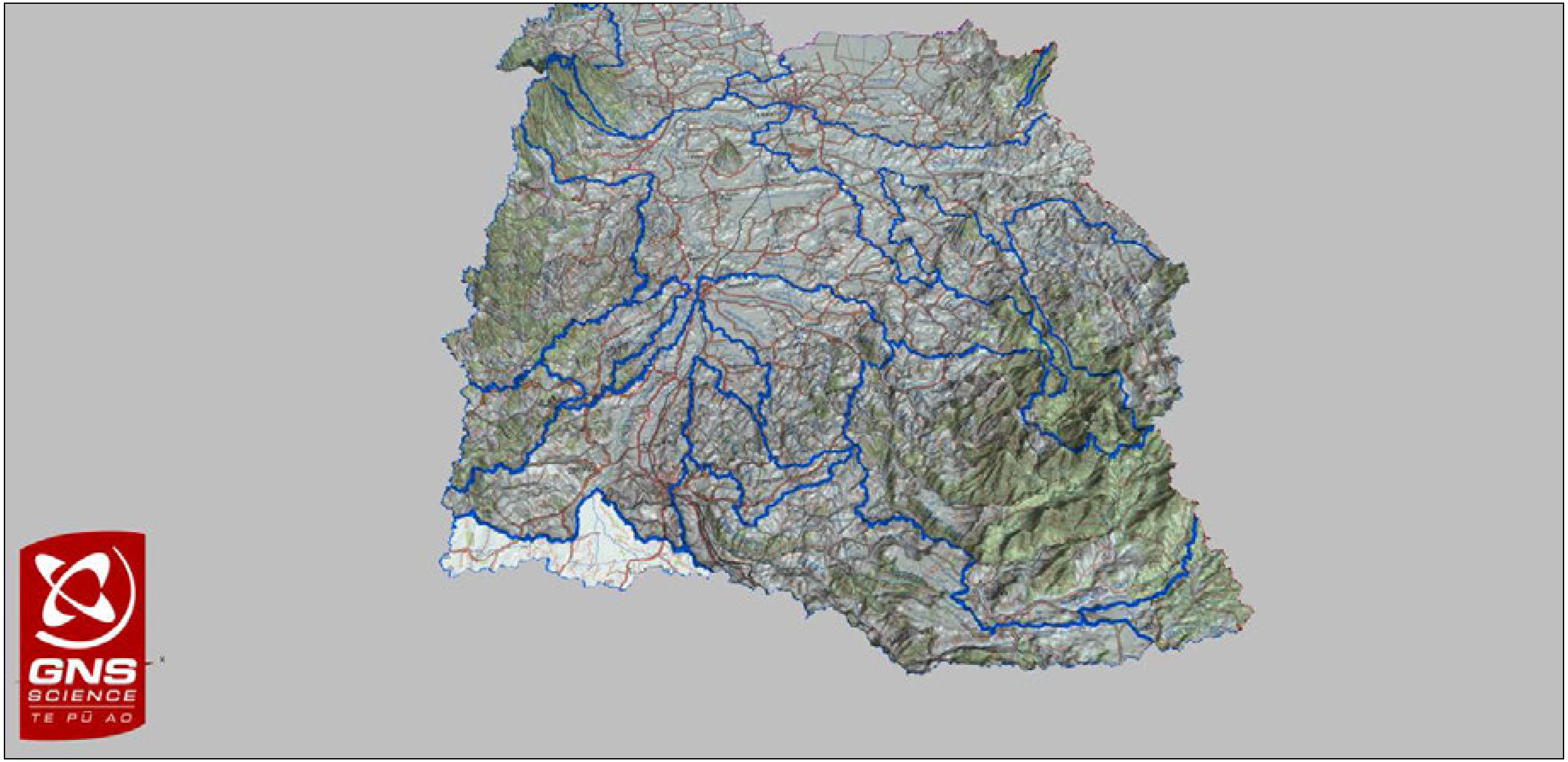

Figure A1.41: Zone: Waipa River. Catchment: Mangarama, 3031371.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Mahoenui Group. Water tables are typically deeper than 3 m. Catchment is generally dry. No wells measure groundwater chemistry in this catchment.

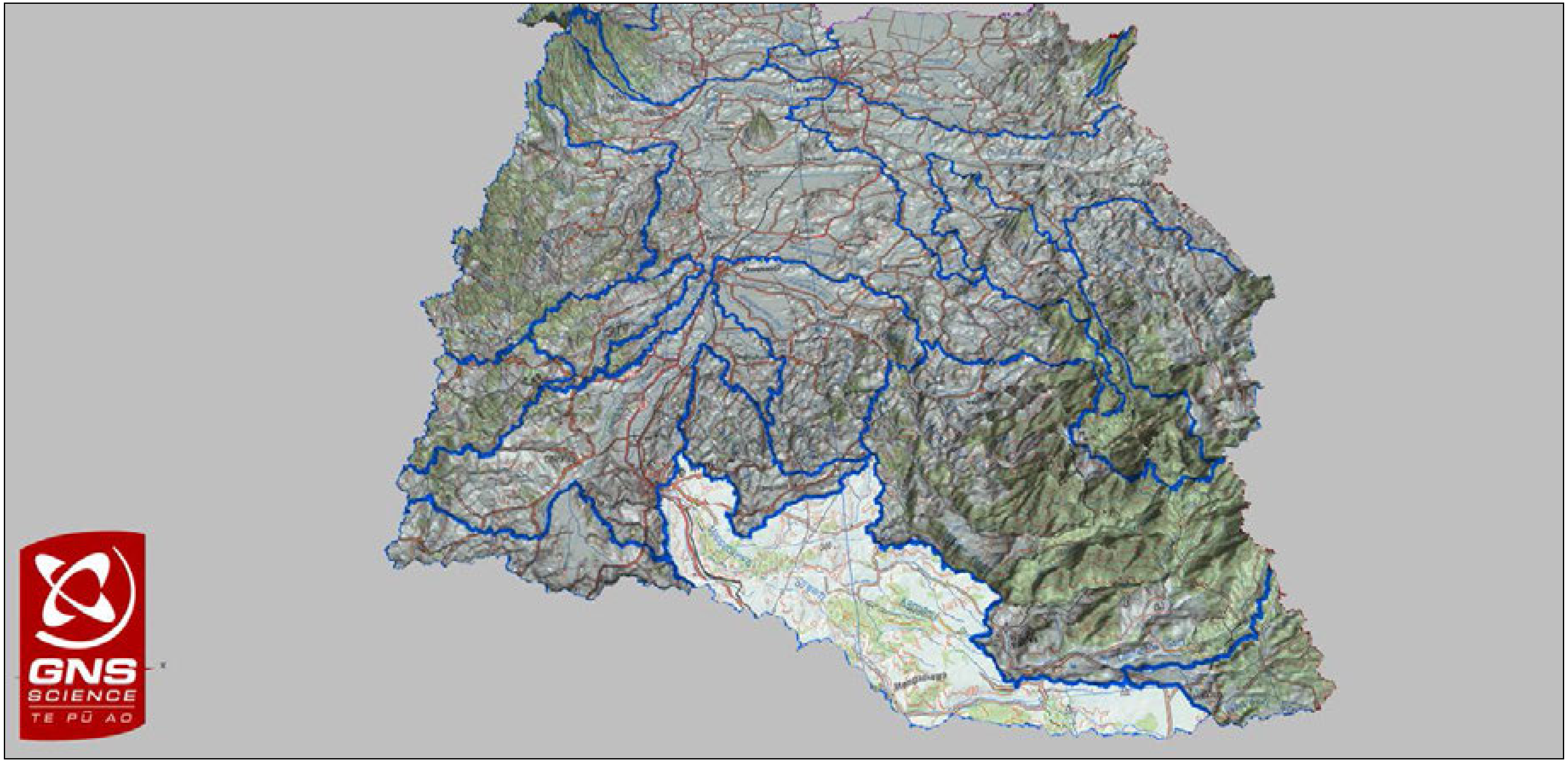

Figure A1.42: Zone: Waipa River. Catchment: Mangaokewa, 3031564.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is unlikely. The water table is typically in the Pakaumanu Group. Water tables are typically deeper than 3 m. Quick flow dominates in upper catchment as basement rocks are prominent. Median nitrate concentrations are elevated, up to 1/2 MAV.

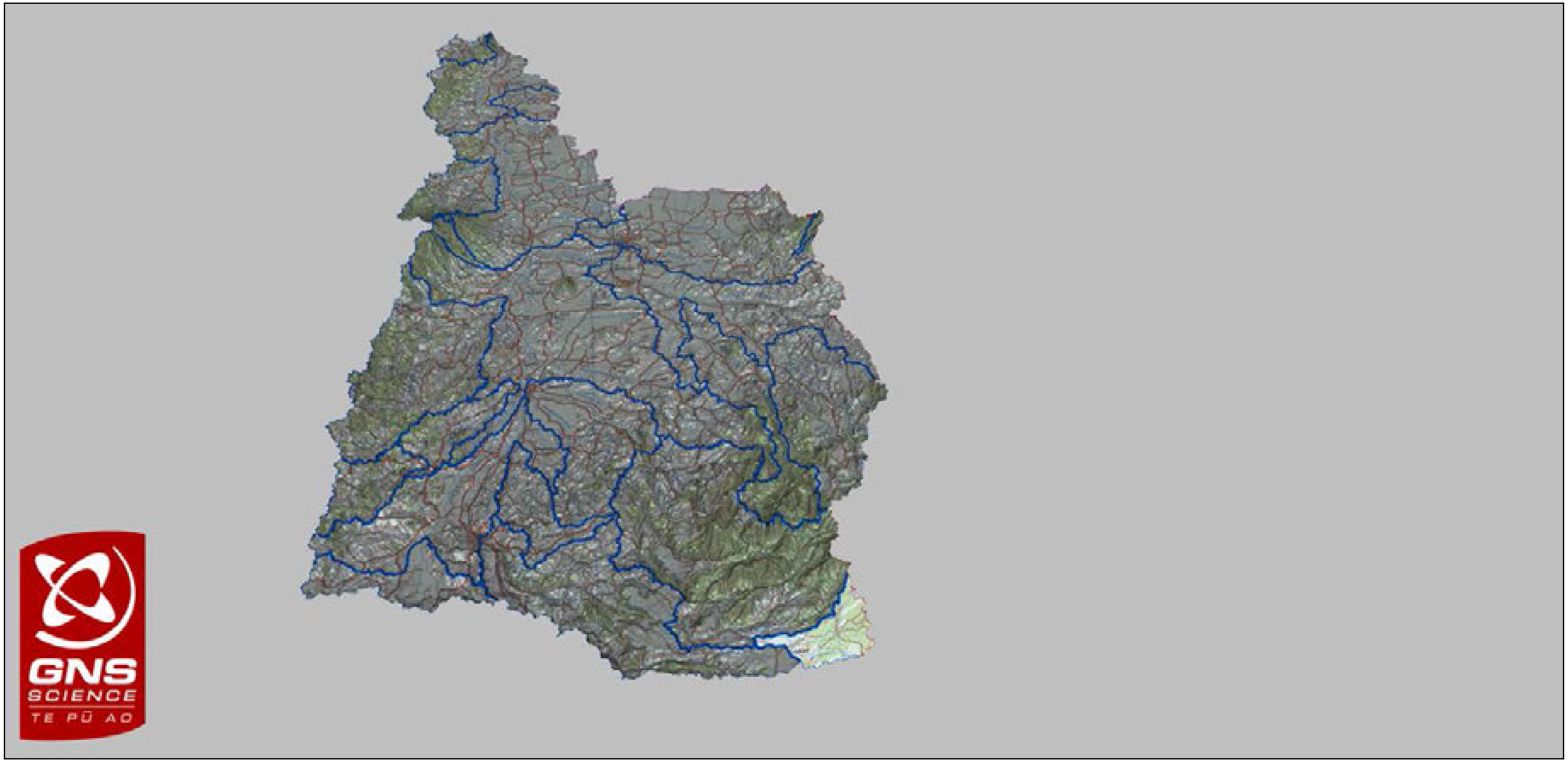

Figure A1.43: Zone: Waipa River. Catchment: Waipa at Mangaokewa Rd, 3036214.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Pakaumanu Group. Water tables are typically deeper than 3 m. Valleys are generally dry as ignimbrite is prominent. No wells measure groundwater chemistry in this catchment.

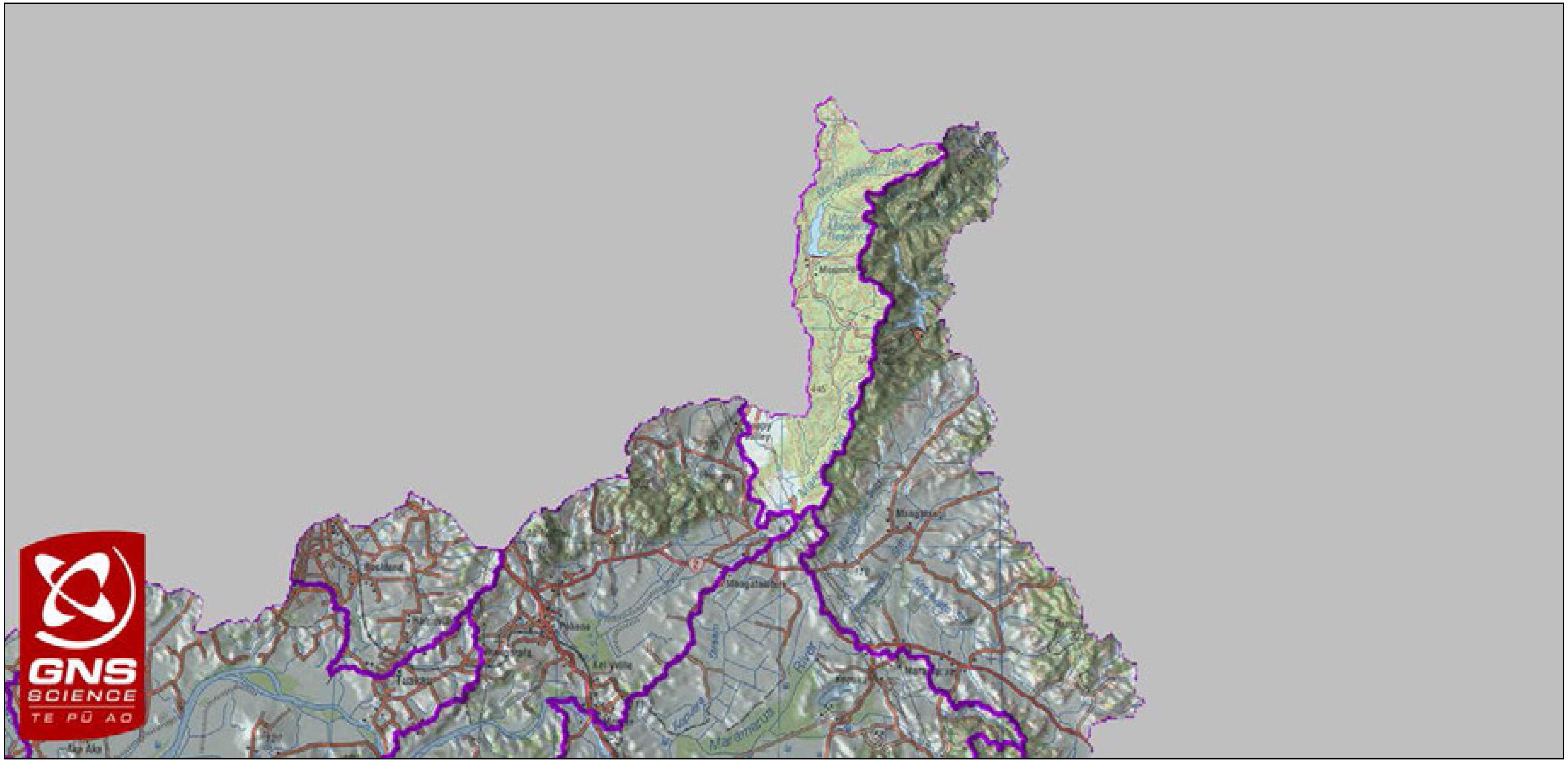

Figure A1.44: Zone: Lower Middle Waikato River. Catchment: Mangatawhiri, 3005110.

Surface flow is dominated by quick flow and groundwater outflow from the catchment is unlikely. The water table is typically in the Basement. Water tables are typically deeper than 3 m. Basement rocks make for quick runoff. No groundwater nitrate-nitrogen chemistry data is available in this catchment.

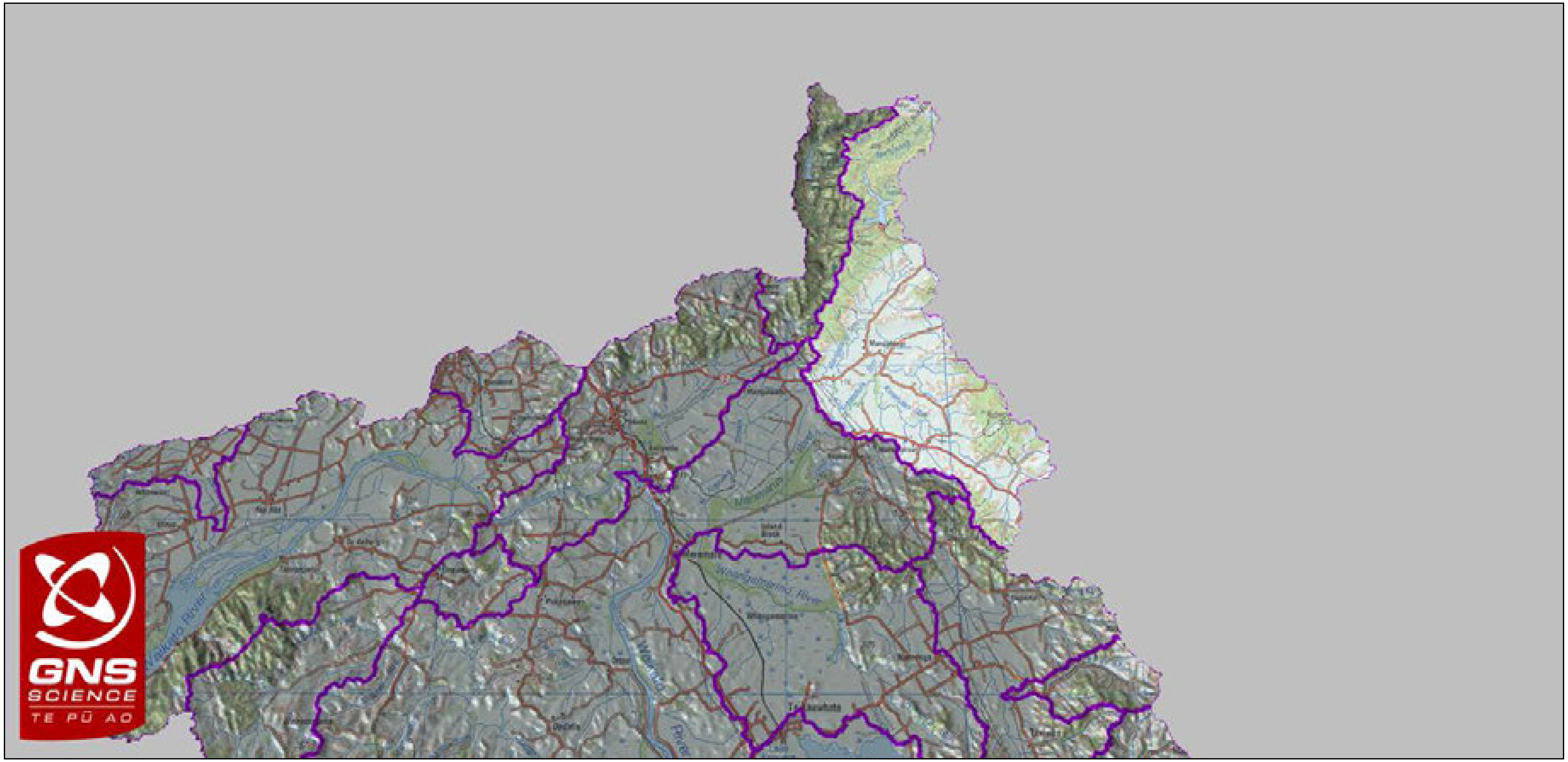

Figure A1.45: Zone: Lower Middle Waikato River. Catchment: Mangatangi, 3006132.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Basement and Tauranga Group sediments that include silts mean that runoff is generally rapid; stream valleys are dry in their upper reaches. Median nitrate concentrations in groundwater can be greater than 1/2 MAV.

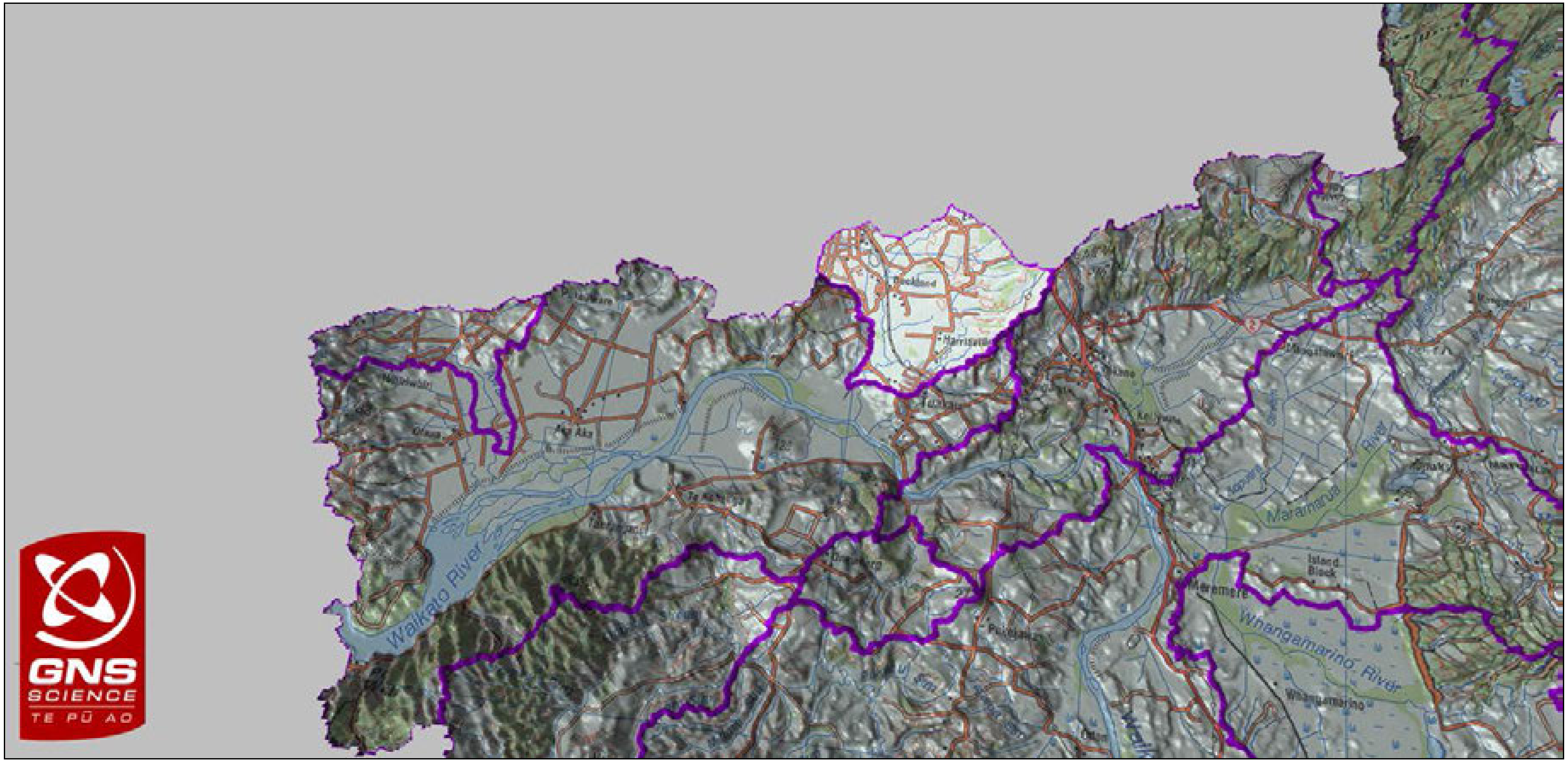

Figure A1.46: Zone: Lower Middle Waikato River. Catchment: Whakapipi, 3006346.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is unlikely. The water table is typically in the Kerikeri Volcanic Group. Water tables are typically deeper than 3 m. The volcanic aquifer is typically associated with relatively large recharge. Median nitrate concentrations in groundwater can be greater than 1/2 MAV.

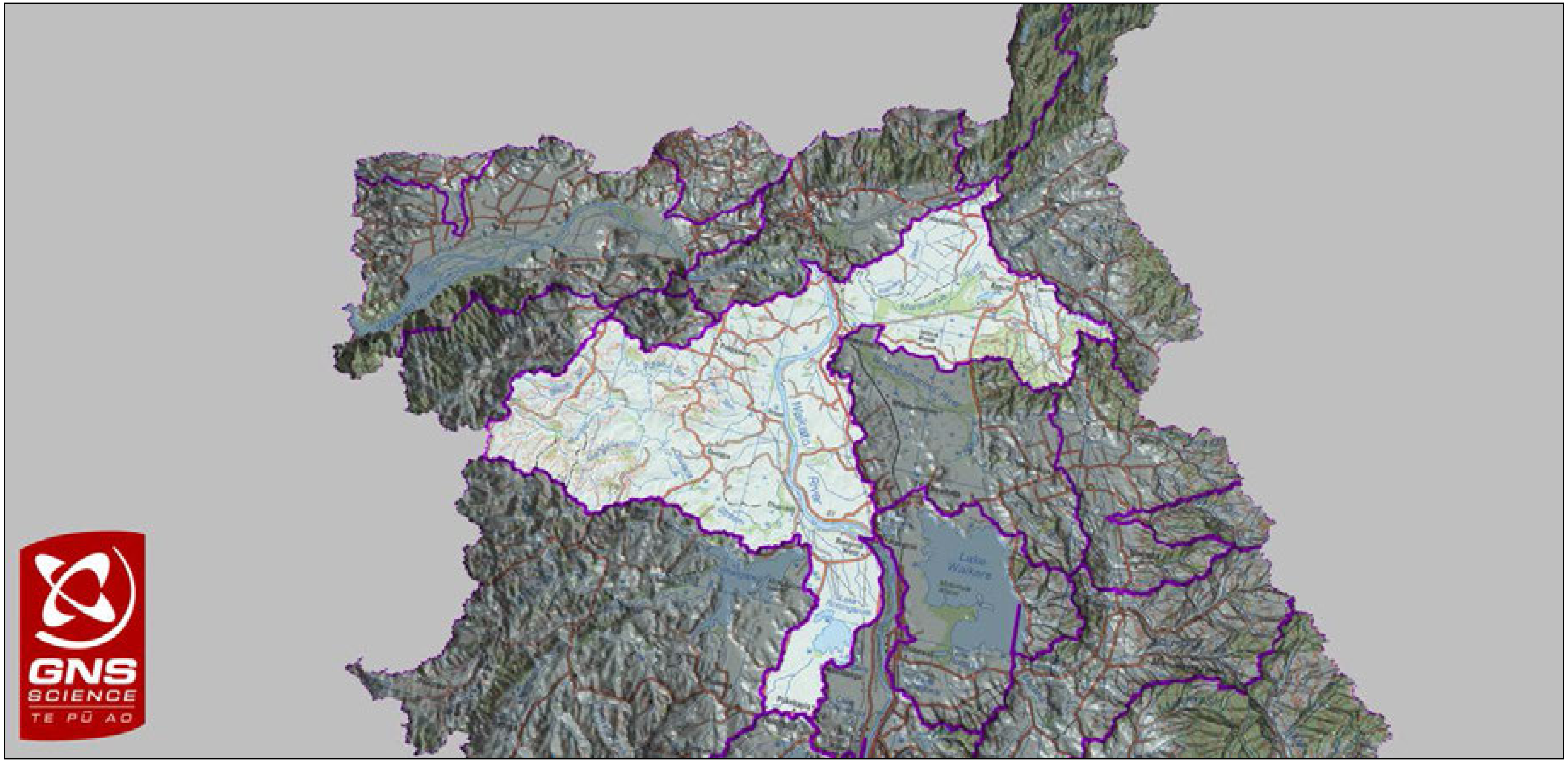

Figure A1.47: Zone: Lower Middle Waikato River. Catchment: Waikato at Mercer Br, 3006806.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is unlikely. The water table is typically in the Tauranga Group. Water tables are typically in the range 0.5 to 3 m. Low-lying areas in the catchment have heavy soils; stream valleys are dry in their upper reaches. Low-lying swampy areas can occur east of the Waikato River. Median nitrate concentrations in groundwater can be greater than MAV.

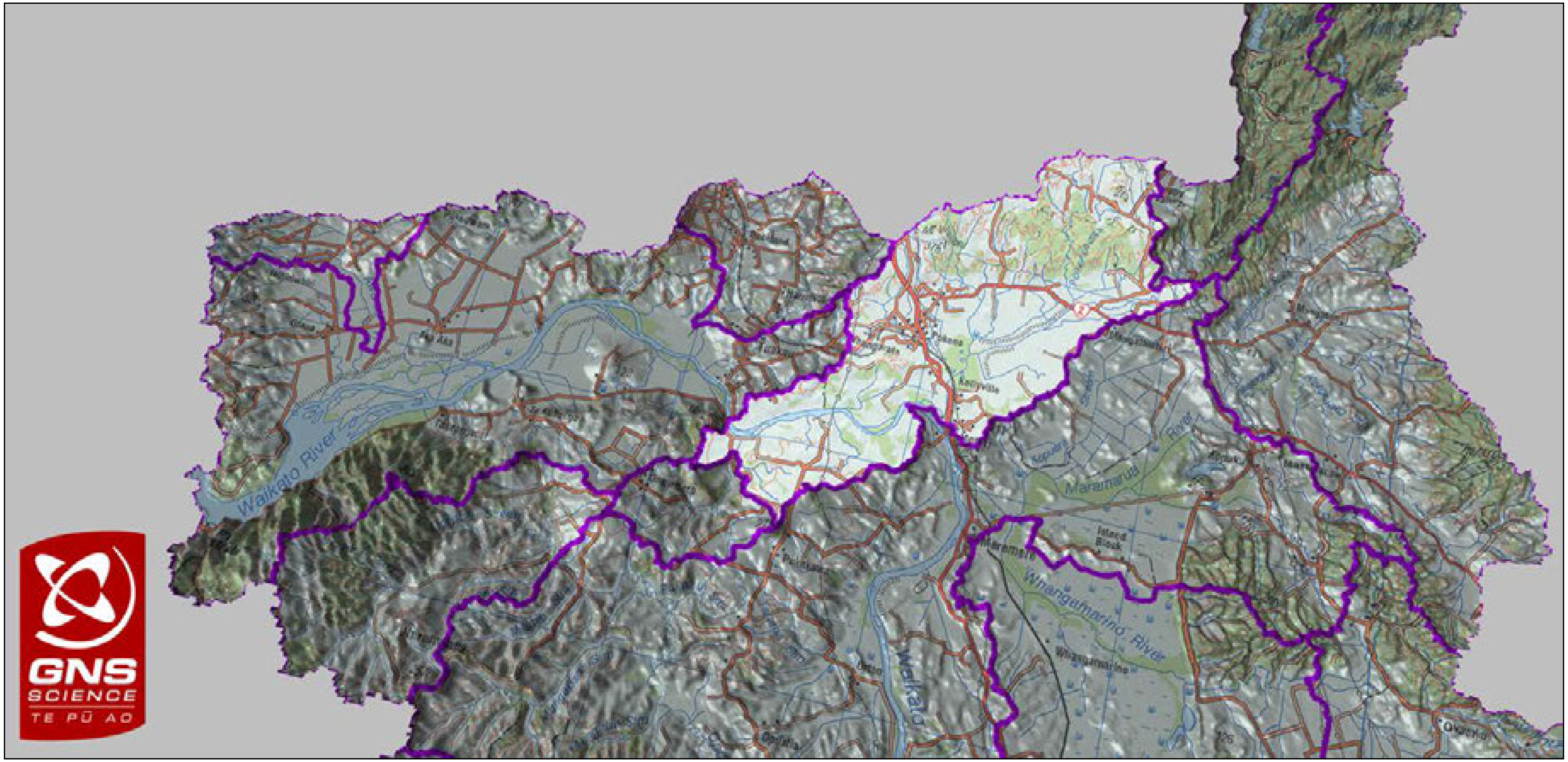

Figure A1.48: Zone: Lower Middle Waikato River. Catchment: Waikato at Tuakau Br, 3007421.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is likely. The water table is typically in the Kerikeri Volcanic Group. Water tables are typically in the range 0.5 to 3 m. Low-lying areas in the catchment have heavy soils. Median nitrate concentrations in groundwater can be greater than MAV.

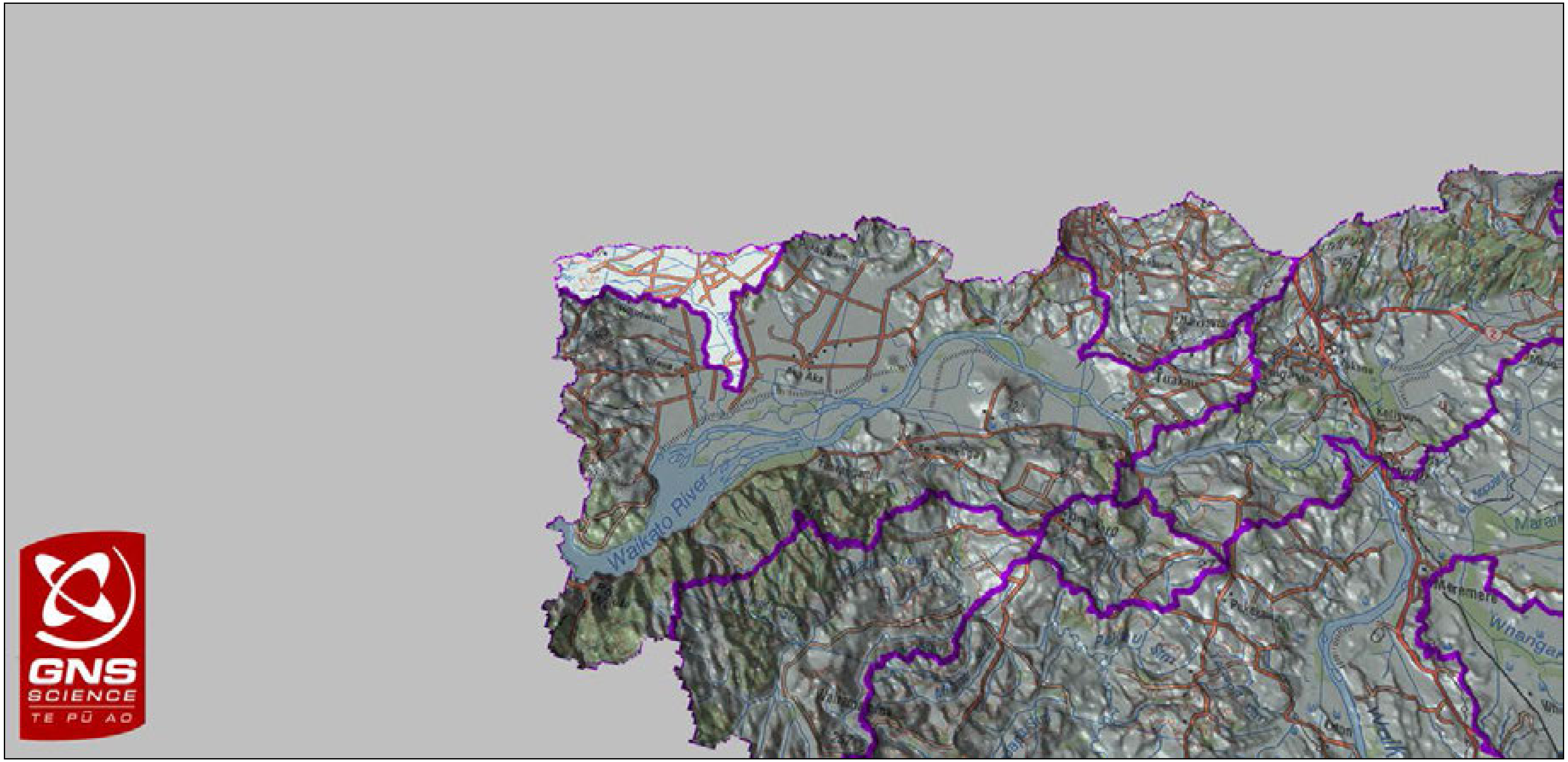

Figure A1.49: Zone: Lower Middle Waikato River. Catchment Awaroa (Waiuku), 3007434.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Awhitu Group. Water tables are typically deeper than 3 m. Stream valleys are typically dry Median nitrate concentrations in groundwater can be greater than MAV.

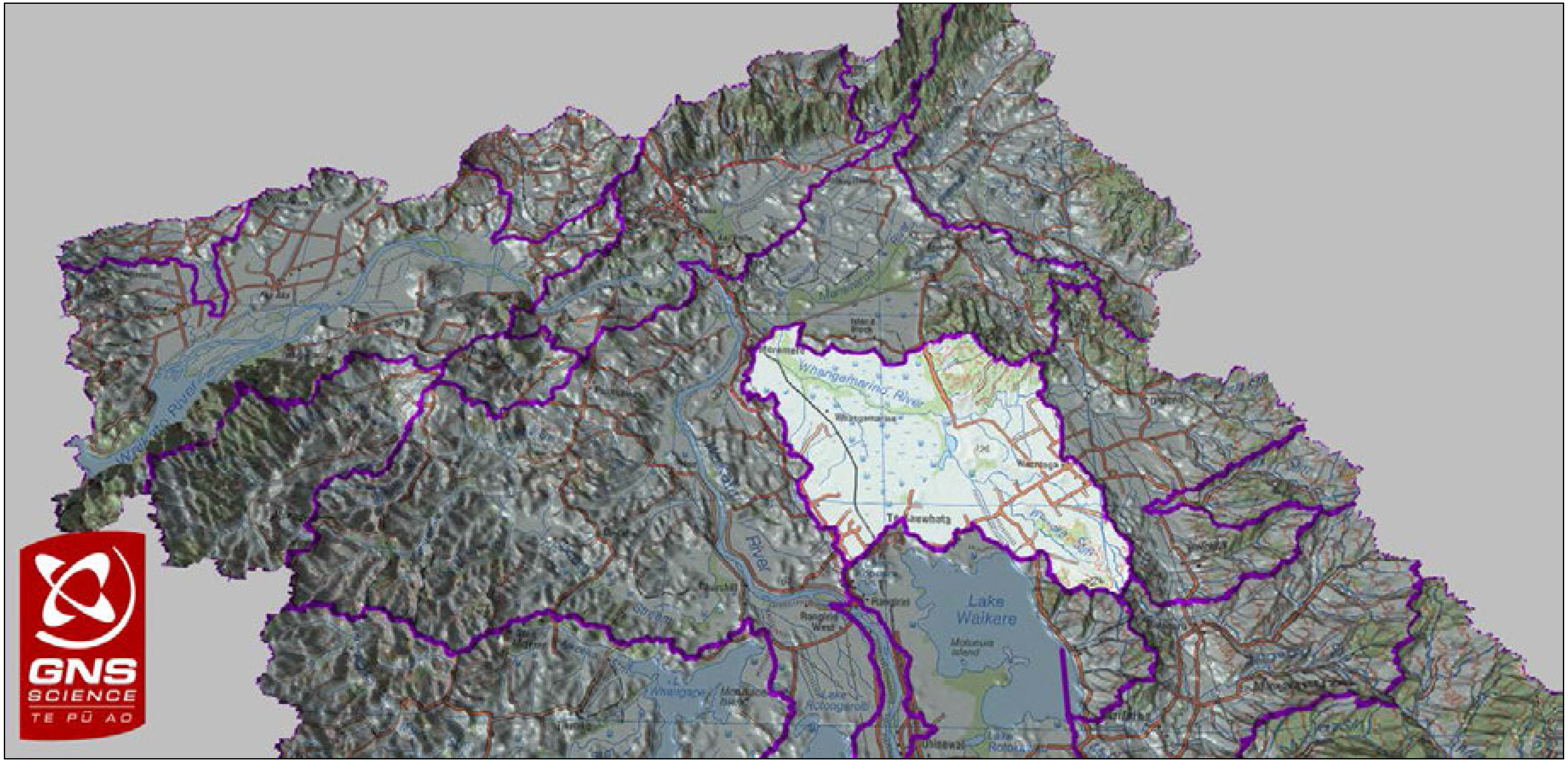

Figure A1.50: Zone: Lower Middle Waikato River. Catchment: Whangamarino at Island Block Rd, 3007681.

Surface flow is dominated by quick flow and groundwater outflow from the catchment is unlikely. The water table is typically in the Tauranga Group. Water tables are typically very shallow, i.e. less than 0.5 m. Swamps dominate the area. No wells measure groundwater chemistry in this catchment.

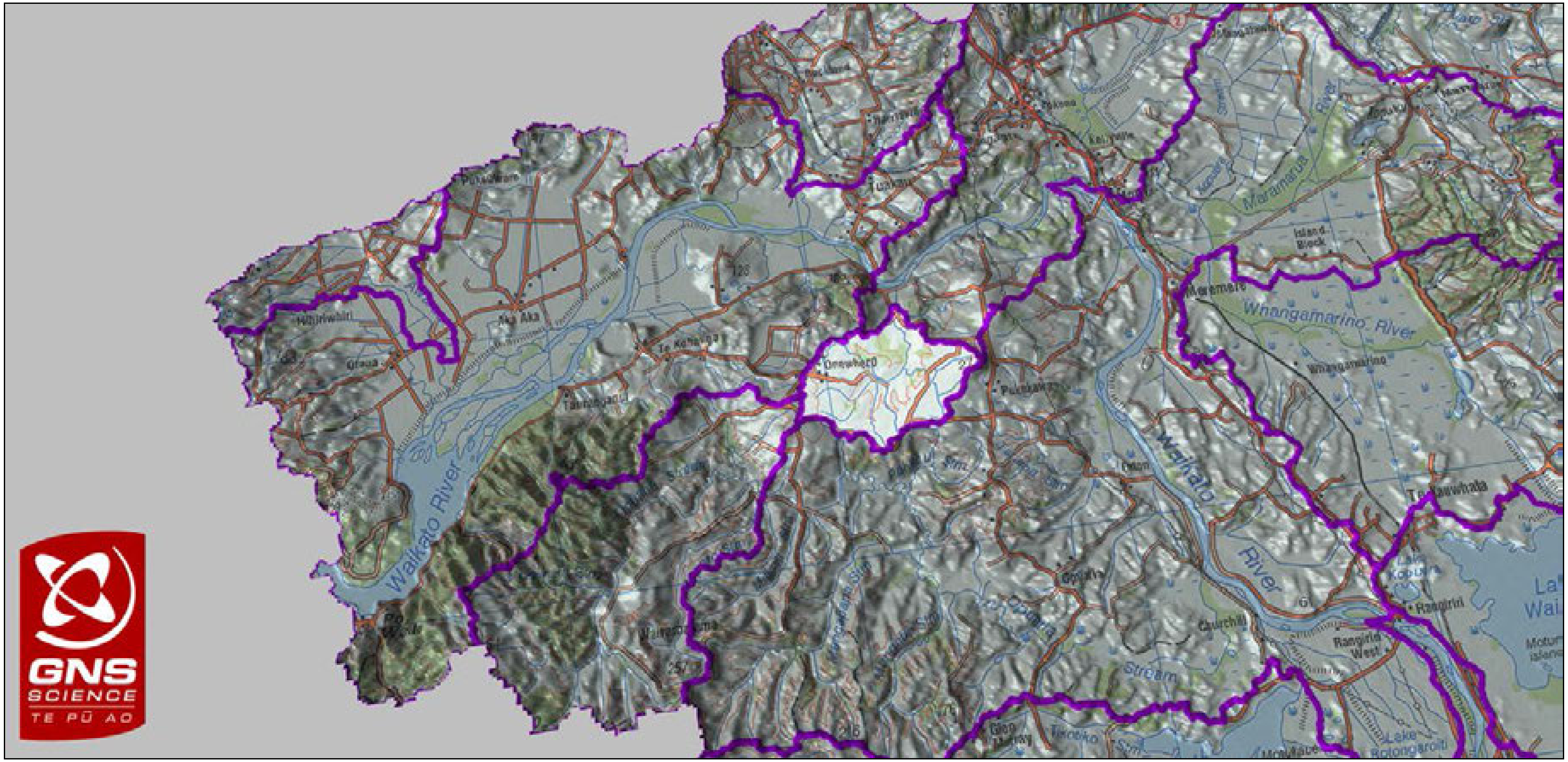

Figure A1.51: Zone: Lower Middle Waikato River. Catchment: Ohaeroa, 3007733.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is likely. The water table is typically in the Kerikeri Volcanic Group. Water tables are typically deeper than 3 m. Stream beds are typically dry in this relatively elevated catchment. Median nitrate concentrations in groundwater can be greater than MAV.

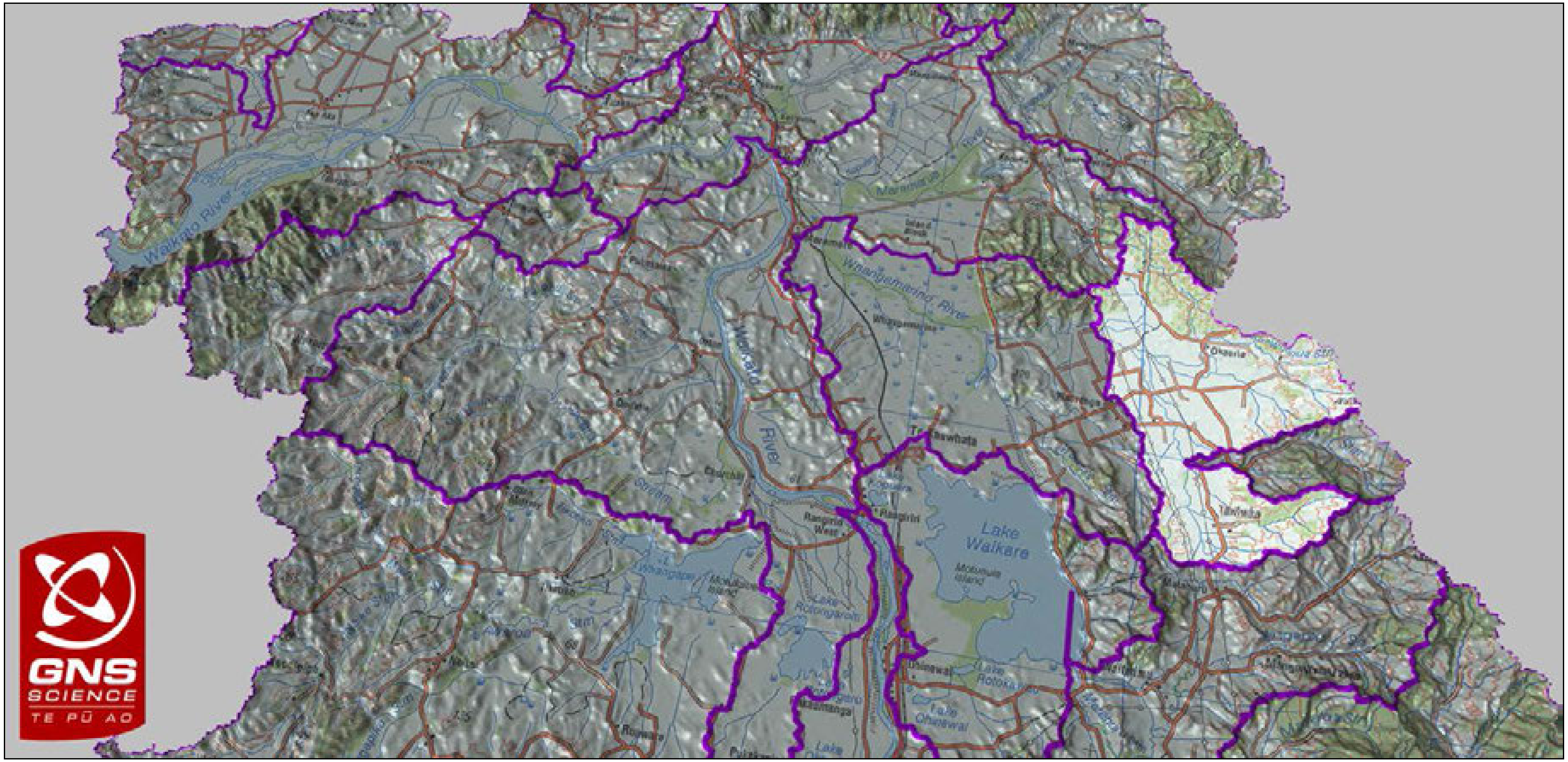

Figure A1.52: Zone: Lower Middle Waikato River. Catchment: Whangamarino at Jefferies Rd Br, 3008369.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Low-lying areas in the catchment have heavy soils. No wells measure groundwater chemistry in this catchment.

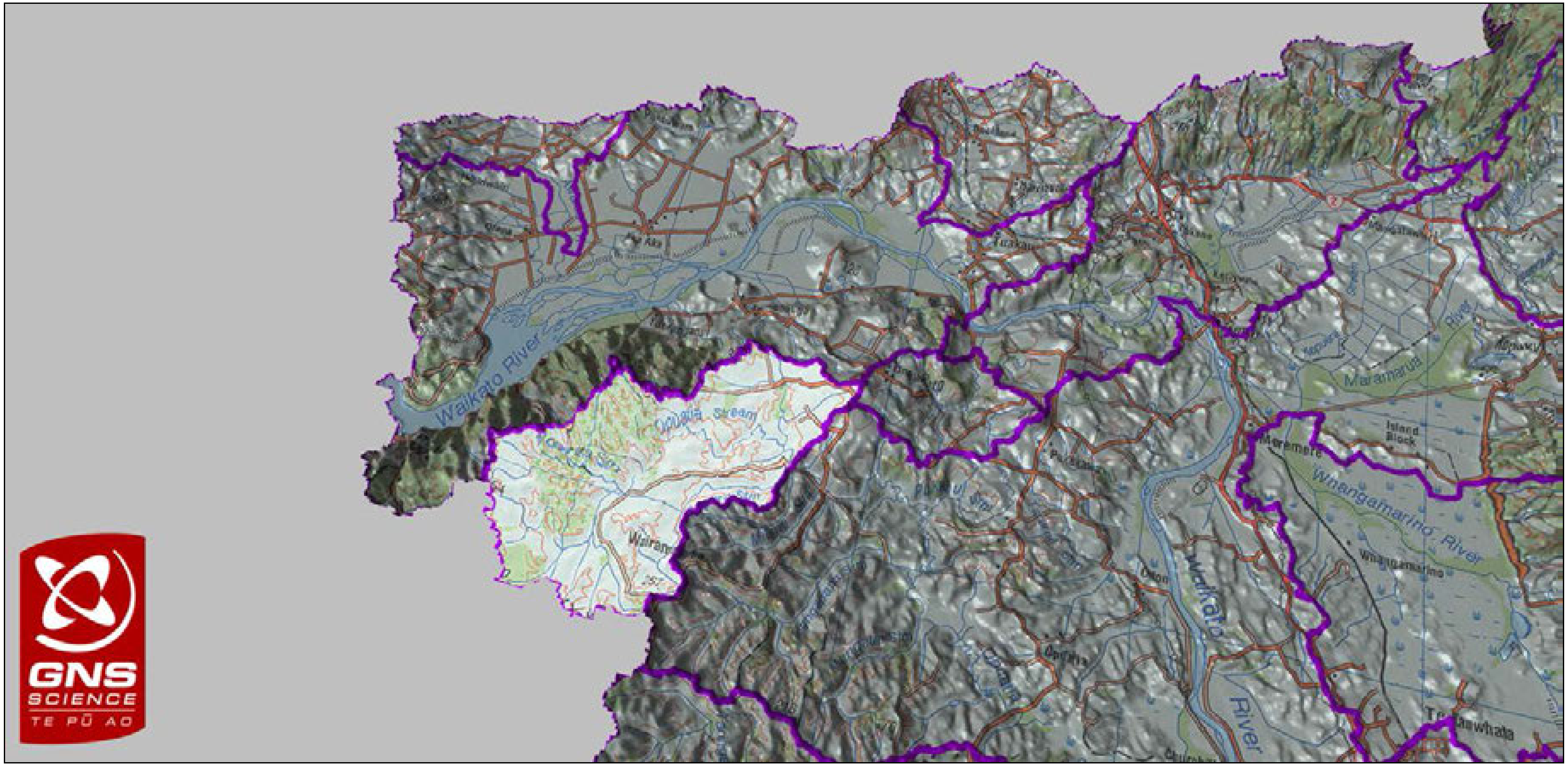

Figure A1.53: Zone: Lower Middle Waikato River. Catchment: Opuatia, 3008985.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Kerikeri Volcanic Group. Water tables are typically deeper than 3 m. Stream beds are typically dry in this relatively elevated catchment. No groundwater nitrate-nitrogen chemistry data is available in this catchment.

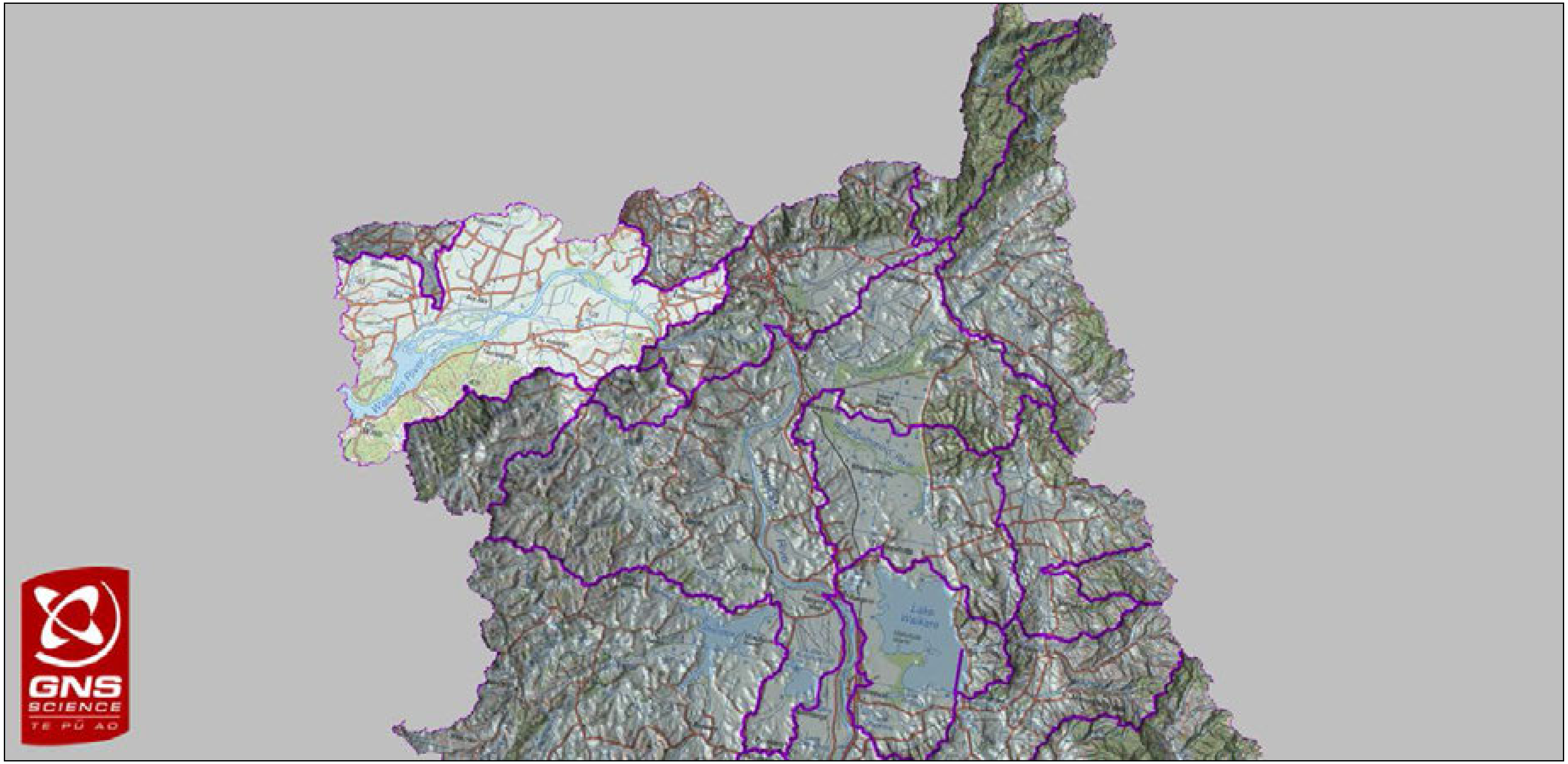

Figure A1.54: Zone: Lower Middle Waikato River. Catchment: Waikato at Port Waikato, 3009006.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically in the range 0.5 to 3 m. The area of the Waikato River valley is very low-lying and drainage systems provide baseflow in the Waikato River valley; other stream valleys are typically dry. Median nitrate concentrations in groundwater can be greater than MAV.

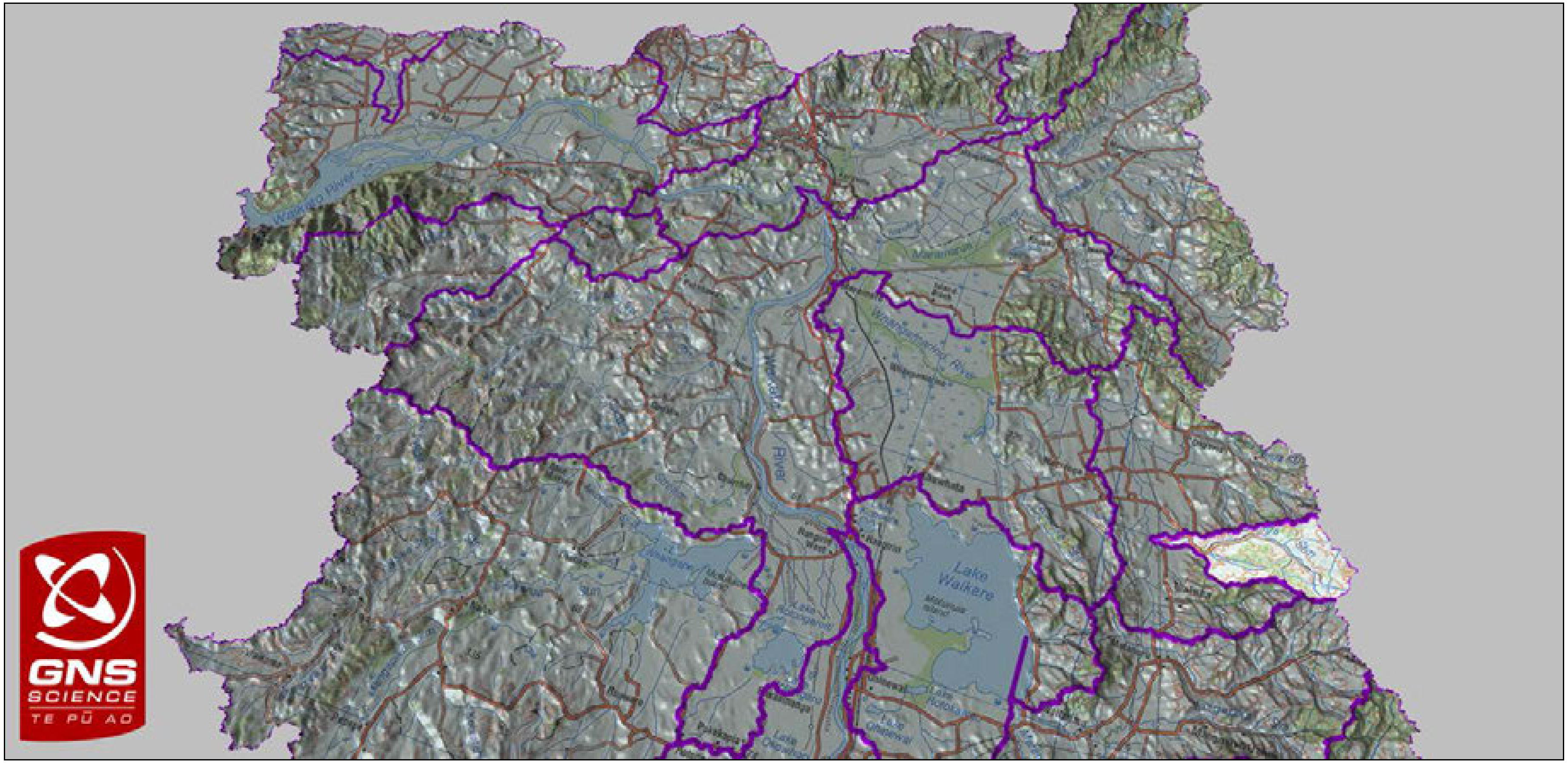

Figure A1.55: Zone: Lower Middle Waikato River. Catchment: Waerenga, 3009556.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Basement. Water tables are typically deeper than 3 m. Most streams are dry; basement rocks and fine sediments in the valleys make for quick runoff. No wells measure groundwater chemistry in this catchment.

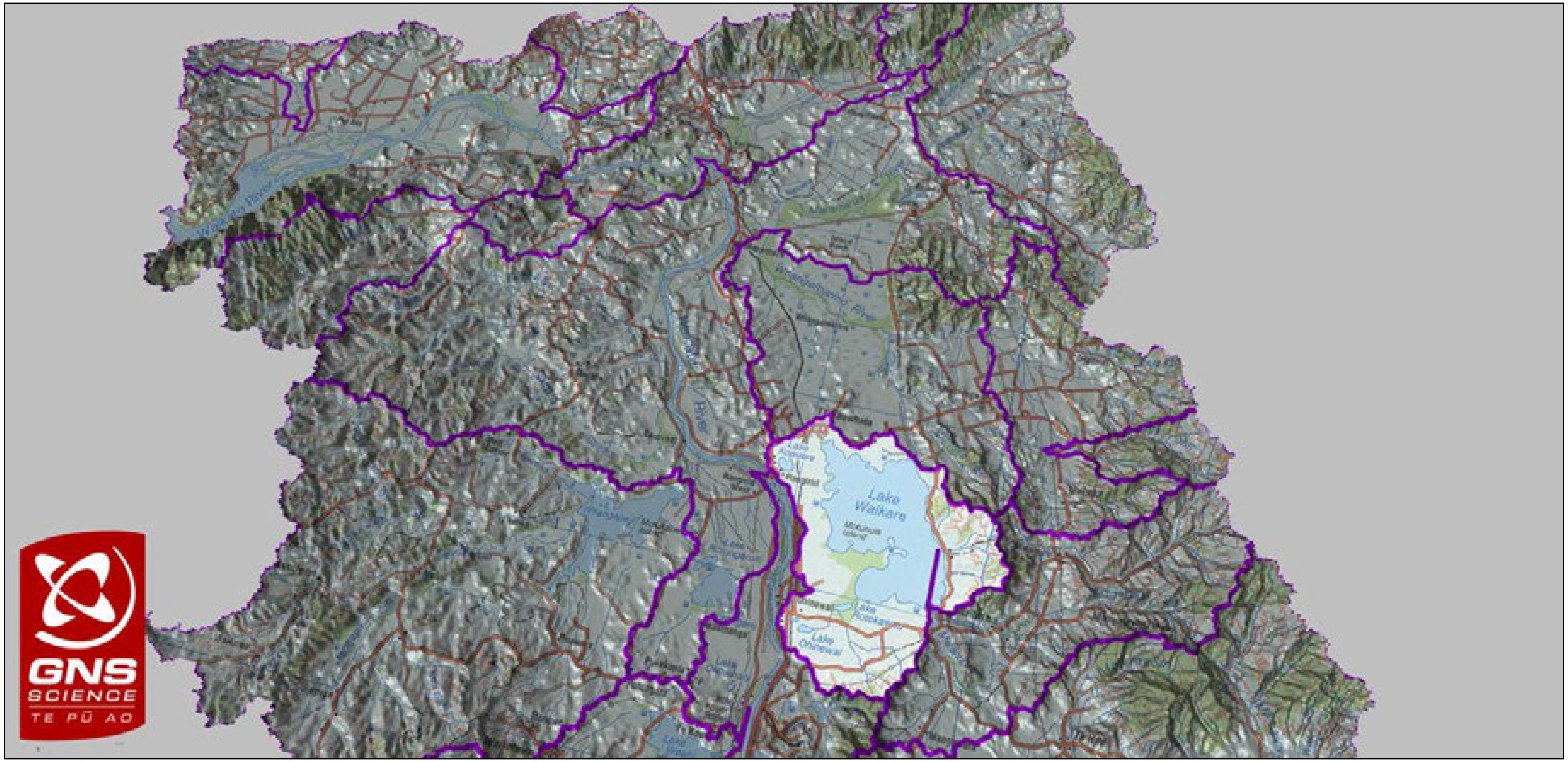

Figure A1.56: Zone: Lower Middle Waikato River. Catchment: Waikare, 3010071.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is unlikely. The water table is typically in the Tauranga Group. Water tables are typically very shallow, i.e. less than 0.5 m. Swamps are common around Lake Waikare. Stream beds are probably typically dry in the middle-upper reaches. Median nitrate concentrations in groundwater can be greater than MAV.

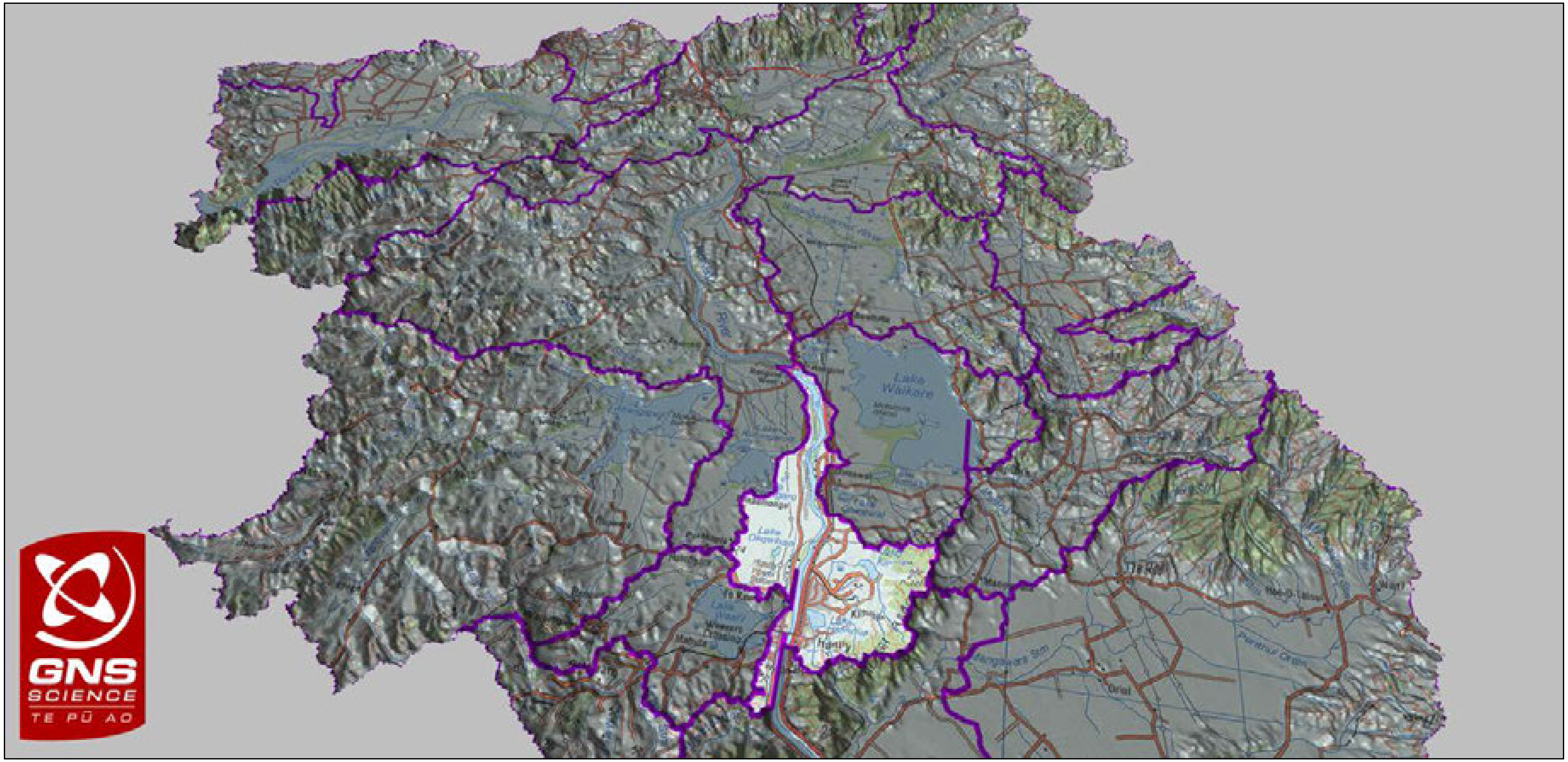

Figure A1.57: Zone: Lower Middle Waikato River. Catchment: Waikato at Rangiriri, 3010604.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Tauranga Group sediments include silt and sands; infiltration is relatively slow. Median nitrate concentration in groundwater is greater than MAV, however, only one well has been sampled.

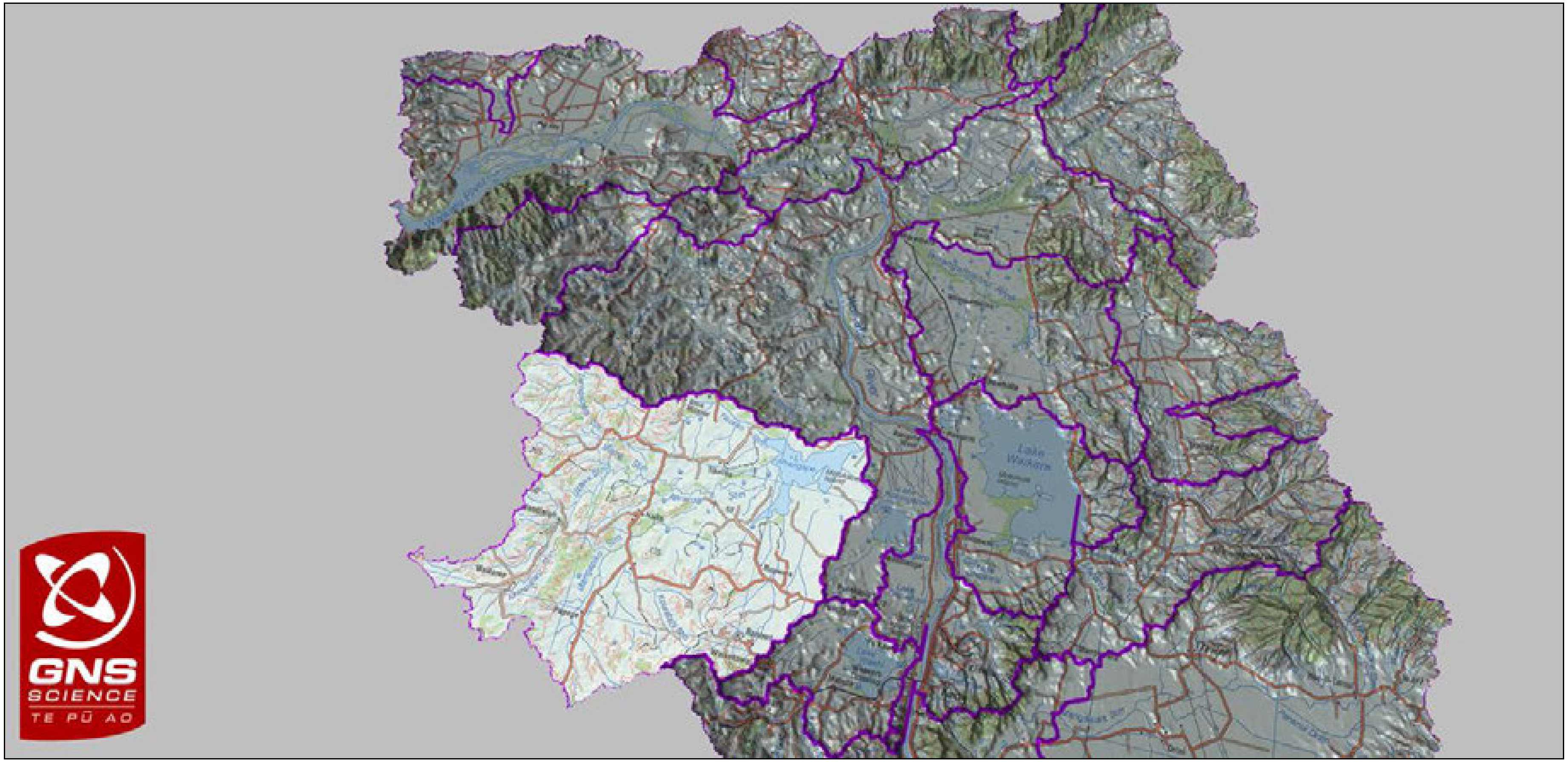

Figure A1.58: Zone: Lower Middle Waikato River. Catchment: Whangape, 3010847.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is unlikely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Stream beds are dry in their upper reaches. Valleys draining to Whangape are typically formed from silts and drained peats. Median nitrate concentrations in groundwater are low in this catchment.

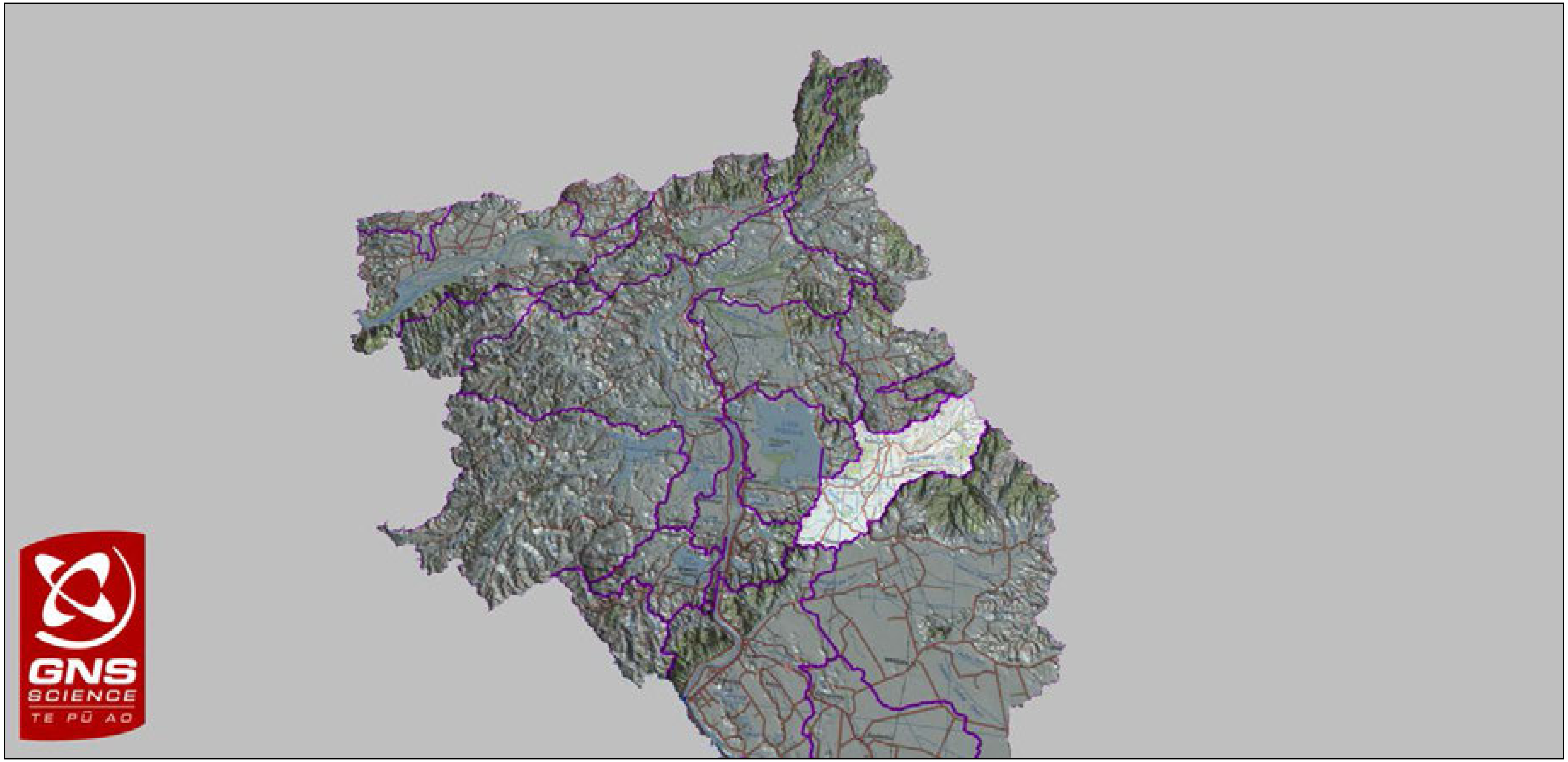

Figure A1.59: Zone: Lower Middle Waikato River. Catchment: Matahuru, 3010952.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is unlikely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Stream beds are typically dry in their upper reaches and basement rocks in the catchment, and fine sediments in the valleys, make for quick runoff. Median nitrate concentrations in groundwater can be greater than 1/2 MAV.

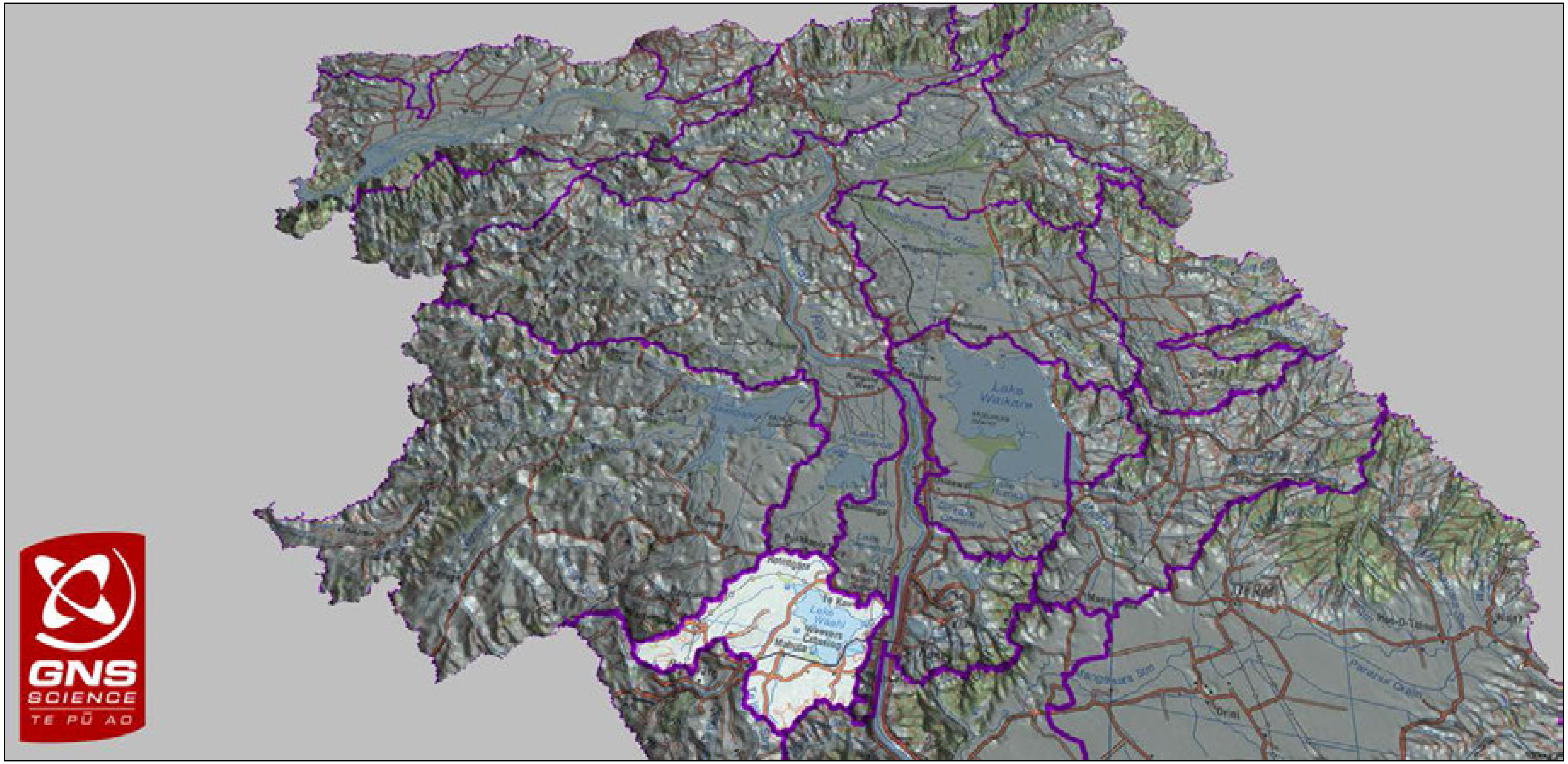

Figure A1.60: Zone: Lower Middle Waikato River. Catchment: Awaroa (Rotowaro) at Harris/Te Ohaki Br, 3012631.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is unlikely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Stream beds are probably typically dry in their upper reaches. Median nitrate concentrations in groundwater are low in this catchment.

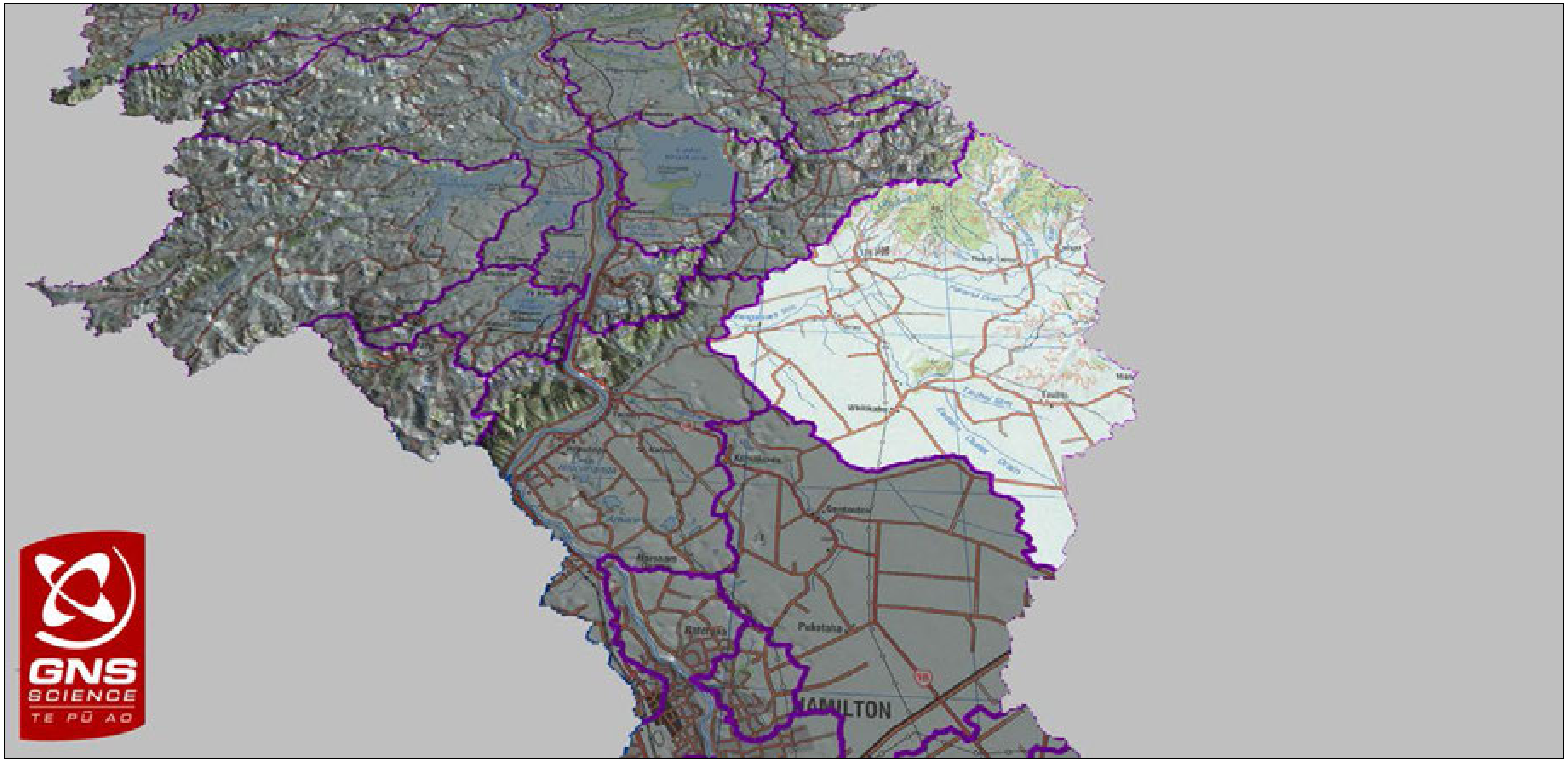

Figure A1.61: Zone: Lower Middle Waikato River. Catchment: Mangawara, 3013137.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is unlikely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Tauranga Group sediments include large areas of silt and drained peats where infiltration is relatively slow. Median nitrate concentrations in groundwater can be greater than 1/2 MAV.

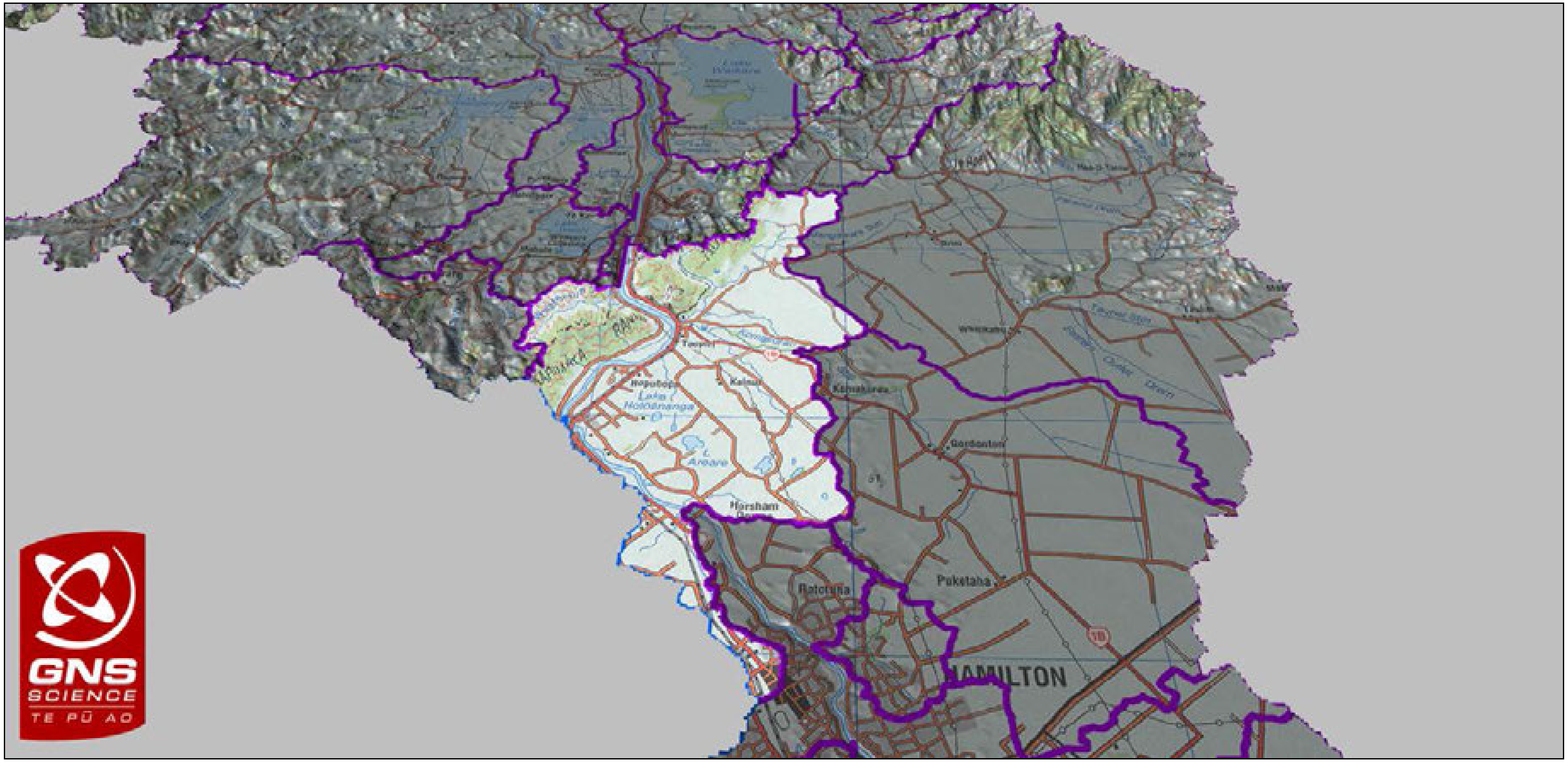

Figure A1.62: Zone: Lower Middle Waikato River. Catchment: Waikato at Huntly - Tainui Br, 3013160.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Tauranga Group sediments include Hinuera Formation where infiltration is relatively rapid and drained peats, where infiltration is slow. Median nitrate concentrations are elevated, up to 1/2 MAV.

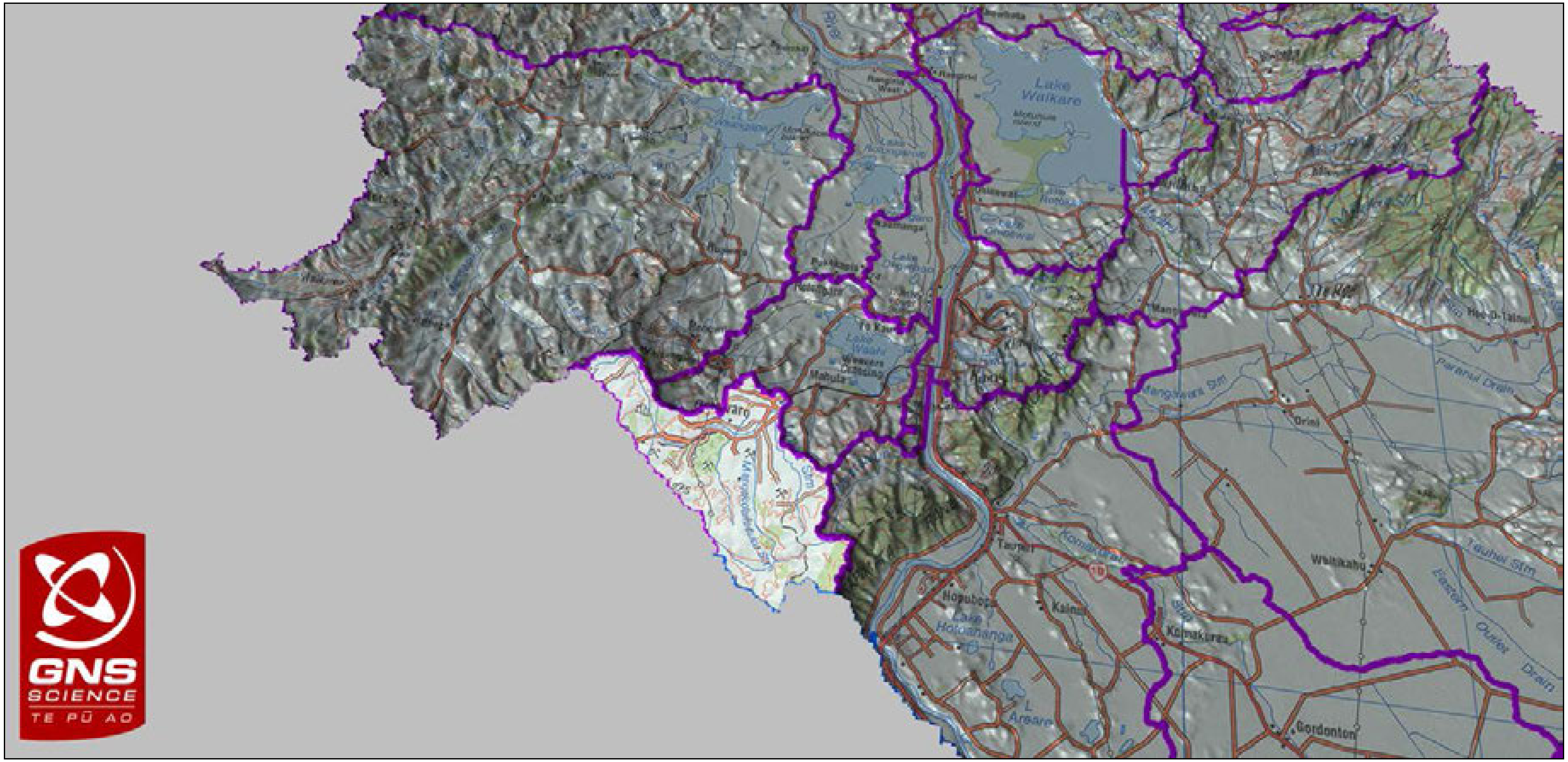

Figure A1.63:Zone: Lower Middle Waikato River. Catchment: Awaroa (Rotowaro) at Sansons Br, 3013581.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is unlikely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Stream beds are probably typically dry in their upper reaches. Median nitrate concentrations in groundwater are low in this catchment.

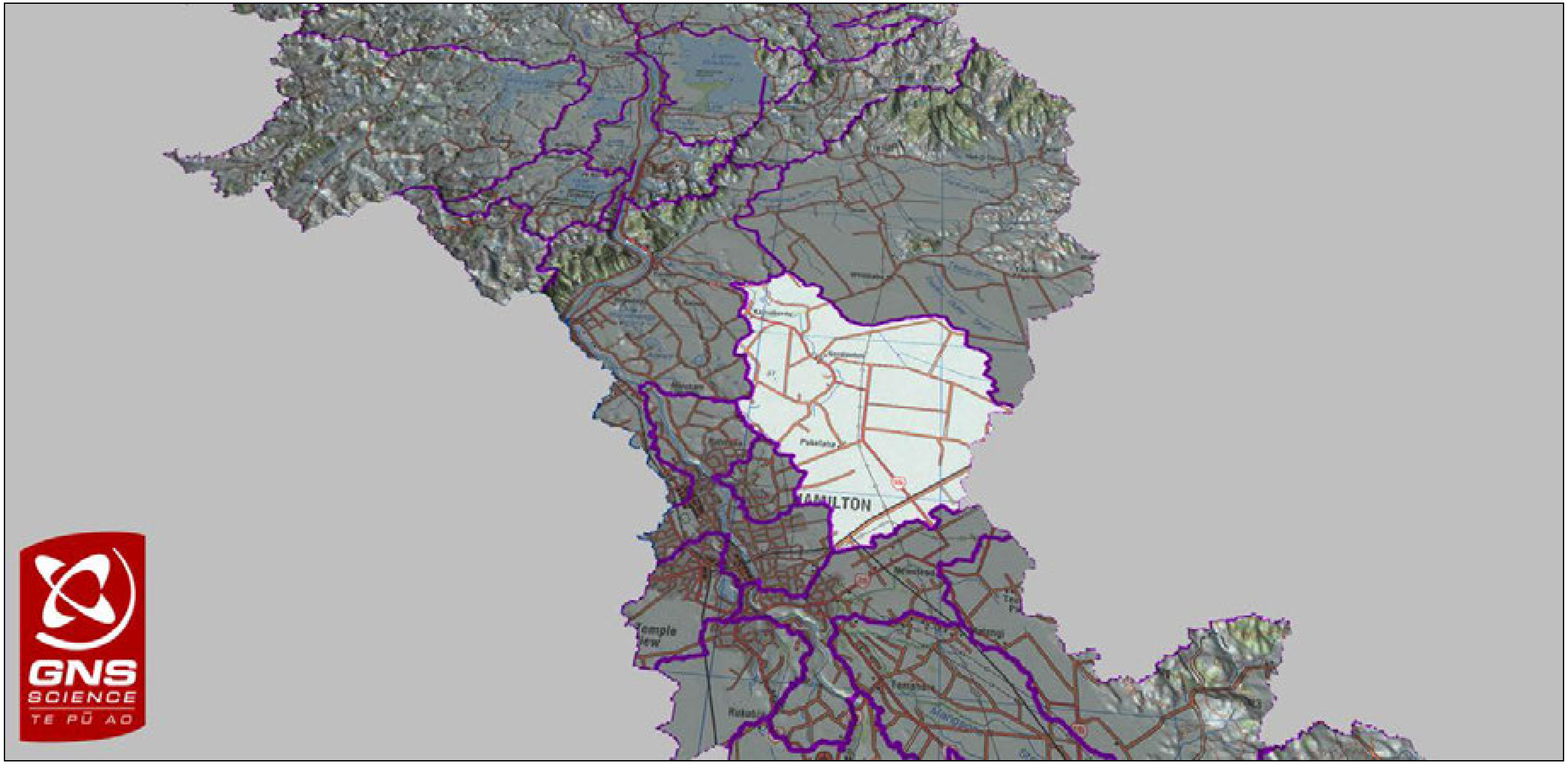

Figure A1.64: Zone: Lower Middle Waikato River. Catchment: Komakorau, 3014466.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is unlikely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Tauranga Group sediments large areas of drained peats, where infiltration is slow. Groundwater generally flows to the Waikato River above Taupiri. Median nitrate concentrations in groundwater can be greater than MAV.

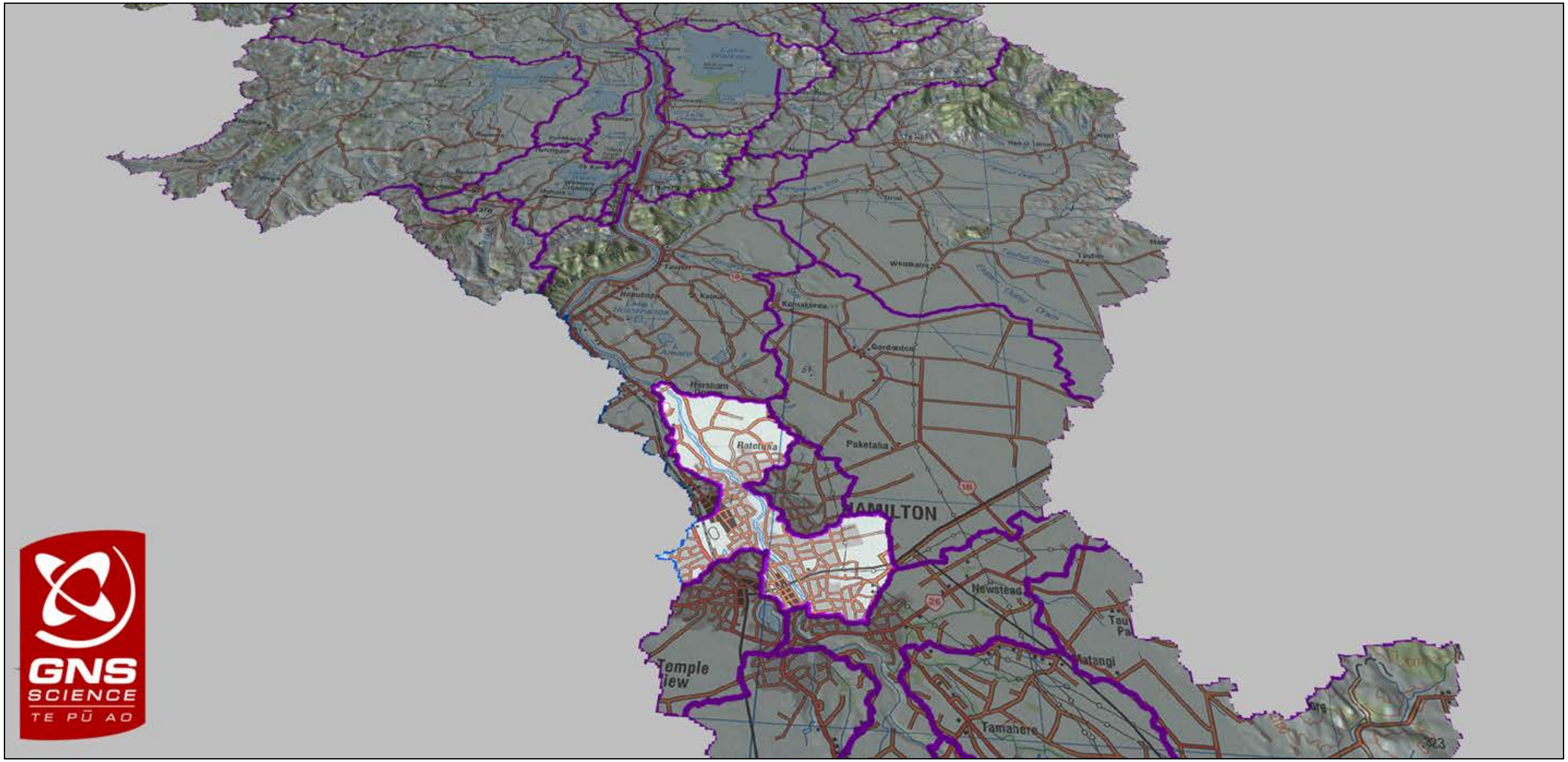

Figure A1.65: Zone: Lower Middle Waikato River. Catchment: Waikato at Horotiu Br, 3015830.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Tauranga Group sediments include Hinuera Formation where infiltration is relatively rapid. Groundwater flows towards the Waikato River. No wells measure groundwater chemistry in this catchment.

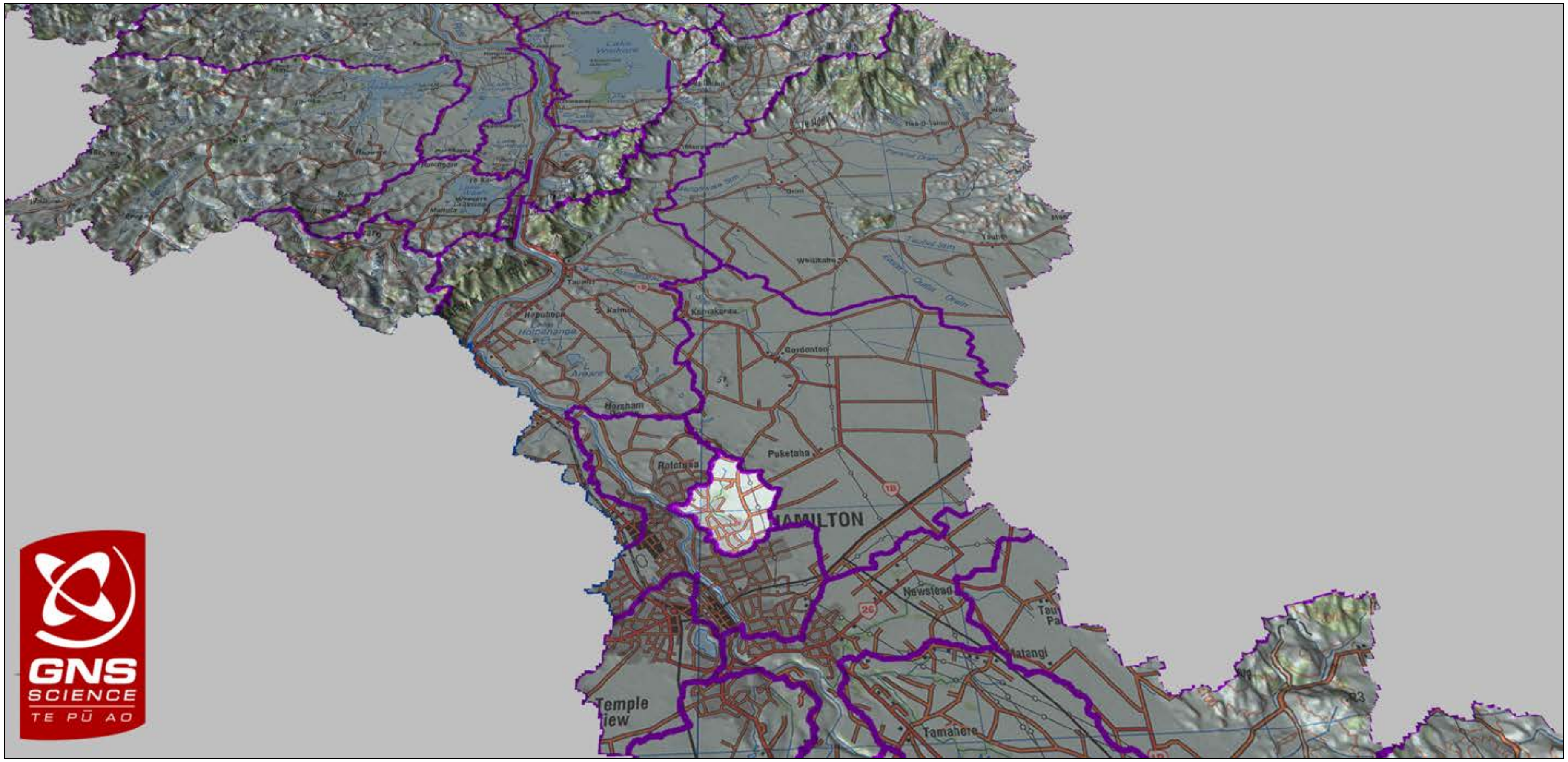

Figure A1.66: Zone: Lower Middle Waikato River. Catchment: Kirikiriroa, 3016924.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Tauranga Group sediments include Hinuera Formation where infiltration is relatively rapid. Groundwater flows towards the Waikato River. No wells measure groundwater chemistry in this catchment.

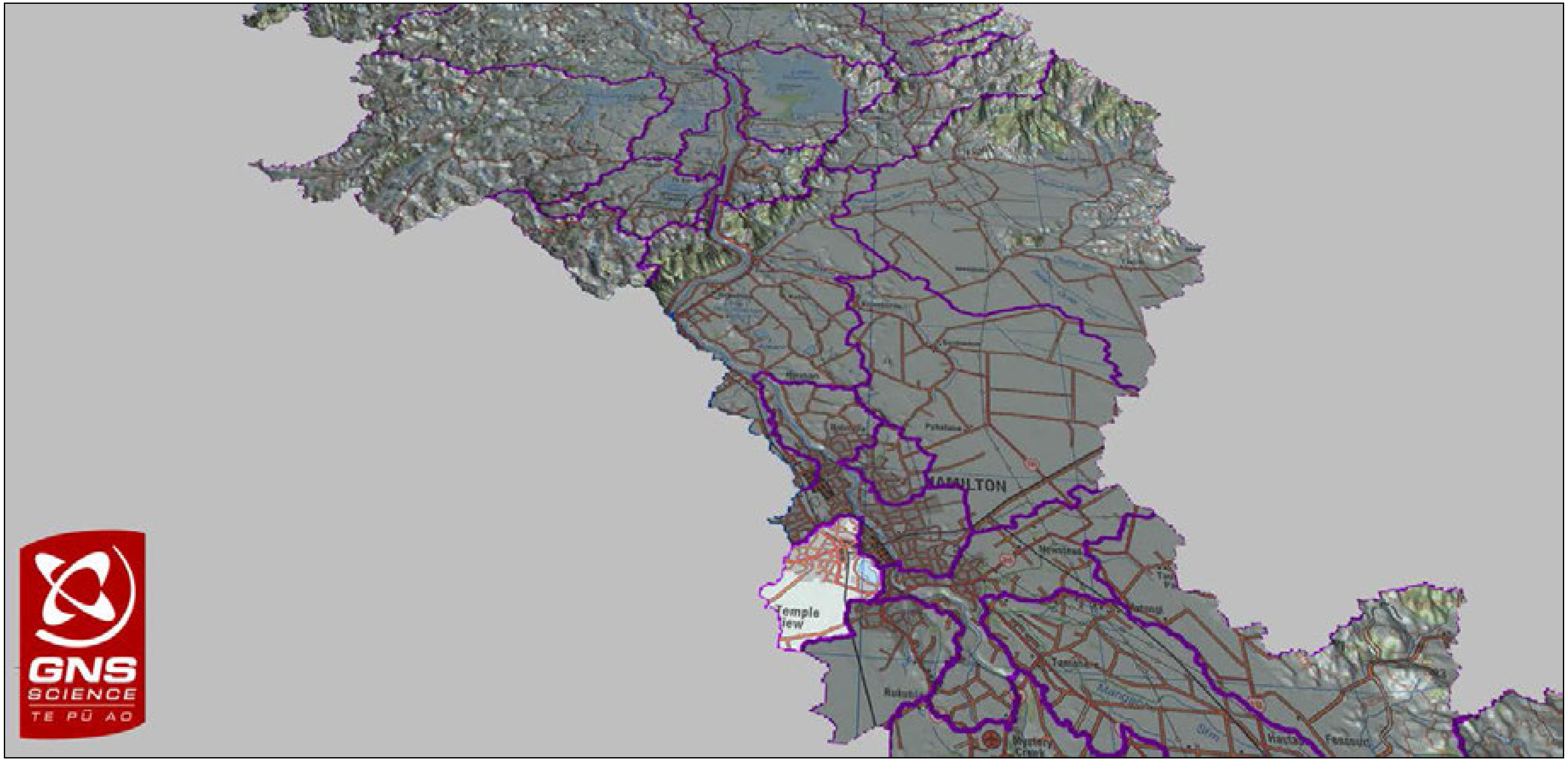

Figure A1.67: Zone: Lower Middle Waikato River. Catchment: Waitawhiriwhiri, 3017487.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Tauranga Group sediments include Hinuera Formation where infiltration is relatively rapid and drained peats, where infiltration is slow. Groundwater flows towards the Waikato River. Median nitrate concentrations in groundwater are low in this catchment.

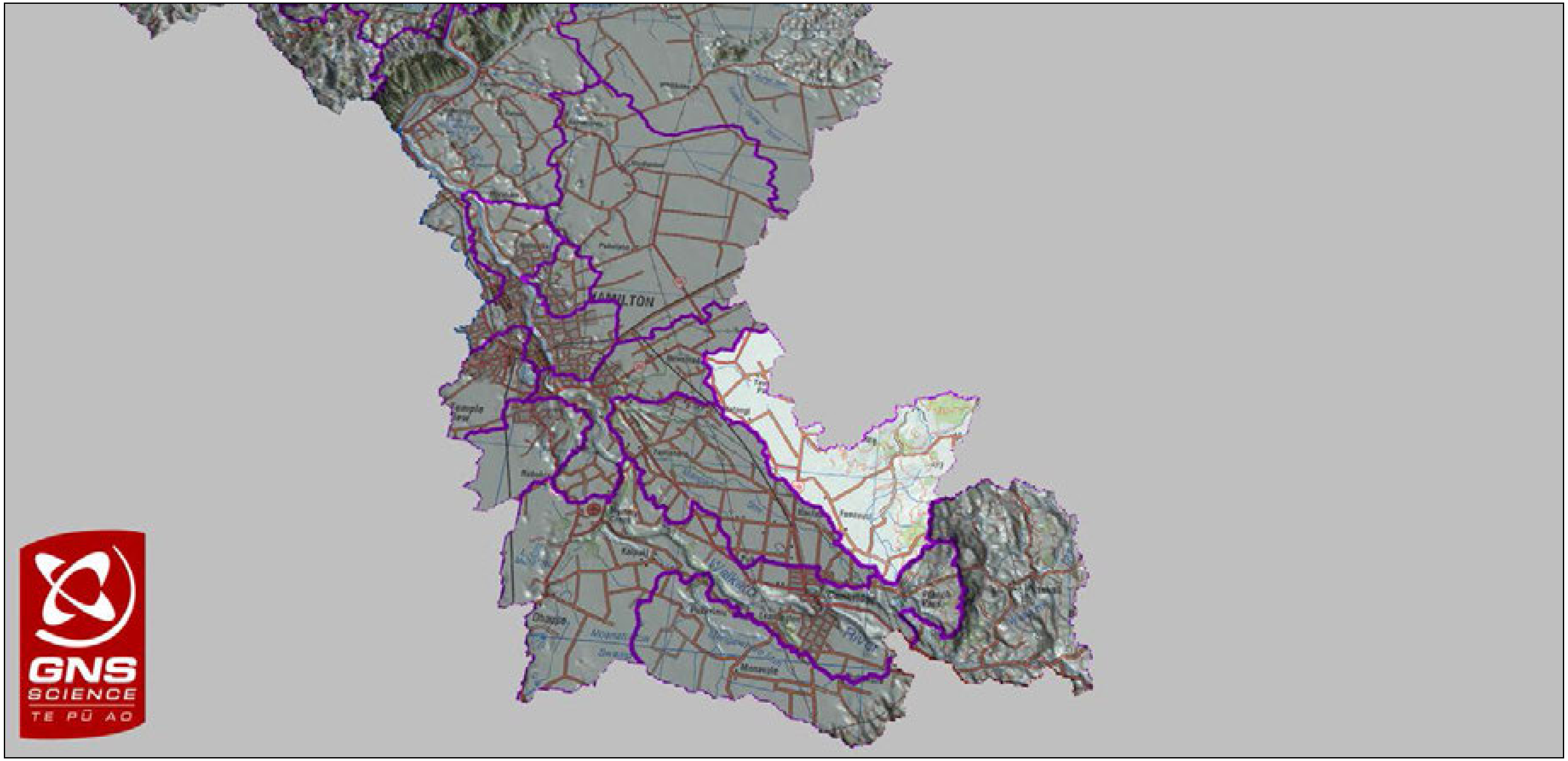

Figure A1.68: Zone: Lower Middle Waikato River. Catchment: Mangaonua, 3017726.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Tauranga Group sediments at the base of the hills include Hinuera Formation where infiltration is relatively rapid. Median nitrate concentrations in groundwater can be greater than 1/2 MAV.

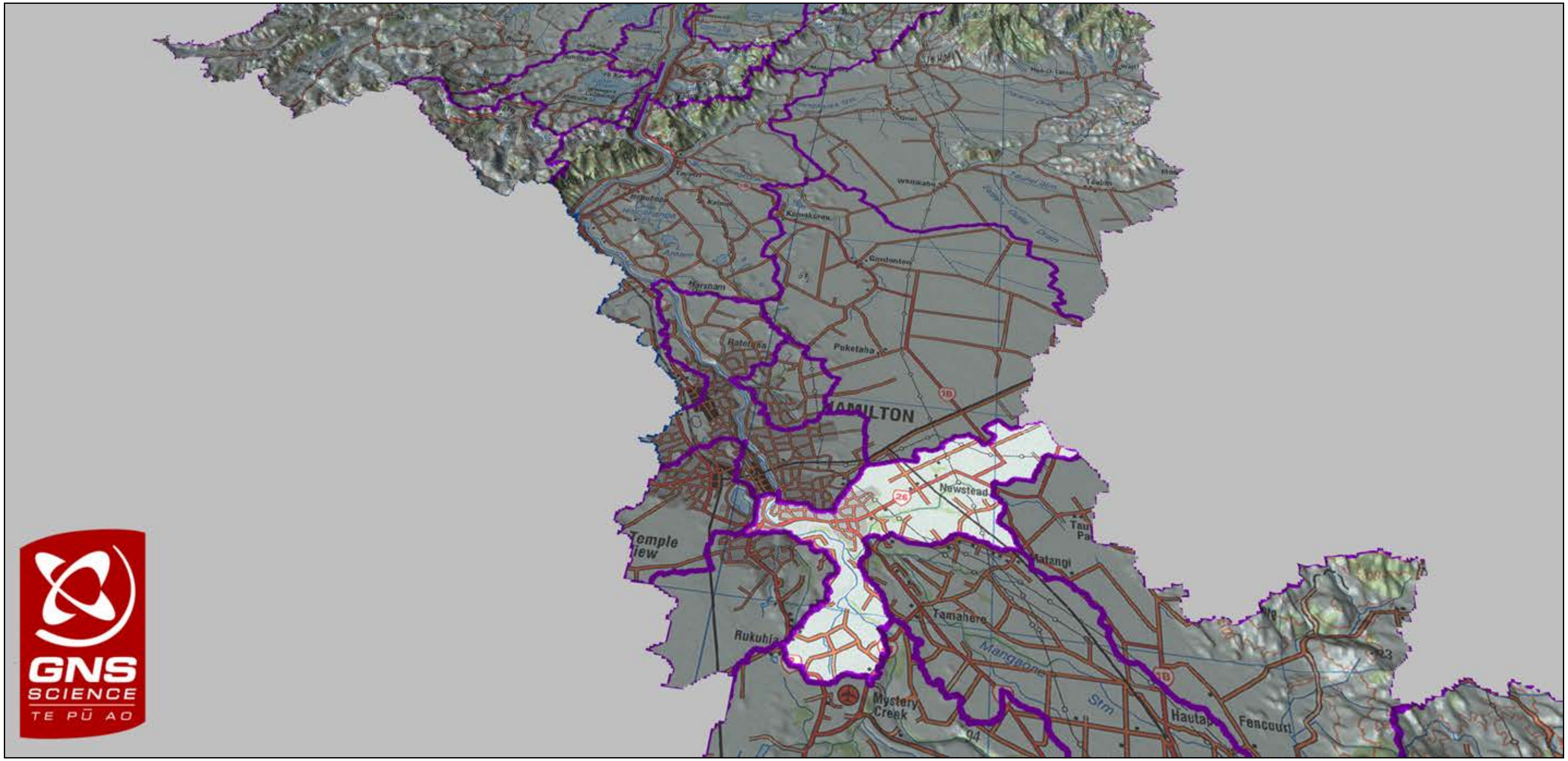

Figure A1.69: Zone: Lower Middle Waikato River. Catchment: Waikato at Bridge St Br, 3017901.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is unlikely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Tauranga Group sediments include Hinuera Formation where infiltration is relatively rapid and drained peats, where infiltration is slow. Groundwater flows towards the Waikato River. Median nitrate concentrations are elevated, up to 1/2 MAV.

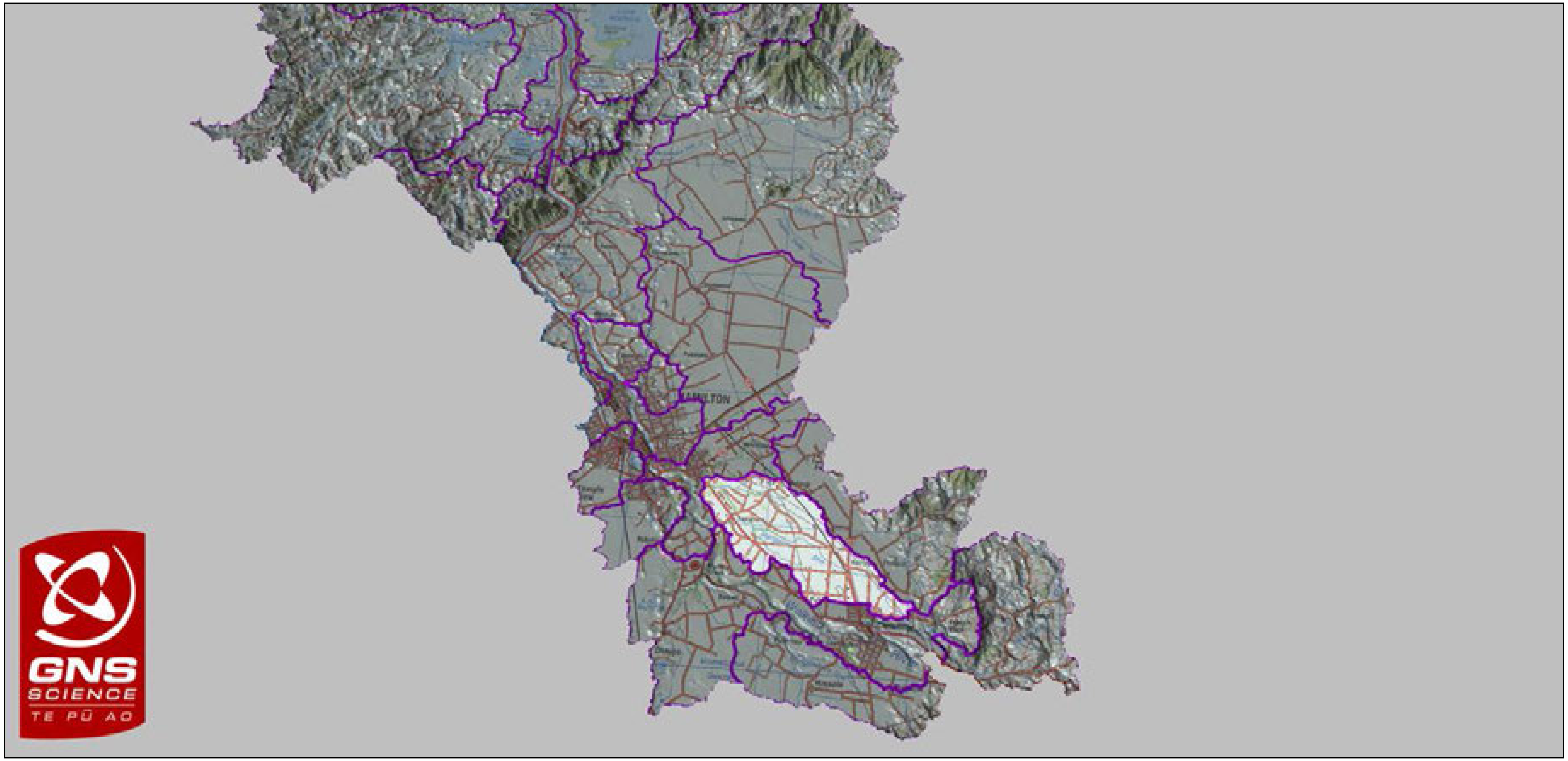

Figure A1.70: Zone: Lower Middle Waikato River. Catchment: Mangaone, 3018213.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Tauranga Group sediments include Hinuera Formation where infiltration is relatively rapid. Groundwater flows down the Mangaone Stream catchment and then towards the Waikato River. Median nitrate concentrations in groundwater can be greater than MAV.

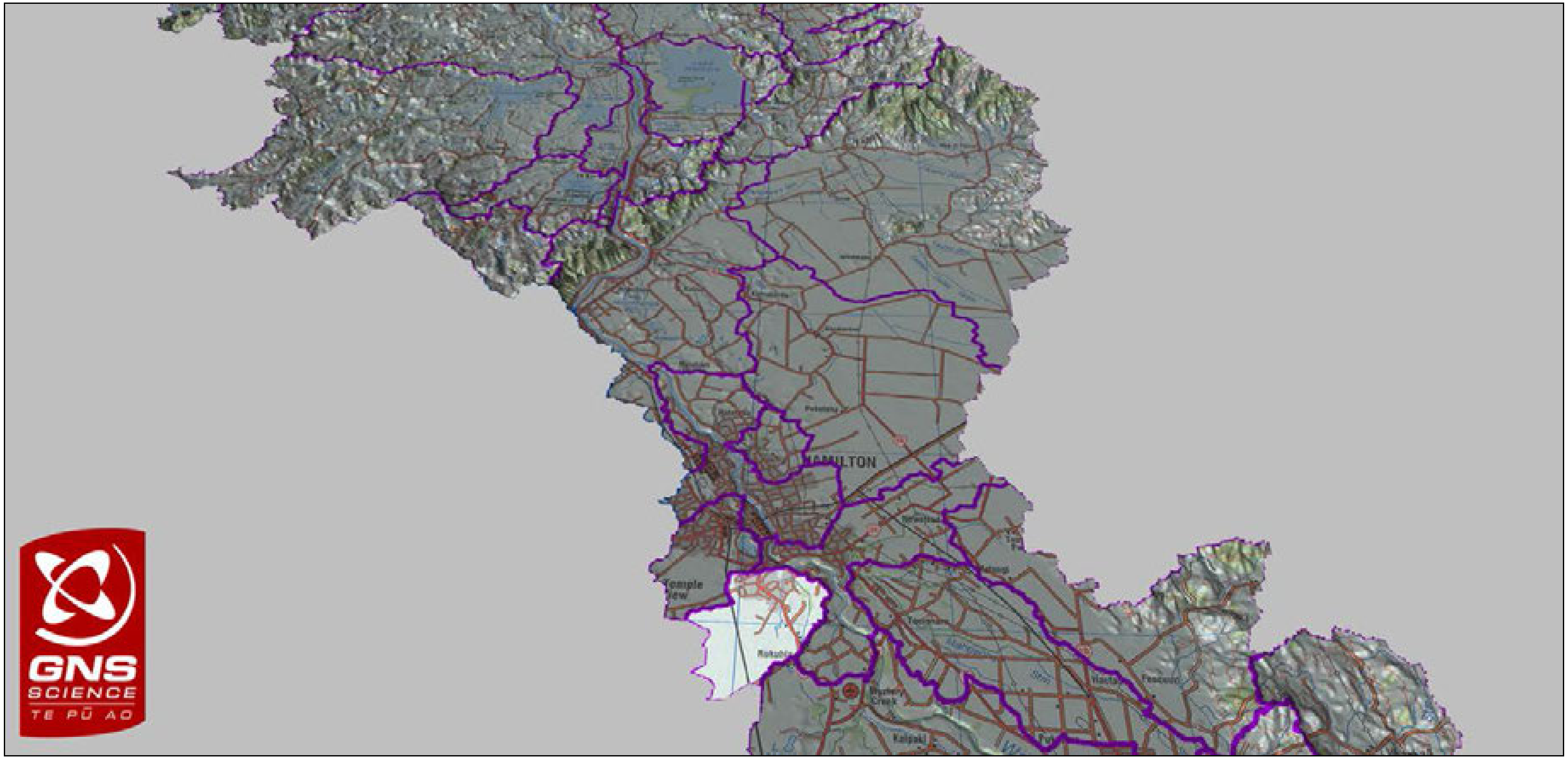

Figure A1.71: Zone: Lower Middle Waikato River. Catchment: Mangakotukutuku, 3018237.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Tauranga Group sediments include Hinuera Formation where infiltration is relatively rapid and drained peats, where infiltration is slow. Groundwater flows towards the Waikato River. No wells measure groundwater chemistry in this catchment.

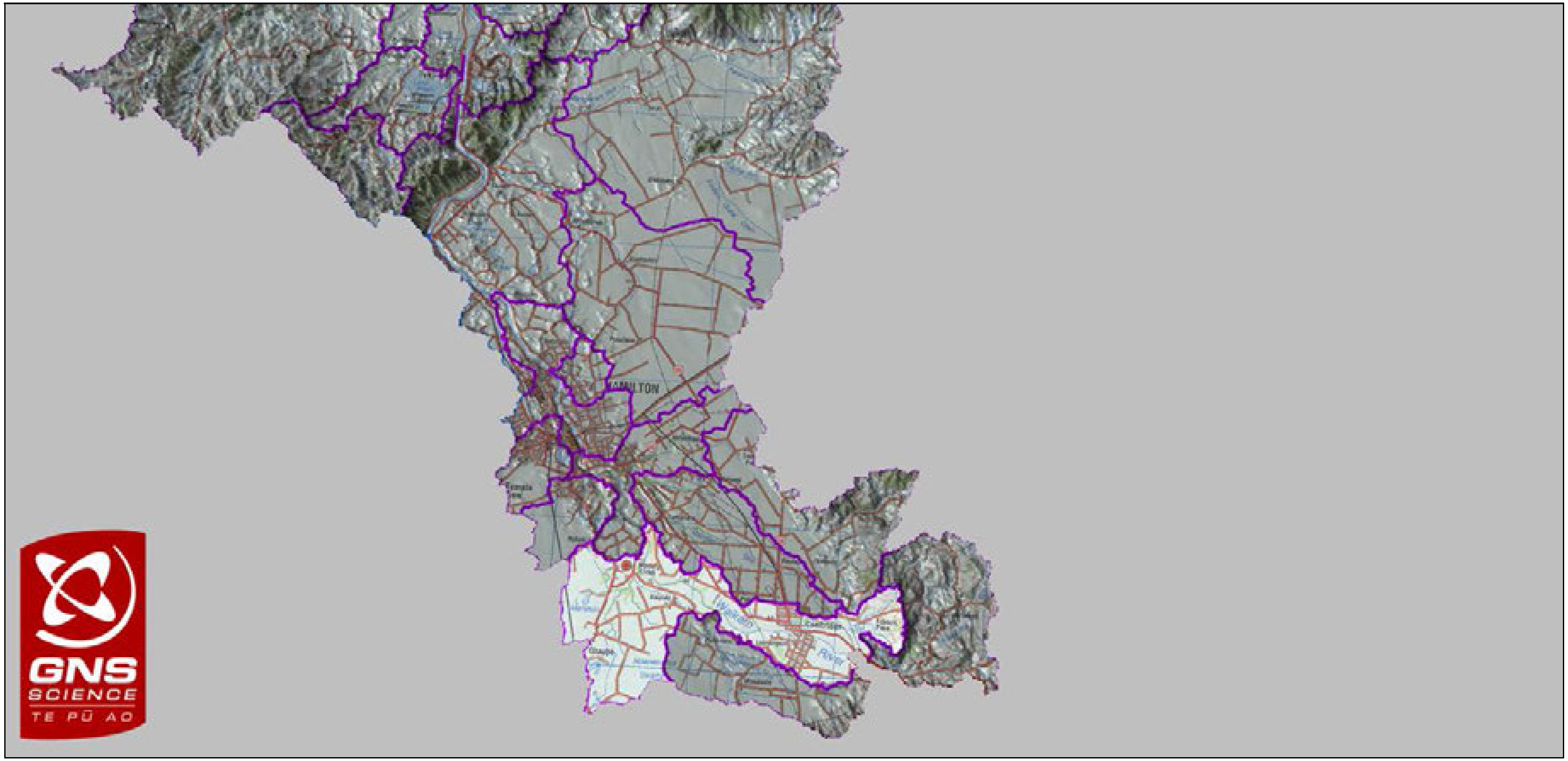

Figure A1.72: Zone: Lower Middle Waikato River. Catchment: Waikato at Narrows, 3018977.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Tauranga Group sediments include Hinuera Formation where infiltration is relatively rapid and drained peats, where infiltration is slow. Median nitrate concentrations in groundwater can be greater than MAV.

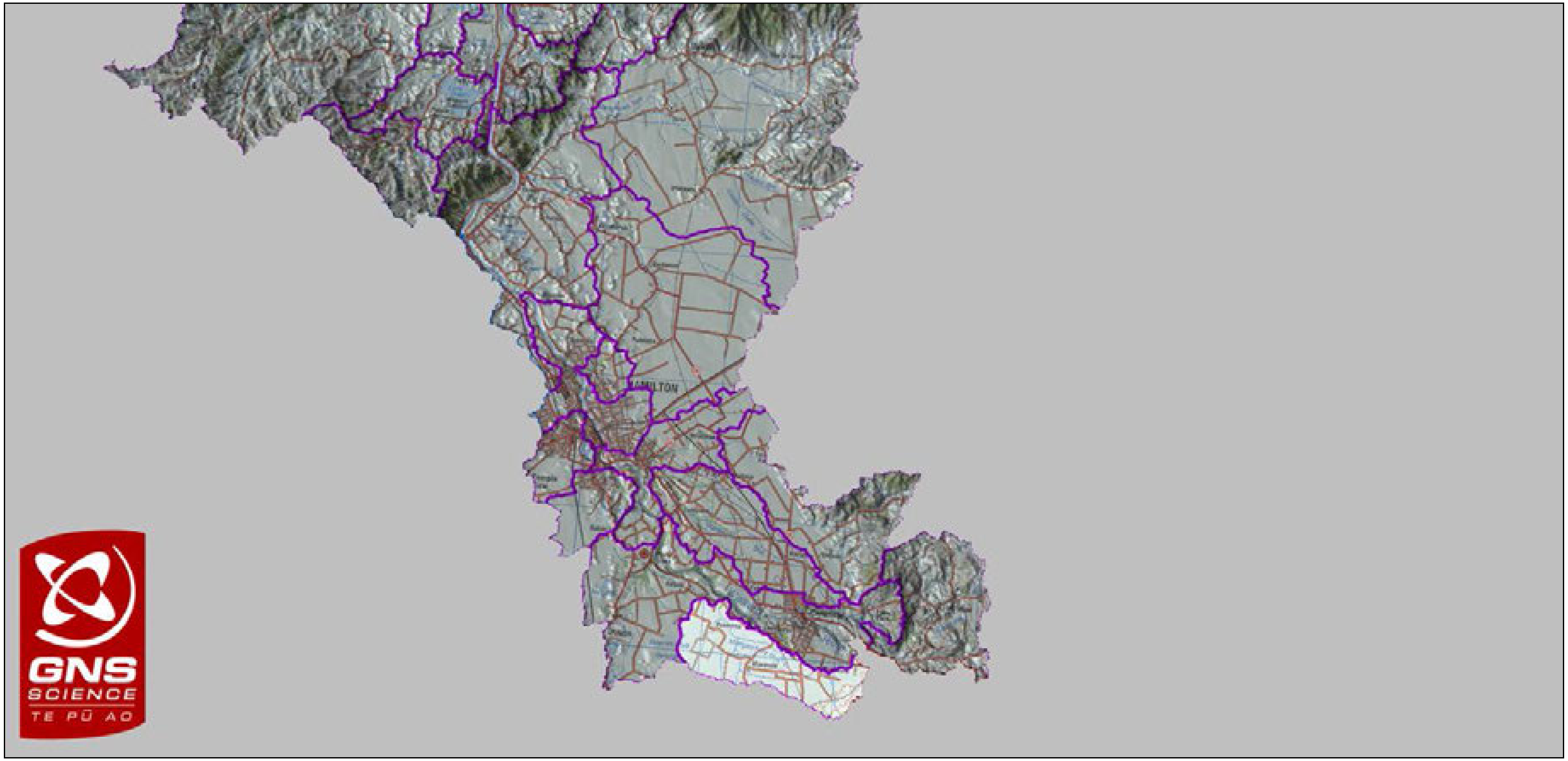

Figure A1.73: Zone: Lower Middle Waikato River. Catchment: Mangawhero, 3020102.

Baseflow and quick flow are both important to surface flow and groundwater outflow from the catchment is likely. The water table is typically in the Tauranga Group. Water tables are typically deeper than 3 m. Tauranga Group sediments include Hinuera Formation where infiltration is relatively rapid and drained peats, where infiltration is slow. Groundwater flows towards the Waikato River. Median nitrate concentrations in groundwater can be greater than 1/2 MAV.

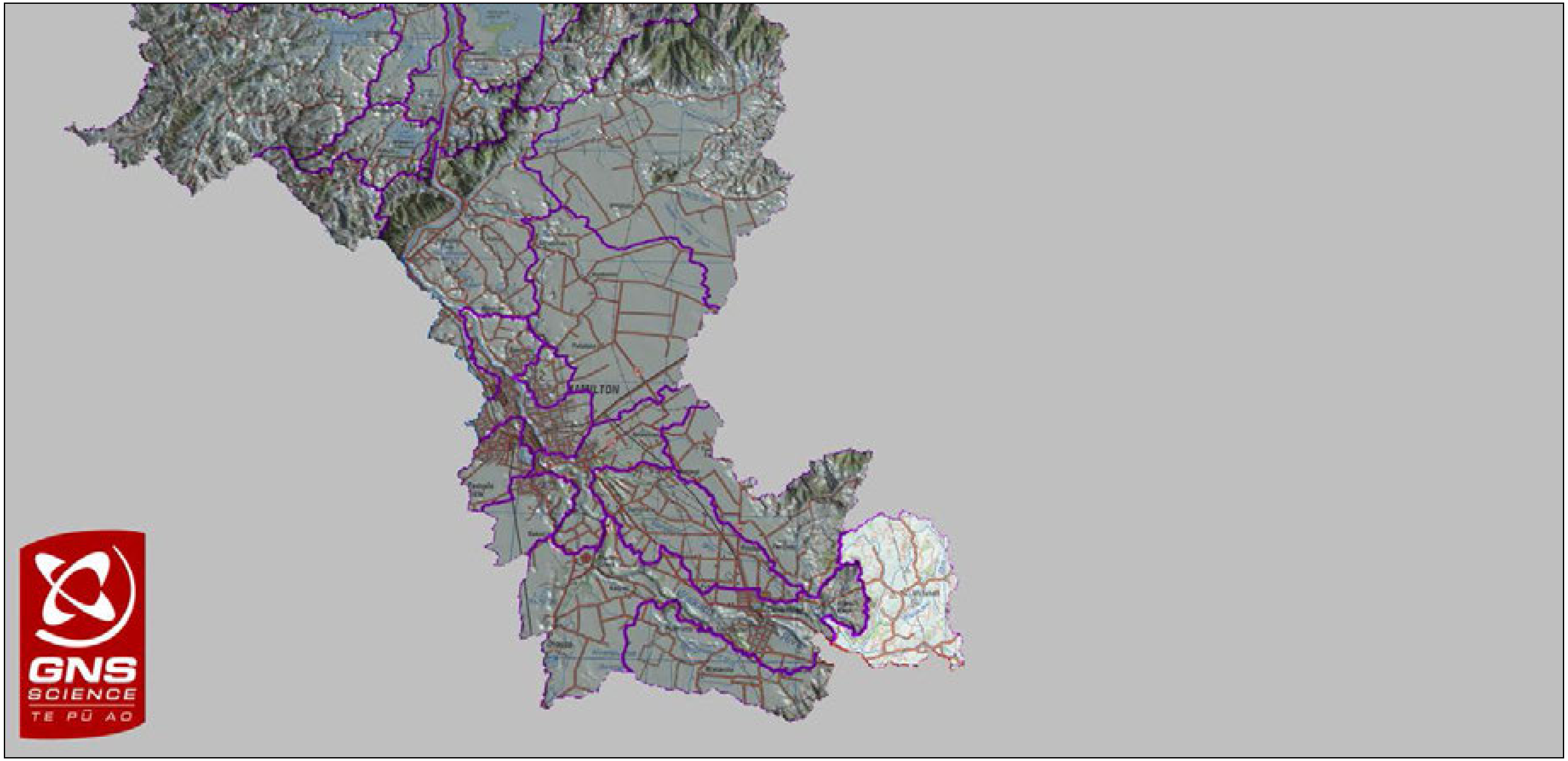

Figure A1.74: Zone: Lower Middle Waikato River. Catchment: Karapiro, 3020352.

Surface flow is dominated by baseflow and groundwater outflow from the catchment is likely. The water table is typically in the Pakaumanu Group. Water tables are typically deeper than 3 m. Valleys are generally dry as ignimbrite is prominent. Median nitrate concentrations in groundwater are low in this catchment.

APPENDIX 2: GEOLOGICAL DATA

Geological data in each HRP catchment includes the thicknesses of the main aquifers in the catchment as estimated with the geological models.

Table A2.1 LMW Geology 1

Catchment Name Units	NZ Reach	Geology dom. surface Qmap	Geology water table aquifer	Principal aquifer geology	Geomorphology comment
Whakapipi	3006346	Kerikeri Volcanic Group	Kerikeri Volcanic Group	Kerikeri Volcanic Group	Hills, dissected by small river valleys
Waikato at Tuakau Br	3007421	Kerikeri Volcanic Group	Kerikeri Volcanic Group	Kerikeri Volcanic Group	Hills, alluvial flats, relict swamps and Waikato River valley
Ohaeroa	3007733	Kerikeri Volcanic Group	Kerikeri Volcanic Group	Kerikeri Volcanic Group	Rolling hills
Awaroa (Waiuku)	3007434	Awhitu Group	Awhitu Group	Awhitu Group	Coastal sands and flat plain
Whangape	3010847	Te Kuiti Group	Tauranga Group	Te Kuiti Group	Hills, relict swamps and Lake Whangape
Waikato at Mercer Br	3006806	Te Kuiti Group	Tauranga Group	Kerikeri Volcanic Group	Hills, swamps, small lakes and Waikato River
Opuatia	3008985	Te Kuiti Group	Kerikeri Volcanic Group	Kerikeri Volcanic Group	Rolling hills
Mangatawhiri	3005110	Basement	Basement	Basement	Greywacke ranges and valleys
Mangatangi	3006132	Basement	Tauranga Group	Tauranga Group	Rolling hills and plain
Whangamarino at Jefferies Rd Br	3008369	Basement	Tauranga Group	Tauranga Group	Hills and alluvial plain
Awaroa (Rotowaro) at Sansons Br	3013581	Te Kuiti Group	Te Kuiti Group	Te Kuiti Group	Dissected valleys
Waikato at Huntly-Tainui Br	3013160	Tauranga Group	Tauranga Group	Tauranga Group	Alluvial plain, small lakes, Waikato River and range to the west
Matahuru	3010952	Basement	Tauranga Group	Tauranga Group	Hills and alluvial plain
Waerenga	3009556	Basement	Basement	Basement	Rolling hills draping a low range
Mangawara	3013137	Tauranga Group	Tauranga Group	Tauranga Group	Alluvial plain and Hills
Komakorau	3014466	Tauranga Group	Tauranga Group	Tauranga Group	Alluvial plain with drainage network
Waikato at Bridge St Br	3017901	Tauranga Group	Tauranga Group	Tauranga Group	River plain dissected by Waikato River
Mangakotukutuku	3018237	Tauranga Group	Tauranga Group	Tauranga Group	river plain
Mangaonua	3017726	Tauranga Group	Tauranga Group	Tauranga Group	Basement ranges flattening to river plain
Mangaone	3018213	Tauranga Group	Tauranga Group	Tauranga Group	River plain
Whangamarino at Island Block Rd	3007681	Tauranga Group	Tauranga Group	Basement	Alluvial plain, swamps and small lakes
Waikato at Rangiriri	3010604	Tauranga Group	Tauranga Group	Tauranga Group	Plain, swamp with small lakes and Waikato River
Waikato at Horotiu Br	3015830	Tauranga Group	Tauranga Group	Tauranga Group	Alluvial plain
Kirikiriroa	3016924	Tauranga Group	Tauranga Group	Tauranga Group	Alluvial plain
Waitawhiriwhiri	3017487	Tauranga Group	Tauranga Group	Tauranga Group	Alluvial plain
Waikato at Port Waikato	3009006	Tauranga Group	Tauranga Group	Tauranga Group	Waikato River valley including coastal sands, flanks of volcanoes and dissected valleys
Mangawhero	3020102	Tauranga Group	Tauranga Group	Tauranga Group	River plain and foothills on flanks of Maungatauteri
Waikato at Narrows	3018977	Tauranga Group	Tauranga Group	Tauranga Group	River plain dissected by Waikato River
Karapiro	3020352	Basement	Pakaumanu Group	Pakaumanu Group	Low hills and stream valleys
Awaroa (Rotowaro) at Harris/Te Ohaki Br	3012631	Tauranga Group	Tauranga Group	Tauranga Group	Dissected valleys down to relict swamps and Lake Waahi
Waikare	3010071	Tauranga Group	Tauranga Group	Tauranga Group	Lake Waikare, swamp and small lakes

Table A2.2 Waipa Geology 1

Catchment Name Units	NZ Reach	Geology dom. surface Qmap	Geology water table aquifer	Principal aquifer geology	Geomorphology comment
Waipa at SH23 Br Whatawhata	3017829	Tauranga Group	Tauranga Group	Tauranga Group	Flat river plain
Kaniwhaniwha	3019566	Alexandra Group volcanics	Tauranga Group	Tauranga Group	Basalt cone flattening out to alluvial plains.
Mangapiko	3022010	Tauranga Group	Tauranga Group	Tauranga Group	Flat river plain with elevation increasing to the east into basement ranges and andesite/lahar deposits.
Mangauika	3023179	Alexandra Group volcanics	Alexandra Group volcanics	Alexandra Group volcanics	Basalt cone.
Mangaohoi	3023476	Maungatautari Formation	Maungatautari Formation	Maungatautari Formation	Cone of andesite/lahar deposits.
Puniu at Bartons Corner Rd Br	3023180	Tauranga Group	Tauranga Group	Tauranga Group	Basement and ignimbrite ranges flattening to river plain to the northwest.
Waipa at Pirongia-Ngutunui Rd Br	3022669	Tauranga Group	Tauranga Group	Tauranga Group	Flat river plain with two small basalt cones in the centre and a large basalt cone to the west (Pirongia).
Waitomo at Tumutumu Rd	3028966	Mahoenui Group	Mahoenui Group	Mahoenui Group	Limestone and mudstone dominated hills with small incised river valley
Mangapu	3027166	Mahoenui Group	Holocene sediments	Mahoenui Group	Incised river valleys.
Mangaokewa	3031564	Pakaumanu Group	Pakaumanu Group	Pakaumanu Group	Ignimbrite ranges flattening to the west
Waipa at Otewa	3029370	Greywacke	Pakaumanu Group	Pakaumanu Group	Greywacke and ignimbrite ranges
Waipa at Mangaokewa Rd	3036214	Pakaumanu Group	Pakaumanu Group	Pakaumanu Group	Ignimbrite ranges
Ohote	3017348	Tauranga Group	Tauranga Group	Tauranga Group	flat river plain
Waipa at Otorohanga	3027129	Holocene sediments (Tauranga? check)	Holocene sediments (Tauranga? check)	Holocene sediments (Tauranga? check)	Basement ranges in the southeast flattening to river plain in the northwest.
Waitomo at SH31 Otorohanga	3026779	Te Kuiti Group	Mahoenui Group	Mahoenui Group	River valley
Mangatutu	3024473	Pakaumanu Group	Pakaumanu Group	Pakaumanu Group	Basement and Ignimbrite ranges shallowing to a river plain to the north.
Firewood	3015451	Basement (Murihiku terrane)	Tauranga Group	Tauranga Group	Steep Basement ranges with small Quaternary valleys
Moakurarua	3023962	Basement (Murihiku terrane)	Alexandra Group volcanics	Alexandra Group volcanics	Steep Basalt cone in the north and basement ranges in the west.
Puniu at Wharepapa	3025988	Pakaumanu Group	Pakaumanu Group	Pakaumanu Group	Basement and Ignimbrite ranges
Mangarapa	3028468	Te Kuiti Group	Tauranga Group	Tauranga Group	Incised river valley
Mangarama	3031371	Mahoenui Group	Mahoenui Group	Mahoenui Group	Incised river valley
Waipa at Waingaro Rd Br	3015066	Tauranga Group	Tauranga Group	Tauranga Group	Steep basement ranges in the west flattening to river plain

Table A2.3 UW Geology 1

Catchment Name Units	NZ Reach	Geology dom. surface Qmap	Geology water table aquifer	Principal aquifer geology	Geomorphology comment
Waikato at Karapiro	3020656	Pakaumanu Group with Maungatautari Formation	Pakaumanu Group	Pakaumanu Group	Broad valley of Waikato River
Pokaiwhenua	3023849	Whakamaru Group	Whakamaru Group	Whakamaru Group	Mamaku Plateau down to rolling country
Waikato at Waipapa	3030247	Whakamaru Group	Whakamaru Group	Whakamaru Group	Rolling country, domes and Waikato River
Tahunaatara	3032435	Tauranga Group	Tauranga Group	Tauranga Group	Mamaku Plateau down to rolling country
Mangakino	3036710	Whakamaru Group	Whakamaru Group	Whakamaru Group	Dissected plateau on flanks of mountains
Waikato at Ohakuri	3035123	Tauranga Group	Tauranga Group and volcanic lithologies	Tauranga Group and volcanic lithologies	Valleys (Reporoa Basin and Ngakuru) and volcanic lithologies (e.g., domes) and the Waikato River
Waiotapu at Campbell	3034280	Rotoiti Formation	Rotoiti Formation	Rotoiti Formation	Dacite domes and dissected pumice flats
Torepatutahi	3038300	Kaingaroa Formation	Whakamaru Group	Whakamaru Group	Kaingaroa Plateau down to Reporoa Basin
Waiotapu at Homestead	3037105	Tauranga Group	Tauranga Group	Tauranga Group	Reporoa Basin flanked by Kaingaroa Plateau and Paeroa Range
Waikato at Ohaaki	3039804	Oruanui Formation	Oruanui Formation	Tauranga Group	Waikato River Valley and valleys (commonly dry) through non-welded ignimbrite
Pueto	3042044	Oruanui Formation	Oruanui Formation	Tauranga Group	Kaingaroa Plateau and valleys (commonly dry) through non-welded ignimbrite
Little Waipa	3023862	Whakamaru Group	Whakamaru Group	Whakamaru Group	Rolling country
Mangamingi	3027230	Whakamaru Group	Whakamaru Group	Whakamaru Group	Rolling country
Whakauru	3027821	Whakamaru Group	Whakamaru Group	Whakamaru Group	Flanks of Mamaku Plateau down to rolling country
Mangaharakeke	3032678	Ohakuri Formation	Ohakuri Formation	Ohakuri Formation	Flanks of Mamaku Plateau and dome
Waikato at Whakamaru	3035301	Maroa Group	Ignimbrite (Mokai/Pukaehua/Ohakuri)	Ignimbrite (Mokai/Pukaehua/Ohakuri)	Domes
Waipapa	3035556	Oruanui Formation	Mokai Formation	Mokai Formation	Valley on flanks of domes
Otamakokore	3031549	Rotoiti Formation	Rotoiti Formation	Rotoiti Formation	Pumice valley coming off a dome
Whirinaki	3031392	Rhyolite lava	Rotoiti Formation	Rotoiti Formation	Pumice valley in Paeroa Range
Mangakara	3037027	Tauranga Group	Tauranga Group	Tauranga Group	Paeroa Range down to Reporoa Valley
Kawaunui	3034452	Tauranga Group	Tauranga Group	Tauranga Group	Paeroa Range down to Reporoa Valley

Table A2.4 LMW Geology 2

Catchment Name	NZ Reach	Water table Aquifer	Water table Aquifer	Principal Aquifer	Principal Aquifer	Groundwater gradient (m/m)	Effective aquifer thickness (m)	Average aquifer thickness (m)
Units		Transmissivity est. $m^2\ d^{-1}$	Velocity estimate (Darcy) $m\ d^{-1}$	Transmissivity est. $m^2\ d^{-1}$	Velocity estimate (Darcy) $m\ d^{-1}$			
Whakapipi	3006346	0.0005	0.0000002	0.0005	0.0000002	0.027	56	56
Waikato at Tuakau Br	3007421	0.0005	0.0000000	0.0005	0.0000000	0.003	54	54
Ohaeroa	3007733	0.0005	0.0000004	0.0005	0.0000004	0.033	46	46
Awaroa (Waiuku)	3007434	0.0005	0.0000001	0.0005	0.0000001	0.02	82	82
Whangape	3010847	247	0.0197600	0.0005	0.0000000	0.008	100	180
Waikato at Mercer Br	3006806	247	0.0392955	0.0005	0.0000001	0.007	44	44
Opuatia	3008985	0.0005	0.0000001	0.0005	0.0000001	0.01	58	58
Mangatawhiri	3005110	4.6	0.0004600	4.6	0.0004600	0.01	100	100
Mangatangi	3006132	247	0.0617500	247	0.0617500	0.006	24	24
Whangamarino at Jefferies Rd Br	3008369	247	0.1940714	247	0.1940714	0.011	14	14
Awaroa (Rotowaro) at Sansons Br	3013581	4.6	0.0012341	4.6	0.0012341	0.011	41	41
Waikato at Huntly-Tainui Br	3013160	247	0.0024700	247	0.0024700	0.001	100	202
Matahuru	3010952	247	0.0855000	247	0.0855000	0.009	26	26
Waerenga	3009556	247	1.9760000	247	1.9760000	0.04	5	5
Mangawara	3013137	247	0.0145294	247	0.0145294	0.005	85	85
Komakorau	3014466	247	0.0024700	247	0.0024700	0.001	100	409
Waikato at Bridge St Br	3017901	247	0.0098800	247	0.0098800	0.004	100	168
Mangakotukutuku	3018237	247	0.0247000	247	0.0247000	0.01	100	145
Mangaonua	3017726	247	0.0087176	247	0.0087176	0.003	85	85
Mangaone	3018213	247	0.0089818	247	0.0089818	0.002	55	55
Whangamarino at Island Block Rd	3007681	247	0.0023903	4.6	0.0000445	0.0003	31	31
Waikato at Rangiriri	3010604	247	0.0112273	247	0.0112273	0.002	44	44
Waikato at Horotiu Br	3015830	247	0.0172900	247	0.0172900	0.007	100	548
Kirikiriroa	3016924	247	0.0247000	247	0.0247000	0.01	100	616
Waitawhiriwhiri	3017487	247	0.0197600	247	0.0197600	0.008	100	471
Waikato at Port Waikato	3009006	247	0.0179636	247	0.0179636	0.004	55	55
Mangawhero	3020102	247	0.0074100	247	0.0074100	0.003	100	153
Waikato at Narrows	3018977	247	0.0074100	247	0.0074100	0.003	100	120
Karapiro	3020352	15	0.0056667	15	0.0056667	0.017	45	45
Awaroa (Rotowaro) at Harris/Te Ohaki Br	3012631	247	0.1045000	247	0.1045000	0.011	26	26
Waikare	3010071	247	0.0037424	247	0.0037424	0.001	66	66

Table A2.5 Waipa Geology 2

Catchment Name	NZ Reach	Area (ha)	Water table Aquifer	Water table Aquifer	Principal Aquifer	Principal Aquifer	Groundwater gradient (m/m)	Effective aquifer thickness (m)	Average aquifer thickness (m)
Units			Transmissivity est. $m^2 d^{-1}$	Velocity estimate (Darcy) $m d^{-1}$	Transmissivity est. $m^2 d^{-1}$	Velocity estimate (Darcy) $m d^{-1}$			
Waipa at SH23 Br Whatawhata	3017829	31505.98	247	0.0007410	247	0.0007410	0.0003	100	150
Kaniwhaniwha	3019566	10259.35	247	0.1070333	247	0.1070333	0.013	30	30
Mangapiko	3022010	28069.41	247	0.0123500	247	0.0123500	0.005	100	110
Mangauika	3023179	978.13	0.0005	0.0000005	0.0005	0.0000005	0.107	100	350
Mangaohoi	3023476	430.73	0.005	0.0000050	0.005	0.0000050	0.1	100	340
Puniu at Bartons Corner Rd Br	3023180	22785.38	247	0.0035286	247	0.0035286	0.001	70	70
Waipa at Pirongia-Ngutunui Rd Br	3022669	43607.05	247	0.0296400	247	0.0296400	0.006	50	50
Waitomo at Tumutumu Rd	3028966	4317.76	33600	31.9200000	33600	31.9200000	0.038	40	40
Mangapu	3027166	16169.99	32	0.0025600	33600	2.6880000	0.004	50	50
Mangaokewa	3031564	17419.08	15	0.0027500	15	0.0027500	0.011	60	60
Waipa at Otewa	3029370	28665.43	15	0.0040000	15	0.0040000	0.016	60	60
Waipa at Mangaokewa Rd	3036214	3220.68	15	0.0022500	15	0.0022500	0.015	100	120
Ohote	3017348	4040.85	247	0.0074100	247	0.0074100	0.003	100	460
Waipa at Otorohanga	3027129	13888.96	8	0.0016000	8	0.0016000	0.006	30	30
Waitomo at SH31 Otorohanga	3026779	4392.88	33600	16.8000000	33600	16.8000000	0.015	30	30
Mangatutu	3024473	12269.05	15	0.0026250	15	0.0026250	0.014	80	80
Firewood	3015451	3372.21	247	0.3705000	247	0.3705000	0.015	10	10
Moakurarua	3023962	20630.08	0.0005	0.0000000	0.0005	0.0000000	0.005	60	60
Puniu at Wharepapa	3025988	16852.57	15	0.0015000	15	0.0015000	0.007	70	70
Mangarapa	3028468	5442.97	247	0.1976000	247	0.1976000	0.008	10	10
Mangarama	3031371	5528.24	33600	21.0000000	33600	21.0000000	0.025	40	40
Waipa at Waingaro Rd Br	3015066	15484.4	247	0.0024700	247	0.0024700	0.001	100	200

Table A2.6 UW Geology 2

Catchment Name	NZ Reach	Water table Aquifer	Water table Aquifer	Principal Aquifer	Principal Aquifer	Gradient (m/m)	Effective aquifer thickness (m)	Average aquifer thickness (m)
Units		Transmissivity est. $m^2\ d^{-1}$	Velocity estimate (Darcy) $m\ d^{-1}$	Transmissivity est. $m^2\ d^{-1}$	Velocity estimate (Darcy) $m\ d^{-1}$			
Waikato at Karapiro	3020656	18	0.0036000	18	0.0036000	0.02	100	667
Pokaiwhenua	3023849	18	0.0041311	18	0.0041311	0.014	61	61
Waikato at Waipapa	3030247	18	0.0036000	18	0.0036000	0.02	100	787
Tahunaatara	3032435	247	0.0494000	247	0.0494000	0.008	40	40
Mangakino	3036710	18	0.0023400	18	0.0023400	0.013	100	326
Waikato at Ohakuri	3035123	247	0.0617500	247	0.0617500	0.025	100	150
Waiotapu at Campbell	3034280	28	0.0056000	28	0.0056000	0.02	100	150
Torepatutahi	3038300	18	0.0025200	18	0.0025200	0.014	100	405
Waiotapu at Homestead	3037105	247	0.3211000	247	0.3211000	0.013	10	10
Waikato at Ohaaki	3039804	28	0.0070000	247	0.0617500	0.025	100	140
Pueto	3042044	28	0.0056000	247	0.0494000	0.02	100	140
Little Waipa	3023862	18	0.0034615	18	0.0034615	0.01	52	52
Mangamingi	3027230	18	0.0013846	18	0.0013846	0.005	65	65
Whakauru	3027821	18	0.0020455	18	0.0020455	0.01	88	88
Mangaharakeke	3032678	8	0.0013600	8	0.0013600	0.017	100	1500
Waikato at Whakamaru	3035301	13	0.0028600	13	0.0028600	0.022	100	1500
Waipapa	3035556	17	0.0042500	17	0.0042500	0.025	100	800
Otamakokore	3031549	28	0.0070000	28	0.0070000	0.025	100	200
Whirinaki	3031392	28	0.0070000	28	0.0070000	0.025	100	150
Mangakara	3037027	247	1.2350000	247	1.2350000	0.05	10	10
Kawaunui	3034452	247	0.0802750	247	0.0802750	0.013	40	40

APPENDIX 3: WATER BUDGETS.

Water budget components are summarised in three zones for each HRP catchment including inter-catchment water flows.

Cells coloured yellow in each summary are the estimated flows in the main stems of the Waikato River and Waipa River.

This appendix also summarises baseflow and quick flow from the land in each HRP catchment.

Table A3.1. Water budget of the Upper Waikato zone. The numbers highlighted in yellow are the estimated Waikato River flows, Figure 3.3.

Catchment name	Catchment number	Inflow				Outflow		
		Rainfall mean annual (m^3/s)	Surface flow (Waikato River) mean (m^3/s)	Surface flow (other) mean (m^3/s)	Groundwater mean (m^3/s)	AET mean (m^3/s)	Surface mean (m^3/s)	Groundwater mean (m^3/s)
Above Ohakuri								
Pueto	3042044	9.7[1]	0.0	0.0	0.0	4.9	4.8	0.0
Waikato at Ohaaki	3039804	11.5	151.0	4.8	0.0	7.1	160.2	0.0
Torepatutahi	3038300	9.7[1]	0.0	0.0	0.0	5.3	4.4	0.0
Waiotapu at Campbell	3034280	3.0[1]	0.0	0.0	0.0	1.5	1.5	0.0
Kawaunui	3034452	1.0	0.0	0.0	0.0	0.5	0.1	0.4
Mangakara	3037027	1.1	0.0	0.0	0.0	0.6	0.2	0.3
Waiotapu at Homestead	3037105	8.8	0.0	1.8	0.7	5.1	3.7	2.5
Whirinaki	3031392	0.5	0.0	0.0	0.0	0.3	0.1	0.1
Otamakokore	3031549	2.2	0.0	0.0	0.0	1.1	1.0	0.1
Waikato at Ohakuri	3035123	24.2	160.2	9.2	2.7	13.2	183.1	0.0
Above Whakamaru								
Tahunaatara	3032435	10.2	0.0	0.0	0.0	5.0	4.6	0.6
Mangaharakeke	3032678	2.7	0.0	0.0	0.0	1.3	0.7	0.7
Waipapa	3035556	4.7	0.0	0.0	0.0	2.3	1.6	0.8
Waikato at Whakamaru	3035301	20.5	183.1	6.9	2.1	10.7	201.9	0.0
Above Waipapa								
Mangakino	3036710	11.1	0.0	0.0	0.0	5.0	3.8	2.3
Waikato at Waipapa	3030247	34.6	201.9	3.8	2.3	16.2	226.4	0.0
Above Karapiro								
Whakauru	3027821	2.7	0.0	0.0	0.0	1.3	0.4	1.0
Mangamingi	3027230	2.6	0.0	0.4	1.0	1.2	1.1	1.7
Pokaiwhenua	3023849	16.3	0.0	1.1	1.7	8.0	5.2	5.9
Little Waipa	3023862	5.0	0.0	0.0	0.0	2.6	1.9	0.5
Waikato at Karapiro	3020656	24.6	226.4	7.1	6.4	13.4	251.1	0.0

[1]includes a minor adjustment to rainfall as the Tait (2006) estimate has P-AET that is less than surface outflow.

Table A3.2. Water budget of the Waipa zone. The numbers highlighted in yellow are the estimated Waipa River outflows from HRP catchments (Figure 3.4).

Catchment name	Catchment number	Inflow			Outflow		
		Rainfall adjusted mean annual (m^3/s)[1]	Surface flow mean (m^3/s)	Groundwater mean (m^3/s)	AET mean annual (m^3/s)	Surface flow mean (m^3/s)	Groundwater mean (m^3/s)
Group above Otorohanga							
Waitomo at Tumutumu Rd	3028966						
Waitomo at SH31 Otorohanga	3026779						
Mangarama	3031371	3.2	0	0	1.3	1.3	0.6
Mangaokewa	3031564	9.4	0	0	3.9	5.3	0.2
Mangarapa	3028468	2.8	0	0	1.3	0.3	1.2
Mangapu	3027166	9.3	6.9	2	3.8	14.4	0
Waipa at Mangaokewa Rd	3036214	1.8	0	0	0.7	0	1.1
Waipa at Otewa	3029370	18.1	0	1.1	6.3	12.9	0
Waipa at Otorohanga	3027129	5.8	12.9	0	3.3	13.2	2.2
1191_13	3027129+3027166 +3022669 (part)		15.2	14.6		29.8	0
Group above Pirongia							
Puniu at Wharepapa	3025988	9.1	0	0	4	2.4	2.7
Mangatutu	3024473	7.2	0	0	2.9	4.3	0
Puniu at Bartons Corner Rd Br	3023180	11.2	6.7	2.7	5.7	14.9	0
Moakurarua	3023962	14	0	0	4.9	4.6	4.5
Waipa at Pirongia-Ngutunui Rd Br	3022669	28	50	7.3	10.8	74.5	0
Group above Waikato confluence							
Kaniwhaniwha	3019566	6.7	0	0	2.5	3.4	0.8
Mangauika	3023179	0.7	0	0	0.2	0.5	0
Mangaohoi	3023476	0.4	0	0	0.1	0.3	0
Mangapiko	3022010	10.1	0.3	0	7	3.4	0
Waipa at SH23 Br Whatawhata	3017829	16.1	81.8	0.8	8.1	87.7	2.9
Firewood	3015451	1.8	0	0	0.8	0.1	0.9
Ohote	3017348	1.8	0	0	1	0.1	0.7
Waipa at Waingaro Rd Br	3015066	8	87.9	4.5	3.9	96.5	0

[1] includes a +7% adjustment to rainfall so that outflow from the Waipai River catchment approximately matches average 1960-2006 flow at catchment 3017829 (Waipa at SH23 Br Whatawhata. In addition a second adjustment is made to rainfall in five catchments (i.e., 3024473, 3023180, 3022669, 3022010, 3023476) as the Tait (2006) +7% estimate has P-AET that is less than surface outflow.

Note also that:

- Outflow from catchment 3015066 (itself) is estimated as the 1960-2006 specific discharge from catchment 3017829 (Waipa at SH23 Br Whatawhata).
- Site 1191-13 includes part (14.2km^2) of catchment 3022669. This part of the catchment is not separated out from the full water budget of 3022669 because estimated flow from the part-catchment is less than 0.1 m^2/s. This flow is calculated assuming the specific discharge at site 668-1 over the part-catchment.
- The distribution of gaugings in catchment 3027166 is poor for the estimation of surface outflow. Therefore, surface outflow from 3027166 is estimate with all P-AET discharging to surface water.

Table A3.3. Water budget of the Lower-Middle Waikato zone. The numbers highlighted in yellow are the estimated Waipa River flows (Figure 3.5).

Catchment name	Catchment number	Inflow			Outflow			
		Rainfall mean annual (m^3/s)	Surface flow (Waikato River) mean (m^3/s)	Surface flow (other) mean (m^3/s)	Groundwater mean (m^3/s)	AET mean (m^3/s)	Surface flow mean (m^3/s)	Groundwater mean (m^3/s)
Above Taupiri								
Mangawhero	3020102	2.1	0	0	0	1.4	0.4	0.3
Karapiro	3020352	2.6	0	0	0	1.7	0.3	0.6
Waikato at Narrows	3018977	5	251.1	0.7	0.9	3.3	254.4	0
Mangakotukutuku	3018237	1.1	0	0	0	0.7	0.2	0.2
Mangaone	3018213	2.6	0	0	0	1.7	0.8	0.1
Mangaonua	3017726	3.1	0	0	0	2	0.5	0.6
Waikato at Bridge St Br	3017901	1.9	254.4	1.5	0.9	1.3	257.4	0
Waitawhiriwhiri	3017487	0.9	0	0	0	0.6	0.2	0.1
Kirikiriroa	3016924	0.5	0	0	0	0.3	0.1	0.1
Waikato at Horotiu Br	3015830	2	257.4	0.3	0.2	1.3	258.6	0
Komakorau	3014466	6	0	0	0	4.1	1.8	0.1
Mangawara	3013137	14.9[2]	0	0	0	9	5.9	0
Waikato at Huntly-Tainui Br	3013160[1]	7.1	355.1	7.7	0.1	4.3	365.7[1]	0
Above Mercer								
Awaroa (Rotowaro) at Sansons Br	3013581	2.2	0	0	0	1.1	1	0.1
Awaroa (Rotowaro) at Harris/ Te Ohaki Br	3012631	3.5[2]	0	0	0	1.2	2.3	0
Waikato at Rangiriri	3010604	2.5	365.7	3.3	0.1	1.7	369.9	0
Matahuru	3010952	4.6[2]	0	0	0	2.7	1.9	0
Waikare	3010071	3.6[2]	0	1.9	0	2.6	2.9	0
Waerenga	3009556	0.8	0	0	0	0.5	0.1	0.2
Whangamarino at Jefferies Rd Br	3008369	3.9	0	0.1	0.2	2.5	0	1.7
Whangamarino at Island Block Rd	3007681	5.5	0	2.9	1.7	3.7	5	1.4
Mangatangi	3006132	9.1	0	0	0	5.2	2.8	1.1
Whangape	3010847	14	0	0	0	7.9	6.1	0
Opuatia	3008985	3.4	0	0	0	1.8	0	1.6
Waikato at Mercer Br	3006806	18.3	369.9	6	12	11.5	394.7	0
Above Port Waikato								
Ohaeroa	3007733	0.9	0	0	0	0.5	0.2	0.2
Mangatawhiri	3005110	6.3[2]	0	0	0	1.9	4.4	
Awaroa (Waiuku)	3007434	1.1	0	0	0	0.7	0.2	0.2
Whakapipi	3006346	2.1	0	0	0	1.2	0.9	0
Waikato at Port Waikato	3009006	12.6	401.9	1.1	0.2	7.2	408.6	0

[1] includes inflow from the Waipa River.
[1] includes an adjustment to rainfall where P-AET is less than surface outflow.
Note also that inflows to Lake Waikare (catchment 3010071) from the Waikato River are not considered in this water budget as the outflow measurements appear biased by flood flows.

Table A3.4 Water budgets with estimated flows in mm/year.

- Note that river and groundwater inflows are 'assigned' to the receiving catchment to balance the water budgets. However, this assignment has no physical meaning.

Catchment name	Catchment number	Inflow: rainfall mean annual (mm/yr)	Inflow: surface flow (Waikato River) mean (mm/yr)	Inflow: surface flow (other) mean (mm/yr)	Inflow: groundwater mean (mm/year)	Outflow: AET mean (mm/year)	Outflow: surface flow mean (mm/year)	Outflow: groundwater mean (mm/year)
Pueto	3042044	1527	0	0	0	772	756	0
Waikato at Ohaaki	3039804	1250	16416	522	0	772	17416	0
Torepatutahi	3038300	1408	0	0	0	769	639	0
Waiotapu at Campbell	3034280	1556	0	0	0	778	778	0
Kawaunui	3034452	1478	0	0	0	739	148	591
Mangakara	3037027	1552	0	0	0	847	282	423
Waiotapu at Homestead	3037105	1355	0	277	108	785	570	385
Whirinaki	3031392	1461	0	0	0	876	292	292
Otamakokore	3031549	1517	0	0	0	759	690	69
Waikato at Ohakuri	3035123	1436	9507	546	160	783	10866	0
Tahunaatara	3032435	1545	0	0	0	757	697	91
Mangaharakeke	3032678	1572	0	0	0	757	408	408
Waipapa	3035556	1475	0	0	0	722	502	251
Waikato at Whakamaru	3035301	1447	12928	487	148	755	14255	0
Mangakino	3036710	1578	0	0	0	711	540	327
Waikato at Waipapa	3030247	1572	9176	173	105	736	10289	0
Whakauru	3027821	1606	0	0	0	773	238	595
Mangamingi	3027230	1584	0	244	609	731	670	1036
Pokaiwhenua	3023849	1572	0	106	164	771	501	569
Little Waipa	3023862	1481	0	0	0	770	563	148
Waikato at Karapiro	3020656	1437	13229	415	374	783	14673	0
Waitomo at Tumutumu Rd	3028966	2264	0	0	0	730	1242	292
Waitomo at SH31 Otorohanga	3026779	1795	0	1220	287	790	503	2010
Mangarama	3031371	1825	0	0	0	742	742	342
Mangaokewa	3031564	1702	0	0	0	706	960	36
Mangarapa	3028468	1622	0	0	0	753	174	695
Mangapu	3027166	1814	0	1346	390	741	2808	0
Waipa at Mangaokewa Rd	3036214	1763	0	0	0	685	0	1077
Waipa at Otewa	3029370	1991	0	0	121	693	1419	0
Waipa at Otorohanga	3027129	1317	0	2929	0	749	2997	500
Puniu at Wharepapa	3025988	1703	0	0	0	749	449	505
Mangatutu	3024473	1851	0	0	0	745	1105	0
Puniu at Bartons Corner Rd Br	3023180	1550	0	927	374	789	2062	0
Moakurarua	3023962	2140	0	0	0	749	703	688
Waipa at Pirongia-Ngutunui Rd Br	3022669	2025	0	3616	528	781	5388	0
Kaniwhaniwha	3019566	2059	0	0	0	768	1045	246
Mangauika	3023179	2257	0	0	0	645	1612	0
Mangaohoi	3023476	2929	0	0	0	732	2196	0

Catchment name	Catchment number	Inflow: rainfall mean annual (mm/yr)	Inflow: surface flow (Waikato River) mean (mm/yr)	Inflow: surface flow (other) mean (mm/yr)	Inflow: groundwater mean (mm/year)	Outflow: AET mean (mm/year)	Outflow: surface flow mean (mm/year)	Outflow: groundwater mean (mm/year)
Mangapiko	3022010	1135	0	34	0	786	382	0
Waipa at SH23 Br Whatawhata	3017829	1612	0	8188	80	811	8778	290
Firewood	3015451	1683	0	0	0	748	94	842
Ohote	3017348	1405	0	0	0	780	78	546
Waipa at Wainaro Rd Br	3015066	1629	0	17902	916	794	19653	0
Mangawhero	3020102	1238	0	0	0	826	236	177
Karapiro	3020352	1216	0	0	0	795	140	281
Waikato at Narrows	3018977	1214	60975	170	219	801	61777	0
Mangakotukutuku	3018237	1281	0	0	0	815	233	233
Mangaone	3018213	1213	0	0	0	793	373	47
Mangaonua	3017726	1208	0	0	0	779	195	234
Waikato at Bridge St Br	3017901	1181	158166	933	560	808	160031	0
Waitawhiriwhiri	3017487	1277	0	0	0	851	284	142
Kirikiriroa	3016924	1278	0	0	0	767	256	256
Waikato at Horotiu Br	3015830	1167	150180	175	117	758	150880	0
Komakorau	3014466	1154	0	0	0	788	346	19
Mangawara	3013137	1309	0	0	0	791	519	0
Waikato at Huntly-Tainui Br	3013160	1293	64648	1402	18	783	66577	0
Awaroa (Rotowaro) at Sansons Br	3013581	1521	0	0	0	761	691	69
Awaroa (Rotowaro) at Harris/Te Ohaki Br	3012631	2334	0	0	0	800	1534	0
Waikato at Rangiriri	3010604	1150	168293	1519	46	782	170226	0
Matahuru	3010952	1364	0	0	0	800	563	0
Waikare	3010071	1090	0	575	0	787	878	0
Waerenga	3009556	1288	0	0	0	805	161	322
Whangamarino at Jefferies Rd Br	3008369	1268	0	33	65	813	0	553
Whangamarino at Island Block Rd	3007681	1207	0	637	373	812	1098	307
Mangatangi	3006132	1475	0	0	0	843	454	178
Whangape	3010847	1390	0	0	0	784	606	0
Opuatia	3008985	1517	0	0	0	803	0	714
Waikato at Mercer Br	3006806	1278	25826	419	838	803	27557	0
Ohaeroa	3007733	1396	0	0	0	776	310	310
Mangatawhiri	3005110	2918	0	0	0	880	2038	0
Waikato at Tuakau Br	3007421	1330	82007	956	42	831	83502	0
Awaroa (Waiuku)	3007434	1384	0	0	0	881	252	252
Whakapipi	3006346	1425	0	0	0	814	611	0
Waikato at Port Waikato	3009006	1412	45028	123	22	807	45779	0

Table A3.5. Calculations of surface flow at Waikato Regional Council flow recorder sites, with estimates of the base flow index (BFI).

The mean and median flows are rounded to one decimal place.
The BFI estimate is :

- median flow divided by mean flow, rounded to two decimal places;
- BFI is set to 1.0 where median flow divided by mean flow is greater than 1.00.

HRP catchment name	HRP catchment number	WRC site number	Type	Site name	Mean flow m3/s	Median flow m3/s	BFI estimate
Pueto	3042044	802_1	Gaugings	Broadlands Rd Br	4.8	5	1
Waikato at Ohaaki	3039804		Gaugings	sum (8 sites)	2.8	2.7	0.96
Torepatutahi	3038300	1057_6	Gaugings	Vaile Rd Br	4.4	4.2	0.95
Waiotapu at Campbell	3034280	1186_2	Stage (1960-2006)	Campbell Rd Br	1.5	1.4	0.93
Kawaunui	3034452	240_5	Gaugings	SH5 Br	0.1	0.1	1
Mangakara	3037027	380_1	Gaugings	Butcher Rd	0.2	0.2	1
Waiotapu at Homestead	3037105	1186_9	Stage (1960-2006)	Reporoa Rd	3.7	3.3	0.89
Whirinaki	3031392	1323_1	Gaugings	Corbett Rd	0.1	0.1	1
Otamakokore	3031549	683_4	Stage (1960-2006)	Hossack Rd	1	0.9	0.9
Waikato at Ohakuri	3035123		Sum of 15 gauging sites		4.3	4.1	0.95
Tahunaatara	3032435	934_1	Stage (1960-2006)	Upper Atiamuri	4.6	3.9	0.85
Mangaharakeke	3032678	359_2	Gaugings	SH30 Br	0.7	0.7	1
Waipapa	3035556	1202_7	Gaugings	Tirohanga Rd Br	1.6	1.6	1
Waikato at Whakamaru	3035301		Sum of 6 gauging sites		9.5	8.7	0.92
Mangakino	3036710	388_1	Gaugings	Sandel Rd	3.8	3.7	0.97
Waikato at Waipapa	3030247		Sum of 2 stage recorders and 7 gauging sites		21.9	18.9	0.86
Pokaiwhenua	3023849	786_2	Stage (1960-2006)	Arapuni - Putaruru Rd	5.2	4.7	0.9
Whakauru	3027821	1287_8	Gaugings	Sloss Rd Bridge	0.4	0.4	1
Mangamingi	3027230	407_1	Gaugings	Paraonui Rd Br	1.1	0.9	0.82
Little Waipa	3023862	335_1	Gaugings	Arapuni - Putaruru Rd	1.9	1.8	0.95
Waikato at Karapiro	3020656		Sum of 15 gauging sites		1.9	1.7	0.89
Mangaokewa	3031564	414_13	stage flow 1960-2006	Te Kuiti Pumping Station	5.3	3.5	0.66
Mangarapa	3028468	444_1	gaugings	Otorohanga Rd	0.3	0.2	0.67
Mangarama	3031371	443_5	gaugings	Te Anga Rd Br (Oparure Rd)	1.3	1.3	1
Mangapu	3027166	1191_12	gaugings	SH3 Otorohanga	2	2	1

HRP catchment name	HRP catchment number	WRC site number	Type	Site name	Mean flow m3/s	Median flow m3/s	BFI estimate
Waipa at Mangaokewa Rd	3036214	414_19	one gauging only		0	0	na
Waipa at Otewa	3029370	1191_7	stage flow 1960-2006	Otewa	12.9	8.5	0.66
Waipa at Otorohanga	3027129+3027166	1191_13	stage flow 1960-2006	SH31 Br Otorohanga	29.8	20.3	0.68
Waitomo at Tumutumu Rd	3028966	1253_3	stage flow 1960-2006	Aranui Caves Br	1.7	1.1	0.65
Waitomo at SH31 Otorohanga	3026779	1253_8	gaugings	Waitomo Valley Rd	0.7	0.7	1
Moakurarua	3023962	555_3	gaugings	Symes Rd Br	4.6	3.9	0.85
Puniu at Wharepapa	3025988	818_11	gaugings	Wharepapa Rd	2.4	1.6	0.67
Mangatutu	3024473	476_7	stage flow 1960-2006	Walker Rd Br	4.3	3.3	0.77
Puniu at Bartons Corner Rd Br	3023180	818_2	stage flow 1960-2006	Bayleys Rd Br	14.9	10.7	0.72
Waipa at Pirongia-Ngutunui Rd Br	3022669	1191_2	stage flow 1960-2006	Pirongia-Ngutunui Rd Br	74.5	56.9	0.76
Mangauika	3023179	477_13	gaugings	Treatment Stn [G]	0.5	0.3	0.6
Mangaohoi	3023476	411_7	gaugings	Mamakumaru Farm	0.3	0.2	0.67
Mangapiko	3022010	438_18	stage flow 1960-2006	Bowman Rd	2.1	1.1	0.52
Kaniwhaniwha	3019566	222_16	gaugings	Wright Rd	3.4	1.7	0.5
Waipa at SH23 Br Whatawhata	3017829	1191_11	stage flow 1960-2006	SH23 Br Whatawhata	87.7	62.6	0.71
Ohote	3017348	624_1	gaugings	Blackett Rd	0.1	0.1	1
Waipa at Wainaro Rd Br	3015066	1191_6	gaugings	Ngaruawahia Br	497.4	542.8	1
Firewood	3015451	124_3	gaugings	Waingaro Rd	0.1	0.1	1
Karapiro	3020352	230_5	Gaugings	Hickey Rd Bridge	0.3	0.3	1
Mangaonua	3017726	421_20	Gaugings	Woodside Rd near SH26	0.5	0.4	0.8
Mangawhero	3020102	488_1	Gaugings	Cambridge-Ohaupo Rd	0.4	0.3	0.75
Waikato at Narrows	3018977	sum of 3 sites	Gaugings		0.8	0.8	1
Mangaone	3018213	417_7	Gaugings	Annebrooke Rd Br	0.8	0.5	0.63
Mangakotukutuku	3018237	398_1	Gaugings	Peacockes Rd	0.2	0.1	0.5
Waitawhiriwhiri	3017487	1236_3	Gaugings	Victoria Street	0.2	0.1	0.5
Waikato at Bridge St Br	3017901	sum of 2 gaugings and 1 stage site	Gaugings		2.1	1.5	0.71
Komakorau	3014466	sum of 2 sites	Gaugings		1.8	1.8	1

HRP catchment name	HRP catchment number	WRC site number	Type	Site name	Mean flow m3/s	Median flow m3/s	BFI estimate
Kirikiriroa	3016924	253_3	Gaugings	Confluence At River Rd	0.1	0.1	1
Waikato at Horotiu Br	3015830	sum of 7 sites	Gaugings		0.1	0.1	1
Mangawara	3013137	481_4	stage flow 1960-2006		5.9	2.9	0.49
Waikato at Huntly-Tainui Br	3013160	sum of 4 sites	Gaugings		0.2	0.1	0.5
Matahuru	3010952	516_5	stage flow 1960-2006		1.9	1.2	0.63
Waerenga	3009556	1098_3	Gaugings	Waipuna Gorge Rd	0.1	0.1	1
Whangamarino at Jefferies Rd Br	3008369	sum of 2 sites	Gaugings		0	0	na
Waikare	3010071	sum of 2 sites	Gaugings		16.8	16.6	0.99
Whangamarino at Island Block Rd	3007681	1293_15	Gaugings	Ropeway Recorder	5	0	0
Awaroa (Rotowaro) at Sansons Br	3013581	39_11	stage flow 1960-2006		1	0.5	0.5
Awaroa (Rotowaro) at Harris/Te Ohaki Br	3012631	1097_1	Gaugings	Te Ohaki Rd	2.8	2.3	0.82
Waikato at Rangiriri	3010604	249_1	Gaugings	Ralph Rd Br	0.4	0.4	1
Whangape	3010847	330_2	Gaugings	Glen Murray Rd Outlet	14.6	15.2	1
Mangatangi	3006132	453_7	Gaugings	Stubbs Bridge	1	0.5	0.5
Waikato at Mercer Br	3006806	sum of 10 sites	Gaugings		12	9.2	0.77
Mangatawhiri	3005110	459_7	Gaugings	Lyons Rd Br	4.4	0.2	0.05
Waikato at Tuakau Br	3007421	sum of 4 sites	Gaugings		5.9	2.1	0.36
Whakapipi	3006346	1282_8	stage flow 1960-2006		0.9	0.5	0.56
Ohaeroa	3007733	612_9	Gaugings	SH22 Br	0.2	0.1	0.5
Opuatia	3008985	664_2	Gaugings	Hira Rd (L)	0	0	na
Awaroa (Waiuku)	3007434	41_4	Gaugings	Floodgates	0.2	0.2	1
Waikato at Port Waikato	3009006	sum of 27 sites	Gaugings		7.3	6.3	0.86

APPENDIX 4: GROUNDWATER CHEMISTRY

Table A4.1. Summary of groundwater chemistry in the Health Rivers Project area.

Catchment Name	NZ Reach	Number of wells with chemistry measurements	Period of measurements	Groundwater N		Groundwater P		Groundwater salinity		Groundwater E. coli		Groundwater redox indicators			
				Nitrate mg/L as N - filterable		Phosphorus mg/L as P- Reactive - filterable		Electrical conductivity		Escherichia coli		Manganese mg/L All forms as Mn - filterable		Iron mg/L All forms as Fe - filterable	
				median range	trend	median range	trend	median range	trend	median range	trend	median range	trend	median range	trend
				mg/L	mg/L/decade	mg/L	mg/L/decade	uS/cm	uS/cm/decade	cfu/100 ml	cfu/100 ml/ decade	mg/L	mg/L/decade	mg/L	mg/L/decade
Mangatawhiri	3005110	1	1987—1987	no data	no data	0.09 (44ND)	no stat. sig. trends	no data	no data	no data	no data	no data	no data	0.17	insufficient data
Mangatangi	3006132	14	2000—2015	<0.05 — 8.4	insufficient data	<0.04 — 0.33 (6ND)	insufficient data	no data	no data	no data	no data	<0.001 — 0.84 (7ND)	insufficient data	<0.02 — 10.4 (4ND)	insufficient data
Whakapipi	3006346	8	1987—2015	<0.05 — 9.8 (1ND)	0.27 — 0.42	<0.005 — 0.004 (4ND)	insufficient data	10.9 — 142 (4ND)	0.41 — 6.6	<1 — 7 (6ND)	insufficient data	0.001 — 0.05 (4ND)	no stat. sig. trends	<0.1 (3ND)	insufficient data
Waikato at Mercer Br	3006806	21	1987—2015	<0.05 — 31.6 (7ND)	-1.1 — 0.23	0.01 — 0.08 (8ND)	no stat. sig. trends	14 — 390 (13ND)	0.15 — 1.9	<2 (18ND)	insufficient data	<0.01 — 0.31 (10ND)	no stat. sig. trends	<0.1 — 3.5 (5ND)	no stat. sig. trends
Waikato at Tuakau Br	3007421	7	1987—2015	0.45 — 26.1 (1ND)	0.84	0.01 — 0.6 (2ND)	insufficient data	323 (6ND)	insufficient data	<1 (6ND)	insufficient data	<0.001 — 0.28 (2ND)	insufficient data	<0.02 — 0.26 (1ND)	insufficient data
Awaroa (Waiuku)	3007434	13	1987—2015	<0.002 — 15.6 (5ND)	-0.36 — 0.7	0.01 — 0.55 (6ND)	no stat. sig. trends	17.9 — 388 (7ND)	0.61	<1 — 29 (9ND)	insufficient data	<0.005 — 0.02 (8ND)	no stat. sig. trends	<1 — 0.07 (7ND)	no stat. sig. trends
Whangamarino at Island Block Rd	3007681	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
Ohaeroa	3007733	6	1987—2015	0.15 — 12.2 (2ND)	no stat. sig. trends	<0.005 — 0.12	insufficient data	19.4 — 159 (3ND)	no stat. sig. trends	<1 (4ND)	insufficient data	0.001 — 0.14 (3ND)	insufficient data	<0.1 — 0.25 (1ND)	insufficient data
Whangamarino at Jefferies Rd Br	3008369	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
Opuatia	3008985	2	1987—1996	no data	no data	0.05 (1ND)	insufficient data	no data	no data	no data	no data	no data	no data	<0.1 (1ND)	insufficient data
Waikato at Port Waikato	3009006	44	1987—2015	<0.05 — 17.9 (21ND)	0.037 — 0.046	<0.004 — 0.34 (21ND)	no stat. sig. trends	12.2 — 360 (38ND)	0.067 — 0.89	<1 — 60 (40ND)	insufficient data	<0.09 — 1.2 (34ND)	no stat. sig. trends	<0.2 — 4 (22ND)	insufficient data
Waerenga	3009556	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
Waikare	3010071	6	1993—2015	<0.05 — 16.6 (1ND)	insufficient data	0.02 — 0.03 (4ND)	insufficient data	no data	no data	no data	no data	<0.001 — 0.15 (3ND)	insufficient data	<0.04 — 3.4 (2ND)	insufficient data
Waikato at Rangiriri	3010604	2	1995—2000	23.7 (1ND)	insufficient data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
Whangape	3010847	4	1987—2015	0.74 — 1.4 (1ND)	insufficient data	0.02 — 0.04 (1ND)	insufficient data	no data	no data	no data	no data	<0.001 — 0.09 (1ND)	insufficient data	<0.02 (1ND)	insufficient data
Matahuru	3010952	2	1995—2015	5.5 (1ND)	insufficient data	<0.004 — 0.012	insufficient data	no data	no data	no data	no data	0.01 (1ND)	insufficient data	<0.02 (1ND)	insufficient data
Awaroa (Rotowaro) at Harris/Te Ohaki Br	3012631	1	1995—2012	<0.05	insufficient data	0.03	insufficient data	no data	no data	no data	no data	0.01	insufficient data	<0.02	insufficient data
Mangawara	3013137	12	1995—2015	<0.05 — 6.5 (2ND)	-0.52	<0.004 — 0.15 (3ND)	insufficient data	34 — 280 (10ND)	no stat. sig. trends	<1 — 16 (10ND)	insufficient data	<0.001 — 0.75 (3ND)	no stat. sig. trends	<0.02 — 2.9 (3ND)	insufficient data
Waikato at Huntly-Tainui Br	3013160	2	1987—2015	0.25 — 2.2	insufficient data	0.01 — 0.38	insufficient data	no data	no data	no data	no data	0.001 — 0.004	insufficient data	<0.02	insufficient data
Awaroa (Rotowaro) at Sansons Br	3013581	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
Komakorau	3014466	6	1992—2015	2.3 — 29	-2.2 — -0.63	<0.004 — 0.06 (2ND)	insufficient data	30.2 — 280 (2ND)	no stat. sig. trends	<1 — 54 (2ND)	insufficient data	0.01 — 0.11 (2ND)	no stat. sig. trends	<0.02 — 0.21 (2ND)	insufficient data
Waipa at Waingaro Rd Br	3015066	6	1996—2015	<0.05 — 8.1 (1ND)	insufficient data	0.02 (5ND)	insufficient data	no data	no data	no data	no data	1.2 (5ND)	insufficient data	<0.02 (5ND)	insufficient data
Firewood	3015451	3	1992—2015	<0.05 — 0.52 (1ND)	insufficient data	0.01 — 0.12 (1ND)	insufficient data	no data	no data	no data	no data	<0.06 — 0.36	insufficient data	<0.1	insufficient data
Waikato at Horotiu Br	3015830	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data

Catchment Name	NZ Reach	Number of wells with chemistry measurements	Period of measurements	Groundwater N		Groundwater P		Groundwater salinity		Groundwater E. coli		Groundwater redox indicators			
				Nitrate mg/L as N - filterable		Phosphorus mg/L as P- Reactive - filterable		Electrical conductivity		Escherichia coli		Manganese mg/L All forms as Mn - filterable		Iron mg/L All forms as Fe - filterable	
				median range	trend	median range	trend	median range	trend	median range	trend	median range	trend	median range	trend
				mg/L	mg/L/decade	mg/L	mg/L/decade	uS/cm	uS/cm/decade	cfu/100 ml	cfu/100 ml/ decade	mg/L	mg/L/decade	mg/L	mg/L/decade
Kirikiriroa	3016924	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
Ohote	3017348	3	1995—2015	<0.05 — 0.1 (1ND)	insufficient data	0.02 — 0.02 (1ND)	insufficient data	no data	no data	no data	no data	0.001 — 0.39 (1ND)	insufficient data	<0.02 (1ND)	insufficient data
Waitawhiriwhiri	3017487	3	1994—2015	0.07 — 0.2 (1ND)	insufficient data	0.06 (2ND)	insufficient data	no data	no data	no data	no data	0.08 (2ND)	insufficient data	0.04 — 0.86 (1ND)	insufficient data
Mangaonua	3017726	10	1987—2015	<0.05 — 8.9	-0.38 — -0.1	<0.004 — 0.04 (2ND)	no stat. sig. trends	19.5 — 216 (4ND)	-10.5 — -0.29	<1 — 18 (6ND)	insufficient data	<0.005 — 0.12 (3ND)	no stat. sig. trends	<0.04 — 0.05 (1ND)	no stat. sig. trends
Waipa at SH23 Br Whatawhata	3017829	24	1995—2015	0.02 — 15.4 (3ND)	-0.79 — 0.65	<0.004 — 0.2 (5ND)	no stat. sig. trends	9.9 — 150 (16ND)	-0.54 — 0.53	<1 — 9.5 (20ND)	insufficient data	<0.005 — 1.5 (10ND)	no stat. sig. trends	<0.02 — 76 (9ND)	no stat. sig. trends
Waikato at Bridge St Br	3017901	10	1987—2015	1.6 — 4.3 (5ND)	no stat. sig. trends	0.04 — 0.1 (8ND)	insufficient data	19.8 — 177 (6ND)	no stat. sig. trends	<2 — 10 (7ND)	insufficient data	0.001 — 0.001 (8ND)	insufficient data	<0.02 (7ND)	insufficient data
Mangaone	3018213	24	1987—2015	0.16 — 24.3 (7ND)	-1.6 — 1.2	0.01 — 0.09 (11ND)	insufficient data	21 — 297 (14ND)	0.57	<1 — 5 (19ND)	insufficient data	<0.001 — 0.006 (16ND)	no stat. sig. trends	<0.02 — 0.07 (16ND)	insufficient data
Mangakotukutuku	3018237	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
Waikato at Narrows	3018977	12	1995—2015	<0.05 — 17.4	-1.2 — -0.32	0.02 — 0.1 (4ND)	insufficient data	26.2 — 276 (4ND)	0.67 — 0.88	<1 — 6 (8ND)	insufficient data	<0.001 — 0.05 (4ND)	insufficient data	<0.04 — 0.09	insufficient data
Kaniwhaniwha	3019566	4	1995—2015	<0.5 — 0.42 (1ND)	insufficient data	0.09 — 0.14 (2ND)	insufficient data	no data	no data	no data	no data	0.002 — 0.11 (2ND)	insufficient data	<0.02 (2ND)	insufficient data
Mangawhero	3020102	2	1995—2015	10 (1ND)	insufficient data	0.03 (1ND)	insufficient data	no data	no data	no data	no data	0.01 (1ND)	insufficient data	<0.02 (1ND)	insufficient data
Karapiro	3020352	4	1995—2015	0.31 — 1.5 (1ND)	insufficient data	<0.004 — 0.37	insufficient data	no data	no data	no data	no data	<0.001 — 0.002 (1ND)	insufficient data	<0.02 — 0.02 (1ND)	insufficient data
Waikato at Karapiro	3020656	32	1937—2015	<0.05 — 12.8 (6ND)	0.055	<0.004 — 0.34 (14ND)	insufficient data	12.2 — 130 (30ND)	0.18	<1 (31ND)	insufficient data	<0.001 — 0.94 (12ND)	insufficient data	<0.02 — 3.2 (11ND)	insufficient data
Mangapiko	3022010	10	1987—2015	<0.002 — 6.8 (2ND)	insufficient data	<0.004 — 0.13 (4ND)	insufficient data	no data	no data	no data	no data	<0.001 — 0.07 (3ND)	insufficient data	<0.02 — 0.3 (1ND)	insufficient data
Waipa at Pirongia-Ngutunui Rd Br	3022669	18	1987—2015	<0.05 — 3.4 (3ND)	0.052	<0.004 — 0.16 (9ND)	insufficient data	10.2 — 99 (16ND)	insufficient data	<1 — 2 (16ND)	insufficient data	<0.001 — 0.49 (9ND)	insufficient data	<0.02 — 11.9 (9ND)	insufficient data
Mangauika	3023179	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
Puniu at Bartons Corner Rd Br	3023180	10	1993—2015	<0.05 — 4.8 (2ND)	insufficient data	0.01 — 0.22 (3ND)	insufficient data	no data	no data	no data	no data	<0.001 — 0.001 (4ND)	insufficient data	<0.04 (4ND)	insufficient data
Mangaohoi	3023476	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
Pokaiwhenua	3023849	24	1996—2015	<0.05 — 7 (3ND)	no stat. sig. trends	0.02 — 0.08 (17ND)	insufficient data	10.5 — 186 (16ND)	insufficient data	<1 (23ND)	insufficient data	<0.001 — 0.18 (12ND)	insufficient data	<0.04 — 0.04 (10ND)	insufficient data
Little Waipa	3023862	9	1995—2015	0.12 — 6.7	insufficient data	0.07 — 0.11 (7ND)	insufficient data	180 (8ND)	insufficient data	no data	no data	<0.001 — 0.005 (2ND)	insufficient data	<0.02 — 0.05 (2ND)	insufficient data
Moakurarua	3023962	4	1995—2015	0.23 — 7.6	no stat. sig. trends	<0.004 — 0.05	insufficient data	17.1 — 280 (2ND)	insufficient data	no data	no data	<0.001 — 0.005 (1ND)	insufficient data	<0.02 (1ND)	insufficient data
Mangatutu	3024473	2	2000—2015	0.33 — 3.3	insufficient data	0.03 (1ND)	insufficient data	no data	no data	no data	no data	0.001 (1ND)	insufficient data	<0.02 (1ND)	insufficient data
Puniu at Wharepapa	3025988	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
Waitomo at SH31 Otorohanga	3026779	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
Waipa at Otorohanga	3027129	10	1978—2015	0.14 — 33 (1ND)	0.15	0.01 — 0.13 (5ND)	insufficient data	7.7 — 100 (5ND)	no stat. sig. trends	<1 (9ND)	insufficient data	<0.001 — 0.007 (5ND)	insufficient data	<0.02 — 0.04 (4ND)	insufficient data
Mangapu	3027166	15	1995—2015	<0.05 — 5.9 (2ND)	no stat. sig. trends	<0.004 — 0.05 (8ND)	insufficient data	26.9 — 1009 (6ND)	insufficient data	<1 (13ND)	insufficient data	<0.001 — 0.47 (7ND)	insufficient data	<0.2 — 4.6 (2ND)	insufficient data
Mangamingi	3027230	11	1986—2014	<0.05 — 13.3	no stat. sig. trends	<0.1 — 0.05 (5ND)	insufficient data	17.5 — 171 (5ND)	insufficient data	<1 (8ND)	insufficient data	<0.001 — 0.09 (6ND)	insufficient data	<0.02 — 0.31 (5ND)	insufficient data
Whakauru	3027821	5	2009—2011	0.05 — 0.07	insufficient	no data	no data	no data	no data	no data	no data	<0.001 (4ND)	insufficient	<0.02 (4ND)	insufficient

Catchment Name	NZ Reach	Number of wells with chemistry measurements	Period of measurements	Groundwater N		Groundwater P		Groundwater salinity		Groundwater E. coli		Groundwater redox indicators			
				Nitrate mg/L as N - filterable		Phosphorus mg/L as P- Reactive - filterable		Electrical conductivity		Escherichia coli		Manganese mg/L All forms as Mn - filterable		Iron mg/L All forms as Fe - filterable	
				median range	trend	median range	trend	median range	trend	median range	trend	median range	trend	median range	trend
				mg/L	mg/L/decade	mg/L	mg/L/decade	uS/cm	uS/cm/decade	cfu/100 ml	cfu/100 ml/ decade	mg/L	mg/L/decade	mg/L	mg/L/decade
					data								data		data
Mangarapa	3028468	3	2004—2015	0.12 — 0.78	insufficient data	0.01 — 0.04 (1ND)	insufficient data	no data	no data	no data	no data	<0.001 — 0.008	insufficient data	<0.02 — 0.03	insufficient data
Waitomo at Tumutumu Rd	3028966	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
Waipa at Otewa	3029370	2	2015—2015	0.09 — 0.17	insufficient data	0.01 — 0.014	insufficient data	no data	no data	no data	no data	<0.001	insufficient data	<0.02	insufficient data
Waikato at Waipapa	3030247	5	1996—2015	<0.05 — 7.2 (1ND)	insufficient data	0.08 — 0.09 (2ND)	insufficient data	no data	no data	no data	no data	<0.001 — 0.31 (3ND)	insufficient data	<0.02 — 0.43 (2ND)	insufficient data
Mangarama	3031371	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
Whirinaki	3031392	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
Otamakokore	3031549	6	1993—2015	2.7 — 15.6 (2ND)	-1.3 — -0.59	0.02 — 0.1 (4ND)	insufficient data	28.2 — 205 (4ND)	-0.34	<1 (5ND)	insufficient data	<0.001 — 0.04 (3ND)	no stat. sig. trends	<0.02 — 0.04 (2ND)	insufficient data
Mangaokewa	3031564	1	2015—2015	4.5	insufficient data	0.07	insufficient data	no data	no data	no data	no data	<0.001	insufficient data	<0.02	insufficient data
Tahunaatara	3032435	5	2000—2015	<0.05 — 0.8 (1ND)	insufficient data	0.01 (4ND)	insufficient data	no data	no data	no data	no data	<0.001 — 0.007 (3ND)	insufficient data	<0.02 — 0.02 (2ND)	insufficient data
Mangaharakeke	3032678	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
Waiotapu at Campbell	3034280	4	2004—2015	<0.05 (2ND)	insufficient data	0.04 (3ND)	insufficient data	no data	no data	no data	no data	<0.001 — 0.42 (2ND)	insufficient data	<0.02 — 0.68 (1ND)	insufficient data
Kawaunui	3034452	3	1995—2012	<0.05 — 1.7	insufficient data	0.01 (2ND)	insufficient data	no data	no data	no data	no data	0.001 (2ND)	insufficient data	<0.02 (2ND)	insufficient data
Waikato at Ohakuri	3035123	31	1980—2015	<0.05 — 10.5 (14ND)	insufficient data	<0.004 — 0.19 (22ND)	insufficient data	no data	no data	no data	no data	<0.001 — 1.2 (17ND)	insufficient data	<0.04 — 24 (9ND)	insufficient data
Waikato at Whakamaru	3035301	6	1993—2015	<0.05 — 7.8 (2ND)	insufficient data	0.05 (5ND)	insufficient data	no data	no data	no data	no data	0.001 — 0.03 (4ND)	insufficient data	<0.04 — 2.6 (2ND)	insufficient data
Waipapa	3035556	11	1986—2013	<0.05 — 4.3 (5ND)	insufficient data	no data	no data	no data	no data	no data	no data	<0.001 — 1.1 (5ND)	insufficient data	<0.1 — 0.52 (5ND)	insufficient data
Waipa at Mangaokewa Rd	3036214	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data
Mangakino	3036710	13	1987—2015	<0.05 — 9.4 (2ND)	no stat. sig. trends	<0.004 — 0.13 (6ND)	insufficient data	9.4 — 85.2 (11ND)	0.76	no data	no data	<0.001 — 1.4 (5ND)	insufficient data	<0.02 — 57 (4ND)	no stat. sig. trends
Mangakara	3037027	3	2008—2015	0.21 — 11.2	insufficient data	0.06 (2ND)	insufficient data	no data	no data	no data	no data	<0.001 — 0.001	insufficient data	<0.02	insufficient data
Waiotapu at Homestead	3037105	23	1992—2015	<0.05 — 5.7 (3ND)	0.005	0.01 — 3.2 (12ND)	insufficient data	5.1 — 401 (17ND)	insufficient data	<1 (22ND)	insufficient data	<0.001 — 0.88 (10ND)	insufficient data	<0.04 — 19.1 (8ND)	insufficient data
Torepatutahi	3038300	35	1937—2015	<0.05 — 14 (4ND)	-0.7	0.02 — 3.1 (27ND)	insufficient data	6.1 — 51 (33ND)	insufficient data	no data	no data	<0.001 — 1.4 (15ND)	insufficient data	<0.02 — 29 (15ND)	insufficient data
Waikato at Ohaaki	3039804	27	1937—2015	<0.05 — 14.8 (12ND)	insufficient data	<0.004 — 0.16 (18ND)	insufficient data	no data	no data	no data	no data	<0.001 — 0.5 (18ND)	insufficient data	<0.1 — 2.6 (16ND)	insufficient data
Pueto	3042044	4	1996—2015	<0.002 — 6.3	-0.3	0.07 — 0.47 (1ND)	insufficient data	19.3 — 164 (2ND)	insufficient data	360 (3ND)	insufficient data	<0.001 — 0.17 (1ND)	insufficient data	<0.02 — 0.58 (1ND)	insufficient data

Item	Description
no data	There was no data available for this catchment
no stat. sig. trends	The p-value from the Mann-Kendall test was above 0.05
insufficient data	There was no enough data to conduct the Mann-Kendall trend test due to either high censoring, or less than 10 data points
86 — 94	Statistically significant (Mann-Kendall p-value<0.05) trend magnitude range (sen slope estimator) is 86 to 94 mg/L/L obtained from more than one well
21	Statistically significant (Mann-Kendall p-value<0.05) trend magnitude (sen slope estimator) is 21 mg/L/decade obtained from a single well

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