REPORT

Source protection zones for new public supply bore fields

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Prepared by
Tonkin & Taylor Ltd
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1 Introduction

1.1 General

Napier City Council (NCC) has engaged Tonkin & Taylor Ltd (T+T) to prepare source protection zones (SPZs) for its proposed redevelopment of public water supply bore fields located in the Napier area.

This report has been prepared to document technical work undertaken to delineate the SPZs and has been prepared in accordance with our Letter of Engagement and agreed contract terms and conditions (dated 18 September 2018) for NCC as our client.

1.2 Project objectives

NCC currently supplies drinking water to its constituents from a network of existing groundwater supply bores, located within the Heretaunga Plains aquifer system. T+T prepared SPZs for the existing NCC public supply bores in December 2018[1]. We understand that SPZs for the existing bores will be used by NCC for water safety planning and assessment until the bores are eventually replaced.

As part of a commitment to providing safe drinking water and to achieve a range of strategic objectives, NCC is planning to consolidate their existing network of bores into two main bore fields. The consolidation and bore field upgrades will result in the decommissioning/dormancy of all but one of the Taradale bores (T6) and the development of a consolidated bore field around the T6 bore. Another consolidated bore field will be developed in the Awatoto area around the A1 and A2 bores. A full description of the new bore fields as they are currently proposed is provided in Section 3.

The objective of the work presented in this report was to develop SPZs for the two proposed bore fields. SPZs for the new bore fields are intended to be updated within the NCC Water Safety Plan (WSP) once the bore fields have been developed and become operational. SPZs for the new bore fields may also be incorporated into the Hawkes Bay Regional Plan, pending the outcome of the Regional Plan Change process that is currently underway.

1.3 Groundwater source protection

A broad range of contaminants, including organic and inorganic contaminants and pathogenic microorganisms pose a significant risk to human health when they are consumed in groundwater supplied as drinking water. This was highlighted by the Havelock North *Campylobacter* outbreak in 2016 which prompted reforms to drinking-water legislation (currently in progress) and encouraged water suppliers to develop a detailed understanding of their drinking-water sources and to manage land-use activities within source-water catchments. Taking steps to prevent contaminants from entering drinking-water sources is one part of a multiple barrier approach to water supply risk management.

The Health Act 1956 covers the high-level obligations of a water supplier, and the Local Government Act 2002 covers broader management obligations. Section 69A of the Health Act 1956 requires drinking-water suppliers to take all practicable steps to comply with the *Drinking-water Standards for New Zealand*[2] (DWSNZ). The DWSNZ are the standards against which the drinking-water quality is measured, and are produced by the Ministry of Health, which has responsibility to ensure appropriate regulations are in place. The Ministry of Health also provides the *Guidelines for Drinking-*

[1] Tonkin + Taylor Ltd. *Source protection zones for public supply bores*. Report for Napier City Council, December 2018.
[2] Ministry of Health. 2018. *Drinking-water Standards for New Zealand 2005 (revised 2018)*. Wellington: Ministry of Health.

water Quality Management for New Zealand[3] ("the Guidelines") to assist drinking-water suppliers in adhering to the DWSNZ.

All drinking-water supplies providing drinking-water to over 500 people must have a Water Safety Plan (WSP) to guide the safe management of the supply[2]. WSPs for drinking-water supplies are intended to reduce the likelihood of contaminants entering supplies in the first place[4], in addition to monitoring of the water supply.

WSPs are intended to ensure the water supplier can effectively manage their water supply as the plan identifies multiple interventions at many levels so that, if one part of the system fails, the other parts may compensate for this failure and provide redundancy. The SPZs presented in this report are intended to be implemented by NCC into their respective WSPs as part of their responsibilities under the Health Act and current version of the DWSNZ.

The DWSNZ are currently undergoing revision, which may result in significant changes to the standard. Currently the DWSNZ do not include requirements for drinking-water suppliers to implement SPZs, but do specify minimum water quality standards for drinking water and encourage development of SPZs as part of water safety planning.

There is currently no national standard for the delineation of SPZs in New Zealand, however GNS has provided a technical description[5] supported by a guideline[6] document. The approach adopted for the delineation of SPZs for the proposed NCC bore fields generally complies with the current industry guidance and peer-reviewed approaches undertaken elsewhere within the Heretaunga Plains Aquifer. However, it must be appreciated that there are number of processes currently underway at a regional and national level that may influence current industry guidance, including:

- Technical discussions within the TANK[7] Hawkes Bay Regional Plan change committee.
- Revision of the DWSNZ and ongoing technical caucusing at a national level.
- Possible revisions to the National Environmental Standard (NES) for Sources of Human Drinking Water[8] (2007).

1.4 Scope of work

Napier City Council is strongly committed to developing tools to understand and manage its public drinking-water source as a part of its wider drive to implement a multi-barrier approach to water security. The development of SPZs for each of the proposed NCC public supply bore fields within the Napier urban area is a key step in the process of management of its current drinking water sources while bore field redevelopment works are being planned and completed over the next three to five years. The management objectives include:

- The definition of investigation boundaries for catchment sanitary inspections (CSI) and risk assessments relating to the proposed NCC public water supply (once consolidated and reconfigured).
- The implementation of SPZs into future versions of the NCC WSPs, when the new bore fields become operational.

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[3] Ministry of Health. 2017. *Guidelines for Drinking-water Quality Management for New Zealand* (3rd ed.). Wellington: Ministry of Health.
[4] https://www.health.govt.nz/publication/framework-how-prepare-and-develop-water-safety-plans-drinking-water-supplies
[5] Moreau. M. et al., 2014. Envirolink Tools Project - Capture Zone Delineation — Technical Report*, GNS Science Report 2013/57*.
[6] Moreau. M. et al, 2014. Capture zone guidelines for New Zealand, *GNS Science Report 2013/56*.
[7] Tutaekuri, Ahuriri, Ngaruroro and Karamu catchments, https://www.hbrc.govt.nz/hawkes-bay/projects/tank/about-tank/
[8]Resource Management (National Environmental Standards for Sources of Human Drinking Water) Regulations 2007 http://www.legislation.govt.nz/regulation/public/2007/0396/latest/DLM1106901.html

- Possible uptake into the Regional Plan and revision to land-use planning rules (uptake and rules to be governed by TANK Plan Change process).

To support these objectives, we have undertaken the following scope of work:

- A review of previous SPZ development work for NCC[1], and adoption of aquifer parameters.
- Development of three SPZs around each bore field including:
  - SPZ1 (immediate protection zone) based on a 5 m setback.
  - SPZ2 (microbial protection zone, based on a one year groundwater travel time) derived from the Analytic Element Modelling method and particle tracking.
  - SPZ3 (capture zone) “that delineates the entire recharge area of a feature [i.e. bore field], truncated as appropriate by flow boundary criteria”[5].
- Completion of a high level sensitivity analysis during this work.

2 Hydrogeological setting

The bore fields investigated in this report are located in the Heretaunga Plains aquifer system (refer Appendix A, Figure 1, Heretaunga aquifer system, for aquifer extent), which covers an area of 300,000 hectares and is the most extensively used aquifer in the region. The aquifer provides water supplies for Napier and Hastings cities, and is extensively used for small community and domestic water supplies and for horticulture, agriculture, and cropping irrigation. An overview of selected features of the Heretaunga Plains aquifer system is provided in HBRC report 4803[9] which was based on previous studies[10,11] and is summarised and updated below. Figure 2 (Appendix A) depicts the hydrogeological conceptual model as described below.

The aquifer system is located in a tectonically active subsiding coastal depression, which extends inland from the sea to Maraekakaho in the west, and from Napier in the north to Cape Kidnappers in the south. The Heretaunga sediments were deposited in the basin over the last 250,000 years, with most hard gravels and other sediments derived from erosion of the upland parts of the Tutaekuri and Ngaruroro catchments. In the last 20,000 years, gravels have also been deposited in the Heretaunga basin from the Tukituki River, and pumice sands have been contributed from the Taupo Volcanic Zone. These terrestrial sediments are interbedded with marine silts and clays from past sea-level oscillations during colder and warmer climates.

During cold glacial periods, sea levels were lower than at present. Sea levels rose (and transgressed inland) during warmer interglacial periods, typically depositing fine-grained marine silts and clays over the terrestrial gravels. The most significant marine transgression occurred from 9,000 to 6,500 years ago. This transgression overlaid terrestrial gravels and other sediments with a thick layer of marine clay which confines the groundwater contained in underlying gravel aquifers on the eastern part of the Heretaunga Plains.

The Heretaunga Plains comprise layers of unconsolidated sediments through which groundwater flows. Coarse sediments such as gravels and sands typically form the productive aquifers beneath the plains. Between these layers, finer sediments such as clay and silt form confining layers. These finer sediments have low permeability and retard the vertical movement of groundwater between aquifers. The collective layering of aquifers is referred to as the Heretaunga aquifer system.

The Heretaunga Plains aquifer system includes at least five primary water-bearing units which were formed during the last 250,000 years. Sediments from the Tutaekuri, Ngaruroro, and Tukituki Rivers, together with coastal, lagoon, estuarine and embayment deposits, have formed both confined and unconfined aquifer units. From the westernmost edge of the Plains near Maraekakaho to Hastings, the aquifer system is predominantly unconfined. Further east, the aquifer system becomes progressively confined where overlain by layers of clay and silt (see Figure 1), with aquifer piezometric heads recorded as 8 m to 10 m above mean sea level at the coast. Regional groundwater flow directions are indicated from the west and north-west (from the Ngaruroro River) east towards the coast. In areas of active pumping, there can be little difference between heads measured in water-bearing units located at different depths, suggesting a connection between these units.

The Heretaunga Plains aquifer system is predominantly recharged by river losses from the Ngaruroro River, with the main discharge area located in the reach between Roy's Hill and Fernhill[9] (see Figure 1, Appendix A). Some rainfall recharge occurs in the western unconfined area of the aquifer. In the vicinity of the NCC bore fields, land surface recharge is prevented by thick confining layers and relatively high groundwater pressures in the underlying aquifer. Although a significant hydrological feature within the Heretaunga Plains, groundwater mean residence time data and surface water

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[9] Gordon, D., Groundwater Quality State of Environment State and Trends, *HBRC Report No. 4803*, September 2016.
[10] Dravid, P.N. and Brown, L.J., 1997. *Heretaunga Plains groundwater study*. Hawke's Bay Regional Council.
[11] Brooks, T., 2006, *Heretaunga Steady State Groundwater Model*, Hawke's Bay Regional Council, Plan number 3765.

budgets[12] suggest that the Tutaekuri River is not directly connected to the Heretaunga Plains confined aquifer in the vicinity of the NCC proposed bore fields.

Hydraulic gradients vary significantly over the Heretaunga Plains. In general terms, hydraulic gradients become steeper towards the west, approaching the main recharge zone between Roy's Hill and Fernhill where water moves from the Ngaruroro River into the Heretaunga Plains groundwater. The area in which the NCC urban supply bore fields are situated can be generally characterised by relatively shallow hydraulic gradients and low groundwater velocities.

[12] Morgenstern U., et al. April 2018. Heretaunga Plains aquifers: groundwater dynamics, source and hydrochemical processes as inferred from age and chemistry tracer data*, GNS Science report 2017/33* (see Figure 4.21 of that report).

3 Napier City Council bore fields

3.1 General

Napier City Council hold a global resource consent[13] to take and use groundwater from eleven existing bores within the Napier Metropolitan area on the Heretaunga Plains. NCC plans to consolidate its existing network of bores into two main bore fields at Awatoto and Taradale. During the redevelopment of the bore fields, three additional bores will be installed at Taradale and two additional bores at Awatoto. The approximate area in which the additional bores will be constructed has been provided by NCC, however the exact location will be determined during further technical work to determine the optimum bore field configurations.

For the purpose of delineating SPZs we have assumed that a new resource consent (or a change to the existing consent) granted for the new bore fields will permit abstraction at rates specified in the existing consent. Once the groundwater take consent is granted for the new bores, it may be appropriate to revise SPZs if permitted abstraction rates vary from the existing consent (for instance if an annual maximum groundwater abstraction rate is specified in the new consent).

The existing consent sets out the following maximum abstraction rates, relevant to SPZ delineation for the new bore fields:

- The maximum 7-day take volume and instantaneous pumping rate from T6 shall not exceed 69,552 m^3 and 115L/s respectively.
- The maximum 7-day take volume and instantaneous pumping rate from A1 shall not exceed 75,600 m^3 and 125L/s respectively.
- The cumulative maximum 7-day volume take from all bores shall not exceed 387,744 m^3. This equates to an average cumulative rate of 641 L/s and a maximum annual abstraction rate of approximately 20 million m^3/yr.

For the purposes of delineating SPZs, we have assumed that the final bore locations will not vary sufficiently from the approximate locations provided by NCC to significantly impact the SPZ2s and SPZ3s provided in this report. However, we recommend that this assumption is confirmed once final bore locations are available. At that time, refinements will be required to the SPZ1 and SPZ2a (5m and 100m buffers respectively).

SPZs are used as a tool for helping water suppliers to develop a detailed understanding of their drinking-water sources and to manage activities within source-water catchments as a barrier to contamination of the source. SPZs have been developed for the proposed Awatoto and Taradale bore fields. The structural characteristics of these bore fields and adopted aquifer parameters at each bore field are summarised in the following sub-sections.

[13] Consent No. WP060658Ta. Issued on 1 March 2010 to NCC by the Hawkes Bay Regional Council.

3.2 Awatoto bore field

3.2.1 Location and description

The existing Awatoto bore field consists of two bores (A1, A2) located along Awatoto Road close to the intersection with McLeod Road. Two additional bores are proposed to be constructed adjacent to these existing bores. We have assumed that the additional bores will be screened at a similar depth and in similar material to that of A2. Information about the existing bores and the proposed bore field is presented in Table 3.1.

Table 3.1: Awatoto bore information

Existing bores					
Bore	**HBRC ID**	**Easting (m NZTM)**	**Northing (m NZTM)**	**Maximum consented pumping rate (L/s)**	**Screen depth (m bgs)**
A1	5913	1935753	5616116	125	74 – 76, 78 - 84
A2	16352	1935454	5616071	125	113 – 118
Modelled bores (assumed location)					
Bore	**Easting (m NZTM)**	**Northing (m NZTM)**	**Assumed maximum consented pumping rate (L/s)**		
AN1	1935594	5616134	125		
AN2	1935525	5616253	125		

3.2.2 Hydrogeology

The Awatoto bore field production aquifer is located beneath marine clay deposits with occasional sand, peat and gravel beds; the thickness of these deposits is approximately 40-50 m (see Figure 14, Appendix B). We consider this sequence to act as a confining layer for the gravel aquifer below. Borehole logs suggest that the more permeable layers (i.e. sand) in the confining unit are laterally discontinuous. This discontinuity, and upward vertical hydraulic gradients observed in the area, suggests that these permeable layers are unlikely to act as significant pathways of groundwater from the ground surface to the underlying aquifer unit.

Below the clay formation is a sequence of blue gravels with intermittent sand and clay units; these deposits are assumed to be of fluvial origin. The lower permeability sand and clay layers are generally 1-3 m thick and borehole logs indicate that these lenses are unlikely to be laterally extensive. Therefore we assume that the gravel formations are hydraulically connected and can be modelled as one aquifer unit. The base of the aquifer unit is not well-defined as bore holes are typically terminated prior to reaching the bottom of the aquifer. Based on the assumption that the gravel formations encountered are hydraulically connected, we have estimated a total aquifer thickness of 40 m which was adopted as a model input parameter. Cross sections, based on geological information from bore logs available on the HBRC website for the Awatoto bore field are shown in Figure 14, Appendix B.

Data from State of the Environment (SOE) observation bores between 2010 and 2017 indicate that the aquifer is artesian, with mean static water levels ranging between 8.9 – 9.5 m above sea level (refer Figure 14, Appendix B) and gradients oriented approximately along a southwest – northeast axis. Age-tracer analysis[14] in bore A2 indicates that the groundwater has a mean residence time of

[14] van der Raaij, R., 11 August 2016. *Groundwater residence time determination for Napier City water supply well A2.* Letter report no. CF 2016/112 LR. GNS Science, sent to Napier City Council.

55 years, with a young groundwater fraction of less than 0.005 %, which suggests that no local recharge of the aquifer is occurring.

Additionally, the geological conditions within the vicinity of the bore fields exhibit relatively high artesian pressures and a relatively thick, low permeability overlying aquitard. We consider that the combination of these conditions means that the development of downward hydraulic gradients is unlikely, and if it did occur, downward travel times through the aquitard would likely be significantly longer than 365 days.

3.2.3 Aquifer properties

A mean transmissivity value of 6,400 m^2/day was derived from pumping tests conducted by Honnor Drilling Ltd and analysed by Lattey Group in February 2016[15]. Based on borehole logs included in the Lattey Group report, supported by results from the HBRC nested piezometer at Awatoto[10], we have assumed an aquifer thickness of 40 m and a calculated value of hydraulic conductivity of 160 m/day.

3.3 Taradale bore field

3.3.1 Location and description

The redeveloped Taradale bore field will comprise four public supply bores: one existing bore (T6) and three additional bores that T+T understands will be constructed adjacent to T6 in the vicinity of Guppy Road. We have assumed that the additional bores will be screened at a similar depth and in similar material to that of T6. No other bores within the Taradale area have been included in the development of SPZs presented in this report.

Table 3.2: Taradale bore information

Existing bores					
Bore	**HBRC ID**	**Easting (m NZTM)**	**Northing (m NZTM)**	**Maximum consented pumping rate (L/s)**	**Screen depth (m bgs)**
T6	4144	1931425	5615483	125 (existing consent states 115 L/s)	60.0 – 72.35
Modelled bores (assumed location)					
Bore	**Easting (m NZTM)**	**Northing (m NZTM)**	**Assumed maximum consented pumping rate (L/s)**		
TN1	1931404	5615354	125		
TN2	1931530	5615323	125		
TN3	1931558	5615436	125		

3.3.2 Hydrogeology

The proposed Taradale bore field production aquifer is overlain by 10-30 m of clay deposits likely of marine/coastal origin (see Figure 13, Appendix B). Below the clay formation is a complex sequence of fluvial sands and gravels with occasional clay units. The bore field is assumed to be screened in the deeper part of this fluvial sequence from approximately 60 m below ground surface where significant (> 15 m) gravel units have been encountered. The lower boundary of the aquifer is generally poorly defined as most bores were terminated before reaching lower confining surfaces. Boreholes in the immediate vicinity of the proposed bore field location suggest that the aquifer is

[15] Lattey Group, July 2016. *Aquifer pump test & assessment of environmental effects for new public supply well no. 16352 (A2)*. For Napier City Council.

between 44 and 57 m thick (bores 4171 and T6 respectively). We have therefore adopted an aquifer thickness of 50 m.

The overlying clay deposits are considered to confine an aquifer in the lower fluvial unit, as indicated by artesian conditions encountered at depth[16]. Cross section boreholes in the vicinity of present-day watercourses (Ngaruroro River and Tutaekuri-Waimate Stream) report some surficial gravel layers associated with the Tutaekuri River gravel fan. However, we consider these gravels unlikely to be connected to the aquifer of interest as the surficial deposits are underlain by clay units, and groundwater age and water budget estimates[12] indicate that the aquifer does not receive recharge from either the Tutaekuri River in this area or from rainfall.

Data from State of the Environment (SOE) observation bores between 2010 and 2017 and from previous investigations[16] indicate that the aquifer is artesian, with mean static water levels ranging between 9.2 – 12.7 m above sea level (refer Figure 13, Appendix B) and gradients approximately oriented along a south-southwest – north-northeast axis. Due the relatively high artesian pressures, thickness and low permeability of the confining layer, and the likely level of drawdown in the supply bores, we do not consider the risk associated with gradient reversals close to the bores during extraction to be significant.

3.3.3 Aquifer properties

A 'best-fit' transmissivity value of 17,885 m^2/day was reported for bore T6 by Beca[17]. Adopting this value, and a 50 m aquifer thickness based on borehole logs, a hydraulic conductivity of 360 m/day was derived. This conductivity value is broadly consistent with a mean value of 430 m/day reported by GHD[16] for the Taradale bore field, derived from pumping testing of the nearby T2 bore in April 2018.

[16] GHD Ltd; June 2018; *Bore security investigation Assessment of bore security;* Report 51/37522/02. Prepared for Napier City Council.

[17] Beca Carter Hollings & Ferner Ltd; August 1998; *Pump test analysis, Proposed T6 water bore, Guppy Road*; Prepared for Napier City Council.

4 Methods

4.1 Overview

The GNS Capture Zone Delineation[5] report recommends three zones for wells, springs and groundwater-fed lakes and wetlands in New Zealand:

- *'An immediate protection zone, delineated by a minimum distance of 5 m around the hydrogeological feature.*
- *A protection zone surrounding the immediate protection zone, specifically to guard against microbial contamination. This protection is to be either: a safeguarding distance; or a one-year travel time. The travel time refers to the time it takes groundwater to flow from a given point to the feature. This zone is designed to protect against microbial contamination in typical New Zealand settings.*
- *A capture zone surrounding the protection zone, for protection from other types of contaminants. This capture zone is to be defined by either: a catchment or hydrogeological boundary; or a travel time of either 10 or 50 years. This capture zone protects the hydrogeological feature from any contaminant that enters the groundwater system as a result of land use activity and then migrates in the aquifer towards the hydrogeological feature (the possibility of contaminant degradation or sequestration is not considered).'*

Within this document we refer to these zones as follows:

- Source Protection Zone 1 (SPZ1) is the immediate 5 m protection zone.
- Source Protection Zone 2 (SPZ2) is the zone to protect against microbial contamination.
- Source Protection Zone 3 (SPZ3) is the zone for protection against other types of contamination.

To define the microbial protection zone (SPZ2) around the wells we adopted a one-year travel-time criterion and to define the total capture zone (SPZ3) we adopted a ten-year travel-time criterion modified by hydrogeological considerations (e.g. allowing for flow boundaries and changes in groundwater flow direction) in order to provide suitably protective zones.

4.1.1 Our adopted approach for development of SPZs

We have adopted the following approach to define each of the SPZs at each bore or bore field:-

- Source Protection Zone 1 (SPZ1) is the immediate 5 m protection zone around each bore. This is a minimum distance and therefore may be larger. The focus of this reporting is on development of SPZ2 and SPZ3 zones. At the presentation scale (refer to figures in Appendix A) we have not shown the SPZ1 around each well.
- Source Protection Zone 2 (SPZ2) is the zone to protect against microbial contamination. The SPZ2 zones have been created by delineation of the boundary delineated by including all of the sensitivity analyses and also the 1, 3, 6 and 12 month travel-time assessments.
  - Source Protection Zone 2a (SPZ2a) has been defined as a 100 m protection zone surrounding bores that are screened below confining layers[18]. The SPZ2a zone accounts for contamination pathway risks by allowing for greater controls to be placed on land uses in close proximity to the bore field that have the potential to deliver contamination.

[18] Environment Canterbury, April 2019. Section 16, Schedule 1: Community Drinking-Water Protection Zones (Table S1A), *Canterbury Land and Water Regional Plan*. https://eplan.ecan.govt.nz/eplan/#Rules/0/28/1/24867, last accessed 16 April 2019.

- Source Protection Zone 3 (SPZ3) is the zone for protection against other types of contamination by delineating the entire recharge area of a feature, truncated as appropriate by flow boundary criteria[5]. This zone has been developed considering 10-year particle travel times and by using hydrogeological judgement considering groundwater dynamics from age data[12] and the effect of no-flow or recharge boundaries.

GNS recommends that a sensitivity-type approach be adopted to delineate the microbial protection zone (SPZ2) and the total capture zone (SPZ3) by varying input parameters within known bounds, or by ±25 % if insufficient data about the parameter distribution is available. Average or median values for input parameters should be used for a "best estimate" calculation, whereas the SPZ2 and SPZ3 should be delimited by the outer edges of the zones obtained through input parameter variations. We have followed this approach for the development of SPZs for the proposed Napier urban area bore fields by systematically varying the "best estimate" parameters by ±25%. Our adopted approach is fully described in Section 4.2.3.

4.2 Modelling

Modelling of groundwater flow for the delineation of source protection zones was conducted using the Analytic Element Modelling (AEM) method[19] with conservative solute transport modelled with particle tracking. These methods are widely used for the delineation of capture zones for hydrological features[20,21] and are recommended in the GNS 2014 report (see Table 7 of that report). The AEM method has been implemented previously in the Heretaunga Plains aquifer system for the delineation of existing bore fields for NCC[1] and urban supply well SPZs[22] for Hastings District Council.

The Hawkes Bay Regional Council (HBRC) has previously developed a transient groundwater flow model of the Heretaunga Plains aquifer system using MODFLOW that is calibrated to stream depletion and hydraulic head observations[23]. Due to a paucity of groundwater monitoring data (i.e. SOE monitoring bores) in the area of the NCC bore fields, T+T has adopted the modelled transient hydraulic heads from layer two of the HBRC calibrated model (model number HPM035) and integrated these into AEM methods. The HBRC model development report[23] indicates that the calibrated transient model is generally able to reflect the groundwater dynamics in the area of the bore fields (refer to bores 222 and 15022, as depicted in Figure 4.1). It was not within the scope of works for this project to assess or use the HBRC numerical model for delineating SPZs directly.

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[19] Haitjema H., 1995. *Analytic Element Modelling of Groundwater Flow*, Academic Press (Elsevier).
[20] Toews, M.W. & Moreau, M.F., October 2014. Groundwater protection zone delineation of Matamata supply wells. *Waikato Regional Council Technical Report 2014/63*, prepared by GNS Science.
[21] Raymond, H.A., Bondoc, M., McGinnis, J., Metropulos, K., Heider, P., Reed, A. and Saines, S., 2006. Using analytic element models to delineate drinking water source protection areas. *Groundwater*, 44(1).
[22] Tonkin + Taylor Ltd. *Source protection zones for public supply bores*. Report for Hastings District Council, October 2018.
[23] Rakowski, P. & Knowling M., 2018. *Heretaunga Aquifer Groundwater Model Development Report*, Hawkes Bay Regional Council (refer Figure 5-18 et. seq.).

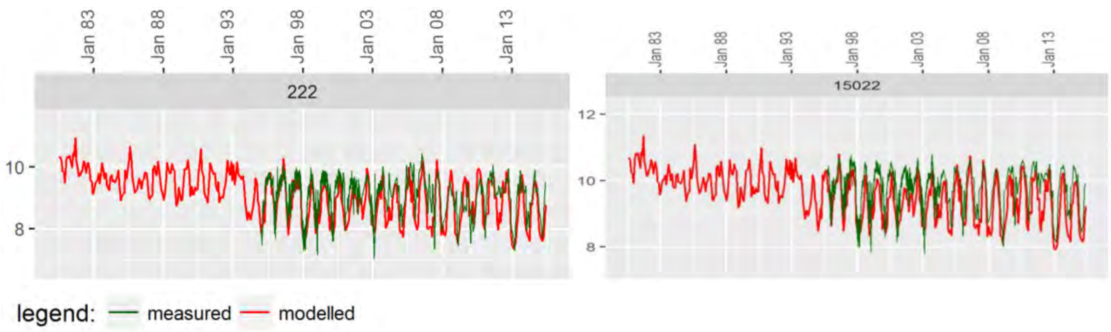

Figure 4.1: Transient calibration plots for two closest HBRC calibration targets. The horizontal axis is date and the vertical axis is groundwater level in metres (refer to HBRC model development report[23]).

The AEM method is computationally efficient, thus allowing for a large number of model scenarios and parameter sensitivities to contribute to SPZ delineation in a suitable timeframe. The AEM methods implemented here have a low number of parameters, which avoids additional model complexity that may not necessarily be justified or constrained by the available observation data, whilst adequately capturing regional-scale groundwater flow and transport dynamics.

T+T used AnAqSim[24] software for the derivation of SPZs. AnAqSim is commercial hydrogeological modelling software that provides an interactive computer environment for AEM and associated particle tracking methods. The software includes functions for modelling pumping wells, including the influence of hydrological features, such as rivers, recharge, and no-flow boundaries.

4.2.1 Uniform flow

Regional-scale groundwater source protection zones were delineated by applying a uniform flow condition within the aquifer of interest. Uniform flow model parameters (flow direction and hydraulic gradient) were derived from HBRC numerical model outputs (see section 4.2.2.3).

T+T implemented a modified uniform flow equation approach using the AnAqSim software by including a flow barrier in the model. This modification was necessary to account for Pliocene limestones and mudstones to the west of the NCC bore fields that are expected to act as a barrier to flow in the aquifer system. The inclusion of the flow barrier also accounts for deviation in flow directions close to this boundary.

4.2.2 Input parameters

The AEM method requires the following model input parameters:

- Hydraulic conductivity;
- Aquifer thickness;
- Effective porosity;
- Hydraulic gradient and groundwater flow direction;
- Hydraulic boundaries; and
- Pumping scenarios.

A number of sensitive input parameters were considered further prior to developing the protection and capture zones. The following subsections discuss the selection of input parameters for the model. The adopted aquifer properties are summarised in Table 4.1 below.

[24] http://www.fittsgeosolutions.com/anaqsim/, release 2019-1.

4.2.2.1 Hydraulic conductivity and aquifer thickness

The derivation of hydraulic conductivity and aquifer thickness input parameters are described in sections 3.2.2 and 3.3.2 for the Awatoto and Taradale bore fields respectively. These input parameters are summarised in Table 4.1 below.

4.2.2.2 Effective porosity (n_{eff})

Effective porosity is defined as the interconnected pore volume in a porous medium that contributes to fluid flow. Given the known sensitivity of the size of the protection zones and capture zones to effective porosity, T+T had previously conducted a literature review (see Appendix C) to obtain estimates of effective porosity (n_{eff}).

The literature review determined reasonable n_{eff} values required for SPZ modelling based on particle travel times in the Heretaunga Plains aquifer system. When using complementary pumping and field test data to model groundwater flow in heterogeneous, channelised alluvial aquifer systems, the required transport n_{eff} will actually be smaller than core and laboratory n_{eff} estimates, because the majority of flow is through highly permeable pathways[25,26], which make up only a small fraction of the bulk aquifer system.

Since aquifer models are generally simplified to only a few geological layers (averaging out the true geological heterogeneity within an aquifer system), the n_{eff} used in the transport modelling should be a “bulk” n_{eff} that reflects the fraction of high permeability flow paths in regards to the bulk aquifer system. Therefore, n_{eff} values required for groundwater transport modelling in a simplified aquifer model could range from 0.003-0.15 (and may be smaller depending on the percent of highly permeable flow paths observed in an aquifer). For the purpose of the AEM method, we have adopted a n_{eff} of 0.02 and delineated the SPZ2 and SPZ3 using a sensitivity range of 0.015 – 0.025.

[25] Where these exist as highly porous coarse gravel lenses embedded within a matrix of sandy gravels and sand lenses they are referred to as open framework gravels.

[26] Dann, R., et al., 2009. Characterization and Estimation of Hydraulic Properties in an Alluvial Gravel Vadose Zone. *Vadose Zone Journal*, Volume 8, No. 3 August 2009.

Table 4.1: Summary of aquifer properties

Input parameter	Awatoto	Taradale
Hydraulic conductivity (m/day)	160	360
Aquifer thickness (m)	40	50
Effective porosity[1] (-)	0.02	0.02

1 See Appendix C

4.2.2.3 Hydraulic gradient and groundwater flow direction

Hydraulic gradients and flow directions were derived for each bore field from monthly piezometric contours for the stress periods between July 2008 and June 2015 from the HBRC numerical model[23]. Groundwater flow paths were approximated by successively drawing flow lines perpendicular to upstream 0.2 m piezometric contours, beginning from the centre of the bore field and up to a maximum path-line length of 3 km. The flow direction recorded for that monthly period and bore field was the angle of the first segment of the path line counter-clockwise from East, and the gradient was the mean gradient over the entire length of the path line. The calculated hydraulic gradients and flow directions were then aggregated into average, minimum and maximum values with a rolling average window of one, three, six and twelve months for each bore field.

The individual minimum and maximum values of hydraulic gradient and modelled groundwater flow direction for each bore field and rolling average period were applied as input parameters for model scenarios. During model solution, the uniform flow condition is modified by other model parameters (such as bore field pumping rates and flow barriers) so that the resulting groundwater flow regime is not necessarily uniform.

For “best estimate” capture zones and sensitivity analyses, the mean gradient and flow direction of all bores comprising a bore field was used. Table 4.2 summarises the groundwater flow directions and hydraulic gradients derived from analysis of the transient HBRC model.

By incorporating the modelled extremes in groundwater flow directions and hydraulic gradients over several years, we consider that temporal impacts to regional-scale groundwater flow regimes from seasonal changes, and private/commercial pumping are reflected by the shape and aspect of the SPZs presented.

Table 4.2: Summary of flow direction and hydraulic gradient derived from the transient HBRC model.

Input parameter	Awatoto	Taradale
Hydraulic gradient (%)		
Mean	0.0318	0.0266
Minimum	0.0280	0.0176
Maximum	0.0373	0.0362
Flow direction[1] (°)		
Mean	29.6	44.3
Minimum	25.2	39.5
Maximum	35.7	48.6

[1] Degrees anti-clockwise from East.

4.2.2.4 Hydraulic boundaries

A hydraulic boundary has been included in the AEM to represent mudstones and limestones to the west of Taradale. These formations are considered to have a very low permeability and contribute negligible amounts of groundwater to the Heretaunga aquifer. Within the AEM the formations are approximated as a 'leaky barrier' boundary with a conductance[27] of 0.0001/day. The barrier is congruent with the boundary of the HBRC numerical model, apart from where the Tutaekuri River enters the Heretaunga Plains. Groundwater age data[12] suggests that the Tutaekuri River does not recharge the lower Heretaunga Plains aquifer significantly and therefore the leaky barrier spans the Tutaekuri River between the mudstones and limestones at this location.

4.2.2.5 Pumping rates

For the purposes of our assessment, NCC requested that we model SPZs on the basis of a maximum instantaneous cumulative pumping rate of **650 L/s** (their current consent[13] allows for a long-term maximum average of 641 L/s)**.** This rate also aligns with stream depletion assessments that have already been undertaken for the proposed bore fields.

Because of the nature of its existing global resource consent, NCC currently have operational flexibility to move their abstraction between the bore fields within the consent area. Accordingly we have assumed that there are a range of potential pumping scenarios for the new bore fields, which must be considered and accounted for when developing SPZs.

The following constraints to pumping rates have been proposed:

- Each individual bore has a maximum pumping rate of 125 L/s[28].
- Each bore field has a maximum pumping rate of 500 L/s.
- The maximum total pumping rate for all bore fields is **650 L/s** with a cumulative maximum seven-day volume take of no greater than **393,120 m^3**.

These constraints have been used to develop pumping scenarios for the development of SPZs in this report.

To allow for the most conservatively large pumping scenarios, we have assumed that NCC will focus abstraction on a single bore field at any one time. Thus, two main pumping scenarios were developed:

- *Pumping scenario A*: bores that comprise the bore field of focus were pumped at their corresponding consented maximum instantaneous rate of take. The residual consented cumulative maximum seven-day volume take was then redistributed evenly among the remaining bores.
- *Pumping scenario B*: Pumping is spread equally among all bores.

The modelled pumping scenarios are summarised in Table 4.3. The SPZ2 comprise the envelope of all zones delineated for each of the pumping scenarios. For SPZ3 delineation with the 10-year travel time criterion, only Pumping Scenario A was included.

[27] In AnAqSim, conductance is equal to the hydraulic conductivity of the barrier divided by the barrier thickness.
[28] Based on discussions with NCC, we have assumed that the current maximum consented abstraction rate for T6 (115L/s) will be increased to 125L/s in the new consent.

Table 4.3: Pumping scenarios used to develop source protection zones

Bore field	Awatoto bore field pumping rate	Taradale bore field pumping rate	Cumulative seven-day volume take
Pumping scenario A			
1	500L/s (125L/s per bore)	150L/s (37.5 L/s per bore)	393,120 m^3/ 7 days
2	150L/s (37.5 L/s per bore)	500L/s (125L/s per bore)	393,120 m^3/ 7 days
Pumping scenario B			
1	325 L/s (81.25 L/s per bore)	325 L/s (81.25 L/s per bore)	393,120 m^3/ 7 days

NCC abstracted a total of approximately 10 million cubic meters of groundwater from their bores over 12 months from June 2017 to July 2018 (nearly half of their current consented allowance). Accordingly, the long term pumping rates adopted for SPZ development in this report are considered to be highly conservative, but necessary to allow for the current consent limits to be exercised in the future.

4.2.3 Sensitivity analyses

The GNS capture zone delineation report[5] recommends that the average or median values for input parameters should be used for the “best estimate” area calculation whereas the SPZ2 and SPZ3 zones should be delineated by the outer edges of the zones obtained through input parameter variations. This means that the SPZ2 zones delineated in this way include, and are larger than, the “best estimate” area.

Previous work[22] undertaken by T+T in the Heretaunga Plains aquifer system has indicated that the shape and extent of source protection zones are sensitive to aquifer thickness, hydraulic conductivity and effective porosity. Therefore, these input parameters (see Table 4.1 above), as well as hydraulic gradient, were each increased or decreased by 25%. The flow direction used was the twelve-month “best estimate” – sensitivity to changes in flow direction are already considered, as described in section 4.2.2.3.

4.2.4 Model Assumptions, limitations and uncertainty

Hydrogeological modelling has inherent uncertainties and limitations, depending on the approach taken and the input parameters adopted. This section provides a summary of the assumptions, limitations and uncertainties associated with the AEM method and the input parameters adopted for delineating SPZs for the existing NCC bore fields. These include:

- Conservatism:
  - The adopted analytical approach incorporates steady state conditions, which provides conservatively large SPZs in comparison to some other modelling approaches.
  - Using a maximum abstraction of 650L/s conservatively assumes that NCC pumps to slightly more than their full 7-day maximum volume for a full year continuously. Given that actual long-term groundwater abstraction rates are significantly less than this and currently demand-driven (and therefore highly seasonal), it is highly unlikely that peak abstraction rates would be maintained for full year. Additionally, in some cases we model scenarios where NCC abstracts continuously at its full consent limit from one bore field. We consider this an unlikely scenario, but necessary to allow for NCC to exercise the full operational flexibility assumed to be offered by their future global consent.

- Incorporating modelled extremes in flow direction and hydraulic gradients and incorporation of sensitivity analysis of input parameters into the final SPZs creates conservatively large SPZs

- Limitations/ assumptions:
  - The confining layer above the Heretaunga aquifer provides an additional layer of protection against ingress of surface water into the aquifer if the piezometric surface remains above ground level and the confining layer is intact.
  - The development of downward gradients close to pumping centres and bore fields has not been explicitly modelled. Our understanding from NCC is that the bore field layout will be designed with the objective of reducing the risk of drawing groundwater levels below the shallow unconfined water level. Additionally, even under sub-artesian conditions we consider vertical travel times through the upper confining layers are likely to be significantly greater than one year.
  - We have not explicitly modelled pumping from other bores within the Heretaunga Plains (e.g. neighbouring irrigation bores). We have assumed that the groundwater level contours used to determine flow directions and hydraulic gradients already broadly reflect regional scale effects to groundwater flow regimes caused by other groundwater abstractions.
  - We did not explicitly consider any potential change in the size of the protection zone area that may result from considering rainfall recharge or changes in seepage from surface water features. However the SPZ3 capture zones have been developed using hydrogeological knowledge to account for known hydraulic boundaries and regional-scale groundwater flow regimes.
  - The approach adopted assumes that the hydraulic conductivity of the aquifer is isotropic and homogeneous. The approach does not explicitly consider the effect of more permeable channels which may be present as a result of fluvial deposition, or connections between aquifer storeys caused by faulting.
  - We have assumed that the mudstone and limestone formations (e.g. the hills to the west of Taradale) do not form part of any SPZs i.e. there is negligible groundwater contribution to the Heretaunga Plains aquifer system from these formations.
  - Based on groundwater age data and geology, we have assumed that the Tutaekuri River is not in direct connection with the aquifer which will be pumped.

Overall, we consider that the combination of the AEM method adopted and the input parameters adopted have resulted in SPZs which have sufficient conservatism to allow for the uncertainties and limitations presented above.

5 Results

5.1 Groundwater flow

Groundwater piezometric surfaces generated using the AEM method are generally consistent with the piezometric surfaces from the HBRC calibrated transient groundwater model in the immediate vicinity of the bore fields for a single iteration.

Figure 5.1 shows that the AEM contours (0.2 m interval) represent the groundwater flow conditions at a scale relevant for regional modelling of source protection zones. It should be noted that SPZs are composed of multiple AEM realisations and therefore account for variation in flow direction and hydraulic gradient.

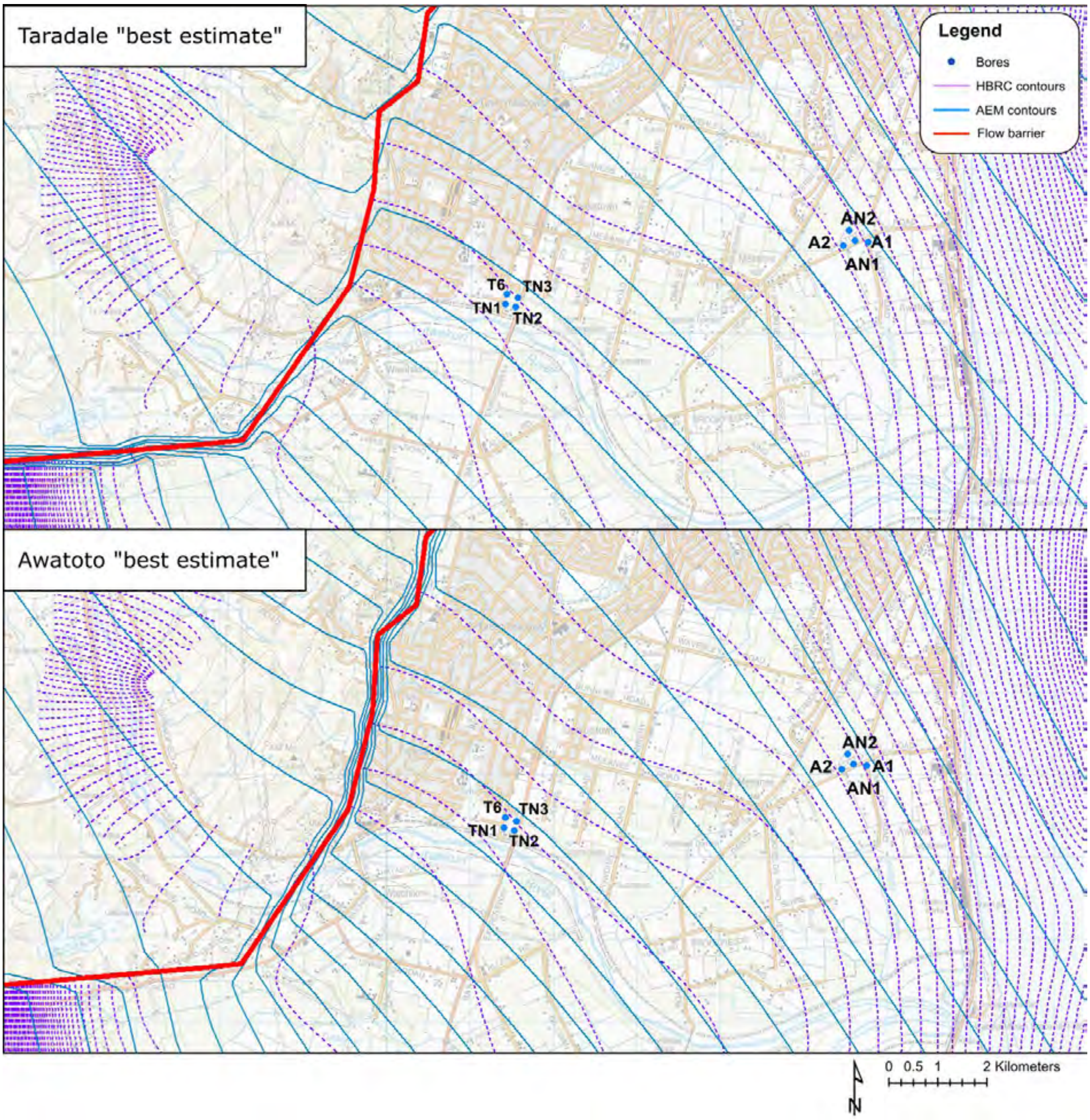

Figure 5.1: Comparison of piezometric contours (0.2 m interval) between a single HBRC model stress period (October 2008, purple dashed line) and the AEM method for a single run without pumping (blue lines). The low-permeability barrier is shown in red.

5.2 Source protection zones

The SPZs created for the NCC urban bore fields using the AEM are described in this section. The one-year travel time source protection zones (SPZ2) are depicted below in Figure 5.2 and comprise the one-year travel time capture zones as well as those delineated during sensitivity analyses (see Section 4.2.3). The SPZs are depicted in greater detail in the figures in Appendix A.

5.2.1 Awatoto bore field

The SPZ2 for the Awatoto bore field has the form of an ellipse that is slightly elongated approximately along a south-southwest – north-northeast axis. The SPZ2 boundaries extend beneath the Tutaekuri River near its mouth, however any interaction is unlikely due to extensive confining layers above the main aquifer unit. The SPZ3 extends southwest up the catchment into the unconfined portion of the aquifer, where rainfall recharge and recharge from the Ngaruroro River occurs. The main discharge area of the Ngaruroro River between Roy's Hill and Fernhill forms a natural hydrological boundary for the SPZ3.

We note that the one, three, six and twelve month travel-time zones for this bore field extend into parts of the aquifer that extend eastwards, beyond the coastline. Assessment of saline intrusion risk is not within the scope of this report, but has been assessed by GNS[29].

5.2.2 Taradale bore field

Source protection zones for the Taradale bore field are orientated approximately in a south-southwest – north-northeast direction and are influenced by the flow barrier to the west. The SPZ2 passes beneath the Tutaekuri River and extends as far as the Ngaruroro River northeast of Twyford. The SPZ3 extends southwest up the catchment into the unconfined portion of the aquifer, where rainfall recharge and recharge from the Ngaruroro River occurs. As for the Awatoto bore field, the main discharge area of the Ngaruroro River forms a natural hydrological boundary for the source protection zone.

[29] Rawlinson Z.J., White J.T., February 2019. Scenario modelling to assess effects of proposed new municipal well fields at Awatoto and Guppy Roads, Napier. GNS Science Consultancy Report 2019/12.

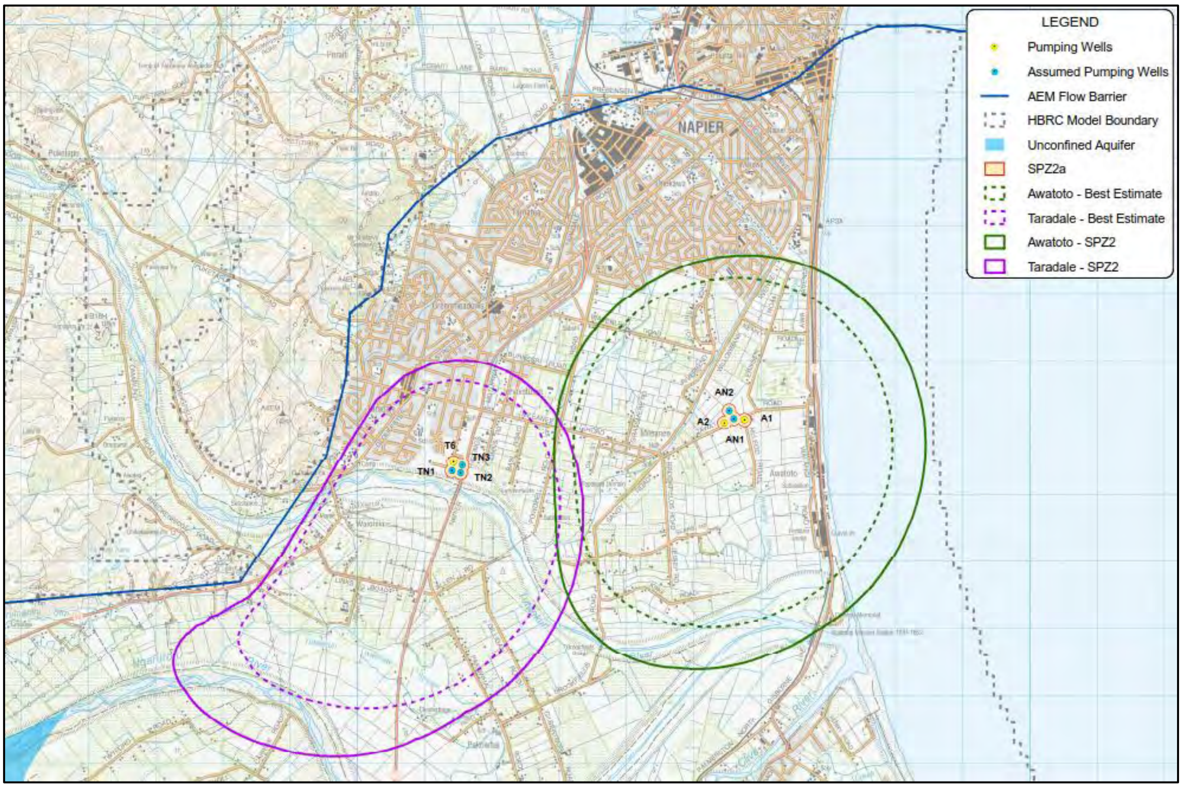

Figure 5.2: Napier City Council new public supply bore fields – Source Protection Zones 2, comprising areas where travel times are expected to be one year or less, and 100 m protective zones around bore fields beneath the confining layer (see Figure 7, Appendix A, for scale).

T+T has used hydrogeological boundaries and judgement of regional scale groundwater flow dynamics information to constrain the total catchment zones (SPZ3). The total catchment zones (SPZ3) are shown in Figure 5.3 below.

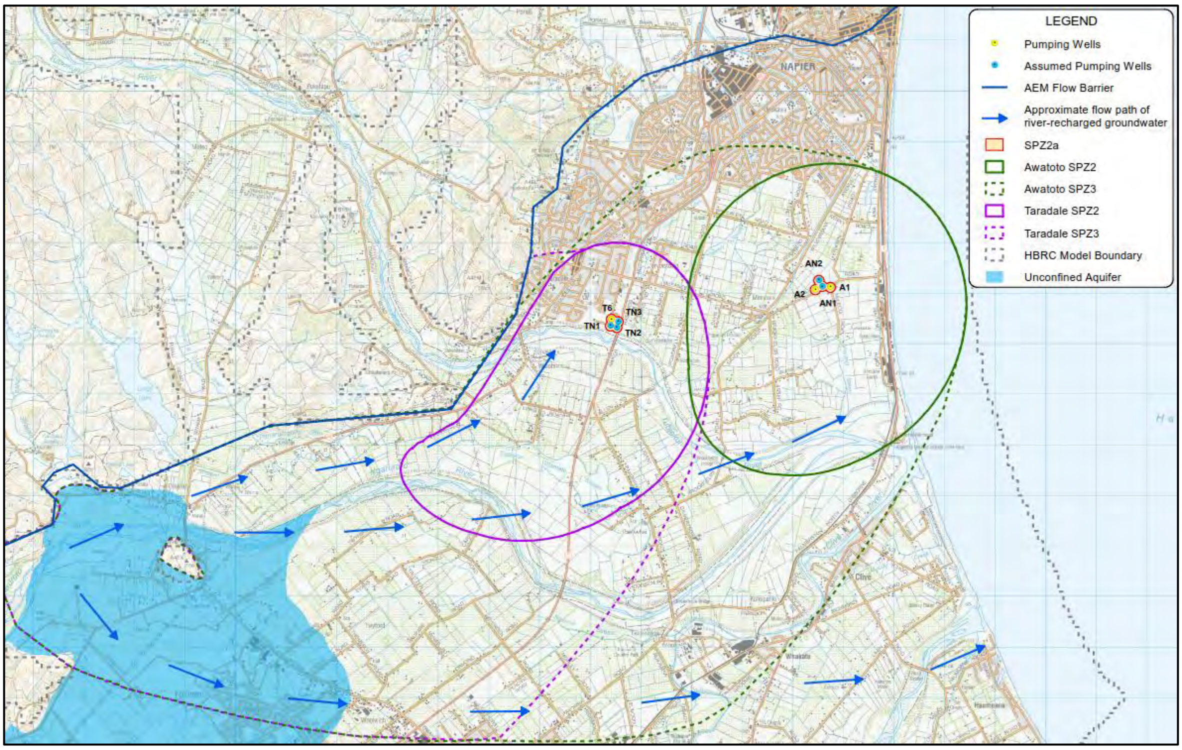

Figure 5.3: Napier City Council new public supply bore fields – Source Protection Zones 3 (see Appendix A, Figure 11 for scale).

All SPZ figures are included in Appendix A. Figures 3 and 5 show the 1, 3, 6 and 12 month travel-time zones used to support the development of SPZ2s for each bore field. Figures 4 and 6 show the sensitivity results (i.e. for the variation of effective porosity, aquifer thickness, isotropic hydraulic conductivity and hydraulic gradient in accordance with the GNS guidelines). Figure 7 shows the fully developed SPZ2 obtained through all of the input parameter variations and the one, three, six and twelve month travel times and sensitivity results. Figure 8 shows the SPZ3 capture zones developed for each bore field.

The individual bore field SPZ2, SPZ2a, SPZ2 “best estimate” and SPZ3 capture zones are shown for Awatoto and Taradale bore fields on Figures 9 and 10 respectively. Figure 11 shows the combined bore field SPZ2, SPZ2a, and SPZ3 capture zones on a single figure.

6 Discussion

6.1 Shape and extent of Source Protection Zones

The shape and extent of the source protection zones reflect the input parameters used in the AEM method. The flow barrier used in the AEM to represent low-permeability Pliocene mudstones and limestones influences the shape of the SPZs by restricting groundwater flow from these areas; the Taradale SPZs are most affected by this barrier. This influence is less pronounced in areas further away from the barrier (i.e. Awatoto bore field).

The SPZ2 for the Taradale bore field does not intercept an area of springs to the west of the Raupare Stream[30] and we therefore consider these springs are unlikely pose an immediate risk of microbial contamination to the Taradale borefield. The Taradale SPZ2a encompasses two springs in the Waiohiki area (see Wilding[30], Figure 3-35), however the springs are likely to be located within recent surficial gravels deposited by the Tutaekuri River, and recharged by the river. The disconnection between recharge from the Tutaekuri River is discussed in Section 3.3.2 of this report. The Awatoto SPZ2 does not intercept any known springs.

The SPZs developed for Awatoto and Taradale bore fields are the aggregation of capture zones for multiple pumping wells for the given pumping scenarios described in section 4.2.2.5. The shape of the SPZs are therefore somewhat sensitive to changes in abstraction from individual pumping wells. However, as the maximum abstraction rate from all bore fields applied in the AEM is greater than current long-term operational pumping rates, we believe that the SPZs are suitably conservative to allow for a range of potential pumping scenarios within the bore field. If changes to the maximum consented abstraction rates are made following the bore field redevelopment, or if updated hydrogeological information becomes available from pumping testing of the new bores, it may be appropriate to refine the SPZs on the basis of adjusted input parameters.

In order to evaluate the total capture zone for SPZ3s, we have used hydrogeological judgement. This included the exclusion of areas that are assessed as not contributing groundwater flow to the NCC bore fields such as:

- Areas to the outside of the main recharge area of the Ngaruroro River.
- Mudstone/limestone outcrops which are assumed to form no-flow boundaries.
- The Tutaekuri River.

6.2 Use and implementation of mapped SPZs

We understand that the mapped SPZs may be used to inform water safety planning as follows:

- An immediate capture zone (SPZ1) around each bore based on existing bore water security requirements set out in the DWSNZ (i.e. a 5 m radius).
- A microbial protection zone 2 (SPZ2 – Figure 9, Appendix A) where microbial contamination sources within the zone may pose a risk to the supply, if able to migrate to the aquifer.
- A capture zone 3 (SPZ3 – Figure 10, Appendix A) where more conservative contaminants (such as nitrates) could pose a risk to the supply if able to migrate to the aquifer.

The SPZ2 and SPZ3 zones have been determined using parameters derived from activities such as transient numerical modelling, borehole drilling, pump testing, and reported groundwater levels. As indicated in the preceding section and in the sensitivity analysis section, it should be noted that the protection zone boundaries may be subject to variation, depending on the parameters adopted.

[30] Wilding, T., June 2018. *Heretaunga Springs: Gains and losses of stream flow to groundwater on the Heretaunga Plains*. HBRC Report No. RM18-13-4996, Hawke's Bay Regional Council.

7 Conclusions and recommendations

7.1 Conclusions

Napier City Council (NCC) has engaged Tonkin & Taylor Ltd (T+T) to prepare source protection zones (SPZs) for its proposed redevelopment of public water supply bore fields located in the Napier Urban area. This report sets out the approach adopted to define the SPZs.

NCC currently supplies drinking water to its constituents from a network of groundwater supply bores, located within the Heretaunga Plains. Contaminants such as pathogenic microorganisms can pose a risk to human health when they enter drinking water supplies. Taking steps to prevent such contaminants from entering drinking water sources is part of a multiple barrier approach to reduce this risk to people.

The current DWSNZ do not include requirements for drinking water suppliers to implement SPZs, but do specify minimum water quality standards for drinking water and encourage development of SPZs as part of water safety planning.

There is currently no national standard for the delineation of SPZs in New Zealand, however GNS has provided a technical report with guidelines[5]. Following the Havelock North *Campylobacter* outbreak in 2016 reforms to drinking water legislation are currently being undertaken, which are likely to include requirements for regional councils and water suppliers to develop a detailed understanding of their drinking-water sources and manage land-use activities within source-water catchments. The delineation of SPZs is the first step to allow for the assessment and management of land uses within groundwater catchments and to support a multi-barrier approach.

SPZs have been delineated for the proposed new Awatoto and Taradale bore fields. The structural characteristics of these bore fields have been obtained from existing information including HBRC well completion reports and testing conducted by others on behalf of NCC.

T+T derived the SPZs using the Analytic Element Modelling method as implemented in the AnAqSim software. A modified uniform flow model was used with an additional flow barrier, representing low permeability mudstones and limestones to the west of Taradale.

To define the microbial protection zone (SPZ2) around the wells T+T adopted a one-year groundwater travel time and to define the capture zone (SPZ3) adopted a ten-year travel time modified by hydrogeological considerations (e.g. groundwater flow boundaries), based on the GNS recommendations for the delineation of suitable protective zones.

These input parameters to the Analytic Element Model included:

- Bore pumping rates;
- Aquifer thickness;
- Hydraulic conductivity;
- Effective porosity;
- Hydraulic gradient and groundwater flow direction; and
- Hydraulic boundaries.

Figure 9 (Appendix A) shows the SPZ2 zones developed for each bore field including the sub-zone SPZ2a – this comprises areas located within 100 m of bores with bore screens located beneath the confining layer.

The source protection zones SPZ2 and SPZ3 developed for the NCC bore fields are intended to be implemented by NCC within their WSP as part of their responsibilities under the Health Act and the DWSNZ. We understand that the mapped SPZs will be used to inform water safety planning as follows:

- An immediate capture zone (SPZ1) around each bore based on existing bore water security requirements set out in the DWSNZ (i.e. a 5 m radius).
- A microbial protection zone 2 (SPZ2 – Figure 9) where microbial contamination sources within the zone may pose a risk to the supply, if able to migrate to the water supply bore.
- A capture zone 3 (SPZ3 – Figure 10) where more conservative contaminants (such as nitrates) could pose a risk to the supply if able to migrate to the water supply bores.

7.2 Recommendations

We set out below our recommendations based on our discussion in Section 6 above:

- When final bore locations are available, SPZ1 and SPZ2a boundaries should be revised to account for minor expected changes to bore locations. If the extent of the final bore fields varies from the assumed extent in this report, SPZ2 and SPZ3 may also need to be reviewed and revised if required.
- The SPZ1 is based on a 5 m buffer from the supply wells. This is a minimum distance, and we recommend that NCC allow for a greater buffer distance where possible (i.e., within the full land parcel owned/managed by NCC around the bore heads).
- If pumping operations, maximum consented rates (for example if a maximum annual volume is imposed) or hydrogeological parameters (for instance hydraulic conductivity values derived from pumping testing of the new bores) vary significantly from those adopted herein, then we recommend additional modelling to determine if there is any change to the SPZs.
- Flexibility in the water safety planning framework should be provided to allow for potential changes in groundwater conditions across the Heretaunga Plains which may affect the extent of the SPZ2 and SPZ3 zones. These reviews may be triggered by a specific review period (e.g. five-yearly) or following major land use (e.g. modified pumping rates and volumes) or natural changes (e.g. major floods or earthquakes).
- Additional aquifer testing may be undertaken to reduce some uncertainties associated with input parameters. This may include routine piezometric surveys of groundwater bores within the NCC pumping aquifer(s), given the paucity of SOE data, as well as tracer testing in the vicinity of NCC bore fields to confirm effective porosity estimates in deep aquifers.
- We recommend that management controls be developed to protect the aquitard in the marine environment from any works in the seabed. Although outside of the scope of this report, we note that saline intrusion may present an environmental risk to the supply aquifer where the integrity of the overlying aquitard is compromised and/or where hydraulic head gradients are downwards to the pumping aquifer.

8 Applicability

This report has been prepared for the exclusive use of our client Napier City Council, with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose, or by any person other than our client, without our prior written agreement.

Tonkin & Taylor Ltd

Report prepared by:	Authorised for Tonkin & Taylor Ltd by:
Jeremy Bennett Hydrogeologist	Tony Cussins Project Director

Technical review completed by:

Chris Shanks
Hydrogeologist

6-May-19
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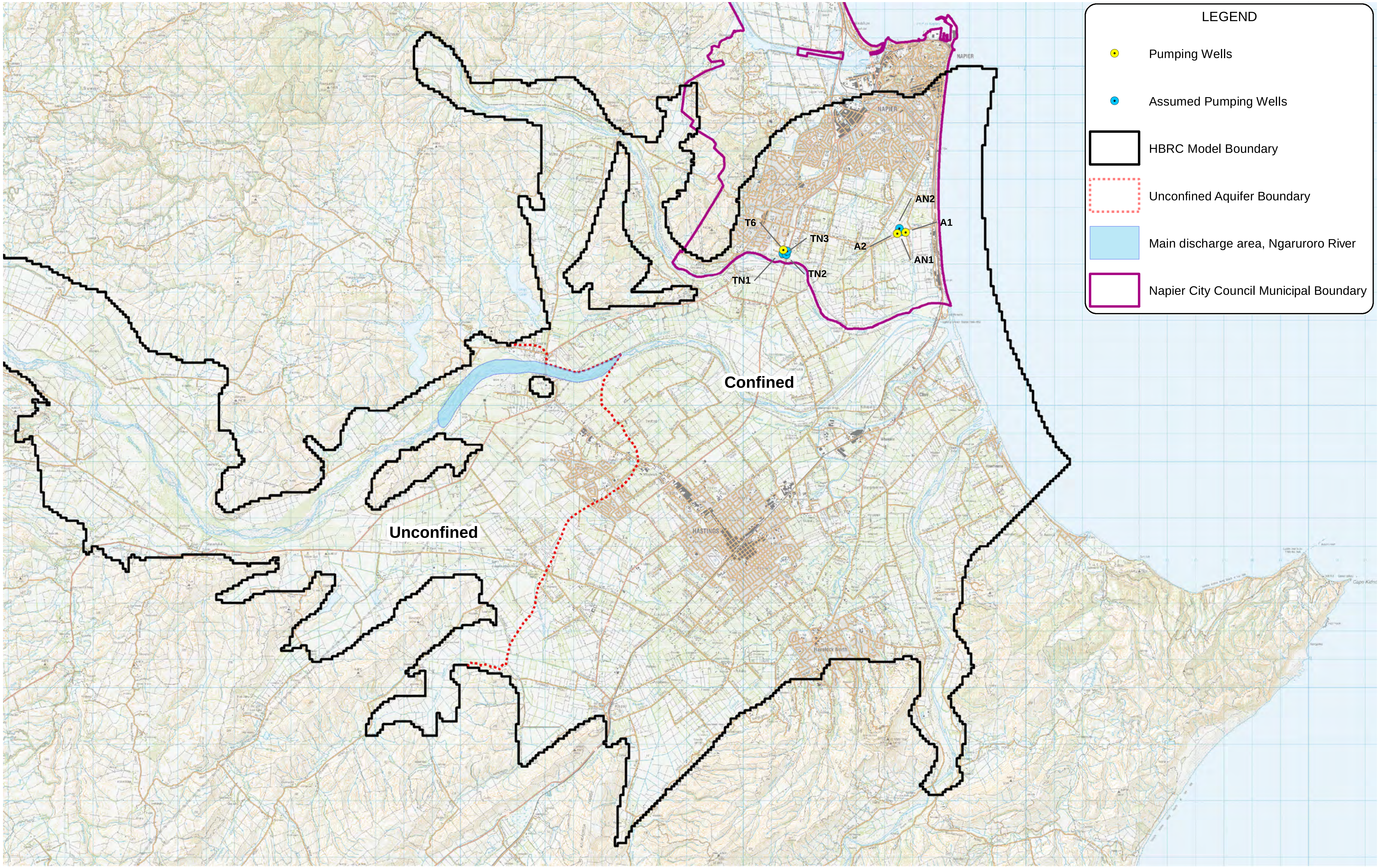
Appendix A: Figures

1. **Site plan**
2. **Hydrogeological conceptual model**
3. **Awatoto SPZ2 development – 1, 3, 6 and 12 month travel times**
4. **Awatoto SPZ2 Development – sensitivity results**
5. **Taradale SPZ2 development – 1, 3, 6 and 12 month travel times**
6. **Taradale SPZ2 Development – sensitivity results**
7. **Source Protection Zone 2**
8. **Source Protection Zone 3**
9. **Awatoto SPZ2 and SPZ3**
10. **Taradale SPZ2 and SPZ3**
11. **All SPZ2 and SPZ3 zones**



Notes: Service Layer Credits: LINZ Data Service under creative commons license 3.0

Heretaunga Plains Confined and Unconfined Aquifer Shapefile Source - HBRC GIS

Main discharge area, Ngaruroro River - Adapted from Mortgenstern U., et al. April, 2018.
Heretaunga Plains aquifers: groundwater dynamics, source and hydrochemical processes as inferred from age and chemistry tracer data, GNS Science report 2017/33. Ref:Figure 4.210 of that report

A3 SCALE 1:125,000

0 1 2 3 4 5 (km)

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Location Plan

Tonkin+Taylor

105 Carlton Gore Rd, Newmarket, Auckland
www.tonkintaylor.co.nz

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NAPIER CITY COUNCIL
SOURCE PROTECTION ZONES FOR PUBLIC SUPPLY BORES
NAPIER URBAN AREA
SITE PLAN

FIGURE No. Figure 1

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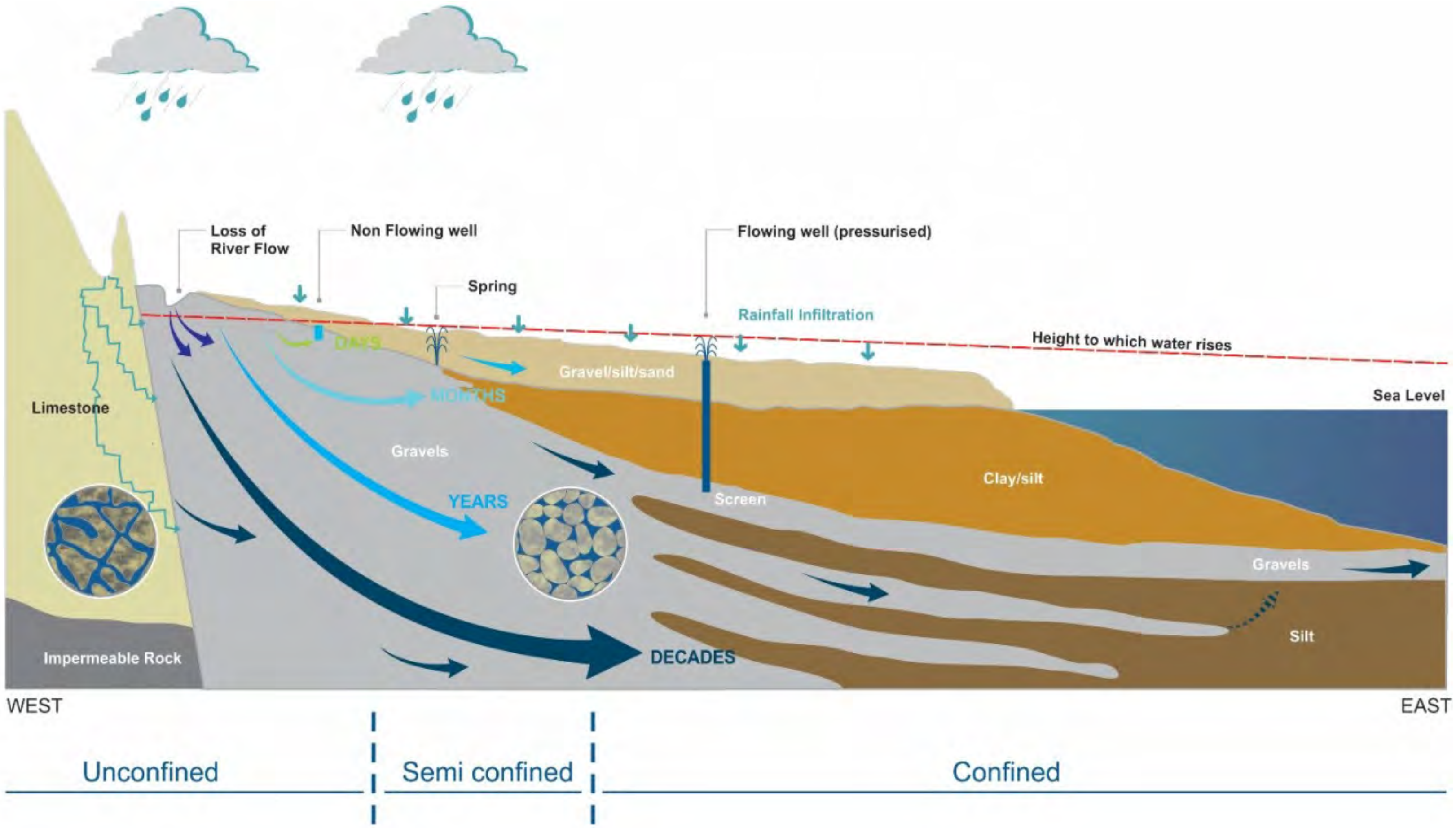

Notes:
Conceptual model sourced from HBRC Report No. RM 1619 - 4803 (Groundwater Quality State of Environment; State and Trends; September 2016)

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NAPIER CITY COUNCIL
SOURCE PROTECTION ZONES
HERETAUNGA PLAINS
HYDROGEOLOGICAL CONCEPTUAL MODEL

FIGURE No. Figure 2.

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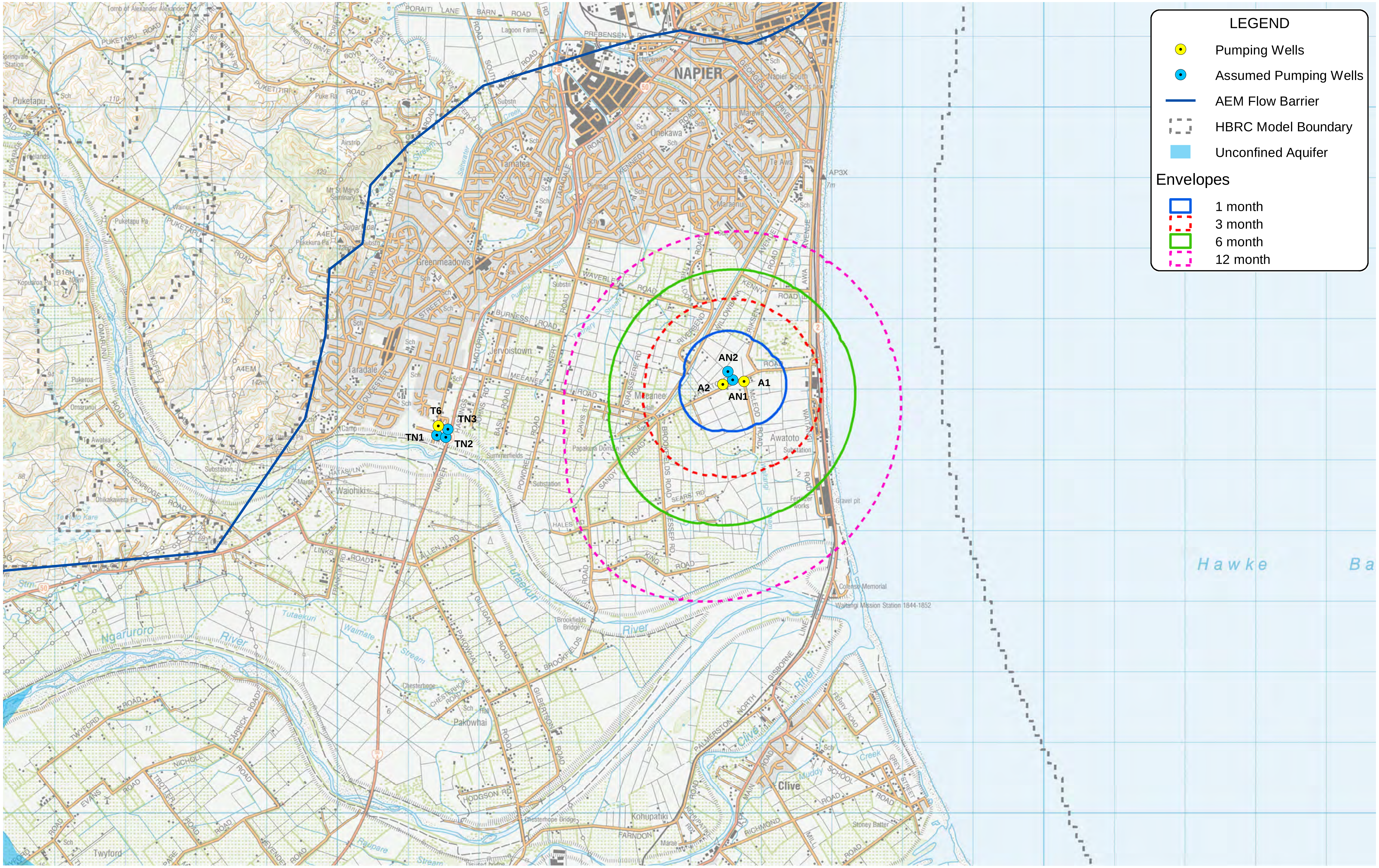

Notes:
Heretaunga Plains Confined / Unconfined Aquifer - HBRC GIS
Service Layer Credits: LINZ Data Service under creative commons license 3.0

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Location Plan

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NAPIER CITY COUNCIL
SOURCE PROTECTION ZONES FOR PUBLIC SUPPLY BORES
NAPIER URBAN AREA
Awatoto SPZ2 Development 1, 3, 6 and 12 Month Travel Times

FIGURE No. Figure 3 Rev. 0

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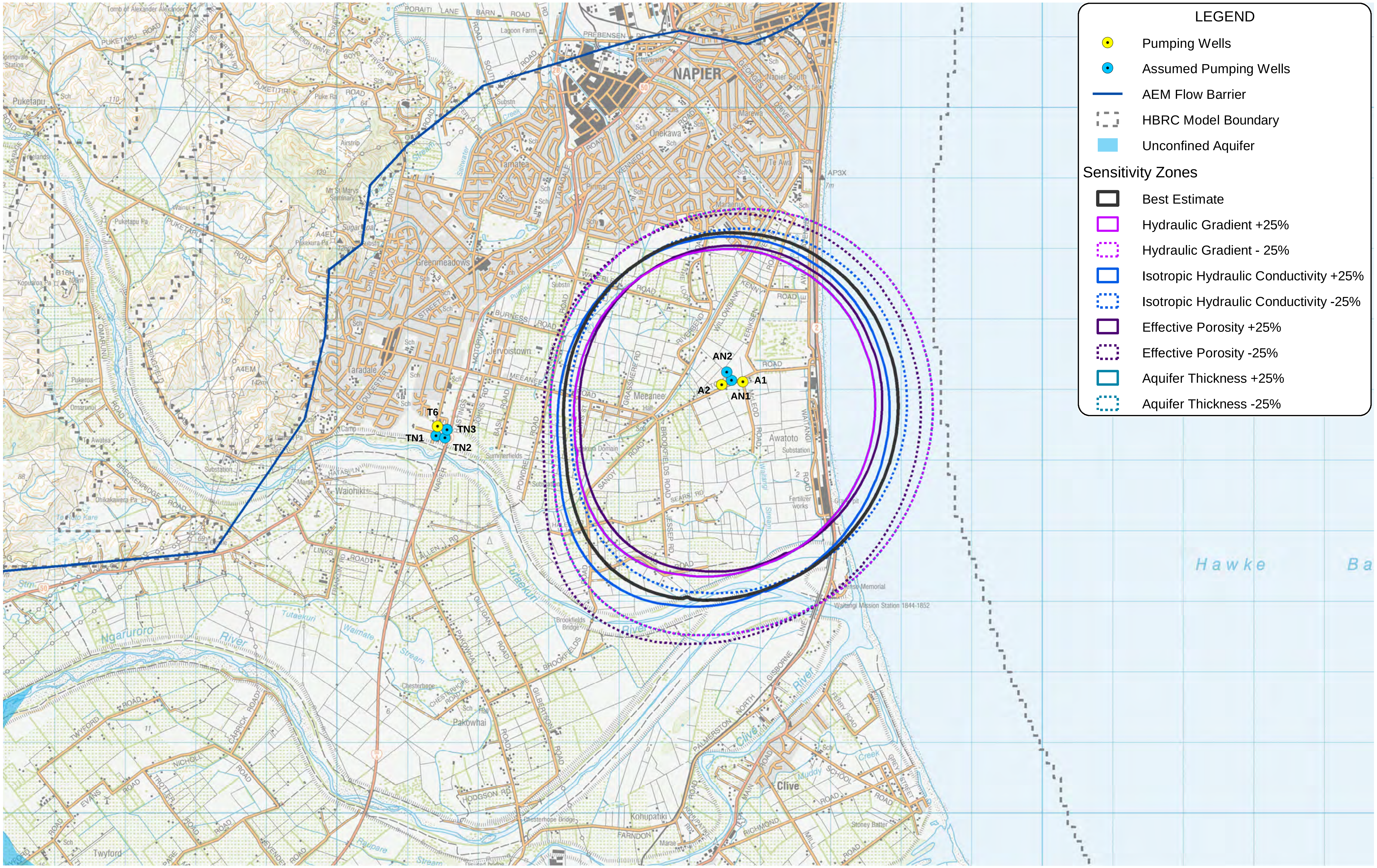

Notes:
Heretaunga Plains Confined / Unconfined Aquifer - HBRC GIS
Service Layer Credits: LINZ Data Service under creative commons license 3.0

A3 SCALE 1:50,000
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Location Plan

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PROJECT No. 1008476		

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SOURCE PROTECTION ZONES FOR PUBLIC SUPPLY BORES
NAPIER URBAN AREA
Awatoto SPZ2 Development - Sensitivity Results

FIGURE No. Figure 4
Rev. 0

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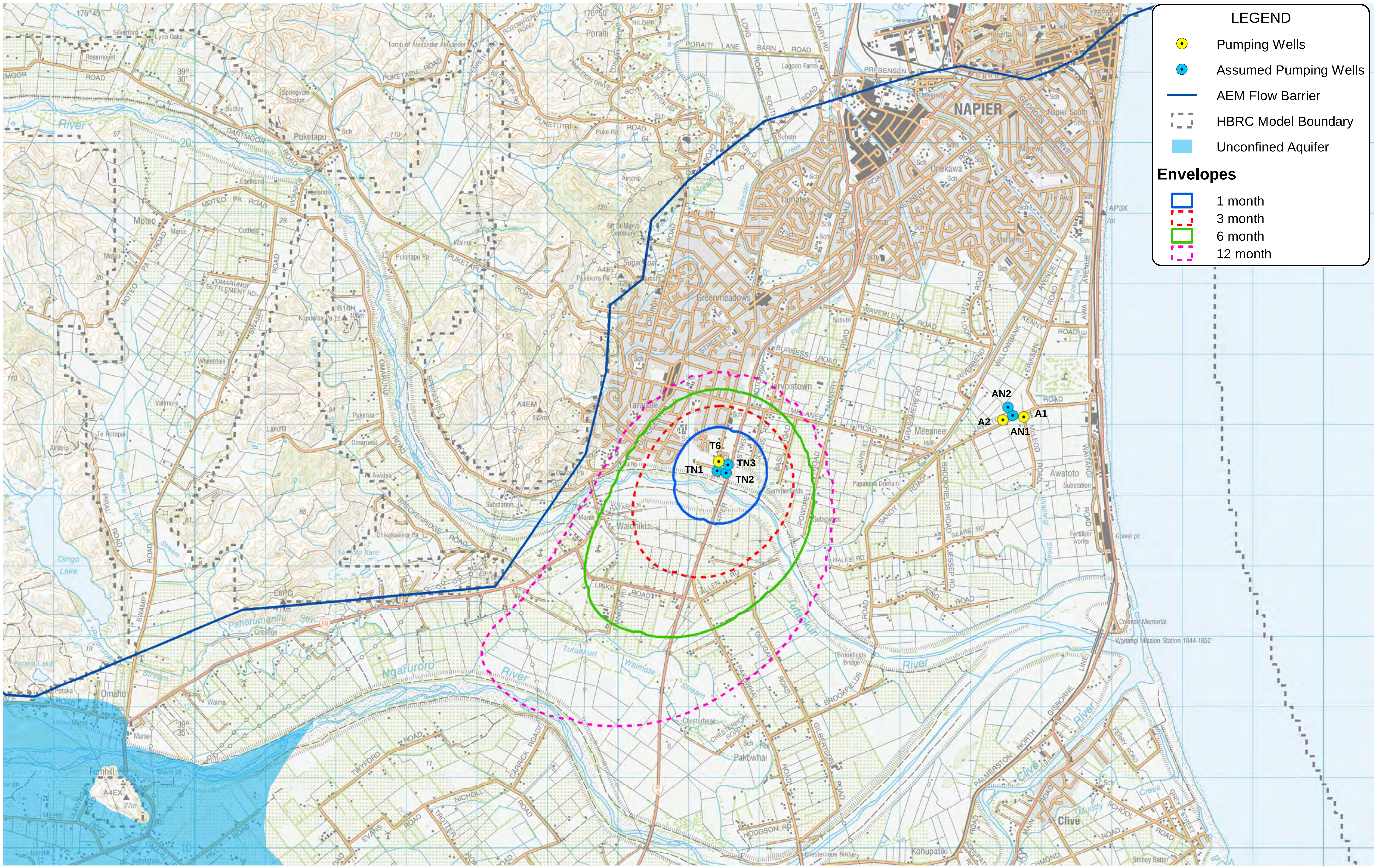

Notes:
Heretaunga Plains Confined / Unconfined Aquifer - HBRC GIS
Service Layer Credits: LINZ Data Service under creative commons license 3.0

A3 SCALE 1:50,000
0 0.5 1 1.5 2 2.5 (km)


Location Plan

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SOURCE PROTECTION ZONES FOR PUBLIC SUPPLY BORES
NAPIER URBAN AREA
Taradale SPZ2 Development 1, 3, 6 and 12 Month Travel Times

FIGURE No. Figure 5
Rev. 0

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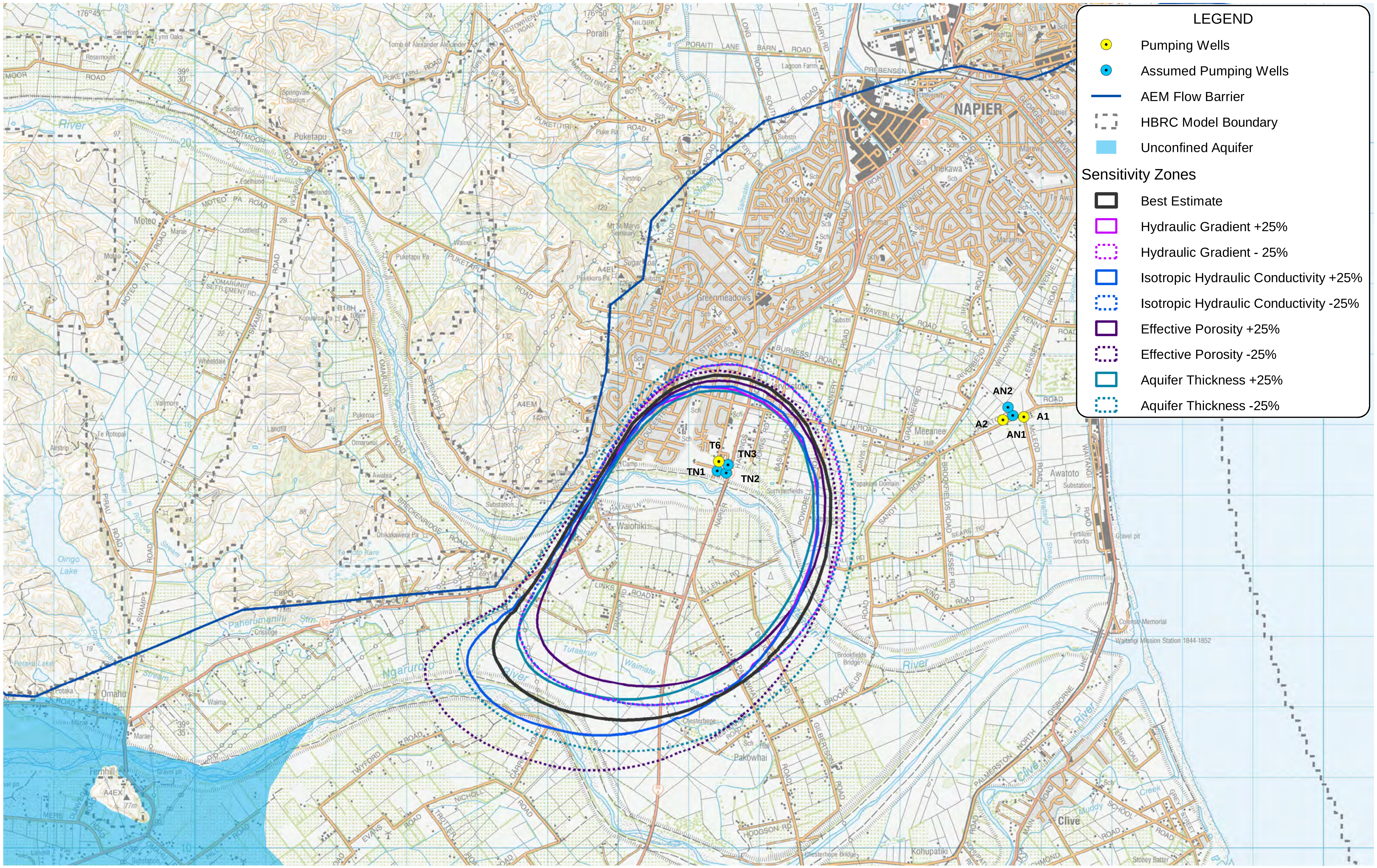

Notes:
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A3 SCALE 1:50,000

0 0.5 1 1.5 2 2.5 (km)

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SOURCE PROTECTION ZONES FOR PUBLIC SUPPLY BORES
NAPIER URBAN AREA
Taradale SPZ2 Development - Sensitivity Results

FIGURE No. Figure 6

Rev. 0

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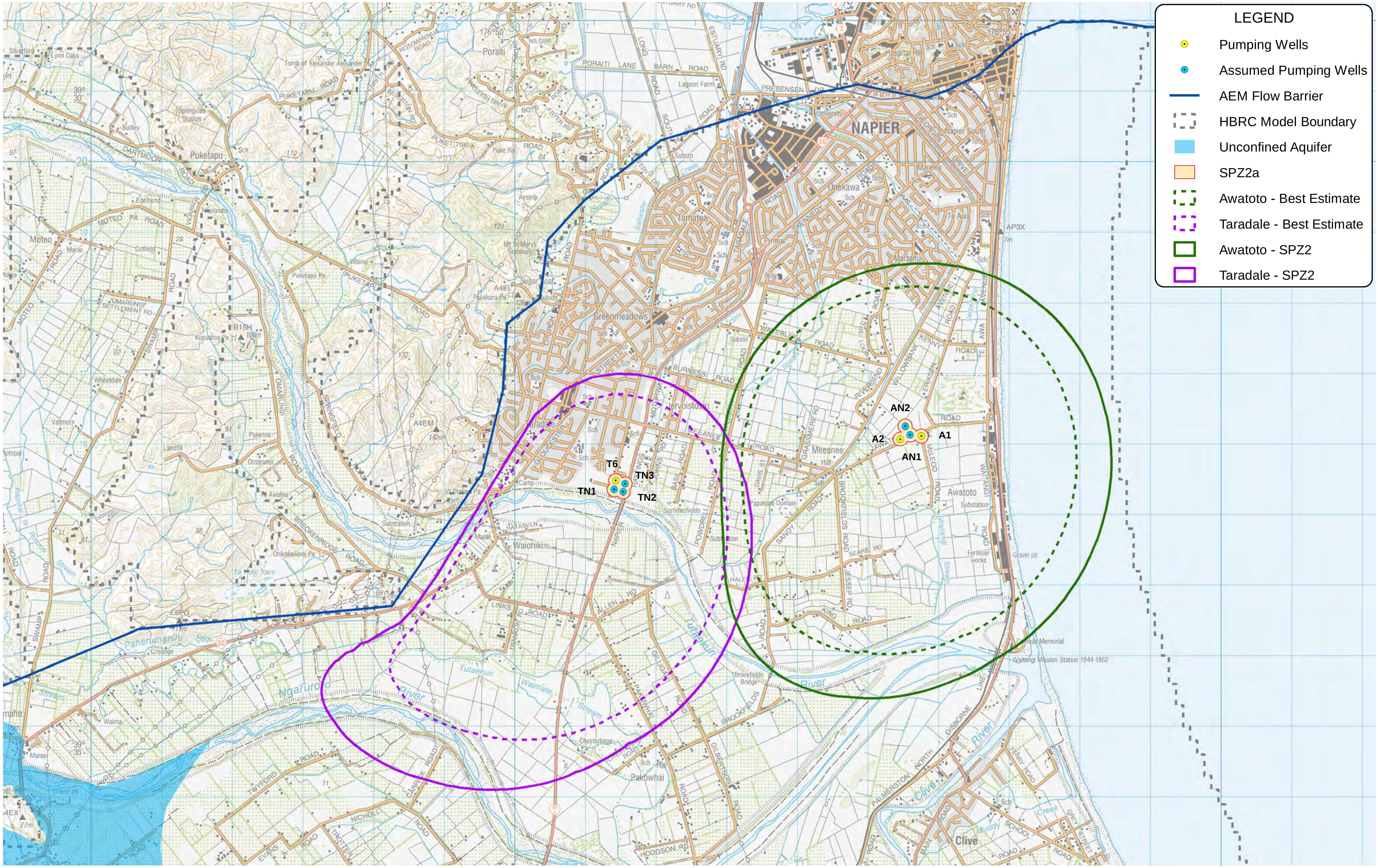

Notes:

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A3 SCALE 1:50,000

0 0.5 1 1.5 2 2.5 (km)

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SOURCE PROTECTION ZONES FOR PUBLIC SUPPLY BORES

NAPIER URBAN AREA

Source Protection Zone 2

FIGURE No. Figure 7

Rev. 0

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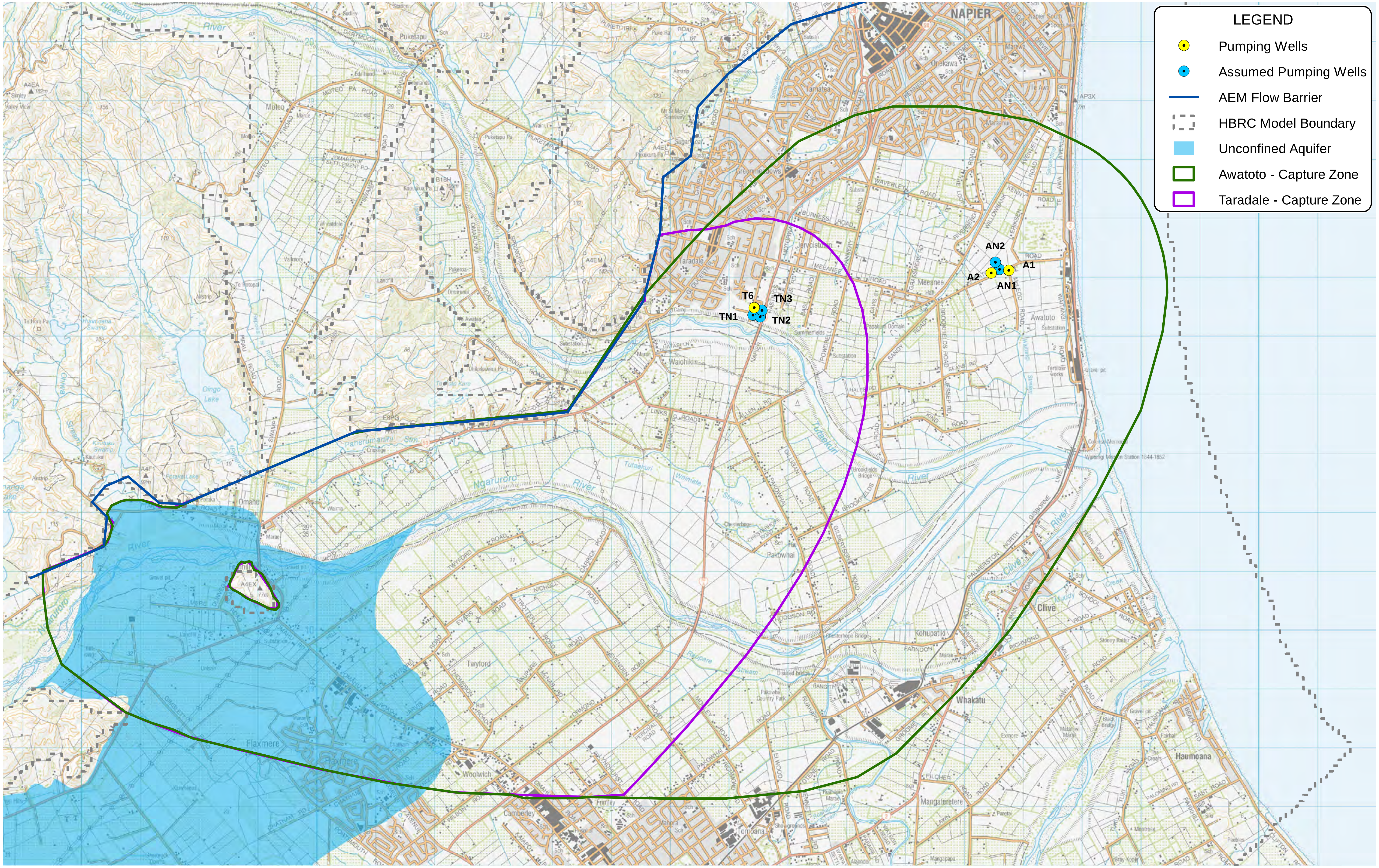

Notes:
Heretaunga Plains Confined / Unconfined Aquifer - HBRC GIS
Service Layer Credits: LINZ Data Service under creative commons license 3.0

A3 SCALE 1:60,000
0 0.5 1 1.5 2 2.5 (km)

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SOURCE PROTECTION ZONES FOR PUBLIC SUPPLY BORES
NAPIER URBAN AREA
Source Protection Zone 3

FIGURE No. Figure 8

Rev. 0

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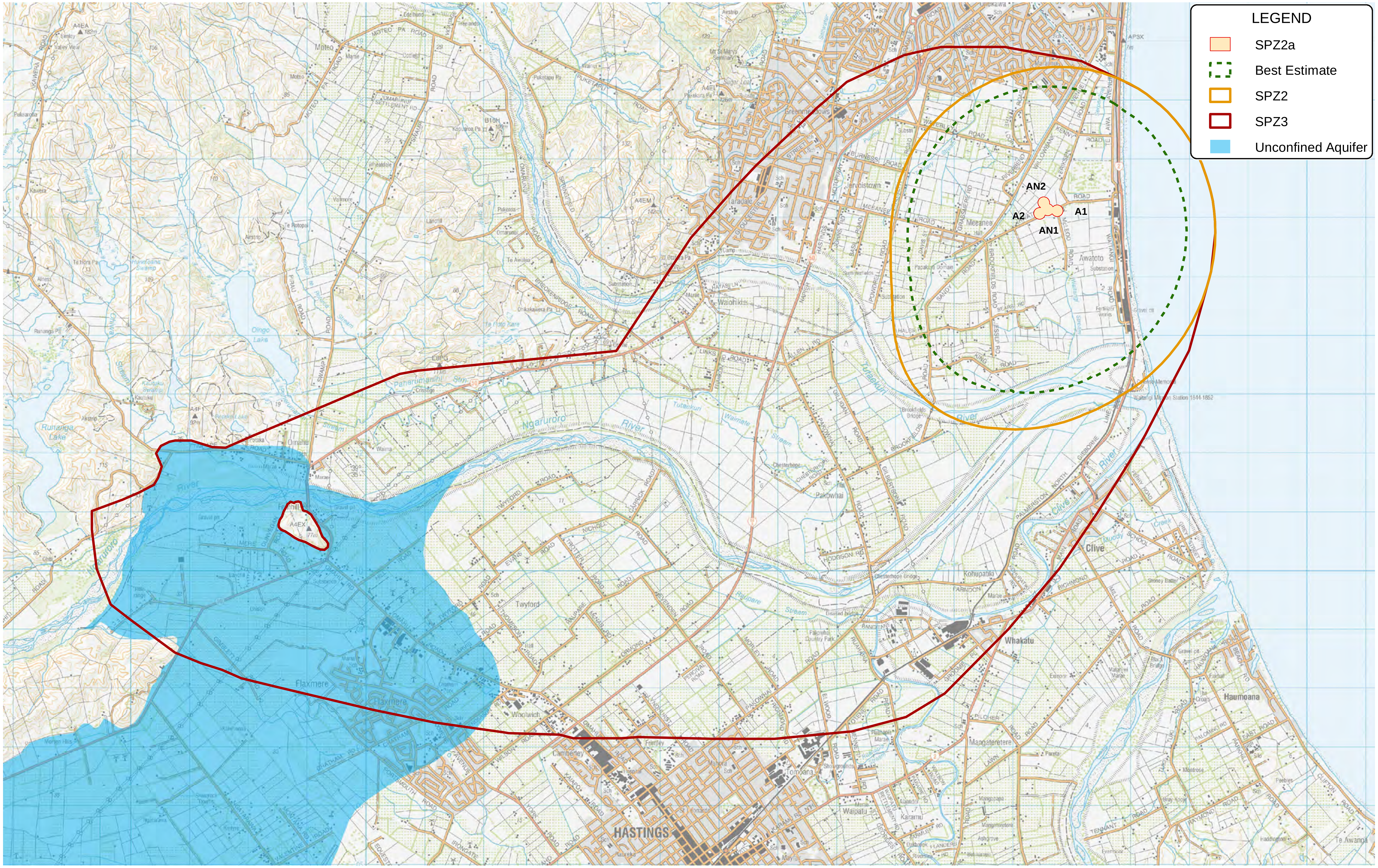

Notes:
Heretaunga Plains Confined / Unconfined Aquifer - HBRC GIS
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A3 SCALE 1:60,000
0 0.5 1 1.5 2 2.5 (km)

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SOURCE PROTECTION ZONES FOR PUBLIC SUPPLY BORES
NAPIER URBAN AREA
Awatoto SPZ2 and SPZ3

FIGURE No. Figure 9
Rev. 0

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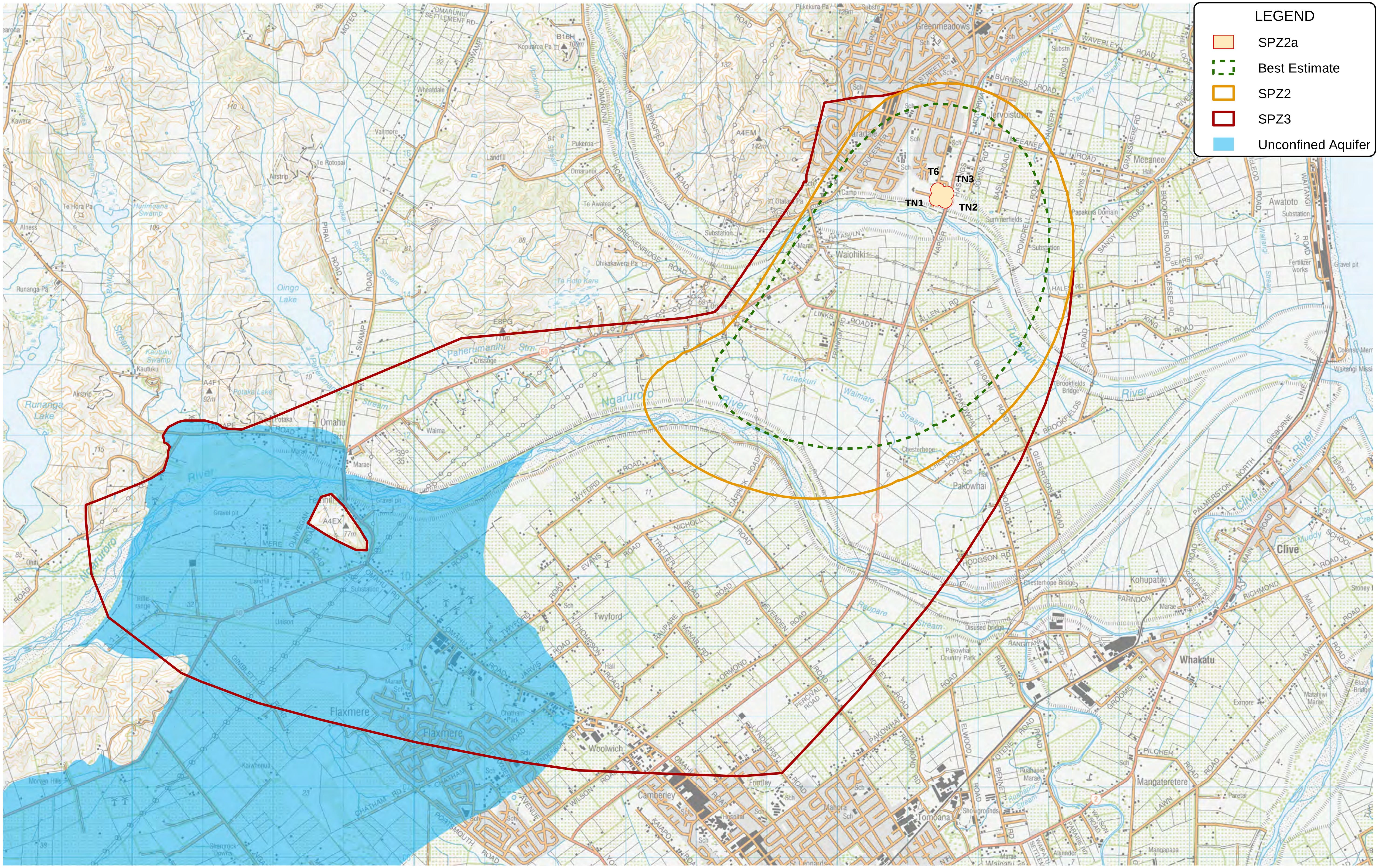

Notes:
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A3 SCALE 1:50,000
0 0.5 1 1.5 2 2.5 (km)


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SOURCE PROTECTION ZONES FOR PUBLIC SUPPLY BORES
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Taradale SPZ2 and SPZ3

FIGURE No. Figure 10
Rev. 0

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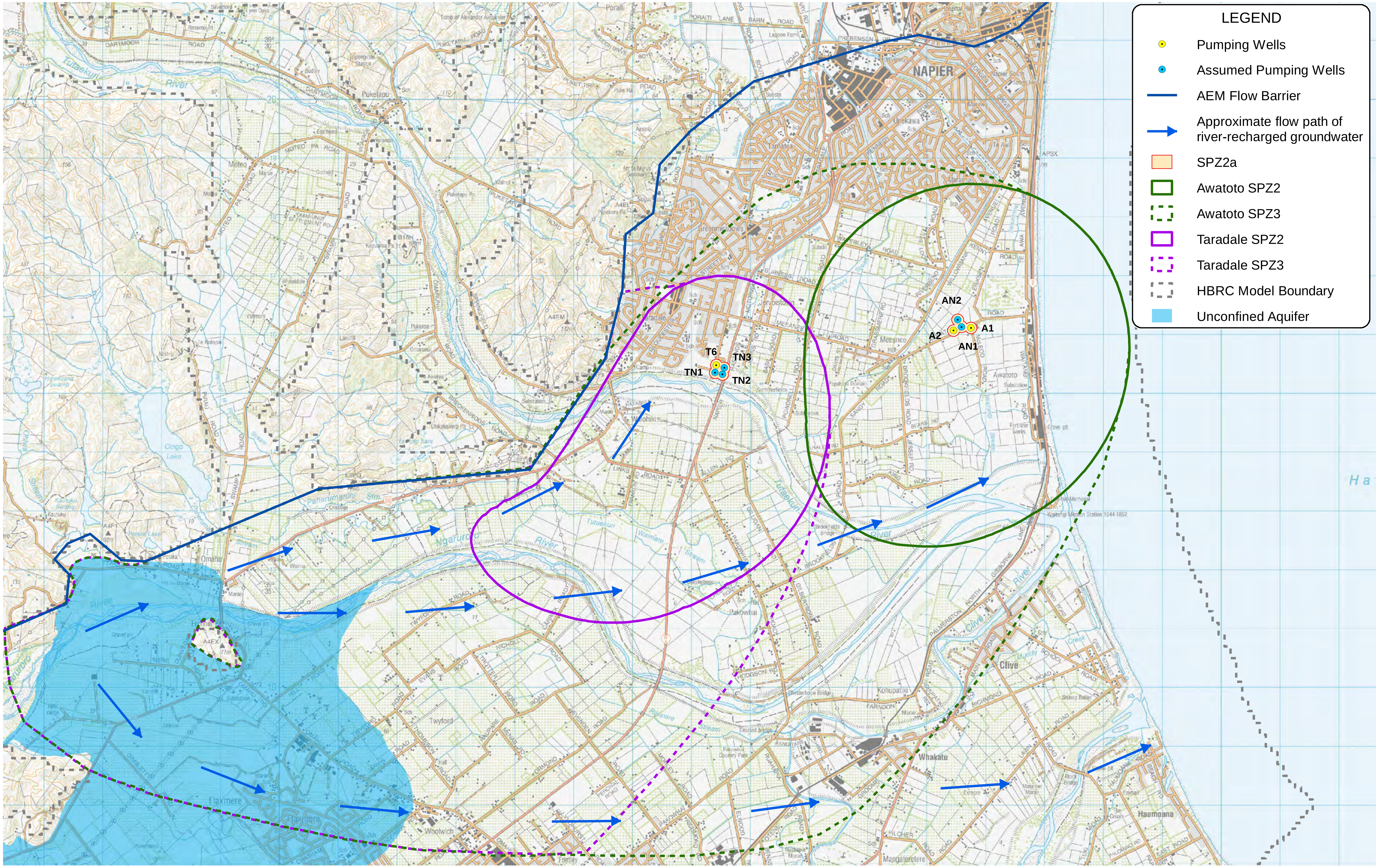

Notes:
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Groundwater flow paths adapted from Fig 4.17, GNS report 2017/33
Service Layer Credits: LINZ Data Service under creative commons license 3.0

A3 SCALE 1:60,000
0 0.5 1 1.5 2 2.5 (km)


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SOURCE PROTECTION ZONES FOR PUBLIC SUPPLY BORES
NAPIER URBAN AREA
All SPZ2 and SPZ3 Zones

FIGURE No. Figure 11 Rev. 0

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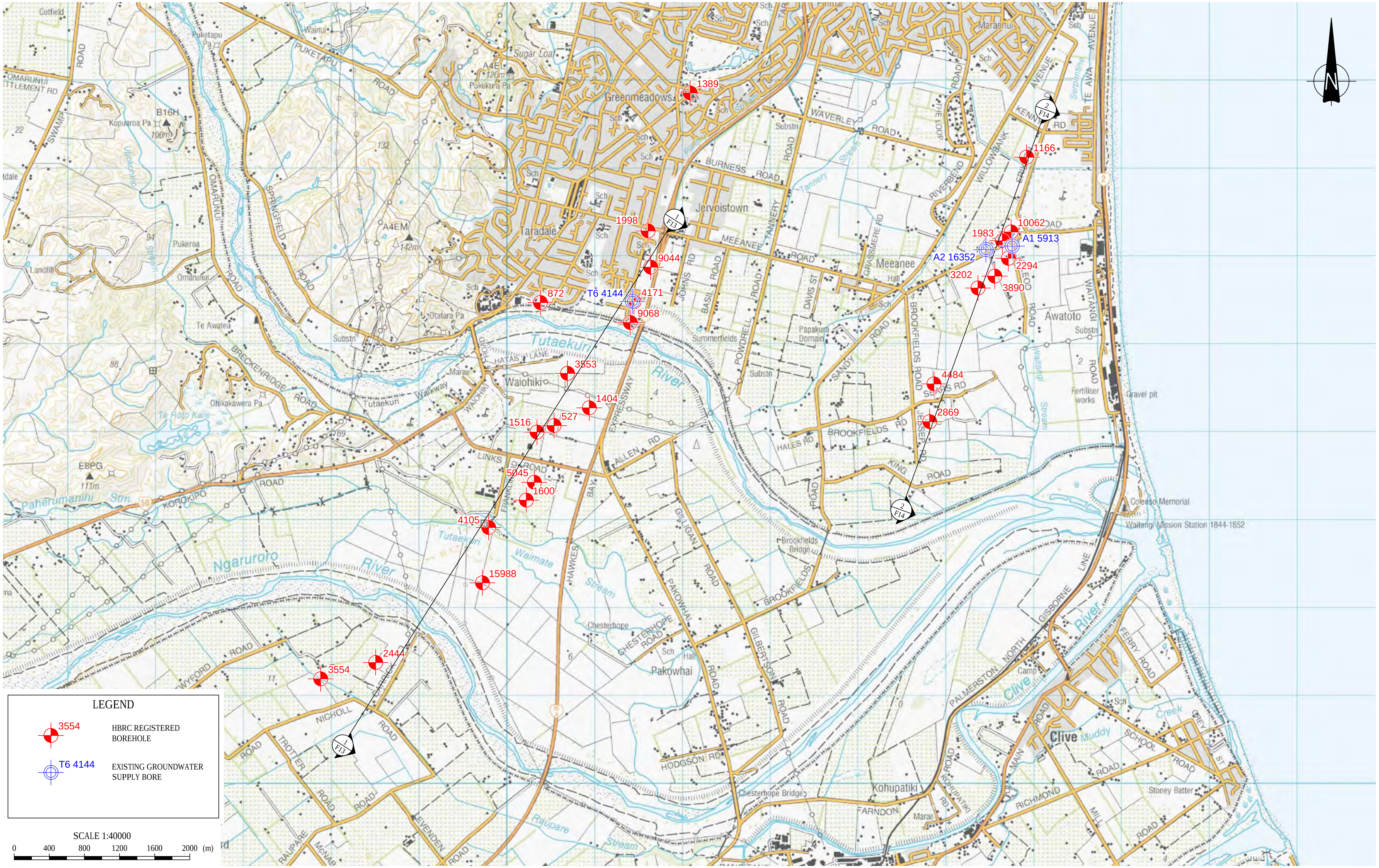
Appendix B: Geological cross sections

12. Geological cross section location map
13. Taradale geological cross section 1
14. Awatoto geological cross section 2



NOTES:

1. AERIAL PHOTO SOURCED FROM LINZ DATA SERVICE <https://data.linz.govt.nz/layer/50767-nz-topo50-maps/> , LICENSED BY LINZ FOR RE-USE UNDER THE CREATIVE COMMONS ATTRIBUTION 4.0 NEW ZEALAND LICENCE (CC BY 4.0). ACCESSED 08/03/2019.

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SOURCE PROTECTION ZONES FOR PUBLIC SUPPLY BORES

Geological Cross Section Location Map

FIG. No. Figure 12

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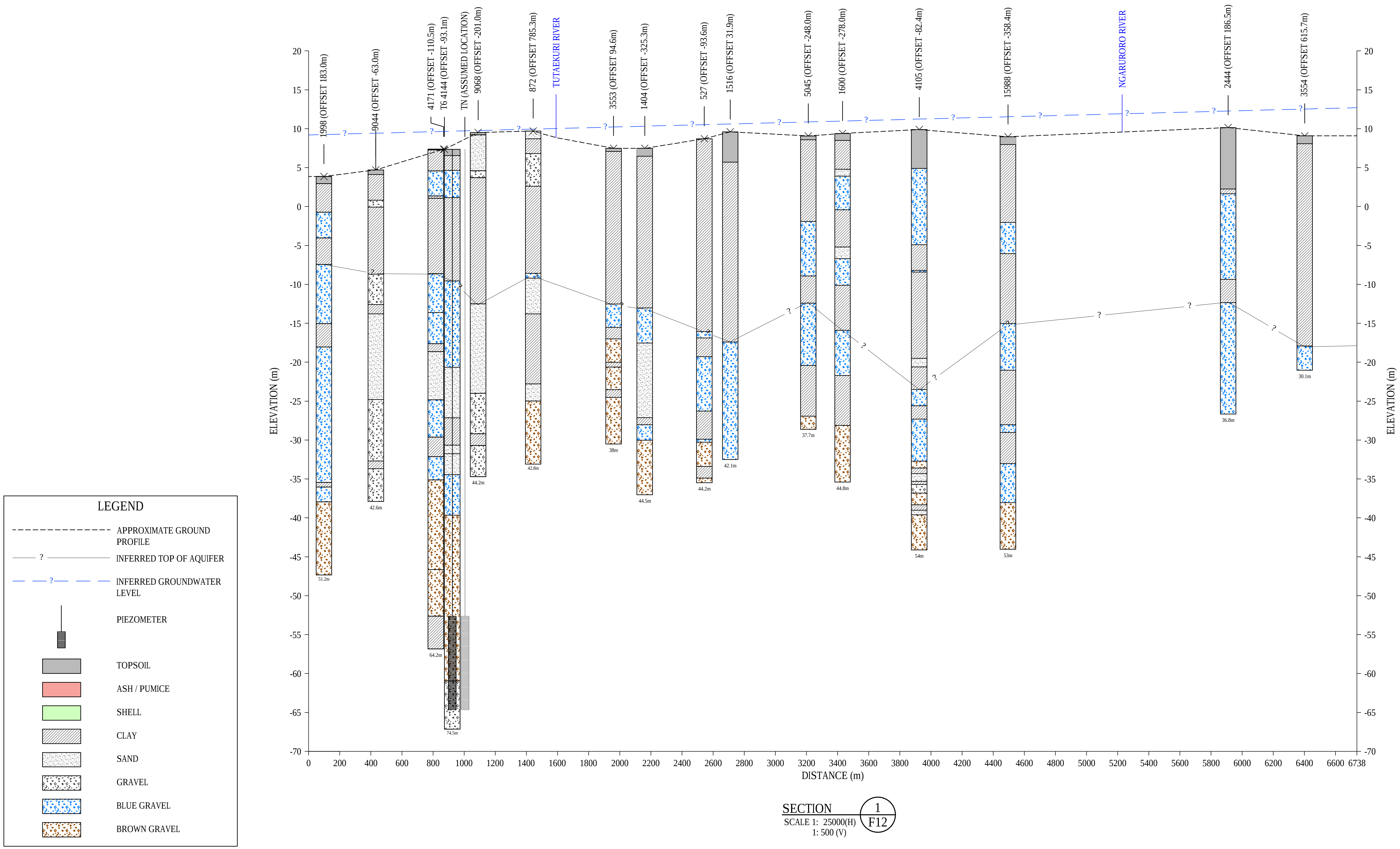

SECTION 1 / F12
SCALE 1: 25000(H)
1: 500 (V)

A3 SCALE 1:500
0 5 10 15 20 25 (m)

A3 SCALE 1:25000
0 0.5 1.0 1.5 (km)

ORIGINAL IN COLOUR

NOTES:

1. ALL DIMENSION ARE IN METRES UNLESS NOTED OTHERWISE.

EXISTING GROUND PROFILE BASED NZ 8m DIGATAL ELEVATION MODEL (2012) SOURCED FROM LINZ DATA SERVICE <https://data.linz.govt.nz/layer/51768-nz-8m-digital-elevation-model-2012/> , LICENSED BY LINZ FOR RE-USE UNDER THE CREATIVE COMMONS ATTRIBUTION 4.0 NEW ZEALAND LICENCE (CC BY 4.0). ACCESSED 08/03/2019.

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SCALES (AT A3 SIZE) AS SHOWN		
PROJECT No. 1008476		

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SOURCE PROTECTION ZONES FOR PUBLIC SUPPLY BORES

Taradale Geological Cross Section 1

FIG. No. Figure 13

REV. 0

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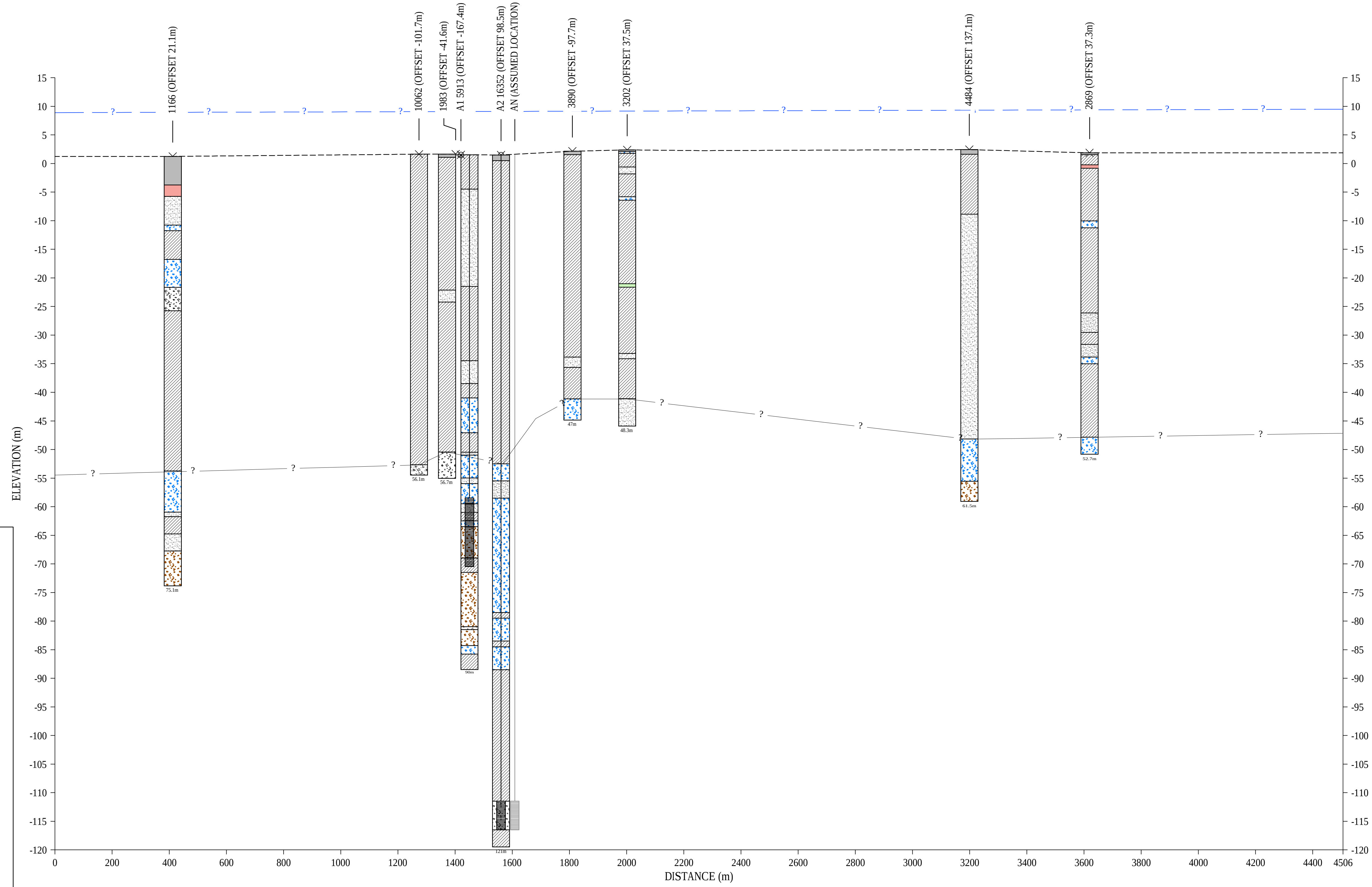

SECTION 2 F12

SCALE 1: 15000(H)
1: 7500(V)

LEGEND

- APPROXIMATE GROUND PROFILE
- INFERRED TOP OF AQUIFER
- INFERRED GROUNDWATER LEVEL
- PIEZOMETER
- TOPSOIL
- ASH / PUMICE
- SHELL
- CLAY
- SAND
- GRAVEL
- BLUE GRAVEL
- BROWN GRAVEL

A3 SCALE 1:750

0 5 10 15 20 25 30 35 40 (m)

A3 SCALE 1:15000(H)

0 0.2 0.4 0.6 0.8 1.0 (km)

ORIGINAL IN COLOUR

NOTES:

1. ALL DIMENSION ARE IN METRES UNLESS NOTED OTHERWISE.

EXISTING GROUND PROFILE BASED NZ 8m DIGATAL ELEVATION MODEL (2012) SOURCED FROM LINZ DATA SERVICE <https://data.linz.govt.nz/layer/51768-nz-8m-digital-elevation-model-2012/> , LICENSED BY LINZ FOR RE-USE UNDER THE CREATIVE COMMONS ATTRIBUTION 4.0 NEW ZEALAND LICENCE (CC BY 4.0). ACCESSED 08/03/2019.

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SCALES (AT A3 SIZE) AS SHOWN		
PROJECT No. 1008476		

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SOURCE PROTECTION ZONES FOR PUBLIC SUPPLY BORES

Awatoto Geological Cross Section 2

FIG. No. Figure 14

REV. 0

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Appendix C: Effective porosity evaluation

C1.1.1 Introduction

Tonkin & Taylor Ltd have previously undertaken a literature review[1] of effective porosities (n_{eff}) in the Heretaunga Plains aquifer system for the purpose of delineating groundwater source protection zones. Estimates of effective porosity are required as input parameters for particle tracking software (e.g. MODPATH, AnAqSim) used for travel time estimates, together with parameters such as hydraulic gradient and hydraulic conductivity to calculate particle velocities. The effective porosities reported in this appendix are derived from tracer testing both within the Heretaunga Plains aquifer system, and other aquifer systems reported in the groundwater literature.

The purpose of this literature review is to obtain conservative (i.e. providing faster travel times) estimates of n_{eff} as input for particle travel time modelling for evaluation of wellhead protection areas for in the Heretaunga Plains aquifer system.

C2 Background

Groundwater velocity can be measured from tracer tests or calculated using the following equation:

$$V = Ki/n_{eff} \tag{1}$$

where *V* is the groundwater velocity, *K* is the hydraulic conductivity (evaluated from pumping tests), *i* is the measured hydraulic gradient, and n_{eff} is the effective porosity (estimated from laboratory and field techniques, obtained from reference documents or published data, or back calculated using equation 1).

Effective porosity is defined as the interconnected pore volume in a rock that contributes to fluid flow in a reservoir/aquifer[2]. According to Bear (1972), effective porosity in terms of fluid flow transport should not be confused with the specific yield of an aquifer.

C3 Effective porosity data

Published n_{eff} values for sands and gravels give values ranging from 0.1-0.4 (Handbook of Groundwater Development, 1990; Sara, 2003; Gelhar et al., 1992; Fetter, 1994; Dann et al., 2008; PDP, 2002; Thorpe, 1982).

However, it has been shown from a number of tracer test studies that the transport n_{eff} of a heterogeneous, channelised aquifer could actually be much smaller (up to two orders of magnitude) than those estimated/calculated from laboratory measurements, logs, and rock physics, when calculating bulk aquifer characteristics using complementary pumping and tracer test data (Dann et al., 2008; Stephens et al., 1998; Tonkin + Taylor, 2016).

Dann et al. (2008) carried out both pumping and tracer tests on the Canterbury Plains aquifer at the Burnham field site, Christchurch. They found that the pumping tests gave K values that represented flow through the bulk aquifer (K_{bulk}), whereas their tracer test gave K values reflecting flow through a preferential flow path (high permeability gravel channel; K_{pc}) (Table 1). This has also been observed by PDP (2002), who point out that there is often a discrepancy between K derived from pumping tests and K derived from tracer tests. They note that K from pumping tests are smaller than K from tracer tests, because the pumping tests are drawing water from “both low and high permeability strata”, whereas, tracer tests are measuring the “fastest moving groundwater”.

Since flow in the Canterbury Plains aquifer is predominately through high permeability channels, Dann et al. (2008) speculate that the aquifer system works like a dual permeability system. In order to use their tracer test results to derive/match K for the bulk aquifer, Dann et al. (2008) had to use

[1] Tonkin + Taylor Ltd. *Source protection zones for public supply bores*. Report for Hastings District Council, October 2018.
[2] http://www.glossary.oilfield.slb.com/Terms/e/effective_porosity.aspx

an n_{eff} two orders of magnitude smaller than the calculated (from volume replacement methods or particle size distributions) porosities (n) for their permeable channel material (Table 2). This smaller transport n_{eff} reflects the fraction of permeable channels within the total volume of the aquifer (the same definition used in a dual permeability model for the n_{eff} of the fractures). In the case of the field test site, the permeable channels make up about 1% of the overall aquifer, and therefore the transport n_{eff} is on the order of 0.0032 (using an initial n_{eff} of 0.32 for the gravels (Table 2) and then multiplying that by the fraction the channels make-up of the overall aquifer (0.01); Table 1).

Appendix C Table 1: K values derived from pumping and tracer tests for the Canterbury Plains aquifer at the Burnham field site (Dann et al., 2008). T is transmissivity, b is aquifer thickness, V is groundwater velocity, and i is the hydraulic gradient.

Test Type	T (m^2/day)	b (m)	V (m/day)	n_{eff}	i	K (m/day)
Pumping test 2	556	5.5	N/C	N/C	N/C	K_{bulk}: 100 (calculated from K=T/b)
Tracer test	N/C	N/C	70 (derived from tracer tests)	0.2 (from Pang et al., 1998)	0.0024 (measured)	K_{pc}: 5833 (calculated from $K=Vn_{eff}/i$)
Tracer test (deriving K_{bulk})	N/C	N/C	70 (derived from tracer tests)	0.0032 (calculated from n_{eff}=0.01*initial n_{eff})	0.0024 (measured)	K_{bulk}: 93.3 (calculated from $K=Vn_{eff}/i$)

Appendix C Table 2: Table 2: Calculated n values from volume replacement methods and particle size distributions, and initial neff values, assuming initial neff is 90% of the calculated n (Dann et al., 2008).

Calculated n for the permeable channel	Initial n_{eff} (90% of the calculated values)
0.27, 0.338, 0.39	0.24, 0.304, 0.351

Similarly, Stephens et al. (1998) conducted a tracer test at a groundwater reclamation well field at the Tucson International Airport Superfund site, Arizona, USA (alluvial aquifer, dominated by sand and gravel, with some layers of silt and clay) and found that the n_{eff} obtained from calibrating a numerical flow and transport model (n_{eff} = 0.17) was smaller than n_{eff} estimated from logs, core and particle size techniques (0.31-0.32).

In terms of the Heretaunga Plains aquifer, which is a heterogeneous, alluvial channel dominated aquifer, Thorpe et al. (1982) carried out tracer tests at four test sites to look at the potential for surface contamination reaching the aquifer. They measured velocity data from well to well tracer tests, based on peak concentrations in an observation well at a known distance from the injection well (Table 3).

Using equation 1, and the hydrogeological data collected by Thorpe et al. (1982), we have calculated a range in transport n_{eff} for the Heretaunga Plains, at their four tests sites (Table 3). K_{bulk} values were determined from:

$$T = bK_{bulk} \tag{2}$$

Appendix C Table 3: Measured hydrogeological data, and Kbulk and neff calculated from equations 1 and 2, using pumping and tracer test data from the four test sites used by Thorpe et al. (1982) in their contamination transport study of the Heretaunga Plains aquifer.

Well site	T (m^2/day) (average from pumping tests)	b (m) (effective aquifer thickness)	K_{bulk} (m/day) (calculated from equation 2)	V (m/day) (mean peak velocity from tracer tests)	i (average from tracer tests)	n_{eff} (calculated using equation 1)
Roys Hill	25,000	50	500	135	5.75×10^{-3}	0.02
Flaxmere (FL)	32,000	50	640	23	1.55×10^{-3}	0.04
Ngatarawa	255	50	5.1	18	1.1×10^{-3}	0.0003
Flaxmere (FM)	8350	50	167	5.5	1.9×10^{-3}	0.06

The calculated n_{eff} values in Table 3 are significantly smaller than those measured from field density tests for the Heretaunga Plains aquifer (0.25) (Thorpe et al. 1982). On this basis the range of calculated n_{eff} using mean peak velocity data is 0.003 to 0.06. Values of n_{eff} range between 0.02 – 0.06 for sites that have similar aquifer properties to the NCC proposed public supply bore fields, with 0.02 being the most conservative value.

In addition, Tonkin + Taylor undertook a bacteriological contamination investigation (2016, job no. 31301.100) in the Brookvale Road water supply bores, located in Brookvale Road, Havelock North (part of the Heretaunga Plains aquifer) to determine the source of the 2016 Havelock North gastroenteritis outbreak. They modelled travel times within the capture zone, using a two layer aquifer model, and found that they needed to use n_{eff} values in the range 0.01-0.15 to match travel times from tracer tests (using K derived from pumping tests) (Stephens et al. (1998) followed a similar process to estimate n_{eff} at their field site in Arizona).

C4 Discussion

Table 1 shows that in order for Dann et al. (2008) to match K_{bulk} from their pumping test, using velocities derived from their tracer test, they had to use a “bulk” n_{eff} that reflects the percentage of permeable pathways throughout the whole aquifer profile, rather than a n_{eff} estimated specifically for the high permeable strata (gravel). We also see this in the transport studies of Stephens et al. (1998), Thorpe et al. (1982), and Tonkin + Taylor (2016), where derived n_{eff} values are an order of magnitude less than values reported in the literature for n_{eff} measured/calculated from core, laboratory or geophysical methods for gravels.

It appears that even though the main fluid flow pathways for groundwater transport are through highly permeable channels within an heterogeneous, alluvial aquifer; because the majority of groundwater flow studies and numerical groundwater flow models use a simplified, average aquifer model, an n_{eff} for the dominate flow paths needs to be in the context of the average, bulk aquifer. This is similar to the definition used for the n_{eff} for fractures in a dual-permeability (dual porosity) reservoir model. The fractures are the dominant pathways for fluid flow to the wells, but their porosity in terms of the bulk reservoir is very small (fracture void space per unit bulk volume) (Douglas and Arbogast, 1990).

Therefore, if using K calculated from pumping tests (which give a bulk aquifer K) as used to calculate groundwater flow velocities from complementary tracer tests, the n_{eff} used in the modelling needs to reflect the fraction of high permeability pathways within the bulk aquifer.

C5 Conclusions

We have carried out a literature review to determine reasonable n_{eff} values required for source protection zone modelling based on particle travel times in the Heretaunga Plains aquifer system. When using complementary pumping and field test data to model groundwater flow in heterogeneous, channelised alluvial aquifer systems, the required transport n_{eff} will actually be smaller than core and lab n_{eff} estimates, because the majority of flow is through highly permeable pathways that make up only a small fraction of the bulk aquifer system. Since aquifer models are generally simplified to only a few geological layers (averaging out the geological heterogeneity within a true aquifer system), the n_{eff} used in the transport modelling should be a "bulk" n_{eff} that reflects the fraction of high permeability flow paths in regards to the bulk aquifer system. Therefore, n_{eff} values required for groundwater transport modelling in a simplified aquifer model could range from 0.003-0.15 (and may be smaller depending on the percent of highly permeable flow paths observed in an aquifer) (Dann et al., 2008; Stephens et al., 1998; Thorpe et al., 1982; and Tonkin + Taylor, 2016). For sites with similar aquifer properties to the NCC proposed bore fields, the range for n_{eff} based on mean peak velocities is between 0.02 – 0.06. The minimum value of n_{eff} = 0.02 is the most conservative value.

References

Bear, J., 1972, *Dynamics of fluids in porous media*, Elsevier, New York, p. 764.

Dann, R. L., Close, M. E., Pang, L., Flintoft, M. J., and Hector, R. P., 2008, Complementary use of tracer and pumping tests to characterize a heterogeneous channelized aquifer system in New Zealand, *Hydrogeology Journal*, 16, 1177-1191.

Douglas, J., Arbogast, T., 1990, Dual-porosity models for flow in naturally fractured reservoirs, *Dynamics of fluids in hierarchical porous media*, Academic Press, London, pp.177-221.

Fetter, C. W., 1994*, Applied Hydrogeology*, Third Edition, Prentice-Hall, Inc., p. 691.

Gelhar, L. W., Welty, C., and Rehfeldt, K. R., 1992, A critical review of field-scale dispersion in aquifers, *Water Resources Research*, vol. 28, no. 7, 1955-1974.

PDP (Pattle Delamore Partners Ltd), 2002, *Groundwater model audit guidelines*, prepared for the Ministry for the Environment.

Roscoe Moss Company, 1990, *Handbook of Groundwater Development*, John Wiley and Sons, p. 493

Sara, M. N, 2003*, Site Assessment and Remediation Handbook*, CRC Press, p. 1160.

Stephens, D. B., Hsu, K., Prieksat, M. A., Ankeny, M., D., Blandford, N., Roth, T. L., Kelsey, J. A., and Whitworth, J. R., 1998, A Comparison of estimated and calculated effective porosity, *Hydrogeology Journal*, 6, 156-165.

Thorpe, H. R., Burden, R. J., Scott, D. M., 1982, Potential for contamination of the Heretaunga Plains aquifer, *Water and Soil technical publication*, 24, p. 149.

Tonkin + Taylor, 2016, *Bacterial Contamination Investigation*, job no. 31301.100.