Capture zone delineation of community supply wells and State of the Environment monitoring wells in the Greater Wellington Region

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ABSTRACT

Greater Wellington Regional Council (GWRC) commissioned GNS Science to delineate capture zones for community supply wells and for State of the Environment (SOE) wells. A capture zone (CZ) is defined as the total source area that contributes groundwater to a well. The objective of delineating CZs for community supply wells is to help form policy for a natural resource plan. CZs for SOE wells can help understand geochemistry and trends in water quality by evaluating the land use in the CZs for each well. Existing calibrated groundwater flow models for Hutt Valley, Kapiti Coast and the Wairarapa Valley were used delineate CZs for wells within these modelling domains. The transient models were largely used “as is”, with modifications to implement additional wells to delineate CZs. Particle tracking techniques were used to trace the outline of CZs around each well, using a combination of forwards tracking particles on the water table and/or backwards particle tracking around each well screen. The simulations were run several times in order to conduct a sensitivity analysis, by varying hydraulic parameters and particle release times. A maximum CZ shape was obtained by aggregating pathlines from all sensitivity simulations. In addition to tracing the total CZ shape, each zone was subdivided into shallow and deep zones, based on a 3-dimensional evaluation of particle pathlines below the water table. A shallow CZ is the areal extent on the surface that contributes to a well’s water source, while a deep CZ is the source region found below the water table. Travel times of pathlines were used to delineate microbial protection zones (PZs) based on a 1-year travel time to each well. The resulting maps show four different zones of shallow and deep CZ and PZ polygons.

KEYWORDS

Capture zone, protection zone, groundwater quality, water supply, numerical modelling, particle tracking, State of the Environment, Wellington

1.0 INTRODUCTION

The National Environmental Standard (NES) for Sources of Human Drinking Water (New Zealand Legislation, 2007) is intended to reduce the risk of contaminating drinking water sources by requiring regional councils to consider the effects of activities on drinking water sources in their decision making. In recognition of the NES, Greater Wellington Regional Council (GWRC) commissioned GNS Science to delineate capture zones of community supply wells within the three major catchments of the Wellington region, namely the Hutt Valley, Kapiti Coast and the Wairarapa Valley. Mapping of capture zones for municipal supply wells is common practice throughout the world to help protect the quality of municipal groundwater supplies (US EPA 1987; 1994). A review of international capture zone delineation approaches and capture zone guidelines for New Zealand can be found in Moreau *et al*. (2014a).

Additionally, GWRC commissioned GNS Science to delineate capture zones for their network of 71 State of the Environment (SOE) monitoring wells. These SOE wells are used to evaluate state and trends in groundwater quality across the Wellington region (Daughney, 2010). The aim of the capture zone delineation of each SOE well is to understand the origin of the groundwater that is being sampled. In turn, this will assist with the interpretation of hydrochemical data, for example in terms of relating groundwater quality to the effects of land use.

A capture zone (CZ) is defined as the total source area that contributes groundwater to a hydrological feature, e.g., a well, spring, wetland or lake. For a well, it consists of the up-gradient and down-gradient areas that will drain into a pumping well (Fetter, 1994) and is usually described by an elongated zone against the direction of groundwater flow. Figure 1 illustrates the general shape of the CZ for a well in an idealised homogeneous unconfined aquifer.

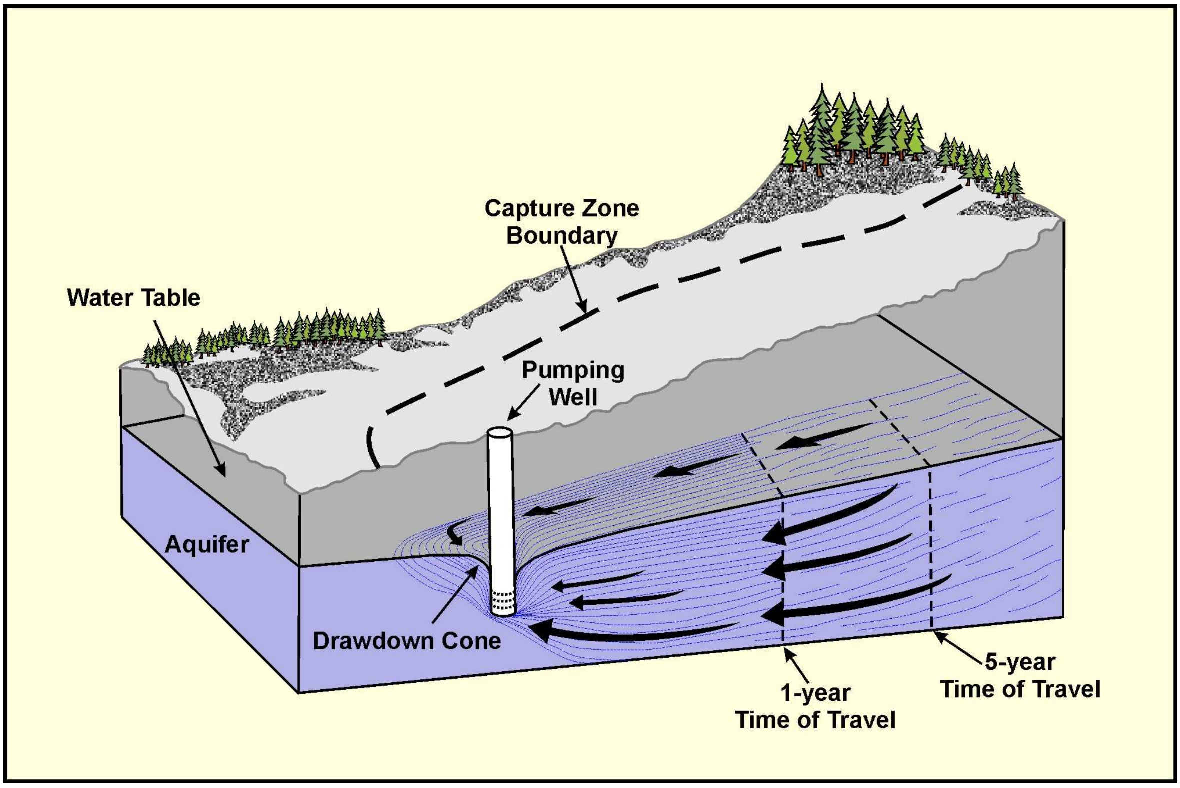

Figure 1: Idealised shape of the capture zone for a well in a homogeneous, unconfined aquifer (modified from Ministry of Environment, British Columbia, 2004).

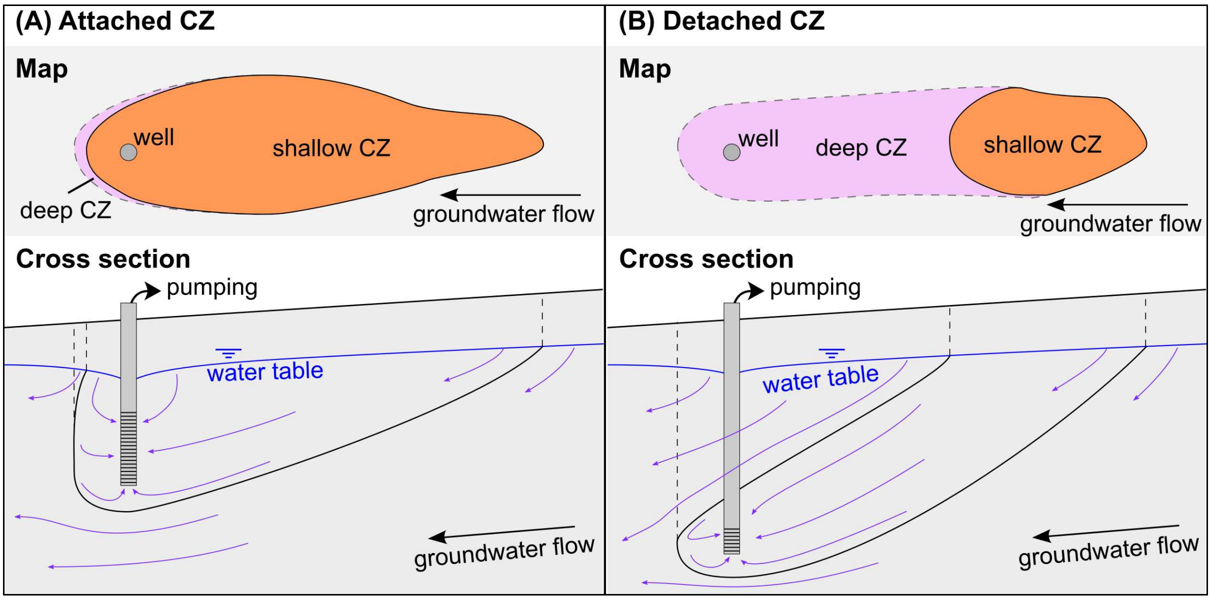

Figure 2: Generalised capture zones (CZs) in map and cross section view, showing shallow and deep zones, and the difference between (A) attached and (B) detached CZ types. A shallow CZ is the mapped region where surface recharge may reach the pumped well, whereas the deep CZ is an area below the water table that may reach the pumped well. An attached CZ delineates a shallow CZ polygon that includes the location of the pumped well, whereas the pumped well for a detached CZ is located outside the shallow CZ polygon (disjoint).

Figure 2 shows generalised illustrations of capture zones delineated by the GWRC models, and introduces terminology used throughout this report to describe their characteristics. The primary distinction between the attached and detached CZ types is that the location of the well is within or outside the mapped shallow CZ polygon. An attached CZ is typically characterised by shallow, unconfined wells, where groundwater recharge flows down from the surface into the CZ for the pumped well. A detached CZ may be characterised for pumped wells that are deeper, are confined, and/or are screened in hydrostratigraphic units that have limited vertical flow. A total CZ represents the combined shape of all pathlines to a pumped well, regardless of depth or groundwater travel time.

The actual shape of the CZ for a particular well is controlled by many factors, such as the pumping rate of the well and the hydrogeological properties of the aquifer (porosity, hydraulic conductivity, flow boundaries, confinement status and piezometric gradient). A maximum CZ delineates a mapped area that takes account for all known hydrological uncertainties, and is formed by aggregating CZ results from several different numerical simulations with varied properties, and can be based on a sensitivity analysis of model parameters.

For management purposes, the mapped CZ is often defined on the basis of groundwater travel times, i.e. the time that it takes for groundwater to flow to a pumping well. The travel time threshold should allow the water supply authorities to have a sufficient response time between occurrences of contamination in the CZ and arrival of the contaminants at the wells. For pumped wells located away from natural flow boundaries, the capture zone guidelines for New Zealand (Moreau *et al*., 2014a) recommend a 50-year threshold as a proxy. Where this is impractical, a lower threshold could be used, although it should be kept in mind that this results in an underestimation of the actual capture zone. Furthermore, the guidelines recommend the delineation of two protection zones: (1) immediate protection zone and (2) the microbial protection zone. The immediate protection zone represents a zone of at least 5 m radius around a well to provide protection from direct contamination, e.g., spills. This safeguarding distance is based on a review of international guidelines, but should be adjusted to individual circumstances to guarantee an adequate response time towards contamination. The microbial protection zone (PZ) is determined by either a 1-year travel time zone or a safeguarding distance to ensure a sufficient time for bacteria and virus degradation. Different PZs can be defined by different travel times, as specified by different contaminant types.

Different methodologies for CZ delineations can be applied depending on data availability and the needs to fulfil the project purpose. Two presentations were given by GNS Science to GWRC during the course of the project to discuss various aspects that needed to be considered in order to develop the most adequate methodology. On the basis of decisions made during the preceding discussions and following meetings, the CZ delineation was accomplished using numerical groundwater flow models. These numerical groundwater flow models were provided by GWRC and cover the three areas of the Wellington region. In total, CZs were delineated for 223 wells, including 97 community supply and 67 SOE wells. CZs outside the groundwater model boundaries are not delineated in this report.

This report is divided into seven sections: Section 1 of this report provides background and introductory information about this study; Section 2 describes the numerical models used in this study; Section 3 details the methods used in this investigation; Section 4 shows maps of results obtained in this study for the Wellington region; and Sections 6 and 7 provide discussion and recommendations.

2.0 GROUNDWATER FLOW MODELS

For the objectives of this project, GWRC has provided five numerical groundwater flow models: the Hutt Valley model (HAM3), the Kapiti Coast model and three Wairarapa models (Lower Valley, Middle Valley and Upper Valley models).

Figure 3 illustrates the model domains and the geographical setting of the study area.

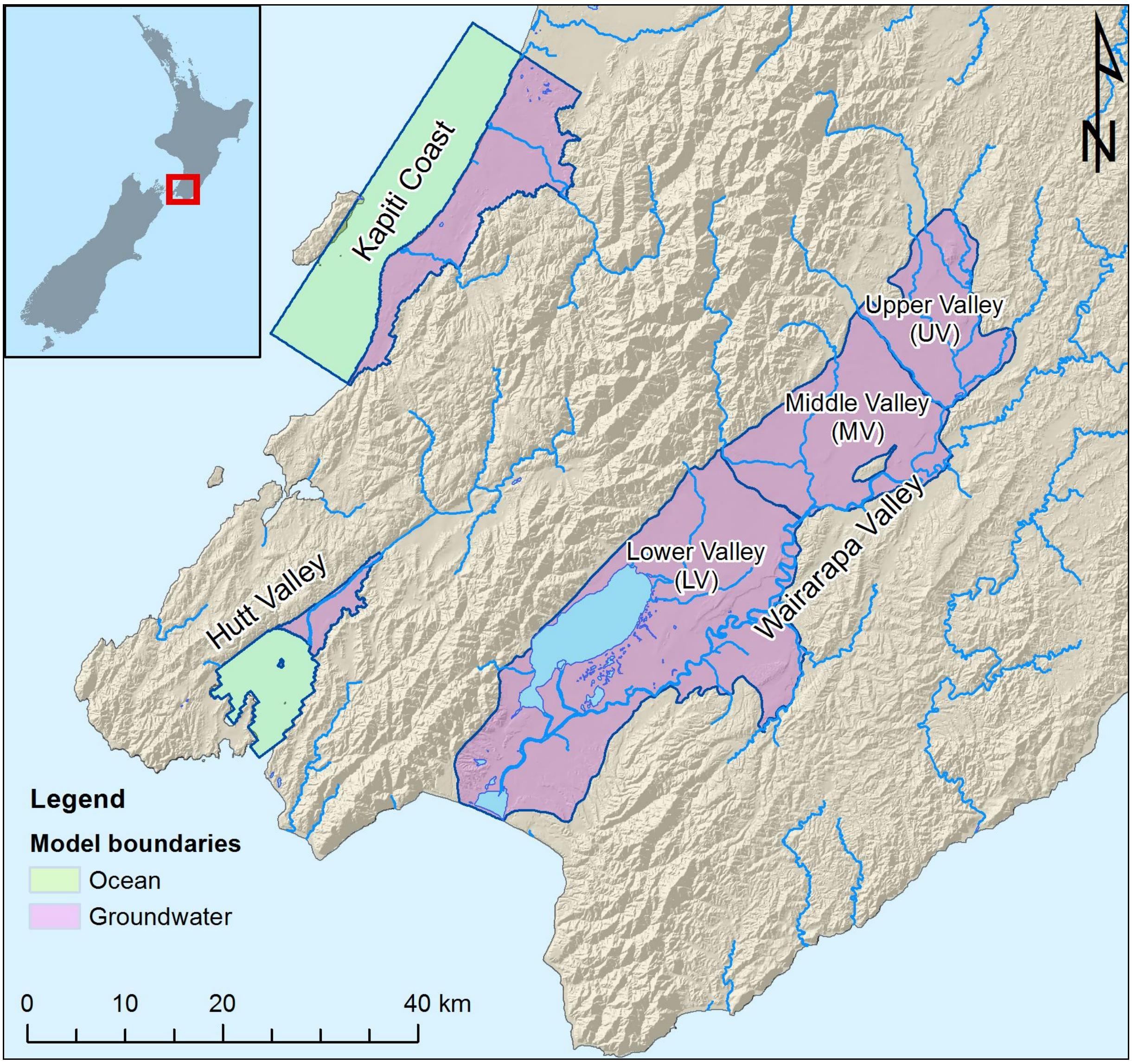

Figure 3: Geographical setting and model domains. Ocean boundaries are simulated with constant heads on the uppermost layer, and groundwater or inactive cells beneath. Outer inactive cells from each model are not shown.

The models and the respective model reports act as the main data source upon which a geological and hydrogeological description was derived in the following sections for each area of interest. The geology of the Wellington Region has been intensively investigated and a good summary is contained in the memoirs accompanying the 1:50,000 geological map (Begg and Mazengarb, 1996), and the 1:250,000 scale QMAP (Begg and Johnson, 2000).

2.1 HUTT AQUIFER MODEL (HAM3)

The Hutt Aquifer Model version 3 (HAM3) was constructed in 2012 using the USGS MODFLOW-2000 three-dimensional numerical groundwater flow code (Harbaugh *et al.*,

2000) in conjunction with the data processing interface Groundwater Vistas (ESI, version 6). The model is a transient flow model representing a 5-year period from 2007 to 2012 and is divided into 260 weekly stress periods (5 time steps per stress period; Gyopari, 2014).

The model domain extends from Taita Gorge to the entrance of Wellington harbour and the active model grid covers an area of 107.5 km². The grid has been rotated 37° to align it with the principal groundwater flow direction and the north-western fault-bound edge of the basin. The grid cell size is 100 m × 100 m, which was applied to the entire on-shore portion of the model and is also used offshore as far as the Somes Island area. Further offshore, the grid spacing progressively increases to a maximum of 500 m. The model consists of eight layers to represent the stratified nature of the leaky aquifer system, with the uppermost three layers defined as unconfined.

The geology and hydrogeology as described within this section are based on the model and refer to the model report (Gyopari, 2014).

2.1.1 Geology

The Hutt Valley is an alluvial basin associated with the Wellington Fault. The total length of the basin between Taita Gorge and the Wellington harbour entrance is approximately 23 km and narrows towards the Taita Gorge. The basin bedrock is composed of Permian to Mid Jurassic (280 – 200 Ma) Torlesse Greywacke – a hard metamorphosed sandstone, siltstone and mudstone sequence of fracture-controlled secondary permeability, generally regarded to be 'groundwater basement'. The Somes Island ridge is a notable basement high that is a fault-bounded horst structure. The Hutt River has deposited sediment into the Lower Hutt-Wellington Harbour basin from about the middle and later Quaternary period to the present (over the last 500,000 years). The sedimentary sequence is associated with the progradation of a delta into a subsiding basin centred on the harbour.

Distinctive and laterally continuous lithostratigraphic units can be identified in the basin: essentially representing a sequence of confined aquifers and aquitards in the lower part of the Hutt Valley, and a coalescing unconfined to semiconfined gravel-dominated sequence in the upper part of the valley.

2.1.2 Hydrogeology

Seven major hydrostratigraphic units can be identified in the Hutt Valley catchment. From youngest to oldest these are as follows:

- **Taita Alluvium** (Holocene): highly variable laterally semi-contemporaneous; locally loose coarse gravel with high transmissivities; forms the floor of the Hutt Valley and is an unconfined aquifer in the north; the maximum thickness is 25 – 30 m.
- **Melling Peat/Petone Marine Beds** (Holocene): dominated by organic sediments, silts, sands and local gravels; overall represents a leaky aquitard unit; deposits thicken as a low permeability wedge occurs from about 5 km inland of Petone foreshore; Petone Marine Beds form the harbour floor where they continue to accumulate; the maximum thickness is 0 – 30 m.
- **Upper Waiwhetu Aquifer** (Pleistocene): glacial coarse highly permeable gravels; the principal aquifer; distributed throughout the entire valley and sub-harbour; the maximum thickness is 20 -- 55 m.

- **Lower Waiwhetu Gravels** (Pleistocene): glacial matrix-rich gravels; significantly lower permeability than Upper Waiwhetu Gravels; distributed throughout the entire valley and sub-harbour basin; the maximum thickness 10 – 20 m.
- **Wilford Shell Beds** (Pleistocene): interglacial predominantly silts and sands; represents an aquiclude separating the Waiwhetu and Moera Basal gravels; occurs from about Knights Road (3 km inland from foreshore) extending into the sub-harbour basin; the maximum thickness is ~30 m.
- **Moera Gravels** (Pleistocene): penultimate glacial matrix-rich gravel aquifer; has moderate water bearing potential; distributed throughout the entire valley and sub-harbour; the maximum thickness is ~60 m.
- **Older Deposits/Basal Gravels**: sequence of compact gravels, silts, sands and clays; distributed over the sub-harbour basin, extending onshore at depth; the maximum thickness is >100 m.

The hydrostratigraphic units and their implementation in the model with their respective hydrogeological properties are shown in Table 1.

Table 1: Hydrostratigraphic units, layer configuration and hydrogeological properties of the HAM3 model. K_x and K_y are horizontal hydraulic conductivity values and K_z is vertical hydraulic conductivity.

Hydrostratigraphic unit	Model layer	K_x and K_y [m/d]	K_z [m/d]	Specific storage S_s [L^{-1}]	Specific yield S_y [-]
Taita Alluvium (TA) or Melling Peat	1–3	292.45–1400 (TA) 100 (peat) 1000 (recent floodplain)	0.1–0.12 0.1 0.22	7.97E-5	0.07
Petone Marine Beds	2–3	100 (onshore) 0.63 (offshore)	0.1 1.77E-4	3.15E-5	0.1
Upper Waiwhetu Aquifer	4	1400 (onshore) 1000 (offshore)	0.12 1.03	3.18E-5	0.1
Lower Waiwhetu Aqufer	5–6	335.7	10	6.05E-5	0.1
Wilford Shell Bed	6	6.37	1.77E-4	4.42E-5	0.01
Moera Gravels	7	200	0.96	4.42E-5	0.01
Older Basal Gravels	8	30	1	4.42E-5	0.01

The Upper Waiwhetu Artesian Aquifer (model layer 4), from Boulcott down-valley to beneath Wellington Harbour, represents the main hydrostratigraphic unit in terms of water allocation for water supply of the Hutt Valley. The Waiwhetu Aquifer, as well as the Taita Alluvium and the Moera aquifers, receives recharge sourced from leakage through the bed of the Hutt River in the upper part of the groundwater catchment. Here, the aquifers become unconfined upstream of Boulcott. The river has a complex recharge-discharge relationship with the shallow unconfined Taita Alluvium aquifer, but generally loses water to underlying aquifers in the area between Taita Gorge and Boulcott/Kennedy Good Bridge. Between Boulcott and the coastline, in the area where the Waiwhetu aquifers are confined, the river generally gains groundwater. A proportion of the river bed losses in the recharge zone remains in the highly permeable Taita Alluvium and flows southwards to the coast, or returns to the river in its lower reaches. The remainder of the loss reaches the deeper aquifers. The Upper Waiwhetu Aquifer receives vertically infiltrating water transmitted through the overlying Taita Alluvium, which is in hydraulic continuity with the river bed. Aquifers below the Upper Waiwhetu Aquifer exhibit a relatively small throughflow because of significantly lower hydraulic conductivities (reducing with increasing depth and compaction) and lower hydraulic gradients. The aquifer recharge dynamics and river losses are, however, strongly influenced by the abstraction regime, river conditions and unconfined aquifer levels.

2.1.3 Groundwater Allocation

One of the key purposes of the version 3 model development in 2012 was the identification of a sustainable management of the Waiwhetu Aquifer and the saline intrusion risk at the Petone foreshore. The aquifer yield is dependent upon aquifer storage/head conditions in the unconfined part of the aquifer and upon recharge potential from the Hutt River, but is also constrained by the foreshore saline intrusion groundwater level threshold.

When the model was developed in 2012 the consented groundwater takes amounted to 33.7×10^6 m³/year, of which ca. 90% was associated with the GWRC public water supply take (Waterloo and Gear Island wellfield in Lower Hutt City). These wells supply the Lower Hutt region and are operated under the same groundwater consent (WGN970036). The consented mean daily abstraction amounts to 83,115 m³/d.

Other major water takes include the industrial wells of Unilever NZ Trading Ltd and Avalon Studios, and the Hutt Valley Health wells (Hospital wells, main and emergency). The Hospital wells are the only wells that abstract water from the shallow unconfined aquifer in the Taita Alluvium. The other wells generally abstract water from the Upper Waiwhetu Artesian Aquifer.

The original model uses the metered annual volumes for the GWRC public water supply that rarely exceeded 25×10^6 m³/year, and 75% of the consented rate for the other major groundwater allocations.

2.2 KAPITI COAST MODEL

The Kapiti Coast model has been constructed using the USGS MODFLOW2000 three-dimensional numerical groundwater flow code in conjunction with the data processing interface Visual MODFLOW (Schlumberger Water Services). The model is a transient groundwater flow model representing a 19-year period (6930 days) from 1 July 1992 to 21 June 2011 by using 990 weekly stress periods (10 time steps per stress period; Mzila *et al.*, 2014). The calibrated transient model was set up using 4 years of data for the period from 1 July 2008 to 21 June 2011. The model consists of 7 layers, with the uppermost layer being defined as unconfined.

The model domain extends from Paekakariki in the south to about 5 km north of Otaki and covers an area of about 172 km², which is 38 km in length and 3.5 km wide in the Waikanae area to 8 km wide in the Otaki valley area. The grid has been rotated 57° to align with the coastline. The default cell size is 250 m × 250 m across the on-shore portion of the grid, increasing progressively to 1,000 m at the western off-shore boundary.

The geology and hydrogeology as described within this section are based on the model and refer to the model report (Mzila *et al.*, 2014).

2.2.1 Geology

The sedimentary sequence underlying the Kapiti Coast comprises a complex assemblage of fluvial and coastal sediments accumulated as a result of geological processes occurring along the western coast of the lower North Island over the past 400,000 years. These processes include significant variations in sedimentation rates and relative sea levels accompanying cyclic variations in climate between cold glacial and temperate interglacial conditions; structural deformation resulting in active uplift in the Tararua Range and development of a large sedimentary basin to the west; as well as altered sediment supply resulting from episodic volcanic eruptions in the central North Island.

The stratigraphic succession for the Kapiti Coast comprises the following major units:

- **Q1**: alluvial, aeolian and beach deposits associated with deposition over the current interglacial period (Aranuian, 14 ka to present).
- **Q2**: extensive highly heterogeneous glacial outwash deposits typically comprising poorly sorted gravel with sand and silt accumulated on the Otaki and Waikanae river alluvial fans during the last glacial period (Otiran, 70 to 14 ka).
- **Q3**: fine grained sediments that grade from silt-bound gravels near the coast to fine-grained, typically silt dominated, organic-rich materials further inland; deposits accumulated during an interstadial period during the middle stages of the Otiran glacial period.
- **Q4**: poorly sorted alluvial gravel, sand and silt (similar to the Q2 materials) deposited during the early stages of the Otiran glacial period.
- **Q5**: beach deposits largely comprising marine gravel and sand accumulated in a shallow coastal environment during the last interglacial period (Kaihinuan, 125 to 75 ka); typically recorded at depths of between 60 to 100 m bgl.
- **Q6 – Q8**: weathered, poorly to moderately sorted gravel accumulated during the penultimate glacial period (Waimean, 180 to 125 ka).
- **Greywacke Basement**: greywacke rocks of the Rakaia Terrane form the geological basement across the Kapiti Coast.

2.2.2 Hydrogeology

The groundwater system is coincident with the occurrence of late Quaternary and Holocene alluvial sediments that have accumulated within the basinal structure in the greywacke bedrock. Groundwater is found virtually throughout the entire sedimentary sequence, the major difference being the relative permeability which differentiates more permeable ‘aquifers’ from intervening lower permeability aquitard materials. The Greywacke of the Rakaia Terrane is generally considered to form the groundwater basement for the Kapiti Coast area, although it exhibits appreciable secondary porosity due to fracturing and jointing.

The primary hydrostratigraphic units and their configuration in the model in conjunction with their hydrogeological properties are illustrated in Table 2.

Table 2: Hydrostratigraphic units, model layer configuration and hydrogeological properties of the Kapiti model. K_x and K_y are horizontal hydraulic conductivity values and K_z is vertical hydraulic conductivity.

Hydrostratigraphic unit	Model layer	K_x and K_y [m/d]	K_z [m/d]	Specific storage S_s [L^{-1}]	Specific yield S_y [-]
Shallow unconfined Holocene sand and gravel aquifers (Q1) deposited along the seaward margin of the coastal plain	1	3.5–5.0	0.0014–0.05	1.00E-05	0.25
Coarse, well-sorted Holocene alluvium (Q1) adjacent to main rivers draining the Tararua Range	1	~200	0.5	1.00E-05	0.25
Late Quaternary sand/ gravel/ silt terrestrial alluvium and marine deposits, moderate to low permeability, forming a stratified aquifer system that becomes progressively confined with depth, comprised of at least 4 cyclothems Q2 – glacial outwash gravels (aquifer) Q3 – interglacial sands/silts (aquitard) Q4 – glacial outwash gravels (aquifer) Q5 – interglacial sands/silts (aquitard) Q6 – glacial outwash gravels (aquifer) Q7,Q8 – older cold and warm period sediments	1–7	aquitard: 2.5–3.0 aquifer: 3.1–200.1	aquitard: 0.0003–0.01 aquifer: 0.01–1.8	Layer 2–6: 9.76E-06 Layer 7: 1.06E-06	Layer 2–6: 0.25 Layer 7: 0.15
Foothill alluvium, poorly sorted narrow band of locally derived slope and outwash materials accumulated along the foot slopes of the Tararua Range	1–7	5.0	0.05	0.01	

2.2.3 Groundwater Allocation

For the purpose of resource management, the Kapiti Coast was divided into six groundwater management zones of similar hydrogeological characteristics on the basis of landform, subsurface geology, hydraulic properties, and aquifer chemistry (WRC, 1994). However, re-analysis for the most recently developed Kapiti Coast model identified several areas where the boundaries of the current groundwater management zones do not necessarily reflect the spatial and depth distribution of individual hydrogeological environments. The following four revised zones were identified in Mzila *et al.*, (2014): Otaki, Te Horo, Waikanae and Raumati.

When the model was developed in 2011 there were 93 consented wells on the Kapiti Coast with a combined consented allocation of 56,800 m³/day. About 73% of this total was allocated for seasonal irrigation use (primarily for horticulture or cropping). An estimation of the actual abstraction for irrigation use is problematic since there is no consistent metered data available. To adequately implement seasonal changes in groundwater allocation in the model, it was assumed that irrigation demand is driven by the amount of water required to satisfy the soil moisture deficit (SMD) – the amount of water needed to bring the soil to field capacity.

Provision of water for public/community water supply constitutes the bulk of the remaining consented take of approximately 27%. For the model calibration, metered data has been used to represent the annual public/community water supply allocation.

Major changes in groundwater allocation to the model developed in 2011 are constituted by the full implementation and application of the Waikanae wellfield, which represents the newly established major water supply for the Waikanae, Paraparaumu and Raumati communities.

2.3 WAIRARAPA MODELS

The Wairarapa Valley is divided into three regions: the Lower Valley (LV), the Middle Valley (MV) and the Upper Valley (UV), all represented by individual groundwater flow models.

The models were developed in 2007 and 2008 (Gyopari and McAlister, 2010a, 2010b, 2010c) using the finite element model FEFLOW (Diersch, 2002). FEFLOW (Finite Element subsurface FLOW system) is an interactive groundwater modelling system for three-dimensional flow and transport in subsurface water resources developed by DHI-WASY GmbH (DHI-WASY, 2013). The finite element meshes were generated using the Triangle algorithm (Shewchuk, 2002) and consist of 6-node triangular prisms. The distances between nodes vary between 100 m around refined areas of interest, such as rivers, and 500 m over the alluvial fan areas.

The following geological and hydrogeological description is based on the models and refers to the respective model reports (Gyopari and McAlister, 2010a. 2010b, 2010c). Due to the hydrogeological complexity of the area, only the major hydrostratigraphic units and their general hydrogeological nature and distribution within each model domain are described. See Gyopari and McAlister (2010a, 2010b, 2010c) for further model implementation details such as the hydraulic conductivity and specific storage/ specific yield values used.

2.3.1 Regional Geological Setting

The Wairarapa Valley groundwater basin occupies a northeast-southwest orientated structural depression 110 km long and up to 15 km wide. The basin is bounded by basement greywacke that outcrops on the fringing Tararua Range to the north and west and is also exposed as isolated uplifted blocks, such as Tiffen Hill. The Aorangi Range and hills to the east are formed by Early Pleistocene/late Tertiary marine strata (mudstones) that lie above the greywacke basement. The north-western edge of the Wairarapa Valley is controlled by the Wairarapa Fault. Numerous other major faults and folds cross-cut the basin and deform younger (Quaternary age) infill fluvial sediments. This deformation – both the broad regional strain and more local deformation associated with faults and folds – strongly influences the hydrogeological environment. The Wairarapa Valley basin contains an unconsolidated sequence of Quaternary age fluvial sediments. The younger late Quaternary deposits (Q1 to Q8) consist of greywacke-sourced gravels and sands derived from erosion of the Tararua Range and deposited by southeast flowing rivers and alluvial fan systems. These host a relatively shallow ‘dynamic’ groundwater system and are the main water bearing formations. Older sediments (mQa and eQa) also contain limited quantities of groundwater and are exploited by some wells. However, these aquifers tend to be low-yielding and are regarded as a minor resource containing extensive very low permeability aquitard sequences.

2.3.2 Lower Valley Model

The Lower Valley model (Gyopari and McAlister, 2010a) is a transient 3-D saturated flow model representing a ca. 16-year period from 1 July 1992 to 1 October 2008 by using weekly stress periods and the FEFLOW automated time-step control. The model consists of 17 model layers (18 slices) with the uppermost layer being defined as unconfined, phreatic surface.

The Lower Valley catchment encompasses Lake Wairarapa, Lake Onoke, the Martinborough terraces and the Tauherenikau fan. The Lower Valley model domain covers an area of 643 km² and incorporates the lowland catchments of the Tauherenikau and Ruamahanga rivers, Lake Wairarapa and Lake Onoke. The domain is 42.5 km in length, extending from the southern edge of the Waiohine plains to the coast at Lake Onoke. The maximum width of the modelled catchment is approximately 20 km, extending from the base of the Tararua Range to the eastern hills and Martinborough terraces, also taking in the Huangarua valley. Te Maire ridge consists of an uplifted greywacke basement block and is represented as an area of very low permeability.

2.3.2.1 Hydrostratigraphy

Six broad hydrostratigraphic units are recognised within the Lower Valley catchment on the basis of formation lithology, well yield and aquifer properties. Table 3 lists the units, their spatial distribution and the general nature of their hydraulic properties.

Table 3: Principal hydrostratigraphic units of the Lower Valley catchment.

Hydrostratigraphic unit	General hydrogeological nature	Distribution
Unit A: Alluvial fan gravels (Q2–Q8)	Poor-moderate aquifers: generally low hydraulic conductivity, poorly sorted gravels with silts/clay and organic lenses. Improved sorting distally, where higher well yields are obtained such as in the Kahutara area. Poor well yields on the upper fan areas. Includes the side fans in the Onoke/ Narrows area.	Tauherenikau fan Huangarua valley Onoke/Narrows
Unit B: Unconfined aquifer (Q1)	Good aquifer: generally high hydraulic conductivity, reworked gravels, strong connection with rivers.	Ruamahanga valley Tauherenikau fan Huangarua valley
Unit C: Confined aquifers (Q2, Q4 and Q6)	Aquifers: medium-high hydraulic conductivity, discrete, highly confined units (<10 m thick)	Lake basin Ruamahanga valley (south) Onoke/Narrows
Unit D: Silt/clay aquitards (Q1, Q3, Q5, and Q7)	Aquitards: very low hydraulic conductivity, silty/clay estuarine and swamp deposits.	Lake basin Ruamahanga valley (south) Onoke/Narrows
Unit E: Martinborough terrace deposits	Low hydraulic conductivity, compact, clay-bound alluvial terrace sequences with silt aquitards.	Martinborough terraces
Unit F: Flow barriers	Uplifted fault or terrace features of very low permeability forming regional flow barriers.	Te Maire ridge Harris anticline Martinborough Fault (at depth)

2.3.2.2 Groundwater abstraction

Groundwater abstraction in the catchment has more than doubled over the last decade primarily due to demand for seasonal pasture irrigation. At the time of initial groundwater model development in 2008, there were 142 consented wells with a combined allocation of 202,000 m^3/day and 40.3×10^6 m^3/year. Annual meter readings show that in general resource consent holders do not exceed 10 – 30% of their annual allocation. Modelling of actual abstraction using soil moisture demands indicates that peak current usage is about 100,000 to 130,000 m^3/day. This is equivalent to about 65% of the consented daily rate. Groundwater abstraction currently constitutes more than about 25% of the total catchment recharge from surface water during the summer months and appears to have an impact on aquifer discharge (base flow) quantities.

The Martinborough water supply constitutes the major public/community groundwater supply in the Lower Valley catchment with a currently consented daily take of 7,773 m^3/day.

2.3.3 Middle Valley Model

The Middle Valley model (Gyopari and McAlister, 2010b) is a transient 3-D saturated flow model representing a ca. 15-year period from 1 July 1992 to 1 May 2007 by using weekly stress periods and the FEFLOW automated time-step control. The model consists of 9 model layers (10 slices) with the uppermost layer being defined as an unconfined, phreatic surface.

The Middle Valley catchment covers an area of ca. 270 km^2 and encompasses the plains area between the Waingawa River in the north and the Waiohine plains south of Greytown. The active model domain contains the lowland catchments of the Waiohine, Mangatarere and middle Ruamahanga rivers on the main valley floor. Tiffen Hill consists of an uplifted greywacke basement block and is represented as an impermeable area (or hole in the model domain). The model domain is approximately 13 km wide between the Tararua foothills and the Ruamahanga River (NW–SE), and approximately 19.5 km in length between the Waingawa River and the edge of the Greytown/Waiohine plains (NE–SW).

2.3.3.1 Hydrostratigraphy

Five broad hydrostratigraphic units are recognised within the Middle Valley catchment on the basis of formation lithology, well yield and aquifer properties. Table 4 lists the units, their spatial distribution and the general nature of their hydraulic properties.

Table 4: Principal hydrostratigraphic units of the Middle Valley catchment.

Hydrostratigraphic unit	General hydrogeological nature	Distribution
Alluvial fan gravels (Q2 – Q8)	Poor aquifers: low hydraulic conductivity, poor yields.	Major fan systems on western valley side of Waiohine, Waingawa and Mangatarere rivers.
Unconfined aquifer (Q1)	Aquifer: high hydraulic conductivity, reworked, strong connection with rivers.	Main river channels, Waiohine floodplain, Ruamahanga floodplain.
Aquifers (Q2 – Q4, Q6, and Q8)	Aquifers: medium–low hydraulic conductivity, layered gravel/sand/silts.	All distal fan areas either at surface or below Q1 deposits.
silts/clay aquitards (Q5 and Q7)	Aquitards: very low hydraulic conductivity, silty/ clay swamp deposits.	Parkvale, Carterton, Ruamahanga, Fernhill.
Uplifted blocks	Aquitards: very low or low hydraulic conductivity, form flow barriers.	Tiffen Hill/Fernhill.

2.3.3.2 Groundwater abstraction

Groundwater abstractions in the catchment have more than doubled over the past 10 years primarily due to demand for seasonal pasture irrigation. At the time of initial groundwater model development (2007), there were 126 consented wells with a combined allocation of about 155,000 m³/day and 28×10^6 m³/year. Annual meter readings show that water users do not normally exceed 50% of their annual allocation (10 – 30% being the norm). A metering study showed that resource consent holders tend to abstract between 50 – 70% of their consented daily rate. Historical groundwater abstraction for the catchment was modelled using soil moisture deficit in conjunction with available annual meter records to estimate demand periods.

The Carterton and Greytown water supply constitute the major public/community groundwater supplies in the Middle Valley catchment with a currently consented daily take of 6,480 m³/day and 5,184 m³/day, respectively.

2.3.4 Upper Valley Model

The Upper Valley model (Gyopari and McAlister, 2010c) is a transient 3-D saturated flow model representing a ca. 16-year period from 1 July 1992 to 1 October 2008 using weekly stress periods and the FEFLOW automated time-step control. The model consists of 4 model layers (5 slices) with the uppermost layer being defined as an unconfined, phreatic surface.

The Upper Valley catchment encompasses an area of 160 km² largely to the northeast of the Waingawa River and centred on the town of Masterton. The model domain incorporates the alluvial fans of the Waingawa, Waipoua and Ruamahanga rivers, and also the Te Ore Ore plain. The length of the model domain is about 14 km extending from the Wairarapa Fault to the southern edge of the Te Ore Ore plain. The width is approximately 10 km, extending from the base of the eastern hills in the north-east to the Waingawa River. The smaller Waipoua, Kopuaranga and Whangaehu tributaries of the Ruamahanga River also occur in the catchment along with numerous small streams and spring systems on the lowland fans and plains. Agriculture is the dominant land use in the catchment, particularly sheep and beef farming. The Te Ore Ore plain is an intensively farmed area within the catchment where a significant amount of groundwater abstraction occurs for irrigation purposes.

2.3.4.1 Hydrostratigraphy

Four broad hydrostratigraphic units are recognised within the Upper Valley catchment on the basis of formation lithology, well yield and aquifer properties. Table 5 lists the units, their spatial distribution and the general nature of their hydraulic properties.

Table 5: Principal hydrostratigraphic units of the Upper Valley catchment.

Hydrostratigraphic unit	General hydrogeological nature	Distribution
Unit A: Alluvial fan gravels – Tararua-sourced (Q2)	Poor-moderate aquifers, generally low hydraulic conductivity, poorly sorted gravels with silts/clay and organic lenses. Improved sorting distally, where higher well yields are. Poor well yields generally at depth in the upper fan areas.	Widespread
Unit B: Holocene alluvium – Tararua-sourced (Q1)	Unconfined aquifer, generally high hydraulic conductivity, reworked gravels, strong connection with rivers.	Widespread, associated with main drainage systems
Unit C: Tararua-sourced basin fill alluvium (Q2)	Heterogeneous mixture of predominantly Tararua-sourced alluvium, some persistent water-bearing horizons, low permeability silt/clay lenses of limited lateral extent. Recognised as a single unit. Aquifers: medium-high hydraulic conductivity, gravel rich, discreet, thin (semi) confined units.	Te Ore Ore basin
Unit D: Eastern hill sourced basin fill alluvium (Q2)	Heterogeneous mixture of predominantly eastern hill-sourced alluvium, generally rich in fines but with occasional gravel horizons (possibly Tararua-sourced). Recognised as a single unit. Lower bulk hydraulic conductivity than Q2 – Q8 Tararua basin fill.	Te Ore Ore basin

2.3.4.2 Groundwater abstraction

Groundwater abstraction is primarily due to demand for seasonal pasture irrigation. At the time of initial groundwater model development (2008), the total consented groundwater allocation was about 46,000 m³/day and 8.25×10^6 m³/year. About 85% of the total abstraction occurs on the Te Ore Ore plain and from wells near the Ruamahanga River upgradient of Lansdowne Hill. Annual meter readings between 2002 to 2008 show that water users do not normally exceed 50% of their annual allocation (10 – 30% being the norm). A metering study showed that resource consent holders tend to abstract about 60 – 70% of their consented daily rate. During the 2007/08 irrigation season the metered abstraction was about 27,000 m³/day, or 60% of the allocated daily volume. Historical groundwater abstraction rates for the catchment were modelled using soil moisture deficits to estimate demand periods in conjunction with available annual meter records.

The Opaki and Masterton water supply constitute the major public/community groundwater supplies in the Upper Valley catchment with a currently consented daily take of ca. 1,500 m³/day and 2,000 m³/day, respectively.

3.0 METHODS

3.1 GENERAL CZ DELINEATION METHODOLOGY

The Capture Zone guidelines for New Zealand (Moreau *et al*., 2014a) and the associated Technical Report (Moreau *et al*., 2014b) illustrate various CZ delineation methods that can be applied depending on the data availability and the required accuracy for different project objectives. Since there is no specific policy in New Zealand on CZ delineations, it is up to the "modeller" to determine the most appropriate method, which would best be done in consultation with the regional authority.

In order to illustrate and discuss the various aspects that need to be considered prior to policy decision making regarding CZ delineation, two consultative presentations were held with GWRC during the course of the project. The presentations included issues concerning different delineation techniques, data availability, the mapping of CZs, the dealing with uncertainties such as hydrogeological properties and abstraction patterns, and the dealing with temporal variation and well interference. A further meeting was held to determine the different mapping objectives. The agreements between GNS Science and GWRC were as follows:

- This project only uses numerical techniques – excluded from the project were wells that are located outside the model domains and those that cannot be adequately simulated by the numerical models
- Data availability: included in the project are all community supply wells, regardless of the population they supply; excluded from the project are wells without coordinates; for wells with missing information on well depths and pump rates, assumptions were made
- Specifications of capture zones to be determined: immediate protection zone of 5 m radius, microbial protection zone of 1-year travel time, other time divisions such as 5 and 10 years travel time and the total capture zone (depending on the model simulation time, which ranges from 2 years to 19 years); in the case of detached CZs (i.e. Figure 2), mapping of immediate protection zone, intermediate zone (where restricted conditions might apply) and detached CZ should be undertaken
- Hydrogeological uncertainties: sensitivity analysis to be applied to community supply wells to obtain maximum CZ extent; sensitivity analysis for SOE wells not required unless it is easily obtained; otherwise only application of "best parameter estimates" is required
- Abstraction: consented rates for community supply wells; for unconsented wells (mainly SOE wells) this is set to 20 m^3/day, unless otherwise specified
- Combine CZs in the case of wellfields to take well interference into account
- Emergency wells are treated the same as any other well
- Temporal variations shall be taken into account by evaluating capture zones at different times of the year
- Mapping: separate maps for SOE wells, and community supply wells that supply more than 25 people or more than 500 people. Maps may display the probability of capture based on different thresholds, including maximum capture range, and

protection zones for groundwater travel times of 1-year, 5-years and the total model simulation time. Maps to be used for policy will show populations of 500 people and groundwater travel times of 1-year.

Based on the agreements, CZs have been delineated for a total of 158 wells within the groundwater models, including 99 community supply wells and 67 SOE wells. Their locations and distribution over the model domains are illustrated in Figure 4.

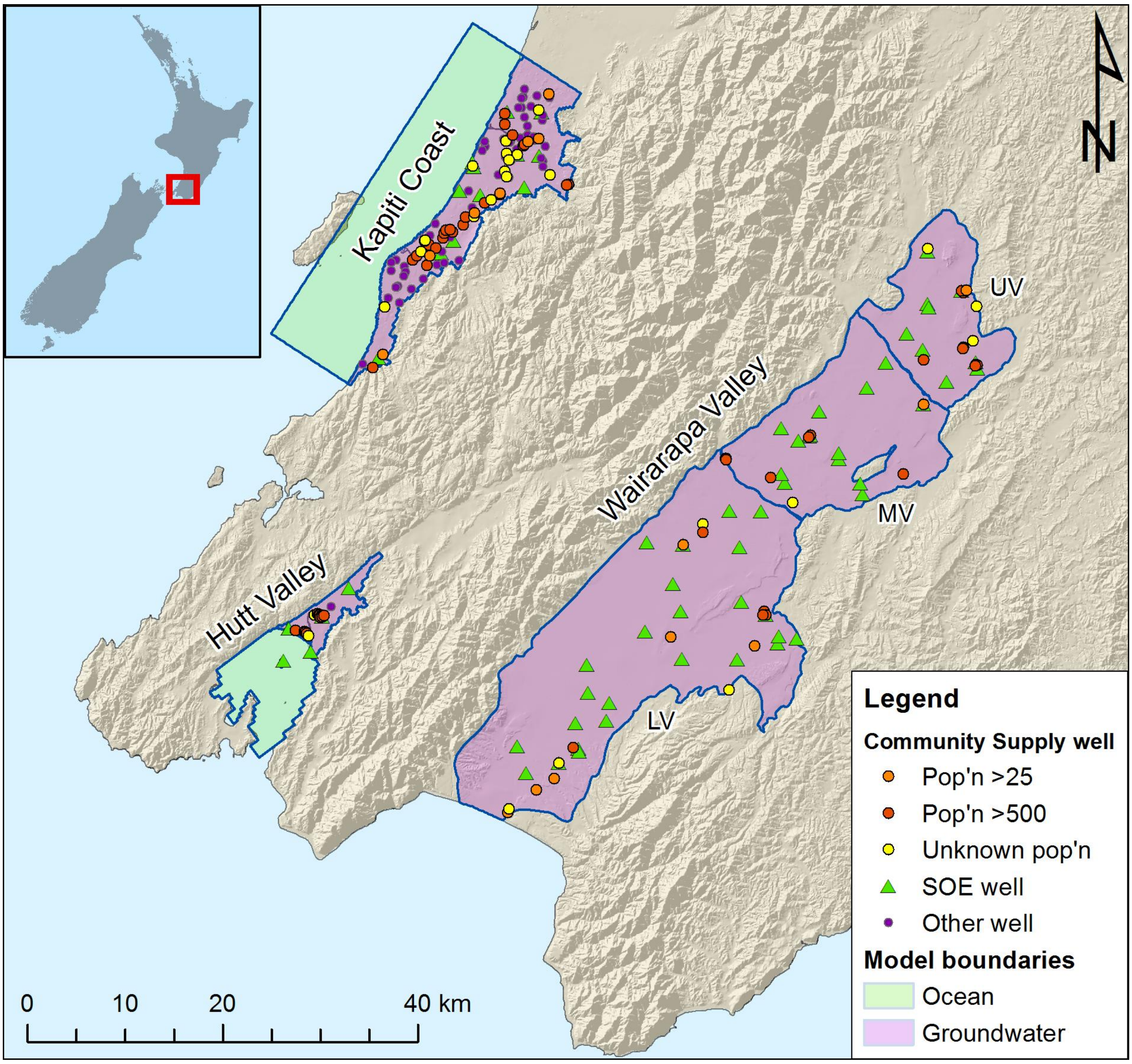

Figure 4: Well locations within the respective model domains: showing community supply wells based on population (pop'n) thresholds, State of the Environment (SOE) wells, and other wells that are not either SOE or community supply wells. Note that some SOE wells are also community supply wells, and have stacked symbols.

3.2 MODELLING TECHNIQUE USED FOR THE CZ DELINEATION

The modelling technique used for the CZ delineation in this project involves pathline/ endpoint generation of particles in a transient flow field. Particle tracking is a commonly used numerical technique to delineate CZs based on an advective or advective-dispersive transport solution of particle flow paths and travel times. Particles can be tracked along with groundwater flow (forward tracking) or in the opposite direction of groundwater flow (reverse tracking). In transient models, particles are tracked for the length of the simulation. This might result in particles that are not captured within the model simulation time. Further details on particle tracking are supplied in Section 3.4.

The particle pathline generation requires different features or post-processing software depending on the numerical code used for the model development. For the MODFLOW models (HAM3 and Kapiti Coast model) the particle tracking post-processing program USGS MODPATH (version 3 and 5) was used. MODPATH requires groundwater flow budget and groundwater head results from MODFLOW (Pollock, 1994).

The modelling technique involves a combination of forward and reverse particle tracking due to the non-uniqueness of particle flow paths. For the forward tracking technique the starting particles were put on the water table (one per cell). This was accomplished using a script that determined each particles position using the model grid definition and hydraulic head data at the release time. Seasonality effects on the CZ extent and travel times have been incorporated by systematically varying particle release times.

For the backward tracking technique, sets of 25 particles were distributed with a horizontal radius of 25 m around each well screen at three vertical locations (top, middle and bottom of the screen; 75 particles in total). This particle configuration was initially arbitrarily defined, then tested to ensure they adequately defined the capture zones. The particle release time was set to the end of the last pumping season.

For the FEFLOW models (Wairarapa models) the delineation of CZs has been accomplished using the random-walk particle tracking feature that is available in FEFLOW version 6.2.

In contrast to advective pathlines generated by MODPATH, the random-walk particle tracking method incorporates diffusion and dispersion, bringing field-line analysis a large step closer to a full advection-dispersion solution by assigning the required additional dispersive parameters: molecular diffusion and coefficients of dispersivity. The advantage of this option is that it does not require the setup of a transport problem, so that preprocessing and computational effort remain comparably low. To visualize the pathlines in a transient flow field the computation requires loading a full simulation record of a transient model. The pathlines were calculated backwards from 100 starting points (seeds) that were distributed with a horizontal radius of 25 m around each well boundary condition node. The release time was set to the end of the last pumping season.

Due to the incorporation of dispersion and the accompanied spreading of pathlines, the backward random walk tracking technique was considered as sufficient. Hence, forward tracking was not supplementary undertaken for FEFLOW models.

3.3 MODIFICATIONS TO THE NUMERICAL MODELS

Modifications to the original models provided by GWRC include the subsequent implementation of abstraction wells, the adjusting of pumping rates and schedules to meet the agreements described in section 3.1 and the systematic variation of input parameters during the sensitivity analysis.

No other modifications to the original models have been undertaken except for the output control of the Kapiti Coast model. Time steps were reduced from 10 to 5 time steps per stress period to reduce computation time and output file size.

HAM3 and Wairarapa models used initial heads that were provided by GWRC with the models for the transient flow simulations. For the Kapiti Coast model an initial head file was generated using the last time step of the first full simulation.

3.3.1 Well Implementation

Since yearly changes apply to abstraction patterns, not all of the wells that were subjects of this project were originally implemented in the numerical models obtained from GWRC. In addition, most of the SOE monitoring bores only represent a minor portion of the total water allocation or were mainly used for monitoring purposes. Hence, water takes from these wells were mostly neglected in the initial model development process. Therefore, a total of 52 community supply wells and 38 SOE monitoring wells had to be subsequently incorporated into the original models.

The well implementation and the adjustment of pumping rates and schedules were generally approached as follows:

- Coordinates, depth information and consented pumping rates were extracted from the GWRC database.
- Coordinates that were only available in one projection were converted into the respective other projection using LINZ online coordinate conversion or other GIS tools. Note: coordinates might differ from other sources due to the use of different conversion methods.
- Depth and screen depth assumptions in case of missing well construction information: 10 m depth below ground elevation (usually first model layer) was used unless otherwise specified, e.g., “confined well”. The screened interval was assigned to the lowest three meters of the well.
- For unconsented abstraction wells (mostly SOE monitoring wells) a pumping rate of 20 m³/day was applied. This value represents the upper limit for groundwater abstraction without the requirement of groundwater consent.
- For consented abstraction wells the maximum consented daily volume was applied. If the consent is restricted to only a certain amount of days per year, the pumping period was applied to the dry period (summer).
- For existing SOE pumping wells, no changes were applied to the pumping rate and schedule.
- For existing community supply wells, the abstraction rates were modified to meet the maximum consented daily rate and schedule.

More detailed and model related specifications are described in the following subsections. A summary of wells is listed in Table 6, showing the number of existing wells and the number of subsequently implemented wells for each model domain. A complete list of the SOE and community supply wells can be found in Appendix 1. CZ delineation was accomplished for 158 wells. There are 8 community supply wells that are also used as SOE monitoring wells.

Table 6: Number of community supply and SOE wells per region (total number, number of existing and subsequently implemented wells). The number in brackets indicates the number of consented wells.

	Hutt Valley model	Kapiti Coast model	Wairarapa Valley			Total
			LV model	MV model	UV model	
Community supply wells	**14**	**45**	**16**	**11**	**13**	**99**
In original model existing	10	26	3	4	4	48
Subsequently implemented	4 (0)	19 (5)	13 (2)	7 (1)	9 (7)	52
SOE wells	**6**	**13**	**25**	**14**	**9**	**67**
In original model existing	2 (1 supply well)	5 (2 supply wells)	15 (1 supply well)	4 (2 supply wells)	3 (1 supply well)	29
Subsequently implemented	4 (0)	8 (0)	10 (2, 1 supply well)	10 (0)	6 (0)	38

3.3.1.1 Pumping scenario Waterloo/Gear Island wellfield (Hutt Valley)

The Waterloo and the Gear Island wells represent the major water supply for the Lower Hutt region and are operated under the same groundwater consent (WGN970036).

Figure 5 shows the metered abstraction of the Waterloo and the Gear Island wells over the 5 year model simulation time. The red line represents the mean daily consented abstraction. As illustrated, the Gear Island wells haven't been much used over the past decade.

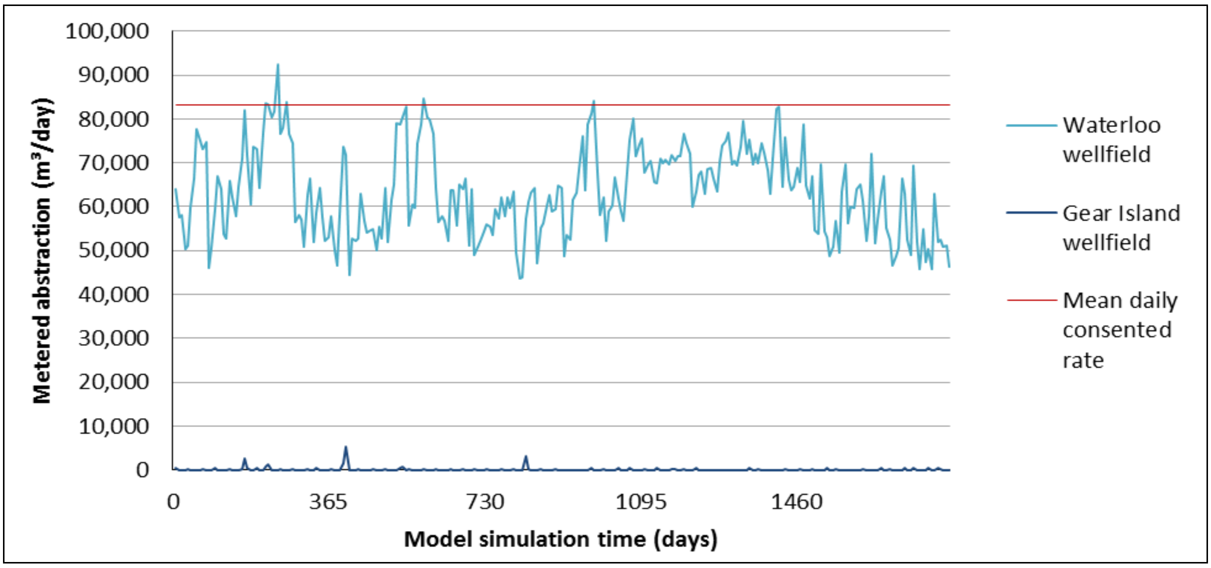

Figure 5: Metered abstraction of the Waterloo and Gear Island wellfield over the simulation period in comparison to the mean daily consented rate over a moving 12-month period (red line). The maximum consented limit (not shown) is 115,000 m^3/d.

In order to achieve realistic CZ extents but also meet the agreements with GWRC to apply the consented rates (as written in section 3.1), two pumping scenarios were applied to the Waterloo and Gear Island wellfield:

1. The mean consented daily rate of 83,115 m³ was equally distributed among the 11 wells. This approach is in accordance with the agreements with GWRC, however, it is most likely expected to result in an overestimation of the CZs of the Gear Island wells and an underestimation of the CZs of the Waterloo wells.

2. Historical measured data as implemented in the original HAM3 was used. For the third Gear Island well, which was subsequently implemented in the model, the same abstraction time series as for the other two Gear Island wells was applied.

3.3.1.2 Pumping scenario Waikanae wellfield (Kapiti Coast)

The water supply for Kapiti Coast's largest urban area – the Waikanae, Paraparaumu and Raumati communities – is based on a run-of-river system on the Waikanae River (CH2M Beca Ltd., 2012). However, this existing water supply is under stress in terms of its capacity to meet the peak water demand in summer. Hence, in dry summer periods, when the river is at low flow, the public water supply is supplemented or entirely provided by groundwater from the Waikanae wellfield through river recharge or emergency public water supply. A running flow of 750 L/s in the Waikanae River is required to be maintained also during summer low flow. Due to the run-of-river system and the supplementary groundwater abstraction, the Kapiti Coast's water supply represents a special case in terms of abstraction patterns.

The Kapiti Water Supply Project shall incorporate a sustainable 50-year water supply solution (out to the year 2060) by adapting well operation to the increasing water demand within four stages (see Table 7). This River Recharge with Groundwater Scheme was developed by CH2M Beca Ltd. (2012). The consent (WGN130103) granted in 2013 out to the year 2048 incorporates the first three stages. The total rate of groundwater abstracted from the wells in the Waikanae wellfield shall not exceed a combined total of 30,700 m³/d and 2,300,000 m³/yr. This corresponds to an abstraction over approximately 75 days per year, but is dependent on recharge conditions during the dry season and is therefore variable.

Note: Stage 4 of the River Recharge with Groundwater Scheme developed by CH2M Beca Ltd. is not incorporated into the project since the granted consent expires in 2048.

The wellfield comprises a total of 12 wells and two backup wells (PW1 and PW5). Only the wells K13, K10, Kb4, K4, K5 and K6 were operating in the past; N2 has been commissioned in 2014; and N3, S1 and S2 are planned to be installed in the future. K13 was decommissioned in 2014 due to poor water quality (CH2M Beca, 2012).

Table 7 lists the maximum instantaneous abstraction rates (based on the maximum yield) from each production well specified for each stage.

Table 7: Maximum instantaneous abstraction rates (L/s) from each production well specified for each stage (CH2M Beca Ltd., 2012). The shaded rows represent wells that were not simulated for capture zone analysis, since they are outside the time range of analysis.

Well no.	Before 2014	Stage 1 2014–2033	Stage 2 2033–2041	Stage 3 2041–2048	Stage 4 2051–2060
K13	58	-	-	-	-
K10	17	36	36	36	36
Kb4	35	35	45	45	45
K4	65	65	80	80	80
K5	36	36	46	46	46
K6	58	58	58	58	58
KB7	-	8	8	8	8
K12	-	10	10	10	10
N2	-	25	25	25	25
N3	-	-	25	25	25
S1	-	-		25	25
S2	-	-			20
Total (L/s)	**269**	**273**	**333**	**358**	**378**
Total (m³/day)	**23,200**	**23,600**	**28,800**	**30,900**	**32,700**

The groundwater abstraction scheme applied within this project complies with the Table 7 represented scheme. Since the Kapiti Coast model simulation time accounts for 19 years, three abstraction scenarios were simulated:

1. The first scenario simulates stage 1 (2014–2033). Abstraction rates were used as listed in Table 7 for the wells K10, KB4, K4, K5, K6, KB7, K12 and N2. In accordance with the consent conditions, the daily peak volume was only abstracted over a 75 day period during summer.

2. A second model simulation represents the pumping scheme of stage 2 and 3 (2033–2048). Pumping rates were increased respective to Table 7 and wells N3 and S1 were commissioned. The daily peak volume was only abstracted over a 75 day period during summer.

3. Since the pumping period of 75 days is variable, a third model simulation was accomplished, which represents stage 1 with pumping rates averaged over a 180 day period. The averaged pumping rates amounted to ca. 50% of the pumping rates used in the first scenario.

3.3.2 Sensitivity Analysis

The uncertainty of hydrogeological input parameters associated with each capture zone was considered by varying values of hydraulic conductivity, specific yield (drainable porosity)/specific storage and river/stream bed conductivity (transfer rate of Cauchy boundary in FEFLOW). The guidelines recommend a range of ±25% around the best parameter estimate (Moreau *et al*., 2014b). The best parameter estimates were established by a PEST calibration during the model development process.

First, the sensitivity analysis was applied to those hydraulic conductivity and specific yield/ specific storage zones that revealed the highest relative sensitivity according to the model calibration as presented in the model reports, or were expected to have a large impact on the CZ extent or travel time.

Secondly, combined sensitivities were analysed by systematically increasing and decreasing all hydraulic conductivity, specific yield (drainable porosity)/specific storage and river/stream bed conductivity values by ±25%. Table 8 lists the accomplished sensitivity analysis for each model.

Table 8: Sensitivity analysis accomplished for each model.

	Most sensitive parameters	K_x, K_y, K_z	S_y or S_s	River / stream bed conductivity	Dispersivity
HAM3	Kx3, Kx5, Kx7, Kz4, Kz6 (also Ss4, Ss3, Sy1)	✓	✓	✓	-
Kapiti model	Kx7, Kz7, Kx8, Kz9	✓	✓	✓ (+15%)*	-
Wairarapa models	-	✓	✓	✓ (transfer rate)	✓

* The stream bed conductivity was increased by only 15% because the model could not converge for higher values

The most sensitive parameters were only tested for the HAM3 and the Kapiti Coast model. Due to the complex hydrogeology in the Wairarapa Valley and the high number of parameters that revealed a strong relative sensitivity, only a combined analysis of parameter sensitivity on the CZ extent and travel times as presented in Table 8 was accomplished.

The sensitivity analysis was applied to both pumping scenarios in the Hutt Valley as described in section 3.3.1. For the Kapiti Coast model, a sensitivity analysis was applied only to Stage 1 pumping from the Waikanae wellfield for 2014–2033. A sensitivity analysis of the other two pumping scenarios (Stage 2 and 3) is considered to be of minor relevance and is beyond the scope of this project.

3.4 MAPPING TECHNIQUES

Groundwater flow was traced between water sources (recharge, streams, etc.) and wells using particle tracking schemes, which simulates the adjective component of groundwater transport. MODPATH models use a postprocessor MODPATH (Pollock, 1994), which is built into the Groundwater Vistas and Visual MODFLOW software used to run the Hutt Valley and Kapiti models, respectively. FEFLOW has built-in particle tracking post-processors, which include a random walk method. CZs can be constructed by drawing around the area where particle pathlines flow to each well.

Table 9 lists the number of simulations that were accomplished for each model scenario by applying different particle release times and by varying input parameters (sensitivity analysis).

Table 9: Number of total simulations for each individual model.

	Hutt Valley		Kapiti Coast			Wairarapa Valley		
	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 3	**LV**	**MV**	**UV**
Forward simulations	34	29	19	1	1	-	-	-
Backward simulations	23	23	9	1	1	9	9	9
Total No. of simulations	**57**	**52**	**28**	**2**	**2**	**9**	**9**	**9**

The varying number of simulations among the models is due to variable computation and post-processing times (0.5 – 6 hours) and the number of input parameters that were changed during the sensitivity analysis.

Also, note that the maximum pathline travel time for forwards or backwards techniques is limited by the simulated duration of each transient model, which is 5 years for HAM3, 19 years for Kapiti Coast, and 15 – 16 years for the Wairarapa models.

3.4.1 Forwards Tracking

The forwards tracking technique is done by using gridded starting particles on the water table, and simulating their pathlines through the aquifer to either a discharge boundary (river reach, drains, sea, springs or pumping wells), or to the position at the end of the simulation. A map can be constructed by classifying the starting locations with the exit location. For instance, the capture zone area for a pumped well can be mapped on the water table by identifying the starting locations of particles that discharged at the specified well boundary location. Discharge points were assigned unique codes that were used to build a raster map of groundwater catchments for each discharge code. A forward tracking simulation and raster map was generated for each sensitivity simulation, which show the surface locations of captured particles by each pumping well of interest.

An advantage of the forwards tracking scheme is that a complete map of the aquifer discharges is made on the water table. Disadvantages of this technique are that particles are placed at locations that do not help identify capture zones for water wells, as they flow to other boundaries; low flow wells do not capture particles (and do not get mapped); and, it does not map the total capture zone shape at depth.

Starting particles were placed on a grid similar to the finite-difference MODFLOW grid. Particles for the Hutt Valley model were on a 100 m regular grid, and particles for the Kapiti Coast mode were on a 125 m regular grid. The FEFLOW models for the Wairarapa Valley do not require a forward tracking technique, since it uses a random-walk backwards tracking technique (see Section 3.1).

For the two MODFLOW models, starting particle locations were determined with a script that loaded the top cell elevations and hydraulic heads. Starting particles were placed in the centre of each grid, with an elevation of the highest head for each row and column, or the top of the grid if the head is above the uppermost active grid.

Result files from each MODPATH run includes an ENDPOINT file, which was archived and processed into a classified raster, where each row and column correspond to the exit boundary condition or pumped well. Further processing of sensitivity runs into a final vector polygon is described later.

Protection zones can be derived from the same result files by reclassifying the codes that are greater than a time threshold as particles still in transit, rather than assigned to an exiting boundary condition. This time threshold was set to 1 year only, as described in the Capture Zone Guidelines for a *microbial protection zone* (Moreau *et al.*, 2014a), or simply a protection zone (PZ).

3.4.2 Backwards Tracking

FEFLOW and MODFLOW use a backwards particle tracing scheme, where particles are placed around each well screen and the pathlines are tracked backwards to a starting location, such as a point on the water table, a source boundary condition (like a stream), or a location within the aquifer at the start of the simulation. This technique traces the full 3-dimensional capture zone shape around the well, which needs to be interpreted with respect to the pathline depth below the water table.

For MODPATH simulations, rings of 25 particles with a radius of 25 m were placed at three elevations around the top, middle and bottom elevations of each pump well screen (75 particles per well). For FEFLOW simulations, a random-walk method was used by selecting the pump well nodes, using a radius of 25 m and 100 particles per node.

Backwards pathline results were loaded into a PostGIS geospatial database for analysis. Here, each particle pathline is a LineString in which each coordinate has at least five dimensions: *x*, *y*, *z*, time, and depth below water table at the time. The first four dimensions are available in results from both MODPATH and FEFLOW (in a Shapefile), however depth below water table was determined by calculating the particle's distance below the highest hydraulic measure at a point at *x*, *y* and time. After loading into a geodatabase, each pathline was classified by the pumped well screen, and by the flow simulation, which allows all of the pathlines to be easily queried for processing into mapped zones.

Backwards pathlines were subdivided into time-limited and depth-limited extents, which can be used to define protection zone and surface capture zones, respectively. With geographic information systems (GIS), 2D representations of pathlines can be displayed on a map as a LineString object. These can be fractionated using a normalised linear referencing system (LRS), where 0 represents the first coordinate at the pumped well, and 1 represents the last coordinate where the particle starts (e.g., recharge on the water table). This is visualised in Figure 6 for a single particle pathline. Any fraction between [0 1] represents the 2D distance along the LineString where other dimensions are linearly interpolated. While the full pathline has LRS subdivision [0 1], time-limited subdivisions are defined between [0 f_t], and depth-limited subdivisions are defined between [f_d 1], where f_t and f_d are the fractions of the pathline LineString that contain the time and depth extents of analysis.

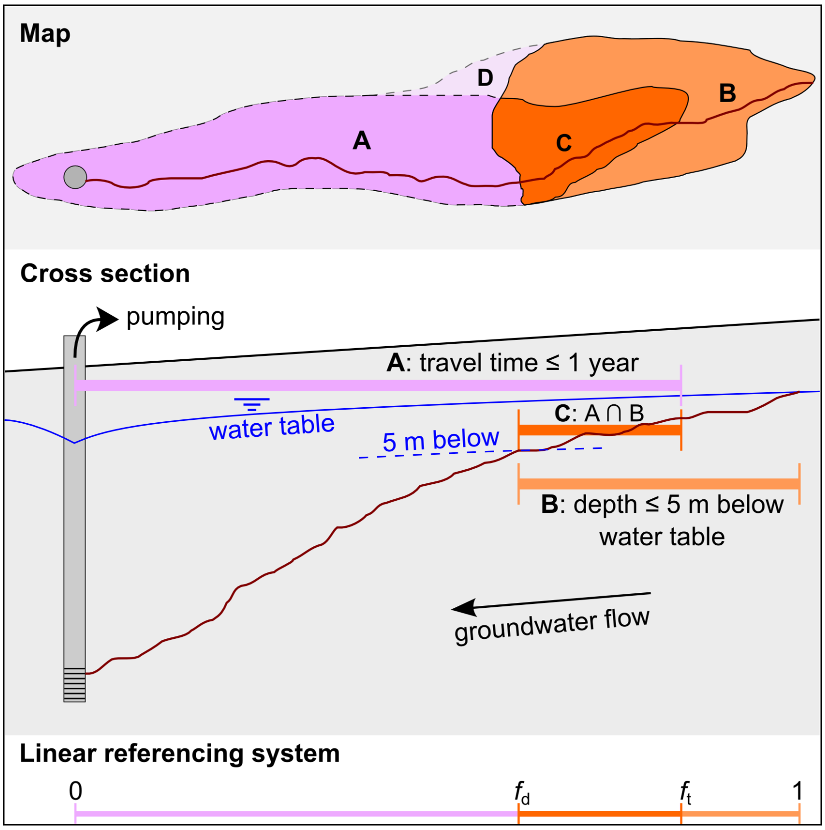

Figure 6: Schematic of a particle, and how it is classified on a map, in cross section, and along a 2D linear referencing system. Region A shows time-limited pathlines (e.g., ≤ 1 year); region B shows shallow or depth-limited pathlines (e.g., ≤ 5 m below water table); region C is derived from the intersection of regions A and B, showing pathlines that are time- and depth-limited, and region D is the remaining region, representing pathlines that have (e.g.,) > 1 year travel time and depth > 5 m below the water table. The four styles of the map view are the same as the maps in the results section. This is a detached CZ (see Figure 2), since the pumped well is disjoint from the shallow CZ.

The LRS subdivision fractions were determined using a linear-interpreted analysis of time and depth below water table dimensions of each particle with respect to the map-project 2D distance from the well.

The time extent used for this study is 1 year, as defined in the guidelines as the microbial protection zone (Moreau *et al*., 2014a), but other time-based protection zones (PZs) could also be determined from the data. Time-limited pathlines show the extent of the PZ from the pump well to either the source or the position in the aquifer that reaches 1 year of travel time, or whichever is sooner. Travel times of 5-years were also evaluated for Kapiti Coast and Wairarapa models, however presenting these results would increase the complexity of viewing the mapped results.

The capture zone guidelines (Moreau *et al*., 2014a) does not consider depth extents of capture zones, so a modification was required to evaluate the extents of capture below the water table, such that it can be split into a shallow and deep CZs using a depth-limited threshold below the water table (Figure 6). A depth-limited threshold below the water table is used to define the depth extent of shallow capture zones, where a smaller depth threshold will result in a smaller shallow CZ extent. Between [0 f_d] the pathline is considered to be part of the deep capture zone, since the pathline remains below the depth threshold until reaching the pumped well. Between [f_d 1] the pathline is part of the shallow capture zone. A capture zone is generally defined to be the areal extent on the surface that contributes to a well's water source; therefore the shallow CZ is equivalent to this definition.

Depth-limited thresholds used for each model were initially arbitrary set at several depth values, and extents of the resulting zones were compared. Capture zones for the Hutt Valley model used a depth threshold of 1 m, since the aquifer is confined. The Wairarapa models use a depth threshold of 10 m, since many of the aquifers are in highly permeable unconfined alluvial aquifers, where a depth boundary on the water table between shallow and deep capture may be more extended. The Kapiti models use a depth threshold of 5 m.

To assess particle tracking results from the sensitivity and pump well configurations, frequency rasters were assembled, which describe pathline counts from each simulation. These counts can be used to trace an outline for each capture zone for either a single well or a group of wells. Frequency rasters for backwards tracking used a fixed 10 m grid size, with extents obtained from the full pathline results from all simulations for each capture zone for a well or wellfield. There are no existing GIS tools that can produce polygons that wrap around collections of lines, so a new methodology was developed. The processing was accomplished with custom Python modules, using GDAL and OGR extensions, which are popular open source libraries used to process raster and vector geospatial data. Other modules used include NumPy and SciPy for raster array processing, and Shapely for other vector processing.

Figure 7 illustrates how a capture zone polygon is generated from backwards-tracking particle tracking for either a single pumped well or a group of wells (e.g., wellfield). Most parameters and thresholds used in the methodology were iteratively defined after countless trials. They produce CZ polygons that consistently trace the outline of pathlines for pumped wells from all model regions, and for all pathline substrings. The intention of this method is to consistently draw zones around a collection of pathlines, which is an improvement over manual tracing of zone boundaries which is slower and subject to interpretation by the draftsperson.

a) Particle pathlines from each sensitivity analysis simulations are queried for the well or group of wells. For either depth-limited or time-limited pathlines, substrings of the full pathlines are processed using predetermined f_d or f_t fractions. These substrings are often shorter on one end than the full pathlines.
b) The vector pathlines are converted to a gridded raster with 10 m resolution. This is accomplished by burning a value of 1 into pixels where one or more lines are traced, and 0 in all other locations. The extents of the raster are established from the extents of all pathline results without any depth or time limited substring processing.
c) Rasterised results from each sensitivity simulation results are accumulated or added to form a frequency raster, which shows the location of counts of where the particles from each simulation are located. For example, with 12 sensitivity runs a location with a count of 6 will indicate that half of the sensitivity runs simulate particles flow past that location. Values of the frequency raster can be normalised (divided by total number of simulations) and evaluated at different statistical thresholds between 0 and 1, but this was not done.
d) The frequency raster is clipped to a maximum of 4, regardless of the total number of simulations. This step is done only because a higher value will yield a larger capture zone area with the subsequent processing steps.
e) A Gaussian blur is performed on the clipped frequency raster, which effectively removes gaps between closely-spaced pathlines. This was performed by processing a full discrete linear convolution of two input rasters, using the fast Fourier transform

method. The first array was formed by padding the clipped frequency raster by a radius of 10 pixels (or 100 m meters) with zero values, and the second array was formed by generating a normalised Gaussian-shaped kernel with a diameter of 21 pixels (or 210 m). The end result is a somewhat blurred raster, where the boundaries between individual pathlines is less distinguishable.

f) The blurred raster result is clipped to select a threshold of a frequency value of 0.25. The evaluated threshold is then polygonised to a vector result to represent the capture zone polygon.

g) The polygon boundary is smoothed using a Douglas–Peucker algorithm.

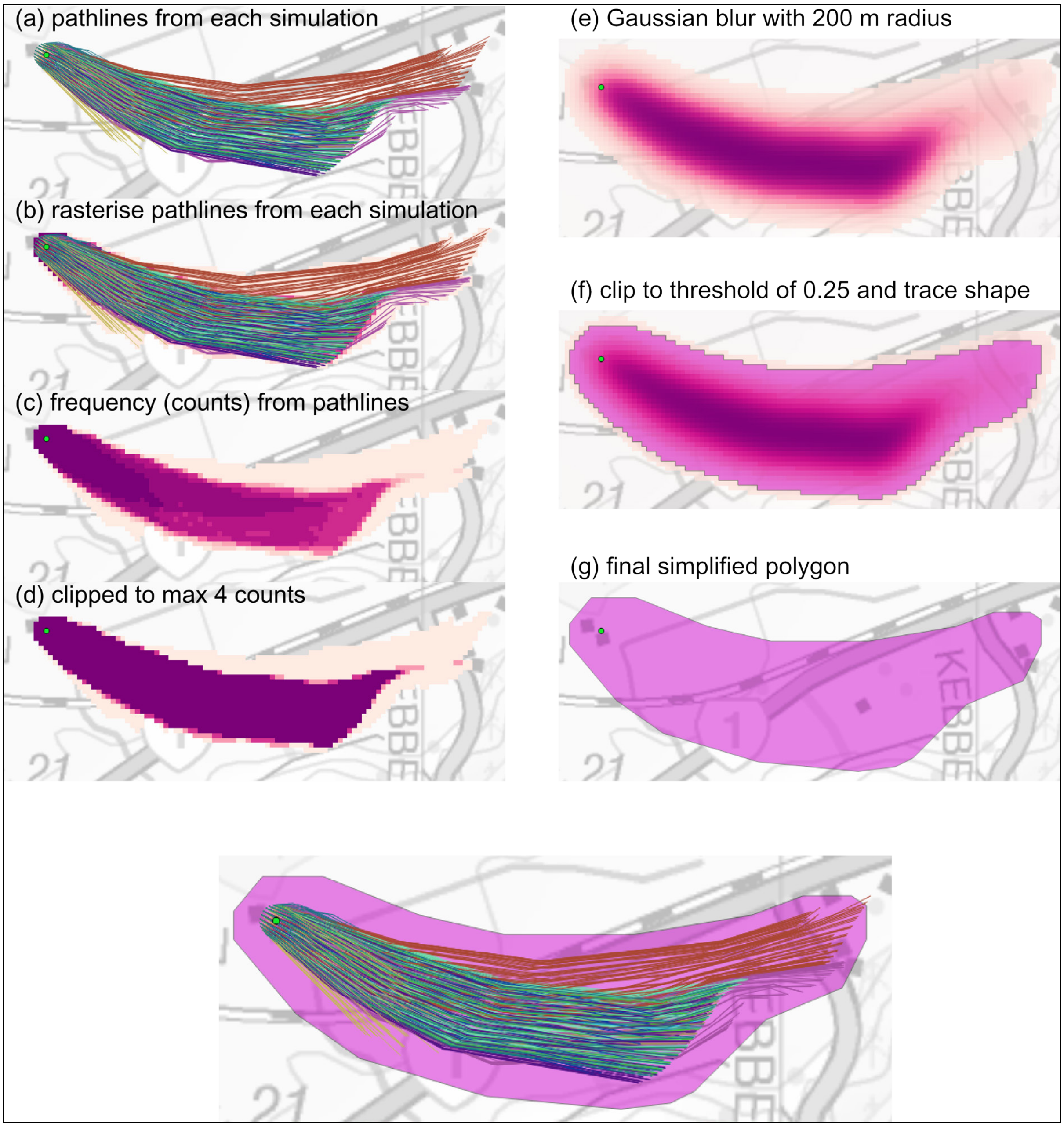

Figure 7: Processing for backwards pathlines to make a capture zone polygon, described in text. Subfigures (a) and (b) show different coloured lines that show pathlines to a pumped well from different sensitivity analysis simulations. Subfigures (c) to (f) show colour shading from light pink to dark purple, which represents a frequency or intensity of values of a raster. The purple polygons in subfigures (f) and (g) show the capture zone polygon.

With the technique described in Figure 7, three sets of polygons were generated from the backwards particle tracking results for (1) the total CZ using all pathlines, (2) for the protection zone using time-limited pathlines, and (3) for the shallow zone using depth-limited pathlines. A shallow protection zone was determined from the latter two polygon results by finding the spatial intersection of the protection zone and shallow zone polygons, as shown in Figure 8. Symbols used for the set theory are described in Table 10.

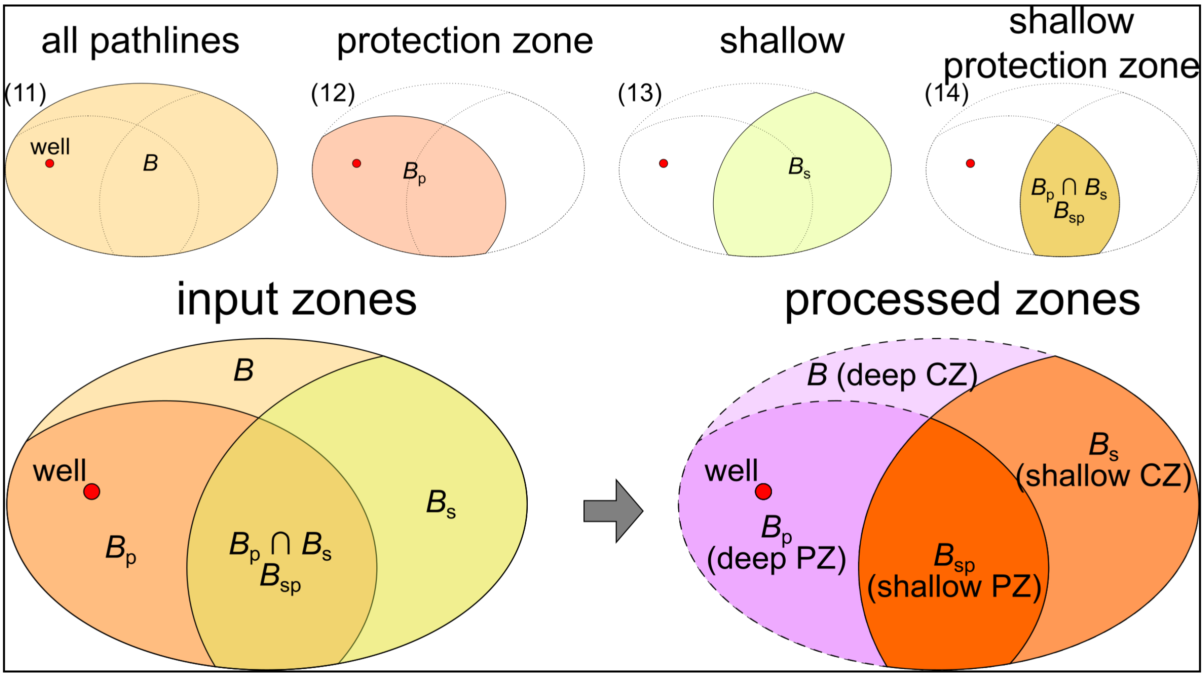

Figure 8: Processing zones from backwards particle tracking results from FEFLOW simulations. Notations used to describe each zone are described in Table 10. In the 'processed zones' subfigure, the four names (in parentheses) and styles are the same as used for maps in the results section.

Table 10: Notation used to describe zones in Figure 8 and Figure 9.

	Symbol	Description
Operator	∪	union, showing combinations of each set
	∩	intersection, showing common area where both sets exist
Set	*B*	backwards particle sets
	F	forwards particle sets
	C	union of forwards and backwards sets into a combined set
Subset in subscript	s	shallow, as defined by a depth threshold below water table; applies only to backwards particles
	p	protection zone, as defined by a travel time of 1 year or less to the well
	sp	intersection of shallow and protection zone subsets

3.4.3 Combining Forwards and Backwards Results

Forwards and backwards MODPATH simulations were combined by processing the polygons determined from each particle direction result sets. The backwards particle set processing is the same as described in the previous section. Protection zone and shallow subsets were independently determined for forwards and backwards sets, and then combined through spatial union to produce four processed zones. This processing is illustrated in Figure 9.

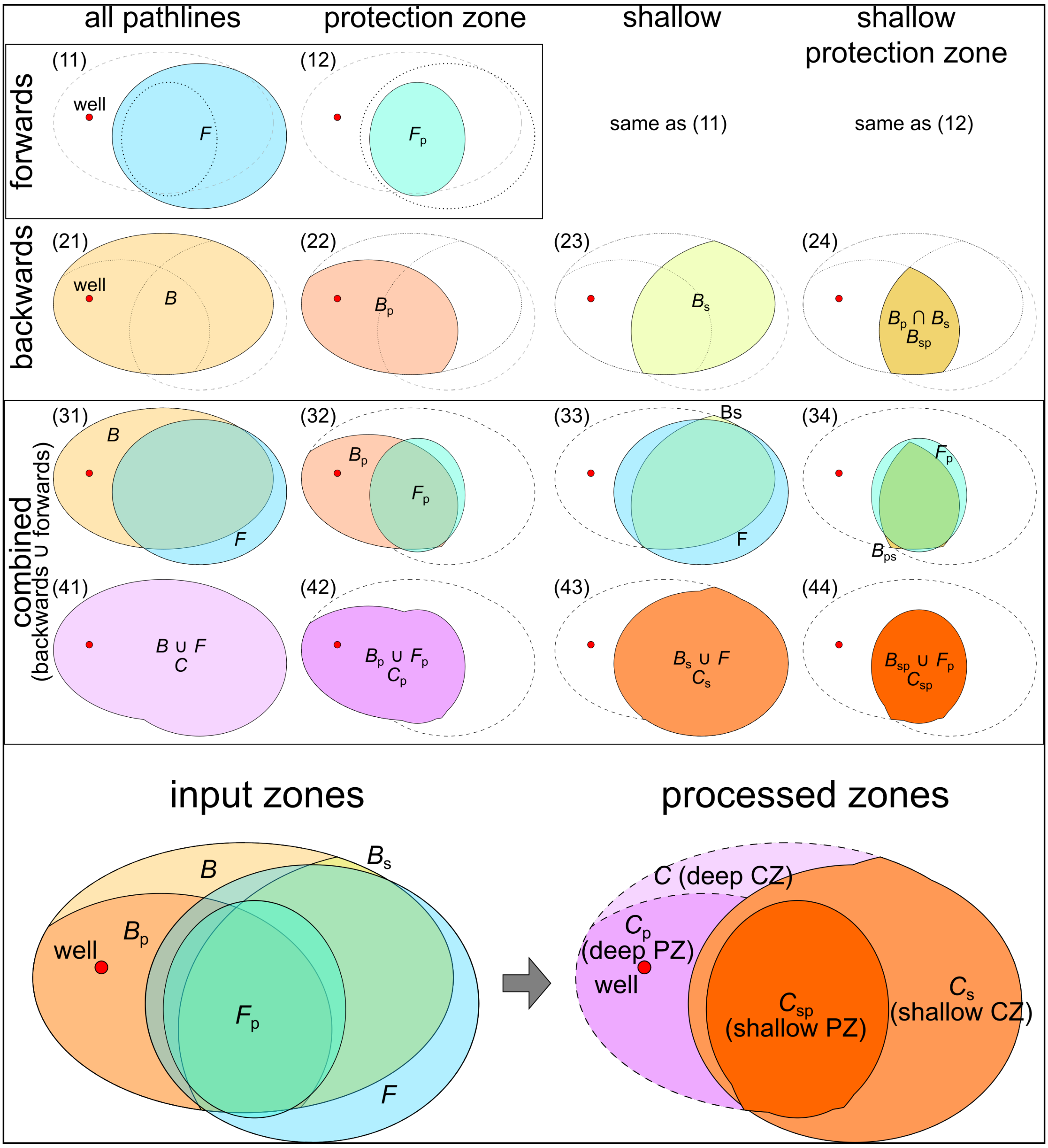

Figure 9: Processing zones from combining forwards and backwards particle tracking results from MODPATH. The matrix of subfigures is indexed using parenthesis (row col). Notations used to describe each zone are described in Table 10. In the 'processed zones' subfigure, the four names (in parentheses) and styles are the same as used for maps in the results section. Note that the upper figures show the derivation of zones, and that only the "processed zone" figure is a representation of the final mapped zones shown in the Results section of this report.

4.0 RESULTS

Mapped zones were determined for all pumped wells in each model, and their extent are summarised in Tables 11 – 15, and shown in Figures 10 – 17. The maps show the same three regions, and present views of the individual and combined zones to wells or groups of wells that are of interest for different purposes or end-users. Mapped zones for individual wells (Figures 10, 12, 16, 17) are often stacked, since some nearby wells have similar zones. Combined zones for groups of wells (Figures 11, 14 – 16) do not show individual zone boundaries for each well, and are most useful for showing results for groups, such as community supply wells for informing policy.

The maps show four styles of polygons. Mapped *capture zones* (CZs) represent the 2D area where groundwater flows to a well, at any depth (deep and shallow). Mapped *protection zones* (PZs) are similar to CZs, except that they represent groundwater flow to a well with a travel time of 1 year or less. As a result, a PZ is often smaller than a CZ. The distinction between *deep* and *shallow* zones is important for interpretation of the mapped zones. *Shallow zones* represent the area on the land surface or near the water table that may flow towards a well. *Deep zones* are the remaining area, below the water table, where groundwater flows towards a well. For these regions, water on the surface does not flow into the well, however, fluid from injection wells below the water table may flow into the well.

The first result map (Figure 10) shows individual zones for all wells processed. Community supply wells have been split into population groups estimated by ESR and provided by GWRC. Some community supply wells have no population estimates, and remain unknown. Maps are shown for all community supply wells (including unknown population estimates) as combined zones (Figure 11), for individual wells (Figure 12), combined zones for populations of 25 or more (Figure 13), and combined zones for populations of 500 or more (Figure 14). Combined zones were also mapped for community supply wells (Figure 15) that were specifically listed in Schedule M2 of the Draft Natural Resources Plan (GWRC, 2014), and the labels are also the same as listed in the Draft Plan, which may be different than named elsewhere in this report. Individual zones are shown for SOE wells (Figure 16). Remaining zones that were processed from a model, but are neither a community supply or SOE well are shown in Figure 17. Note that some wells are shown in multiple figures, for instance wells that are both a community supply well and SOE monitoring well.

Figures 10 – 17 show each of the three regions, which are individually rotated and scaled to best fit in the figure. Groundwater model boundaries are shown from the numerical model for each region, which are the limits of where groundwater can be simulated. The “Ocean” boundary for Hutt Valley and Kapiti Coast models consists of constant head boundaries on the top layer, and normal groundwater flow for deeper layers. The black and white base map shown is the LINZ 1:250k topographic map.

Summaries in Tables 11 – 15 show which wells were included in the analysis, and other attributes to help identify which figure they are represented in. The area columns are a summary of the mapped area of each zone, rounded to the nearest 0.001 km² or 0.1 ha. The total CZ is always the largest area, since other zones are subsets of the total. The total PZ similarly represents protection zone polygons for all depths, and is always larger than the shallow PZ. Where blank, the zone was not identified. For instance, some deeper wells with slow moving water do not have a shallow CZ, since the simulation time of the model is not long enough to simulate the flow of these pathlines.

Results that are not shown include zones for different depth thresholds that define shallow, and zones for different travel times that define PZs, such as 5 year travel times. These combinations of results are not shown as they would either increase the complexity of the maps, or would require additional figures to present the data.

Table 11: Summary of capture and protection zone analysis for Hutt Valley.

Well name (policy name, if different)	**In policy**	**Community supply population**	**SOE**	**Area (km²)**			
				Total CZ	**Total PZ**	**Shallow CZ**	**Shallow PZ**
Bloomfield (R27/1177)	Y	>500		3.526	3.219	0.494	0.484
Buick Street (R27/1138)	Y	>500		4.557	3.677	0.783	0.677
Colin Gr (R27/4064)	Y	>500		4.57	4.170	1.019	0.938
Gear 1 (BQ32/0033)	Y	>500		6.146	5.594	0.600	0.588
Gear 2 (BQ32/0034)	Y	>500		19.127	15.81	3.505	2.997
Gear 3 (BQ32/0035)	Y	>500		17.680	17.518	6.240	6.165
Hautana (R27/0001)	Y	>500		4.298	3.525	1.524	1.340
Hospital				3.991	3.986	3.313	3.216
Hutt City Council		unknown		3.197	3.195	0.402	0.400
IBM 1			Y	0.310	0.069		
IBM 2			Y	3.534	2.975	1.112	0.902
Mahoe 6 (R27/1181)	Y	>500		4.365	4.166	1.492	1.470
Penrose 4 (R27/1179)	Y	>500		4.190	3.813	1.730	1.670
Penrose 7 (R27/4057)	Y	>500		11.750	11.376	7.304	6.819
Petone Pure Water		unknown		10.056	9.333	1.368	1.359
Somes			Y	6.890	0.236	0.734	
R27/1182			Y	9.444	5.169	0.638	0.259
Avalon			Y	1.128	1.125	0.166	0.164
Unilever				12.753	12.160	2.188	2.141
Willoughby 5 (R27/1180)	Y	>500		4.753	4.554	1.774	1.766
Willoughby 8 (R27/4058)	Y	>500	Y	6.132	6.105	4.269	4.253

Table 12: Summary of capture and protection zone analysis for Kapiti Coast. Note that two community supply wells (K13 and S2) were not analysed, and no zones are shown in the maps.

Well name (policy name, if different)	**In policy**	**Community supply population**	**SOE**	**Area (km²)**			
				Total CZ	**Total PZ**	**Shallow CZ**	**Shallow PZ**
5132.00				0.291	0.021	0.157	
K4 (R26/6291)	Y	>500		0.827	0.084		
K5 (R26/6293)	Y	>500		0.538	0.031		
K6 (R26/6839)	Y	>500		0.462	0.065		
K10 (R26/6804)	Y	>500		0.288	0.026		
K12 (R26/6299)	Y	>500		0.319	0.041		
K13		>500		Not analysed: decommissioned in 2014			
KB4 (R26/6307)	Y	>500		0.648	0.074	0.021	
KB7 (R26/6311)	Y	>500		0.239	0.027		
N2 (R26/7255)	Y	>500		0.357	0.045		
N3		>500		0.150	0.017		
PW1 (R26/6559)	Y	>500		0.207	0.031		
PW5 (R26/6666)	Y	>500		0.509	0.051		
R25/5058				0.160	0.023		
R25/5078				0.790	0.047	0.349	
R25/5100			Y	0.225	0.023		
R25/5109		unknown		0.041	0.036	0.041	0.035
R25/5121				0.100	0.051		
R25/5129				0.460	0.044	0.169	
R25/5135		unknown	Y	0.598	0.044	0.091	
R25/5148				0.331	0.027	0.226	
R25/5153				0.490	0.026	0.052	
R25/5156				0.353	0.030		
R25/5164			Y	0.037	0.017	0.034	0.014
R25/5165			Y	0.030	0.012	0.030	0.012
R25/5168				0.273	0.029	0.170	
R25/5190			Y	0.027	0.019	0.027	0.018
R25/5208		unknown		0.590	0.046		
R25/5220		>500		0.808	0.224	0.808	0.223
R25/5228	Y	>500		2.923	0.103	0.674	
R25/5233			Y	2.186	0.188	0.572	

Well name (policy name, if different)	In policy	Community supply population	SOE	Area (km²)			
				Total CZ	Total PZ	Shallow CZ	Shallow PZ
R25/5235	Y	>500		4.874	0.076	3.559	
R25/5242				0.218	0.041		
R25/5245				0.527	0.107	0.439	0.023
R25/5246		unknown		1.073	0.126		
R25/5258				0.533	0.155	0.291	0.041
R25/5262				0.091	0.018		
R25/5264				0.132	0.019		
R25/7075				0.111	0.020		
R25/7085		unknown		0.038	0.014	0.038	0.014
R26/0009				0.017	0.014	0.017	0.014
R26/5057				0.174	0.020		
R26/6248				0.061	0.013		
R26/6503			Y	0.063	0.018	0.060	0.015
R26/6512				0.041	0.012		
R26/6516				0.039	0.014		
R26/6521				0.054	0.014		
R26/6529				0.035	0.012		
R26/6541				0.069	0.018		
R26/6549				0.068	0.017		
R26/6557				0.097	0.017		
R26/6563				0.104	0.018		
R26/6565				0.053	0.016		
R26/6585				0.056	0.025	0.006	
R26/6587			Y	0.054	0.018	0.047	0.012
R26/6624			Y	0.059	0.018	0.056	0.016
R26/6674				0.05	0.027	0.047	0.024
R26/6676				0.093	0.018		
R26/6749				0.161	0.016		
R26/6799				0.260	0.030	0.243	0.016
R26/6835				0.029	0.022	0.020	0.015
R26/6895				0.293	0.020	0.081	
R26/6964				0.041	0.018	0.038	0.016

Well name (policy name, if different)	In policy	Community supply population	SOE	Area (km²)			
				Total CZ	Total PZ	Shallow CZ	Shallow PZ
R26/6965				0.045	0.015	0.03	
R26/6966				0.021	0.011	0.019	0.011
R26/7044		unknown		0.059	0.026	0.051	0.022
R26/7134				0.531	0.108	0.531	0.108
R26/7135				0.531	0.108	0.531	0.108
R26/7156				0.068	0.016	0.049	0.003
R26/7158	Y	>500		0.539	0.117	0.539	0.115
R26/7252		unknown		0.128	0.026		
S1		>500		0.174	0.015		
S2		>500		Not analysed: part of Stage 4, CH2M Beca scheme			
S25/5114				0.516	0.044		
S25/5115				1.817	0.249	1.336	
S25/5116				0.898	0.018	0.587	
S25/5125			Y	0.962	0.364	0.848	0.255
S25/5200			Y	0.091	0.03	0.028	
S25/5220				0.822	0.274	0.019	
S25/5227				1.259	0.026	0.006	
S25/5247				1.501	0.267	0.313	
S25/5249?				0.622	0.133	0.622	0.132
S25/5256		unknown	Y	0.416	0.034	0.283	
S25/5285				1.180	0.056		
S25/5287				1.347	0.026	0.003	
S25/5293				0.697	0.283	0.697	0.279
S25/5299				2.346	0.131	1.155	0.131
S25/5300				0.180	0.025	0.173	0.018
S25/5314				0.439	0.038	0.439	0.038
S25/5319				0.795	0.05	0.162	
S25/5322			Y	1.008	0.043	0.818	
S25/5328		unknown		1.083	0.104	0.112	
S25/5329				2.357	0.232	0.998	
S25/5330				2.745	0.295	0.269	
S25/5344				0.356	0.046	0.116	

Well name (policy name, if different)	In policy	Community supply population	SOE	Area (km²)			
				Total CZ	Total PZ	Shallow CZ	Shallow PZ
S25/5345				0.572	0.300	0.572	0.298
S25/5372				0.255	0.027	0.114	
S25/5376				0.040	0.021	0.040	0.020
S25/5379	Y	>500		0.024	0.020	0.023	0.019
S25/5390		unknown		0.506	0.016		
S25/5399				0.221	0.023		
S25/5402				0.877	0.041	0.406	
S25/5414				0.158	0.020	0.065	
S25/5443	Y	>500		0.049	0.040	0.049	0.040
SW11		>25		0.023	0.018	0.023	0.018
SW21		>25		0.023	0.017	0.023	0.017
SW22		unknown		0.079	0.015	0.079	0.014
SW23		unknown		0.080	0.029	0.081	0.028
SW27		>25		1.404	0.027	0.011	
SW31		unknown		0.023	0.021	0.023	0.021
SW38		>25		0.059	0.037	0.059	0.036
SW44		unknown		0.141	0.043	0.138	0.038
SW46		unknown		0.088	0.021	0.085	0.021
SW6		>25		0.428	0.116	0.229	
SW7		>25		0.997	0.292	0.923	0.234
SW8		>25		0.031	0.021	0.031	0.021
SW9		>25		0.031	0.021	0.031	0.021
UNK_1		>500		1.309	0.364	1.309	0.358
UNK_3		>500		0.995	0.389	0.995	0.385
UNK_4				1.007	0.033	0.607	
UNK_5				0.221	0.026	0.187	0.001

Table 13: Summary of capture and protection zone analysis for the Lower Wairarapa Valley model.

Well name	In policy	Community supply population	SOE	Area (km²)			
				Total CZ	Total PZ	Shallow CZ	Shallow PZ
R28/0001		>25		9.623	7.682	6.637	5.035
R28/0022		unknown		4.909	3.52	4.905	3.518
S27/0009			Y	12.977	12.253	12.968	12.246
S27/0035		>25		3.365	2.489	3.361	2.486
S27/0038		unknown		0.597	0.596	0.596	0.596
S27/0049		>500		6.529	5.702	5.804	5.039
S27/0070			Y	3.807	2.617	3.791	2.608
S27/0136			Y	1.803	1.277	1.695	1.193
S27/0156			Y	3.257	2.761	2.667	2.234
S27/0202			Y	3.055	2.182	3.046	2.178
S27/0268			Y	7.229	5.179	1.931	1.152
S27/0283			Y	42.253	33.282	34.022	25.833
S27/0291		>25		54.366	2.489	15.272	0.683
S27/0299			Y	9.332	8.352	6.917	6.027
S27/0344			Y	4.804	4.78	4.742	4.72
S27/0389			Y	18.809	10.238	18.728	10.169
S27/0396	Y	>500	Y	0.921	0.913	0.887	0.884
S27/0404	Y	>500		1.089	1.088	1.015	1.014
S27/0433			Y	60.744	43.106	5.371	3.686
S27/0435			Y	58.368	52.819	8.062	7.691
S27/0442			Y	27.134	20.285	2.4	1.454
S27/0495			Y	49.251	47.708	34.468	33.259
S27/0522			Y	23.843	15.019	23.122	14.334
S27/0571			Y	14.151	10.103	13.808	9.787
S27/0585			Y	6.94	4.546	2.128	1.531
S27/0588		unknown	Y	0.49	0.479	0.485	0.475
S27/0594			Y	3.185	2.658	1.955	1.819
S27/0602			Y	95.789	74.315	9.975	7.49
S27/0607			Y	4.597	4.166	2.101	1.869
S27/0614			Y	3.108	3.057	1.844	1.814
S27/0615			Y	3.372	2.836	3.366	2.834
S27/0616		>500		1.675	1.148	1.674	1.147
S27/0681			Y	4.954	4.888	4.939	4.875
S27/0695	Y	>500		0.867	0.863	0.852	0.848
S27/0910	Y	>500		0.934	0.934	0.934	0.934
SW163		>25		18.804	13.56	18.618	13.497
SW166		>25		1.507	1.5	1.47	1.463
SW193		>25		2.901	0.388	2.53	0.377
SW199		unknown		0.792	0.789	0.782	0.78

Table 14: Summary of capture and protection zone analysis for the Middle Wairarapa Valley model.

Well name (policy name, if different)	**In policy**	**Community supply population**	**SOE**	**Area (km²)**			
				Total CZ	**Total PZ**	**Shallow CZ**	**Shallow PZ**
BP33/0006 or BP33/0022 (BP33/0022)	Y	>500		0.219	0.21	0.219	0.21
BP33/0008	Y	>500		0.207	0.189	0.202	0.187
BP33/0009	Y	>500		0.225	0.203	0.223	0.203
S26/0117			Y	6.775	1.305	6.768	1.304
S26/0223			Y	3.853	0.936	3.850	0.935
S26/0299			Y	3.825	3.591	3.819	3.589
S26/0439			Y	0.800	0.695	0.794	0.689
S26/0457			Y	2.529	0.814	2.524	0.810
S26/0467			Y	9.239	2.853	9.232	2.850
S26/0568			Y	11.022	0.498	9.232	0.010
S26/0576			Y	23.761	1.495	23.615	1.363
S26/0705	Y	>500	Y	14.909	0.639	14.001	0.556
S26/0756			Y	30.615	0.437	30.586	0.428
S26/0762			Y	4.421	0.296	4.417	0.295
S26/0824	Y	>500	Y	18.964	3.150	18.957	3.144
S26/0846			Y	5.486	0.673	4.709	0.430
S26/0880	Y	>500		4.364	1.974	4.358	1.971
S26/0918		>500		20.395	0.464	15.511	0.319
S26/0919	Y	>500		20.573	3.164	20.564	3.162
S27/0714		unknown		4.143	1.971	4.141	1.969
SW158		>500		18.321	1.382	18.312	1.377
SW159		>25		5.357	2.031	5.347	2.023
T26/0332			Y	5.474	1.855	5.435	1.839

Table 15: Summary of capture and protection zone analysis for the Upper Wairarapa Valley model.

Well name	In policy	Community supply population	SOE	Area (km²)			
				Total CZ	Total PZ	Shallow CZ	Shallow PZ
BP34/0044		unknown		0.782	0.058	0.780	0.057
SW145		>25		8.074	3.152	8.061	3.143
T26/0003			Y	0.522	0.055	0.521	0.055
T26/0087			Y	2.022	0.284	1.722	0.197
T26/0099			Y	1.940	0.587	1.850	0.546
T26/0206			Y	1.877	0.411	1.784	0.366
T26/0243	Y	>500		4.123	0.548	3.945	0.404
T26/0255		>25		1.335	0.208	1.328	0.206
T26/0257		>25		2.028	0.190	2.025	0.188
T26/0259	Y	>500	Y	1.982	0.224	1.974	0.224
T26/0265		unknown		3.513	0.467	3.510	0.466
T26/0277		>25		1.479	0.192	1.476	0.192
T26/0284		unknown		0.982	0.368	0.980	0.367
T26/0413			Y	19.683	5.927	18.209	4.491
T26/0430			Y	1.714	0.343	1.712	0.341
T26/0489			Y	6.058	2.459	4.890	1.311
T26/0492	Y	>500		8.973	4.037	8.021	3.094
T26/0493	Y	>500		7.065	3.254	6.007	2.206
T26/0538			Y	7.503	7.079	7.496	7.076
T26/0549	Y	>500		3.870	0.802	3.568	0.540
T26/0696		>500		2.743	0.341	2.738	0.336

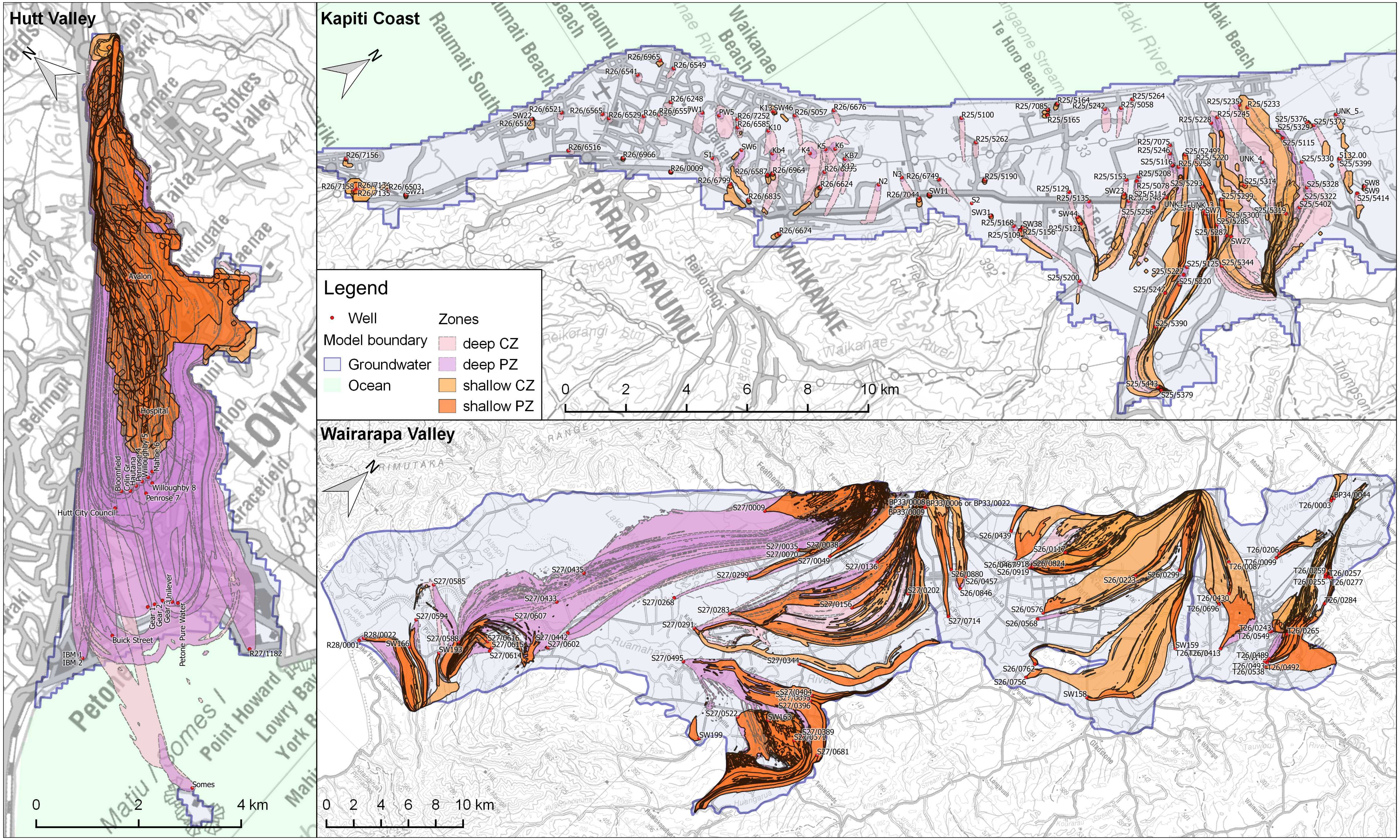

Figure 10: Individual zones for all wells.

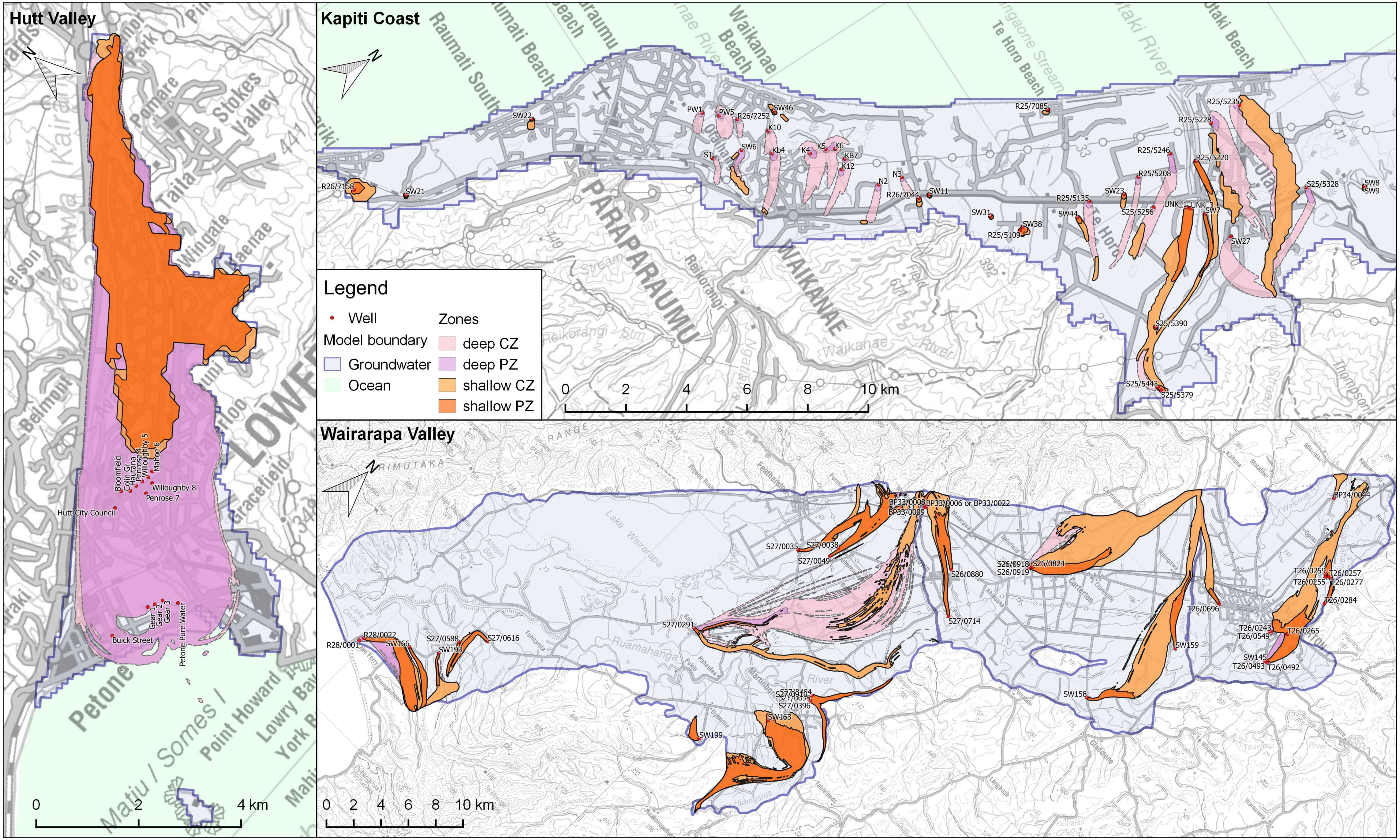

Figure 11: Combined zones to community supply wells.

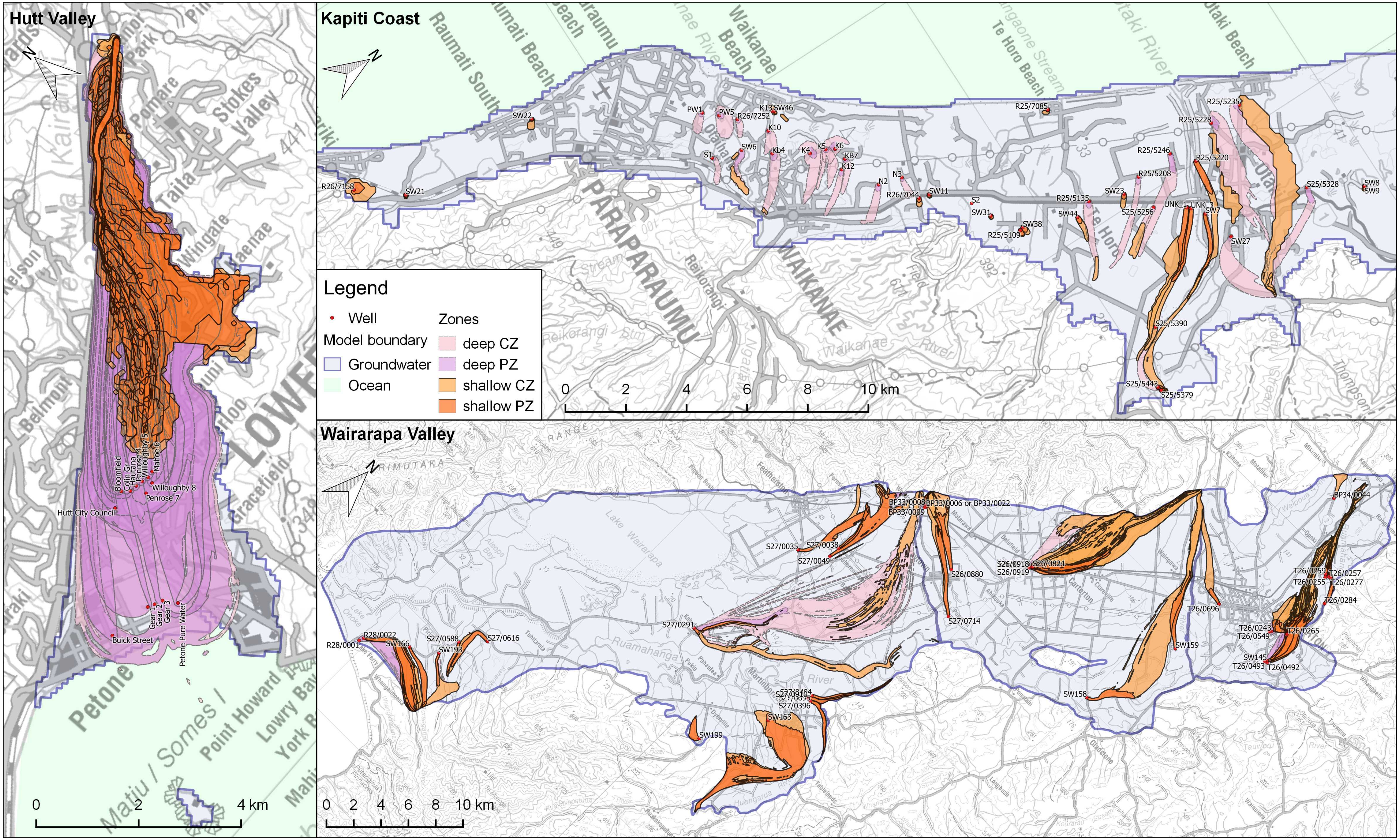

Figure 12: Individual zones to community supply wells.

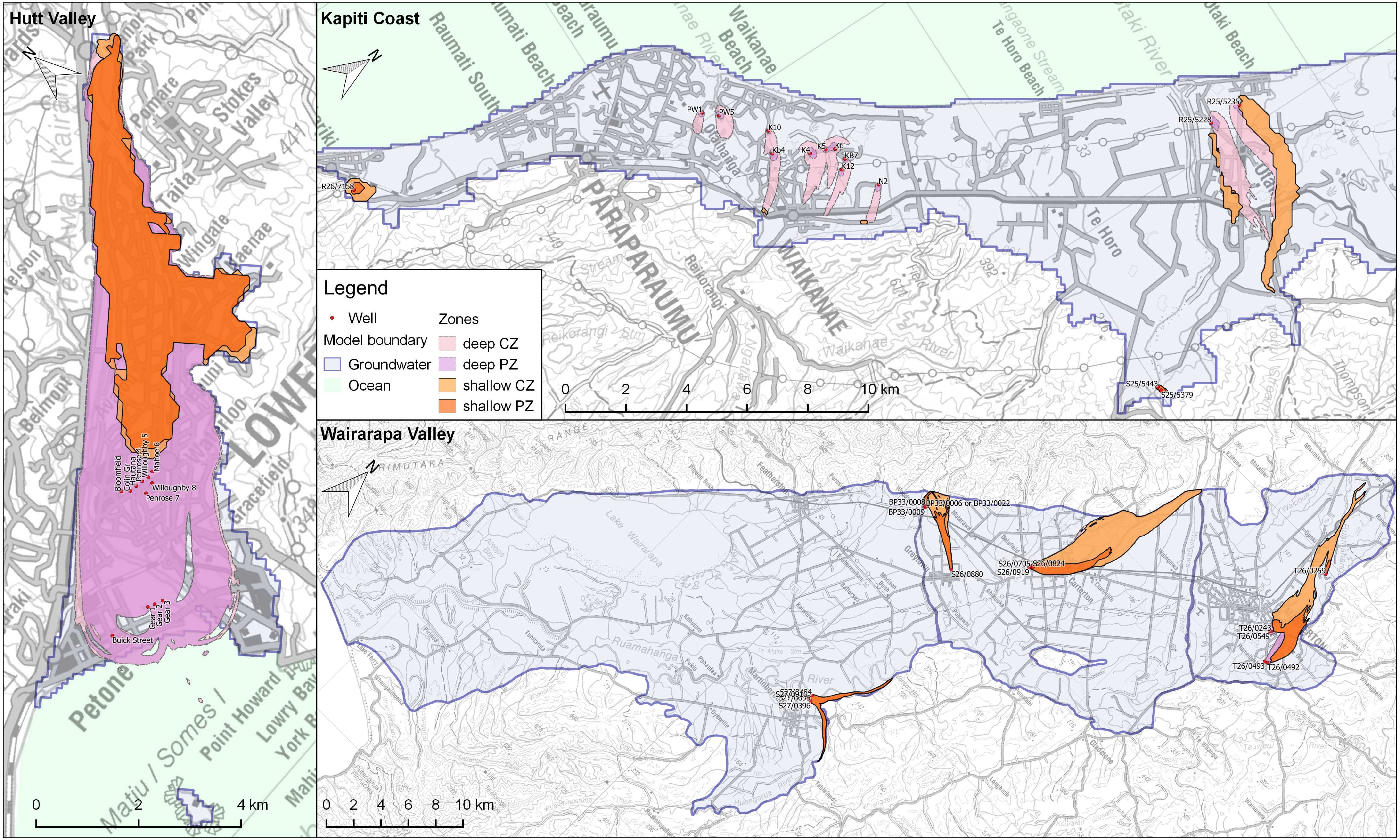

Figure 13: Combined zones for community supply wells defined by GWRC draft policy (GWRC, 2014). Note that well names shown in this figure only are also the same as in policy, and may be displayed differently in other figures.

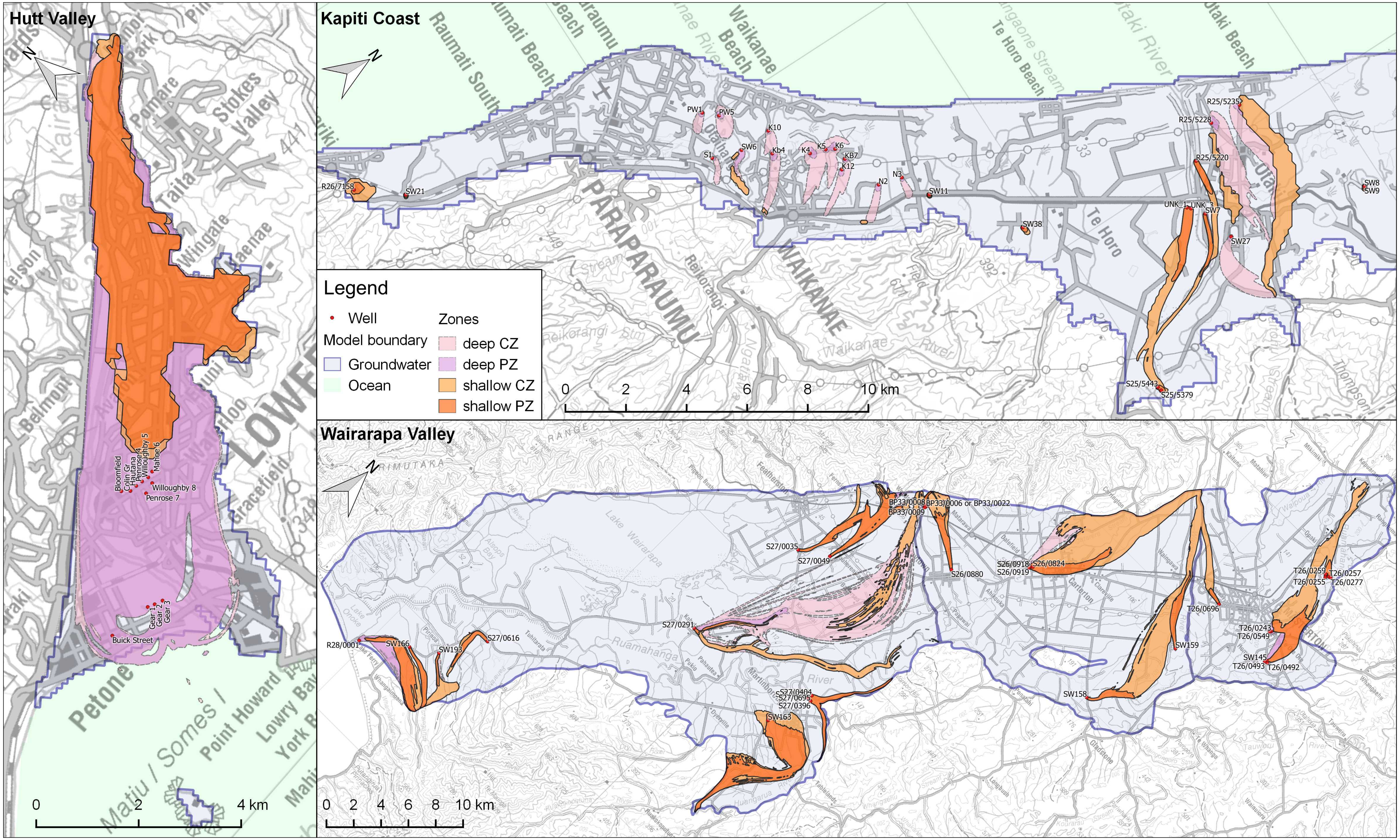

Figure 14: Combined zones for community supply wells with a population of at least 25 people.

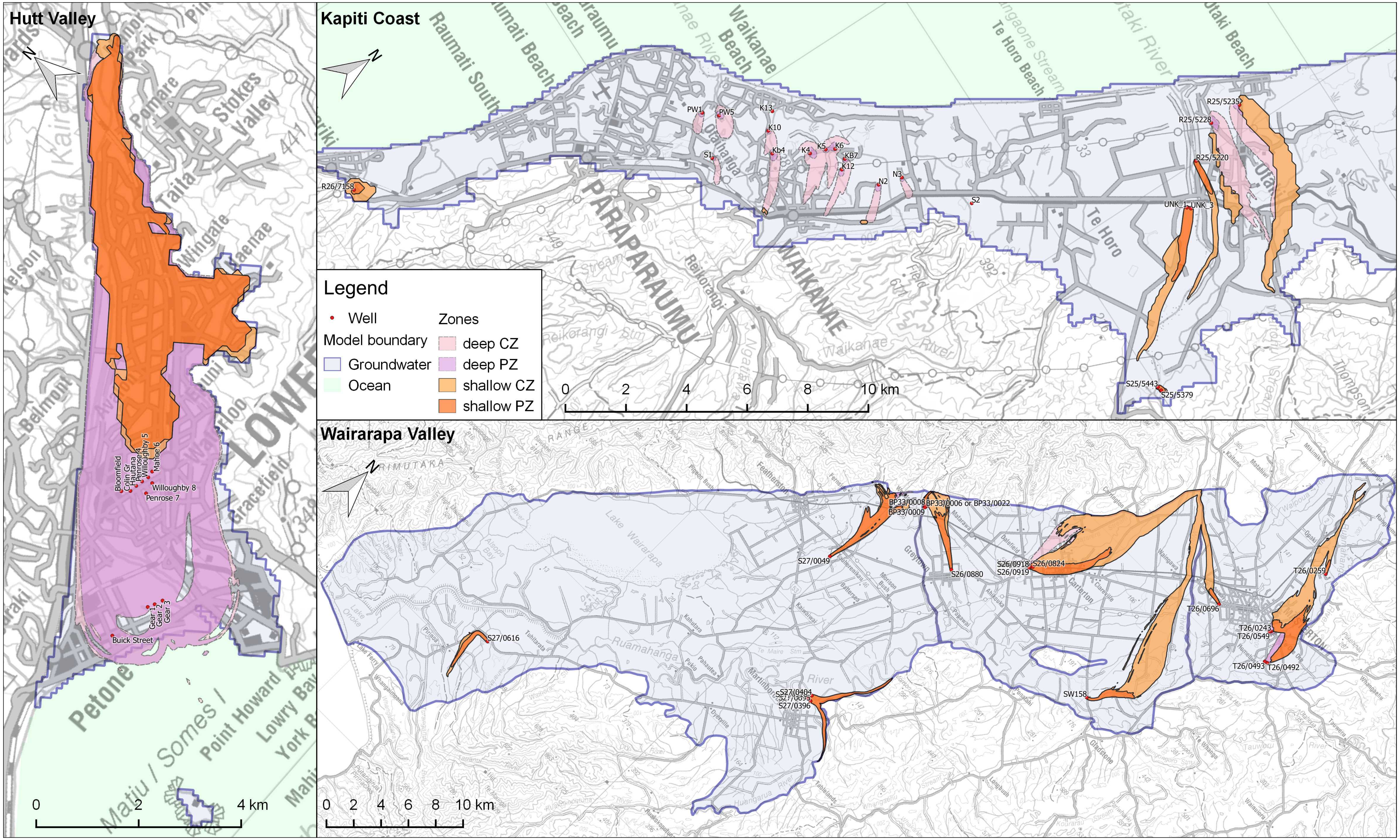

Figure 15: Combined zones for community supply wells with a population greater than 500 people. These mapped zones are intended for capture zone policy.

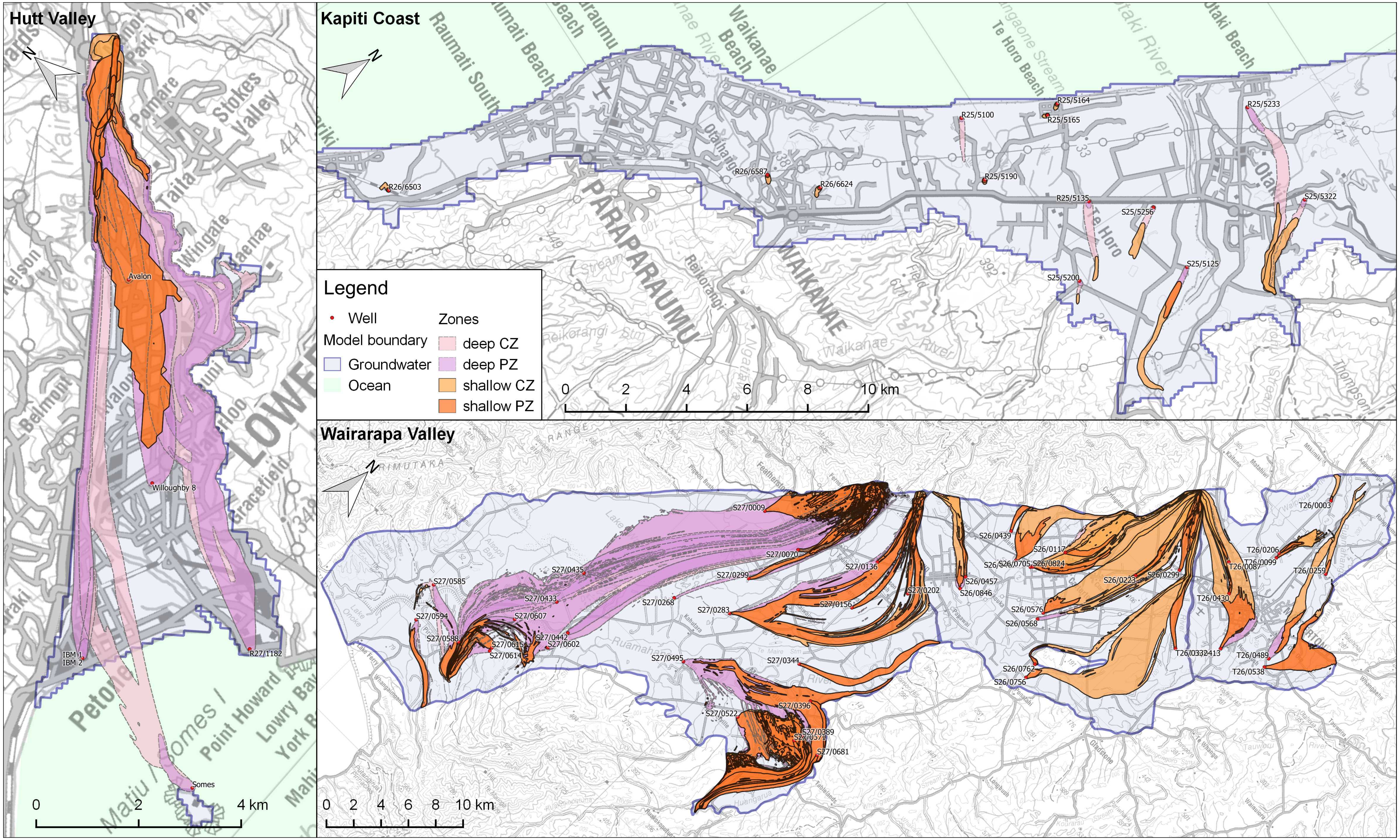

Figure 16: Individual zones for SOE wells.

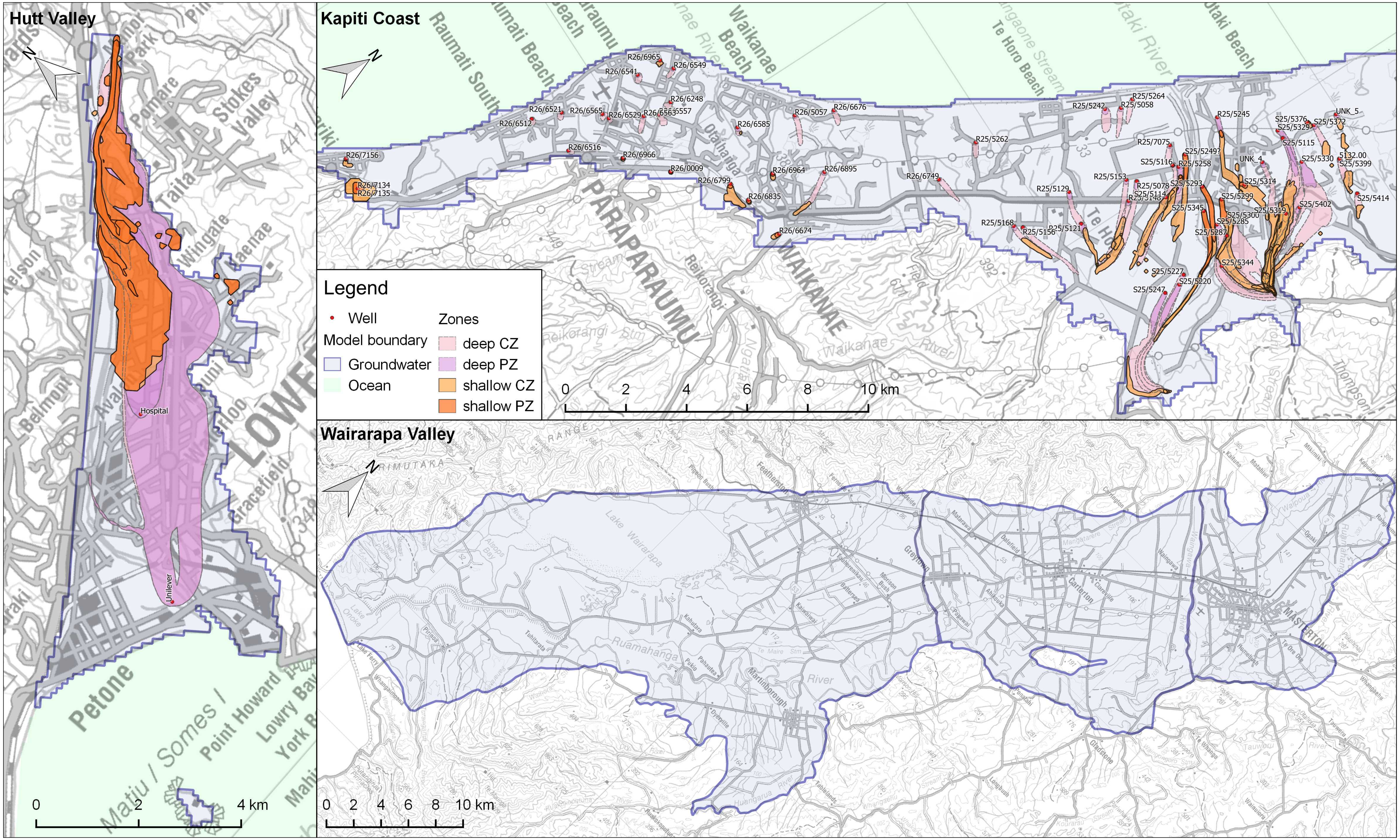

Figure 17: Individual zones to wells that have not been identified as community supply wells and are not SOE wells, but remained in the models for analysis.

5.0 DISCUSSION

5.1 HUTT VALLEY MODEL

Almost the whole Hutt Valley is mapped as part of a capture zone to one or more wells, however much of the zone is confined and not influenced by surface activities. The shallow CZ, which may be influenced by surface activities, is northeast of the Waterloo Wellfield about 0.5 km upgradient. However, much of the flow entering the model for Hutt Valley enters along the upper reaches of the Hutt River between Manor Park and Taita, as shown in the particle frequency map in Figure 18. Regions near the Waterloo Wellfield show relatively smaller frequencies of particles flowing, suggesting that this area is much less likely to be a source of capture to the wells, and this zone could be much further than 0.5 km upgradient.

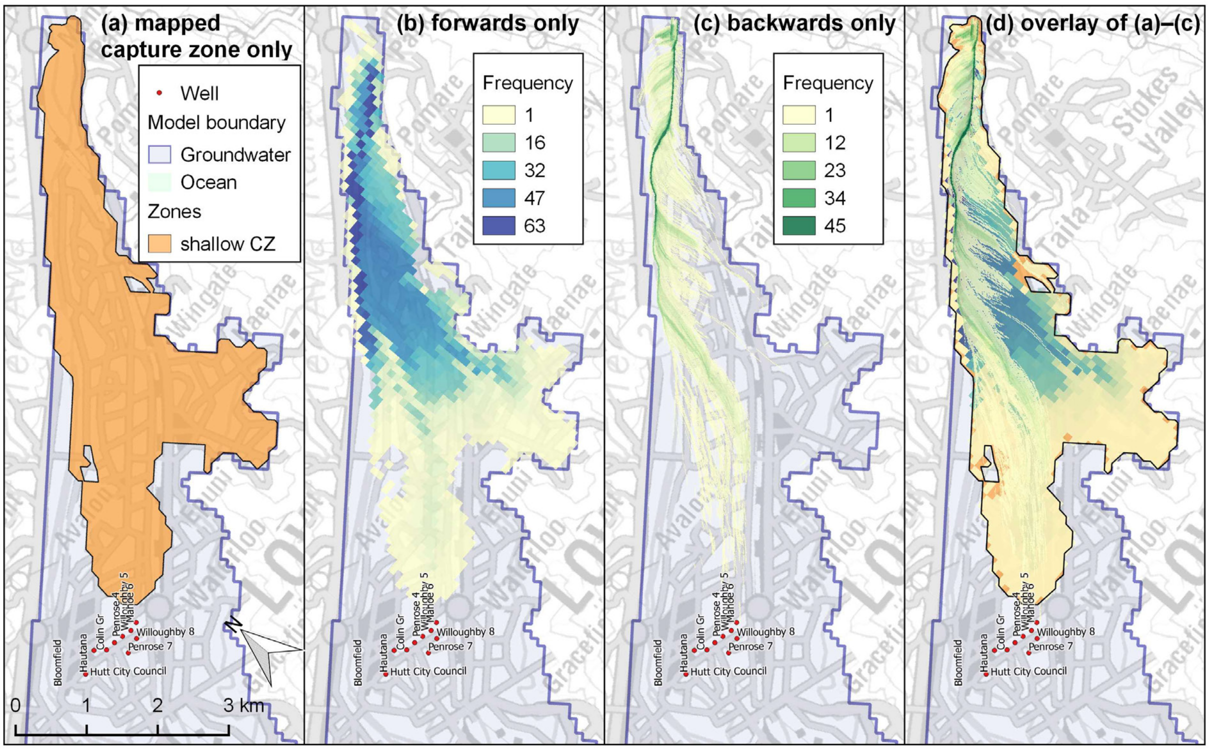

Figure 18: Maps of community supply wells for the Hutt Valley, showing (a) mapped capture zones (same as Figure 14, but without deep CZ or any PZs), (b) forward particle frequency with 100 m resolution, (c) backward particle frequency of shallow pathlines with 10 m resolution, and (d) overlay of previous layers. While this map shows the Waterloo Wellfield, other community supply wells that are part of this result are not shown, and include the Gear Island wells, Buick Street and Petone Pure Water.

There is not much difference between CZs and 1 year PZs for this model, as it simulates fast flowing groundwater. The model cannot resolve CZs larger than 2 years, which is the length of the transient simulation of the model.

5.2 KAPITI COAST MODEL

Groundwater in the Kapiti Coast model generally moves much slower than in other models, which results in small zones, which in many cases does not reach the surface. This is, in-part, a limitation of using the transient modelling approach for particle simulation, where the maximum travel is the same as the transient simulation of the model (about 19 years). If the model were extended to run longer, some of these CZs would be larger and extend to the surface as a shallow CZ. Extending the simulation time of a transient groundwater flow model is not a trivial task, and was outside the scope of work. However, since 19-years is beyond the time-frame of interest for forming policy, this is a minor limitation.

5.3 WAIRARAPA VALLEY MODELS

Capture zones in the Lower Valley are some of the largest and diverse in the Wellington Region (up to 34 km²). For example, SOE wells near Pirinoa and Tuhitarata start in streams near Featherston, and flow underneath Lake Wairarapa and Ruamahanga River. However, no shallow CZs are from Lake Wairarapa, since groundwater is flowing towards Lake Wairarapa, and not from it. Some wells in the Wairarapa models, such as S26/0846 near Greytown, show all four mapped zones, and could be visualised in the approach of the schematic in Figure 6.

5.4 MAPPING TECHNIQUES

Methods used for MODFLOW/MODPATH models (Hutt Valley and Kapiti Coast) combine forward and backwards particle mapping techniques. This strategy was used for these models since flowpaths in each direction are not always the same. For example, where the flowpaths converge in one direction, they would need to diverge in the opposite direction. The difficulty with MODPATH is that flowpaths cannot diverge, each advective-driven particle has only one pathway and cannot be split to diverge. By simulating forwards and backwards flowpaths, these zones can be confidently mapped.

Methods used for FEFLOW models (Wairarapa Valley) use backwards particle mapping techniques only. However, a random walk particle tracking technique was used for the FEFLOW model, which overcomes the problem of diverging flow pathways. For instance, two particles starting at the same location near a well screen will flow backwards with small random variations that enable them to diverge to different starting locations as they are tracked backwards.

The mapped zones in this report are conservative in the sense that their size and shape consider a wide range of uncertainties. The boundaries do not mark absolute boundaries of the CZs and PZs, and as such, may delineate zones that may not contribute groundwater to wells. Some of the uncertainty analysis runs, for instance, may not realistically portray groundwater flow, and as a result would map a zone larger than it should be. Conversely, different recharge rates, pump well rates and combinations of pump wells may yield different zones, which could be in areas that are currently unmapped.

Other sensitive aspects of this study include the threshold for the depth below water table, used for depth-limited pathlines in mapping shallow zones. The choice of this value changes the mapped boundary of shallow and deep zones. Aquifer porosity is also a sensitive parameter, which changes the mapped boundary of the 1 year PZ.

5.5 USE OF RESULTS FOR INFORMING POLICY

The maps shown in the results section have four zones, with the following recommendations on how the zones should be used to inform policy in Table 16.

Table 16: Description and possible policy interpretations of the mapped zones.

Zone name	Description	Policy recommendations
Deep CZ	Represents regions below the water table that may flow to a well. Water in these mapped zones is not captured between the land surface and the water table.	Policy may be exempt from these regions. However, considerations may include restrictions for activities below the water table, such as injection wells, and possibly geotechnical wells. Also, activities that may result in release of a dense non-aqueous phase liquid (DNAPL) from the surface may apply, as these contaminants flow below the water table. The distinction of travel time is not important for forming policy for activities below the water table, and deep CZ and deep PZ could be merged into one deep zone.
Deep PZ	Same as deep PZ, but often smaller since it represents groundwater travel times of 1 year or less.	
Shallow CZ	Represents the regions where water may flow to a well. From a vertical perspective, this is from the land surface to the water table.	Restrictions for activities that may adversely affect water quality to the wells.
Shallow PZ	Same as shallow CZ, but often smaller since it represents groundwater travel times of 1 year or less.	Same as shallow CZ, except that restrictions for microbial protection may apply to this zone only, but be permitted outside the shallow PZ.

Furthermore, an immediate CZ using an arbitrary fixed radius method is recommended for protection of community supply wells. If the well is near livestock or other hazards, a fence is recommended to protect this zone. An arbitrary fixed radius could vary depending on region or land-use, as it is not based on any scientific principle. A minimum radius of 5 m is recommended.

5.6 USE OF RESULTS FOR SOE WELLS

Individual shallow CZs for each well can be used to help identify areas where groundwater is recharged. Furthermore, the total CZ shows the regions that groundwater flows to reach the well. These tools can help interpretation of groundwater quality.

5.7 RECOMMENDATIONS

5.7.1 Recommendation for Policy

The techniques and methods described in this report can be reused for running scenarios of well configurations and pump rates to consider different mapped CZs that could be implemented in policy. By evaluating different scenarios, the risk of contamination can be minimised by evaluating the land uses and activities within the mapped zones.

Well configurations for the Hutt Valley were set based on current configurations of community supply wells. Gear Island wells were simulated pumping at their maximum consented rates, even though their metered rates are much lower since they are for emergency water supply. The presence of the Gear Island Wells in the community supply well analysis has a large impact on the mapped size of CZs for the Hutt Valley. By pumping the wells at their metered rates, and/or removing the Gear Island wells from the CZ analysis for the community supply wells, the mapped capture zones in the Lower Hutt region would be much smaller.

5.7.2 Recommendations for Future Numerical Analyses

The uncertainty analysis undertaken in this analysis was accomplished by identifying a few sensitive parameters from each model, and modified these values by ±25%. This is a basic approach, and is recommended where the input parameter distributions are not well understood. This uncertainty analysis could be improved by using stochastic techniques, such as a Monte Carlo method. For instance, random samplings from parameter distributions of model inputs could be used to run more numerical simulations. This technique would require ideally 1000s of groundwater simulations, and may require models to be run on larger high-performance computing clusters. Pathline results would then be transferred to frequency rasters for post-analysis of capture and protection zones.

The maximum CZs in this report are determined on pathline frequency raster based on a zero probability threshold, which delineates zones for all sensitivity analysis, regardless if they are realistic or not. By running and analysing more sensitivity simulations (e.g., from a stochastic technique), unrealistic simulation results could be statistically removed from the capture zone analyses. For example, the bottom-most 1% of simulations could be removed from the zone analysis, or where only 1 in 100 simulations suggest flow occurs to a well. A probability threshold above zero could not be used for the analysis in this report, since the number of simulations from each region was between 9 and 57.

6.0 SUMMARY

GWRC commissioned GNS Science to delineate CZs of community supply wells within the three major catchments of the Wellington region, namely the Hutt Valley, Kapiti Coast and the Wairarapa Valley. The main objective of the CZ delineation was to reduce the risk of contaminating drinking water sources by identifying groundwater source areas of water supplies. Furthermore, CZs were delineated for SOE wells to understand the origin of the groundwater that is being sampled and to interpret hydrochemical data.

GWRC provided five numerical groundwater flow models: the Hutt Aquifer model (HAM3), the Kapiti Coast model, and three Wairarapa Valley models (LV, MV and UV). CZs were delineated only for wells that were located within the model domains and could be adequately simulated by the models. The general CZ delineation methodology was developed in conjunction with GWRC and giving effect to any NES (National Environmental Standards).

Modifications to the original models include the subsequent implementation of abstraction wells, the adjusting of pumping rates and schedules to meet the maximum consented rates and the systematic variation of input parameters during the sensitivity analysis.

The modelling technique involves pathline/endpoint generation of particles in a transient flow field based on an advective or advective-dispersive transport solution of particle flow paths and travel times. Particles were put on the water table and tracked along with groundwater flow (forward tracking), and/or circularly set around the well screens and tracked in the opposite direction of groundwater flow (reverse tracking). For the MODFLOW models (HAM3 and Kapiti Coast model) the particle tracking post-processing program USGS MODPATH (version 3 and 5) was used. Seasonality effects on the CZ extent and travel times have been incorporated by systematically varying particle release times using the forward tracking technique. For the FEFLOW models (Wairarapa models) the delineation of CZs has been accomplished using the random-walk particle tracking method which additionally incorporates diffusion and dispersion.

The uncertainty of hydrogeological input parameters associated with each CZ was considered by varying values of hydraulic conductivity, specific yield (drainable porosity)/specific storage and river/stream bed conductivity (transfer rate of Cauchy boundary in FEFLOW) by ±25% around the initial value as recommended in the guidelines (Moreau *et al*., 2014a).

CZs were mapped by generating raster maps for each simulation based on assigned discharge location codes. The raster maps were then aggregated to determine the capture probability of the surface area based on the simulation counts. CZs were generated from the complete model simulation time, and protection zones (PZs) were generated from 1-year travel times to each well. Additionally, shallow and deep fractions of the zones were distinguished by evaluating the 3D data, with respect to the depth below water table.

In total, CZs were delineated for 158 wells, including 99 community supply wells (55 wells supplying more than 500 people) and 67 SOE wells.

7.0 LIMITATIONS

The modelling of the CZ extents and travel times was restricted by the model simulation time. The HAM3 simulation time only accounts for 5 years which hence represents the maximum particle travel time. Although the Kapiti Coast model simulates a period of ca. 19 years, some particles were fully simulated between the well and water table within that time.

The numerical groundwater models from GWRC where largely used "as is", with any substantive changes detailed within this report, such as the addition or modification of wells and pumping rates. The models were never calibrated as groundwater transport models, but modifications to effective porosity and storage parameters have been included as part of the sensitivity analyses. Because the groundwater models were not calibrated as transport models, the travel times of particle pathlines may not be accurate; however, their flow pathways should remain the same. Potential inaccuracies of travel times could shift the boundary of the 1-year isochrone for the protection zones within capture zones and/or the total length of the capture zone (where pathlines are limited by the simulation time). Transport models can be calibrated and/or validated with tracer data.

Delineating capture zones using particle pathlines requires many assumptions, often based on arbitrary selections, as there are no best practices for their application. This includes the particle arrangements on the water table for forwards tracking, and/or the particle arrangements around the well screen for reverse tracking. Only a limited number of particle release times were assessed. To distinguish between shallow and deep pathlines, a depth below water table threshold was used, and was determined for each model based on best guesses. Lastly, to consistently render polygon zones around pathlines, a Gaussian technique was developed to process the mapped zones shown in the results. The intent of the technique was to avoid manual drafting of zones, but is not based on a rigid statistical method.

A further project limitation was that the CZ delineation was only accomplished for wells that are located within one of the five model domains. However, the drinking water supply list of GWRC contains further 41 wells that are located outside the model domains. Furthermore, the list contains 28 wells that are missing spatial information. From the wells that were excluded from the CZ analysis, none would be covered by policy for drinking water supply wells for populations of 500 or more people.

8.0 ACKNOWLEDGEMENTS

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APPENDICES

APPENDIX 1: SOE MONITORING WELLS USED IN MODELS

	Model domain	Well No.	NZTM 2000 Datum			GW consent code	Pump rate [m³/d]	Days/yr	Pump rate [m³/yr]
			Easting	Northing	Depth				
1	Hutt	R27/0320 / IBM 1	1756996	5434508	114.60		20.0	365	7,300
2	Hutt	R27/1171 / Somes	1756493	5431227	23.20		20.0	365	7,300
3*	Hutt	R27/1180	1760435	5435698	39.00	WGN970036	see list of supply wells		
4	Hutt	R27/1182	1759274	5432161	38.00		20.0	365	7,300
5**	Hutt	R27/1183 / Avalon	1763084	5438691	25.00	WGN120019	2,419.2	364	880,589
6	Hutt	R27/1265 / IBM 2	1756998	5434516	48.30		20.0	365	7,300
7**	Kapiti	R25/5100	1774552	5479451	48.20	WGN070011	162.0	126	20,412
8*	Kapiti	R25/5135	1779152	5481483	93.27	WGN070204	see list of supply wells		
9***	Kapiti	R25/5164	1775873	5482367	0.00		20.0	365	7,300
10	Kapiti	R25/5165	1776019	5481886	8.00		20.0	365	7,300
11***	Kapiti	R25/5190	1776678	5478988	0.00		20.0	365	7,300
12	Kapiti	R25/5233	1779398	5487565	18.70		20.0	365	7,300
13	Kapiti	R26/6503	1766253	5462295	14.80		20.0	365	7,300
14	Kapiti	R26/6587	1772634	5473057	12.96		20.0	365	7,300
15	Kapiti	R26/6624	1773933	5474297	10.20		20.0	365	7,300
16	Kapiti	S25/5125	1782734	5483013	10.00		20.0	365	7,300
17**	Kapiti	S25/5200	1781183	5479785	45.80	WGN080029	129.6	156	20,218
18*	Kapiti	S25/5256	1780491	5483153	30.78	WGN070168	see list of supply wells		
19**	Kapiti	S25/5322	1782983	5487486	27.00	WGN080409	112.3	140	15,722
20	LV	S27/0009	1793895	5443481	10.50		20.0	365	7,300
21	LV	S27/0070	1797508	5443111	14.60		20.0	365	7,300
22	LV	S27/0136	1802217	5446389	20.40		20.0	365	7,300
23**	LV	S27/0156	1803403	5442776	20.70	WAR090020	432.0	210	90,720
24**	LV	S27/0202	1805461	5446520	4.80	WAR110293	100.8	150	15,120
25**	LV	S27/0268	1793453	5434055	58.40	WAR100049	2,732.4	210	573,804
26**	LV	S27/0283	1797276	5436168	19.00	WAR100038	1,250.3	182	227,551
27**	LV	S27/0299	1796504	5438936	17.40	WAR100100	3,326.4	196	651,974
28**	LV	S27/0344	1803348	5437340	16.00	WAR030117	2,720.2	210	571,234

	Model domain	Well No.	NZTM 2000 Datum			GW consent code	Pump rate [m³/d]	Days/yr	Pump rate [m³/yr]
			Easting	Northing	Depth				
29	LV	S27/0389	1807205	5433792	17.85		20.0	365	7,300
30*	LV	S27/0396	1805859	5435962	17.00	WAR120245	see list of supply wells		
31**	LV	S27/0433	1787692	5427839	44.60	WAR100103	3,456.0	210	725,760
32	LV	S27/0435	1787608	5430805	44.00		20.0	365	7,300
33	LV	S27/0442	1789891	5426884	177.70		20.0	365	7,300
34**	LV	S27/0495	1797227	5431330	37.50	WAR090370	3,801.6	210	798,336
35	LV	S27/0522	1803032	5431324	21.00		20.0	365	7,300
36**	LV	S27/0571	1807158	5433014	32.00	WAR080541	51.8	210	10,886
37**	LV	S27/0585	1780321	5422598	42.00	WAR100110	1,598.4	182	290,909
38*	LV	S27/0588	1784844	5420713	11.70	WAR050099	see list of supply wells		
39	LV	S27/0594	1781351	5419721	44.00		20.0	365	7,300
40**	LV	S27/0602	1789626	5425302	60.95	WAR100040	2,160.0	150	324,000
41**	LV	S27/0607	1786289	5425037	38.00	WAR100037	1,552.5	154	239,085
42	LV	S27/0614	1786778	5421924	35.80	WAR100045	1,555.2	210	326,592
43**	LV	S27/0615	1786805	5422158	18.20	WAR100044	864.0	210	181,440
44**	LV	S27/0681	1808952	5433542	5.00	WAR100104	1,296.0	150	194,400
45	MV	S26/0117	1811483	5456780	4.10		20.0	365	7,300
46	MV	S26/0223	1816203	5459285	9.92		20.0	365	7,300
47	MV	S26/0299	1818355	5461870	8.10		20.0	365	7,300
48	MV	S26/0439	1807492	5455180	11.50		20.0	365	7,300
49	MV	S26/0457	1807657	5450331	6.06		20.0	365	7,300
50	MV	S26/0467	1809272	5453850	6.20		20.0	365	7,300
51	MV	S26/0568	1813487	5451921	45.00	WAR110080	2,160.0	150	324,000
52	MV	S26/0576	1813462	5452534	31.00	WAR110014	1,490.4	150	223,560
53*	MV	S26/0705	1810472	5454279	27.40	WAR050013	see list of supply wells		
54**	MV	S26/0756	1815919	5448296	19.00	WAR110246	1,076.0	150	161,400
55	MV	S26/0762	1815702	5449348	9.50		20.0	365	7,300
56*	MV	S26/0824	1810547	5454381	20.60	WAR050013	see list of supply wells		
57**	MV	S26/0846	1807902	5449492	39.30	WAR120069	3,456.0	110	380,160

	Model domain	Well No.	NZTM 2000 Datum			GW consent code	Pump rate [m³/d]	Days/yr	Pump rate [m³/yr]
			Easting	Northing	Depth				
58	MV	T26/0332	1822231	5457402	13.40		20.0	365	7,300
59	UV	T26/0003	1822559	5473237	5.50		20.0	365	7,300
60	UV	T26/0087	1820296	5464750	36.00		20.0	365	7,300
61	UV	T26/0099	1822518	5467619	15.00		20.0	365	7,300
62**	UV	T26/0206	1822582	5467829	28.70	WAR060143	231.8	60	13,910
63*	UV	T26/0259	1825997	5469120	6.10	WAR050016	see list of supply wells		
64	UV	T26/0413	1824486	5459979	23.30		20.0	365	7,300
65***	UV	T26/0430	1822131	5463028	0.00		20.0	365	7,300
66**	UV	T26/0489	1827571	5461855	54.00	WAR100290	598.0	147	87,906
67	UV	T26/0538	1827738	5461169	9.00		20.0	365	7,300

* SOE wells which are also community supply wells
** existing wells in the original models; no changes were applied to pumping rates and schedules
*** depth assumptions have been made

APPENDIX 2: COMMUNITY SUPPLY WELLS USED IN MODELS

	Model domain	GWRC well No./ well name	NZTM 2000 Datum		GW consent code	Pump rate[a] [m^3/d]	Pump rate [m^3/yr]	ID[b]	Name[c]	Population (ESR est.)
			Easting	Northing						
1	HAM3	Bloomfield	1759939	5436076	WGN970036	Waterloo wellfield (see section 3.3.1)	30,253,860	85	Bloomfield Terrace Well	85,899
2	HAM3	Colin Gr	1760059	5435946	WGN970036			86	Colin Grove Well	85,899
3	HAM3	Hautana	1760209	5435926	WGN970036			90	Hautana St Well	164,835
4	HAM3	Mahoe 6	1760639	5435886	WGN970036			92	Mahoe St Well	164,835
5	HAM3	Penrose 4	1760239	5435696	WGN970036			96	Penrose St Well 1	164,835
6	HAM3	Penrose 7	1760349	5435896	WGN970036			97	Penrose St Well 2	164,835
7	HAM3	Willoughby 5	1760499	5435866	WGN970036			103	Willoughby 2 Well 1	85,899
8	HAM3	Willoughby 8	1760469	5435736	WGN970036			104	Willoughby 2 Well 2	85,899
9	HAM3	Gear 1	1758717	5434133	WGN970036	Gear Island wellfield (see section 3.3.1)		87.1	Gear Island Well1	164,835
10	HAM3	Gear 2	1758588	5434201	WGN970036			87.2	Gear Island Well2	164,835
11*	HAM3	Gear 3	1758872	5434064	WGN970036			87.3	Gear Island Well3	164,835
12*	HAM3	R27/1238 or R27/1239	1757729	5434616	WGN090243	30.0	10,920	105	Buick Street	501
13*	HAM3	R27/6441	1759033	5433807	WGN040360	50.0	18250	N.A.	Petone Pure Water	N.A.
14*	HAM3	BQ32/0024	1759625	5435948	WGN120153	41.0	14965	N.A.	Hutt City Council	N.A.
15	Kapiti	K10	1771429	5473877	WGN050025	Waikanae wellfield (see section 3.3.1)	8,372,000	13	K10 - Market Garden	32,100
16	Kapiti	K13	1770959	5474340	WGN050025			14	K13 - Huiawa	32,100
17	Kapiti	K4	1772806	5474625	WGN050025			15	K4 - Cooper 1	32,100
18	Kapiti	K5	1772979	5475130	WGN050025			16	K5 - Nga Manu	32,100
19	Kapiti	K6	1773131	5475400	WGN050025			17	K6 - Wooden Bridge	32,100
20	Kapiti	KB7	1773584	5475489	WGN050025			18.1	KB7	501
21	Kapiti	K12	1773824	5475213	WGN050025			18.2	K12	>500
22	Kapiti	N2	1774906	5475961	WGN050025			18.3	N2	>500
23	Kapiti	N3	1775123	5476732	WGN050025			18.4	N3	>500
24	Kapiti	S1	1771175	5471830	WGN050025			18.5	S1	>500
25	Kapiti	S2	1777094	5478204	WGN050025			18.6	S2	>500
26	Kapiti	KB4	1772130	5473576	WGN050025			19	KB4 - Landfill	32,100
27	Kapiti	PW1	1769742	5472370	WGN050025	3,500.0	backup	26	Otaihanga Bore	22,400
28	Kapiti	PW5	1770119	5472787	WGN050025	3,500.0	backup	48	Waikanae Bore	9,500
29	Kapiti	UNK_1	1781083	5484086	WGN000154	3,024.0	1,100,736	12	Kebbel	>500
30	Kapiti	UNK_3	1781180	5484178	WGN060343	150.0	26,000	1	Amos Water Scheme (John Guthrie)	>500

	Model domain	GWRC well No./ well name	NZTM 2000 Datum		GW consent code	Pump rate[a] [m³/d]	Pump rate [m³/yr]	ID[b]	Name[c]	Population (ESR est.)
			Easting	Northing						
31	Kapiti	R26/7044	1775982	5476885	WGN060173	34.6	12,594	2	Awatea Water Company Ltd	N.A.
32	Kapiti	S25/5256	1780491	5483154	WGN070168	302.4 (182 days/year)	55,037	3	B & J Bertelsen	N.A.
33*	Kapiti	S25/5443	1785536	5480051	WGN010125	691.2	504,576	4.1	Bores next to Otaki River	700
34*	Kapiti	S25/5379	1785683	5480085	WGN010125	691.2		4.2	Bores next to Otaki River	700
35	Kapiti	R25/5246	1779283	5484586	WGN070139	360.0 (210 days/year)	75,600	5	Craig & Janine Jones	N.A.
36	Kapiti	R26/7158	1765616	5461344	WGN040122	864.0	314,496	29	Paekakariki Bore	1,700
37	Kapiti	S25/5390	1783820	5481068	WGN080356	30.2	11,007	30	R Davis (Riverlea Farm Supply)	N.A.
38*	Kapiti	R25/5228	1779183	5486286	WGN080379	3,586.0	2,610,608	35	Tasman Road Bores	5,700
39*	Kapiti	R25/5235	1779183	5487386	WGN080379	3,586.0		36	Tasman Road Bores	5,700
40	Kapiti	S25/5328	1782682	5487768	WGN060098	178.2	64,865	37	Taylors Road Water Company Ltd	N.A.
41**	Kapiti	R25/5109	1778721	5479061	WGN080253	216.0	78,624	39	Te Horo Water Company	N.A.
42	Kapiti	R25/5208	1779363	5483285	WGN060297	400.0	145,600	42	Te Waka Water Company Limited	N.A.
43	Kapiti	R25/5220	1779409	5485156	WGN060321	826.0	277,536	53	Willow Park Community Water Scheme	>500
44	Kapiti	R26/7252	1770556	5473227	WGN100305	134.8	49,202	54	Waikanae Christian Holiday Park Inc.	N.A.
45	Kapiti	R25/5135	1779152	5481483	WGN070204	756.0 (182 days/year)	137,592	55	Windsor Park Ltd	N.A.
46*	Kapiti	R25/7085	1775886	5481994		20.0	7,300	24	Ms K A Green	N.A.
47**	Kapiti	SW6	1771482	5472785		20.0	7,300	6	El Rancho Camp Bore	200
48**	Kapiti	SW7	1781583	5484486		20.0	7,300	7	Firth Stress Crete Bore 1	30
49**	Kapiti	SW8	1783683	5489386		20.0	7,300	8	Forest Lakes Camp Bore	100
50**	Kapiti	SW9	1783683	5489386		20.0	7,300	9	Forest Lakes Camp Bore(Homest)	30
51**	Kapiti	SW11	1776082	5477185		20.0	7,300	11	Gary Rd Bore	25
52**	Kapiti	SW21	1766681	5462685		20.0	7,300	21	MacKays Crossing Bore	400
53**	Kapiti	SW22	1766846	5467540		20.0	7,300	22	Mathews Park, Raumati South	N.A.
54**	Kapiti	SW23	1779583	5482585		20.0	7,300	23	Michael S Hyland	N.A.
55**	Kapiti	SW27	1782683	5484786		20.0	7,300	27	Otaki Racecourse Bore	100
56**	Kapiti	SW31	1777782	5478506		20.0	7,300	31	Stanmore Foods Ltd	N.A.
57*	Kapiti	SW38	1778682	5479185		20.0	7,300	38	Te H2 Oro Bore	90
58**	Kapiti	SW44	1779382	5480885		20.0	7,300	44	The Partnership of Ruth & Paul Pretty	N.A.
59**	Kapiti	SW46	1770982	5474385		20.0	7,300	46	TW2 bore, Waikanae	N.A.
60*	LV	S27/0910	1805664	5436125	WAR120245	1,944.0	2,838,240	168	Martinborough, Herricks Bore	1,505

	Model domain	GWRC well No./ well name	NZTM 2000 Datum		GW consent code	Pump rate[a] [m^3/d]	Pump rate [m^3/yr]	ID[b]	Name[c]	Population (ESR est.)
			Easting	Northing						
61	LV	S27/0396	1805859	5435962	WAR120245	1,944.0		180	Martinborough, Melton Farm	>500
62	LV	S27/0404	1805919	5436009	WAR120245	1,944.0		181	Martinborough, Melton Farm	>500
63	LV	S27/0695	1805712	5436133	WAR120245	1,944.0		182	Martinborough, Melton Farm	1,500
64*	LV	S27/0588	1784844	5420714	WAR050099	28.8	10,512	215	Pirinoa Lake Ferry Rd	N.A.
65*	LV	S27/0291	1796198	5433421		20.0	7,300	171	Kahutara School	106
66*	LV	S27/0616	1785964	5422474		20.0	7,300	173	Kohunui Marae Bore	4,000
67*	LV	R28/0001	1779278	5415357		20.0	7,300	176	Lake Ferry Hotel Bore	50
68*	LV	R28/0022	1779590	5415973		20.0	7,300	177	Lake Ferry Spring	N.A.
69*	LV	S27/0035	1797507	5443107		20.0	7,300	200	South Featherston School	65
70*	LV	S27/0049	1799190	5444641		20.0	7,300	203	Tauherenikau Racecourse	>500
71*	LV	S27/0038	1799520	5445281		20.0	7,300	206	Tin Hut (Tauherenikau)	N.A.
72**	LV	SW163	1804778	5432779		20.0	7,300	163	Brackenridge Bore	130
73**	LV	SW166	1782275	5417983		20.0	7,300	166	Gateway Holiday Park - Bore	25
74**	LV	SW193	1784175	5419283		20.0	7,300	193	Pirinoa - Bore	80
75**	LV	SW199	1802258	5428086		20.0	7,300	199	Section Zero Ltd	N.A.
76	MV	S26/0705	1810472	5454279	WAR050013	1,728.0 (200 days/year)	345,600	152	Carterton - Bore 1	>500
77	MV	S26/0824	1810547	5454381	WAR050013	1,728.0 (200 days/year)	345,600	153	Carterton - Bore 2	>500
78	MV	S26/0919	1810386	5454186	WAR060191	2,160.0 (200 days/year)	432,000	154	Carterton - Bore 3	>500
79*	MV	S26/0918	1810374	5454173	WAR070010	864.0 (200 days/year)	172,800	155	Carterton - Bore 4	>500
80	MV	S26/0880	1806464	5450018	WAR120244	5,184.0	1,892,160	167	Greytown	2,000
81***	MV	BP33/0009	1801858	5451849		20.0	7,300	165.1	Featherston	2,600
82***	MV	BP33/0008	1801829	5451832		20.0	7,300	165.2	Featherston	>500
83***	MV	BP33/0006 or BP33/0022	1801830	5451828		20.0	7,300	165.3	Featherston	>500
84*	MV	S27/0714	1808755	5447477		20.0	7,300	192	Papawai Marae	N.A.
85**	MV	SW158	1820174	5450433		20.0	7,300	158	Hurunui O Rangi Marae- Bore	501
86**	MV	SW159	1822085	5457579		20.0	7,300	159	Taratahi Ag.Training Cntr Bore	100
87*	UV	T26/0277	1826377	5469030	WAR120233	30.8		109	Trinity Schools Trustboard	472
88*	UV	T26/0257	1826377	5469200	WAR120233	30.8	33,634	122	Trinity Schools Trustboard	472
89*	UV	T26/0255	1826227	5468980	WAR120233	30.8		137	Trinity Schools Trustboard	472

	Model domain	GWRC well No./ well name	NZTM 2000 Datum		GW consent code	Pump rate[a] [m³/d]	Pump rate [m³/yr]	ID[b]	Name[c]	Population (ESR est.)
			Easting	Northing						
90	UV	T26/0259	1825997	5469120	WAR050016	605.0	220,220	130	Opaki Water Supply Association Inc.	>500
91*	UV	BP34/0044	1822779	5473396	WAR120281	900.0	328,500	131	Opaki Water Supply Association Inc.	N.A.
92	UV	T26/0284	1827547	5467580	WAR120226	100.8	36,691	134	Ordish Aqua Ltd	N.A.
93	UV	T26/0492	1827566	5461568	WAR110053	360.0	262,080	147.1	Wainuioru water scheme	>500
94*	UV	T26/0493	1827516	5461629	WAR110053	360.0		147.2	Wainuioru water scheme	>500
95	UV	T26/0243	1826227	5463379	WAR110043	432.0	194,400 (150 days/year)	148.1	Te Ore Ore	>500
96***	UV	T26/0549	1826157	5463279		432.0		148.2	Te Ore Ore	>500
97***	UV	T26/0696	1822033	5462077		432.0		148.3	Te Ore Ore	>500
98*	UV	T26/0265	1827334	5464050		20.0	7,300	143	Te Ore Ore Marae	N.A.
99**	UV	SW145	1827486	5461578		20.0	7,300	145	Wainuioru Rural Water - Bore	184

[a] Pump rate as implemented in model, 365 days of pumping unless otherwise specified
[b] ID number from the drinking water supply bore list of GWRC
[c] Well name from the drinking water supply bore list of GWRC
* wells were subsequently implemented in the models
** wells without any bore information, depth assumptions have been made
*** planned to be used for public water supply (pers. Comm. Lindsay)

Note: Well coordinates were extracted from the GWRC well database; for wells without GWRC well no. the coordinates were extracted from the original models if available or from the drinking water supply bore list of GWRC. If necessary, NZMG1949 coordinates were transformed into NZTM2000 using LINZ online conversion. Coordinates might differ from other data sources and differ from the well coordinates in the FEFLOW models due to the assignment of wells to mesh nodes and the dependency on mesh resolution. Community supply bores with missing well numbers were named SW plus a number that corresponds to the ID[1].

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