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Delineation of protection (capture) zones for the Putaruru well field and the Blue Spring on the Waihou River

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EXECUTIVE SUMMARY

GNS Science has delineated the time of travel (TOT) protection zones (PZs) and capture zones (CZs) for the Putaruru well field and Blue Spring. The study consisted of a literature review of relevant information for the area of interest, sampling of groundwater age tracers and mapping of the PZs and CZs using the semi-analytic groundwater model GFLOW. The GFLOW model allowed us to represent regional groundwater flow patterns in the large modelling area of 1417 km^2 with local surface water features such as rivers and streams. The constructed model represented three hydrogeologic zones and was calibrated to groundwater heads, stream flow and the mean residence time (MRT) of 57 years for well GS #2 and 56 years for the Blue Spring estimated from isotope tracers.

The 1-year, 5-year and Total TOT CZs have been produced for both Putaruru well field and Blue Spring using values in the calibrated numerical model. The sensitivity and uncertainty in the mapped CZs were addressed by incorporating the uncertainty associated with the groundwater recharge, riverbed conductance, porosity, hydraulic conductivity and aquifer thickness in the calibrated model. The resulting 42 mapped TOT CZs were aggregated into “combined” 1-year, 5-year and Total TOT CZs. The combined CZs thus represent the maximum probable size, given uncertainties in model parameters. Therefore, mapped CZs and PZs can be used for source water protection of the Putaruru well field and Blue Spring.

In addition, GNS Science recommends the following:

1) identify potential contamination sources within the mapped 1-year and 5-year CZs;

2) measure groundwater levels quarterly at nearby monitoring wells to confirm the groundwater flow direction;

3) collect groundwater chemistry data (major ions, major nutrients and isotopes) in the Putaruru well field and Blue Spring and nearby wells to identify connectivity of these wells to land-use activities and surface water features such as drains and streams;

4) collect field data on local hydrogeology (bore logs, slug tests, aquifer tests) and surface water features (water levels, flows and bed conductance) to gain better understanding of local groundwater flow patterns, and update the numerical model if relevant; and

5) refine the delineated CZs by including updated information of the area in the numerical model. The groundwater flow and transport model can be imported from the GFLOW groundwater flow model by using an extract feature. In addition, the tritium concentrations can be used as primary calibration targets for the transport model at the Blue Spring.

1.0 INTRODUCTION

GNS Science was commissioned by Waikato Regional Council (WRC) to delineate protection zones (PZ) and capture zones (CZ) for the Putaruru well field and the Blue Spring (Figure 1.1). The Putaruru well field and the Blue Spring serve as a main source of drinking water for the town of Putaruru, South Waikato. South Waikato District Council (SWDC) would like to increase its consent to abstract a maximum of 3,800 m^3/day from the Putaruru well field. The Blue Spring is also used by Coca-Cola Amatil for a bottled water source due its pristine water quality. The PZ and CZ delineation was requested by WRC to facilitate the protection of groundwater quality at these drinking water supply sources (Hadfield 2012; Pascoe 2012).

An example of the PZ and CZ is shown in Figure 1.2. In Figure 1.2, the CZ is shown on the ground surface and indicates the boundary at which groundwater flow is diverted into the pumping well from the surrounding aquifer. The mapped CZ extends to the groundwater divide while the PZ is represented by a smaller area of 1-year and 5-year time of travel (TOT) that is defined for management purposes. These 1-year and 5-year TOT PZs indicate the arrival time of groundwater to a pumping well and are also referred to as TOT CZs. Protection and capture zones are required by law in many countries to secure drinking water supply wells and springs from potential contamination (Kreye et al. 1996; US EPA 1987, 1991, 1993, 1994). However, there is no mandatory requirement for CZ and PZ delineation for water supply wells in New Zealand. GNS Science and ESR are currently preparing New Zealand CZ delineation guidelines utilising existing delineation methodologies adapted to Zealand settings. The CZ and PZ delineated for the Putaruru well field and the Blue Spring in this current study utilised the methodologies that have been identified by the CZ guideline project.

This report provides the PZ and CZ delineated for the Putaruru well field and Blue Spring and provides associated recommendations for source water protection and future work. First, the available geology, hydrogeology, hydrology data were collated for the area of interest. Second, groundwater samples were collected from the Putaruru well field and Blue Spring to determine groundwater chemistry and isotope tracer concentrations. These isotope tracers allow us to estimate groundwater age, which is equivalent to transit time and is defined as the time elapsed from the input of water into the aquifer to the time of abstraction or sampling (McDonnell et al. 2010). A groundwater sample is a composite of water ages, reflecting the different transit times along all of the flow paths that converge at the sampling point (see Appendix 1). This concept of age distribution at a single well is embodied in the criteria used in the Drinking Water Standards for New Zealand to evaluate security of groundwater supply. Specifically, a secure groundwater supply is defined as one having less than 0.005% of water less than one year old (MoH 2008). Next, a numerical model was constructed using the Analytic Element Method (AEM) and calibrated to groundwater levels, streamflows and groundwater age determined from isotope tracers. The calibrated model was used for the PZ and CZ delineation and accompanying sensitivity and uncertainty analysis. Finally, the mapped PZ and CZ for the Putaruru well field and Blue Spring are shown with recommendations for future work.

2.0 SITE-SPECIFIC AND REGIONAL SETTING

This section summarises the collated data used for delineation of PZ and CZ for the Putaruru well field and the Blue Spring. The collated data are described in terms of site specific information, geology, hydrogeology, hydrochemistry, isotope analysis and calibration targets for the numerical model.

2.1 Putaruru well field

The Putaruru well field consists of three drinking water production wells and one observation well. Two drinking water production wells have WRC ID numbers 72_3848 and 72_3839 and are referred to as Glenshae well (GS) #2 and GS #3, respectively (Figure 2.1). GS #2 is 70 m deep and is screened between 60 and 70 m below ground level (mbgl). GS #3 is 180 m deep and is screened between 94 and 180 mbgl. GS #2 is normally in service with GS #3 used as a backup standby well and to provide additional flow to meet peak water demand during the summer period (Whyte 2008). The observation well OB1 is located next to GS #3. In addition, an earlier water supply well (GS #1) is still onsite, but is no longer in operation. GS #1 is apparently located between the town reservoir and GS #2 (Figure 2.1). In order to provide for the pumping rate of 3,800 m^3/day, simultaneous operation of both GS #2 and GS #3 would be required to consistently reach that level of flow (Zemansky et al. 2011).

2.2 Blue Spring

The Blue Spring is located approximately 4 km east of Putaruru, South Waikato on the true right bank of the Waihou River (Figure 2.2). The ground elevation at the Blue Spring is approximately 125 m above mean sea level (amsl). The Blue Spring is a natural flowing spring of artesian nature that can be classified as a “fracture spring” based on the United States Geological Survey (USGS) spring classification (Zemansky 2007). The groundwater of the Blue Spring flows through fractured volcanic ignimbrite rock and ponds on the surface in the natural cavity. The water from the cavity overflows into the Waihou River a few meters away from the Blue Spring.

The Blue Spring has two estimates of groundwater discharge of 58890 m^3/day in March 1988 and of 43027 m^3/day in September 2001 (van Kampen 2001; Hadfield 2011). These estimated discharge values were obtained by measuring flow of Waihou River upstream and downstream of Blue Spring. Department of Conservation (2011) reports the Blue Spring flow rate to be 60480 m^3/day.

SWDC takes up to 4000 m^3/day from the Blue Spring under WRC consent 101869 and Coca-Cola Amital takes up to 200 m^3/day under WRC consent 107608. A pipe is installed underneath the Waihou river bed to take water from the Blue Spring. The spring water flows into the pipe that is connected to a pumping station on the other side of the Waihou river bank and is transferred to other facilities.

2.3 Geology

Putaruru is on the northwestern edge of the Taupo volcanic zone (TVZ), which is “a complex basin of volcanic-tectonic subsidence in the central North Island” (Martin 1961). Stratiform rhyolitic pyroclastic ignimbrites from the various volcanic eruptions are the dominant shallow geologic materials, with Mamaku ignimbrite as the youngest litho-stratigraphic unit followed next by Whakamaru ignimbrite. Reportedly, the ignimbrites average 30 m in thickness and extend over areas exceeding 2,590 km^2 (Martin 1961). Figures in older papers indicate that Putaruru is on the northern end of a large zone in which Whakamaru ignimbrites outcrop and, with the exception of an area around Lake Maraetai, extends southward to the western side of Lake Taupo (Ewart 1965; LaMarche and Frogatt 1993; Brown and Fletcher 1999).

The portion of the most recent geologic map (QMAP) covering the Putaruru area has been reproduced as Figure 2.3 (Leonard et al. 2010). Details of the geologic units indicated on that map by the colour code are listed in the caption. The map indicates that Putaruru is located within an area predominantly composed of Whakamaru ignimbrites. In addition, there are small areas of alluvial materials to the immediate west of Putaruru (Tauranga Group and Hinuera Formation alluvium) and outcrops of Pakaumanu Group and Mangaokewa Formation ignimbrites in close proximity to the northwest and a little further to the west, respectively, toward the Waikato River (Leonard et al. 2010).

Figure 2.4 is an enlargement of the hand drawn geologic map produced by Fransen (1982) for the Blue Spring area around the northwestern end of Leslie Road (Zemansky et al. 2011). The study area is within a rectangle with its long side extending to the east-southeast from Whites Road (State Highway 28). It includes the headwaters of the Waihou River and Blue Spring. There is alluvium along part of the river and Mamaku ignimbrite over most of the central and eastern parts of the study area. This geologic map also shows that Whakamaru ignimbrite surrounds most of Putaruru with the exception of a west-east strip of Hinuera Formation alluvium from the south end of Putaruru extending to the west.

Although the general features of the geology are consistent with that of the map in Figure 2.3 more detail and complexity is evident in Figure 2.4. Whakamaru ignimbrite predominates in the vicinity of Blue Spring and to the west of it, but there is a substantial zone of Waimakariri ignimbrite to the north of Blue Spring and Leslie Road. There are thin zones of alluvial sands and gravels (yellow) along the westernmost segments of streams (from southwest to northeast, respectively, these are the Waihou River, Purere Stream, and Waipare Stream). There are also strips of Waihou ignimbrite (blue) around the higher elevations through which the streams cut. The higher elevations to the west consist of Waimakariri ignimbrite, but east of Blue Spring Mamaku ignimbrite becomes more predominant (Fransen 1982).

2.4 Hydrogeology

The area including Putaruru town is identified as a North Island ignimbrite aquifer (variously as “South Waikato Ignimbrites” and “Whakamaru Ignimbrites”). This aquifer is roughly circular in shape and centred around Tokoroa. The volume of water available within it has been estimated at 1.2 billion m^3. This was based on an assumption that the aquifer is confined and that it has an assumed area of 2.5 billion m^2 (2,500 km^2), a saturated thickness of 60 m, and a storativity of 0.008 (White & Reeves 2002; White et al. 2004). A literature search was unsuccessful in identifying any information regarding the hydrogeology of this area in the published scientific literature. There is surprisingly little information available regarding the hydrogeology of the Blue Spring other than its flow rate that was discussed earlier. The geologic model developed by Cameron & White (2010) for the upper Waikato catchment does not include the Putaruru well field. Cameron & White (2010) suggested values of effective porosity from 0.02 to 0.3 for Whakamaru and 0.3 for Mamaku layers in the geologic model.

Hydraulic testing of water supply wells at the Glenshae Park well field in Putaruru indicates that characteristic values of hydraulic conductivity and storativity for the shallow aquifer (to a depth to about 120 m) would be on the order of 5 m/day and 0.015, respectively (Zemansky et al. 2011).

2.5 Hydrology

Surface water features such as rivers and streams, rainfall stations, and stream gauging points for the area of interest are shown in Figure 2.5. Relevant rainfall monitoring stations were selected depending on completeness of their data record from NIWA's National Climate Database (NIWA 2011) and are summarized in Table 2.1. Flows at the gauging points were measured by Dell (1982) during low flow conditions. The gauging point #14 is in the same location as the WRC gauging station at the Pinedale Bridge on the Oraka Stream that was installed in 2010. The WRC gauging station reports a range of water depth of 1 to 3 m in Oraka Stream at Pinedale Bridge.

The Putaruru well field and Blue Spring are located in surface water catchments of the Waikato River and Waihou River. The Putaruru well field is located approximately on the surface water catchment divide of the Waikato and Waihou rivers (Pascoe 2011). The small streams and drains southwest of Putaruru flow into the Waikato River and small streams and drains northeast of Putaruru discharge into the Waihou River. The Waihou River has several tributaries: Waihirere Stream, Waimakariri Stream and Purere Stream. The Waipare stream is a tributary of Waimakariri stream. The Oraka Stream flows parallel to the Waihou River near Putaruru well field and discharges into the Waihou River near Matamata. The Blue Spring is located in the Waihou River surface water catchment that coincides with the Lake Rotorua surface water catchment. Dell (1982) reported an area of 26.49 km^2 near the town of Mamaku along Marareroa Road that has no surface water drainage. This area may supply rainwater via groundwater pathways to both the Waihou and the Rotorua surface water catchments.

Table 2.1 Mean of mean annual precipitation (in mm) for the period of record at rainfall monitoring stations in the area of interest (from NIWA 2011).

Station ID Number	Name	Start of record	End of record	Elevation, [msl]	Years of complete record	Mean precipitation, [mm/y]
1711	Putaruru	1941	1971	152	30	1462.69
1712	Putaruru	1913	1931	N/A	4	1328.13
1713	Pinedale Block	1929	1933	213	4	1356.03
1714	Tirau, Aliscroft	1950	1966	122	15	1310.27
1716	Putaruru, Lichfield	1917	1987	198	54	1425.50
2200	Putaruru, Puketurua	1958	1973	155	14	1373.19
12453	Tirau, Circle K	1996	2011	115	14	1209.76
17030	Matamata, Hinuera Ews	1999	2011	106	5	1123.02
22146	Karapiro Heights	2002	2011	140	9	1216.18

N/A – "Not available"

2.6 Hydrochemistry

Water samples were taken by Waikato Regional Council (WRC) staff from well GS #2, well GS #3 and Blue Spring on 17th of February, 2011. These samples were analysed for a range of water quality variables by Hill Laboratories in Hamilton. Results of the analysis were provided to GNS Science by Hadfield (2011) and are presented in Table 2.2. Analysis of February 2011 water samples indicates a compliance with NZ Drinking Water Standards (Ministry of Health 2008).

The water sampled from Blue Spring was similar to the water sampled from well GS #3 and both of these sources of water were marginally better in quality than the water sampled from well GS #2.

Zinc was a major exception to this rule (at concentrations of 0.0057 and 0.005 mg/L, respectively, from well GS #2 and Blue Spring but 0.26 mg/L from well GS #3). This may be because the sample analysed for zinc was not filtered. Sample results indicate there may have been sediments in the sample from well GS #3 contributing to the results for total elements such as iron and manganese and possibly zinc.

Dissolved iron was below the detection limit in samples from all three sources but total iron was 0.5 mg/L in the sample from well GS #3 compared to less than the detection limit of 0.021 mg/L for well GS #2 and Blue Spring.

The water of the shallower well GS #2 has significantly higher nitrate-N (3.1 mg/L) compared to GS#3 (1.59 mg/L) and Blue Spring (0.61 mg/L). All waters are oxic, ruling out de-nitrification processes. The high nitrate of the water in bore GS #2 indicates that the recharge zone is likely to include dairy or dry stock farms.

Table 2.2 Hydrochemistry data from wells GS #2 and GS #3 and Blue Spring on 17th of February, 2011 (from Hadfield 2011).

	Constituent	Units	well GS #2	well GS #3	Blue Spring
General Variables	pH	SU	6.5	6.6	6.6
	Ammonia-nitrogen	mg/L	<0.01	<0.01	<0.01
	Conductivity	uS/cm	114.0	86.0	79.0
	Free CO_2	mg/L	18.4	14.0	14.5
	Hardness	mg/L as $CaCO_3$	21.0	15.9	12.2
	Silica	mg/L	79.0	85.0	75.0
	Total dissolved solids	mg/L	76.0	58.0	53.0
Cations and Trace Elements	Boron	mg/L	0.052	0.028	0.0095
	Calcium	mg/L	3.9	2.7	2.5
	Copper	mg/L	0.00132	<0.00053	0.00092
	Iron (dissolved)	mg/L	<0.02	<0.02	<0.02
	Iron (total)	mg/L	<0.021	0.51	<0.021
	Magnesium	mg/L	2.6	2.2	1.44
	Manganese (dissolved)	mg/L	<0.0005	0.0028	<0.0005
	Manganese (total)	mg/L	0.00068	0.0036	<0.00053
	Potassium	mg/L	5.3	4.2	3.9
	Sodium	mg/L	9.8	7.8	8.6
	Zinc	mg/L	0.0057	0.26	0.005
Anions	Alkalinity	mg/L as $CaCO_3$	27.0	26.0	28.0
	Bromide	mg/L	0.06	0.06	0.06
	Chloride	mg/L	9.9	6.5	6.0
	Iodine	mg/L	<0.0010	<0.0010	<0.0010
	Nitrate-nitrogen	mg/L	3.1	1.59	0.61
	Sulphate	mg/L	3.3	1.7	1.6
	Fluoride	mg/L	0.09	0.07	0.07

2.7 Existing models in the Putaruru well field and Blue Spring area

There is no numerical model developed for Waihou river surface water catchment. Aqualinc (2010, 2011) developed a regional finite-difference groundwater flow model for the upper Waikato catchment to assist WRC with decision making processes regarding protection of water quality. The active area of the upper Waikato catchment model does not cover the Putaruru well field and Blue Spring. Daughney et al. (2011) developed a FEFLOW groundwater flow model for the Rotorua surface water catchment that extends up to the town of Mamaku. Structure, implemented hydrogeologic properties and modelled groundwater levels in both models were investigated for the development of the groundwater flow model for the Putaruru well field and Blue Spring.

2.8 Calibration targets

2.8.1 Groundwater heads

Groundwater head measurements are used as calibration targets to be matched by modelled heads from the groundwater flow models. Bores with groundwater levels were obtained from the Rotorua catchment FEFLOW model developed by Daughney et al. (2011), the WRC web-interface (Hadfield 2011) and the upper Waikato catchment model developed by Aqualinc (2011). Out of these bores, 110 groundwater observation wells that are 5-400 m deep and have calculated depth-to-groundwater relative to terrain elevation were selected for the area of interest. The terrain elevation was obtained from Digital Terrain Model (DTM) with 20 m resolution and used to obtain groundwater elevations at these bores relative to mean sea level (msl). Therefore, these calculated groundwater elevations are expected to have an error of up to 20 m due to uncertainties in the bore locations and DTM elevations.

2.8.2 Stream flow

Stream flow measurements are matched by modelled stream flows in the groundwater flow models by implementing gauging points with measured stream flow as calibration targets in the model. Relevant stream gauging data that are available near the Putaruru well field and Blue Spring were used in the model calibration (Figure 2.6). Stream flows were measured by Dell (1982) at several locations in the Waihou River catchment during low flow conditions. These stream flow values provide an additional constraint to the groundwater flow model and should be used in model calibration. There are no stream flow gauging points on the Pokaiwhenua or Waipapa streams located in the Waikato River catchment.

2.8.3 Mean Residence Time (MRT)

The Mean Residence Time (MRT) obtained from measured Tritium (^3H), sulphur hexafluoride (SF_6), and chlorofluorocarbons (CFCs) tracers in a groundwater sample can be used as a calibration target for a numerical model. The modelled MRT can be obtained by constructing cumulative frequency distribution (CFD) curves from groundwater particle tracking (Luther & Haitjema 1998) and/or by direct numerical modelling of groundwater age (Daughney et al. 2011). Moreover, the tracer concentrations can be modelled by solving the convolution integral of the CFD and/or by obtaining tritium ratio (TR) from the groundwater flow and contaminant transport model (Troldborg 2004; Abrams et al. 2011; Gusyev et al. 2011). In this study, the MRT obtained from tracers is compared to modelled MRT using particle tracking in the groundwater flow model.

The MRT obtained from tracers can guide development of numerical models and help to evaluate uncertainty of aquifer properties and model structure. Cook & Herczeg (1999) provide a relationship between MRT [T] of groundwater and aquifer properties in a partially confined aquifer:

$$MRT = \frac{nH}{R\eta} \tag{1}$$

where *n* [-] is the aquifer porosity, *H* [L] is the thickness of the confined aquifer or the average saturated thickness of the unconfined aquifer, *R* [L/T] is the groundwater recharge and *η* [-] is the fraction of the volume in the unconfined the aquifer to the total volume (Maloszewski &

Zuber 1982). The uncertainty can be assessed by selecting different values of aquifer porosity, aquifer thickness and groundwater recharge in equation (1) while preserving the MRT value obtained from tracers.

3.0 AGE TRACER RESULTS AND INTERPRETATION

GNS Science staff collected water samples from wells GS #2 and GS #3 and the Blue Spring on 17th of February, 2011. Tritium, sulphur hexafluoride (SF_6) and chlorofluorocarbons (CFCs) concentrations were determined in these samples (Table 3.1). The wells GS #2, GS #3 and the Blue Spring have TR values of 0.695, 0.327 and 0.593, respectively. The water of deep well GS #3 is contaminated with CFC12. The concentration of 715 pptv exceeds the maximum equilibrium concentration of the atmosphere of 540 pptv. Therefore, the contamination originates from the groundwater. The water of well GS #2 does not show such high CFC12 contamination. This suggests that the recharge zone is different for the two wells. The recharge zone for well GS #3 is likely to include an urban area which is usually the source of CFC12 contamination in groundwater. The results are interpreted to obtain mean groundwater age (or MRT) using methodology in Appendix 1 and the following conclusions are drawn from the isotope, gas, and hydrochemistry results.

Tritium time series data and lumped parameter models provide a robust groundwater age interpretation for hydrological systems. To obtain groundwater age, an Exponential Piston Flow model (EPM) was used with the tritium input from Kaitoke with a scaling factor 0.9. The EPM has two distribution parameters, namely 1) the percentage of exponential model (EM) within the total flow volume and 2) the MRT. These two parameters are adjusted to obtain the best fit between the EPM prediction and the measured tritium concentrations. For the wells GS #2 and GS #3, no tritium tine series data are available which would enable determination of the EM traction. Therefore, an estimated value of 100% is used to reflect the high degree of mixing in the ignimbrite formation. For the Blue Spring, both parameters could be determined due to availability of tritium time series data (Dell 1982). The groundwater of the shallower well GS #2 has a MRT of 57 years and the groundwater of the deeper bore GS #3 is considerably older with MRT of 160 years. The groundwater of Blue Spring has MRT of 56 years with 73% EM. The 73% fraction of for Blue Spring means that there is no very young water present. This model is justified by the fact that the spring water inlet is situated deep in the shaft and the youngest water from the surface would not be collected by the spring water inlet.

The lumped parameter model established for tritium was applied for SF_6 and CFCs concentrations to derive groundwater age. The groundwater ages obtained from the gas tracers (CFCs, SF_6) are 25-30 years younger due to most likely a result of gas exchange in the unsaturated zone. This age difference is similar to previous results of groundwater from ignimbrite formations and supports the age derived from tritium. The younger gas ages suggest recharge in an area with an unsaturated zone about 50 m deep.

The hydrochemistry data support the tritium and gas tracer observations. The water in GS #2 is more elevated in Ca, Na, Cl, K, Mg, and SO_4, all of which can be derived from natural or agricultural sources. If derived from natural sources, the concentrations of these substances are generally highest in the oldest groundwater, whereas if derived from agricultural sources, the concentrations are often observed to be highest in the youngest groundwater (Morgenstern & Daughney 2011). This suggests that GS #2 is supplied by recharge of relatively recent origin that occurs within an intensive agricultural area, compared to the older water from well GS #3 and the Blue Spring. The higher Si and F concentrations in the water of GS #3 compared to GS #2 and the Blue Spring are consistent with older groundwater age.

Table 3.1 Age tracer data and age interpretation for well GS #2, well GS #3, and Blue Spring using an exponential piston flow model, with the Kaitoke tritium input scaled by a factor of 0.9.

Site Name		well GS #2	well GS #3	Blue Spring
Tritium sample number		TWK45	TWK46	TWK44
Sample Date		17/02/11	17/02/11	17/02/11
TR		0.695	0.327	0.593
± TR		0.03	0.024	0.027
CFC sample number		FWK121	FWK122	FWK120
CFC Sample Date		17/02/11	17/02/11	17/02/11
SF6 sample number		SWK103	SWK104	SWK102
SF6 Sample Date		17/02/11	17/02/11	17/02/11
Calculated Atmospheric Partial Pressure [pptv]	SF6	1.85	0.58	1.72
	±	0.16	0.07	0.17
	C-11	133	132	107
	±	10	9	8
	C-12	476	715	442
	±	35	45	31
Calculated recharge temperature, ^{o}C		11.2	11.1	10.7
±		1.3	1.2	1.2
Calculated excess air, mL(STP)/kg		1.4	1.5	0.0
±		0.6	0.5	0.6
E%PM approx., %		100	100	
E%PM determ., %				73
MRT approx., [y]		57	160	56

4.0 PROTECTION AND CAPTURE ZONES

4.1 Criteria and method

In this study, the time of travel (TOT) criterion and the numerical modelling method were selected based on the available data and the desired level of delineation accuracy. The 1-year, 5-year and Total TOT provide a high level of accuracy for PZ and CZ delineation based on the time between occurrences of contamination in the capture zone and arrival of the contaminants at the well or spring. In addition, the MRT obtained for the Putaruru well field and Blue Spring from groundwater age tracers allows us to verify the delineated PZ and CZ.

The semi-analytic groundwater flow model GFLOW was selected for the numerical modelling method because it has relatively modest data requirements and produces accurate PZs (US EPA 1994). The GFLOW model is a single layer steady-state model that is based on the Analytic Element Method (Haitjema 1995). Semi-analytic models are able to represent a large scale groundwater system while accounting for locally detailed conjunctive surface-groundwater interactions and are thus often used as screening models (Hunt 2005).

4.2 Capture Zone Mapping

4.2.1 Model set-up

Figure 4.1 shows the area of the GFLOW model constructed for the Putaruru well field and Blue Spring area. In the conceptual model, the aquifer system receives groundwater recharge from rainfall and is drained by streams and the Waikato and Waihou rivers. The modelled aquifer was divided in three hydrogeologic zones to represent Pakaumanu (Zone 0), Whakamaru (Zone 1) and Mamaku formations (Zone 2). No rainfall recharge was assigned to Zone 0 and uniform rainfall recharge was assigned to Zones 1 and 2. The groundwater divide located at the town of Mamaku and the Waikato River is implemented as a constant head boundary with the use of line-sinks (Haitjema 1995). The elevation of the groundwater divide was estimated from groundwater elevations of 5 nearby monitoring wells. Perennial surface water features such Waihou River, Oraka Stream, Waimakariri Stream, Pokaiwhenua Stream, Waipapa Stream and Purere Stream are implemented as Cauchy boundary conditions by line-sinks with streambed resistance. These line-sinks are assigned constant head values that were obtained at several locations from the contour lines of the 1:50,000 topographic map. The streambed resistance values range from 5 days to 50 days. Small drains were also implemented in the model with flow a routing option to allow for determination of surface water flows in the model (Haitjema 1995). The aquifer was assigned a uniform thickness of 280 m and a bottom elevation of -100 m below msl. Wells GS#2 and GS#3 were represented as discharge specified wells with their maximum pumping rates of 3000 m^3/day and 800 m^3/day, respectively (Zemansky et al. 2011). The Blue Spring was represented as a discharge specified well with groundwater abstraction of 45000 m^3/day to represent steady-state low flows.

4.2.2 Calibration of groundwater flow model

The groundwater flow model was calibrated to groundwater levels and stream flows. The fit between modelled and measured groundwater levels for 110 monitoring wells implemented in the model is shown in Figure 4.2. The average and median differences were 0.3 and 1.7, respectively. The fit between modelled and measured stream flows for 16 gauging points implemented in the model is shown in Figure 4.3. Figures 4.2 and 4.3 were produced with groundwater recharge of 390 mm/year (10.68E-04 m/day) for Zones 1 and 2 and hydraulic conductivity values of 5 m/day for Zones 1 and 2 and of 3.5 m/day for Zone 0. These values are considered to represent the average conditions in the modelled area.

The aquifer porosity in the groundwater flow model was calibrated to MRTs for the Putaruru well field and Blue Spring obtained from groundwater tracers (Table 4.2). The modelled MRTs were obtained from cumulative transit time distributions that were produced from the GFLOW model with forward particle tracking for 300 model years with a step size of 10 m. The modelled MRTs of 56 years for the Blue Spring and of 57 years for the well GS #2 were produced with aquifer porosity values are 0.135 for Zone 1 and 0.165 for Zone 2. The modelled MRT for the well GS #3 was 160 years with aquifer porosity of 0.38. The modelled MRTs are matched exactly to the MRTs estimated from isotope tracers (Table 3.1). The calibrated aquifer porosities are consistent with literature values of similar aquifer materials.

The calibrated model was used for the CZ mapping using backward particle tracking. The delineated CZs are shown in Figure 4.4 for the Putaruru well field and in Figure 4.5 for the Blue Spring.

4.2.3 Sensitivity and Uncertainty of mapped Capture Zones

Sensitivity analysis on delineated CZs was investigated by changing only one parameter such as hydraulic conductivity and rainfall recharge in the calibrated model. Twelve CZs were mapped for sensitivity analysis using 25% lower or 25% higher hydraulic conductivity values for Zones 0, 1 and 2 and rainfall recharge rates that are representative of dry (292 mm/year) or wet (457 mm/year) conditions.

Uncertainty of the delineated CZ was evaluated by changing both hydraulic conductivity and rainfall recharge based on in a systematic sensitivity analysis method that maintained a good model calibration while providing CZs that accounted for uncertainty in aquifer parameters (Esling et al. 2008). Twelve CZs were delineated using combinations of rainfall recharge rates and hydraulic conductivity values for Zones 1, Zone 2 and Zones 1-2 that were 25% lower or 25% higher than values in the original model.

To represent uncertainty due to surface water features, riverbed conductance values in the nearby rivers and streams were adjusted to be 25% lower or 25% higher compared to the calibrated model. Ten CZs were delineated using combinations of 25% lower or 25% higher riverbed conductance values and 25% lower or 25% higher hydraulic conductivity and rainfall recharge values in the model.

CZ uncertainty due to model structure was investigated using MRT obtained from groundwater tracers (Table 4.2). The MRTs of 57 years for the well GS #2 and 56 years for the Blue Spring can be obtained with different values of aquifer thickness, aquifer porosity and groundwater recharge from equation (1). Therefore, four CZs were delineated with aquifer porosity of 0.05 and aquifer thickness values of 180 and 380 m below msl using 25% lower higher hydraulic conductivity and rainfall recharge values. In addition, four CZs were delineated by modifying the line-sink that represents the constant head boundary at the groundwater divide. The line-sink was extended and shortened and the groundwater heads were increased and decreased by 10 m.

The different cases listed above resulted in the sum of 42 mapped CZs that had very similar shape and extent and are therefore not individually shown. Instead, these 42 CZs were aggregated into one “combined” CZ. The combined CZs for the Putaruru well field and the Blue Spring are shown in Figure 4.3 and Figure 4.4, respectively. The combined CZ thus represents the maximum probable size, given uncertainties in rainfall recharge rates, hydraulic conductivity riverbed conductance and aquifer porosity values.

4.3 Comparison between mapped capture zones

The TOT CZs based on the groundwater flow model have similar elongated shapes due to the simplified representation of regional hydrogeology in the model. The TOT CZs extend to the model boundary, which represents the groundwater divide near the town of Mamaku. Several streams occur within the delineated CZs and may affect groundwater at the Putaruru well field and Blue Spring. The Waihou River with its tributaries and the Waimakariri stream occur within the Blue Spring CZ. The Oraka and Pokaiwhenua streams occur within the Putaruru well field CZ. The TOT CZ widens after it intersects the Pokaiwhenua stream.

For the Blue Spring, the mapped 1-year, 5-year and Total TOT CZs from the model with calibrated parameter values are 0.526 km², 2.235 km² and 63.81 km², respectively. Incorporating uncertainties to generate "combined" TOT CZs results in a 1-year TOT CZ with an area of 2.488 km², 5-year TOT CZ with an area of 11.05 km² and Total TOT CZ with an area of 91.59 km².

For the Putaruru well field, the mapped 1-year, 5-year and Total TOT CZs from the model with calibrated parameter values are 0.035 km², 0.202 km² and 7.119 km², respectively. Incorporating uncertainties to generate "combined" TOT CZs results in a 1-year TOT CZ with an area of 0.213 km², 5-year TOT CZ with an area of 1.015 km² and Total TOT CZ with an area of 70.91 km².

5.0 SUMMARY AND RECOMMENDATIONS

GNS Science has delineated the time of travel (TOT) protection zones (PZs) and capture zones (CZs) for the Putaruru well field and Blue Spring. The study consisted of a literature review of relevant information for the area of interest, sampling of groundwater age tracers and mapping of the PZs and CZs using the semi-analytic groundwater model GFLOW. The GFLOW model allowed us to represent regional groundwater flow patterns in the large modelling area of 1417 km^2 with local surface water features such as rivers and streams. The constructed model represented three hydrogeologic zones and was calibrated to groundwater heads, stream flow and the mean residence time (MRT) estimated from isotope tracers of 57 years for well GS #2 and 56 years for the Blue Spring.

The 1-year, 5-year and Total TOT CZs have been produced for both Putaruru well field and Blue Spring using values in the calibrated numerical model. The sensitivity and uncertainty in the mapped CZs were addressed by incorporating the uncertainty associated with the groundwater recharge, riverbed conductance, porosity, hydraulic conductivity and aquifer thickness in the calibrated model. This resulted in 42 mapped TOT CZs which were then aggregated into "combined" 1-year, 5-year and Total TOT CZs. The combined CZs thus represent the maximum probable size, given uncertainties in model parameters. Therefore, mapped CZs and PZs can be used for source water protection of the Putaruru well field and Blue Spring.

In addition, GNS Science recommends the following:

1) identify potential contamination sources within the mapped 1-year and 5-year CZs;
2) measure groundwater levels quarterly at nearby monitoring wells to confirm the groundwater flow direction;
3) collect groundwater chemistry data (major ions, major nutrients and isotopes) in the Putaruru well field and Blue Spring and nearby wells to identify connectivity of these wells to land-use activities and surface water features such as drains and streams;
4) collect field data on local hydrogeology (bore logs, slug tests, aquifer tests) and surface water features (water levels, flows and bed conductance) to gain better understanding of local groundwater flow patterns, and update the numerical model if relevant; and

5) refine the delineated CZs by including updated information of the area in the numerical model. The groundwater flow and transport model can be imported from the GFLOW groundwater flow model by using an extract feature. In addition, the tritium concentrations can be used as primary calibration targets for the transport model at the Blue Spring.

6.0 ACKNOWLEDGEMENTS

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FIGURES

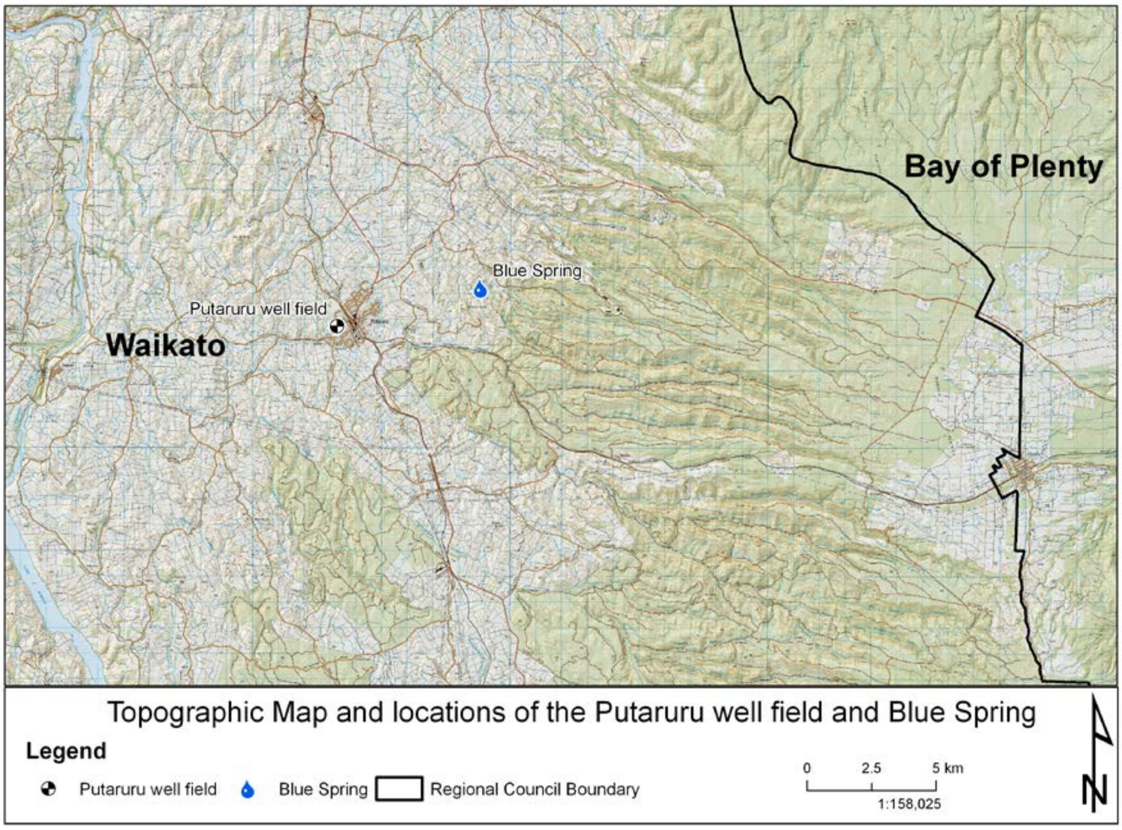

Figure 1.1 Locality map showing the Putaruru well field and Blue Spring.

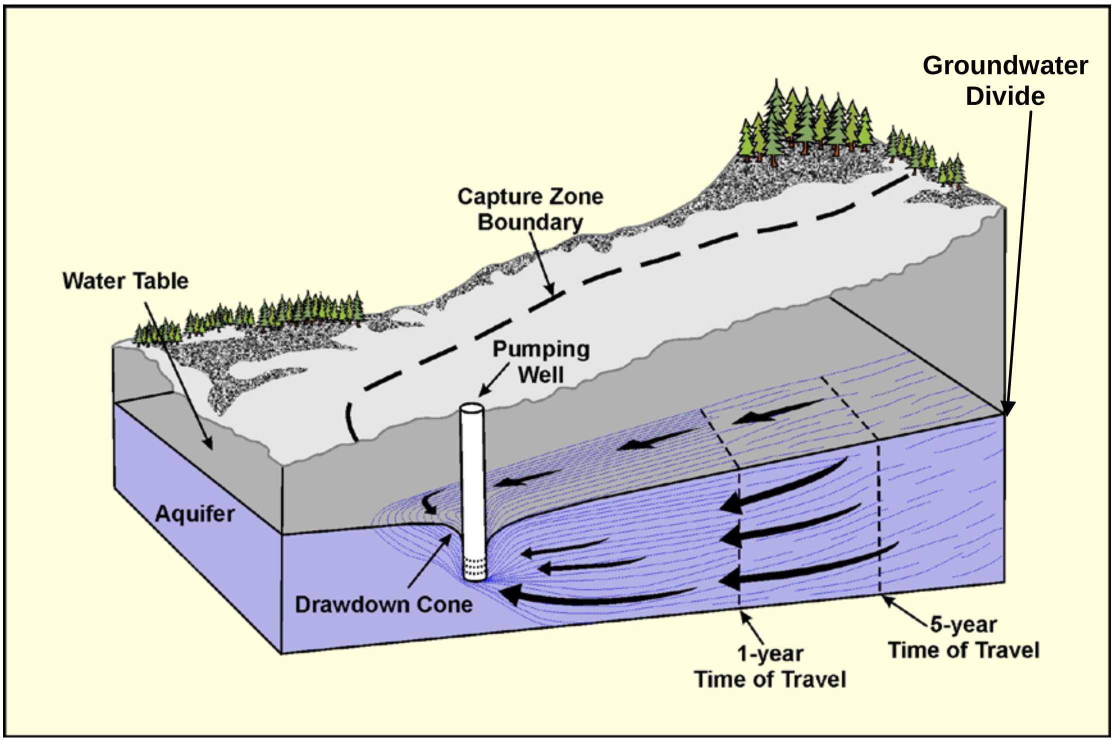

Figure 1.2 Idealised shape of the capture zone for a well in a homogeneous anisotropic unconfined aquifer. The regional groundwater flow direction is from right to left (Fetter 1994).

Figure 2.1 Aerial photo of the Putaruru well field with one observation well OB1 and three Glenshae wells GS #1, GS #2 and GS #3. (Zemansky et al. 2011).

Figure 2.2 Location map of the Blue Spring on the true right bank of the Waihou River.

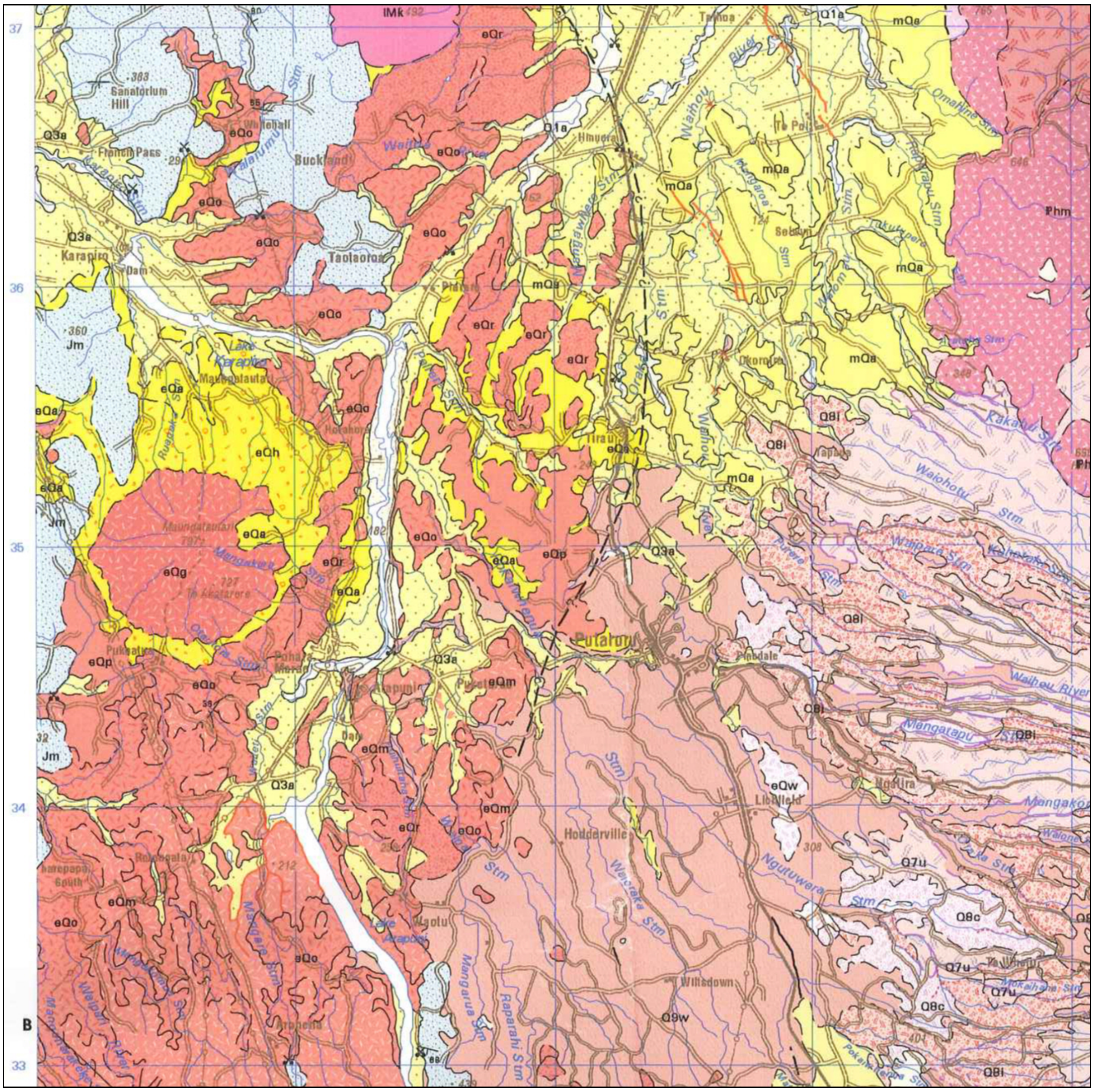

Figure 2.3 Geologic Map of Putaruru Vicinity (Leonard et al. 2010).

Light yellow (Q3a) – Fluvial sands and gravels;
Dark yellow (eQa) – Fine-grained sand and silt;
Pink (Q9w) – Variably welded ignimbrite;
Light red (eQp) – Undifferentiated ignimbrite;
Pink with white stippling (eQm) – Partly welded ignimbrite

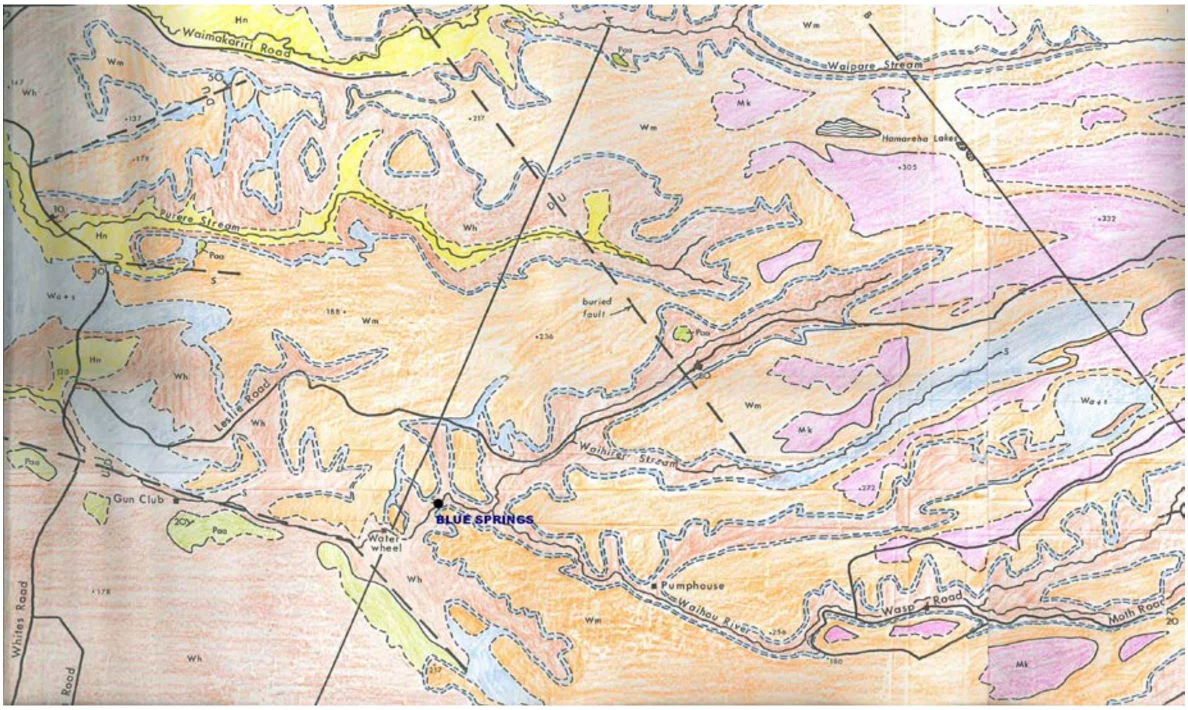

Figure 2.4 Geologic Map of Blue Springs Vicinity (Fransen 1982).

Yellow (Hn) – Fluvial sands and gravels; Green (Paa) – Mainly Ahuroa ignimbrite;
Brown (Wh) – Whakamaru ignimbrite; Purple (Mk) – Mamaku ignimbrite;
Light Orange (Wm) – Waimakariri ignimbrite; Light Blue (Wa + s) – Waihou ignimbrite and interbedded sediments

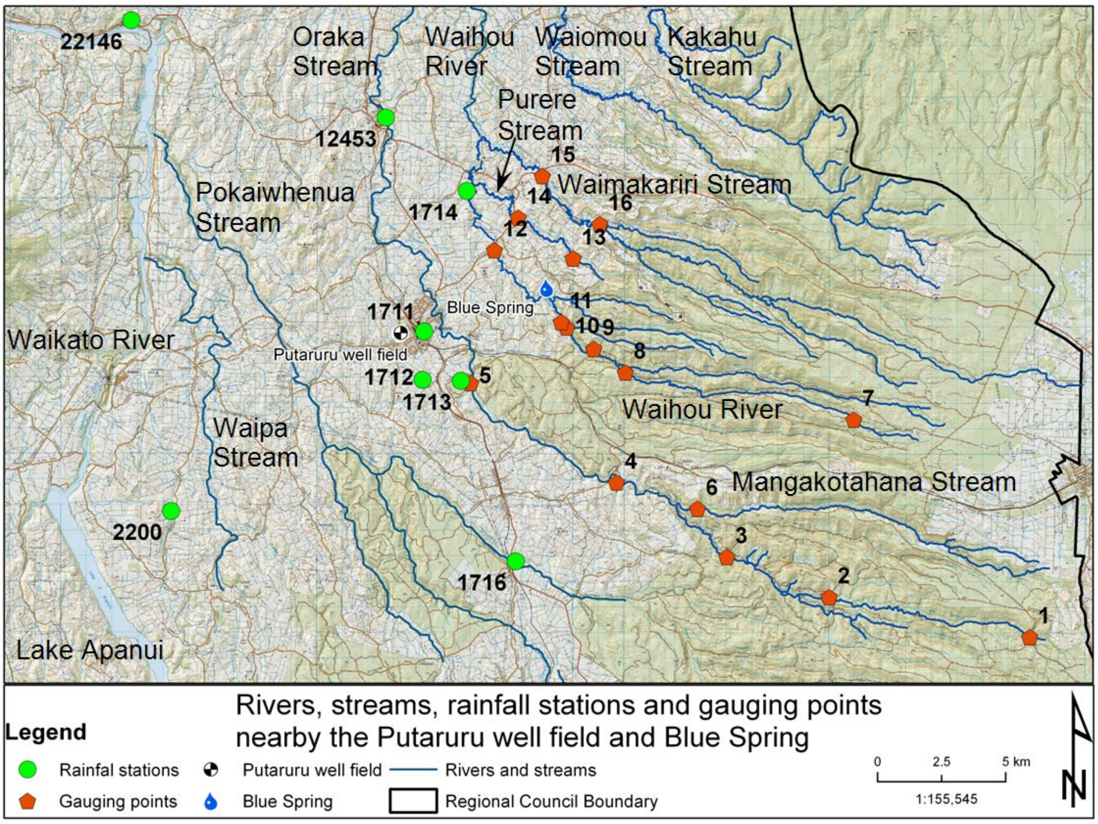

Figure 2.5 Rivers, streams, rainfall stations and stream gauging stations nearby the Putaruru well field and Blue Spring. The numbers by the gauging points and rainfall stations are site IDs.

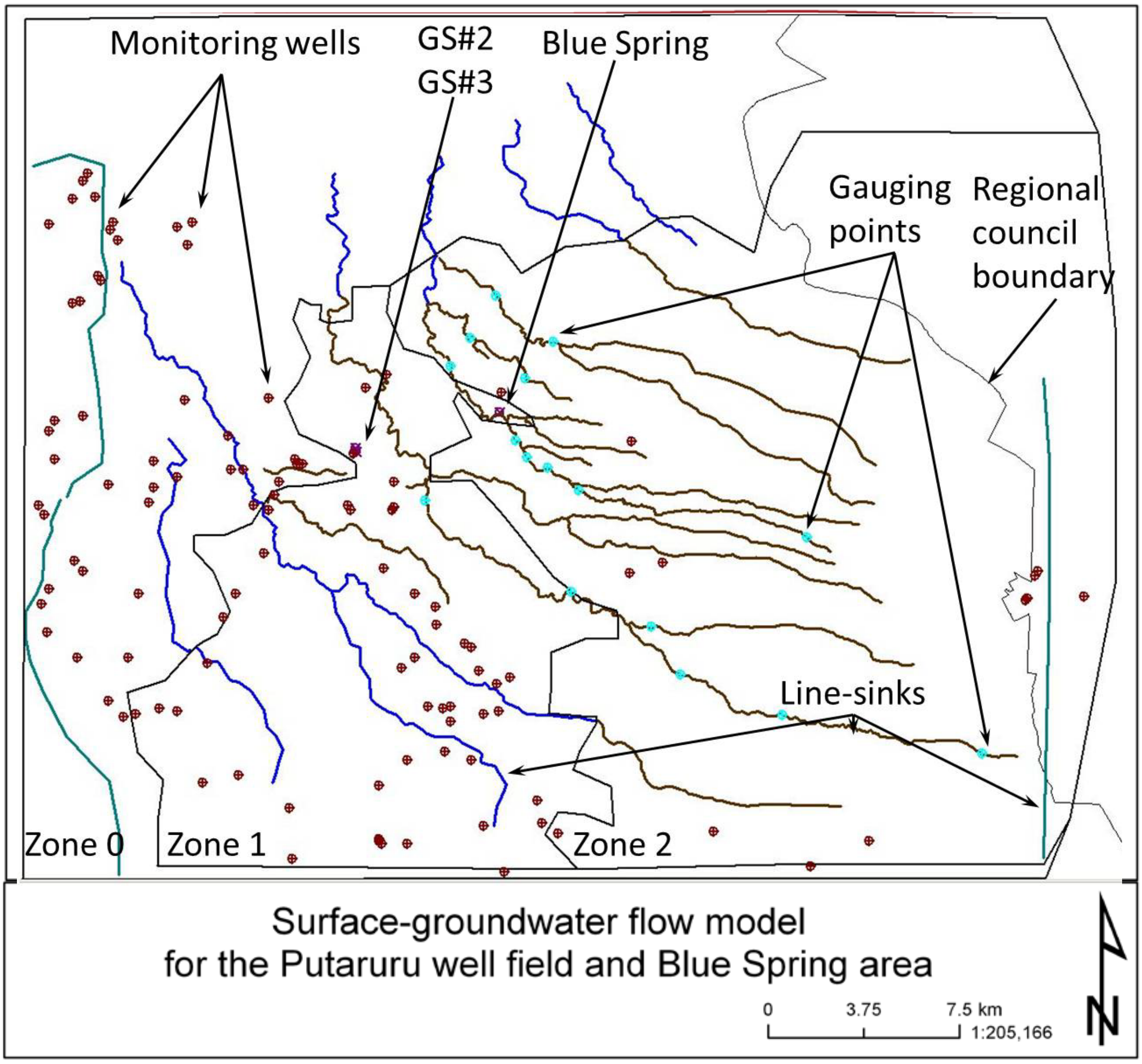

Figure 4.1 Area around the Putaruru well field and the Blue Spring as modelled in the regional surface-groundwater flow model GFLOW. Line sinks, which represent rivers and streams, are represented by the green, blue, and brown lines. Purple points represent the pumping wells GS#2, GS#3 and Blue Spring. Red points represent observation wells with known groundwater level and blue points represent gauging stations. Solid black lines represent an area of different properties (Zone 0, 1 and 2). The regional council boundary represents the location of groundwater divide that coincides with the surface water catchment boundary of the Waihou River and the Lake Rotorua.

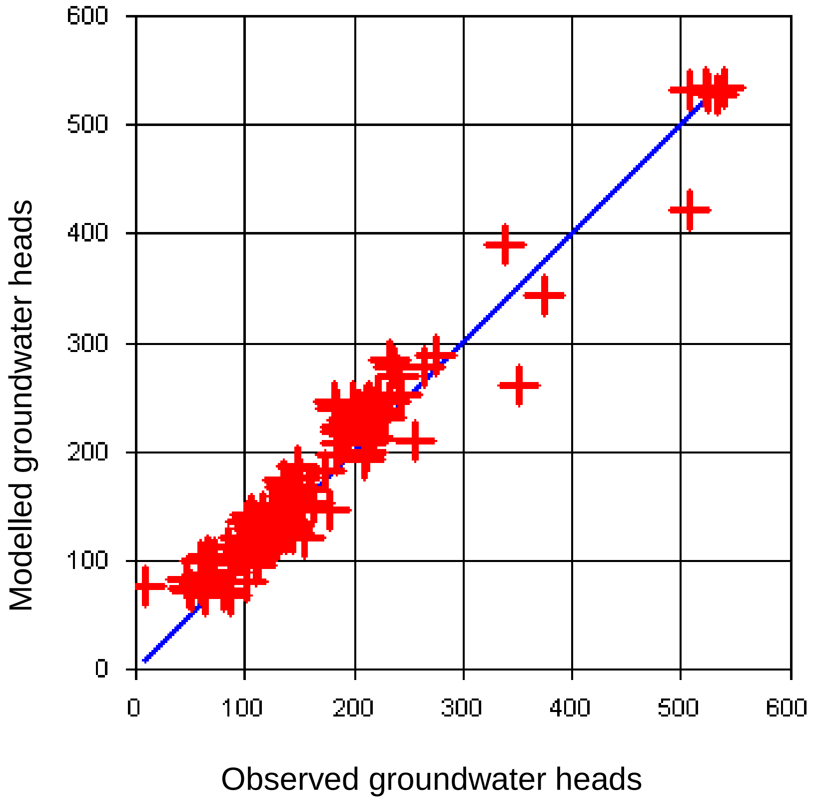

Figure 4.2 Modelled vs. observed groundwater heads in meters from the calibrated GFLOW model.

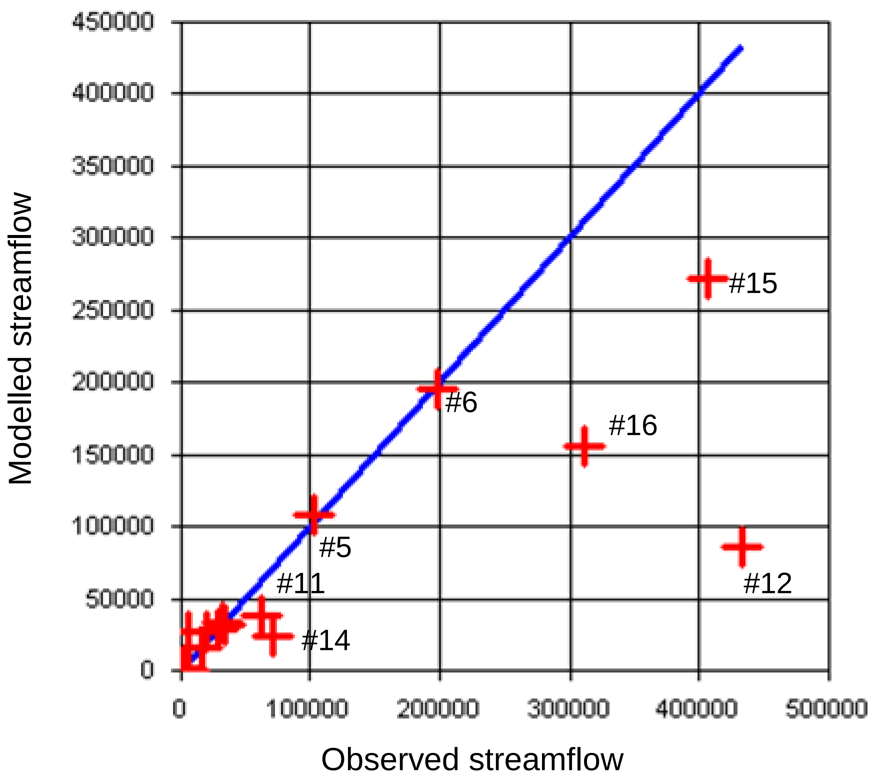

Figure 4.3 Modelled vs. observed streamflows in m^3/day from the calibrated GFLOW model.

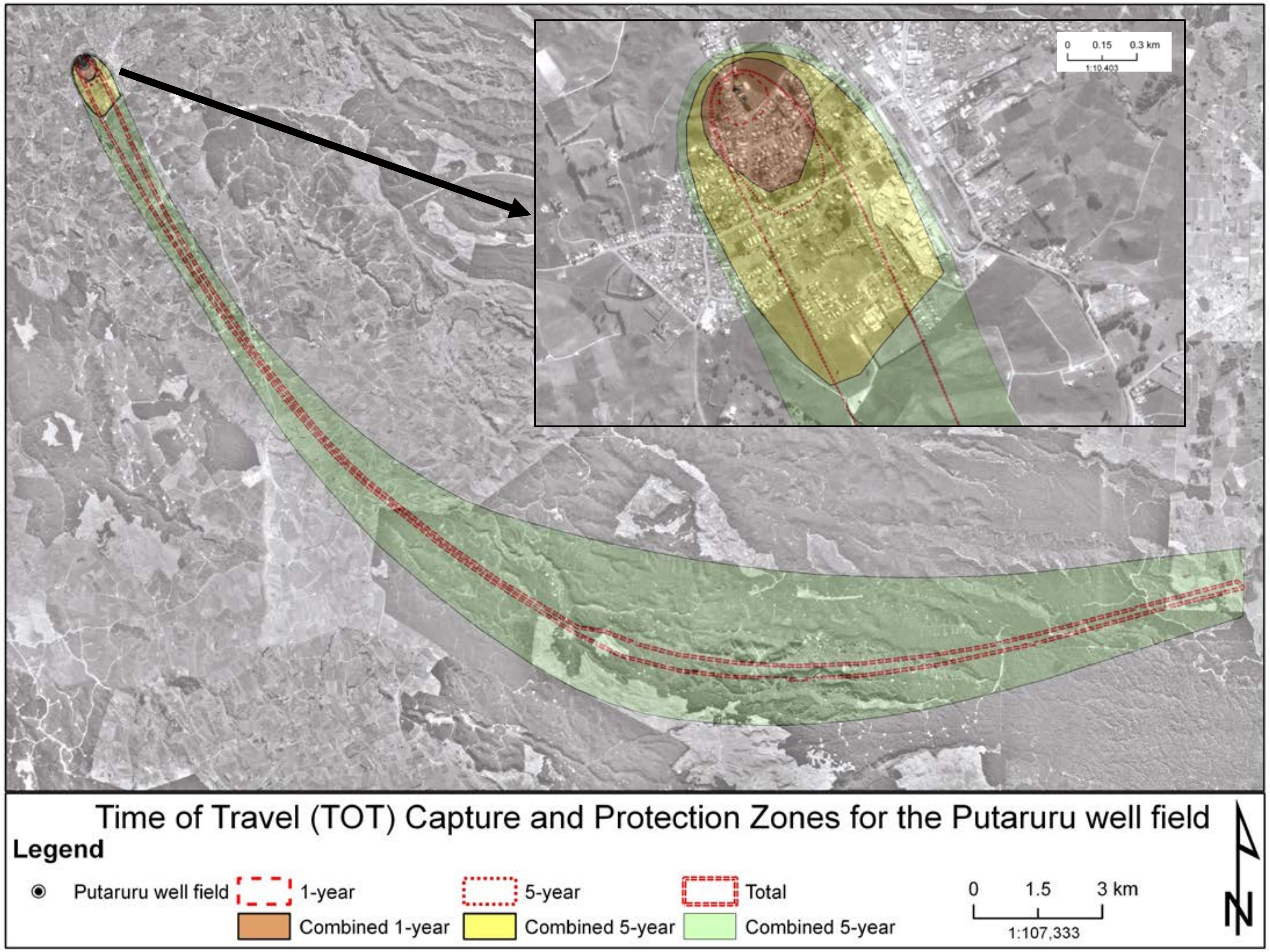

Figure 4.4 Time of Travel (TOT) Capture Zones (CZs) delineated for the Putaruru well field. Dashed lines represent TOT CZs mapped using average values in the calibrated model; solid lines represent "combined" TOT CZs based on sensitivity and uncertainty analysis.

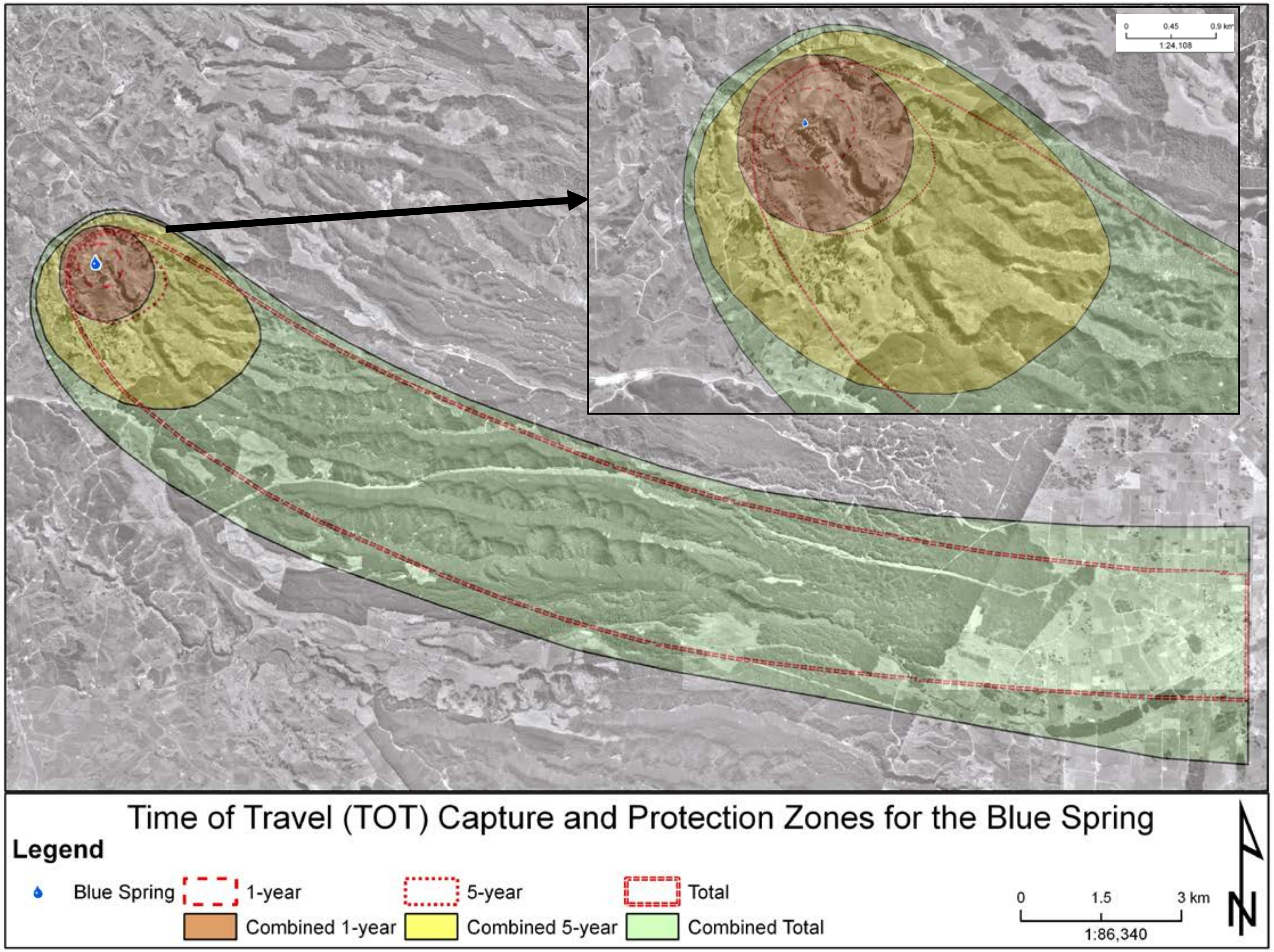

Figure 4.5 Time of Travel (TOT) Capture Zones (CZs) delineated for the Blue Spring. Dashed lines represent TOT CZs mapped using average values in the calibrated model; solid lines represent "combined" TOT CZs based on sensitivity and uncertainty analysis.

APPENDICES

APPENDIX 1 METHODOLOGY OF GROUNDWATER AGE DATING

1.1 Tritium, CFC and SF_6 method

Tritium is produced naturally in the atmosphere by cosmic rays, but large amounts were also released into the atmosphere in the early 1960s during nuclear bomb tests, giving rain and surface water high tritium concentrations (Figure 1). Surface water becomes separated from the atmospheric tritium source when it infiltrates into the ground, and the tritium concentration in the groundwater then decreases over time due to radioactive decay. The tritium concentration in the groundwater is therefore a function of the time the water has been underground. Additionally, detection of superimposed bomb tritium in the groundwater allows for establishment of groundwater mixing models and age distribution of the groundwater (Morgenstern 2004). Groundwater dating using tritium is described in more detail in Cook & Herczeg (1999), Stewart & Morgenstern (2001), and Morgenstern & Taylor (2005). The low-level tritium analysis procedure used at GNS Science is described in detail in Morgenstern & Taylor (2005).

As a result of the superimposed atmospheric tritium "bomb" peak in the 1960s, ambiguous ages can occur with single tritium determinations (i.e., the tritium concentration can indicate any of several possible groundwater ages between 0 and 40 years). This ambiguity can be overcome by using a second tritium determination after about three or more years, or combined age interpretation of tritium data and data from an independent dating method for example CFCs or SF6. CFC and SF6 concentrations in the atmosphere have risen monotonously during that time and therefore can resolve tritium ambiguity if they are not altered in the aquifer.

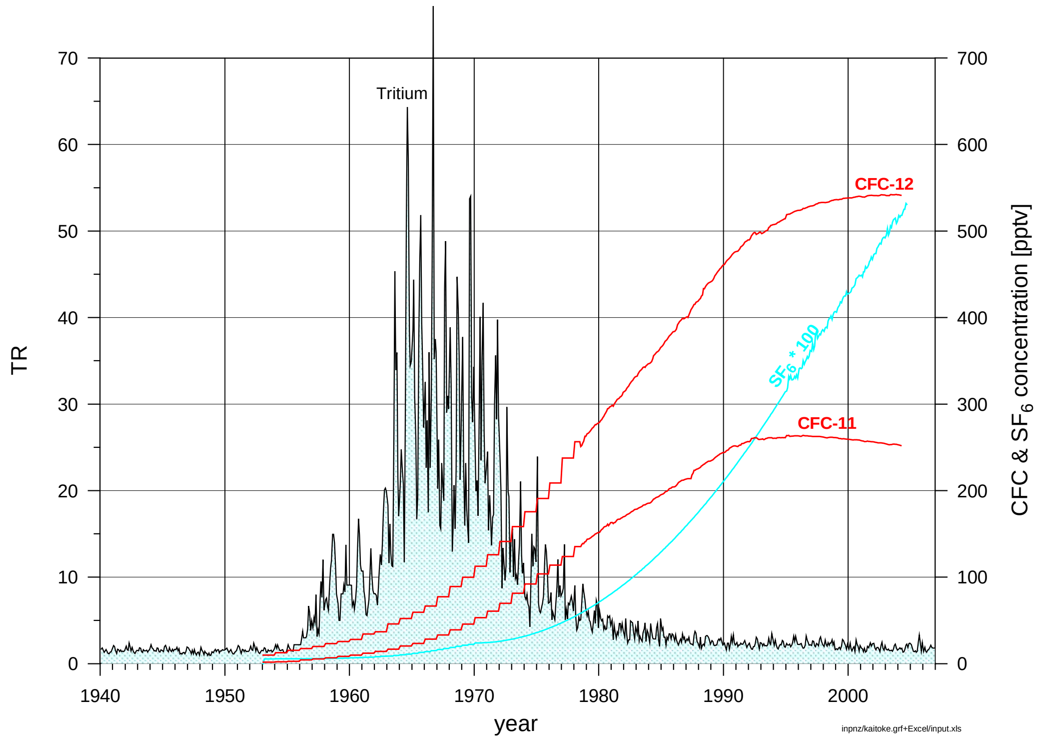

Figure A1 Tritium, CFC and SF_6 input for New Zealand rain. Tritium concentrations are from rain at Kaitoke, 40km north of Wellington (monthly data), and CFC and SF_6 concentrations are for southern hemispheric air. TR=1 represents a $^3H/^1H$ ratio of 10^{-18}, and 1 pptv is one part per trillion by volume of CFC or SF_6 in air, or 10^{-12}. Tritium data from before 1960 are reconstructed from Antarctic ice cores. Pre-1978 CFC data are reconstructed according to Plummer & Busenberg (1999), and scaled to southern hemisphere by factor 0.83 (CFC-11) and factor 0.9 (CFC-12). Post-1978 CFC data are from Tasmania. Pre-1970 SF_6 data are reconstructed (USGS Reston), 1970-1995 data are from Maiss & Brenninkmeijer (1998), and post-1995 data was measured in Tasmania.

Chlorofluorocarbons (CFCs) are entirely man-made contaminants. They were used for refrigeration and pressurising aerosol cans, and their concentrations in the atmosphere have gradually increased (Figure A1). CFCs are relatively long-lived in the atmosphere and slightly soluble in water and therefore enter the groundwater systems with groundwater recharge. Their concentrations in groundwater record the atmospheric concentrations when the water was recharged, allowing determination of the recharge date of the water. CFCs have been phased out of industrial use in the 1990s because of their destructive effects on the ozone layer. Thus rates of increase of atmospheric CFC concentrations slowed greatly in the 1990s, meaning that CFCs are not as effective for dating water recharged after 1990.

Sulphur hexafluoride (SF_6) is primarily anthropogenic in origin, but can also occur in some volcanic and igneous fluids. Significant production of SF_6 began in the 1960s for use in high-voltage electrical switches, leading to increasing atmospheric concentrations (Figure A1). The residence time of SF_6 in the atmosphere is relatively long (800-3200 years). It holds considerable promise as a dating tool for post-1970s groundwater because, unlike CFCs, atmospheric concentrations of SF_6 are expected to continue increasing for some time (Busenberg & Plummer, 1997).

Tritium is a conservative tracer in groundwater. It is not affected by chemical or microbial processes, or by reactions between the groundwater and aquifer material. Tritium is an isotope of hydrogen and therefore is a component of the water molecule. Therefore, age information is not distorted by any bio- or geo-chemical reaction occurring underground. For CFCs, a number of factors can modify the concentrations in the aquifer, including microbial degradation of CFCs in anaerobic environments (CFC-11 is more susceptible than CFC-12), and CFC contamination from local anthropogenic sources (CFC-12 is more susceptible to this) Plummer & Busenburg (1999). CFC-11 has been found in New Zealand to be less susceptible to local contamination and age estimates agree better with tritium data. Note that CFC and SF6 ages do not take into account travel time through unsaturated zones.

Tritium with its pulse-shaped input into groundwater systems (Figure A1) is very sensitive to the flow model (distribution of residence times in the sample). With a series of tritium measurements, and/or additional CFC and SF_6 measurements, age ambiguity can usually be resolved. In that case, both the mean groundwater age and the age distribution can be obtained.

1.2 Groundwater Mixing Models

Groundwater comprises a mixture of water of different ages due to mixing processes underground. Therefore, the groundwater doesn't have a discrete age but has an age distribution. Various mixing models with different age distributions describe different hydrogeological situations (Maloszewski & Zuber 1982). The piston-flow model describes systems with little mixing (such as confined aquifers and river recharge), while the exponential model describes fully mixed systems (more like unconfined aquifers and local rain recharge). Real groundwater systems which lie between these two extremes can often be described by a combination of the exponential and piston-flow models representing the recharge, flow and discharge parts of a groundwater system. The output tracer concentration can be calculated by solving the convolution integral, and the mean residence time (MRT) can be obtained from the tracer output that gives the best match to the measured data. If the second parameter in the age distribution function, the fraction of mixed flow, cannot be estimated from hydrogeologic information, then several independent tracers (tritium and CFC/SF_6) or several tritium measurements over time are necessary.

Schematic groundwater flow situations are shown in Figure A2. The unconfined aquifer situation is described by the exponential model (EM). Flow lines of different length containing water of different age converge in the well or the stream, and the abstracted water has a wide range of ages with an exponential age distribution. The confined aquifer situation is described by the piston flow model (PM) with a narrow range of ages. The partly confined aquifer situation is described by the exponential-piston flow model (EPM). The free parameter is the fraction of mixed (exponential) flow within the total flow volume (represented by E_%PM, with the fraction given in %), or the ratio η of the total flow volume to the volume of the exponential part. The water has a wide range of ages, but because part of the flow is piston flow, the age distribution has a minimum age (no water can be younger than the time necessary to pass through the piston flow part). The piston flow part can be represented by a partly confined flow with no vertical input of young water from the surface, or it can be represented by a significant unsaturated zone with vertical piston flow toward the water table and mixing of different ages below the water table.

As an example, the age distribution for the exponential-piston flow model for different fractions of mixed flow is shown in Figure A3 for water with a mean residence time of 50 years. Water with a high fraction of exponential flow of 90% has a wide range of ages, starting at 5 years and still significant contributions of old water with ages over 150 years. Despite the mean residence time of 50 years, significant fractions of the water are younger than 50 years. The discharging water can therefore partly be contaminated before the mean residence time of 50 years has elapsed. About 2% of the water can already be contaminated after five years. With each further year, increasingly contaminated water arrives at the spring or well. The total fraction of water within a certain age range can be obtained by integrating the age distribution over the specified age range. This is equal to the area below that part of the curve, with the total area below the whole curve being 100% water fraction. The fraction of water that is younger than a specified age is called the young water fraction (yf). The young water fraction younger than 40 years is 54% in the example in Figure A3 (hatched area).

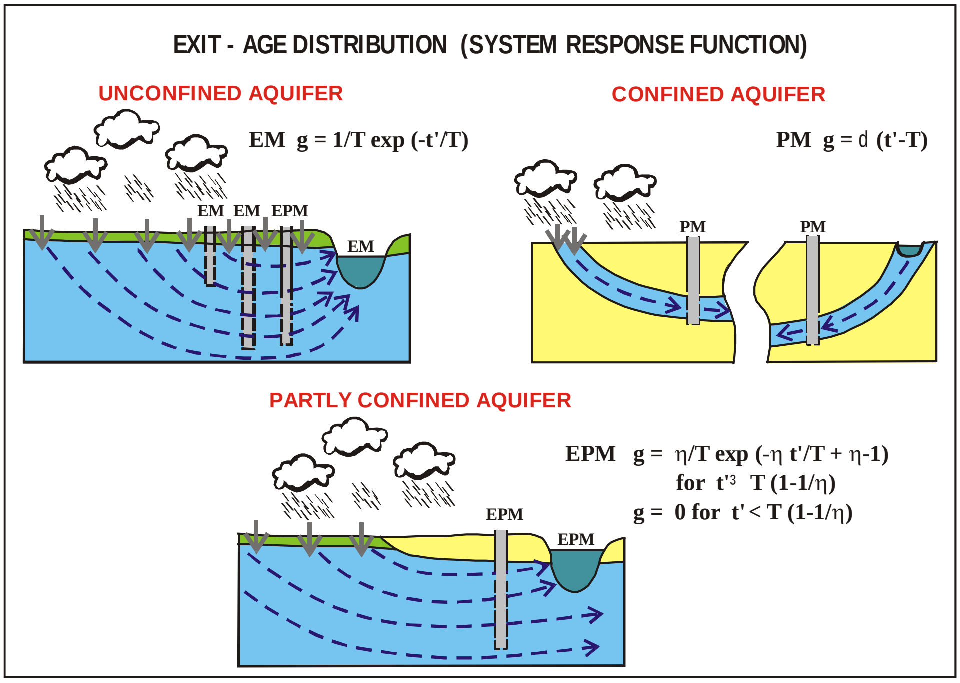

Figure A2 Schematic groundwater flow situations and corresponding age distribution functions (see Maloszewski & Zuber (1982) for theoretical background).

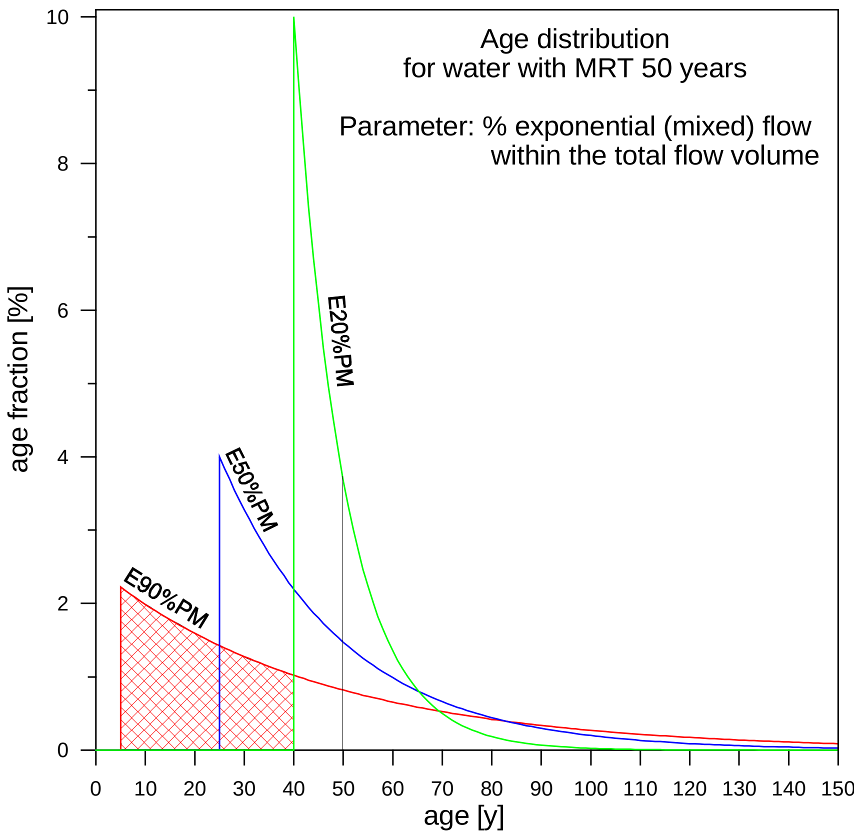

Figure A3 Age distribution for the exponential-piston flow model.

In a flow situation with less mixed (exponential) flow, the age distribution of the water is less wide-spread. At 50% exponential flow, the minimum age is 25 years, and the water does not contain significant fractions older than 150 years. At only 20% exponential flow, the age distribution is relatively peaked around the mean residence time. The minimum age is 40 years, and there is an insignificant amount of water older than 100 years. This water would just start to show a contaminant introduced 40 years ago, but this contaminant would arrive in a relatively sharp front, with 10% contribution in the first year of arrival after 40 years' time.

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