Update of the national groundwater volume stock account: 1994 to 2020

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To whom it may concern,

Update of the national groundwater volume stock account

This letter report describes the calculation of groundwater volumes in New Zealand for the period 1994 to 2020, following the same methodology as White and Reeves (2002) and the reviewed parameters from Moreau and Bekele (2015). This report updates the previous groundwater volumes stock account reports (White and Reeves 2002; White 2007; Moreau-Fournier and Cameron 2011; Moreau and Bekele 2015). The first two sections of this report provide the description of the methodology, including parameter estimation and data limitations. The estimated volumes for the period 2010 to 2020 are then presented by region and by aquifer type (confined or unconfined). Comparison of the latest results to those of White and Reeves (2002), White (2007) and Moreau and Bekele (2015) for the period 1994 to 2020 is also provided. The final part of this report is a list of recommendations to improve estimates of groundwater volume that could be incorporated in future reporting.

At Statistics New Zealand's request, the following files are provided as digital attachments to this report:

- Tabulated groundwater level time series at indicator wells (CR2020_113_LR_indicator_level_at_jun30.csv).
- Tabulated aquifer properties (CR2020_113_LR_aquifer_properties.csv).
- Tabulated groundwater volumes and annual volume changes per region per aquifer confinement status using 1994 as the reference year (CR2020_113_LR_groundwater_volumes_1994.csv).
- Tabulated groundwater volumes and annual volume changes per region per aquifer confinement status using 2003 as the reference year (CR2020_113_LR_groundwater_volumes_2003.csv).
- A new R script (CR2020_113_LR_groundwater_volume_calculations.R) reproducing calculations based on previous excel worksheets (e.g., Moreau and Bekele 2015).

1.0 METHODOLOGY

Groundwater in the saturated zone occurs within voids created by pore space and fractures in rock formations (Fetter 1994). Void spaces may have been present since the formation of an aquifer (e.g., interstices between sand grains during deposition); or through physical or chemical processes (e.g., fracturing, rock dissolution by groundwater). The saturated rock formation, through which groundwater moves, is called an aquifer (Fetter 1994). For the purpose of groundwater volume calculations in this report, aquifers have been classified as either unconfined or confined. The confinement status has implications on the way groundwater is stored and moves within the aquifer (Moreau and Bekele 2015). Semi-confined aquifers are assumed to have confined aquifer storage characteristics for the purpose of this report.

To calculate the volume of groundwater in an aquifer, the volume of saturated rock (areal extent multiplied by saturated thickness) is multiplied by the water storage parameter. The change in groundwater volume in an aquifer over time is estimated using water level measurements from an indicator well to calculate variations in saturated thickness compared to the reference year (1994) using the following equation:

Change in groundwater volume (m^3) = Groundwater volume (m^3) x Change in indicator well water level (m).

1.1 Water Level at Indicator Wells

New Zealand aquifers are numerous (more than two hundred), diverse (material, flow-process, hydraulic properties, extent) and unevenly distributed between regions (Figure 1.1 and Figure 1.2; White (2001)). The aquifers identified by White (2001) have been used to estimate the national groundwater volume stock account since the first account by White and Reeves (2002), and this report will use the aquifers for consistency. Up to 2015, previous groundwater stock-takes were based on the water level data from 15 indicator wells across the country using June 1994 as the reference date (Moreau-Fournier and Cameron 2011). in 2015, a review on the estimates identified two replacement wells and 22 new indicator wells. Northland Indicator Well 5347011 (8.8 m deep) was deemed unlikely to fully penetrate the aquifer, and therefore not a suitable representation of the aquifer. It was replaced by nearby (c. 50 m) Well 5347012 (61.4 m deep) on regional council recommendation. Decommissioned Tasman Indicator Well 6710 was replaced by nearby (c. 500 m) Well WWD6713, sunk in the Arthur Marble aquifer, also on regional council recommendation.

The 2015 calculated groundwater volumes included a revised national overview for the 2010–2014 time period using June 2003 as the reference date (Moreau and Bekele 2015, Table 1.1). This modification was necessary because water level records for all the new indicators wells were only available from 2003.

In this update, partial water level records (ending prior to 2020) were collected for eight of the 37 indicator wells, including one of the original wells (R26/6738, Table 1.1). In all cases, this corresponded to the time period when, following a network review, the water level monitoring ceased. In these instances, the corresponding aquifer was reassigned to the original indicator proxy. Water level monitoring frequency varies between regions and wells. Where measurements were not available on June 30th for each year, values were calculated using linear interpolation in R-Studio (dplyr and imputeTS packages; Wickham and Francois 2016; RStudio Team 2016; R Core Team 2017; Moritz 2020). While reconstructing time series prior to 2003, there were some differences noted on water levels at June 30th between each report. These differences may be due to the water level interpolation method or well datum correction (e.g., improved geolocation and ground elevation improvements). The water level was corrected from the offset using water level reported on June 30th 2013, which was one of the only two years for which there was a complete record across all indicator wells.

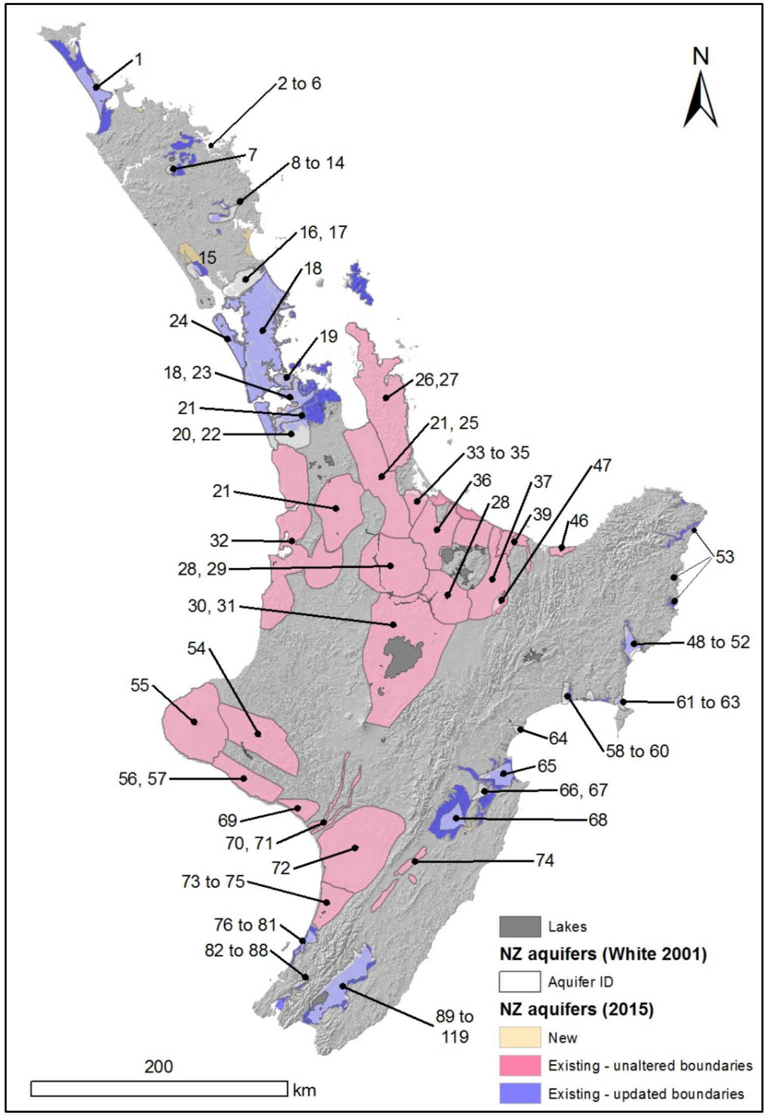

Figure 1.1 Location of North Island aquifers (from Moreau and Bekele 2015). The aquifer IDs are listed in Table 1.2. Note that some of the polygons represent more than one aquifer listed in the table (e.g., “73 to 75”).

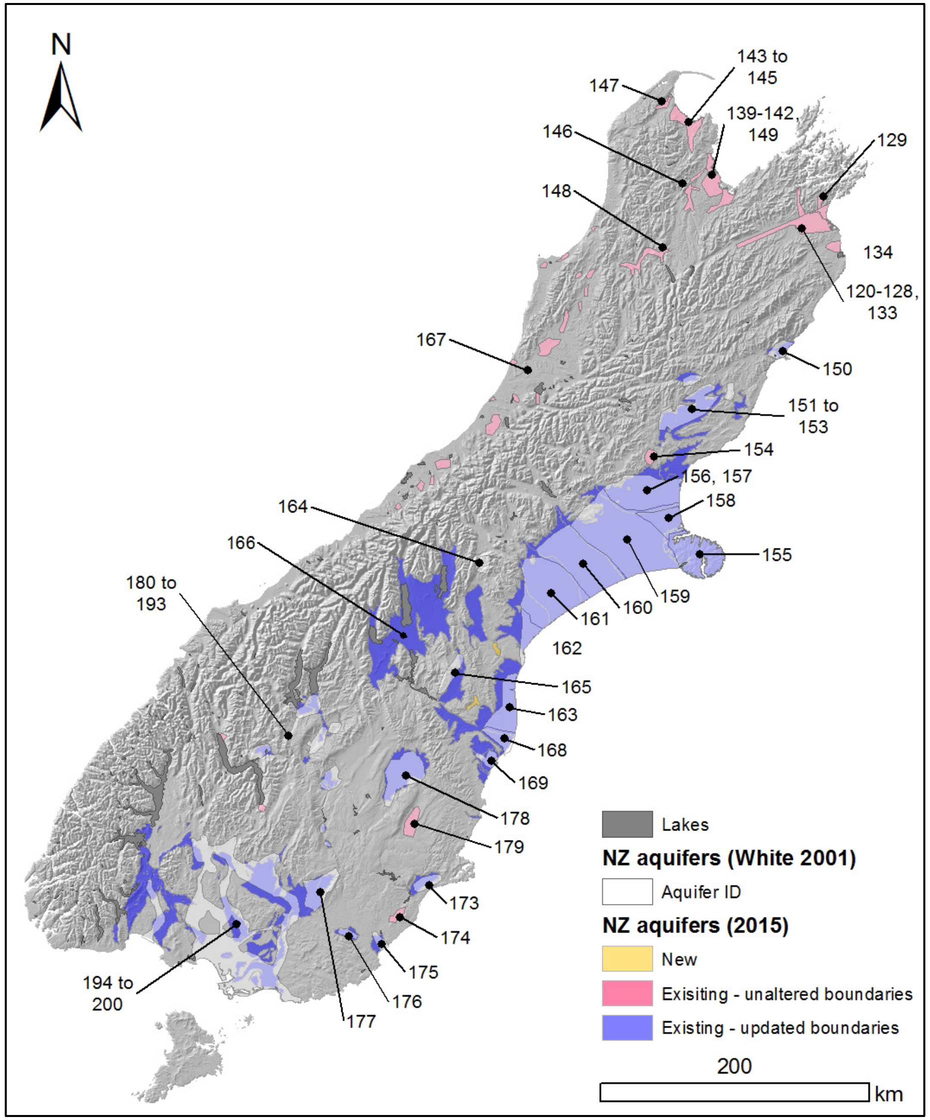

Figure 1.2 Location of South Island aquifers (Source Moreau and Bekele 2015). The aquifer IDs are listed in Table 1.3. Note that some of the polygons represent more than one aquifer listed in the table (e.g., “143 to 145”).

Table 1.1 Indicator wells used to estimate changes in groundwater volume. The asterisk indicates wells that have been replaced since 1994. Grey highlight indicates original wells used since the first stocktake in 2002. Italic font indicates wells at which the water level record did not extend to 2020 and aquifer assignment was reverted to the original well indicator proxy.

Region	**Well ID**	**Well Name**	**Easting (NZMG)**	**Northing (NZMG)**	**Aquifer Name (from White 2001)**
Auckland	6498003	6498003	2673100	6473400	Auckland volcanics
Auckland	7418027	7418027	2676400	6446700	Kaawa Formation
Bay of Plenty	Well951	Well951	2810900	6371210	Mamaku Plateau
Canterbury	M35/0931	M35/0931	2459890	5746883	Central Plains
Gisborne	*GPD147*	*GPD147*	*2029020*	*5712946*	*Matokitoki Gravel*
Gisborne	GPC062	GPC062	2035299	5708057	Te Hapara sand
Gisborne	*GPD124*	*GPD124*	*2030444*	*5712747*	*Shallow fluvial*
Gisborne	GPD130	GPD130	2940100	6268100	Makauri Gravel
Gisborne	GPF090	GPF090	2941600	6271600	Makauri Gravel
Gisborne	*GPG019*	*GPG019*	*2028836*	*5718861*	*Waipaoa Gravel*
Manawatu-Wanganui	302026	302026	2705336	6125531	Wangaehui-Turakina
Manawatu-Wanganui	304019	304019	2720848	6124639	Rangitikei
Manawatu-Wanganui	332018	332018	2700332	6090431	Coastal
Manawatu-Wanganui	336991	336991	2736800	6092600	Manawatu
Manawatu-Wanganui	338051	420075	2766498	6100097	Tararua
Manawatu-Wanganui	343171	2700337	2700337	6090412	Coastal
Manawatu-Wanganui	352311	363251	2704864	6061400	Horowhenua, Tararua, Coastal
Marlborough	*P28W/1634*	*P28W/1634*	*2596850*	*5977780*	*Rarangi Shallow*
Marlborough	P28W/3069	P28W/3069	2575839	5962765	Omaka River Valley
Marlborough	P28W/3821	P28W/3821	2577700	5968000	Wairau
Northland	5347012*	5347012*	2582818	6641058	Kaikohe
Otago	F41/0105	F41/0203	2177500	5572500	Wakatipu Basin
Otago	*G40/0120*	*G40/0120*	*2214800*	*5610600*	*Hawea Flat*
Otago	*G42/0695*	*G42/0695*	*2223600*	*5548200*	*Dunstan Flats*
Otago	G43/0157	G43/0072	2220502	5516944	Roxburgh East
Otago	G43/0158	G43/0209	2224326	5504171	Ettrick Basin
Otago	I44/0848	Momona Bore	2292700	5472500	Lower Taieri Plain
Otago	J41/0178	Webster well	2344800	5560500	Waiareka and Deborah volcanic
Taranaki	GND0508	GND0508	2604103	6231609	Taranaki Volcanic
Taranaki	GND0519	Bayly	2629100	6208900	Matemateaonga Formation
Taranaki	GND0708	Corrigan	2623900	6185600	Whenuakura Formation
Taranaki	GND1194	GND0213	2634534	6170483	Marine Terrace
Tasman	WWD6713*	WWD6713*	2718600	6573700	Takaka Valley – Arthur Marble
Waikato	69_163	Ferguson	2715600	6379500	Tauranga Group sediments – Tauranga Group
Wellington	*R26/6738*	*McCardle*	*2685700*	*6038400*	*Kapiti Coast – Waikanae*
Wellington	S26/0743	Baring	2725045	6013506	Wairarapa Valley – Parkvale
West Coast	*Hunter2*	*WCRC-Hunter2*	*2391500*	*5876900*	*West Coast alluvial (Quaternary deposits)*

Table 1.2 Regions and names of North Island aquifers (White 2001).

Region		Number on Figure 1.1	Aquifer Name
Northland		1	Aupouri
		2	Kerikeri
		3	Okaihau
		4	Waimate North
		5	Pakaraka
		6	Ngawha
		7	Kaikohe
		8	Matarau
		9	Glenbervie
		10	Three Mile Bush
		11	Maunu
		12	Whatitiri
		13	Maungatapere
		14	Maungakaramea
		15	Ruawai
		16	Tara
		17	Mangawhai
		18	Waitemata Formation
		19	Auckland volcanics
Auckland		20	South Auckland volcanics
		21	Tauranga Group sediments
		22	Kaawa Formation
		23	Greywacke
		24	Auckland coastal aquifers
Waikato		20	South Auckland volcanics
		21	Tauranga Group sediments
		22	Kaawa Formation
		25	Hinuera Formation
		26	Coromandel volcanic
		27	Coromandel sand
		28	Waiotapu Ignimbrite
		29	Whakamaru ignimbrites
		30	Taupo ignimbrites
		31	Taupo sand
		32	Otorohanga and Orahiri limestone
Bay of Plenty		33	Aongatete Ignimbrite
		34	Waiteariki Ignimbrite
		35	Western Bay Rhyolite
		36	Mamaku Plateau
Bay of Plenty		37	Matahina Ignimbrite
		38	Pongakawa Breccia
		39	Rangitaiki Plains
		46	Opotiki
		47	Galatea Basin
	Coastal Aquifers	40	Waihi Beach Rhyolite
		41	Katikati Gravel
		42	Mt Maunganui sand
		43	Matakana Island sand
		44	Maketu warm water
		45	Maketu Pumice
Gisborne		53	Waiapu and Tolaga Bay flats
	Waipaoa Valley	48	Te Hapara sand
		49	Shallow fluvial
		50	Waipaoa Gravel
		51	Makauri Gravel
		52	Matokitoki Gravel
Taranaki		54	Matemateaonga Formation
		55	Taranaki Volcanic
		56	Marine Terrace
		57	Whenuakura Formation

Region		Number on Figure 1.1	Aquifer Name
Hawke's Bay		64	Esk Valley
		65	Heretaunga Plains
		66	Poukawa Basin
		67	Papanui Stream Valley
		68	Ruataniwha Plains
	Northern Coastal	58	Wairoa Valley
		59	Nuhaka coastal
		60	Nuhaka limestone
		61	Mahia sand
		62	Mahia alluvium
		63	Mahia
Manawatu-Wanganui		69	Wanganui
		70	Wangaehui-Turakina
		71	Rangitikei
		72	Manawatu
		73	Horowhenua
		74	Tararua
		75	Coastal
Wellington		76	Waiotohu
	Kapiti Coast	77	Otaki
		78	Hautere
		79	Coastal
		80	Waikanae
		81	Raumati-Paekakariki
	Hutt Valley	82	Lower Hutt
		83	Upper Hutt
		84	Black Creek
		85	Wainuiomata
		86	Mangaroa
		87	Pakuratahi
		88	Akatarawa
	Wairarapa Valley	89	Upper Opaki
		90	Opaki
		91	Rathkeale
		92	Masterton
		93	Te Ore Ore
		94	Upper Plain
		95	Fernridge
		96	West Taratahi
		97	East Taratahi
		98	Mangatarere
		99	Carterton
		100	Parkvale
		101	Matarawa
		102	Fern Hill
		103	Hodders
		104	Greytown
		105	Middle Ruamahanga
		106	Moroa
		107	Ahikouka
		108	Battersea
		109	Tauherenikau
		110	Woodside
		111	Te Maire Ridge
		112	South Featherston
		113	Riverside
		114	Tawaha
		115	Mangaroa
		116	Martinborough Terraces
		117	Huangarua
		118	Lower Valley
		119	Pirinoa Terraces

Table 1.3 Regions and names of South Island aquifers (White 2001).

Region		Number on Figure 1.2	Aquifer Name
Marlborough		120	Wairau
		128	Rarangi Shallow
		129	Tuamarino Valley
		130	Rai Valley
		131	Pelorus Valley
		132	Kaituna Valley
		133	Upper Wairau Valley
		134	Lower Awatere Valley
	Southern Valleys	121	Benmorven
		122	Brancott
		123	Fairhall River Gravels
		124	Taylor – Burleigh
		125	Omaka – Hawkesbury
		126	Omaka River Valley
		127	Deep Wairau
Tasman		146	Motueka River Terraces
		147	Aorere Gravel
		148	Buller River Terraces
		149	Marahau River
	Waimea Plains	135	Appleby Gravel Unconfined
		136	Hope Minor Confined and Unconfined
		137	Upper Confined
		138	Lower Confined
	Moutere Valley	139	Shallow Moutere
		140	Middle Moutere
		141	Deep Moutere
		142	Motueka/Riwaka Plains
	Takaka Valley	143	Arthur Marble
		144	Takaka Limestone
		145	Takaka Valley Gravel
Canterbury	North Canterbury	150	Kaikoura Plain
		151	Hanmer Basin
		152	Parnassus Basin
		153	Culverden Basin
		154	Waipara Basin
		155	Banks Peninsula
	Canterbury Plains	156	Ashley Downs
		157	Waimakariri-Ashley plains
		158	Christchurch-West Melton
		159	Central Plains
Canterbury	Canterbury Plains	160	Rakaia-Ashburton plains
		161	Ashburton-Rangitata plains
		162	Rangitata-Levels plains
		163	South Canterbury
	South Canterbury	164	Fairlie Basin
		165	Hakataramea Basin
		166	MacKenzie Basin
West Coast		167	West Coast alluvial

Region		Number on Figure 1.2	Aquifer Name
Otago		168	Lower Waitaki Alluvium
		169	Papakaio
		170	Waiareka and Deborah volcanic
		171	Kakanui-Kauru Alluvium
		172	Shag Alluvium
		173	Lower Taieri Plain – East and West
		174	Tokomairiro Basin
		175	Lower Clutha Plain
		176	Kuriwao Basin
		177	Pomahaka Basin
	Central Otago aquifers	178	Maniototo Basin
		179	Strath Taieri Basin
		180	Ettrick Basin
		181	Roxburgh East
	Alexandra Basin	182	Dunstan Flats
		183	Earnscleugh Terrace
		184	Manuherikia Alluvium
		185	Springvale Terrace
		186	Kingston
		187	Pisa Terrace
	Upper Clutha Valley	188	Lindis Valley
		189	Lowburn Valley
		190	Wanaka Basin
		191	Hawea Basin
		192	Glenorchy
		193	Wakatipu Basin
Southland		194	Southland colluvial
		195	Southland alluvial
		196	Coastal aquifers
		197	Tertiary lignite measures
		198	Tertiary limestone
		199	Chatton Formation
		200	Caples and Murihiku Terrain

1.2 Aquifer Parameter Estimation

1.2.1 Aquifer Area

Aquifer area was estimated using the 2015 aquifer map polygon boundaries shown on Figure 1.1 and Figure 1.2 for the aquifers identified in the 2001 map of White (2001). For polygons containing more than one aquifer, the areal extent for each aquifer was based on geological information and experience (White and Reeves 2002). New aquifers shown on the 2015 aquifer map were not used in the groundwater volume calculations, because the necessary hydrogeological information (confinement status, aquifer properties and indicator wells) were not available (Moreau and Bekele 2015).

1.2.2 Saturated Aquifer Thickness

Saturated aquifer thickness was initially based on a winter (June) groundwater level measurement from the indicator wells and information obtained from existing reports, geophysical survey data, and geological maps (White and Reeves 2002). These values were reviewed by regional authorities in 2015 and subsequently updated (Moreau and Bekele 2015). Assigned saturated aquifer thicknesses range from less than 1 m to 800 m.

1.2.3 Storage (Porosity and Storage Coefficient)

Individual aquifer volume and condition (unconfined or confined) for the two hundred aquifers used in this report are the same as those used by Moreau and Bekele (2015). Most aquifers in New Zealand do not have measured values of porosity or storage coefficient (White and Reeves 2002). Where available, the value for storage used in the calculations was the mid-point of the range of measured or reported values collated for the 2015 reporting. For the 143 unconfined aquifers, there were 31 measured porosity coefficients ranging from 0.05 to 0.3. Where no measured or reported values were available, a porosity of 0.2 (average) was attributed to unconfined aquifers, as per previous reports (e.g., Moreau and Bekele 2015). Unconfined aquifers commonly have a larger porosity than 0.2 with recorded values up to 0.36 for coarse gravel and up to 0.6 for silt (Domenico and Schwartz 1990). A relatively conservative estimate of porosity has been chosen because porosity usually declines with depth as a function of increasing overburden pressure, and some of the aquifers are up to 350 m thick. In addition, the wide range of aquifer materials considered in this report means that a high estimate is not appropriate (White and Reeves 2002). For the 64 confined aquifers, there were 35 measured storage coefficients ranging from 0.00005 to 0.04. Where no measured or reported values were available, a storage coefficient of 0.008 was attributed to confined aquifers, as in previous reports (e.g., Moreau and Bekele 2015).

1.3 Changes in Groundwater Volumes

Two sets of New Zealand groundwater volumes were calculated as follow:

1. Groundwater volumes for the 1995 to 2020 period compared to the 1994 levels, using the original 15 indicator wells. These volumes are consistent with the approach used previously (White and Reeves 2002; White 2007; Moreau-Fournier and Cameron 2011; Moreau and Bekele 2015). These are only reported as annual changes in this report.
2. Groundwater volumes for the 2010–2020 period compared to the 2003 levels, using the 15 original indicators wells. These calculations are considered as a refinement of the assessment.

Groundwater volumes were calculated using a customised R script run in R-Studio (dplyr and imputeTS packages; Wickham and Francois 2016; RStudio Team 2016; R Core Team 2017; Moritz 2020). Estimates of groundwater volume are reported in m^3 to be consistent with previous reports, and for ease of comparison with estimates of water storage for surface water features.

2.0 DATA LIMITATIONS

Data limitations for the estimation of aquifer volumes are summarised below:

- All of the values used in this report are based on a mixture of often scarce measurements and expert knowledge applied over large scales. Therefore, all results must be considered in the qualitative sense. And similarly, the uncertainty of these results must also be considered in qualitative terms such as low, medium and high reliability rather than attributing standard error terms to these results. It is also important to keep in mind that the results represent analyses at a regional scale and cannot be considered indicative at sub-regional scales, except in an average sense. Finally, it is important to realise when combining uncertainties, that they can propagate through to the uncertainty of the final product. For example, combining a high reliability result and a low reliability result could give a low reliability result.
- The groundwater volume calculation is based on the 200 aquifers identified by White (2001) and their 2015 revised boundaries (Moreau and Bekele 2015). During the 2015 update, new aquifers were identified, however suitable indicator wells were not systematically identified, because regional aquifer shapefiles became available only as a result of or after the December 2014 consultation undertaken as part of the 2015 update (Moreau and Bekele 2015). It will be useful in the future to identify such wells and integrate these to future groundwater stock take assessment.
- Aquifer delineation was largely based on the geological map (White 2001; Moreau and Bekele 2015). Limitations exist in using a geological map to delineate aquifer boundaries, as key hydrogeological parameters such as hydraulic conductivity, transmissivity, storage coefficient and groundwater level may not be available for all geological units. It was beyond the scope of this study to acquire comprehensive hydrogeological parameters that defined the heterogeneity of all mapped aquifers. Rather a simple, lumped, model approach was applied. The calculations assume uniform values for thickness, storage coefficient and porosity throughout an aquifer. Measured or reported storage coefficient were available for 20% of the unconfined aquifers and 55% of the confined aquifers.
- These volume estimates do not reflect the amount of water that can be abstracted from an aquifer which is constrained by physical, hydrochemical, and/or economic constraints. It was beyond the scope of this project to estimate sustainable aquifer yield as this requires knowledge of spatiotemporal aquifer recharge and existing groundwater abstraction and their effect on discharge environs.
- It is assumed that an indicator well(s) assigned to a region is/are representative of all groundwater changes in all aquifers in that region. Generally, there are different responses (in amplitude and response times) in different aquifers depending on characteristics such as confining nature, depth, porosity, abstraction, and location of the recharge zone.
- Although uncertainty is not quantifiable for New Zealand aquifer parameters and areas, trends in groundwater volumes can be considered, because aquifer area, aquifer thickness, and porosity/storage coefficient are constant numbers/values.

3.0 GROUNDWATER VOLUMES

3.1 Annual Changes in Groundwater Volumes (Relative to 1994)

A reference date of June 1994 was used in this project to create consistency with previous reports (White and Reeves 2002; White 2007; Moreau-Fournier and Cameron 2011; Moreau and Bekele 2015). Unlike the previous reports, this was done by offsetting water level using overlapping years and revised values for aquifer thickness, porosity, storage coefficient, and aquifer areas. Annual changes in groundwater volumes are reported per region for the 2015 to 2020 period in Table 3.1 and in the digital file for the full time period. The changes in groundwater volume for all regions during the period 2015 to 2020 are less than 1% (Table 3.1 and Figure 3.1). The largest change in groundwater volume on a yearly basis occurred in Waikato, with a loss of 3.3 x 10^9 m^3 in 2020. The second largest variation occurred in Wellington, with a 2.9 x 10^9 m^3 decrease in 2016. The largest annual gain in groundwater volume was observed in Tasman with a 1.5 x 10^9 m^3 increase in 2016.

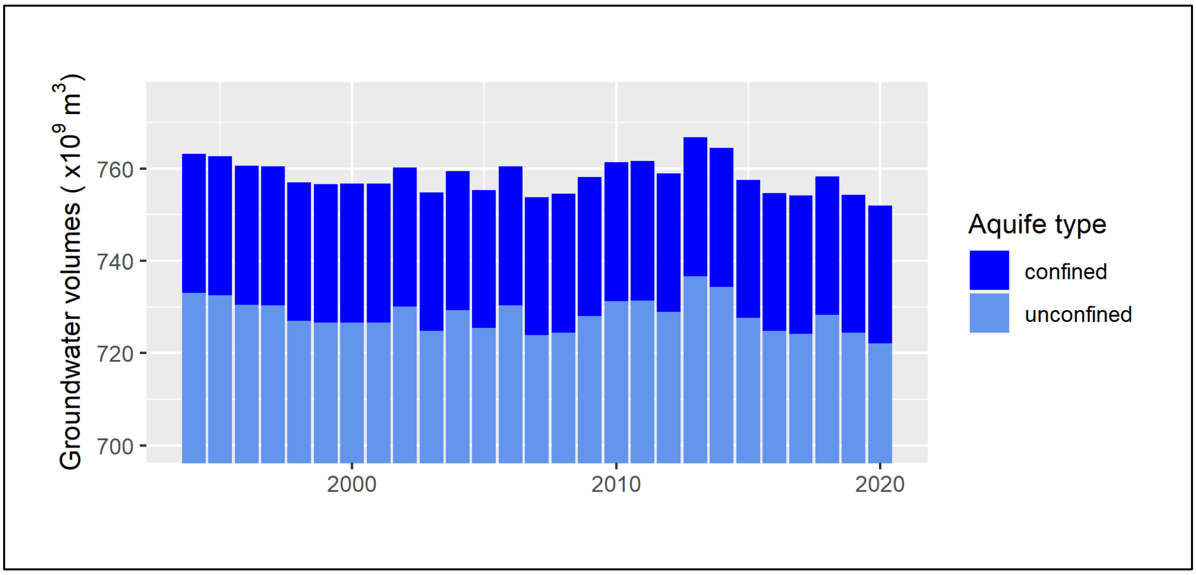

Figure 3.1 Variation of groundwater volumes over the 1994–2020 period based on this study's estimates. Changes in total volume are of less than 1%.

Table 3.1 Summary of groundwater volume changes in 10^9 m^3 of water for each region, relative to 1994, using the original 15 indicator wells or their replacement.

Region	Aquifer Condition	June 2015	June 2016	June 2017	June 2018	June 2019	June 2020
Auckland	Unconfined	-0.04	0.06	0.00	0.00	-0.01	0.05
	Confined	0.00	0.01	0.00	0.00	0.00	0.01
	Total Volume	-0.05	0.07	0.00	0.00	-0.01	0.06
Bay of Plenty	Unconfined	-0.11	-0.11	0.05	0.02	-0.09	-0.17
	Confined	-0.02	-0.02	0.01	0	-0.02	-0.03
	Total Volume	-0.13	-0.13	0.06	0.02	-0.1	-0.2
Canterbury	Unconfined	-1.82	-2.75	-2.64	0.77	-0.77	-2.45
	Confined	-0.01	-0.02	-0.02	0.01	-0.01	-0.02
	Total Volume	-1.83	-2.77	-2.66	0.78	-0.78	-2.47
Gisborne	Unconfined	-0.02	-0.04	0.00	0.01	-0.02	-0.03
	Confined	0.00	0.00	0.00	0.00	0.00	0.00
	Total Volume	-0.02	-0.04	0.00	0.01	-0.02	-0.03
Gisborne	Unconfined	-0.02	-0.05	0.00	0.01	-0.03	-0.03
	Confined	0.00	0.00	0.00	0.00	0.00	0.00
	Total Volume	-0.02	-0.05	0.01	0.01	-0.03	-0.03
Hawke's Bay	Unconfined	1.05	-0.14	-0.12	-0.01	-0.43	-0.62
	Confined	0.00	0.00	0.00	0.00	0.00	0.00
	Total Volume	1.06	-0.14	-0.12	-0.01	-0.43	-0.62
Manawatu-Wanganui	Unconfined	-0.06	-0.03	-0.06	-0.06	-0.07	-0.05
	Confined	0.00	0.00	0.00	0.00	0.00	0.00
	Total Volume	-0.06	-0.03	-0.07	-0.06	-0.08	-0.06
Marlborough	Unconfined	-0.04	0.06	0.00	0.00	-0.01	0.05
	Confined	0	0.01	0.00	0.00	0	0.01
	Total Volume	-0.05	0.07	0.00	0.00	-0.01	0.06
Northland	Unconfined	0.04	0.14	0.17	0.22	-0.01	0.1
	Confined	0.01	0.05	0.06	0.07	0	0.03
	Total Volume	0.05	0.18	0.22	0.29	-0.01	0.14
Otago	Unconfined	-0.04	-0.54	-0.49	-0.13	-0.24	-0.42
	Confined	0.00	0.00	0.00	0.00	0.00	0.00
	Total Volume	-0.04	-0.54	-0.49	-0.13	-0.24	-0.42
Southland	Unconfined	-0.21	-0.31	-0.84	-1.01	-0.5	-0.72
	Confined	-0.01	-0.02	-0.05	-0.06	-0.03	-0.04
	Total Volume	-0.22	-0.33	-0.89	-1.07	-0.53	-0.76
Taranaki	Unconfined	-0.37	-0.99	-0.69	-0.36	-0.93	-0.76
	Confined	0.00	0.00	0.00	0.00	0.00	0.00
	Total Volume	-0.37	-0.99	-0.69	-0.36	-0.93	-0.76
Tasman	Unconfined	0.4	1.49	-0.34	-0.34	0.00	0.32
	Confined	0.01	0.02	0.00	0.00	0.00	0
	Total Volume	0.41	1.51	-0.35	-0.35	0.00	0.32
Waikato	Unconfined	-1.46	-2.07	-1.11	-0.96	-2.65	-3.14
	Confined	-0.07	-0.1	-0.05	-0.05	-0.13	-0.15
	Total Volume	-1.53	-2.17	-1.16	-1	-2.78	-3.29
West Coast	Unconfined	-0.2	-0.29	-0.06	-0.1	-0.18	-0.27
	Confined	0.00	-0.01	0.00	0.00	0.00	-0.01
	Total Volume	-0.2	-0.29	-0.07	-0.1	-0.18	-0.27
Wellington	Unconfined	-0.05	-0.07	-0.2	-0.24	-0.12	-0.17
	Confined	-0.05	-0.07	-0.2	-0.24	-0.12	-0.17
	Total Volume	0.04	0.14	0.17	0.22	-0.01	0.1
New Zealand Total	**Unconfined**	**-2.91**	**-5.7**	**-6.33**	**-2.18**	**-6.05**	**-8.36**
	Confined	**-0.09**	**-0.09**	**-0.05**	**-0.03**	**-0.19**	**-0.21**
	Total Volume	**-3**	**-5.79**	**-6.38**	**-2.21**	**-6.24**	**-8.57**

3.2 Revised Groundwater Volumes (2015 to 2020)

The estimated groundwater volume in New Zealand aquifers is between 760 x 10^9 m^3 and 766 x 10^9 m^3 for the 2015 to 2020 period, of which less than 4% (c. 30 x 10^9 m^3) is stored in confined aquifers. The remaining 96% (c. 730 x 10^9 m^3) is stored in unconfined aquifers (Table 3.2). These aquifers are close to the land surface, under the direct influence of the climate. Recharge is mainly due to percolation through the unsaturated zone of water in excess of field capacity. Note that this estimate is based on an incomplete record at well R26/6738 (ending in 2014), which affects the volume calculated for the Wellington region (6.0 x 10^9 m^3 on average over the 2010–2014 period with full record and 3.3 x 10^9 m^3 on average over the 2015–2020 period).

Canterbury region has the largest calculated groundwater storage. The average groundwater volume for Canterbury during the period 2015–2020 is estimated to be 514 x 10^9 m^3 (Table 3.2), or approximately 74% of New Zealand's groundwater. Waikato has approximately 34.1 x 10^9 m^3 of groundwater (5%), which is the second-largest regional groundwater volume, closely followed by Bay of Plenty and Taranaki, with 31.5 x 10^9 m^3 (5%) and 25.0 x 10^9 m^3 (4%), respectively. All other regions have more than 1 x 10^9 m^3 of groundwater (Figure 3.2), with the exception of Marlborough (0.60 x 10^9 m^3). These values are similar to previous groundwater volumes estimated for the 1994–2001 (White and Reeves 2002), 2002–2005 (White 2007), 2005–2010 (Moreau-Fournier and Cameron 2011) and 2010–2014 (Moreau and Bekele 2015) periods.

The mean annual groundwater storage volume for all of New Zealand (c. 763 x 10^9 m^3 of water) for the period 2015 to 2020 is considerably greater than the allocated consumptive annual groundwater use (0.5 x 10^9 m^3) estimated in 2010 (Aqualinc Research Ltd. 2010), or the modelled maximum annual volume for consumptive non-hydropower from groundwater takes (43 x 10^9 m^3) in 2018 (Booker and Henderson 2019). The same comparison at the regional level indicated that the 2010 regional allocated annual groundwater use represents 0.3 to 10% of the 2010 calculated groundwater volume, with most regions under 0.5% (Aqualinc Research Ltd. 2010). Unfortunately, there was no regional breakdown of the modelled maximum annual volume for consumptive non-hydropower from groundwater takes (Booker and Henderson 2019).

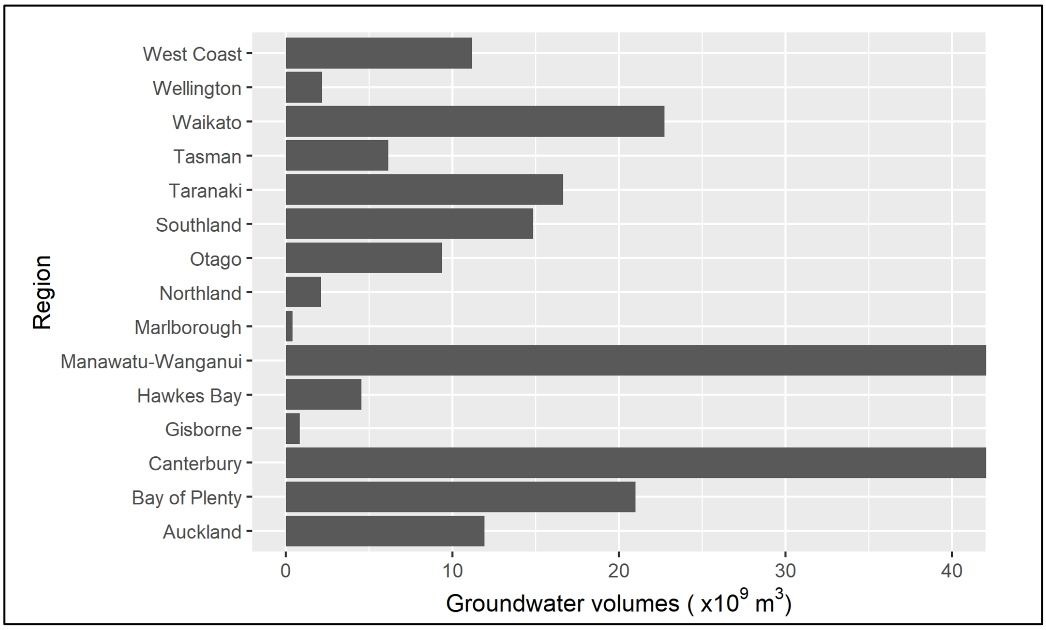

Figure 3.2 Distribution of revised groundwater volumes by region (2010–2017 averages). Canterbury is not completely shown with an average volume of 517 x 10^9 m^3.

Table 3.2 Summary of groundwater volumes in 10^9 m^3 of water for each region, using the 37 indicator wells and revised parameters for the 2015–2020 period, relative to 2003.

Region	Aquifer Condition	June 2015	June 2016	June 2017	June 2018	June 2019	June 2020
Auckland	Unconfined	5.99	6.09	6.03	6.03	6.02	6.08
	Confined	11.85	11.86	11.85	11.85	11.85	11.86
	Total Volume	17.83	17.95	17.88	17.88	17.87	17.94
Bay of Plenty	Unconfined	28.5	28.5	28.6	28.6	28.5	28.4
	Confined	2.95	2.95	2.98	2.97	2.95	2.94
	Total Volume	31.4	31.4	31.6	31.6	31.5	31.4
Canterbury	Unconfined	514	513	514	517	516	514
	Confined	2.45	2.44	2.44	2.46	2.45	2.44
	Total Volume	517	516	516	520	518	516
Gisborne	Unconfined	1.07	1.33	1.27	1.28	1.26	1.24
	Confined	0.01	0.01	0.01	0.01	0.01	0.01
	Total Volume	1.09	1.34	1.29	1.29	1.27	1.25
Gisborne	Unconfined	6.74	6.71	6.77	6.77	6.73	6.73
	Confined	0.09	0.09	0.09	0.09	0.09	0.09
	Total Volume	6.83	6.8	6.85	6.86	6.82	6.81
Hawke's Bay	Unconfined	66.6	65.5	65.5	65.6	65.3	65.1
	Confined	0.07	0.07	0.07	0.07	0.07	0.07
	Total Volume	66.7	65.6	65.6	65.7	65.4	65.2
Manawatu-Wanganui	Unconfined	0.54	0.57	0.54	0.55	0.53	0.55
	Confined	0.05	0.05	0.05	0.05	0.05	0.05
	Total Volume	0.59	0.62	0.59	0.6	0.58	0.6
Marlborough	Unconfined	5.99	6.09	6.03	6.03	6.02	6.08
	Confined	11.85	11.86	11.85	11.85	11.85	11.86
	Total Volume	17.83	17.95	17.88	17.88	17.87	17.94
Northland	Unconfined	1.69	1.78	1.81	1.86	1.64	1.75
	Confined	1.39	1.42	1.43	1.45	1.37	1.41
	Total Volume	3.07	3.2	3.25	3.31	3.01	3.16
Otago	Unconfined	14.34	13.85	13.9	14.25	14.14	13.97
	Confined	0.01	0.01	0.01	0.01	0.01	0.01
	Total Volume	14.36	13.87	13.91	14.26	14.16	13.98
Southland	Unconfined	19.04	18.94	18.4	18.24	18.75	18.53
	Confined	3.65	3.65	3.61	3.6	3.64	3.62
	Total Volume	22.7	22.6	22.0	21.8	22.4	22.1
Taranaki	Unconfined	25.0	24.5	24.6	24.9	24.5	24.7
	Confined	0.26	0.26	0.26	0.26	0.26	0.26
	Total Volume	25.3	24.8	24.9	25.2	24.7	24.9
Tasman	Unconfined	9.07	10.16	8.33	8.33	8.67	8.99
	Confined	0.33	0.35	0.32	0.32	0.33	0.33
	Total Volume	9.41	10.51	8.65	8.65	9	9.32
Waikato	Unconfined	27.7	27.1	28.0	28.2	26.5	26.0
	Confined	6.87	6.84	6.89	6.89	6.81	6.79
	Total Volume	34.6	33.9	34.9	35.1	33.3	32.8
West Coast	Unconfined	3.2	3.11	3.33	3.29	3.22	3.13
	Confined	0.08	0.08	0.08	0.08	0.08	0.08
	Total Volume	3.28	3.18	3.41	3.38	3.29	3.21
Wellington	Unconfined	11.14	11.15	11.22	11.14	11.23	11.31
	Confined	11.14	11.15	11.22	11.14	11.23	11.31
	Total Volume	1.69	1.78	1.81	1.86	1.64	1.75
New Zealand Total	**Unconfined**	**735**	**733**	**732**	**736**	**732**	**730**
	Confined	**30.1**	**30.1**	**30.1**	**30.1**	**30.0**	**30.0**
	Total Volume	**765**	**763**	**762**	**766**	**762**	**760**

4.0 RECOMMENDATIONS

The following should be considered to improve the reliability of estimates of groundwater volume in New Zealand:

- The 2015 aquifer map (Moreau and Bekele 2015) used in this study is an improvement from the 2001 aquifer map (White 2001), but it remains a work in progress. The 2015 map requires updating to reduce uncertainties in the volume estimates. To complete the update of the 2015 map is not a trivial task and requires a review from New Zealand experts and regional authorities. Recently released digital maps of New Zealand Hydrogeological Systems (Moreau et al. 2019) and New Zealand Hydrogeological-Units (White et al. 2019) provided good progress towards an update of the 2015 maps but a finalised output remains work in progress. These datasets should however be considered as future opportunity for to refine the method and aquifer properties assignment used in the groundwater stock account.
- Groundwater volumes and annual changes in volumes are presented in this report by region. It is now possible to report on these using the nationally consistent New Zealand Hydrogeological Systems GIS dataset (Moreau et al. 2019). These hydrogeological systems are defined as geographical areas with broadly consistent hydrogeological properties and similar resource pressures and management issues, mapped at the 1:250,000 scale for on-shore New Zealand. System boundaries include geological contacts, structural boundaries such as faults or synclines, and surface water and groundwater divides. Note that a single hydrogeological system may include multiple aquifers.
- Recalculated aquifer areas were updated only where the relevant regional authority endorsed the new area. Refined areal extent and aquifer thickness can be achieved in future reporting, provided a review period with regional authorities is included in future contracting. A review period of between one to six months was suggested by regional authorities, for this purpose.
- Some aquifer parameter values were updated following the December 2014 consultation; however, additional porosity and storage coefficients measured since 2002 could be included. These data are typically submitted to regional authorities as part of the resource consent application process and can be extracted from consent application files held by regional authorities.
- Thirty-seven indicators wells have been used to estimate change in groundwater volume on a national basis. This study enabled the identification of more indicator wells, specifically for the Gisborne, Marlborough, Otago, and Manawatu-Wanganui regions. Inclusion of additional indicator wells should be undertaken, aiming at covering at least 75% of the aquifers (some aquifers are not monitored due to the lack of wells or regional resources). Incorporation of more than one indicator well for each region should also be considered, for example, one well in an unconfined and another well in a confined aquifer for each region.
- There is currently no monitoring network of groundwater levels at the national scale. Since the networks are managed at the regional scale, this means that selected indicator wells may be decommissioned during regional monitoring review. In this study, data collected at eight of the indicator wells ended prior 2020. To ensure regular reporting on the groundwater stock account, it is recommended that a national groundwater level monitoring programme or agreement with all regions is developed. This will ensure that decommissioned wells are replaced.

- Comparison of changes in regional groundwater volumes and allocated abstraction volumes would also be beneficial for putting estimated groundwater storage volumes in context of groundwater. Allocated volumes for significant aquifers are typically available from regional authorities. Similarly, a comparison of regional rainfall and regional groundwater volumes would be a more meaningful approach to examine relationships between rainfall, abstraction and groundwater volume.

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Yours sincerely,

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Attachments (as file attachments in the PDF):

Tabulated groundwater level time series at indicator wells (CR2020_113_LR_indicator_level_at_jun30.csv).

Tabulated aquifer properties (CR2020_113_LR_aquifer_properties.csv).

Tabulated groundwater volumes and annual volume changes per region per aquifer confinement status using 1994 as the reference year (CR2020_113_LR_groundwater_volumes_1994.csv).

Tabulated groundwater volumes and annual volume changes per region per aquifer confinement status using 1994 as the reference year (CR2020_113_LR_groundwater_volumes_2003.csv).

An R script (CR2020_113_LR_groundwater_volume_calculations.R) reproducing calculations based on previous excel worksheets (e.g., Moreau and Bekele 2015).

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