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The Christchurch Artesian System: a historical treatise

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Abstract

The Christchurch Artesian System (CAS) is one of the most important freshwater resources in Aotearoa/New Zealand. Following discovery of artesian water under Ōtautahi/Christchurch in 1858, well-drillers, water resource managers and scientists have proceeded to collectively investigate, monitor and characterise the CAS. This treatise provides a concise history of investigation, data curation and hydrogeological research made on the CAS. It reviews the role government organisations, researchers and well-drillers have played over the years in developing our understanding of its form and function. Having examined the past and present, ideas are provided for topics of future scientific study on the CAS. Suggestions are also made for how public awareness of the CAS might be raised to ensure its recognition as a key asset on which Christchurch depends and thrives.

Keywords

aquifer, Canterbury, Christchurch Artesian System, geology, groundwater, history, hydrology, water well drilling

Introduction

The Christchurch Artesian System (CAS) is one of New Zealand's most important water resources. Groundwater from the CAS has been exploited for over 160 years and today it supplies almost 500,000 people, or ~10% of New Zealand's population. It is used as drinking water for those living in Christchurch and surrounding environs, and for associated industrial activities, market gardening and, at the inland margin, farming and agriculture. Covering 1,500 km^2, the CAS underlies a 90 km long stretch of the coastal north Canterbury Plains, from Leithfield Beach in the north, south to Christchurch city, skirting the inland margin of the Banks Peninsula volcanics, to the Rakaia River mouth in the south (Figure 1). The CAS comprises seven gravel aquifers that are interbedded with low permeability interglacial fluvial marine and coastal deposits of sand, silt, clay and peat.

The CAS is a dynamic system with ongoing groundwater flow from west to east. The aquifers receive recharge from (in order of importance): natural leakage from the alpine rivers (most notably the Waimakariri River) (Dalmer, 1971); rain and irrigation water on the North Canterbury plains; leakage from the foothills' rivers (Ashley/Rakahuri and Selwyn/Waikirikiri), and leakage from water races. It is conceivable the system may even include deep source percolation (Feth, 1964) and contain fossil groundwater such as has been detected in the Canterbury Bight (Morgan and Mountjoy, 2022). Thirty years ago, in a *New Zealand Geographic* article titled 'Nature's Champagne', Yarwood (1993) noted that Christchurch was using twice the amount of water per household that Auckland was and cautioned about over-abstraction problems and the risk of contamination. Per capita water usage rates in Canterbury remain high at about 240 L/day (Christchurch City Council, 2025a), and whilst there is evidence that abstraction of groundwater from the CAS has modified the rates of flow through the system (Stewart and van der Raaij, 2022), so far there are no indications it has promoted the adverse environmental effects Yarwood (1993) alluded to. Nevertheless, with the ever-increasing demand for water, and the potential for over exploitation, good management of the CAS resource is crucial. Ongoing education and raising awareness about the uniqueness and importance of the water resource on which the citizens of Christchurch are totally dependent, has a role to play in ensuring good management.

Three scientific disciplines – geology, hydrology and chemistry – are key for understanding the occurrence, extent, recharge, flow and storage properties of the CAS. As a subject, the CAS has thus featured in a wide range of published literature that is directed at varying audiences, including: the general public (Chilton, 1924; Talbot *et al.,* 1986; Molloy and Brown, 1995; Canterbury Regional Council, 1997; Brown, 2001); groundwater resource managers (Oborn, 1960; Hunt and Wilson, 1974; Wilson, 1973, 1976); historians (Weeber, 1995, 2000, 2001; Weeber *et al.,* 2001); well drillers (Brown, 1990); local territorial authorities (Oborn, 1956); farmers (Collins, 1956); planners (Beanland and Brown, 1994); the mining industry (Brown and Gregg, 1994; Thompson *et al.,* 1995), and researchers (Grant-Taylor, 1967; Wilson, 1977; Brown, 1992, 1994). Les Oborn (Oborn, 1955) was the first of many who have written their academic thesis on CAS subject matter. Fortunately, because of the insight of early Canterbury well drillers and ongoing research by scientists, engineers and Christchurch citizens, 160 years of groundwater data in the form of well logs, well water level measurements and well water chemical and isotope analyses are now available for the CAS.

In this paper we provide a narrative on the CAS, written with a science history perspective. The main objective is to review how the knowledge base of the CAS has been built, thus providing readers with some historical context of science and research of the CAS. We start with a discovery and development section that provides background context to how the CAS was discovered and rapidly exploited for water supply. In the 'building our understanding' section that follows, we review initiatives and investigations that provided the foundational scientific knowledge base of the CAS. Included in this section is a description of the origins of the Wells database. In the 'contributing organisations' section, we describe important roles government science agencies have played over the years, also the well drilling industry. The collection and analysis of hydrological and hydrochemical data is described in the 'hydrogeological data' section. Our treatise concludes with ideas for how the CAS might be promoted as an ongoing subject for public awareness, and future research topics to fill existing gaps in our scientific understanding of the system.

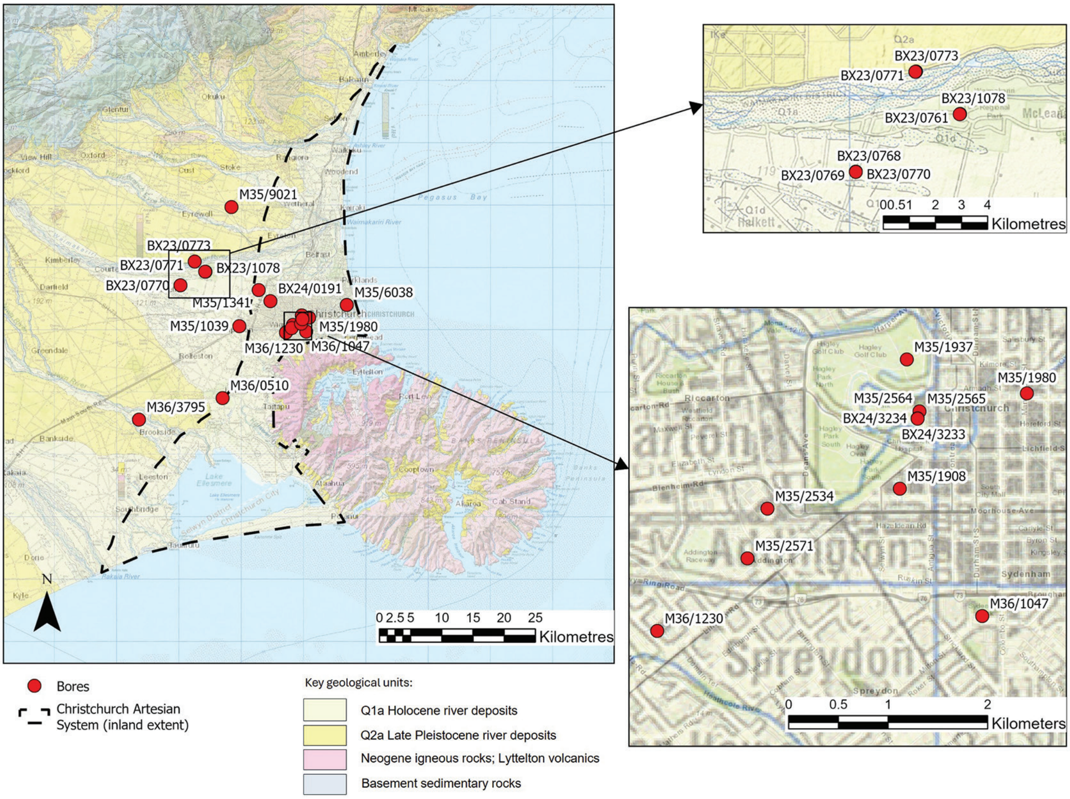


Figure 1 – Location of the Christchurch Artesian System (CAS). Wells referred to throughout the text are marked using their latest identifying number. Selected geological units from GNS's QMAP are colour-coded (Forsyth *et al.,* 2008).

Discovery of the CAS and the age of development

The first years and growth in water demand

Ōtautahi/Christchurch lies on the postglacial coastal fringe of the alpine-fed Waimakariri River floodplain where there is a high water table. In pre-pākehā times, the land comprised extensive swamp behind coastal sand dunes. Freshwater springs were well known to local Māori, (e.g., Te Rūnanga o Ngāi Tahu, 2023; Burbery, In Press) and fed the Ōtakaro/Avon River, Ōpāwaho/Heathcote River, Huritini/Halswell River, Pūharakekenui/Styx River and Ōtūkaikino Creek/south branch Waimakariri (Darling, 1997). European colonisation of Christchurch began in December 1850 when the 'first four ships' arrived at Lyttelton Harbour from England, carrying almost 800 immigrants. From the outset, infrastructure developments of the model Anglican city planned by the Canterbury Association were hampered by drainage. The conditions are commemorated in the poem 'Growl in a Sou'-wester' (*Lyttelton Times,* 11 July 1860): 'Land where men with brains of fog, built a city in a bog!' As more settlers arrived at Christchurch, further problems arose with the provision of potable water. Rainfall was unreliable and wastewater disposal soon polluted local springs, streams and shallow hand-dug wells on which the settlers initially relied. The lack of water for firefighting was another problem to which early Christchurch was very vulnerable, with only shallow hand-dug wells and the Avon River water sources available. *The Press* (25 May 1861) describes a fire in the malt kiln at Willmer's Brewery, Cashel Street at two o'clock in the morning that could not be prevented from spreading to three houses because of the 'miserably insufficient' water supply from Olliver's well. The Town Engine eventually quenched the fire supplied by two 'lines of buckets', one from Olliver's well and the other from the Avon River.

Tapping artesian water

The fortuitous discovery of artesian groundwater under Christchurch is attributed to Mr Richard Taylor when he was digging a well, by hand, at his Avon Brewery, located at 52 Peterborough Street. At 12 ft (3.7 m) he obtained water, but as this was not of satisfactory quality he continued to dig deeper. The high water table interfered with his digging, so he attached a 1½ in (40 mm) auger to a pole and began drilling. Having drilled through about 8 ft (2.4 m) of 'soil', he was 'met by a fountain which rose several feet' (*Lyttelton Times,* 13 February 1858). This was an artesian aquifer in a 6.1 m deep buried gravel channel deposited by the Waimakariri River approximately 3,000 years earlier. These shallow gravel channels extend east into Christchurch and are stratigraphically part of the postglacial Springston Formation (Brown and Wilson, 1988; White *et al.* 2007).

Taylor's discovery in 1858 triggered interest in the artesian groundwater resource that lay beneath the city, at a time when the Christchurch City Council (CCC) were seeking a reliable water supply. In his role as the provincial geologist, Julius von Haast predicted that good quality artesian water was likely to be obtained by drilling deeper wells, although he advised CCC it would be easier to acquire water from a surface source (*Lyttelton Times,* 27 June 1863). CCC opted not to heed Haast's advice; instead, they pursued the notion of supplying Christchurch from a pure artesian water source and in 1863 they purchased drilling apparatus from the failed Kowai Coal Company — the apparatus had originally been used for test drilling a coal prospect at the southern approach to the Kowai River bridge on the West Coast Road, inland from Springfield (Speight, 1928). In February 1864, CCC used their rig to install a 2.5 in. (64 mm) diameter pipe well at 'The Triangle', at the intersection of High and Tuam streets – this being the first of three exploratory public water supply bores they had planned for. In that initial adventure, artesian water was struck at a depth of 81 feet (24.7 m). The water spouted 10 to 15 feet (3.0 to 4.6 m) above ground level and flowed at 60 gallons a minute (3.8 L/s) (Weeber, 2000). The well was tapping the uppermost gravel aquifer of a subsequently proven layered aquifer sequence (the CAS), that was distinct from the overlying shallow Springston Formation gravel aquifers. Almost 100 years later, this aquifer was formally designated as the last glaciation Riccarton Gravel (Suggate, 1958). Thus began the stratigraphic convention of correlating the CAS gravel aquifers with glacial stages, subsequently continued by Brown and Wilson (1988), and with Marine Isotope Stages (MIS) as initiated by Brown *et al.* (1995). In the meantime, the aquifer would be known by drillers, scientists, engineers and citizens of Christchurch as the 'first deep artesian aquifer'.

On 15 February 1864, CCC moved their rig from the High Street/Tuam Street 'Triangle' to the intersection of Colombo, High and Hereford streets, in front of what was then the City Hotel. There they sank the second public artesian well. They located their third experimental well on the triangle intersection of Papanui Road and Peterborough Street. By the end of 1864, CCC had drilled seven artesian wells in the city and fitted them with hand pumps for public water supply, heralding the advent of Christchurch's dependency on the CAS.

Reticulation of the Christchurch City water supply

The pioneering artesian exploits demonstrated in the 1860s spawned a boom in exploitation of groundwater from the CAS, mainly from private wells that targeted the first deep artesian aquifer (Riccarton Gravel). The problem of well interference effects had been recognised as early as 1867 when experiments made on five wells sunk to supply a city fountain (located at the intersection of High and Cashel streets) were noticed to depressurise the water supply in the nearby White Hart Hotel (Weeber, 2001). Water prospectors were encouraged to drill deeper to access deeper artesian aquifers and overcome the problem of falling artesian pressure that the first deep artesian aquifer succumbed to from over abstraction. In addition to windpumps, hydraulic rams that utilised the well artesian head pressure were commonly used to pump water to house roof storage tanks. However, operation of a hydraulic ram wasted a lot of water and contributed to the city's drainage problems. To resolve Christchurch's drainage woes, the Christchurch Drainage Board was formed in 1875, and by 1882 separate drainage and sewage disposal systems were operating, pumping and piping stormwater and sewage to a disposal site at Bromley. Artesian wells were drilled to provide water to 'flush' the sewage lines.

It was not until 1907 that CCC followed up with a reticulated public water supply based on the CAS. Neighbouring boroughs were more forward: Lyttelton Borough commissioned a reticulated water supply scheme in 1877 that was fed by artesian wells at Heathcote with water piped through the Port Hills railway tunnel; Sumner Borough followed in 1902 with wells at Redcliffs, McCormacks Bay and Ferrymead; and Sydenham Borough provided reticulated supply in 1903 using CAS well water. It was June 1909 when the CCC public water supply scheme at Colombo Street, Beckenham was inaugurated. Initially, water from wells tapping the Riccarton Gravel flowed into a tank sunk 3.7 m below ground surface, from which it was pumped into the water main and to a reservoir on the adjacent Port Hills at Cashmere. Beckenham has since remained the city's primary pumping station. In the 1920s its operation was expanded to comprise 6 wells spaced about 20 m apart (Speight, 1926). At that time, CCC's focused investment on one pumping station drew criticism from technical experts who raised concerns around sustainability. It also prompted some advanced thinking on engineering topics such as well design and head loss (*The Star,* 4 July 1922; *The Press,* 1 October 1924). Another technical milestone in terms of water supply from the CAS was the advent of well screen technology and introduction of submersible or 'deep well' pumps, introduced in 1948. Submersible pumps operated by pushing water from the well screen area to the surface and out of the well, replacing the surface pump system which pulled water to the surface. This enabled wells to be drilled and utilised even where there was little or no artesian pressure, particularly to the west of the city. Today, Beckenham and 52 other active pumping stations supply the city's water that is wholly sourced from the CAS. The number of wells at each station ranges from one to six; the wells are 150–460 mm in diameter and vary in depth from 28 to 235 m below ground level (Christchurch City Council, 2025b).

Water for agriculture

As symbolised by the fleece and garb on the city's coat of arms, agriculture has been and continues to be an integral part of Christchurch's development and prosperity. The CAS has long supplied stock and irrigation water to farms positioned along the northern Canterbury Plains coast – the number of which has gradually declined as rural land has ceded to urban expansion. However, it is irrigation and intensive agricultural activities inland of the CAS that have more significant implications for the coastal groundwater resources, especially in terms of groundwater quality. It is for this reason we include a review of irrigation scheme developments upstream of the CAS.

In the development of the Canterbury region, irrigation on farms of the wider Canterbury Plains was soon advanced to increase stock carrying capacity. Malvern County engineer George Frederick Ritso (1883) observed 'no country could be more advantageously situated for irrigation than the Canterbury Plains. The rivers bring down ample supplies of water at the proper season, and the country being overspread with shingle, below a thin covering of good soil, underdraining, which is one of the great expenses of irrigating ordinary lands, is entirely unnecessary'. With regards to groundwater, Ritso (1883) commented 'near the hills water is obtainable in wells at moderate depth, and also near the sea, but there is a stretch of country, about 20 miles in width, where no water can be obtained (except from rivers) at a less depth than 200 feet below the surface. An occasional windmill pump has been erected by one or two of the more enterprising farmers to draw water from depths of about 200 to 300 feet'.

First completed in 1880, the Malvern Water Race that diverts water from the Kowai River near Springfield onto the Canterbury Plains marks the first public works for water supply for agricultural and pastoral purposes in New Zealand (Williams, 1904). At its final stage of completion, the race extended as far as the Christchurch Meat Company, Islington located on the fringe of the CAS. The Malvern Water Race was later complemented by a network of other races that drew water from the Waimakariri, Rakaia, Hawkins and Selwyn Rivers, which today are collectively managed as the Malvern, Paparua and Ellesmere races (Selwyn District Council, 2025). On the north side of the Waimakariri River, irrigation schemes for farms in the Waimakariri-Ashley district were initiated in the 1890s under provisions of the Water Supply Act 1891. They have since evolved into the extensive (23,000 ha) scheme now operated by Waimakariri Irrigation Ltd., as well as the smaller, privately-operated Claxby scheme at Eyreton.

A central plains irrigation scheme was first mooted in the 1930s for an area of 1,050 km^2 between the Rakaia and Waimakariri Rivers divided by the Selwyn River into two sections from the 230 m elevation contour to the 'heavy land' near the coast (Dalmer, 1971). The scheme was eventually completed in three stages as the Canterbury Plains Water (CPW) scheme, between 2015 and 2018. It has capacity to supply river water to irrigate 85,000 ha of land. The CPW scheme is the latest and largest irrigation development up-gradient of the CAS. Shareholder farms have reportedly reduced their reliance on groundwater abstraction by between 50 and 70% as a result.

Building our understanding of the CAS

The start of groundwater monitoring and research

The expansion of well drilling in the 1860s prompted Julius von Haast (Canterbury provincial geologist, 1861–1868; Director of the Canterbury Museum, 1868–1887) to state, 'I need scarcely point out that it would be very important to have all the obtainable information as to the underground water supply of the district carefully collected and mapped, and sections prepared. Such documents would be of the greatest usefulness, their study leading us to conclusions the value of which cannot be over-estimated' (von Haast, 1879). Von Haast's counsel was noted by well drillers, successor museum directors/curators and researchers who ensured the strata penetrated by wells were logged and well water levels recorded. Realising the significance of the groundwater resource and its importance for the future of Christchurch and Canterbury, in 1911 the Canterbury Philosophical Institute set up an Artesian Wells Committee which used a grant from the New Zealand Institute to finance research projects. A notable output of the 'Artesians' was Hilgendorf's (1926) CAS monograph that discussed the groundwater source, well water levels and groundwater chemistry, based on 14 years of data collection.

The first description of the CAS extent was Gray (1883) who, in a verbal paper 'Artesian Waters of Christchurch', elicited that 'an artesian basin appeared to extend from Leeston to Salt Water Creek, but that attempts to get water by this means at Templeton had proved failures'. The term 'Christchurch artesian system' was first used by Page (1901) for the aquifers 'on the other side of the hills' to Lyttelton Harbour. He noted a lack of 'shingle' in wells in Lyttelton Harbour compared with those on the Canterbury Plains, and on the basis of water chemistry analyses, a different groundwater recharge source for artesian wells at the head of Lyttelton Harbour compared with wells at Christchurch. Other researchers assigned other names to the artesian aquifers complex.

Subsidence at the northern Canterbury Plains coast relative to inland uplift of the Southern Alps margin was recognised by Robert Speight (Canterbury College geology lecturer, 1903–1921; professor, 1921–1930; Canterbury Museum curator, 1906–1935) to explain peat and clay in a well at 210 m depth at Islington, to the west of Christchurch, and the shells encountered by 140 m deep wells at New Brighton on the Pegasus Bay coast (Speight, 1911). When Speight (1911) compiled six vertical cross-sections to illustrate the gravel (aquifer) and intervening fine sediment beds underlying Christchurch, he used 102 well drillers' logs to 155 m depth selected from a total of over 500 well logs. This was the first time well logs were used to systematically depict the structure of the CAS. The cross-sections included Islington (west) to New Brighton (east) and Sefton (north of the Ashley River) to Lake Ellesmere, for what Speight referred to as the 'Christchurch artesian area' – the coastal area from the mouth of the Ashley River southwards to the mouth of the Rakaia River.

Symes (1917) used the term 'Christchurch artesian system' but Chilton (1924) referred to 'Christchurch artesian area', 'Christchurch artesian system' and 'Christchurch artesians' in his book *The Christchurch Artesians and the City Water Supply*. It was not until the 1950s, when Collins (1950, 1955), Alley (1951) and Oborn (1956) used 'Canterbury Artesian System', that the term was generally adopted. Oborn (1960) described 'Christchurch Artesian System' with aquifers at depths ranging from 15 ft to more than 500 ft and extending 'from Christchurch City to Leithfield, 24 miles to the north, and to the south-west for 32 miles having an area of approximately 350 square miles (900 km^2)'. He included a map of the southern part of the system south of the Waimakariri River. Wilson (1973) identified 'coastal areas of confined water, where there are at least seven aquifers, each consisting of a westerly derived alluvium or outwash gravel separated by aquicludes consisting of fine-grained estuarine and marine beds deposited during periods of interglacial and postglacial high sea level'. Wilson (1976) preferred 'Christchurch Artesian Area', and 'Christchurch Confined Groundwater Area'. A report commissioned by the North Canterbury Catchment Board

(NCCB) (Talbot *et al.,* 1986) was titled 'The Christchurch Artesian Aquifers'. A small-scale map in Alley (1951), Figure 1 in Wilson (1973) and Figure 6 in Brown and Weeber (1992) were the first maps of the entire CAS. Today, 'Christchurch Artesian System' is the generally accepted name. These early studies did not consider offshore extension of the CAS. This was recognised following research into the offshore geology of Canterbury's continental shelf (Herzer, 1977, 1981) and investigated further by seismic studies (Barnes, 1995; Barnes *et al.,* 2011).

Drilling deeper

In 1868 there were 362 wells within Christchurch city (Raeside and Rennie, 1974). Some of these were flowing artesian bores with artesian heads up to 1 m; others were hand-dug wells from the 1850s. By January 1872, Christchurch's city surveyor W. F. Moore estimated that the number of wells in the city had risen to 654, of which 23 were CCC wells (Weeber, 2000). The population of Christchurch in 1874 was 22,000 – an increase of about 15,000 in the 10 years since the CCC had drilled the first CAS well.

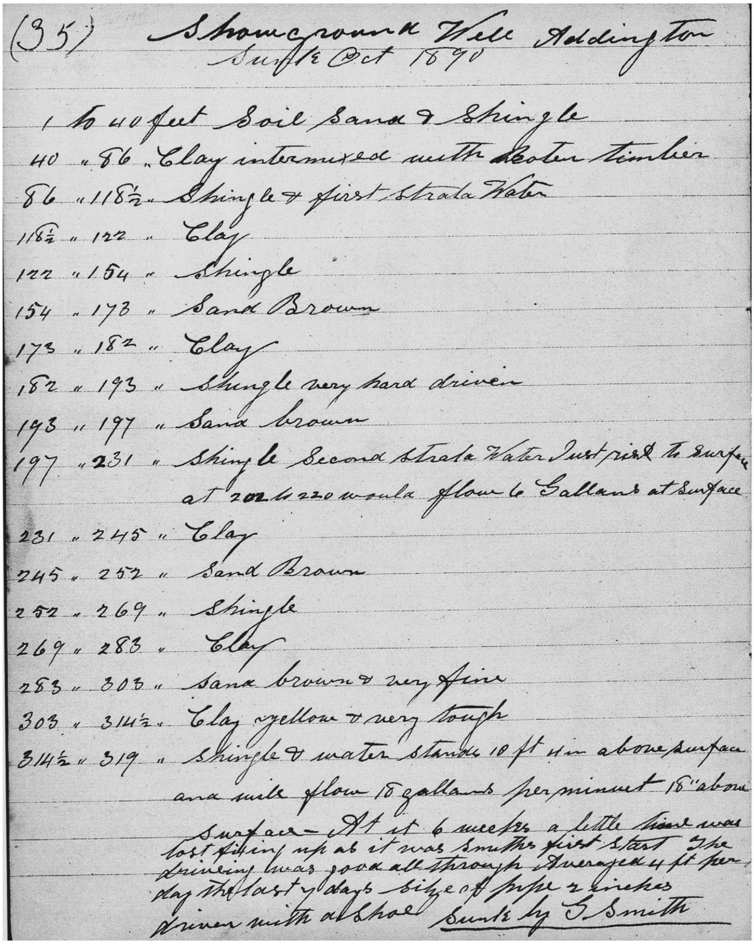
At that time most new wells tapped the first deep artesian aquifer (Riccarton Gravel), and as a result, the artesian head and flow of the aquifer began to decline, such that pumps were required to abstract water. In search for deeper aquifers with better artesian heads, deeper wells were drilled and, in October 1879, a 200 ft (61 m) deep well sunk at the Christchurch Club, Worcester Street was claimed in *The Globe* (25 October 1879) to be 'the deepest sunk in Canterbury'. It was the first well to reach the second artesian aquifer (Weeber, 2000) that, later, was formally designated as the Linwood Gravel Formation (Brown and Wilson, 1988).

In October 1890, a well drilled at the Addington Show Grounds was claimed to be the deepest flowing artesian well in New Zealand and the achievement was commemorated with a plaque that can be found at the Showground Office (Figure 2). The well (M35/2571) was 97.2 m deep, 50 mm diameter and tapped the third artesian aquifer – the Burwood Gravel. It gave an artesian head of 3.1 m (Brown and Wilson, 1988; Weeber, 2000). The fourth artesian aquifer – the Wainoni Gravel – was discovered in that same year when a 129.4 m deep well (M35/2534) was drilled at the nearby New Zealand Railways Addington Workshops. That well provided an artesian head of 5 m and the well water was used to supply a 21.9 m high reinforced concrete water tower that remains an architectural heritage feature at the Tower Junction Retail Complex (see Burbery, In Press). When Page (1901) devised the term CAS in 1901, the deepest well in Christchurch was 148.7 m deep and penetrated five artesian aquifers. This was M35/1908 drilled by Job Osborne Ltd at the West Christchurch School (present day Hagley Community College), Hagley Avenue in February 1901 (Weeber, 2005), tapping what is now known as the Number 5 Gravel aquifer (Brown and Hanson, In Press).

In 1903 Sydenham Borough Council tapped the same aquifer for their public water supply well (M36/1047) at Sydenham Park. That well was 174.3 m deep and had an artesian head of 9.9 m. Further deep wells were drilled, including well M35/1937, which was drilled for the 1906 New Zealand International Exhibition. At 129.1 m deep, the well tapped the Wainoni Gravel. The well provided water for the 1906 Exhibition and water for Victoria Lake, which had been excavated in a former swamp in the park in 1887 to mark Queen Victoria's Silver Jubilee (e.g., Burbery, In Press). Today the free-flowing well provides water to Lake Albert, which was excavated in 1916. Another Job Osborne deep Christchurch well was M36/1230 drilled in 1908 at the Sunnyside Mental Hospital, Lincoln Road, Hillmorton to a depth of

A

B



(35) Showground Well Addington
Sunk Oct 1890

1 to 40 feet Soil Sand & Shingle
40 " 86 " Clay intermixed with [illegible] timber
86 " 118½ " Shingle & first Strata Water
118½ " 122 " Clay
122 " 154 " Shingle
154 " 173 " Sand Brown
173 " 182 " Clay
182 " 193 " Shingle very hard driven
193 " 197 " Sana brown
197 " 231 " Shingle Second Strata Water Just rise to Surface
at 202 to 220 would flow 6 Gallans at Surface
231 " 245 " Clay
245 " 252 " Sand Brown
252 " 269 " Shingle
269 " 283 " Clay
283 " 303 " Sana brown & very fine
303 " 314½ " Clay yellow & very tough
314½ " 319 " Shingle & water stands 10 ft 4 in above surface
and will flow 10 gallans per minuet 18" above
Surface – At it 6 weeks a little time was
lost fitting up as it was Smiths first Start The
driveing was good all through Averaged 4 ft per
day the last 7 days Size of pipe 2 inches
driven with a Shoe Sunk by G. Smith

Figure 2 – Paraphernalia related to the drilling of the 97.2 m deep well at Addington Showgrounds in 1890 – a feat that marked discovery of the third deep artesian aquifer (the Burwood Gravel).
A: Plaque commemorating the drilling of the well in 1890, which at that time was reputed to be the deepest artesian well drilled in New Zealand. **B:** Job Osborne's hand-written log for the well.
(*Photos supplied by John Weeber*)

199.1 m. The artesian aquifer, at 193.6–199.1 m was the sixth deepest CAS aquifer, formally designated as the Belfast Gravel.

It was another 80 years before it was recognised that knowledge of geological processes and stratigraphy was essential for identifying groundwater flow paths and consequently enabling sustainable management of the water resource. This occurred when another well deep enough to encounter the Belfast Gravel (213 m deep) was drilled at Christchurch. In 1989, the Bexley bore (M35/6038) (Brown, 1998) was drilled by McMillan Water Wells Ltd, at the eastern Christchurch suburb of Bexley, 1 km inland from New Brighton. The bore's location, 5 km north of the Banks Peninsula volcanic rock complex, was a compromise. The aim was to have a coastal location to maximize penetrating organic material for paleoenvironment samples; northwards enough to maximise the opportunity to penetrate the complete glacial and interglacial sequence and associated CAS groundwater aquifers, and at a CCC pumping station so that the well could later be used for city water supply. The 433.0 m deep Bexley bore fulfilled the objectives, and deeper middle to late Quaternary interglacial and glacial strata were confirmed (Brown, 1998). The bore identified three more CAS gravel aquifers and three interglacial high sea level deposits forming aquitards. The Bexley bore sequence from the base of the Wainoni Gravel at 163.2 m to the base of the deepest gravel deposit encountered at 232.1–240.7 m, herein described as the Hereora Formation (Brown and Hanson, In Press), was correlated with MIS 11-16 (Brown, 1998).

On the western margin of the CAS, a 259.3 m deep well (M35/9021) was drilled at Tram Road, Swannanoa in 2002, by Clemence Drilling. This well may have penetrated the seven confined gravel aquifers of the CAS, interbedded with yellow clay-bound gravel. The well log records Wainoni Gravel at 147.0–152.8 m depth, underlain by strata that might be the coastal MIS 11-16 sequence, with a sandy gravel aquifer (possibly Hereora Formation) at 251.6–258.2 m deep. At 450.0 m deep, the deepest CAS bore (BX24/0191) was drilled by Clemence Drilling in 2013 at the Burnside Park pumping station, Avonhead. The bore was completed with a well screened at 198.5–202.9 m in Belfast Gravel, although the underlying Hereora Formation is at 243.0–248.5 m and logged as 'well sorted water-bearing gravel'. Clemence Drilling continued drilling to 450 m on their own initiative.

An even deeper bore is the Leeston-1 oil exploration well (M36/3795) (Wood, 1969) drilled by the New Zealand Petroleum Exploration Company in 1969 at Brookside, Selwyn, at the inland margin of the CAS. The bore record reports gravel to 356.6 m, but sediments were not logged in any detail and aquifers were not differentiated, nor were water levels recorded. From 356.6–422.5 m blue-grey clay with thin beds of pebbles including volcanics was logged, together with sand, including quartz sand and fragments of wood. This is probably Kowai Formation from the Pleistocene. At 422.5–585.2 m there was red-brown soft clay and thin bedded tuff (Irwell Volcanic Formation), at 585.2–665.4 m there was yellow-grey pebbly quartz sand then thin green tuffaceous claystone and lapilli tuff where 'heavy artesian flow ensued with much flowing sand'. The water temperature, at 32.3°C, and mineralisation (NaCl 1, 650 ppm) suggest fossil groundwater. Drilling eventually continued and greywacke basement rock was encountered at 1,111.6 m.

Well logs and databases

Water well logs are a fundamental component for CAS hydrogeology research that provide details of the structure and extent of the aquifers. The *New Zealand Water Well Drillers' Guide to Logging Water Wells* (Brown, 1990) was prepared for drillers engaged in water well drilling as a guide to the principles of groundwater occurrence and flow, the types of rock, sediment and soil, and how to recognise and describe the material penetrated during the drilling process. The object of the guide was to help the driller produce an accurate summary of the drilling operations and a geologically useful description of the strata drilled and their water-bearing properties. The guide continues to form an integral part of the New Zealand drilling standards (New Zealand Standards, 2001). Long before the guide was produced, several 19th century Christchurch well drillers realised the importance of logging the details of the strata they were drilling and, as a result, a 144-year accumulation of well drilling information is now available. The systematic collation of this information was initiated by B. W. (Tony) Collins of the New Zealand Geological Survey (NZGS) in 1947 and is the foundation for Environment Canterbury's Wells database – the modern-day data repository for well records, borelogs and associated data from the Canterbury region that can be publicly accessed through the Well Search tool on Environment Canterbury's webpage (https://www.Environment Canterbury.govt.nz/data/well-search/) or via Canterbury Maps (https://canterburymaps.govt.nz/).

The earliest known Christchurch well log features in a scientific paper 'Description of an artesian well sunk at Avonside' (Mollet, 1881). This was the first paper written exclusively about Christchurch artesian wells. The well was located near the junction of New Brighton Road and Dudley Creek, Shirley. It was 32.9 m deep and tapped the Riccarton Gravel. Beginning with a 'well statement' for a well drilled in November 1881 at Doyleston (Weeber, 2000), hundreds of logs of wells drilled by Job Osborne are in the Environment Canterbury Wells database (Weeber, 2005). Many are not included because their exact location is not known. Other early Christchurch drillers who logged the wells they drilled were James W. Horne and J. M. Stewart. Generally, well drillers logged wells and pumping details and readily made this information available, but there were some who did not bother to keep well records and others who regarded their records as private property. Collins's original well database, which was card based, collated most of the available historic and ongoing records, many of which were provided by Osborne and Horne's drilling companies (e.g., Figure 3A). Included also were data collected for groundwater research by NZGS staff since 1946, as well as Alley's (1964) listing of about 1,000 well logs originally used for his Christchurch foundation paper (Alley, 1955). Cooperation between government departments (Agriculture, Public Works and Railways), and city, borough and county councils, Lincoln College, and the Department of Scientific and Industrial Research (DSIR), resulted in the ongoing collection of well log, water level and groundwater chemistry information for the database. Today, well drilling is a regulated activity and submission of borelogs and well details to Environment Canterbury for filing is mandated by rules in the regional plan.

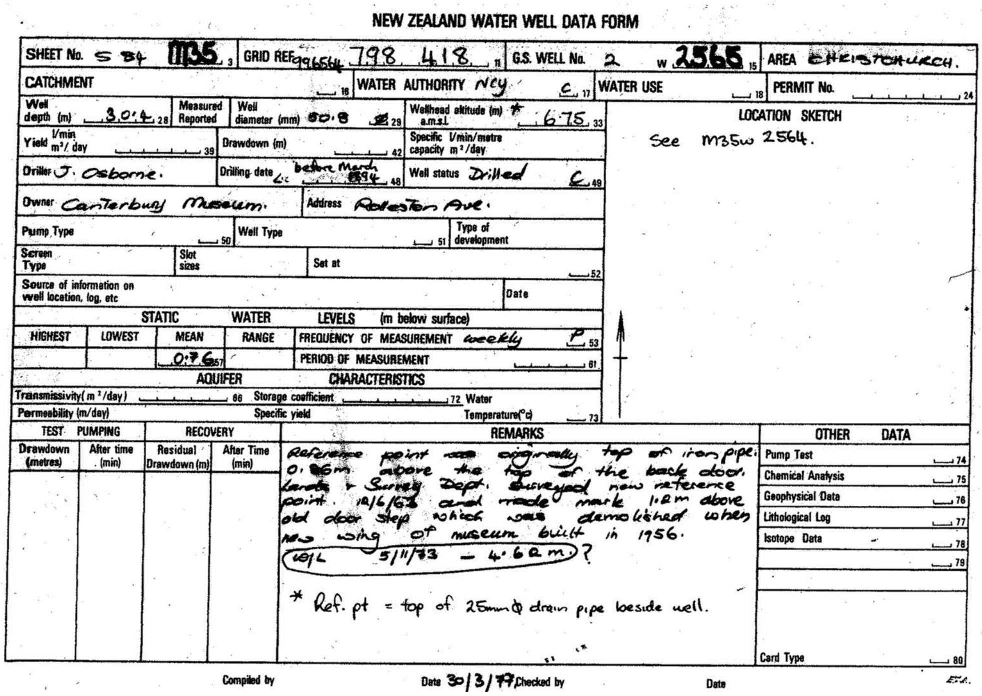
A key component for organisation of the Wells database was the Department of Lands and Survey New Zealand-wide one inch to one mile (1: 63,360) map series NZMS1 (1939-1989). The well numbering system NZGS devised used a geo-referenceable prefix code that corresponded to the NZMS1 map sheet number. Water wells were also given a 'w' identifier before the well number to distinguish them from fossil sample records that used the same geo-referencing system – fossil samples contained an 'f' identifier placed before the sample number. Being a later entity involved in the role of well data collection, the North Canterbury Catchment Board (NCCB) used NZMS260 1:50,000 (1977-2007) map sheet indices to geocode well numbers. Before the aid of computers and geographical information systems (GIS), the mapping of Canterbury's well locations involved an annual pilgrimage to the NZGS mapping unit in Lower Hutt, made by NCCB's groundwater geologist John Weeber. Well locations were marked on 1:10,000 transparent sheets that overlaid printed cadastral maps and were assembled into folders corresponding to the NZMS1 topographic map series. When Canterbury Regional Council came into being in 1992, all available well data at the time were brought into the NZMS260 reference system. Since March 2012, all new well data entries have been assigned georeferenced prefixes that correspond to the modern NZ Topo50 map series.

Digitisation of the Wells database occurred in 1976 when it was uploaded to the University of Canterbury's mainframe computer using punch card inputs (Figure 3B). A laborious task in this data transformation process was manually copying coded well data from New Zealand Water Well Data Forms (known as 'yellow cards') onto computer data entry sheets that were then turned into punch cards. The scope for data input using punch card technology was limited and it wasn't until 1994 that borelog information was entered into the digital database. Although the stratigraphic sequence for CAS was already established (Brown and Wilson, 1988; Brown and Weeber, 1992), the task of applying stratigraphic codes required manual interpretation for each log (of which there were 7,000 at the time)! It was not until personal computers with structured query language functionality became widely available in the late 1990s that the Wells database could be linked to other databases, such as water levels, water chemistry and GIS. A key stage in evolution of database accessibility was when Marc Ettema (of Environment Canterbury) wrote a Microsoft Access user interface in 1999.

In producing his seminal workpiece that plotted the stratigraphy of the CAS, Speight relied on 102 Job Osborne and J. W. Horne well logs to create his set of six hand-drawn geological transects (Speight, 1911) (Figure 4A). In the early 1970s Derek Wilson (NZGS) used mapped well information to produce a physical 3D model of the CAS, built from Perspex sheets encased in a wooden frame. The model was used for many years as a prop to demonstrate the 'club sandwich' structure of the CAS. After the entry of stratigraphic codes into the Wells database, the arduous craft of hand-drawing cross-sections of the CAS was superseded by digital geological models. Marc Ettema aided the process of interrogating the Wells database with a computer program he compiled, 'X-sect', that automatically plotted 2D geological cross-sections (e.g., Figure 4B). The plotting tool saw much use by Environment Canterbury staff and consultants. The first digital 3D geological model of the CAS was a collaborative effort between Otago University, GNS Science and Environment Canterbury (Murray *et al.,* 1998). Earth Vision software was used. The model referenced lithological data from 1,244 well records in the Wells database (80% of which were for bores less than 100 m deep) and modelled the subsurface beneath Christchurch City and a 309.6 km^2 area that encompassed the CAS. Lovell (1998) coincidentally used the same methods to model a smaller section of the CAS focused on Kaiapoi. Murray *et al.'s* (1998) model was later revised by Harfoot and White (2000) who added more data extracted from bores deeper than 150 m. White (2007) later produced models of the Christchurch and Springston formations, covering the top 40 m of the CAS. 4,596 bore records were used to inform that model.

Circa 2005, the Christchurch-based company Applied Research Associates New Zealand (ARANZ), now Seequent, started redeveloping their 3D geological mapping software Leapfrog and partnered with Environment Canterbury to use the CAS as a test case for Leapfrog HYDRO. The collaboration between ARANZ and Environment Canterbury culminated in generation of a number of 3D geological models of the CAS. Leapfrog Geo software was also used by Begg *et al.* (2015) who generated 3D geomorphological and geological models of Christchurch city following the destructive Christchurch Earthquake in 2011. For that work, Begg *et al.* (2015) correlated cone penetrometer test (CPT) results, gathered from geotechnical investigations, with lithological data to provide an expanded dataset (e.g., Figure 4C)[1]. They also mapped, to a depth of 500 m below mean sea level (bmsl), a 1,836 km^2 area of eastern Canterbury, from Amberley Beach to the Rakaia River that incorporated the CAS. Lee *et al.* (2017) similarly supplemented the lithological data available from borelogs of 500 water wells with records from 370 CPTs that were collectively kriged using the MOVE structural modelling suite to generate a high-resolution model that characterises boundaries between significant geological formations as 3D surfaces. For pragmatic reasons, hydrogeological models of the CAS require simplifying assumptions about the architecture of system and over the last 20 years several such models have been produced for water resource management purposes (Callander *et al.,* 2005; Weir, 2018; Hemmings *et al.,* 2018).

A


NEW ZEALAND WATER WELL DATA FORM

SHEET No. S 84 M35 | GRID REF 798 418 | G.S. WELL No. 2 W 2565 | AREA CHRISTCHURCH.
CATCHMENT | WATER AUTHORITY NCY C | WATER USE | PERMIT No.
Well depth (m) 3.04 | Measured Reported | Well diameter (mm) 50.8 | Wellhead altitude (m) a.m.s.l. * 6.75 | LOCATION SKETCH
Yield l/min m³/day | Drawdown (m) | Specific l/min/metre capacity m²/day | See M35w 2564.
Driller J. Osborne. | Drilling date before March 1894 | Well status Drilled C
Owner Canterbury Museum. | Address Rolleston Ave.
Pump Type | Well Type | Type of development
Screen Type | Slot sizes | Set at
Source of information on well location, log, etc | Date
STATIC WATER LEVELS (m below surface)
HIGHEST | LOWEST | MEAN 0.76 | RANGE | FREQUENCY OF MEASUREMENT weekly P | PERIOD OF MEASUREMENT
AQUIFER CHARACTERISTICS
Transmissivity (m²/day) | Storage coefficient | Water
Permeability (m/day) | Specific yield | Temperature (°c)
TEST PUMPING | RECOVERY | REMARKS | OTHER DATA
Drawdown (metres) | After time (min) | Residual Drawdown (m) | After Time (min)
Reference point was originally top of iron pipe 0.86m above the top of the back door. Lands + Survey Dept. surveyed new reference point. 12/6/63 and made mark 1.2m above old door step which was demolished when new wing of museum built in 1956.
SWL 5/11/73 — 4.62m ?
* Ref. pt = top of 25mm ⌀ drain pipe beside well.
Pump Test | Chemical Analysis | Geophysical Data | Lithological Log | Isotope Data | Card Type
Compiled by | Date 30/3/77 | Checked by | Date

Figure 3 – Evolution of the Wells database. **A:** Scanned copy of a New Zealand Water Well Data Form, which were in operation between the 1950s and 1990s. Being printed on yellow paper, the forms were often referred to as the 'yellow card'. Accompanying lithological borelog data were generally annotated on the reverse of the cards or appended as a separate paper record.

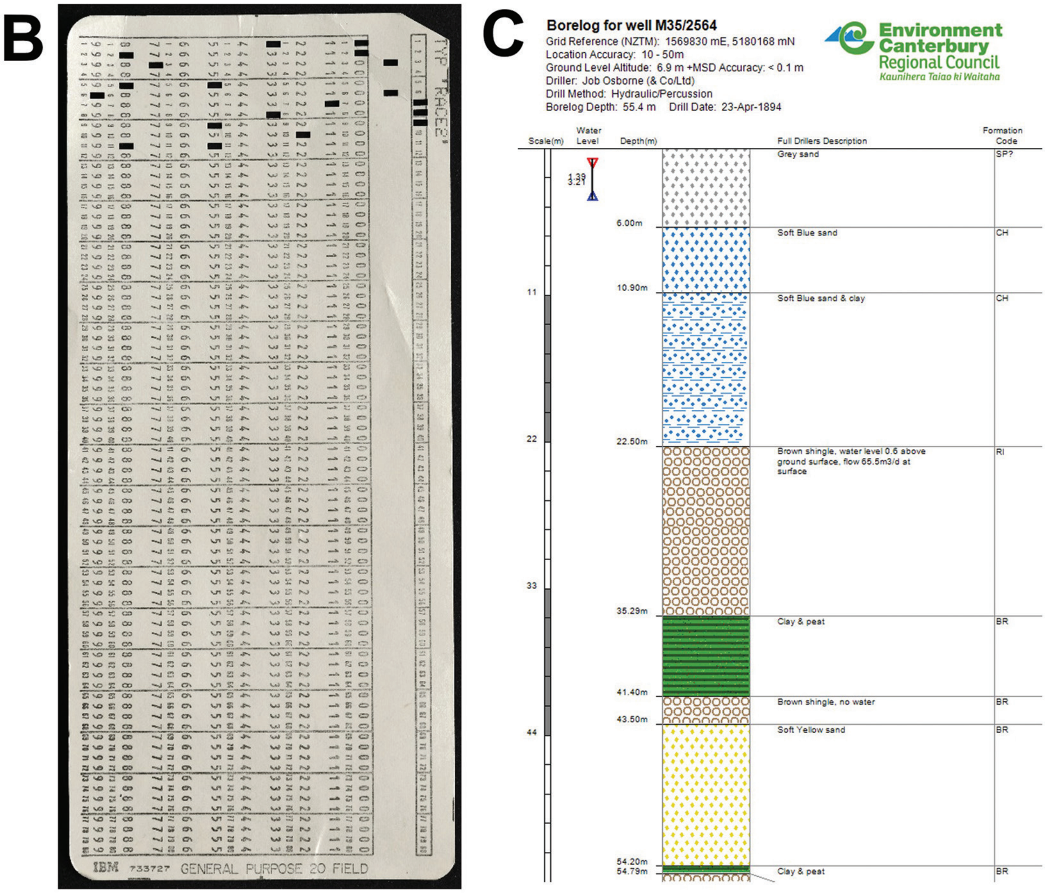


Figure 3 – Evolution of the Wells database. **B:** Example of a well punch card that represents the digital origins of the Wells database. Punched cards were input to the University of Canterbury's mainframe computer, starting in 1976. With no ability to scan images or capacity to upload lithological data, paper yellow cards remained a critical part of the database up until the early 2000s when they were retired (photo supplied by John Weeber). **C:** Example borelog as now presented in the Wells database, accessible to the public using the Well Search app on Environment Canterbury's webpage. Log shown is for the original 'shallow museum well' M35/2564.

[1] The geological dataset of Begg *et al.'s* (2015) geomorphological model 'NZL GNS GM3 Christchurch Geology' can be accessed via GNS's dataset catalogue: https://data.gns.cri.nz/metadata/srv/eng/catalog.search#/metadata/eb71230b-3b10-447d-bde2-abc22c049bca. Seequent's Leapfrog viewer software is required to visualise the data, the freeware is available for download from: https://www.seequent.com/products-solutions/leapfrog-viewer/.

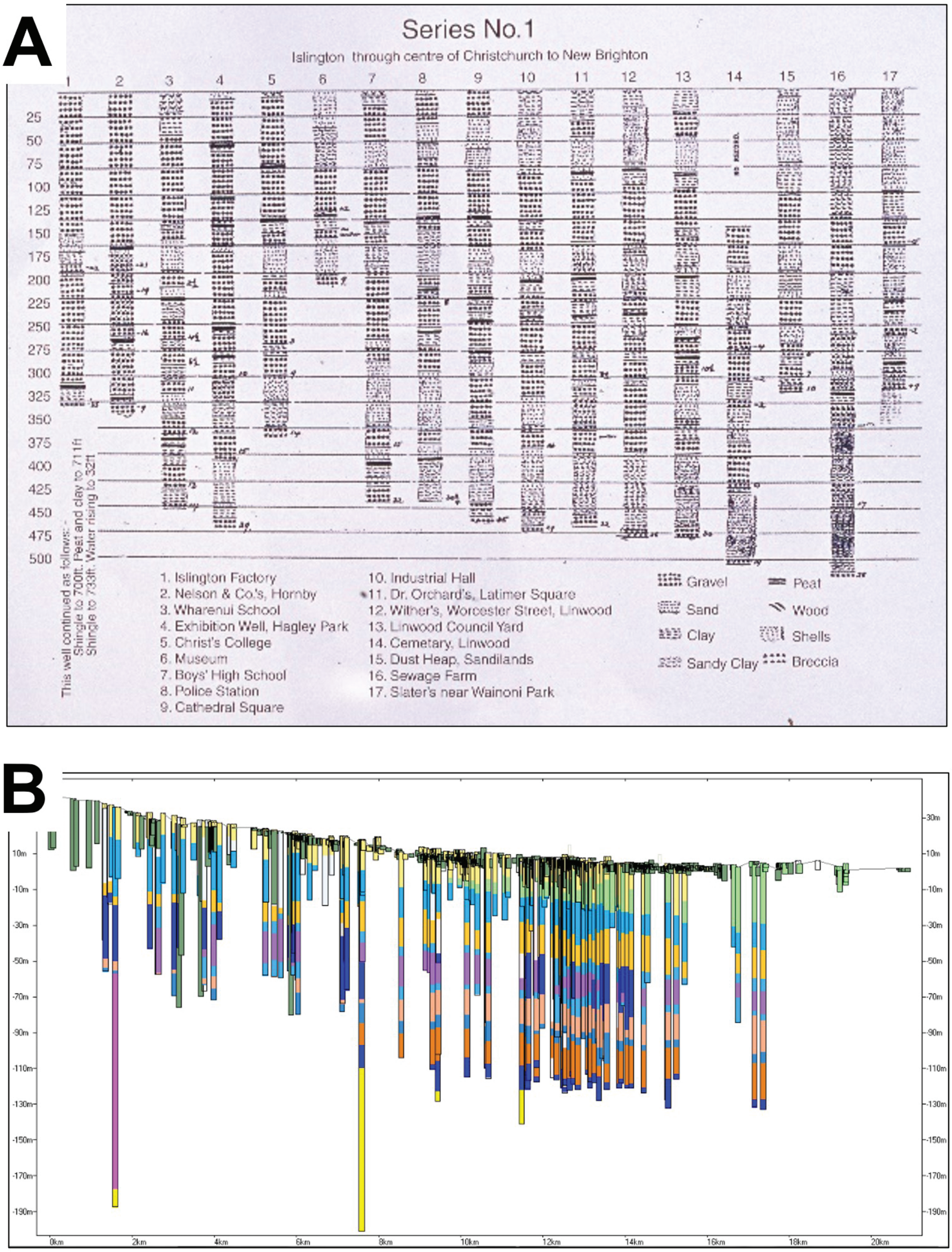


Figure 4 – Historical geological transects drawn for the CAS. **A:** One of six hand-drawn transects for the 'Christchurch artesian area' produced by Speight (1911), informed from 102 well logs provided by well drillers Job Osborne and J. W. Horne. **B:** The same transect line digitally mapped from stratigraphic data held in the Wells database circa 2012, using Environment Canterbury's X-sect plotting program that was compiled by Marc Ettema in the 1990s.

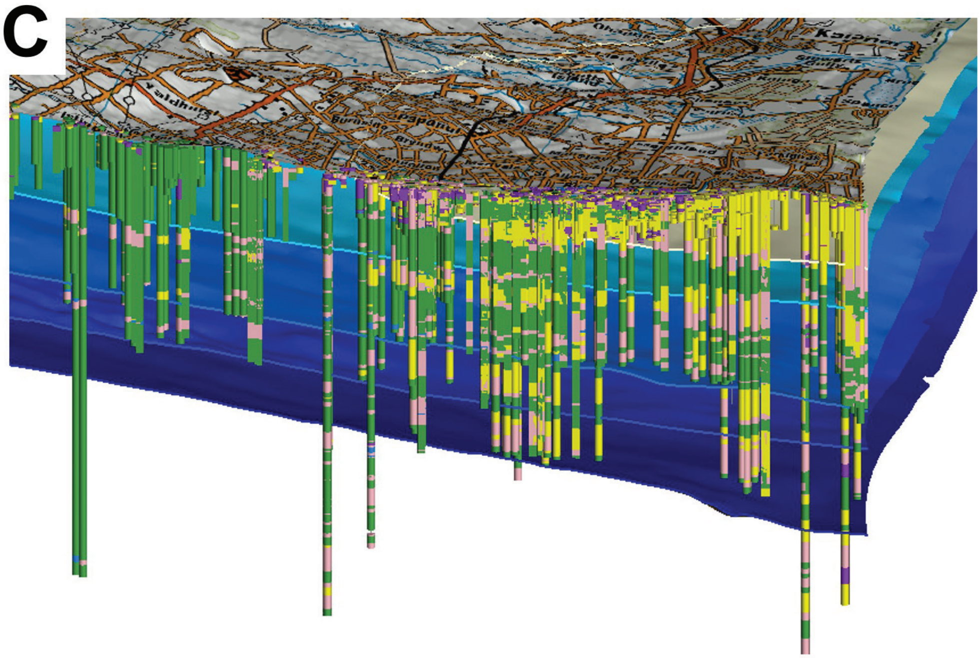


Figure 4 – Historical geological transects drawn for the CAS. **C:** 3D model view of the same transect line exported from Begg et al.'s (2015) geomorphological model of Christchurch, processed using Leapfrog Viewer software. The geological model depth is constrained to the Wainoni Aquifer and only the Christchurch Formation and gravel aquifer units are shown. *(Image supplied by Katie Jones, GNS Science)*

Geophysical surveying

Several geophysical survey techniques (seismic, gravity, magnetic, resistivity and downhole gamma logging) have been used on the Canterbury Plains over the last 80 years, looking for oil prospective structures, strata contacts, basement rock, shallower volcanic rock and groundwater aquifers. In recent years they have also focused on identifying buried faults.

The first geophysical surveys of subsurface strata of the northern Canterbury Plains were magnetic surveys (Jones, 1941). These were on the Canterbury Plains (just west of Christchurch at Wigram and Burnham) and on the New Brighton Spit. Following on from the magnetic surveys of Jones (1941), the first extensive geophysical surveys of the Canterbury Plains were carried out by oil exploration companies. The results and interpretations of the seismic (Kirkaldy and Thomas, 1963) and gravity (Robertson, 1961) survey were collated and reviewed by Brown (1975). Subsequently, Hicks (1989) used gravity to map the buried greywacke rock surface. In North Canterbury, Brown (1975) delineated 'tectonic elements' such as the Rangiora sub-basin, the Banks Peninsula – Sheffield High and the Rakaia Trough.

Resistivity was used in the 1980s to provide an understanding of the gravel structure beneath the Waimakariri River to depths of around 50 m and to estimate hydrogeologic parameters controlling the recharge from the river towards the aquifers beneath the city (Broadbent and Callander, 1991). Broadbent (in Talbot *et al.,* 1986) reviewed the Canterbury Plains' geophysical surveys between the Ashley and Rakaia rivers and was able to identify broad detail of several stratigraphic horizons, including the top of the Torlesse Supergroup (greywacke), the top of Oligocene limestone, the base of the Wanganui series and the Pliocene, and a horizon within the Pliocene – Pleistocene Kowai Gravels that is probably the base of the groundwater reservoir. Figure 4.4 in Talbot *et al.* (1986) and Figure 46 in Brown (2001) show isopachs of Quaternary gravels that are the thickness of young water-bearing sediments between the Ashley and Rakaia rivers. These have a maximum thickness of 600 m at Kaiapoi, where there is a basin. The Quaternary sediments are underlain by older strata, probably as young as early Pleistocene. The structure contours confirmed Quaternary sediments to a depth of 400 m at Woodend, north of the Waimakariri River mouth (Kaiapoi Trough), and 400 m at Te Waihora/Lake Ellesmere (Lake Ellesmere Trough). The geophysics suggests that the greater Christchurch area from Belfast to Weedons, between these two deeper trough structures, might be underlain by about 240 m of Quaternary sediments. It also confirms the existence of the unconformity between the Hereora Formation and the Kowai Formation which signifies a substantial temporal gap, marking a shift from the Late Cretaceous to the Pliocene-Pleistocene epochs (Brown, 1998).

Geophysical surveys have been used to inform the extent of the 'volcanic apron', that is, the extent of the buried volcanics from Banks Peninsula. Sewell *et al.* (1992) estimated the diameter for the Lyttelton volcano as 35 km. More recent works (Barnes *et al.,* 2011) have located the volcanics as a northward-thinning wedge over Paleogene and older Miocene sequences, extending north some 20 km to the Waimakariri River mouth.

Other geophysical seismic surveys centred on coastal Christchurch (Lawton *et al.,* 2014) and Pegasus Bay, offshore of Christchurch (Barnes 1995; Barnes *et al.,* 2011), provide detail of the stratigraphy, including the Kowai Formation unconformable contact and Banks Peninsula volcanics. A shore-normal paleochannel in the offshore Riccarton Gravel up to 2.3 km wide, 5–10 m thick and extending more than 35 km beyond the present-day coastline was recently identified from the seismic reflection data (De Palacio, 2024). High-resolution seismic profiles in Pegasus Bay (Barnes, 1995) extended the Christchurch stratigraphy and MIS classification offshore. Barnes *et al.* (2011) provided imaging >1 km below Pegasus Bay of the Kaiapoi Fault, offshore of the Waimakariri River mouth, vertically displacing overlying strata as young as Linwood Gravel. This is the only fault dislocation of a CAS aquifer so far identified within the MIS 1-16 stratigraphic sequence.

Surveys made following the most recent destructive Christchurch earthquakes identified several buried active faults beneath eastern and southern Christchurch (Beaven *et al.,* 2011 and 2012), including the Port Hills Fault beneath Opawa and the Avon-Heathcote Estuary that tracks to Pegasus Bay and slopes southward beneath the Port Hills. Movement on this fault was the source of the M_W 6.3, 22 February 2011 Christchurch Earthquake (Beaven *et al.,* 2012). The fault did not rupture to the ground surface, but differential offset on the fault resulted in vertical deformation of the ground (Beavan *et al.,* 2012). Subsidence was observed north of the Avon-Heathcote Estuary and uplift (maximum 0.45 m) at the western and southern margins of the Avon-Heathcote Estuary (e.g., Reid *et al.,* 2017; Tonkin and Taylor, 2012). Liquefaction was widespread especially surrounding the Avon and Heathcote Rivers (e.g., Figure 14 in Kaiser *et al.,* 2012).

Lawton *et al.* (2014) collected approximately 41 km of seismic reflection data in and around Christchurch following the 2011 earthquake. Figure 5 shows the location of the seismic lines, as well as the aftershocks that were recorded by June 2011. The goal of the seismic program was to map previously unknown faults in and around the city for hazard assessment and to assist in the post-earthquake recovery effort. The work also revealed the structure of the volcanic apron and overlying deposits.

The survey along the Brighton coast identifies Wainoni Gravel and Kowai Formation, as well as the Port Hills Fault and Banks Peninsula volcanic rock horizons (Figure 5). On New Brighton Spit, the seismic line shows a volcanic rock apron at 120 m bmsl. Further north in Southshore, at about 220 m bmsl, the survey shows the volcanic rock dipping beneath the Kowai Formation surface with a clifflike structure. About 4 km north, at South New Brighton, the survey shows the Port Hills fault at 440 m with possible downward displacement to the north of about 50 m within basal Kowai Formation and definite fault dislocation of volcanic rock. Six kilometres north at the Bexley bore, the Kowai Formation surface is 240 m deep.

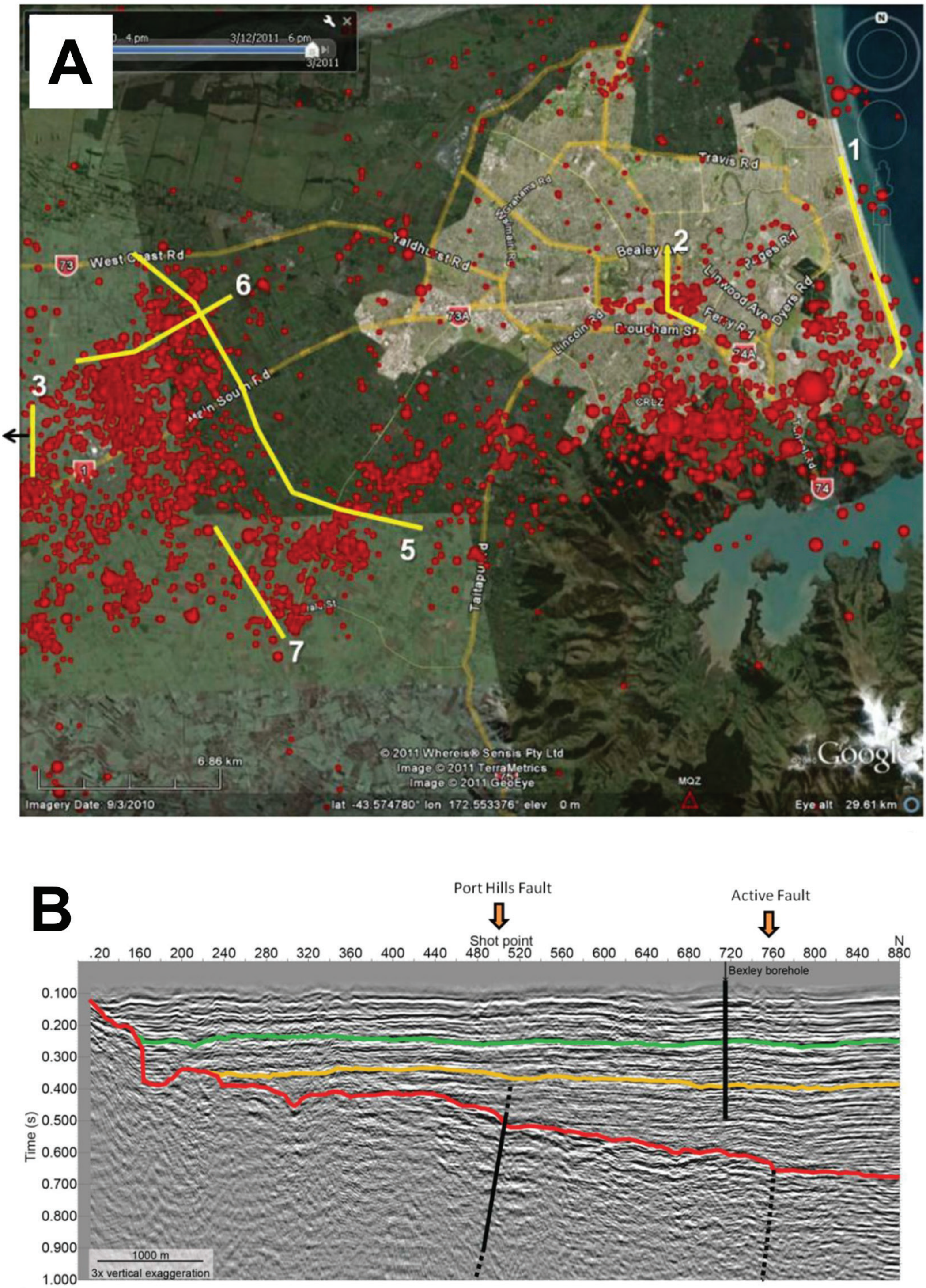
In terms of extending knowledge about late-Quaternary stratigraphy and CAS hydrogeology, the Kaiapoi Trough, identified by geophysics, would offer the best site for a future investigative bore, as this would be the thickest and most complete part of the sequence. A 500 m bore at a coastal location just north of the present Waimakariri River mouth would have potential to provide maximum information for MIS 1-16 aquifer-aquitard sequence, and the unconformity with the underlying Kowai Formation at about 300 m depth.

Contributing organisations

Central government departments and agencies

Numerous organisations have contributed to the understanding of the CAS over the decades, starting from 1865 when New Zealand's first national scientific institutions – the NZGS and the Colonial Laboratory (later the Dominion Laboratory and then Chemistry Division) – were established (Burton, 1965; Mortimer, 2015). In 1871 the government established the Public Works Department (PWD) that preceded the Ministry of Works (MOW), then the Ministry of Works and Development (MWD). Along with the Department of Agriculture (subsequently Ministry of Agriculture), these central government organisations supplied groundwater expertise for individuals, farmers, industry and local government, and collected well data on an *ad hoc* basis, for almost a century. Some exploration well drilling and groundwater monitoring was initiated by the New Zealand Railways Department (NZR) whose rail network required large amounts of water to operate

Opposite: **Figure 5** – Seismic survey of the CAS made after the 2010 Darfield and 2011 Christchurch earthquakes. **A:** Layout of 2D seismic lines (numbered yellow lines) recorded during the Christchurch seismic reflection survey program. Red dots show the epicentres of aftershocks through to June 2011 (data courtesy of S. Bannister, GNS Science). Line 3 was located 10 km further to the west of position shown, along Highfield Road and straddling the Greendale fault surface rupture trace. **B:** Interpreted seismic Line 1 along New Brighton Beach. The red reflector horizon is interpreted as the paleo-topographic surface of the Banks Peninsula Volcanics (~6-9 Myr); the orange reflector horizon is interpreted as the top of Miocene (~5.3 Myr); and the green reflector horizon is interpreted as the top of Kowai Formation (1.63-0.66 Myr).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© 2011 Whereis® Sensis Pty Ltd
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Shot point
Active Fault
Bexley borehole
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and house employees. The information NZR accrued about Canterbury geology and groundwater resources contributed to a better understanding of the CAS (e.g., Gair, 1961).

In 1926 the government established the DSIR, which incorporated the NZGS and the Dominion Laboratory. In the reorganisation of DSIR in 1936, a Crop Research and Botany Division was formed, and the NZGS Soil Survey group became the DSIR Soil Survey Division (later the New Zealand Soil Bureau) (Atkinson, 1976). Irrigation and groundwater formed a research interest across all three of those divisions. A DSIR Geophysics Division was formed in 1951 and in 1959 the Institute of Nuclear Sciences (INS) was formally established from the isotope division of the Physics and Engineering Lab. In 1947 the NZGS opened a Canterbury District Office at Timaru, from which research of Canterbury geology and groundwater was undertaken. The office relocated to Christchurch in 1949, and it was around this time that District Geologist B. W. (Tony) Collins initiated the acquisition of all available Canterbury water well data and its organisation into three water well databases: well logs, water level measurements, and well water chemical analyses. The Canterbury well and water level databases were maintained and expanded in response to the increasing use of groundwater from wells for irrigation and the associated need for information related to geology for locating the aquifers across the region.

Commencing in the 1950s, the NZGS documented their hydrogeological exploits in groundwater bulletins and client reports. In the 1960s, to make the information more generally available, they started a new publication series that included the NZGS Industrial Map Series 1:25,000, which related water supply and geology. During the 1970s and 1980s, several of these map series were produced for the north Canterbury Plains (which included part of the CAS). Data were presented in the form of geological maps on which well locations were plotted and well log cross-sections drawn, accompanied by tables and graphs that documented monitored groundwater levels (Brown, 1973, 1975, 1976; Brown *et al.,* 1984). At that time the NZGS well database for Canterbury contained 5,607 well records.

In 1974 R. B. (Dick) McCammon from the Office of Resource Analysis, United States Geological Survey, was seconded to NZGS, Christchurch to help solve the problem of how to make the well data readily accessible. A computer-based information-retrieval system was to be the answer (McCammon, 1976). The New Zealand water-well data form designed by McCammon (1975) and Brown and McCammon (1976) accommodated 80 specific code items per well, which were transposed onto punch cards for entry into the computer (Figure 3B). Guyon Warren, geologist and NZGS Computer Section manager, oversaw this work as he also did the annual production of transparent overlay sheets for mapping well locations.

Regional authorities

The Water and Soil Conservation Act (1967) saw the establishment of Regional Water Boards and a Water and Soil Division of the Ministry of Works. The Regional Water Boards were incorporated with pre-existing Catchment Boards and became responsible for investigating and reporting all significant resources of natural water within their region. The Water and Soil Division of the MWD was to assist the Water Boards in this role and a 'groundwater team' was duly established, headed by Hugh Thorpe. The team's capabilities were focused on specific area studies of the groundwater hydraulics, contamination potential, geophysics and modelling.

The CAS was within the North Canterbury Catchment Board (NCCB) area. In 1972 M. J. (Mike) Bowden was employed as NCCB's

Water Resources and Design Engineer and oversaw groundwater management. In July 1974 J. H. (John) Weeber was also appointed to the NCCB, as a groundwater geologist. During the 1980s the core of groundwater researchers at NCCB expanded to include J. D. (John) Talbott, John Hughey and Peter Callander who were supported by Bryan Todd, who managed the fieldwork team, and thus played an important role in information gathering. In 1976, the North and South Canterbury Catchment Boards assumed the role of collecting and filing new information. Accordingly, they took over the Canterbury groundwater database, assimilated the NZGS well data and groundwater levels files, and all other available data, and proceeded with its computerisation, following the approach of McCammon (1975) and McCammon and Brown (1976).

Following completion of a major study of the Heretaunga Plains, Hawkes Bay (Ministry of Works and Development, 1979; Thorpe *et al.,* 1982; Scott, 1991) between 1976 and 1978, the MWD Water and Soil Division 'groundwater team' took up residency at the Christchurch Science Centre (present day office of the New Zealand Institute for Public Health and Forensic Science) to work on characterisation of the groundwater resources of the central Canterbury Plains (Scott, 1980; Scott and Thorpe, 1986). They nevertheless supported the NCCB in their CAS research. In 1989 NCCB amalgamated with the South Canterbury Catchment Board, the Waitaki Catchment Commission and the Kaikōura sector of the Marlborough Catchment Board south from the Clarence River, to become Canterbury Regional Council (now Environment Canterbury). Central Government financial support for Regional Councils ceased, and following the restructure of the DSIR and MWD, and subsequent formation of Crown Research Institutes (CRIs) in 1992, Regional Councils assumed total responsibility for their region's water resources, including groundwater. The scope for CRIs to conduct groundwater research has been restrictive with emphasis on short-term, narrow-focus projects, and dependency on consulting fees and government grants to sustain support to Regional Councils. As a result, the traditional long term cooperative research programmes that are a vital component of groundwater studies have languished – a problem that continues to the present day. It is perhaps no coincidence that, from the mid-1980s onwards, there has been growth in the number of consulting firms offering specialist groundwater services.

Environment Canterbury operates under the Resource Management Act (RMA) that was enacted in 1991. They are responsible for protecting and improving outcomes for the environment that includes the CAS. Groundwater protection is incorporated within the regional policy statement, and resource management and consenting decision-making is guided by rules prescribed in the regional plan. Environment Canterbury has the challenge of managing the competing urban and rural interests, covering social, economic, environmental and cultural priorities. That came to a head in 2010 when the Government of the time temporarily appointed commissioners to govern operations. Under the tenure of the commissioners (2010-2016) a planning framework was established, allowing comprehensive and integrated freshwater management. Part of that framework included adoption, in 2012, of the Canterbury Water Management Strategy (CWMS) that was originally drafted by Lincoln Ventures Ltd., a subsidiary of Lincoln University (Morgan *et al.,* 2002). For planning purposes, the Canterbury region was divided into ten water management zones with the CAS expanding across the Christchurch-

West Melton, Selwyn-Waihora and Ashley-Waimakariri zones, and bordered by the Banks Peninsula zone.

The well drilling industry

Drilling methods

Well drilling technology and the prowess of individual drillers had a profound influence on the obtaining of water supply from the CAS aquifers, and on documenting its hydrogeological record. The first drilling rigs were very basic homemade machines that functioned by driving a pipe into the ground. They comprised a tripod, a weight (monkey) and rope, and were powered by hand or with help of a horse. Later, custom built (often by the driller) and commercial drilling rigs used portable steam engines to provide lifting, driving and rotating power. Steam power was eventually replaced by more compact higher horsepower petrol and diesel engines (Weeber, 2000).

For almost 100 years, cable tool methods were used throughout New Zealand for drilling wells of 100–150 mm diameter, many within the CAS. A distinct advantage of the cable tool method was that it provided for the ability to log the geological strata in good detail. Well drilling underwent a revolution in the 1980s with the introduction of rotary-percussion methods to the Canterbury region and which proceeded to become the dominant drilling method. Whilst more efficient at boring than cable tool methods, the grinding action associated with rotary drilling pulverises the gravel media and fluidised drill cuttings are blasted out of the borehole as a slurry. Cuttings might be collected using apparatus such as Cyclone samplers, yet the ability to precisely log sedimentary changes in Canterbury alluvium is nevertheless compromised. Because of rotary drilling methods, the quality of geological well logs for the CAS effectively took a step backwards. This regression has now been corrected with the introduction of sonic drilling techniques which enable continuous geological cores to be obtained. The application of sonic drilling methods has primarily focused on geotechnical and shallow investigation with a rise in popularity in the wake of the 2011 Christchurch Earthquake. The penetration depth in the CAS of available mid-sized sonic drilling rigs in New Zealand is generally limited to about 100 m, and the method has not been widely used in water-well drilling. A more recent development has now seen the introduction of New Zealand's first full-sized sonic rig extending the penetration depth to beyond 100 m (deepest being 187 m achieved in late 2024) and providing new opportunities for the water-well industry.

Notable drilling firms

Between 1881 and 1990 at least 75 commercial well drillers and well drilling firms are known to have operated in the Christchurch – North Canterbury region (Weeber, 2000). One of the first, Job Osborne Ltd., was founded in 1881 and their drilling records represent the most extensive individual drillers' input into CAS. Job Osborne was an innovator and the most important driller in terms of the number of logged wells and the resultant contribution to the CAS hydrogeology. Weeber (2000) provides a brief biography and Weeber (2005) provides an alphabetical list of Osborne's wells. In total, Job Osborne and his successors drilled 2,826 water wells and bores. In July 1882, Job Osborne patented a drilling machine designed to be 'driven by other than manual power for driving pipes for artesian wells'. In 1887 this was superseded by a more complex patented 'double action well driver' operated by two men and powered by a portable steam engine described in detail by Weeber (2000). Job Osborne's diary records that he acquired a Keystone cable tool rig, imported from the USA, in 1903. The last well drilled with Job Osborne as owner was by Sam Taylor in July 1910 at the Christchurch Tepid Baths in Manchester Street. This was well M35/1980, 100 mm diameter and 127.4 m deep tapping Wainoni Gravel. Christchurch City Council (1928) advertised ‘the wonderful artesian water of Christchurch makes the municipal tepid bath the finest in the Southern Hemisphere’. Job Osborne then sold the well drilling business to employee Sam Taylor who was to have a long-term involvement with Christchurch well drilling (1910–1949). Taylor retained the name Job Osborne Ltd as did following owners S. N. (Stan) Geddes (1949–1968) and Aubrey Watson (1968–1980). Job Osborne’s contribution to the CAS as a ‘well-sinker’ is commemorated in the Millenium Water Feature sculpture that decorates Anderson Square, Leeston (Figure 6).

James W. Horne began his well drilling career with Job Osborne in 1888 but left to establish his own well drilling business in 1893 (Weeber, 2000). Horne, like Osborne, meticulously logged the wells he drilled and trained his drillers to do likewise. Unfortunately, a lot of his drilling records have been mislaid and may have been burnt in a fire, and only a small proportion of the logs are now available. Apart from venturing to Hanmer Springs in 1911 to drill three geothermal wells at Queen Mary Hospital, Horne only drilled close to, or within, Christchurch, where coal was readily available for the rigs’ boilers. The deepest well drilled by Horne was in July 1907 at the New Zealand Refrigeration Company Ltd., Islington freezing works. The well (M35/1039) reached a total depth of 223.1 m where the water level rested 10 m below ground level. This well had the distinction of being the deepest well in Christchurch until the Bexley bore (M35/6038) was drilled to 433.0 m in 1989 by McMillan Drilling. J. W. Horne continued running the drilling business until 1912 when it was sold to employees A. B. Clemence and R. McClure. The name J. W. Horne and Co. was retained, and the firm

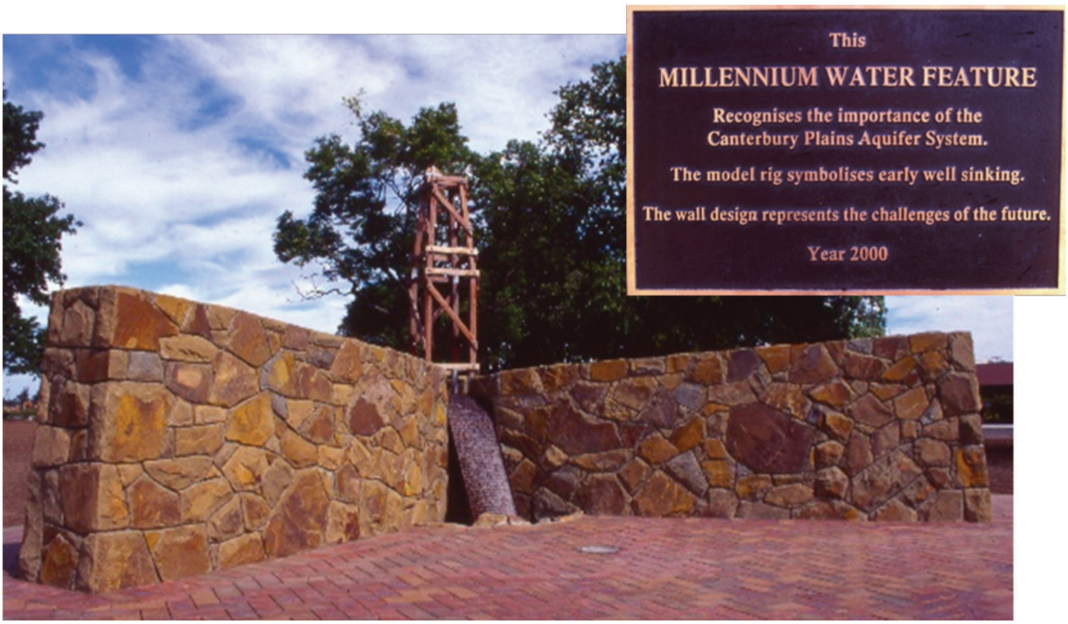

Figure 6 – The Millenium Water Feature, Leeston – a commemorative memorial to pioneering well-sinker Job Osborne who resided at Doyleston and whose drilling innovations and meticulous record keeping contributed greatly to our understanding of the CAS *(Photo supplied by John Weeber*).

remained in the Clemence family until the company was dissolved in 1986.

In 1956 A. M. Bisley, a Hamilton-based agriculture servicing company, began operations including well drilling in the South Island based in Christchurch using a Bucyrus Erie 22W cable tool rig manufactured in Wisconsin, USA. E. V. R. (Russell) Harris, Bisley's South Island manager, had considerable groundwater and well drilling experience (New Zealand Driller, 1982). Starting in 1945 as a driller's assistant on a Brown and Sons drilling rig, he was a partner in Benton and Harris Ltd. (based in Hamilton). He went to the USA in 1955 where he worked at Edward E. Johnson, manufacturers of well screens. Since 1930, Johnson Screens had manufactured stainless steel continuous slot wire wrapped and welded well screens, which basically minimised turbulence in the water as it was drawn into the well from the aquifer. They also published the drilling industry bible, *Groundwater and Wells,* now in its 3rd edition (Sterret, 2007). Russell Harris returned to New Zealand in 1956 where he helped establish A. M. Bisley's drilling arm of the business in Christchurch. Besides well drilling expertise, he promoted well screens and submersible or deep well pumps. In 1964 Harris attended a groundwater engineering course organised by the World Health Organization at the University of Minnesota, then returned to work at Johnson Screens, and finally worked with Pleuger Pumps in Germany before returning to New Zealand. His considerable engineering, groundwater and drilling expertise, in conjunction with the skills of Ben Lagendyke (Bisley's driller), had a substantial impact on city and borough water supply and farm irrigation. Ben Lagendyke could retrieve relatively intact samples of the strata being penetrated at depth with the cable tool rig bailer. Many of these samples were used by NZGS for radiocarbon dating and paleoenvironment determinations from macrofauna (shells) and palynology (pollen) (see Appendix 1 of Brown and Weeber, 1992; and Moar and Mildenhall, 1988). This information was particularly important for Holocene sea level rise studies (see Figure 8 of Brown and Weeber, 1992) and interglacial period climate studies in relation to the Christchurch subsurface stratigraphy and the geology of the aquitards. Harris was a co-author of a New Zealand well commissioning and maintenance manual (Bowden *et al.,* 1983). He retired in 1986 when Bisley's closed their Christchurch branch.

There are three further family drilling dynasties who have had a considerable influence on well drilling and CAS knowledge. In the 1900s J. M. Stewart purchased a former Mines Department Keystone Drilling Machine and began a well drilling enterprise in Dunedin. This was expanded with two more Keystone rigs, one of which was based in Christchurch (Webb, 1992). J. M. Stewart and son R. H. (Bob) Stewart, with their well drilling background, contributed two generations of Stewart expertise with well drilling for CCC wells and consultative advice on the aquifers of the CAS for the Christchurch water supply network. After the Stewarts sold their drilling rigs in 1945, Bob proceeded to worked for the CCC as Water and Drainage Engineer, where, with his drilling expertise, he supported the council to operate a petrol engine-driven Keystone drilling rig they purchased. Before retiring in 1970, he was in charge of the CCC water supply (Webb, 1992).

Another long-term Christchurch well drilling dynasty is the Clemence family, with four generations of well drilling experience. After the Horne drilling company was dissolved in 1986, the Clemence family set up a drilling company in their own name. Dave Clemence had worked as a driller for the DSIR Geophysics Drilling Division in New Zealand and Antarctica, and for South Pacific Island water supplies, prior to establishing Clemence Drilling in 1986. At its peak the company had 18 drilling rigs and employed 60 people. Clemence Drilling has the distinction of drilling the deepest CAS well (BX24/0191) to 450 m in 2013. The company remains active but downsized after the demand for drilling irrigation wells declined in the 2000s.

Three generations of the McMillan family of Southbridge have also been involved in well drilling, starting from when Trevor McMillan expanded his Southbridge blacksmith and farm machinery business into well drilling in 1947 with a cable-tool drilling rig that he built. In 1982 Trevor's son, Lyell, imported a rotary-percussion Schramm rig from the USA followed by a second Schramm a few years later. These rigs required several adaptions to be able to cope with drilling through Canterbury fluvial gravel deposits. Keeping with this ethos, in 2010, McMillan's invested in their first mid-sized sonic drilling rig, followed in 2024 with New Zealand's first full-sized sonic rig. For a time up until 2018, they operated a water quality testing laboratory, in conjunction with the drilling operation. Today McMillan Drilling is the largest drilling company in Christchurch (Australasian Drilling, 2015; https://drilling.co.nz/).

Hydrogeological data

Groundwater level records

Apart from casual observations, and concern when artesian wells stopped flowing and artesian heads declined resulting in hydraulic rams not working, measuring groundwater levels was of no interest to the early settlers of Christchurch. The recording of groundwater levels and artesian heads only began with the early well drillers measuring static water levels during the process of drilling wells. However, long-term well water level monitoring provides an invaluable record of the effect of groundwater abstraction versus recharge, and scientists heeded Haast's (1879) counsel that a database including well water levels was vital for future management of the resource.

Regular CAS well water level observations were begun at the Canterbury Museum 'shallow' and 'deep' wells in 1894 with weekly water level measurements by Museum Curator Captain F. W. Hutton (Hutton, 1896). The 'deep' 55.5 m well M35/2564 tapped Linwood Gravel (see borelog in Figure 3C) and the 'shallow' 30.5 m well M35/2565 tapped the Riccarton Gravel. Water level measuring of these two wells continued on and off for 129 years with people from Canterbury Museum, Canterbury College Geology Department, NZGS and Environment Canterbury contributing to the effort (Figure 7A). The wells were decommissioned in October 2023 as part of the museum redevelopment and have since been replaced by wells BX24/3233 (27.3 m deep) and BX24/3234 (58.0 m deep) located nearby in the Botanic Gardens. Another long-term water level monitored CAS well was M36/0510 at the Canterbury Agricultural College, Lincoln. This was a 103.6 m deep well tapping Wainoni Gravel. Regular water level measurements of this well in the periods 1911–1924 and 1943–1965 are discussed by Hilgendorf (1911, 1926) and Oborn (1960). Measurements ceased in 1986 when the Stewart Building was built on top of the well.

The first continuous well water level recorder used at Christchurch was designed and made by F. W. Hilgendorf (Lincoln College lecturer) and L. P. Symes (Chemist, Canterbury Frozen Meat company, Belfast), and installed on an artesian well on Mays Road, Papanui (of unknown depth) in 1914 (Symes, 1917; Hilgendorf, 1917). This showed a daily fall in level from 6 a.m. to 4 p.m. and an overnight recovery that were attributed to consumptive water use patterns. It also showed a rise in level with rainfall and fluctuations in response to earthquakes

(Hilgendorf, 1926). In 1956 NZGS installed a Leupold and Stevens Type F float weekly continuous water level recorder on a series of Christchurch wells (Brown, 1975). From 1960 to 1977 such a recorder device installed on the Canterbury Museum deep well was made into a working public exhibit. The well identified a range of influences affecting daily and seasonal water level trends and was extremely sensitive to earthquakes, both local and distant. These provided information on ongoing and immediate water level responses and daily and weekly cycles of water level change similar to Symes' Papanui well. In 1982 the Leupold and Stevens recorder at the Museum was replaced with a Foxboro pressure recorder, which continued as a working exhibit until 1998 when the Museum deemed it redundant and monitoring reverted to manual water level measurements (e.g., Figure 7B).

Within the current regional network of 596 water level monitoring wells routinely surveyed by Environment Canterbury, 48 monitor water levels in the CAS. Twenty-five of those wells are instrumented with automated recorder devices (downhole pressure transducers) that monitor more frequently than the standard monthly frequency, and 13 are fully telemetered, providing real-time groundwater level/pressure data. A further 14 wells monitor water levels in surficial strata, overlying the CAS.

Groundwater chemistry

Water quality and impacts of agriculture

After well logs and water level data, well water chemistry data comprised the third data category Tony Collins established in the Canterbury groundwater database. The bulk of the early water chemistry and bacteriological data were obtained by the DSIR Chemistry Division (Drummond and Hogan, 1965, 1967; Hogan, 1976), some of which has only just recently been added to Environment Canterbury's water quality database (Aitchison-Earl and Knottenbelt, 2024). As community drinking water suppliers, CCC, Waimakariri District Council and Selwyn Council are all obligated to test the quality of groundwater abstracted for reticulated community water supply, yet it is Environment Canterbury who conducts routine monitoring to assess the general state and trends of the groundwater resource. Environment Canterbury's standard analytical suite includes nutrients, ions, dissolved metals, the faecal indicator bacterium *Escherichia coli,* and a number of other physio-chemical variables. Of the 376 wells Environment Canterbury routinely survey for water quality, 38 monitor the CAS directly and a further 62 monitor water quality on the plains, between the Ashley and Rakaia Rivers, inland of the CAS.

The alpine river recharge component to the CAS provides some protection of CAS groundwater from the impacts of land-use, particularly under Christchurch city. Nevertheless, Environment Canterbury and CCC have detected small, yet increasing, levels of the highly soluble nitrate ion in shallow public water supply wells about the north of the city, and elevated nitrate concentrations in the Riccarton Gravel aquifer to the south of the city. This is an indication that the CAS is not entirely immune from the impacts of agriculture (Environment Canterbury, 2015; Rosado and Scott, 2020). Numerical groundwater modelling by GNS Science and Environment Canterbury to inform water resource management in the Ashley-Waimakariri zone predicts that groundwater flow transgresses the Waimakariri River boundary (Etheridge and Hanson, 2019), the implication of which is that nitrate leached from intensive agricultural land on the Waimakariri-Eyre River fan complex could potentially affect water quality in the CAS in the future. This revelation prompted Environment

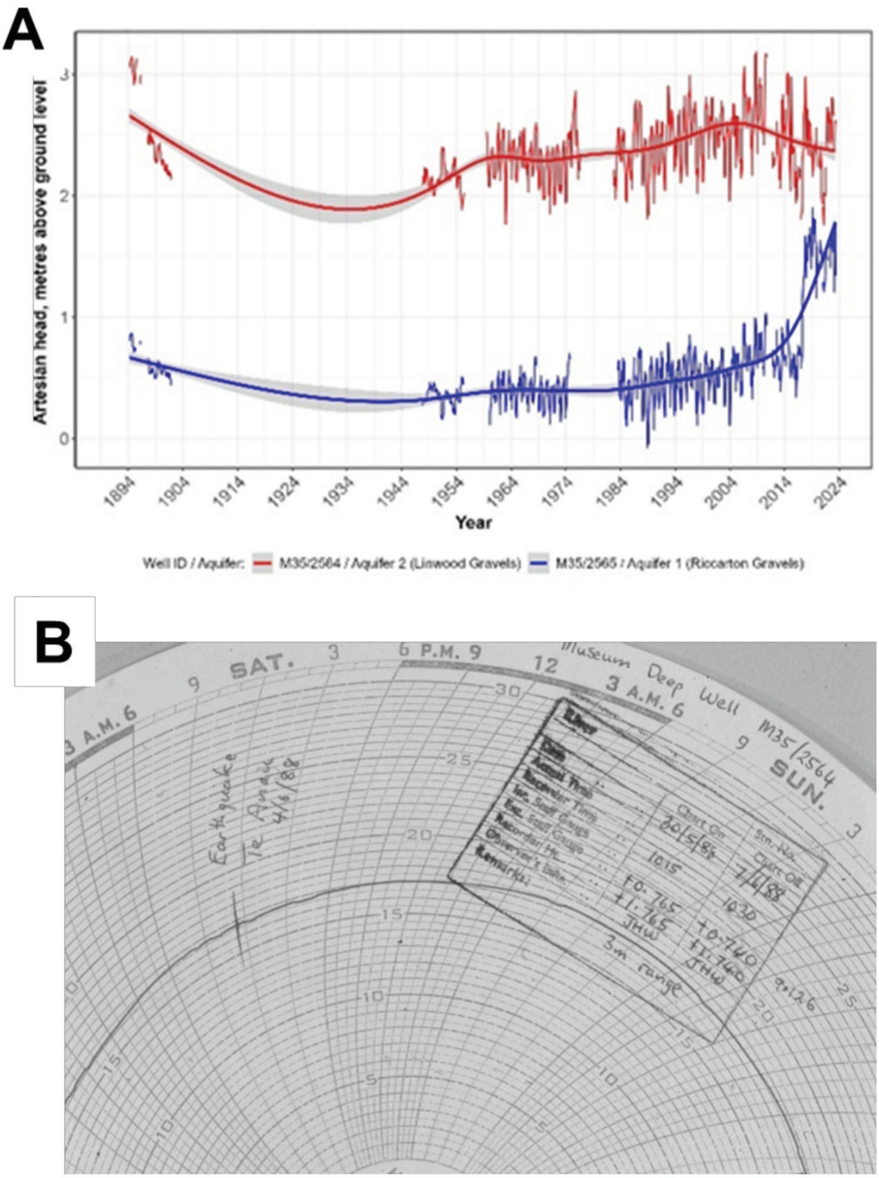

Figure 7 – Groundwater level monitoring records from the museum wells that screened the Riccarton Gravel and Linwood Gravel aquifers, and where water level measurement began in 1894. The museum wells were decommissioned in April 2023 and have since been replaced by two new monitoring wells: BX24/3233 and BX24/3234. **A:** Monthly averaged data from the full available record. Significant gaps in the record occurred between 1901 and 1947; 1955 and 1960, and 1974 and 1983. Localised polynomial regression plot to show general trends. The step increase in water pressure in the Riccarton Gravels that occurred in 2017 can be attributed to the effects of groundwater source heat pumps that inject water into this aquifer. **B:** Example output from the 7-day Foxboro chart recorder for the 'deep' well showing earthquake trace on 4 June 1988. The recorder was a public feature at the museum from 1982 to 1998. *(Photo supplied by John Weeber)*

Canterbury to establish three multi-level well clusters bordering the Waimakariri River, to serve as sentinel monitoring wells. Between 2017 and 2021, a cluster of three monitoring wells (BX23/0771 - BX23/0773; 47.5, 101.3 and 149.2 m deep) were installed on the groynes at Eyreton, on the true-left of the Waimakariri river. On the true-right of the river, three monitoring wells (BX23/0768 – BX23/0770; 105.5, 47.5, 153.0 m deep) were installed on Weedons Road near West Melton airfield, and a further four wells (BX23/0761 - BX23/0763 and BX23/1078; 47.6, 101.9, 150.1 and 292.0 m deep) were installed on McLeans Island (Figure 1). All ten wells have been added to the regional network of groundwater quality monitoring wells and to date have not revealed any evidence of adverse land-use impacts.

Inland of the CAS, groundwater on the Canterbury Plains has long demonstrated impacts of agricultural land-use. Shallow groundwater nitrate concentrations were prominent in the 1970s, prior to irrigation (Burden, 1984; Rutter and Rutter, 2019). When the NCCB first surveyed groundwater under the central Plains (modern Selwyn-Waihora zone) in the 1980s, they found the chemistry to be distinctly stratified. Nitrate impacts were largely confined to within 60 m depth of the water table, below which nitrate concentrations were <1 mg/L NO_3-N. The likely groundwater transport process associated with stratification in the central Plains groundwater system was modelled in Bidwell (2005). Burden (1984) predicted that land-use intensification supported by large-scale irrigation could conceivably raise concentrations across the plain (outside the zones of direct river recharge influence) to above 10 mg/L NO_3-N. Disturbance of the chemocline was not forecast, for the reason that it was presumed the deep groundwater resource would be conserved for potable supply, not irrigation. Rutter and Rutter (2019) performed a more recent review of groundwater nitrate data in the Selwyn-Waihora and Christchurch-West Melton zones, to assess decadal water quality trends since the 1970s, at discrete depth intervals. They found that whilst absolute nitrate concentrations have not increased significantly in the Selwyn-Waihora zone, the depth extent of nitrate pollution has expanded, which conceivably has implications for water quality in parts of the CAS. The now-completed Central Plains Irrigation Scheme has enabled many groundwater-dependent irrigators to convert from groundwater to river-scheme water but has also enabled a change from dry land farming to more intensive, irrigated farming. The scheme represents yet another change in the hydraulic and land-use stressors on the CAS, the predicted effects of which were detailed in Environment Court proceedings (e.g., Bidwell and Norton, 2009). The consent granted for the scheme includes intensive groundwater and surface water quality monitoring to assess the impacts of the scheme on the Canterbury groundwater system.

Groundwater isotope hydrology

The first radiometric analysis of CAS groundwater was made in 1910 by C. C. Farr (Canterbury College Physics lecturer, later inaugural professor of physics) who measured radium emanation from 16 Christchurch wells using a standard solution of radium supplied by Ernest Rutherford. Apart from Riccarton Gravel wells showing similar content, samples from deeper aquifers did not suggest any relationship between radium content and aquifer depth (Farr and Florance, 1910; Chilton, 1924). L. P. Gregory (National Radiation Laboratory, Christchurch) measured concentrations of radium's daughter product, radon, in water from 22 Christchurch city wells and concluded that radon concentrations increase with depth at a given location (Gregory, 1976). In a subsequent survey, he included measurements of gross alpha and beta activity (Gregory, 1980) that showed radioactivity levels of CAS groundwater were well within World Health Organization standards for drinking water. Most recently, radon has been used as an environmental tracer to examine Waimakariri River recharge of groundwater – the river representing the main source of water in the CAS (Close *et al.,* 2013).

The subject of isotope hydrology evolved in the 1950s. In New Zealand it started after a specialist nuclear and isotope analyses laboratory (Institute of Nuclear Sciences – INS) was established by DSIR at Gracefield, Lower Hutt (Rafter, 1965) to investigate and initiate radiocarbon or carbon-14 (^{14}C) dating (Sparks, 2004). Carbon-14 dating of organic material was directly applicable to Holocene geological and archaeological studies. Its use in hydrological study proceeded more slowly because of the additional need to understand variations in the ^{14}C content of atmospheric CO_2 required to interpret sample results. Other isotopic analytical capabilities were developed at the INS including measurement of tritium (^{3}H) and oxygen-18 (^{18}O). Advances in the use of tritium were led by C. B. (Claude) Taylor starting circa 1967, and succeeded by Uwe Morgenstern (e.g., Morgenstern and Taylor, 2009). Research applications of oxygen-18 were led by M. K. (Mike) Stewart, starting in 1980. Collectively, isotopes have been valuable tools for evaluating the age, origin and mixing of groundwater, from which an improved understanding of groundwater flow in the CAS has developed. The isotope hydrology database is now maintained by Earth Sciences New Zealand (previously GNS Science).

With a half-life of 12.32 years, ^{3}H is useful for dating water up to about 200 years old. S. H. (Stuart) Wilson, a geochemist at INS specialising in geothermal water isotopes, was the first to analyse the ^{3}H content of groundwater from the CAS, in 1962. Samples were taken from an 8.1 m deep water table well (M35/1341) at Christchurch Airport, Harewood, and the 55.4 m Canterbury Museum 'deep' well (M35/2564) that tapped the Linwood Gravel aquifer. Wilson's results showed a marked contrast in the two samples' groundwater ^{3}H content. The water table well had high ^{3}H content as a result of the atmospheric thermonuclear bomb testing during the 1950s, whereas the deeper sample from the Linwood Gravel artesian aquifer was low in ^{3}H, which demonstrated it had a pre-bomb provenance and that the aquifer was isolated from younger recharge sources. This established the effectiveness of ^{3}H analyses to provide significant groundwater age information for the CAS aquifers.

The CAS is particularly amenable to ^{14}C groundwater dating applications, because of its low inorganic carbon content. Bicarbonate concentrations are exceptionally low in the rivers on the plains (the losses from which dominate recharge to the CAS), and the quartzo-feldspathic greywacke gravel itself contains very little carbonate. The only notable carbonate material is in shells of shallow marine deposits that are associated with the confining strata of the CAS. To enable interpretation of ^{14}C data as ages, isotopic signatures of carbon-13 (^{13}C) are used to distinguish between the three different sources of carbon: biogenic (organic) carbon from plants, dissolved bicarbonate in Waimakariri River water, and bicarbonate dissolved in rainwater. For the CAS, it is possible to use ^{14}C dating to determine water ages in the range from 50 to 20,000 years, which is usually not possible in terranes with more carbonate, where the age range is more restricted (typically 1,000–20,000 years; Stewart, 2012). The broader age range detectability is particularly convenient for the groundwater age distribution in the CAS.

Groundwater from the CAS was first analysed for ^{14}C in 1976, sampled from four well locations (Stewart *et al.,* 1986). Because of the very low bicarbonate concentrations of the groundwater and analytical methods of that time, water sample volumes of 600 L were required. Samples for ^{14}C analysis have been collected from the CAS for each decade since then. Results from repeated sampling have revealed marked changes in groundwater flow patterns due to the increasing exploitation of the aquifers for Christchurch city water supply (Stewart, 2012; Stewart and van der Raaij, 2019, 2022). The changes are illustrated in Figure 8 for the Wainoni Gravel.

Although covering a different age range (0–200 years), ^{3}H measurements have been very valuable for dating younger groundwaters and for supporting ^{14}C ages (with water with younger ^{14}C ages containing ^{3}H as expected, and water with older ^{14}C ages containing no measurable ^{3}H). Use of chlorofluorocarbon (CFC) analyses in the dating of young groundwater was first applied to the CAS in the late 1990s and those results were found to support ^{3}H ages (Stewart et al., 2002).

Signatures of stable isotopes, most notably ^{18}O, help distinguish between different sources of recharge, such as water leaked from the Waimakariri River versus rainfall. CAS groundwater with a Waimakariri River water provenance has very negative $\delta^{18}O$ values because of its cold, alpine origin, relative to rainfall recharge on the coastal plain for which isotopic fractionation effects are less expressive and so $\delta^{18}O$ values are less negative. Oxygen-18 data have been useful in constraining mixing models and mapping of groundwater with a Waimakariri River provenance (Talbot *et al.,* 1986; Taylor *et al.,* 1989; Dodson *et al.,* 2012).

Future challenges and prospects

The CAS is a national asset. Spanning across the coastal margin of three water resource management zones in the Canterbury Land and Water Regional Plan, it is common for only parts of the CAS to feature in any single study. Rarely is its full extent presented or communicated, which downplays its significance as a hydrogeological system. Below we present some ideas for ongoing data collection and accessibility, future research topics and initiatives for raising public awareness of the CAS.

Data curation and access

The Wells database that is currently maintained by Environment Canterbury is the single most valuable data source for the CAS. It is likely that in the future it will be incorporated into the Wells Aotearoa New Zealand national data repository (https://wellsnz.teurukahika.nz). However, there are a lot of data that are not incorporated within the Environment Canterbury database, including water quality data which are stored separately. In addition, council and other organisations' quality and compliance data are not readily accessible due to data ownership issues. Another source of valuable data, the national hydrology isotope database, is separately held by Earth Sciences New Zealand. A foreseeable improvement in the accessibility to CAS groundwater would be to link all these data, to include water abstraction data, and integrate them into a user-friendly graphical interface. This would make it easier to analyse relationships between hydrological and hydrochemical states.

Public awareness

Aside from surface spring outflows, groundwater is not visible, and so the idiom 'out of sight, out of mind' all too frequently applies to the CAS. The CAS has centred in several socio-political news topics in recent years, e.g., public upset at chlorination of the

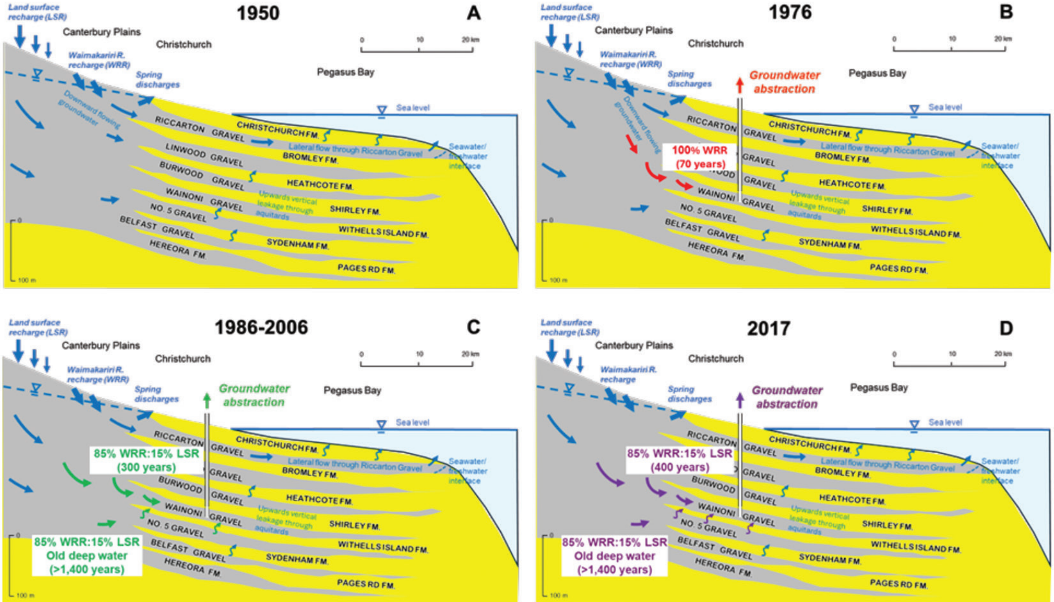

Figure 8 – Conceptual flow models for the CAS over time as informed from long-term monitoring of groundwater isotopic age. **A:** Groundwater age estimates were not available in 1950 and most water abstraction up to that time was focused in the upper gravel strata. Slow flow through the deeper strata was mainly controlled by vertical leakage through aquitard strata. The turnover time of groundwater in the CAS would have been in the order of 1000s of years and the age gradient across Christchurch is expected to have been small. **B:** Four groundwater samples from Aquifer 4 (Wainoni Gravel) were radiocarbon dated in 1976 and all showed very young ages (about 70 years old). Results were supported by indicative tritium ages (Stewart *et al.,* 1996; Stewart, 2012). It is inferred that pumped abstraction from the Wainoni Aquifer drew in young water with a Waimakariri River provenance from the west. **C:** Ages for groundwater in the Wainoni aquifer were more variable in 1986. An unsteady age gradient was detected across the city that ranged from 100 years in the west to 800 years in the east. Shallower groundwater also displayed ages in the range 400–800 years (Stewart, 2012). Repeat sampling in 1994 and 2006 revealed an older water composition, yet a distinct and consistent age gradient that ranged from 300 years in the west to 1200–1400 years in the east (compared to 800 years in 1986). Inferences are that, despite continued pumped abstraction, the system appears to be relaxing back towards its natural state with vertical flow under artesian pressures carrying old water upwards especially on the eastern side of Christchurch. Flows to the CAS inferred from the ^{14}C ages comprised: (1) Waimakariri River water from the west, (2) flow at depth below the river from the west (composed of a mixture of Waimakariri River and inland rainfall waters), and (3) up-flow on the east of Christchurch of much older water from depth (also a mixture of Waimakariri River and inland rainfall waters).
D: Latest ^{14}C sampling in 2017 showed increased ages throughout the Wainoni aquifer (Stewart and van der Raaij, 2022). Although the amount of groundwater abstraction by the city had plateaued from 2006, the centre of abstraction had moved towards the west after the Christchurch earthquake of 2011. Groundwater ages in the Wainoni aquifer ranged from 400 years in the west, circa 1000 years in the centre of the city, to about 1400 years in the east. The implications of the 2017 age results are similar to those from 1994–2006 with older waters now contributing more on the west and central parts of the city.

public drinking water supply (Gill, 2023) and resource consents for water bottling activities (Law, 2022). A lack of public awareness of the scale and function of the CAS is not particularly helpful in such matters. Open debates on CAS topics would benefit from a more informed public.

An initiative that ran through the 1990s, produced by Environment Canterbury, was a groundwater educational project designed for secondary school geography students (Canterbury Regional Council, 1992). Such educational programmes and public relations benefit from a captive audience. The Coca-Cola Europacific Partners New Zealand company explicitly inform consumers that the Wainoni Aquifer is the source for the Pump bottled water they package and retail (Figure 9A). Whilst the public water supply and distribution network is more complex to describe, more explicit public reference to the aquifer strata from which individual pumping stations abstract could form a small step towards raising public awareness and arousing curiosity.

Strategies to raise public awareness of groundwater have been exercised over the years, usually as an Environment Canterbury initiative. Examples include a display at the Canterbury A&P Show that highlighted the health risk from on-site wastewater treatment systems and the importance of good wellhead protection (Figure 9B). Until recently, a permanent exhibit at the Canterbury Museum, the 'Living Canterbury' room, was dedicated to Canterbury environmental science topics. It included an educational display that covered the topic of Canterbury's water resources in which the CAS featured. Canterbury Museum do not plan to restore such an exhibit in the revamped museum (pers. comm. Lynell Bell, Head of Projects and Strategy Delivery, Canterbury Museum). This is a loss and implies that using the Canterbury Museum as a venue for raising public awareness of the CAS will only be achievable through temporary exhibits in future, and those would require a strong collaborative effort and support from the science community. As the local tertiary education provider, the University of Canterbury has an ongoing role to play in teaching about the CAS, as well as research interests.

Throughout the 19th and 20th centuries, there were numerous ornate water fountains in Christchurch city that operated from free-flowing artesian water (see Burbery, In Press). Charles Chilton (biologist and professor at University of New Zealand) was a particularly strong advocate for beautification of the city and promoted the role that artesian water fountains might play in this. In his 1913 illustrated public lecture 'The Evolution

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Opposite: **Figure 9** – Promoting and raising public awareness of the CAS. **A:** Explicit mention of the Wainoni aquifer (the fourth deep artesian aquifer of the CAS) as the source of water bottled by the Coca-Cola Europacific Partners New Zealand company. Marketing spiel on the company website describes the water as being pure spring water (https://www.pump.co.nz/the-pump-story/). The public are not informed that the only route for water to spring from the Wainoni aquifer is via the 144 m deep well the company sunk at Marshlands, and that water abstracted from there is bulk tankered across the city to the bottling plant at Hillsborough. **B:** A display organised by Environment Canterbury at the Canterbury A&P Show in 1998 aimed at raising public awareness of groundwater contamination and drinking water protection *(Photo supplied by John Weeber)*. **C:** Proof of concept – examining how the free-flowing artesian head on the old New Zealand Exhibition well at Lake Albert (well M35/1937) might look if it were adapted to a water fountain feature for beautification and CAS promotion purposes.


A
ains: Spring Water
sourced from the Wainoni Aquifer, Christchurch.
100% RECYCLED PLASTIC
please recycle
RECYCLE ME
C
B
BACK YARD NEWS

of the Water Fountain' he imagined Christchurch with jets of artesian water being like a modest Versailles (*The Star,* 10 April 1913). As evidenced by the removal of the Stewart Fountain in the City Mall in 2017, water fountains may be regarded as expensive frivolities (e.g., Burbery, In Press). Whilst it might not be practical or economically viable to restore artesian fountains, there is one free-flowing artesian well in the city that could be enhanced as a public exhibit and emblem for the CAS: the old supply well to the 1906 New Zealand International Exhibition located on the islet of Albert Lake in North Hagley Park. Conversion of the well head to a fountain feature (as Chilton alluded to more than a century ago) and erection of some signage or a scannable QR code explaining the history of the well and its function could be a small step towards promoting the CAS whilst also celebrating the city's rich history – an exercise that is consistent with CCC's heritage strategy (e.g., Figure 9C).

Research and collaboration

Key areas of CAS hydrogeology that deserve further scientific investigation include improved understanding of the coastal boundary condition, characterising offshore discharge, and quantifying the potential for groundwater to migrate under the Waimakariri River. Similarly, there is scope for long-term monitoring and assessment of the risk that agricultural land-use impacts present to the potable groundwater resource in the CAS. This would be particularly useful towards the southern end of the CAS and about Kaiapoi, distal from the Waimakariri River, where land surface recharge contributes more to the groundwater source.

The long-term isotopic monitoring that has been led by Mike Stewart (GNS Science, now part of Earth Sciences New Zealand) has revealed changes in groundwater flow patterns in the CAS over the last 40 years as an effect of groundwater abstraction. Ongoing changes to the system are expected from both the gradual evolution of the system to adapt to current conditions and to management actions in the future. Further ^{14}C samplings at 10-year intervals are strongly recommended to continue monitoring changes, findings from which will be useful for informing long-term resource management. Further work could be done to reconcile age changes with water abstraction patterns, for which easier accessibility to water usage data is required, as is more prudent monitoring of abstraction rates from discrete aquifers.

The CAS maintains an artesian pressure similar to when first drilled, which is a good sign. As the hydrograph in Figure 7A demonstrates, the operation of ground source heat pumps in Christchurch has had a profound local impact on artesian pressures in the Riccarton Gravel aquifer. Etheridge *et al.* (In Press) provide some analysis of the impact of ground source heat pumps on groundwater levels, but this issue is a worthy topic for further study. The prognosis is for water demand in Christchurch to increase as the population grows, which will inevitably put more strain on the groundwater resource. Long-term strategic planning and water resource management will be required, not an ad hoc approach. Under the current RMA this is the responsibility of Environment Canterbury. To achieve more strategic, long-term thinking and planning for the CAS requires stronger collaboration and a collective effort between Environment Canterbury, drinking water providers (CCC, Selwyn and Waimakariri District Councils), the drinking water regulator Taumata Arowai, hydrological research organisations and specialist consulting firms that harbour groundwater expertise. Perhaps, a century after the original Artesian Wells Committee disbanded, revival of the 'Christchurch Artesians', as a recognised CAS working and science interest group, would be an excellent idea!

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