JOURNAL OF HYDROLOGY (N.Z.) Vol. 15, No. 2, 1976

HYDROGEOLOGY OF METROPOLITAN CHRISTCHURCH

D. D. Wilson*

ABSTRACT

The city of Christchurch and its neighbouring boroughs are built on a foundation of interbedded terrestrial gravels and fine-grained marine and estuarine sediments. The gravels are aggradational deposits derived from the Waimakariri River, the larger part during periods of glacial low sea level. The finer sediments – sands, silts, and peats – have been deposited in estuaries and shallow transgressing seas during warmer periods. The gravels contain high-yielding aquifers and the interbedded finer beds, though heterogeneous, are essentially of low permeability, confining water under pressure in the gravels. Water supplies for the metropolitan area depend entirely on groundwater, and it is important that the resource should be harvested carefully.

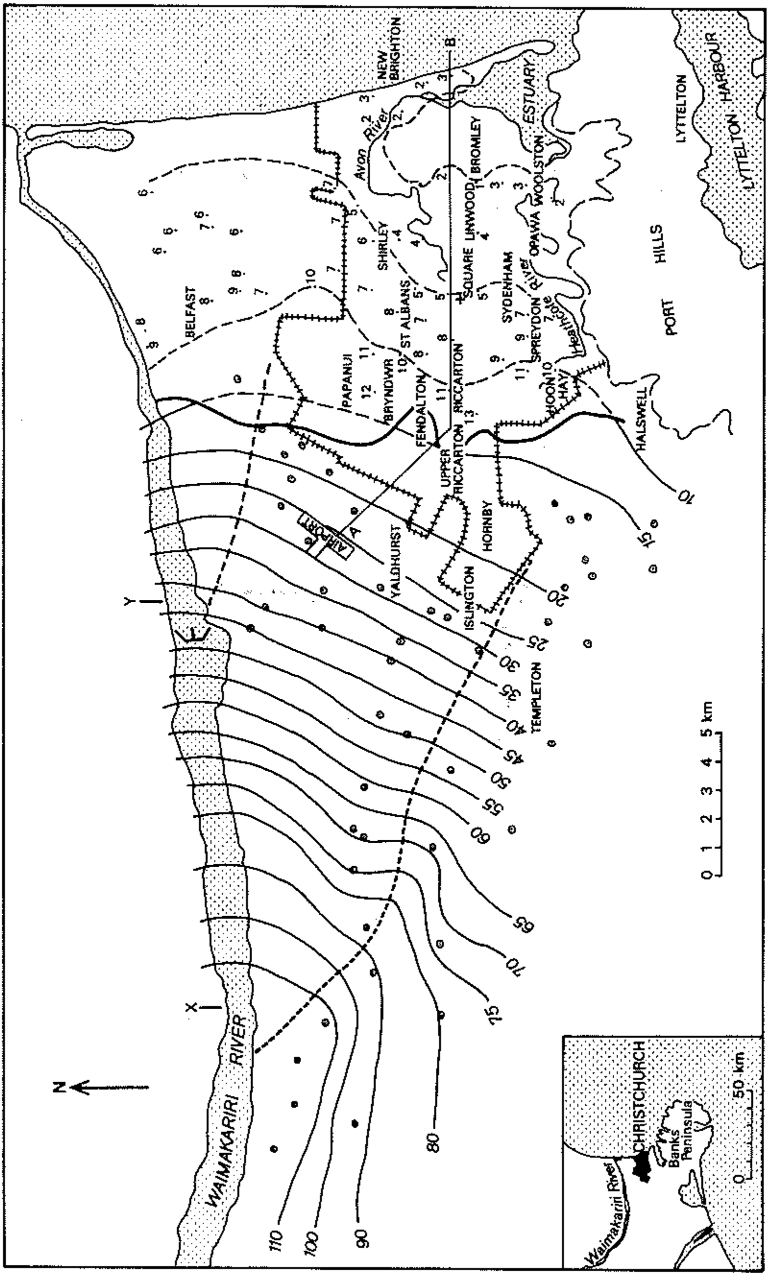
It is suggested that: 1) the area at present uses about one-third of its annual average recharge, a high proportion of which derives from the Waimakariri River; 2) there is, so far, no evidence of long-term permanent decline of water levels and pressure levels, despite short-term decline following periods of heavy use; 3) water quality in the artesian zone is protected from surface contamination or pollution by the filtering effect of fine-grained sediments of Christchurch Formation and by differential pressures that increase with depth; 4) salt-water intrusion is a possibility that cannot be ignored, though there is no sign of its occurrence so far; 5) damaging differential subsidence may occur in Christchurch if groundwater pressures are grossly lowered by abstraction.

INTRODUCTION

The groundwater reservoir underlying Christchurch and its environs supplies an average 100 000 m^3/day (maximum about 150 000 m^3/day) of high-quality water to domestic users, and a comparable amount to industrial users; it also feeds the springs that supply the Avon and Heathcote Rivers, aesthetic assets to the city. A resource of such magnitude clearly requires management and cannot merely be assumed to be inexhaustible or unpollutable.

---

* N.Z. Geological Survey, DSIR, Christchurch.


N
WAIMAKARIRI RIVER
X
Y
BELFAST
NEW BRIGHTON
Avon River
ESTUARY
PAPANUI
SHIRLEY
ST ALBANS
BRYNDWR
FENDALTON
RICCARTON
UPPER RICCARTON
SQUARE
LINWOOD
BROMLEY
WOOLSTON
OPAWA
SYDENHAM
SPREYDON
Heathcote River
HOON HAY
HALSWELL
PORT HILLS
LYTTELTON
LYTTELTON HARBOUR
AIRPORT
A
B
YALDHURST
HORNBY
ISLINGTON
TEMPLETON
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
90
100
110
0 1 2 3 4 5 km
CHRISTCHURCH
Banks Peninsula
Waimakariri River
0 50 km

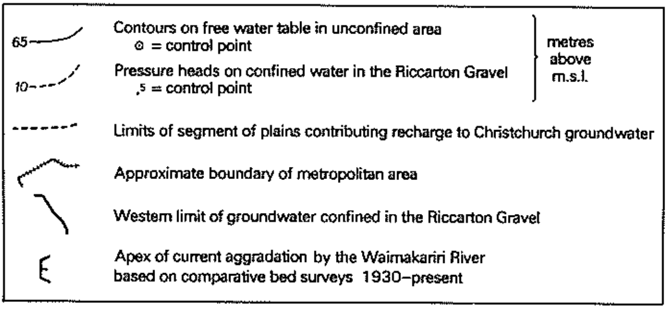


FIG. 1 (*above and opposite*) — Christchurch, New Zealand, and western environs showing water-table contours, limits of confined groundwater in the uppermost confined aquifer (the Riccarton Gravel), boundaries of the recharge area, and the approximate urban boundary. Locality map inset. Between points X and Y on the Waimakariri River, losses from the river of 11, 8 and 7 m^3/s have been gauged from river flows (measured at the Gorge Bridge, west of the area mapped) of 60, 35 and 30 m^3/s, respectively. Geological factors indicate that these losses are predominantly to the southern side of the river.

The N.Z. Geological Survey has, for over a quarter of a century, collected geological and hydrological data in the Christchurch area. Periodic attempts have been made to collate these data, converting complex details into assimilable patterns. Most studies have been tailored to specific needs, and Oborn's (1956) hydrological summary is the only one regionally based. Most of its facts relating to water quality, storage, and changes in storage remain relevant, but new data and new interpretations during the past 19 years dictate the need for an updated report. Suggate's work on the subsurface geology of Christchurch (1958) and sea-level changes (1968), Oborn's detailed work on the incompetence and elasticity of confined aquifers (1960), and the present writer's recent work have all yielded new assessments of the relationship between geology and groundwater availability. This paper describes recharge sources, directions of flow, groundwater pressure variations, risks to groundwater quality, and, finally, a speculative groundwater budget for the Christchurch area. It discusses intrinsic groundwater quality, factors affecting groundwater storage, and water-level trends only very briefly, and does not replace Oborn's (1956) detailed description.

Some evidence has accumulated to confirm that the Waimakariri River is an extremely important source of recharge for the Christchurch area, and hydrogeological discussion cannot therefore be restricted merely to metropolitan Christchurch but must include a description of established trends in the Waimakariri River. This interpretation has taken account of thousands of items of informa-

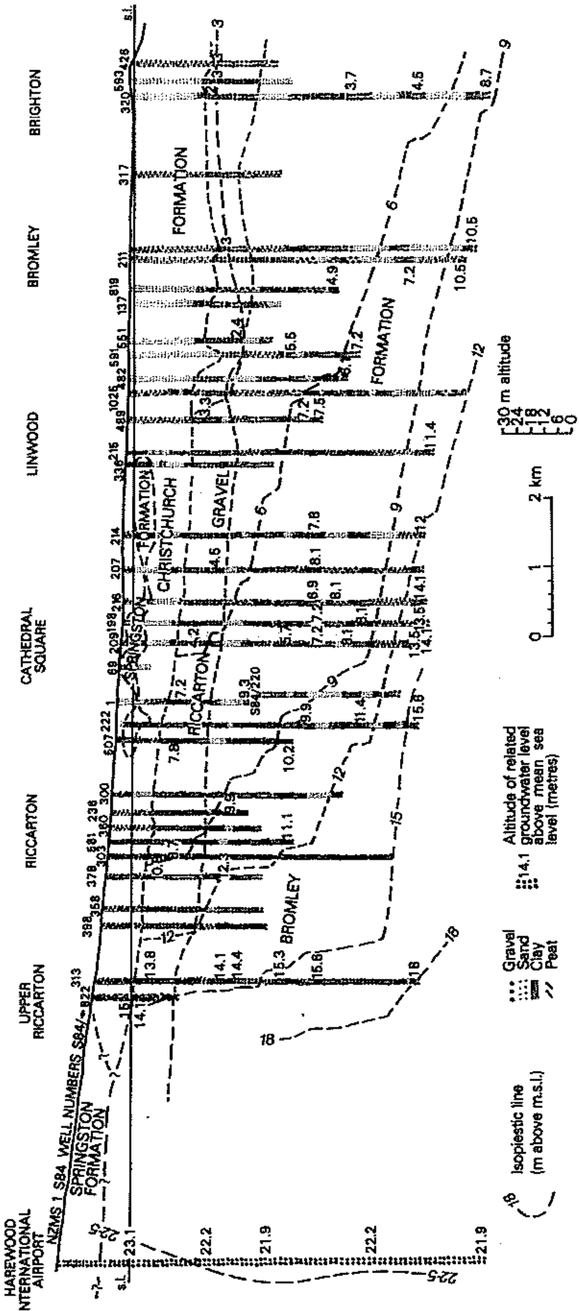


FIG. 2 — Section AB through Christchurch (for locality see Fig. 1) showing stratigraphy and approximate hydrostatic pressure distribution (based on drillers' logs).

tion that are too bulky to publish but which are held for reference in the Christchurch office of the N.Z. Geological Survey.

GEOLOGICAL SETTING

Fig. 2 is a representative east–west section through the Christchurch area (line AB, Fig. 1) based on drillers' logs and illustrates the stratigraphy and groundwater hydrology. The section is through the centre of Christchurch and is based on well logs up to 500 m from the section line. The wedge of dominantly fine-grained beds at the top of the sequence was named the Christchurch Formation by Suggate (1958). Postglacial river alluvium to the west of the wedge, and filling channels in the wedge, is named Springston Formation, after Suggate. The formation includes all postglacial alluvium, and is not now restricted to a phase of postglacial deposition. The highest gravel sequence beneath the wedge was named the Riccarton Gravel, and the heterogeneous underlying sediments were lumped as the Bromley Formation by Suggate (1958). The climatic change that caused the deposition of Christchurch Formation during postglacial time was the latest of a number of climatic fluctuations that caused alternate ice advances (glacial periods of low sea level) and ice retreats (interglacial periods of high sea level) during the Quaternary. Stratigraphic sections through Christchurch, including Fig. 2, show the existence of a number of irregular lenses of fine-grained deposits interbedded with gravels beneath Christchurch. They lack the clear, wedge-shaped sectional outline of Christchurch Formation, and are beyond the range of radiocarbon dating, but it is tempting to regard them, by analogy with dated postglacial sediments, as deposits of interglacial marine transgressions. If such they are, the Bromley Formation consists of a complex of penultimate and older glacial outwash and last interglacial and older transgressive deposits, and the superposition of the interglacial wedges might indicate subsidence, throughout the Quaternary, of the Christchurch area.

The nature of deposition by the Waimakariri River during successive glacial and interglacial periods was deduced (Wilson, 1973) from the physiography and stratigraphy of sediments bounding the river between the foothills and the sea and is summarized diagrammatically in Fig. 3. Essentially, fan building was controlled by fluctuation in river loading between climatic highs and climatic lows during the Pleistocene. Sea-level fluctuations might also have played a part in river regime, and the possibility that tectonic uplift of the foothills also played a part in the progressive eastward shift of fan apices cannot be ignored.

No diagnostic characteristics exist that can be used with confidence to differentiate between glacial outwash gravel and interglacial gravel alluvium, but an order of minimum thickness for postglacial gravel alluvium in the western suburbs of Christchurch can be gauged from the stratigraphy of radiocarbon samples (Table 1).

The proportion of fine material (silt and sand) in outwash and alluvial gravels decreases with increasing distance of transport from the foothills, and these differences in silt content probably explain some observed differences in permeability (Wilson, 1973).

During rapid postglacial sea-level rise (Suggate, 1968: p. 294) the sea transgressed westward over the Christchurch area, depositing marine sediments over the peats and silts that had been deposited earlier in estuaries. Gravel-filled channels within these fine sediments (Fig. 2) indicate temporary incursions of the Waimakariri River. It is possible that similar incursions deposited postglacial (Springston) gravels in the western Christchurch area as the sea transgressed from the east; such gravels may be channelled into the upper part

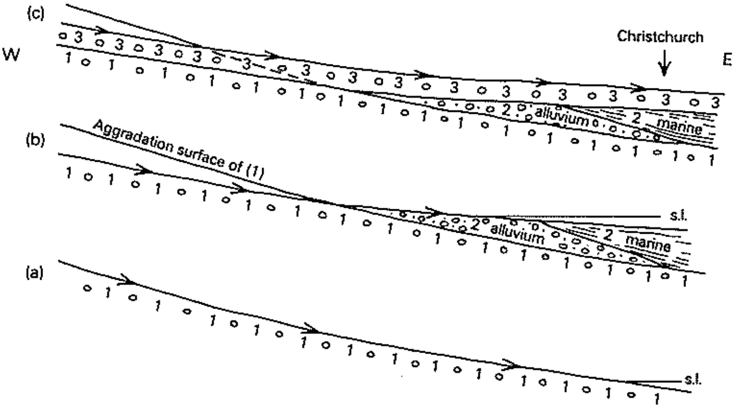


FIG. 3 — Diagrammatic sections through successive glacial–interglacial–glacial deposits to illustrate that interglacial periods are represented only by erosion in the inner plains, but by deposition of alluvial, estuarine and marine deposits near the coast. In each section, river position is indicated by the arrowed line.

a) Glacial period. Glacial outwash (1) debouches from the foothills and builds deposits to a low-sea-level coastline.

b) Interglacial period. Rivers cut trenches in the inland plains and deposit the resulting alluvium (2) on coastal plains. Sea level rises, and as the shoreline shifts westward, estuarine and marine deposits advance behind it.

c) Glacial period. New outwash (3) fills, or partly fills, trenches cut in (1) and spreads over the lower plains, blanketing interglacial deposits (2) near the coast. Sea level falls, and the coastline advances to a position beyond the eastern margin of the diagram. The position of Christchurch is indicated.

TABLE 1 — Comparison of sediment depth and ^{14}C age, western Christchurch.

NZ ^{14}C sample No.	*Sample locality* *Depth below ground surface (m)*	*Locality description*	*Estimated ^{14}C age B.P.*
309	6	Jeffreys Road, Fendalton	4660 ± 20
712	14	Wigram	6450 ± 55
713	8	Sockburn	6330 ± 100
530	14	Canterbury University, Ilam	6980 ± 100

of the Riccarton Gravel, and could be of hydrological significance. Peat at 31 m below sea level in Papanui was dated (NZ99) at 45 000 years and peat from −31 m at Riccarton dated at 43 000 years (NZ121). Deeper peats are recorded in some Christchurch boreholes down to more than 160 m below present mean sea level. Since this is close to the lowest level to which the sea is thought to have fallen at any time during the Pleistocene, some subsidence of the Christchurch area during the late Quaternary seems to be indicated.

Fig. 4, which plots distance inland from the present coastline

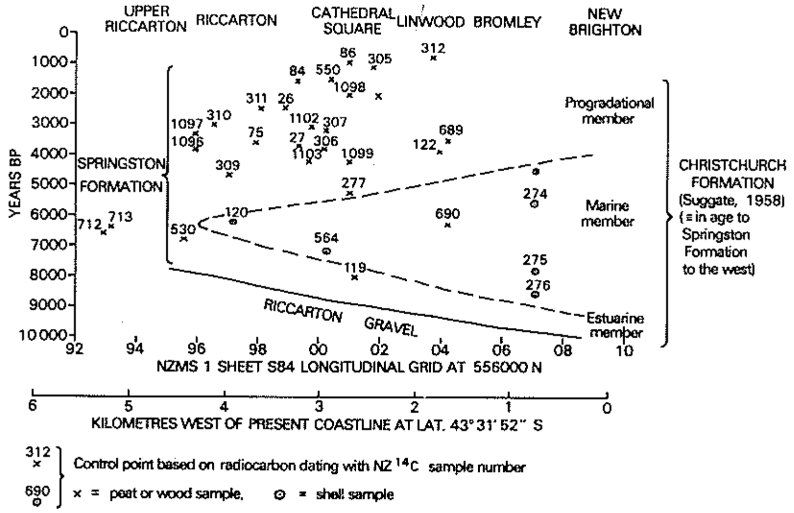


FIG. 4 — Relationship between the age B.P. and the westward distance from the present coastline of radiocarbon-dated samples. The graph indicates marine transgression up to about 6000 years ago, followed by coastal progradation.

against years B.P., based on radiocarbon dates, shows that in eastern and central Christchurch sedimentation over the past 10 000 years has consisted of estuarine deposition, followed by marine deposits then by coastal progradation deposits. Christchurch Formation can thus be subdivided into three members, an 'estuarine and swamp' member of peats and silts formed between 10 000 (and presumably older east of the present coast) and about 6000 years B.P., a 'marine' member of offshore shelly sands deposited during about the same period, and a 'progradational' member of peats, silts, dune sands and gravel channel deposits formed during the relatively stable sea level of the past 6000 years. Towards the heads of postglacial fans, rivers began to entrench into glacial outwash in the inland plains at about this time, and the resultant sediment contributed to coastal progradation.

Fig. 5 is a composite east–west section through Christchurch, showing the relative depths and lateral positions of dated marine and non-marine carbonaceous material. The figure also shows sea levels, based on Suggate's (1968) curve, representing 8000 and 6000 years B.P., and present sea level, and postulates the form of the land surface at each time, and at 4000 and 2000 years B.P. The evidence suggests that the postglacial coastline was furthest west about 6000 years ago when the coast ran south from Papanui through inner Fendalton and around the western limits of Hagley Park. The approximate position is represented by the western limit of confined groundwater shown in Fig. 1. Subsequently the coastline has been pushed eastwards to its present position by progradation.

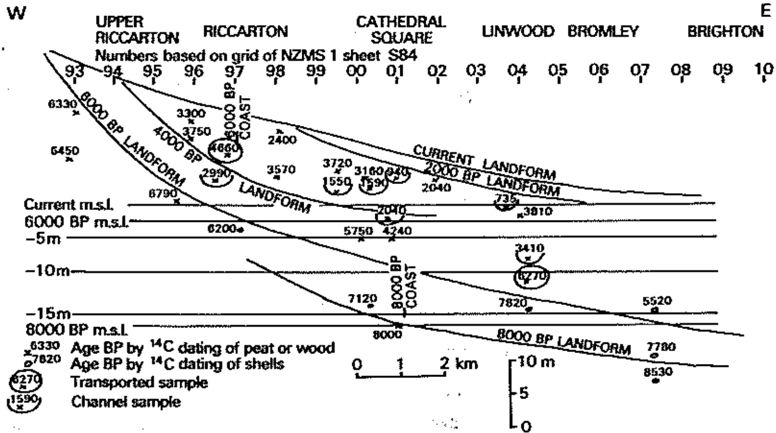


FIG. 5 — Composite west–east section through Christchurch comparing land forms and sea level at intervals during the past 8000 years.

HYDROGEOLOGY

General

Groundwater supplies beneath Christchurch and its neighbouring boroughs come from confined gravel aquifers in and beneath the Riccarton Gravel (Fig. 2). In the east and centre of the city, water flows above the surface from wells penetrating these aquifers; in higher ground further west, static water level does not reach the surface. In both areas, static water level increases with depth.

Principal aquifers are in glacial outwash deposits and perhaps interglacial alluvium. Interglacial and postglacial silts, sands, and peats, are essentially composite confining beds for groundwater, but it is likely that some leakage occurs through them. This leakage would be upwards because of the trend of pressure increase downward. Certainly, some postglacial fine deposits are extremely permeable, as evidenced by high flows of groundwater through temporary building-site excavations in many parts of the city.

Observed Patterns of Groundwater Flow

a) *In the Christchurch recharge area.* The North Canterbury Catchment Board in 1974 located and levelled a wide network of wells between the Waimakariri and Rakaia Rivers, west of the Christchurch metropolis. Water-table contours based on near-simultaneous static levels in these wells are plotted as solid lines in Fig. 1. The contours suggest influent seepage from the Waimakariri River and give a measure of the width of sector through which recharge to Christchurch takes place. This evidence is supported by oxygen-18 isotope counts (pers. comm., C. B. Taylor, Institute of Nuclear Sciences, DSIR) indicating that groundwater is derived from high-country rainfall (typically $-9\ \delta$ value, compared with about -6 of coastal rain) and by repeated measured evidence of water loss from the Waimakariri River in the stretch 33 to 16 km from the coast (Wilson, 1973).

It is necessary to differentiate between downward, horizontal, and upward components of flow (the recharge, lateral flow, and discharge zones of Fig. 6a) by means of vertical sections based on drillhole information. Throughout the unconfined groundwater area west of Christchurch, borehole water levels at neighbouring deep and shallow wells indicate that static water level falls as intake depth increases. At Christchurch International Airport, Harewood (Fig. 1), an imprecise comparison of static level versus intake level was made during drilling of a deep well. The result is shown in Fig. 7; ignoring sudden troughs in static level that are likely to be due to incom-

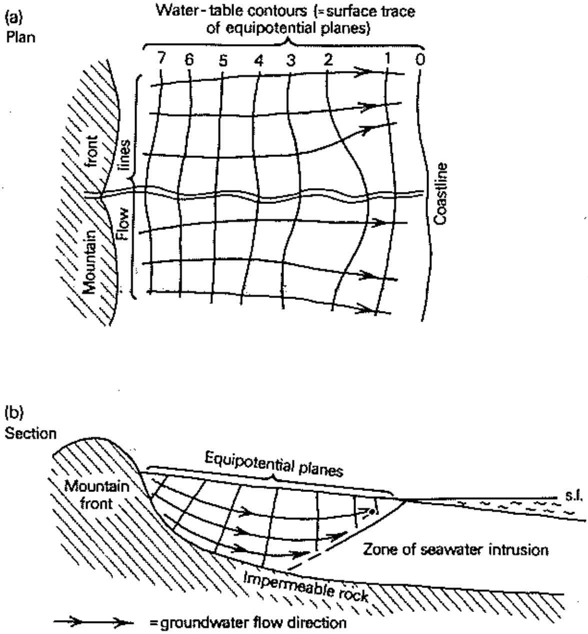


FIG. 6 — Idealized lateral and vertical flow patterns in coastal plains. 6a shows the typical direction of lateral flow, 6b typical vertical components of flow.

plete recovery from test-pumping drawdown, there appears to be an overall lowering of static level as depth increases. There is, at any rate, no hint of static level *rising* as depth increases, a phenomenon so clearly evident a few kilometres further east in the areas of confined groundwater. By contrast, at Islington southwest of Christchurch (Fig. 1), recorded static levels related to aquifers encountered during the drilling of a 223-m deep well at the New Zealand Refrigerating Company Works showed a steady increase with depth (reported static levels are 15 m at 51 m depth, 10.5 m at 92 m depth and 10 m at 223 m). These data suggest that Harewood is in the recharge zone, and Islington is in the discharge zone. However, data available are not completely reliable for either well, and precise recording of static-level changes with depth should be attempted should any new deep wells be constructed.

Fig. 7 also compares the relationship between well depth and specific capacity, demonstrating that specific capacities are highest in the uppermost 30 m of sediments, and below that level remain uniformly low to a depth of 180 m. Similar plots prepared for many other areas of the coastal Canterbury Plains show a similar relationship. It is tempting to relate the sharp change in specific capacity at 30 m to a lithological change at that depth. In the Harewood area the contact between postglacial alluvium and glacial outwash could be close to 30 m.

b) *In metropolitan Christchurch.* The western boundary of the Christchurch urban area is approximately coincident with the western limit of groundwater confinement in the Riccarton Gravel. The dotted contours east of this limit in Fig. 1 are based on drillers' records of hydrostatic pressures related to aquifers penetrated. There are several reasons why the limit between free groundwater and confined groundwater cannot be precisely defined. First, there are many discrete (though probably leaky) aquifers beneath Christchurch to explored limits of about 200 m, and deeper drilling would almost certainly locate more. Each has its own western limit of confined water, determined by the surrounding complex stratigraphy. Thus, the 'artesian limit' shown in Fig. 1 applies only to groundwater in the Riccarton Gravel, though stratigraphy suggests that deeper aquifers are unlikely to be confined more than a few kilometres further westward, and the boundary can be regarded more or less as a generally applicable artesian boundary. Second, the phenomenon of groundwater pressure rising as depth increases

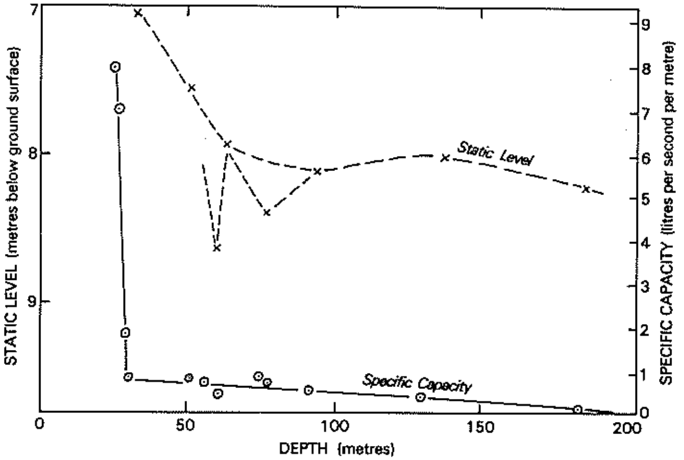


FIG. 7 — Relationships of static levels and specific capacities versus depth in a deep well at Christchurch International Airport, Harewood. The pronounced fluctuations of 'static' level control points between 50 and 100 m are believed to be due to incomplete recovery from intermittent test-pumping, not to natural pressure changes, and the static-level curve has been smoothed accordingly.

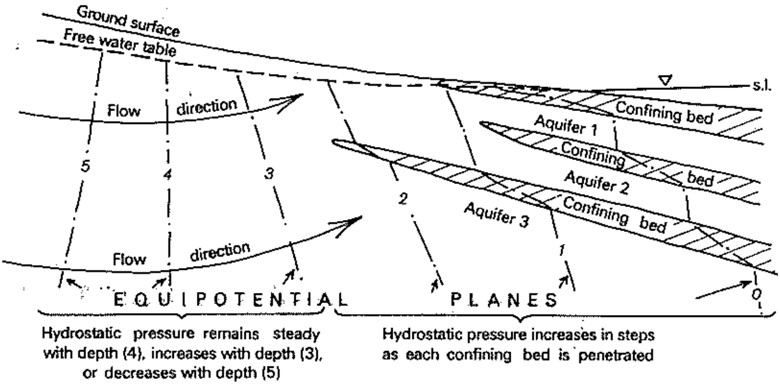


FIG. 8 — The changes in hydrostatic pressure with depth in essentially homogeneous sediments (left) and in interbedded permeable and impermeable sediments (right). The contrast would be essentially similar regardless of the slope of equipotential planes.

does not depend upon stratigraphy alone; as Fig. 6(b) shows there is a natural tendency for groundwater to rise above the salt-water wedge that is present near the coastal region of an alluvial or outwash plain. Confined groundwater, however, requires the intercalation of highly permeable beds (aquifers) and beds of appreciably lower permeability (confining aquitards or aquicludes) and not merely an increasing pressure with depth. Fig. 8 demonstrates diagrammatically this difference between stratigraphic control and hydraulic control. The stratigraphy shown is essentially similar to that under and west of Christchurch. To the west, bore logs indicate an unbroken succession of gravels in which static levels either remain constant with depth, rise steadily with depth (as at Islington) or fall steadily with depth (as at Harewood); further east, aquifers are physically separated by confining beds and pressure appears to increase in steps as each confining bed is penetrated. For convenience, therefore, the term Christchurch Artesian Area, or Christchurch Confined Groundwater Area, is restricted to that area underlain by clearly defined interbedded aquifers and confining beds. For present purposes, despite the limitations already described, the boundary is the western boundary of the Christchurch Formation. An additional qualification must be mentioned: west of the boundary shown, silty overbank deposits of the Waimakariri River and, at depth, poorly sorted glacial outwash deposits occur in the sequence; they may be impermeable enough to act as confining beds and might, therefore, impose steps in the curve relating aquifer pressure and depth.

Elements of Aquifer Recharge

There are two possible primary sources of groundwater – direct infiltration of rainfall and influent seepage from surface streams. A flow net based on water-table contours west of Christchurch was used to define northern and southern boundaries for the sector of plains through which recharge to metropolitan Christchurch must take place. These boundary recharge lines are shown in Fig. 1, and they indicate a 10-km width of plains across which the groundwater of urban Christchurch, excluding the northern township of Belfast, is being recharged. The product of this width in metres and the average transmissivity in m^2/day represents total recharge (in m^3 per day) of the Christchurch area. If 16 000 m^2/day – the figure derived by test-pumping near Hornby (pers. comm., M. Bowden, NCCB) – is assumed to represent an average transmissivity across the recharge area, total flow down a gradient measured at 1:400 (from contours, Fig. 1) would approximate 400 000 m^3/day. However, Hunt's (Hunt and Wilson, 1974) transmissivity pattern would give an average total recharge to Christchurch of about 780 000 m^3/day, and this is likely to be more accurate than a figure based on a single pumping test. The total area recharging Christchurch, as defined by the limiting flow lines of Fig. 1, is about 150 km^2. Average annual rainfall over this area is about 700 mm. If, because there is no runoff from this part of the plains, 50 percent of rainfall escapes evaporation and evapotranspiration, and infiltrates to groundwater, the total accruement to groundwater would be about 50 million m^3/year, an average of about 145 000 m^3/day. This would represent less than 20 percent of estimated total recharge. If a more credible proportion of 10 percent of rainfall infiltrates to groundwater it would contribute an average 29 000 m^3/day, a mere 4 percent of estimated total recharge.

It is difficult to escape the conclusion that the groundwater of Christchurch is recharged predominantly, perhaps to a proportion of 95 percent, by influent seepage from the Waimakariri River.

Groundwater Availability in Metropolitan Christchurch

a) *Groundwater consumption.* Average daily domestic consumption of groundwater by Christchurch city and neighbouring boroughs is about 90 000 m^3 and the maximum demand, dictated largely by summer gardening needs, about 200 000 m^3/day. Industry probably uses a comparable amount, and local rivers are fed by groundwater springs. A reasonable estimate of present-day maximum groundwater abstraction would be 450 000 m^3/day. Municipal authorities pump more than 100 supply wells from a network that spans the city. All the wells tap confined aquifers; the shallower wells are of the order of 20 to 30 m deep, the deeper about 200 m and the average depth about 90 to 100 m.

b) *Groundwater distribution.* Groundwater is plentiful throughout the urban area. Yields tend to fall off as Banks Peninsula is approached, probably because fine-grained loess from the peninsula has been incorporated in aquifers during their formation and has reduced permeability. Gravels at all explored depths have yielded water in the artesian area; west of the artesian area aquifers have been proved to depths approaching 200 m, but highest yields and highest specific capacities, as evidenced at Harewood (Fig. 7), are restricted to the uppermost 30 m; in the south of Christchurch, volcanic rocks dip beneath coastal sediments and dictate the lower limit of aquifers. In general, aquifer permeability tends to decrease with depth and aquifer pressure increases with depth. Wilson (1973: p. 116, Fig. 5) plotted this pressure–depth relationship.

c) *Storage changes with time.* The water levels or artesian heads of monitored wells are known to fluctuate with time. Some of the causes of fluctuations are –

1) Industrial usage: heavy industrial abstraction tends to lower water levels or pressure levels during the working week, but levels recover during industrial holidays and weekends.

2) Overall abstraction: troughs in the water-level curve depend primarily on abstraction rates, and reach lower levels as these rates rise.

3) Pressure: water and pressure levels are affected by offshore (tidal) loading, onshore loading, barometric pressure changes, and earthquake activity (see Oborn, 1960).

4) Recharge: levels, especially peak levels, depend upon the amount of recharge and are clearly higher after years of higher-than-average rainfall.

Assessment of storage changes leans very heavily upon records from the Canterbury Museum deep (55 m) well, which were taken from 1894 to 1902 and from 1947 to the present. These records were examined in 1974 by Prof. R. B. McCammon during the course of an NRAC Fellowship with the New Zealand Geological Survey. He concluded (pers. comm.) that there is no evidence of a long-term decline in water levels. Indeed, high winter rainfall in 1974 caused artesian pressure to rise to near record levels – higher than at any other time during the continuous record from 1947 onwards. Oborn (1956: pp. 17–20) recorded some reported instances of diminishing well yields but concluded that these were due to causes other than general depletion, notably to well screen clogging and aquifer silting, and local interference effects were considered to be the likeliest cause of declining water levels.

It has been suggested that between one-half and two-thirds of average recharge to Christchurch is currently being used during peak periods, and nearly one-quarter during periods of average abstraction. Average daily abstraction is probably of the order of one-third of average daily recharge. A comparison of changing abstraction rates and Museum well levels suggests that there has been no serious decline of hydrostatic head with time, despite increasing abstraction over the past few decades (pers. comm., R. B. McCammon). However, assessment of trends should not continue to depend upon mediocre data from one well and inadequate data from a few other city wells. Steps are currently being taken to monitor several wells precisely.

Groundwater flowing eastward under Christchurch is assumed to discharge naturally somewhere on the continental shelf, where it mixes with seawater. The nature of a freshwater–seawater interface in homogeneous sediments is shown in Fig. 9(a); in the complex stratigraphy present beneath Christchurch and the adjoining continental shelf, the interface will resemble that of Fig. 9(b).

d) *Hydraulics of the Christchurch confined aquifers.* Stratigraphic sections through Christchurch clearly show the complex

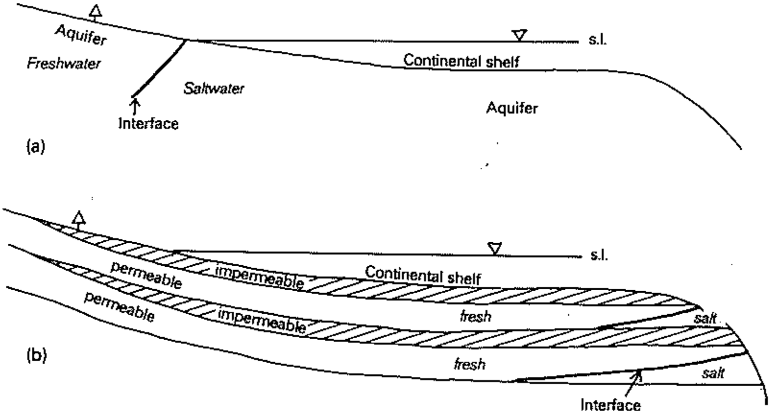


FIG. 9 — The nature of the freshwater–seawater interface.
a) Homogeneous conditions. The interface slopes steeply inland from high-tide level at the coast.
b) Heterogeneous conditions. The interface broadly follows boundaries between permeable and impermeable strata.

interbedding of aquifers and confining beds. Steps in the pressure gradient (Figs. 2 and 8) indicate that the aquifers are essentially discrete. However, there is some evidence that aquifers are leaky. The evidence is based on analyses of sketchy test-pumping by Prof. W. A. Murray (pers. comm.), Le High University (formerly post-doctoral fellow at the University of Canterbury); at a well at Greenpark, south of the area mapped, a plot of drawdown versus time produced the typical shape of a leaky aquifer curve; at Bromley, east of Christchurch, a comparison of drawdown and recovery curves for a pumped well indicated recharge during pumping, and it is likely that the recharge came from higher or lower aquifers.

In confined aquifers, water is released from storage because of two elastic effects – compression of the aquifer skeleton and expansion of the contained water – and not by simple dewatering of pore space as in unconfined aquifers. Typical values of storage per unit aquifer surface area per unit change of head lie in the range of 1×10^{-5} to 1×10^{-3}. Murray (pers. comm.) derived values of 1.86×10^{-5} from tidal fluctuations in east Christchurch, and 1.36×10^{-4} at Greenpark, south of Christchurch, from pumping tests.

Murray's estimates (pers. comm.) of transmissivities in the Christchurch area included 4750 to 8400 m^2/day at Bromley, 4750 m^2/day in southern Christchurch and 8700 m^2/day in western Christchurch. Clearly, improved test-pumping of the area is required to assess aquifer characteristics more accurately.

Oborn (1960) showed that "the aquifers and aquicludes of the Christchurch Artesian System are moderately-to-highly incompetent and elastic, judged by the effects of ocean tides, of the changing water levels of Lake Ellesmere [south of the area considered in this paper] and of earthquakes and passing heavy vehicles upon water levels in wells tapping them. . . . " (p. 81). Data accumulated since 1960 do not contradict these findings. The confined aquifers of Christchurch, in which hydrostatic pressure shows a stepped increase with depth, are undoubtedly recharged from the west, and it is important to decide whether this increase depends upon the 'inlet' pressures of recharge. If aquifer pressures under Christchurch depend upon the altitude of their respective outcrops on the Canterbury Plains – the deeper the confined aquifer, the higher the altitude of the outcrop – 'pipeline' aquifers should themselves be essentially discrete, showing increasing hydrostatic pressure with increasing depth. Hydraulic evidence from the 223-m-deep well at Islington, where hydrostatic pressure increases with depth, does support this; evidence from Harewood is to the contrary. The issue must therefore remain undecided until additional data are available. If downward pressure increase in the city's confined aquifers is not related to 'inlet' pressure differentials, it may relate to differences in permeability in aquifer outlets to the east, between the coast and unlocated egress localities presumably somewhere in Pegasus Bay.

Groundwater Quality

a) *Quality variation.* For all wells, water quality is generally good, but urban pollution is more likely to affect unconfined aquifers. On both sides of the artesian boundary there are peats in the sequence, and water withdrawn from aquifers adjoining these is high in dissolved CO_2, which is corrosive to reticulation equipment. Corrosive water is a problem mainly in western Christchurch, where abstraction is from unconfined aquifers, and is rare in confined aquifers further east. Unconfined groundwater from the Christchurch Formation is at some quality risk, but is rarely used. Bacteriological quality is good, and undesirable chemical concentration is rarely present, though sulphur and iron are known to give an objectionable taste and smell in some wells near the coast. The water is moderately soft (less than 70 ppm $CaCO_3$); Oborn (1956: p. 8) suggested that water in deeper aquifers is usually harder.

b) *Risks of pollution.* In the confined aquifers two factors act as a barrier to groundwater pollution from urban activities. First, there are lenses of essentially fine-grained beds acting as filters above aquifers (the wedge of Christchurch Formation, for instance, is about 50 m thick at the coast, thinning effectively to zero at the artesian boundary). Second, even if leakage channels exist through confining beds pressure differential, increasing downward, prohibits downward seepage. Unless differential pressures are disturbed by excessive, uncoordinated pumping, or by recharge wells of some kind, confined aquifers are protected from vertical pollution from the surface. The possibility of lateral flow of pollutants is discussed later.

The most likely contamination risk to confined groundwater is that heavy pumping might cause movement of brackish and salt water into the aquifers from the east. No near-coastal borehole has yet encountered the interface between fresh and salt water. During glacial advances, when sea levels were at least 100 m below the present one and when the Christchurch coastline was perhaps 60 km east of its present position, glacial outwash must have contained fresh groundwater everywhere west of that coastline. Thus each aquifer beneath Christchurch must have a seaward extension that might contain 'fossil', as well as relatively recent, groundwater. Consequently the freshwater–seawater interface for each aquifer is likely to be far to the east of the present coastline. The exact position of each interface is not important, but its stability is. If groundwater abstraction is causing the interface to move westward, contamination of confined aquifers beneath Christchurch will eventually occur.

West of the artesian limit there are neither demonstrable stratigraphic (filtering) barriers nor differential pressure barriers to vertical infiltration of pollutants. Similarly, groundwater recharging laterally from the west has been subject to contaminating influences long before it reaches the city – from grazing animals, herbicides, pesticides and human activity. So, in this unconfined area, aquifer protection is dependent on, first, prudent efforts to avoid pollutant sources, and, second, the ability of the aquifer to filter out pollution. This ability is more or less inversely proportional to groundwater velocity; in western Christchurch this cannot be precisely determined, but if figures of 1000 m/day for permeability, 1:400 for gradient and 25 percent for porosity – all broadly compatible with available data – are allocated, the figure for velocity approximates 10 m per day or about 4 km per year.

Organic effluent (human and animal wastes) cannot survive long in groundwater, and risks can probably be eliminated by imposing minimum distances of the order of 1 km between pollution sources and supply wells. Heavy grazing and nitrogenous manures can cause nitrate pollution in shallow aquifers.

Chemical effluent can survive for much greater distances than does organic, and can remain toxic despite appreciable dilution. Thus disposal of herbicides, pesticides, and other poisons must be tightly controlled. Accumulated evidence shows that waste dumps, especially if they are on occasions below water-table level, can be a source of chemical pollution.

Isolated examples of coliform pollution of groundwater are known from wells west of the artesian boundary. In each case, there has been cause for suspicion that entry to the aquifer was gained by direct flow near loose or broken casing and not from intergranular flow. In the same area there has been evidence of short-lived chemical pollution, probably caused by disposal of industrial effluent. In confined aquifers, no case of chemical or organic pollution is known, but there is an example of thermal pollution. A city firm obtained water for air-conditioning from a 90-m-deep aquifer at 12°C and returned it to a 30-m-deep aquifer at 18°C. During one hot summer the deep well began to pump water at 18°C, whose only source could have been the higher aquifer. The wells were less than 1 m apart, and the access of warmer water might have been due to a break in the deep-well casing, but there remains a disturbing possibility that the hydrostatic pressure in the deeper abstraction well had been lowered as a result of abstraction, and that in the shallower recharge well raised by recharging water; differential pressures could thus have been so altered that warm recharging water leaked from the higher to the lower aquifer, perhaps through a disturbed zone around the deeper well casing.

Stability Effects of Groundwater Withdrawal

One disconcerting result of heavy pumping of confined aquifers in some overseas areas has been sediment compaction, causing ground subsidence. The compaction is principally due to shrinkage of fine-grained beds following pressure changes in neighbouring aquifers. Peats and clays are common in the sediment sequence beneath Christchurch and are especially prone to shrinkage if pressure upon them is increased by reduction in aquifer hydrostatic pressure. The possibility of subsidence, should future abstraction rates cause pronounced pressure changes, should not be overlooked.

Plans for Resource Investigation

Optimum production from groundwater reservoirs is defined as "practical sustained yield", the rate at which groundwater can be continuously withdrawn without lowering water levels to critical stages, exceeding recharge, or causing undesirable changes in water quality. Only by comparison of long-term records can the effects of groundwater withdrawal be separated from the effects of normal fluctuations. Water-level records and pressure-level records are inadequate in metropolitan Christchurch because they currently lack adequate areal or vertical coverage. It is important that the present policy of extending well monitoring should continue. Undigested data are useless, so it is also important that water-level fluctuations be regularly analysed by competent statisticians so that allocation authorities can be informed of the onset of undesirable change.

Water-level monitoring has the principal aim of *detecting* early stages of reservoir deterioration. *Prediction* of reservoir changes requires the monitoring of many other parameters, plus the application of general and applied research. Much of the investigatory research is expected to begin shortly and will include work on chemical, isotopic and geophysical parameters with both short-term and long-term aims.

The importance of predicting the stability of the freshwater–saltwater interface in confined aquifers has already been discussed. No simple way exists of locating the position, but plans are in hand to date water from deep aquifers under eastern Christchurch by radiocarbon techniques; it is hoped that the age diagnosed will throw light on the extent of recent westward movement of the interface.

ACKNOWLEDGMENTS

The writer is grateful to Dr R. P. Suggate, Director, Geological Survey, Mr B. W. Collins, Geological Survey, Lower Hutt, Mr Guyon Warren, District Geologist, Christchurch, Dr P. B. Andrews, Geological Survey, Christchurch, and Dr B. W. Hunt, Civil Engineering Department, University of Canterbury, for critical re-reading of the manuscript.

REFERENCES

Hunt, B. W.; Wilson, D. D. 1974: Graphical calculation of aquifer transmissivities in northern Canterbury. *Journal of Hydrology (N.Z.) 13*(2): 66–80.

Oborn, L. E. 1956: Groundwater in Metropolitan Christchurch. Unpublished hydrological report held in the Christchurch office of N.Z. Geological Survey. 32 p+maps.

Oborn, L. E. 1960: The incompetent and elastic nature of the Christchurch artesian system. *N.Z. Journal of Geology and Geophysics 3*(1): 81–97.

Suggate, R. P. 1958: Late Quaternary deposits of the Christchurch metropolitan area. *N.Z. Journal of Geology and Geophysics 1*(1): 103–122.

Suggate, R. P. 1968: Postglacial sea-level rise in the Christchurch metropolitan area, New Zealand. *Geologie en Mijnbouw 47*(4): 291–297.

Wilson, D. D. 1973: The significance of geology in some current water-resource problems, Canterbury Plains, New Zealand. *Journal of Hydrology (N.Z.) 12*(2): 103–118.