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THE SIGNIFICANCE OF GEOLOGY IN SOME CURRENT WATER RESOURCE PROBLEMS, CANTERBURY PLAINS, NEW ZEALAND

D. D. Wilson*

ABSTRACT

Accumulated data from nearly 5000 wells show that high-yielding gravel aquifers are in many places present in the lower and middle reaches of the Canterbury Plains, but rarely in upper reaches. Gravel sorting should improve to the east with distance from the foothills and therefore a gradual eastward increase in permeability is to be expected, but not the sudden increases implied by increases in well yields. The increases are probably due to enhanced recharge by influent seepage, suggested by the geometry of water-table contours and proved in some cases by gauged river losses. Influent seepage appears to take place mainly where rivers flow in post-glacial alluvium and the geological boundary between the alluvium and older glacial outwash gravels broadly separates a low-yield inland plains area, where irrigation must depend on surface water, from a high-yield coastal plains area where groundwater can in many places be used.

While flow patterns can be deduced from water-table contours in areas of unconfined water, they must be deduced from pressure differences in confined aquifers. Pressure variations under Christchurch show that flow directions at all levels down to 120 m are towards an area underlying the Christchurch Estuary. This fact may help in monitoring any sea-water intrusion. Other risks to Christchurch, consequent upon its subsurface geology and hydrology, are discussed, and monitoring methods to anticipate them are suggested.

INTRODUCTION

The Canterbury Plain, averaging 50 km in width and with an area approaching 8000 km^2, has been built up by coalescing complex fans consisting principally of gravel transported by rivers from the Alpine ranges and foothills during the fluctuating climatic conditions of Quaternary time. The thickness of gravel has been proved

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* N.Z. Geological Survey, Department of Scientific and Industrial Research, Christchurch.

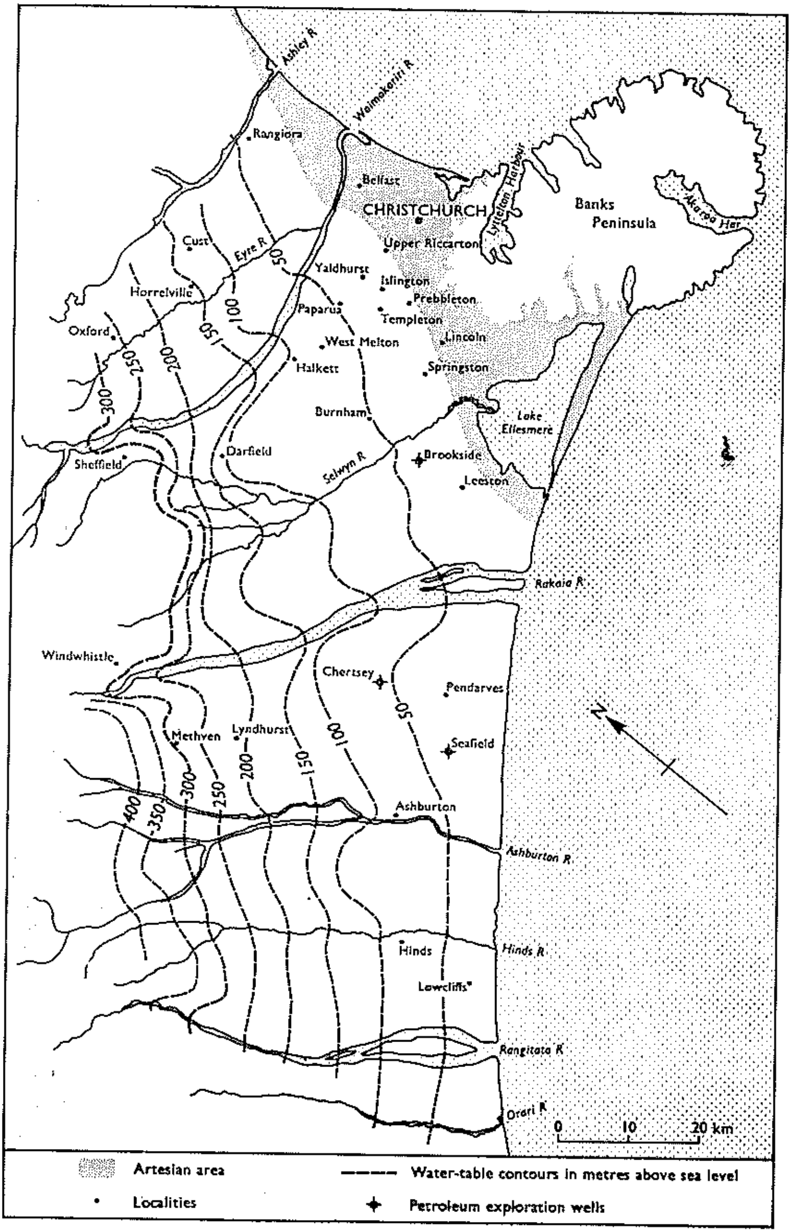

FIG. 1 — Water table of the Canterbury Plains.

in water wells within 16 km of the foothills to exceed 120 m, and petroleum exploration bores have proved in more distal parts thicknesses of 355 m at Brookside, 620 m at Chertsey and 540 m at Seafield. Quaternary marine deposits intercalated with river gravels survive only in a narrow coastal strip north and south of Banks Peninsula.

Groundwater in the plains has long been a source of stock, domestic, public and irrigation supplies, and because of its economic importance has been monitored and studied by the New Zealand Geological Survey since 1947. The degree to which direct rainfall infiltration on the plains on the one hand, and influent seepage from rivers on the other, have contributed to groundwater has been argued by successive geologists and engineers for nearly a century. Collins (1950) demonstrated that well levels show an immediate response to rainfall. More recently the writer has used accumulated water-level data to map (Fig. 1) contours of the groundwater table (an exercise earlier carried out for part of the plain by Oborn, 1955) to localize areas where rivers have a potential towards influent seepage. Several sets of contemporaneous gaugings at points along the Waimakariri River have provided the first practical proof of significant seepage (Dalmer, 1971). This implies that the recharge of groundwater under the Canterbury Plains does not depend only on infiltration from the annual rainfall on the plains (750 mm average), but is supplemented by rivers rising in the Alps and with a total catchment in excess of 13 000 km^2 where the average rainfall is approximately 1700 mm. Groundwater availability is therefore linked with river behaviour, perhaps depending especially on the distribution of routes of influent seepage. This paper attempts to define localities where such seepage is most likely to take place, and then broadly outlines areas of the plains where groundwater may be present in sufficient quantity for irrigation.

Since groundwater supplies are extremely important to metropolitan Christchurch, geological factors relevant to the protection and understanding of the city's confined aquifers are also discussed.

OUTLINE OF HYDROGEOLOGICAL PROVINCES

In Fig. 2 the plains are divided into two lateral segments by the geological boundary between glacial outwash gravels and postglacial alluvium; pre-Quaternary rocks of the foothills (largely sediments) and of Banks Peninsula (largely volcanic) are also mapped even though this paper is not especially concerned with their groundwater potential. All these boundaries are based, with

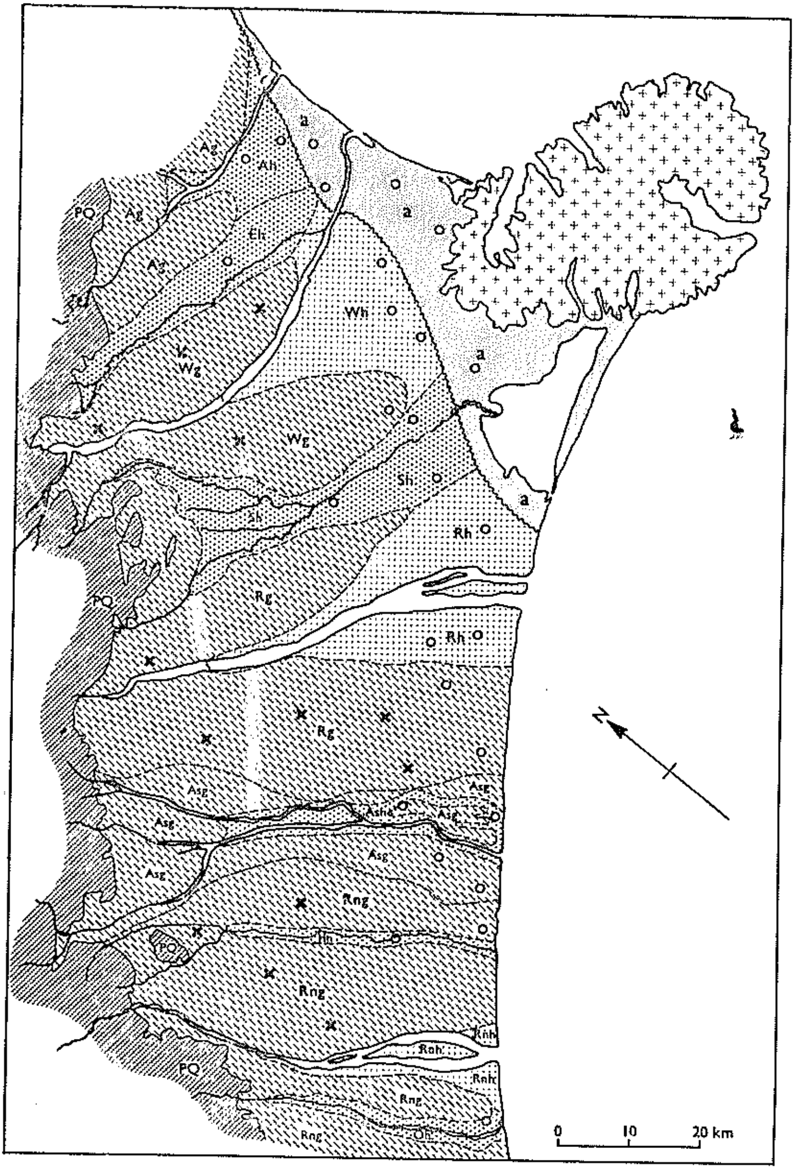

FIG. 2 — Geology related to aquifer properties, Canterbury Plains. (See legend opposite.)

slight modification, on the 1:250 000 Geological Map of New Zealand Sheets 20 (Gair, 1967), 18 (Gregg, 1964), and 21 (Oborn and Suggate, 1959). The plains are further subdivided into transverse segments that are genetically related to their river of origin. These segments are of hydrological significance because influent seepage from any river is more likely to remain in the permeable deposits of the river's own sequence of fans than to cross to neighbouring sectors. The boundaries between fans of adjoining rivers are based on the topographic expression of each fan.

Finally, a coastal sector of confined groundwater to the north and south of Banks Peninsula is also mapped using accumulated borehole data. Thus five provinces are mapped: (1) pre-Quaternary rocks of the foothills and Alps; (2) volcanic rocks of Banks Peninsula; (3) unburied glacial and periglacial outwash gravels of the plains; (4) postglacial alluvium and buried outwash gravels of the coastal and central plains; and (5) the artesian area near Banks Peninsula. Provinces (3) and (4) are subdivided according to river of origin.

GEOLOGY			HYDROLOGY
Postglacial alluvium & estuarine & marine deposits. Thickness increases, surface becomes younger, texture becomes finer, and sorting improves from west to east.	a		Artesian area. Generalized limit for aquifers up to about 150 m depth. Aquifers in postglacial alluvium and buried outwash. Aquicludes principally postglacial and interglacial marine beds.
	h	Minor rivers	Area of unconfined water with some slight confinement as artesian boundary is approached. Permeability increases eastward, as does that of underglacial outwash.
	h	Major rivers	
Periglacial and glacial outwash. Till near foothills. Sorting improves with distance from foothills.	g		Permeability increases eastward
Volcanics of Banks Peninsula.	+		Groundwater potential poor.
Pre-Quaternary.	PQ		Groundwater potential poor.

Prefix relating material to source river:

A = Ashley
E = Eyre
W = Waimakariri
S = Selwyn
R = Rakaia
As= Ashburton
H = Hinds
Rn= Rangitata
O = Orari

O Broad indication of localities where developed wells yield over 1500 litres per minute.

X Broad indication of localities where typical wells yield less than 60 litres per minute.

DETAILS OF HYDROGEOLOGY OF MAPPED PROVINCES

(1) *Pre-Quaternary Sediments of the Foothills*

These consist predominantly of Torlesse Supergroup greywacke (highly indurated sandstone, siltstone, and mudstone) with complexly faulted inliers, or covering remnants of Cretaceous and Tertiary sediments. Although the group contains minor potential aquifers – greywacke crush zones, Cretaceous sandstones, Tertiary limestones, etc. – they cannot be considered as a major source of water, and this paper is more concerned with the role of the foothills as a supplier of sediment and water to the Canterbury Plains. All rocks of the group are relatively impermeable, much of the area is steep, and therefore a high proportion of total rainfall goes to runoff. The rivers formed are unlikely to suffer any appreciable loss by influent seepage above their points of debouchment on to the gravel fans of the Canterbury Plains proper, mainly because the foothills of Tertiary and older beds are more indurated, more often chemically cemented, and therefore less permeable than are Quaternary gravels.

(2) *Volcanic Rocks of Banks Peninsula*

The rocks of Banks Peninsula are dominantly andesitic flows, tuffs, and agglomerates from the volcanic centres at Akaroa Harbour, Lyttelton Harbour, and Mount Herbert. Springs encountered during the excavation of both Lyttelton tunnels, and occurring at the surface at several points on the peninsula, show that some beds, probably jointed zones in lava flows, and inter-granular spaces in clastic and pyroclastic beds, are permeable enough to be termed aquifers. The location of groundwater reservoirs is unpredictable, however, and no high-yielding wells are known on Banks Peninsula.

(3) *Unburied Glacial and Periglacial Outwash Deposits*

Throughout the Late Quaternary the rivers of Canterbury have been transporting debris from the Southern Alps, sorting it to some extent, and with it creating the Canterbury Plains. Most of the transport has been during glacial periods, when sparsely vegetated mountains suffered massive erosion. Each river, minor non-glaciated as well as major glaciated, has built up a suite of outwash fans during at least three glacial periods, and has continued to aggrade its lower reaches during the interglacial and postglacial periods. Boundaries between successive fans are marked by minor changes in slope of the plains surface (Suggate, 1963). For the Waimakariri River, a progressive trend of fan development is evident; the apex of successive, Late Quaternary fans has moved progressively downstream with time (Table 1) so that progressively younger glacial fans are entrenched within their predecessors in their upstream reaches, and fan out over them downstream. As a corollary, there is a progressive reduction of fan gradients with time.

TABLE 1 — Relationship of outwash gradient with age.

Age of fan	*Approx. distance from coast of fan apex (km)*	*Gradient near apex (m/km)*
Last Glaciation – final advance	48	6.5
Last Glaciation – second advance	58	7.5
Last Glaciation – first advance	64	9.5
Penultimate Glaciation	71	11.5

To date, no hydraulic significance has been attached to the boundaries between successive outwash fans, and Fig. 2 maps only the boundary between unburied glacial outwash of all ages and blanketing postglacial alluvium. Outwash deposits of all ages are present beneath postglacial alluvium seaward of this boundary, but show improving hydraulic characteristics, and the hydrological significance of buried outwash is discussed in the following section of this paper.

Wells in unburied outwash gravel areas have explored only the top 100 m of deposits, and yields from wells within 35 km of the foothills rarely exceed a few litres per minute. At greater distances from the foothills there is an increase in water availability. Exceptionally, yields exceed 800 litres per minute.

(4) *Postglacial River Alluvium and Buried Outwash Gravels*

The trend evident throughout the Late Pleistocene of progressive downstream movement of successive fan apices through time continued throughout postglacial times, as evidenced by the succession of overlapping fans – each continuous from a degradational terrace preserved on the south bank of the Waimakariri River. The apex of the oldest postglacial fan, with a gradient of 6 m/km, is about 45 km upstream from the river mouth; the apex of the current fan, which has a gradient of 3 m/km, is about 20 km from the mouth (see appendix in Dalmer, 1971).

There is a remarkable eastward increase in aquifer yield, both in postglacial deposits and underlying buried glacial outwash. The increase is reflected in wells of similar construction in a line eastward from about West Melton to about Upper Riccarton along which specific capacity in cubic metres per day per metre of drawdown increases from lower than 15 at West Melton to about 22 near Paparua, to about 72 near Yaldhurst, to about 720 near Avonhead and to over 1400 in Upper Riccarton. The increase may be in part due to improving sorting, and consequent increasing permeability, but slight arithmetic improvement in sorting is hardly likely to explain almost logarithmic increases in well yields. It is subsequently suggested that a principal reason for the increase is the presence in the lower plains of ancient river channels of high transmissivity proliferating in a downstream direction, and now recharged by influent seepage from the Waimakariri River as well as by normal baseflow due to rainfall infiltration.

(5) *Coastal Areas of Confined Water*

The principal area underlain by confined water is a narrow coastal strip running south-west from the north-eastern boundary of the plains at Waipara River mouth, and widening southward to include all of eastern and central Christchurch. Another area of confined water forms a narrow salient around the western and northern edge of Lake Ellesmere, and includes Lincoln township. 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. The most important area of confined water is that underlying metropolitan Christchurch; the city depends entirely upon groundwater for public and industrial supply. The essential hydrology of the area is that several confined, high-yielding aquifers are protected by thick impermeable deposits, and by natural pressure differentials, from direct vertical contamination or pollution caused by urban activities.

THE ROLE OF RIVERS IN GROUNDWATER RECHARGE

As a consequence of the progressive downstream movement of fan apices through time, the present flood plain of each main river is entrenched within older gravels for much of its course across the plains. Entrenchment is within impermeable outwash gravels in the upper and central plains reaches, and within postglacial alluvium in coastal reaches. The Waimakariri River, in a sector protected by Banks Peninsula from erosion by southerly marine currents, is

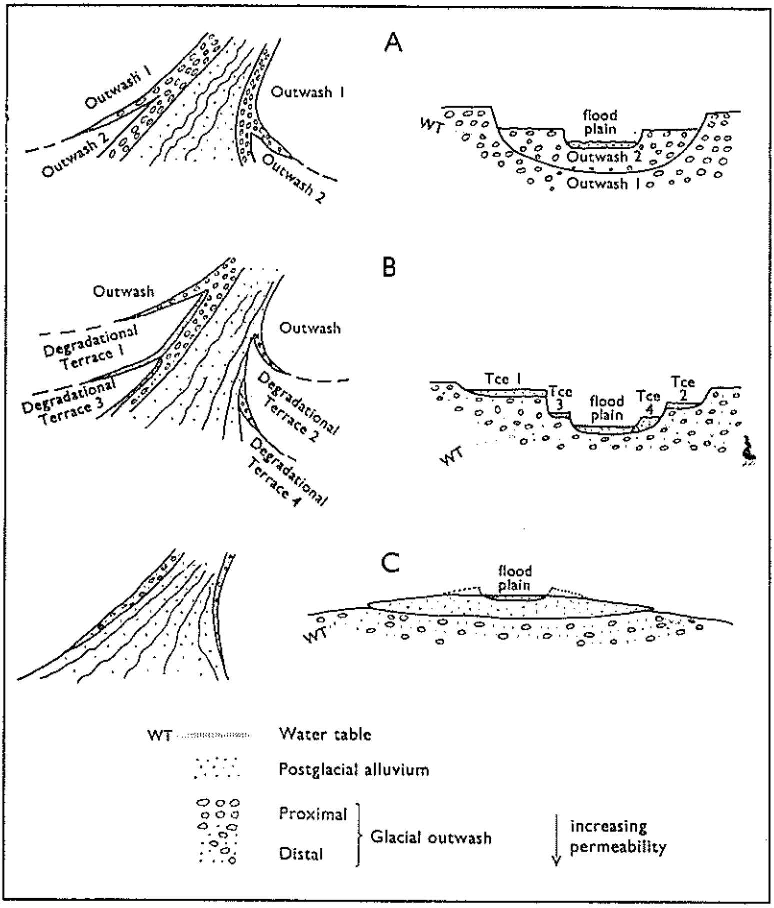

FIG. 3 — Diagrammatic perspective sketches and matching sections of upper, middle and lower river reaches.

A. *Upper plains:* Matching aggradational surfaces of successive outwash fans bound the river's flood plain. The low permeability of outwash deposits and the slope of the water table towards the river militate against influent seepage beyond the flood plain.

B. *Central plains:* Unmatched degradational terraces mark stages of downcutting. At each stage, downcut surfaces with thin lag gravels grade downstream into aggradational fans that overlap earlier surfaces. The water table slopes away from the river, and influent seepage beyond the flood plain is possible, but is likely to be limited by the low permeability of outwash deposits.

C. *Lower plains:* Fans of postglacial alluvium bury older deposits over a wide area. Water-table gradient, high permeability of postglacial alluvium surrounding the flood plain, and improving permeability of outwash (with distance of transport) suggest that widespread influent seepage is possible.

entrenched for about two-thirds of its plains course; the Rakaia, Ashburton, and Rangitata Rivers, in a sector open to marine erosion, are entrenched for almost the whole of their courses. There is no distinct 'base' to each river's visible channel within its flood plain – much of the water flowing within this flood plain – nor is there necessarily a distinct lithological break between the base of each flood plain and older underlying gravel. Thus, losses from a river demonstrated by contemporaneous gauging at two or more points may be due to 'channel losses' – a loss from the visible channels to the enclosing flood-plain gravels – or to 'flood-plain losses' from subsurface flood-plain flow to surrounding older gravels, or to a combination of the two.

Channel loss can be envisaged as the main factor affecting channel flow in rivers in inland parts of the plains, where each river's flood plain is bounded by high banks of relatively impermeable, unsorted, silt-laden, glacial outwash, and underlain by similar material (Fig. 3, A and B). This kind of loss, where total seaward flow remains confined to within a river's flood plain was demonstrated recently by gaugings on the Rakaia River (Stephen, 1972: p. 21). A measured increment of 31 m^3/s to the Rakaia River from Lake Coleridge hydro-electric power station caused a maximum increase in measured flow of 16 m^3/s 3½ hours later at Rakaia Gorge Bridge gauging site, 20 km downstream. A total addition of 31 m^3/s for 5 hours at Lake Coleridge (155 m^{3}s^{-1} h) resulted in a measured addition of 17 m^3/s for about 5 hours at Rakaia Gorge Bridge (about 85 m^{3}s^{-1} h). Smaller known increments, similarly monitored, showed a similar relationship between measured increments at Rakaia Gorge and known increments at Lake Coleridge. Records showed that a rapid return to baseflow conditions at the gauging site followed each increment, so the apparent loss of water between Lake Coleridge and Rakaia Gorge is not due to groundwater storage between the two points. It is therefore probably due to ungauged passage of water through flood-plain gravels underlying and adjoining the river at the gauging site. Since the flood plain at Rakaia Gorge is bounded by solid rock of low permeability, the subsurface flow is likely to be confined to flood-plain gravels.

Flood-plain losses can be expected as the main form of influent seepage in those areas in the lower reaches of rivers where the permeability of gravels bounding the current flood plain are similar to the permeability of the flood plain itself (Fig. 3, B and C). This condition can be expected in areas where the river flows across postglacial gravels, but it is clear that losses to the flood plain can also be expected to any neighbouring gravel that is relatively permeable. Future monitoring should therefore pay special attention to geological boundaries between successive sets of outwash. Influent seepage that probably represents widespread loss to the flood plain has been demonstrated by comparative gaugings along the Waimakariri River, graphed in Fig. 4. The figure shows that losses on five measured occasions varied from 18 percent to 29 percent of total channel flow at the Gorge Bridge, and that the loss was greatest – and furthest upstream – at high stages, decreasing at lower stage. Influent seepage, perhaps partly channel loss and partly flood-plain loss, has also been demonstrated by recent river gaugings below the gorge on the Rakaia River (Stephen, 1972: pp. 29–31).

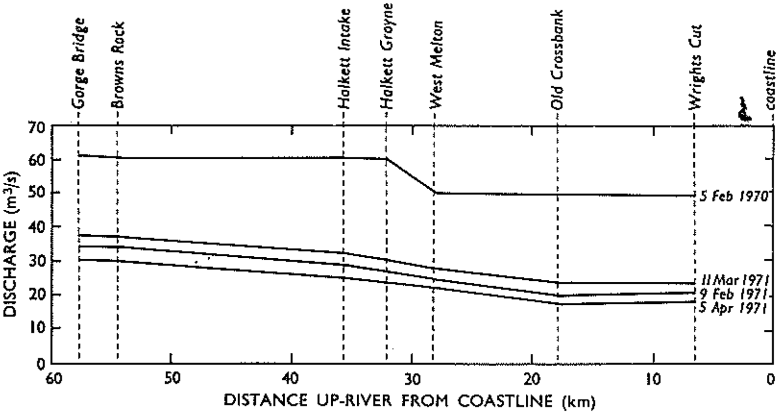

FIG. 4 — Four sets of comparative gaugings on the Waimakariri River, demonstrating losses from the river, especially between 32 km and 18 km from the coast.

The extent to which subsurface seepage takes place within or beyond flood plains cannot be judged merely by co-ordinated river gauging, but judgement is aided by additional factors. These are: firstly, groundwater flow directions, based on the geometry of the water table; secondly, sharp contrasts in well yields that are more likely to be due to increased recharge than to permeability changes; and finally, assessments of permeability differences based on geological history of deposition.

Fig. 1 maps water-table contours in metres above sea level. The contours are based on a series of 'spot heights' produced by converting the depth to groundwater static level at over a thousand located wells to height above sea level. The static water levels from which the 'spot heights' are compiled have been collected over a period of 27 years. Although the lowest recorded level is mapped in

Fig. 1, the essential geometry of the piezometric surface remains similar if the average static levels or maximum static levels are plotted. The significance of the contours is that they represent potential head of groundwater, so that flow directions are always at right angles to contours in the direction of lower head. The plains rivers, including minor rivers, are – almost without exception – crossed in their upper plains reach by contours that are convex upstream, and in lower reaches by contours that are convex downstream. The former arrangement suggests groundwater seepage to rivers, eliminating the likelihood of any loss from flood plains to the surrounding outwash gravel, but not of concealed flow within flood plains. The latter arrangement indicates that influent seepage from rivers is likely. Rapid easterly improvement in some lower-plains well yields suggests the possibility that influent seepage progresses far beyond the present flood plains. The suspected permeability jump between glacial outwash gravels and postglacial alluvium prompts an inference that widespread seepage is most likely in regions where the river flows over the younger beds. Seaward improvement in permeability of outwash gravels, as evidenced by well yields, may indicate that flood-plain loss also occurs where the river flows over glacial outwash material of above-average permeability; this is likely to be in regions most distal from the foothills.

The combination of evidence supports the view that influent seepage beyond each river's flood plain takes place mainly from lower reaches, where the course is over permeable postglacial alluvium. The seepage recharges groundwater not only in postglacial aquifers, but also in outwash aquifers in the lower plains. Although routes of recharge are not precisely known, it is likely that ancient buried river channels, which must form a complex network at all depths in the thick aggradational deposits of the lower plains, play a major part as 'pipelines' for influent seepage.

THE SIGNIFICANCE OF GEOLOGY IN IRRIGATION PLANNING

Wells yielding from 400 to 2000 litres per minute are common throughout the area mapped as postglacial alluvium in Fig. 2. Specific capacities of similarly constructed 15-cm-diameter wells range from 550 to 3000 m^3d^{-1} m^{-1}, values tending to rise from west to east. Transmissivity varies rapidly in lateral and vertical directions, and it is hypothesized that highly permeable aquifers might represent old stream channels, and poorly permeable aquifers are in overbank deposits, all formed during scores of millenia during which aggrading rivers shifted laterally in a complex way. The range of transmissivity has been broadly assessed using sparse test-pumping data, specific capacity data, and field estimates based on sediment appearance, at 100 to 10 000 m^2/d.

In the area mapped as glacial outwash (Fig. 2), yields range from 10 to 100 litres per minute, the higher yields occurring only in a few places near the boundary between glacial and postglacial deposits. Specific capacities range from 15 to 400 $m^3d^{-1}\,m^{-1}$, and transmissivities, assessed by the same speculative methods as those in postglacial material, are probably in the range 10 to 100 m^2/d.

Thus, the geological boundary between glacial and postglacial beds broadly separates areas where irrigation from groundwater is feasible from areas where it is not.

Outwash areas comprise nearly 4000 km^2 of the plains, and for intensive farming would require at least 500 mm of supplementary moisture. This represents 500 000 m^3/km^2, or 0.05 $m^3s^{-1}\,km^{-2}$ applied continuously throughout a 120-day growing season. This quantity is not available from explored aquifers. The alternative is to use surface water, but there are some periods during most growing seasons when river flows would be unable to meet the need.

It is already known* that some minor rivers – the Eyre River is the best-monitored example – control water levels in surrounding areas, so that long periods of negligible river flow cause shortages of groundwater. Some consideration should be given to the possibilities of recharging such minor rivers from neighbouring major rivers, with a view to underground storage of water that normally flows to waste during high stages. In the same way, there may be a possibility of increasing influent seepage to groundwater from major rivers, by way of deliberate flooding of known recharge areas during periods of high river stage.

THE SIGNIFICANCE OF GEOLOGY IN GROUNDWATER PLANNING FOR METROPOLITAN CHRISTCHURCH

Hundreds of borehole logs* indicate a wedge of predominantly fine-grained sediments under Christchurch, over 50 m thick near the coast and gradually thinning westward to disappear below the western suburbs. The sediments, mainly marine and estuarine sand and silt, which may include complex channels of gravel deposited during incursions of the Waimakariri River, have been deposited during conditions of rising sea level during the past 10 000 years.

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* Details held at the office of the N.Z. Geological Survey, Christchurch.

They were described in detail by Suggate (1958), who named them the Christchurch Formation.

The sediments include permeable sands and poorly permeable peats and muds, and they form a heterogeneous multiple aquiclude which confines water under pressure in the uppermost artesian aquifer (Riccarton Gravel: Suggate, 1958) under Christchurch, and also protects the aquifer from direct vertical pollution or contamination. These fine-grained sediments are probably also responsible for diverting groundwater upwards, at their westward limit, to form springs on which the flows of the Avon, Heathcote, and Halswell Rivers depend.

Beneath the Riccarton Gravel is a complex sequence of gravel aquifers, deposited and recharged from the west, interbedded with fine-grained groups of strata similar to the Christchurch Formation, and probably formed in an analogous way during high-sea-level periods that accompanied interglacial stages. All contain groundwater confined under pressure, and the pressure increases with depth. The presence of alternating gravels and fine-grained sequences beneath Christchurch causes complications to groundwater movement, and poses special risks to foundation stability.

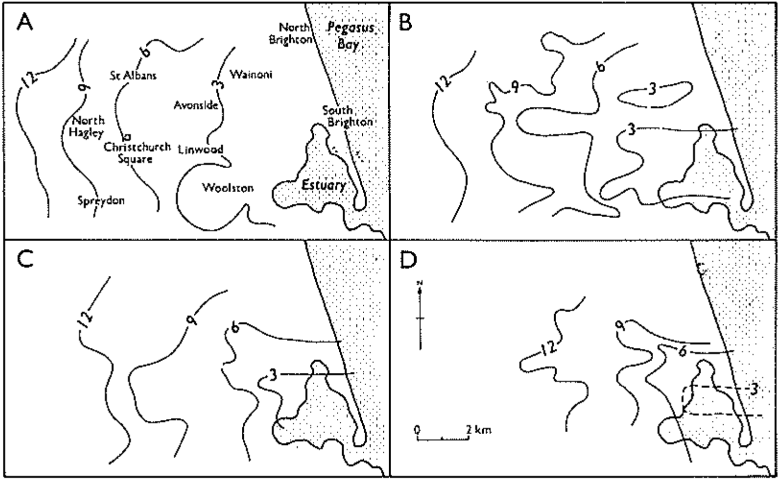

FIG. 5 — Lines of equal hydrostatic pressure (in metres) at depths of (A) 30 m, (B) 60 m, (C) 90 m, and (D) 120 m below mean sea level. The isopiestic lines were constructed by plotting pressures recorded in hundreds of logs from wells drilled in the area over a period of many years. The logs, and the large-scale maps and sections from which this figure was prepared, are available for inspection at the office of the Geological Survey, Christchurch.

Directions of groundwater movement (at right angles to pressure lines) can be deduced from Fig. 5, which maps aquifer pressures at various depths down to the explored limit of about 120 m. (Scattered data from deeper wells are available.) The maps are based on drillers' records* of aquifer pressures in hundreds of wells drilled over a period of about 50 years at widely differing stages of tide and of industrial pumping, factors which are important in causing pressure fluctuations (Oborn, 1960). Despite the consequences of these factors, Fig. 5 indicates at all depths a pattern of pressure variations that is too consistent to ignore. At all levels, there is a zone of pressure decrease towards the Christchurch Estuary. Sea-water intrusion, should it ever occur, is therefore likely to take place first in that area.

The complete explored sequence under Christchurch is saturated with water under pressure. Finer beds in the sequence, especially peat and clay, are liable to suffer compression if internal water pressures are lowered. There are many instances throughout the world of subsidence caused by uncontrolled pumping from complex stratigraphic sequences similar to that underlying Christchurch.† It would therefore be prudent to institute monitoring in Christchurch that would detect the first hint of subsidence, should this ever occur, so that measures could be taken to prevent its continuance.

The Avon and Heathcote Rivers depend entirely upon recharge by groundwater springs. Groundwater abstraction in the lower plains will probably tend to diminish flow in the rivers. In view of their aesthetic value to Christchurch, changes in the quantity and position of feeder springs is worth periodic monitoring.

CONCLUSIONS

The hydraulic boundary between an inner plains area where irrigation groundwater is not available at explored depths, and an outer plains area where it is, broadly coincides with the geological boundary between glacial outwash gravels and postglacial alluvium. The approximate coincidence is demonstrated by yields from existing wells. High-yielding wells of the lower plains may be recharged principally from neighbouring rivers. The pattern of groundwater distribution should assist irrigation planning.

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* The records, and the large-scale maps on which Fig. 5 is based, are available for reference at the Christchurch office of the N.Z. Geological Survey.

† See, for example, *Land Subsidence*: IASH Publication No. 88–89.

Hydrostatic pressures beneath Christchurch, plotted at equal depths below sea level, show a consistent tendency to fall towards a pressure trough situated approximately beneath the Christchurch Estuary. This fact might help towards monitoring against salt-water intrusion from the east. Christchurch depends entirely on groundwater for domestic and industrial supplies, it is aesthetically dependent upon groundwater-fed rivers, and it is underlain by strata of peat and clay at shallow and moderate depths; the city is therefore at threefold risk, in that haphazard mining of groundwater could lead to salt-water intrusion, decline of artesian rivers, and differential subsidence. There is currently no suggestion of imminent risk. but groundwater management should take account of the possibilities. If necessary, artificial recharge of coastal aquifers should be investigated.

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