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

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ABSTRACT

Accumulated data from nearly 5,000 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. Planned recharge

in influent seepage zones may prove to be feasible.

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 down metres are towards an area underlying the Christchurch Estuary. This fact may help in monitoring any seawater intrusion.

INTRODUCTION

The Canterbury Plain, averaging 50 kms in width and with an area approaching 8,000 sq. km, 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 in water wells within 16 kilometres 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 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 on the groundwater table (an exercise earlier carried out for part of the plain by Oborn, 1955) to localise 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 (75 cms average), but is supplemented by rivers rising in the Alps and with a total catchment in excess of 13,000 sq. kms where the average rainfall is approximately 170 cms. Groundwater availability is therefore linked with river behaviour, perhaps depending especially on the distribution of routes of influent seepage. This paper attempts to define, by an interpretation of accumulated data, localities where such seepage is most likely to take place, and subsequently 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. 1 the plains are divided into two lateral segments by the geological boundary between glacial outwash gravels and post-glacial alluvium; pre-Quaternary rocks of the foothills - largely sediments - and of Banks Peninsula - largely volcanic - are also mapped even though this paper is not specially concerned with their groundwater potential. All these boundaries are based, with 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) post-glacial 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.

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 run-off. Essentially the total run-off from each foothills catchment makes its way without appreciable loss to the point of debouchment onto the gravel fans of the Canterbury Plains proper.

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 Peri-glacial 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 inter-glacial and post-glacial periods. Boundaries between successive fans are marked by minor changes in slope of the plains surface (see 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

Age of fan	App. Distance from coast of fan apex. (km)	Gradient near apex (m/km)
Last Glaciation - final advance	48	6.5 (34 ft/ml)
Last Glaciation - second advance	58	7.5 (40 ft/ml)
Last Glaciation - first advance	64	9.5 (50 ft/ml)
Penultimate Glaciation	71	11.5 (61 ft/ml)

To date no hydraulic significance has been attached to the boundaries between successive outwash fans, and Fig. 1 maps only the boundary between unburied glacial outwash of all ages and blanketing post-glacial alluvium. Outwash deposits of all ages are present beneath post-glacial alluvium seaward of this boundary, but show improving hydraulic characteristics, and the hydrologic 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 metres of deposits, and yields from wells within 35 kilometres of the foothills are restricted, almost without exception, to only 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. The eastward increase in yield may be partly due to increased permeability of aquifers with increased distance from the foothills, but it may also reflect recharge, increasing in a downstream direction, by influent seepage.

4) Post-Glacial 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 post-glacial 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 post-glacial fan, with a gradient of 6 m/km, is about 45 kms upstream from the river mouth: the apex of the current fan which has a gradient of 3 m/km, is about 20 kms from the mouth (Mr G. D. Stephen, North Canterbury Catchment Board, in Dalmer, 1971).

There is a remarkable eastward increase in aquifer yield, both in post-glacial 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 litres per minute per metre of drawdown increases from lower than 10 at West Melton to about 15 near Paparua, to about 50 near Yaldhurst, to about 500 near Avonhead and to over 1000 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 incoming of additional recharge by influent seepage from the Waimakariri River.

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 post-glacial high sea-level. The economically most important area of confined water is that underlying Metropolitan Christchurch; the city depends entirely upon groundwater for public and industrial supply. The stratigraphy of the uppermost 120 metres of this area has been thoroughly explored by logged wells and described by Suggate (1958). The essential hydrology of the area is that several confined, high-yielding aquifers, yielding approximately 250 million litres per day without evidence of overdraught, are protected by thick impermeable deposits, and by natural pressure differentials, from direct vertical contamination or pollution caused by urban activities. As a general rule, hydrostatic pressure increases with depth, perhaps as a result of differing hydrostatic heads of points of intake, and perhaps in part dependent on increase of overburden pressure with aquifer depth.

Figure 4 shows maps of aquifer pressures at various depths down to the explored limit of about 120 metres (scattered data from deeper wells is available). The maps are based on drillers' records of aquifer pressures in scores of wells drilled at widely differing stages of tide and of industrial pumping, factors which are important in causing pressure fluctuations (see Oborn, 1960): despite the consequence of these factors, Fig. 4 indicates at all depths a pattern of pressure variations that is too consistent to ignore. At all levels the region of lowest pressure is beneath the Christchurch Estuary. It might be speculated that the geological explanation for this is that the mouth of the Waimakariri River coincided with the present position of the estuary during a large part of Late Pleistocene time. The hydrological consequence of the mapped pressures is that sea water intrusion, should it ever occur, is likely to take place in an area coinciding with the estuary, or seaward from it.

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 post-glacial alluvium in coastal reaches. The Waimakariri River, in a sector protected by Banks Peninsula from erosion by southerly marine currents, is 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 sub-surface flood-plain flow to surrounding older gravels, or 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. 2a 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 (pers. comm. Mr G. D. Stephen, North Canterbury Catchment Board). A measured increment of 31 cumecs (1100 cusecs) to the Rakaia River from the Lake Coleridge Hydro Electric Power Station caused a maximum increase in measured flow of 16 cumecs (560 cusecs) 3½ hours later at Rakaia Gorge Bridge gauging site, 20 kilometres downstream. A total addition of 150 cumec hours at Lake Coleridge resulted in a measured addition of 84 cumec hours at Rakaia Gorge. Smaller known increments, similarly monitored, showed a similar relationship between measured increments at Rakaia Gorge and known increments at Lake

Coleridge. Records showed a rapid return to base flow conditions at the gauging site following 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. 2, b and c). This condition can be expected in areas where the river flows across post-glacial gravels, but clearly 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. 3. 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 stages. 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 Rivers (pers. comm. Mr G. D. Stephen).

The extent to which sub-surface 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.

Figure 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 (the lowest recorded depth in each well has been used) to height above sea level. 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 post-glacial 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 post-glacial alluvium. The seepage recharges groundwater not only in post-glacial aquifers, but also in outwash aquifers in the lower plains. Although routes of recharge are not precisely known, well data suggest that the boundary between glacial and post-glacial deposits broadly constitutes a boundary between an inland plains region with moderate and poor groundwater aquifers and a coastal region with highly permeable aquifers recharged in part by 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 post-glacial alluvium in Fig. 1. Specific capacities of similarly-constructed 15 cm diameter wells are mostly within a range from 400 to 2000 litres per minute per metre of drawdown, and permeabilities are between 1×10^{-3} and 5×10^{-2} cms per second. Yields in the area mapped as glacial outwash are normally in the order of tens of litres per minute, and exceptional yields above 400 litres per minute occur only in a few wells near the boundary between glacial and post-glacial deposits. Specific capacities are generally in the range 10 to 250 litres per minute per metre of drawdown, and permeabilities between 1×10^{-4} and 1×10^{-3} cms per second. Thus the geological boundary between glacial and post-glacial beds broadly separates areas where irrigation from groundwater is feasible from areas where it is not. The boundary drawn is based largely on reconnaissance mapping, and may require amendment by larger-scale mapping, especially in the area south of the Rakaia River.

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Outwash areas underlie about half of the plains, an area of nearly 4,000 sq. kms. Average rainfall during the growing season is about 25 cms, so that supplementary moisture amounting to at least 50 cms is required, and this adds up to a requirement of half a million cubic metres of water applied to each square kilometre, or .05 cumecs (1.8 cusecs) applied continuously throughout the growing season (normally about 120 days). This quantity is not available from the explored aquifers in the outwash areas. Deeper aquifers capable of supplying .05 cumecs per sq. km during the growing season, necessitating yields approaching 4000 litres per min. from wells spaced in a kilometre grid, are hardly a conceivable proposition. The alternative is to use surface water. Even a casual study of limited river stage records shows that during most years there are long periods when river stage would be insufficient to meet the demand during parts of the growing season. It follows that irrigation must either depend on surface reticulation of unstored water, with consequent shortages at low river stages, or on stored water, in the form of on-farm minor reservoirs or large-scale holding reservoirs, recharged during high river stages.

In the area blanketed by post-glacial alluvium groundwater availability may depend to a large extent on influent seepage from parent rivers. There is likely to be a strong contrast between the total amount of water available from fans of major rivers like the Waimakariri, and fans of minor rivers like the Eyre. Each area must therefore be considered on its own merits. Present trends, where individual farmers initiate groundwater irrigation on their own properties, should be encouraged, but proliferation of irrigation wells should be accompanied by monitoring of water level so that rates of water-table decline can be anticipated. In areas where drainage is already a problem because of a high-standing water table, it would be good policy to monitor water-levels regularly, so that adverse effects of irrigation on neighbouring drainage can be assessed.

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 by 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 metres 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. They were described in detail by Suggate (1958), who named them the Christchurch Formation. The sediments include permeable 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 loc. cit.) under Christchurch, and also protects the aquifer from direct vertical pollution or contamination. 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. Figure 4 shows at all plotted depths a region of low pressure under Christchurch Estuary, suggesting that eastward groundwater flow is concentrated towards that region. Seawater contamination of groundwater, should it ever occur, is likely to occur first in that area.

Confined water under Christchurch has been subject to contamination during its journey down the plains, but has also been filtered during several miles of underground travel towards the city from the west. Direct downward contamination from city wastes can only be induced by deliberate introduction under pressure through recharge wells, or by so disturbing pressure differentials under the city that wastes from the surface, or sea-water, are drawn into aquifers under reduced pressure. Current artificial withdrawal of groundwater is not easy to assess, but probably reaches a maximum of the order of 300 million litres per day. There is currently no suggestion of shortage of water, no hint of salt-water intrusion, and little evidence of major disturbance of groundwater pressure differentials, but metropolitan water-use will certainly increase, and removal of groundwater from the lower plains for irrigation may affect recharge. It is therefore reasonable to suggest, in view of the economic importance of Christchurch's high quality groundwater, that competent monitoring of supplies, quantitative and qualitative, should be undertaken.

ACKNOWLEDGEMENTS

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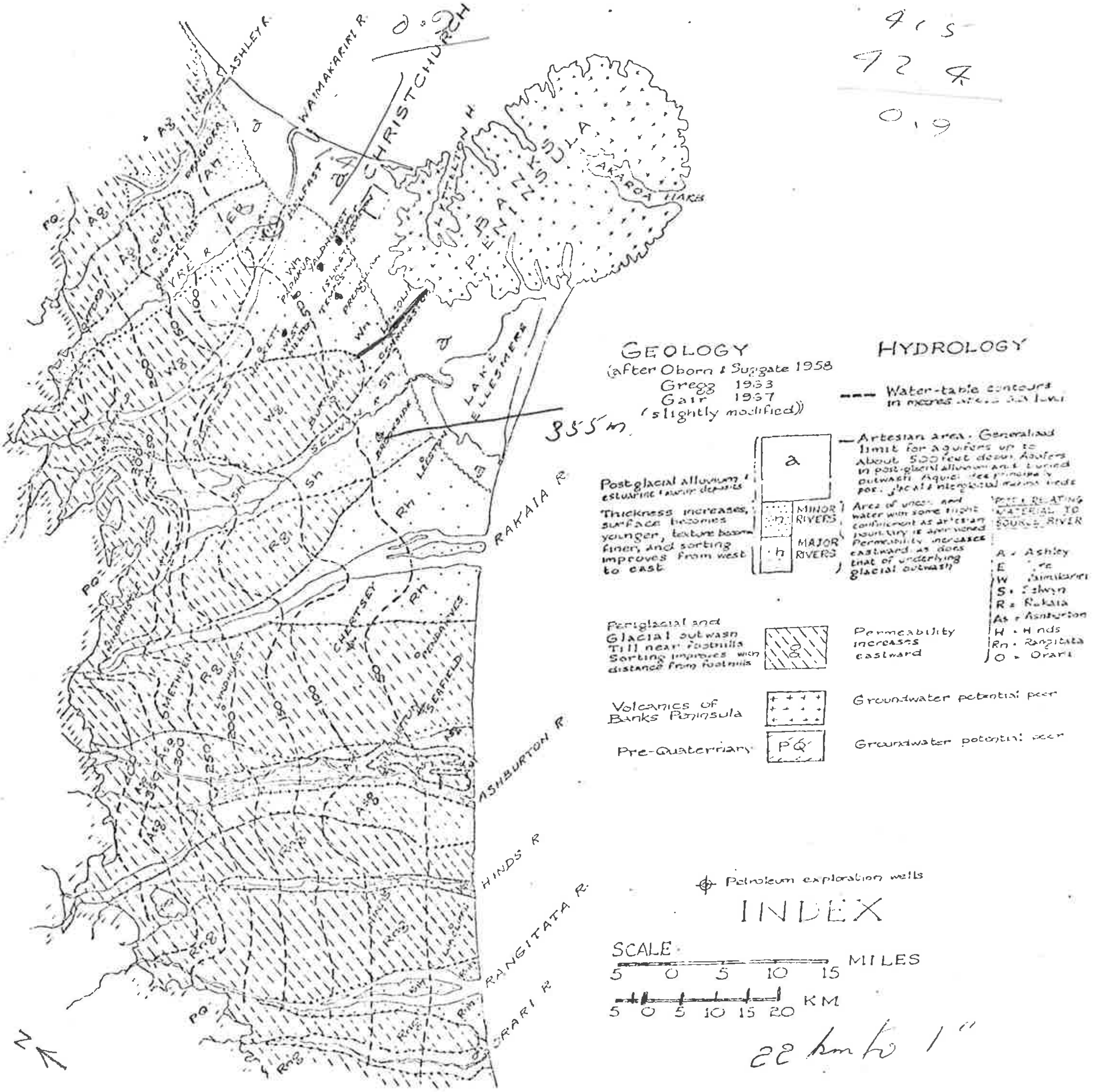
40
41.4



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335m

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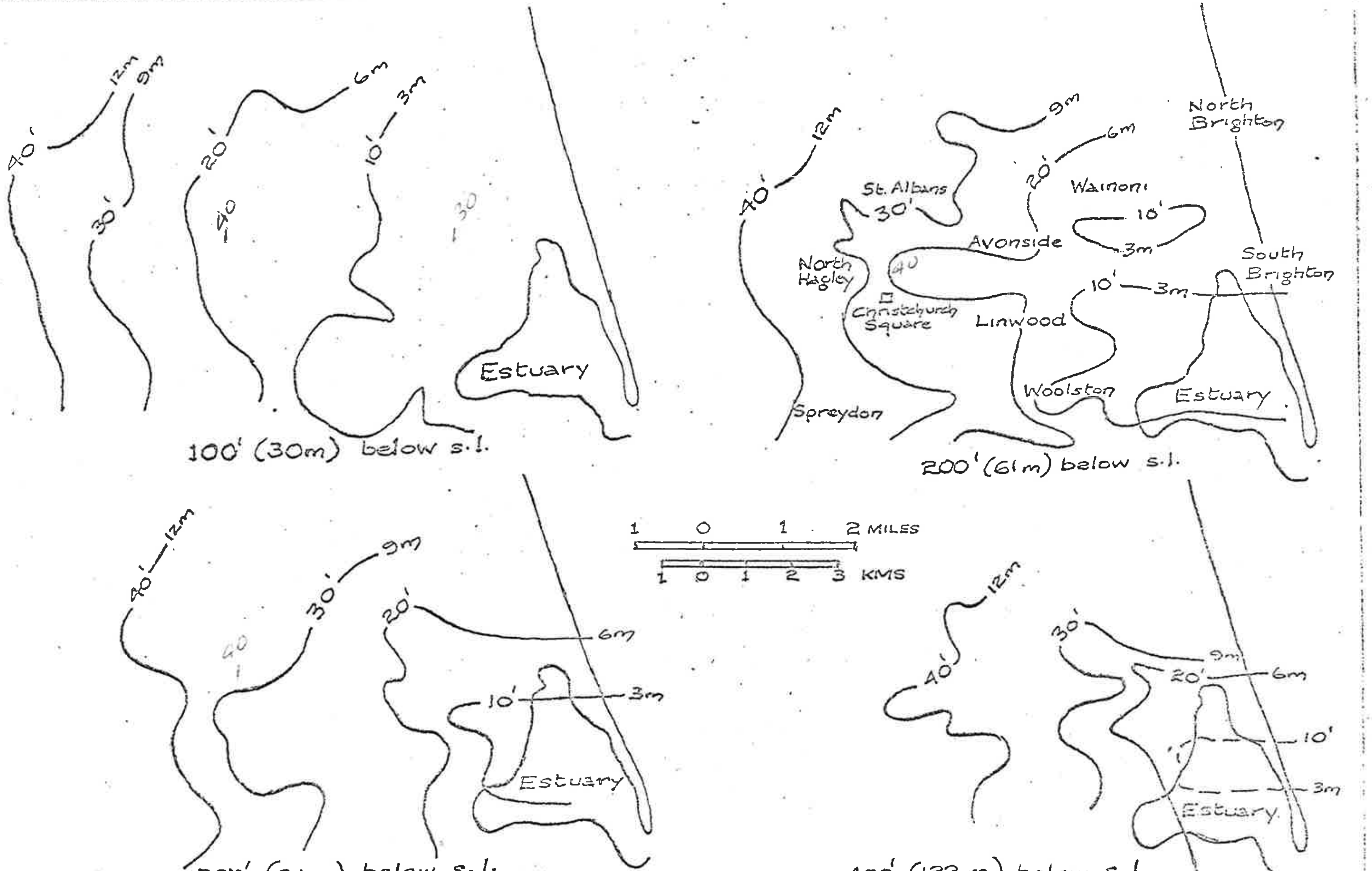
22 km to 1"

FIG. 1 MAP TO ILLUSTRATE THE GEOMETRY OF THE WATER-TABLE AND THE RELATION BETWEEN GEOLOGICAL BOUNDARIES AND HYDROLOGICAL CHARACTERISTICS OF THE CANTERBURY PLAINS, NEW ZEALAND.

D bed = 500 km?



100' (30m) below s.l.

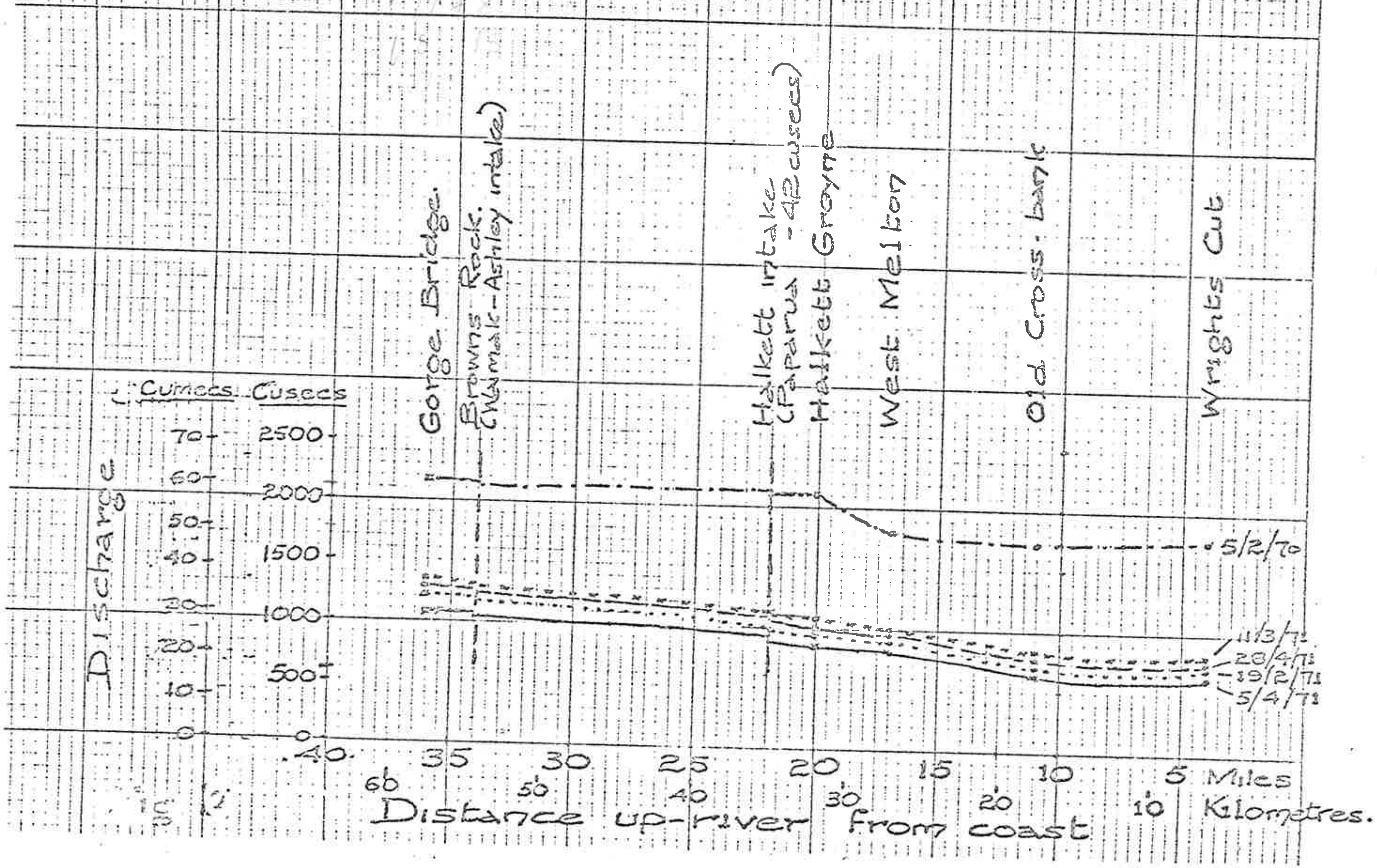
200' (61m) below s.l.

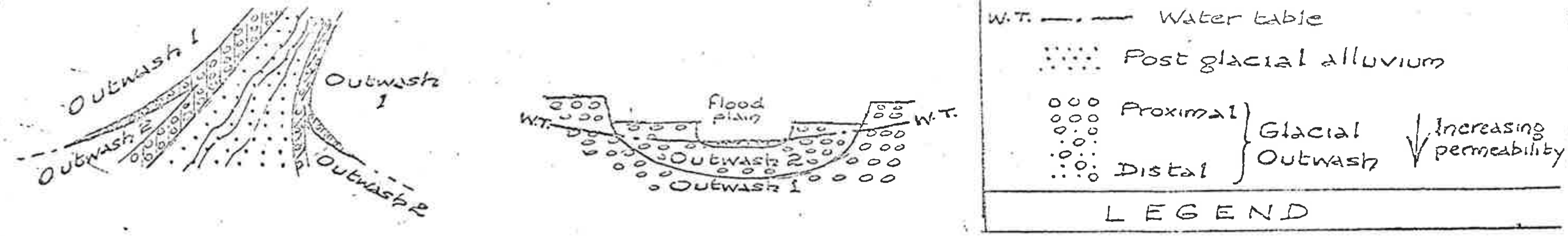
300' (91m) below s.l.

400' (122m.) below s.l.

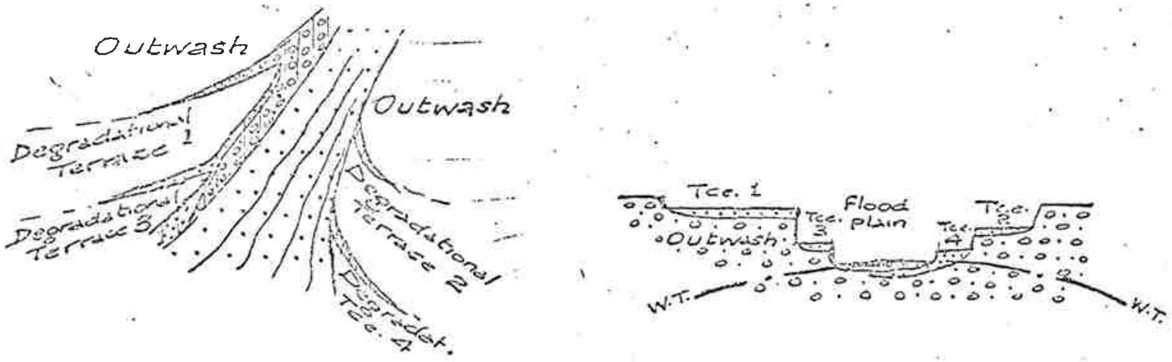
FIG.4 Lines of equal hydrostatic pressure at depths of 100' (30m), 200' (61m), 300' (91m) and 400' (122m) below mean sea level.

Fig 3 Graphs of 5 sets of simultaneous gaugings of the Waimakariri River, demonstrating losses from the river, especially between 20 miles and 11 miles from the coast.

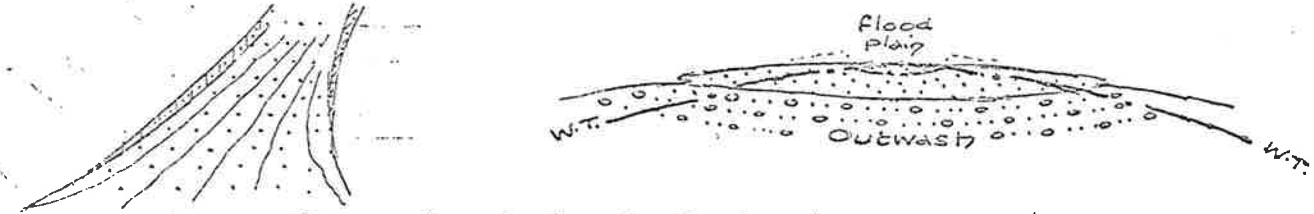




ⓐ Upper plains :- Matching aggradational surfaces of successive outwash fans bound the river's flood-plain. The low permeability of outwash deposits and the slope of the water table towards the river militate against influent seepage beyond the flood plain.



ⓑ 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.



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

Fig. 2. Diagrammatic perspective sketches and matching sections of upper, middle and lower river reaches, with an assessment of seepage possibilities.