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THE GROUNDWATER RESOURCES OF THE CANTERBURY PLAINS

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PREFACE

Lincoln College, the College of Agriculture of the University of Canterbury, sponsors an active research and teaching programme in hydrology, soil conservation and water resources development. The purpose of the Lincoln Papers in Water Resources is to communicate research results and new developments in these fields as rapidly as possible and particularly to report the results of projects undertaken in conjunction with the Department of Agricultural Engineering and the New Zealand Agricultural Engineering Institute.

The N.Z.A.E.I. has a particular responsibility in undertaking research and development in the agricultural engineering aspects of water supply, irrigation and drainage, and into the development of water resources for agriculture on a national basis. Throughout the past decade both the Institute and the Agricultural Engineering Department at Lincoln College have made a series of contributions towards the solution of New Zealand problems in soil and water engineering. These problems are becoming progressively more urgent as the pressures of both agricultural and non-agricultural use on this strictly limited resource intensify.

The current state of knowledge regarding the overall water resource has been evaluated by Dr Huber in his report "Water Resource Development for Expanded Irrigated Agriculture on the Canterbury Plains", which was published as Paper No. 11 in the current series. In the latter Dr Huber has identified some thirty specific research needs which together would provide the further information necessary for optimum water resource development. A key part of this programme is the assessment of the potential role of groundwater in future irrigation projects on the Canterbury Plains.

The Institute has been most fortunate in being able to attract Dr Mandel as visiting specialist in groundwater research and development for a period of six months while on sabbatical leave from the Hebrew University of Jerusalem where he is Professor of Applied Hydrology and Head of the Groundwater Research Centre. During the past twenty years, not only has Dr Mandel excelled academically as a teacher and research worker but he has also contributed to numerous hydrogeological development projects under the auspices of a world renowned Israeli corporation, TAHAL Consulting Engineers Ltd. During his eventful career he has undertaken assignments both in Israel and abroad, having completed projects in Greece, Cyprus, Spain, Mexico, Turkey and Iran.

The current report, which is based upon analysis of the available data together with field investigations, interpreted in the light of his extensive experience, confirms that groundwater has an important part to play in the future development of the Canterbury Plains.

G. T. Ward
Professor of Agricultural Engineering
Director, New Zealand Agricultural Engineering Institute

ACKNOWLEDGEMENTS

The author is indebted to Professor G. T. Ward, Director of the New Zealand Agricultural Engineering Institute and Head of the Department of Agricultural Engineering, and to the staff of Lincoln College for their kind hospitality and assistance. Dr B. van't Woudt (Reader, Department of Agricultural Engineering, Lincoln College) extended precious advice from his vast store of insight and experience.

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Miss B. Atkinson cheerfully typed from the author's deplorable handwriting, Mr K. Nicolle painstakingly collected material and Mr R. Vincent took great pains to get the drawings into shape.

If the contribution of any person or organisation has not been duly acknowledged, please attribute this to oversight, not intention.

S. Mandel

1. INTRODUCTION

The three aims of this report are:

(a) to evaluate the available information on groundwater;

(b) to identify unsolved problems of practical importance;

(c) to suggest lines of investigation that should be pursued for an efficient "optimal" utilization of groundwater for expanded irrigation in the Canterbury Plains.

2. SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

2.1 Groundwater

(a) The groundwater resources of the area total, at least, 1000 MCM/yr (Million Cubic Metres per year). Groundwater is replenished mainly by infiltration from rivers, and to a lesser extent by infiltration of rainfall.

(b) The exploitation of groundwater will be limited by poor aquifers and by the cost of pumping. For these reasons actual exploitation will remain much smaller than average annual replenishment.

(c) Seawater intrusion, at any significant rate, need not be expected, except perhaps in the area of Christchurch.

(d) In the Christchurch area carbon - 14 analyses of groundwater are suggested to investigate the problem of seawater intrusion.

(e) The available information on groundwater is deficient. The following programme of data collection is suggested:

(i) Subsurface mapping of the aquifer by the correlation of borehole-logs. Geological supervision of new drillings to ensure better definition of samples.

(ii) Mapping of important gravel veins (old river channels) by geo-electrical measurements.

(iii) Groundwater-level measurements in a network of boreholes. Measurements at monthly intervals would suffice. Water-level recorders have to be used only in specialised research projects. Existing exploited boreholes can be used for observation.

(iv) Several pumping tests of the interference type. Step drawdown and recovery tests in all new wells.

(v) Complete chemical analysis of all the major groundwater installations and of all new boreholes. The analyses should include: pH, conductivity, temperature (to be measured in the field) Na + K, Ca, Mg, Cl, HCO_3, SO_4, NO_3 and noxious ions wherever their presence is suspected.

(vi) Analyses of the average chlorine-ion content of rainwater.

(f) Further investigations suggested:

(i) Division of the aquifer into smaller natural units utilizing data as under (e) above.

(ii) Determination of groundwater available for exploitation in each of the units.

(iii) Mapping of old river channels which act as groundwater veins.

(iv) Quantitative investigations on vein-like groundwater flow.

(v) Quantitative investigations on underflow.

(vi) Mathematical model of the aquifer.

2.2 Surface Water

(a) The major part of river losses occurs in comparatively short stretches where the river is "perched" above the surrounding gravels. These stretches are situated at the apices of the more recent alluvial fans.

(b) Suggested investigations:

(i) Repeated simultaneous measurements above and below the perched river-stretches in order to determine losses.

(ii) Use of the dye-dilution method for these difficult gaugings.

(iii) Improvement of the dye-dilution method for use in braided rivers.

2.3 Engineering and Economics

(a) Irrigation wells should have a discharge of 30 - 100 m^3/hr, providing for the irrigation of 17 - 50 ha from each well.

(b) Discharges of 30 - 100 m^3/hr can be achieved in the seaward part of the plain, comprising about 30% of the total irrigable area.

(c) For well drilling the following procedure is suggested:

(i) Selection of site on the basis of geological advice assisted by geo-electrical measurements.

(ii) Casings: diameter 12 in - 14 in. Screens: 8 in - 12 in. Depth as necessary to penetrate all potential aquifers to at least 100 m below surface. Development of wells by surging etc, during about 3 - 7 days. Step draw-down and recovery tests during one day by portable pump. Access holes or access tubes for water level measurements should be mandatory.

(d) Much energy is probably wasted by unsuitable pumping equipment and clogged wells. Farmers should receive expert advice on this point.

(e) The conjunctive use of surface and groundwater will probably be economically advantageous, and may help to preserve stipulated minimum flows in rivers. Savings will depend on the possible reduction or elimination of surface storage and on reduced dimensions of installations for conveying river water.

(f) The following investigations should soon be carried out:

(i) Detailed economic feasibility and optimisation studies on the conjunctive use of surface and groundwater.

(ii) Studies on the environmental impact of large-scale river diversion and irrigation in order to define environmental constraints with greater accuracy.

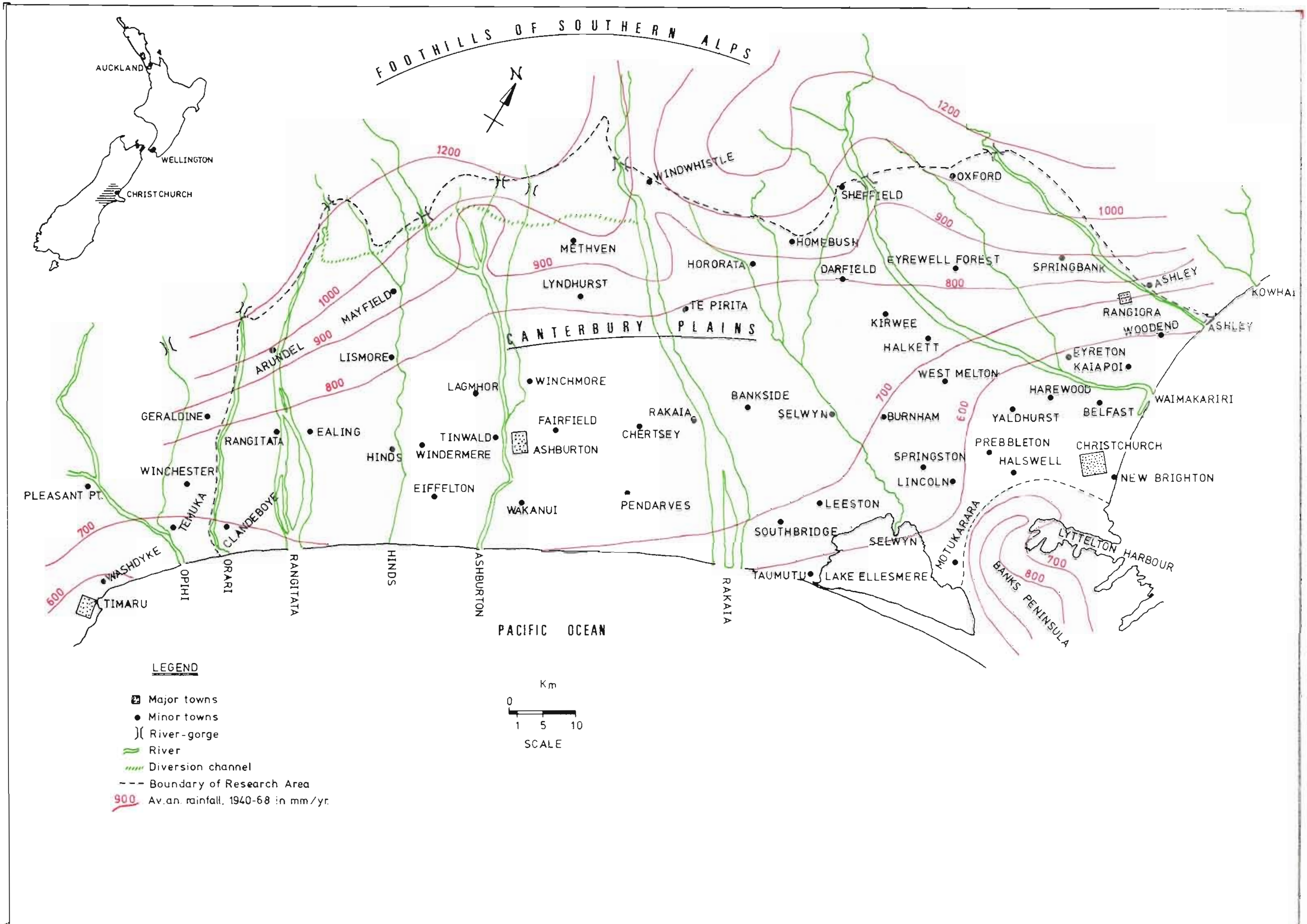


Fig. 1: Orientation and rainfall map

3. UNITS OF MEASUREMENT

The metric system is used, except for water level contour maps and in some dimensions.

The following short table may serve as convenient reference.

Table 1: UNITS OF MEASUREMENT

Metric Unit	Approximate Equivalent
Million Cubic Metres (MCM) or 100 hectare metres (ha/m)	35 million cubic feet 750 acre feet
cubic metres per second (m^3/sec) or 1000 litres per second (litre/sec)	35 cubic ft/sec
litres per second (litres/sec)	13.2 gal/min
cubic metres per hour (m^3/hr)	220 gal/hr = 3.7 gal/min

1 year = 8760 hours = 31 500 000 seconds

4. DESCRIPTION OF THE AREA

4.1 Situation, Boundaries, Topography

The situation and boundaries of the area are shown in fig. 1. The province of Canterbury extends from the Waitaki River in the south to the Conway river in the north and from the seashore in the east to the main watershed in the Southern Alps. For the purpose of this study the "Canterbury Plain" is defined more restrictively, as the area encompassed between the Orari and Ashley rivers in the south and north, the river-gorges in the west, and the seashore and inland boundary of Banks Peninsula in the east and southeast. This area covers about 5800 km^2 (580 000 ha) and contains most of the agriculturally useful land.

The area is a tilted plain with slopes increasing from around 1% in its seaward parts to around 5% in its inland margin, where it reaches maximum elevations of 350 - 500 m. Minor regional slopes extend from a central axis between the Ashburton and Rakaia rivers, towards the southwest and northeast respectively. Rivers running from the Alps to the sea form deeply incised valleys in their upper reaches, tending to spread out downstream. The larger rivers carry great volumes of shingle down from the Southern Alps and have a pronounced "braided" morphology. In the plain there are practically no lateral tributaries.

The seaward part of the area has a rather flat relief while the inland part is characterized by a complicated pattern of terraces terminated by steep bluffs that reflect the late Pleistocene history of the area.

4.2 Geology

4.2.1. Rock Formations

Greywacke, andesites and rhyolites (palaeozoic - mesozoic) crop out around the boundaries of the area. They are succeeded by a narrow fringe of mudstone, siltstone and some limestone (Oligocene - Pliocene). Banks Peninsula is composed of basalts and tuffs (Pliocene).

The plains are covered almost completely by Pleistocene - holocene sediments. Vestigal outcrops of morainic deposits can be seen in a few locations, outwash gravels form extensive terraces, and post-glacial alluvium (gravels, sand and silt) envelops the river valleys. The distinction between outwash gravels and river gravels is based on morphological criteria - from a sedimentological point of view they appear rather alike (Kingma, pers. comm.). The older gravels tend to be weathered and partly indurated. Shallow aeolian deposits (loess) are frequent.

Near the shore there are patches of low overgrown stationary sand-dunes, as well as patches of estuarine swamp deposits. Boreholes in Christchurch encountered several layers of estuarine-marine clays interfingering with gravels. In the area of Lake Ellesmere - Christchurch - Kaiapoi these layers give rise to artesian conditions.

4.2.2. Geological History

Present-day Canterbury started to rise from the sea during the Miocene. During the Pliocene and the early Pleistocene intensive orogenic activity ("Kaikoura Movements") built chains of mountains aligned from northeast to southwest.

During the late Pleistocene the mountains were eroded by glaciers descending from the Southern Alps and their remnants were blanketed by glacial deposits. The "bedrock" below the plain must be assumed to have a very rugged configuration.

Successive advances of glacial ice carried debris down from the Southern Alps, forming extensive moraines. Melt-water at the edges of the ice-sheets transported and rearranged most of the morainic material in the form of "glacial outwash". Rivers degraded the upper part and aggraded the lower part of their valleys. The seashore was foregraded by river fans. A volcanic island offshore from Christchurch, providing shelter from sea-currents, enabled river-gravels to spread out into the sea. Eventually the island was linked to the mainland, thus forming Banks Peninsula.

In the coastal part of the area sand dunes were deposited. Eustatic changes of sea level, probably accompanied by minor tectonic movements, modified the base level of the rivers and may have been reflected inland by changes of the boundary between aggradational and degradational river activity. Nearer to the shore, changes of sea level left their trace in the form of estuarine marine deposits of an impervious to semipervious character, mainly around Christchurch.

4.2.3. Quaternary Stratigraphy

The difficulties of quaternary stratigraphy are here compounded by the absence of macro-fossils (bones) and of human artifacts. Carbon-14 analyses of rare plant remains were made but they cannot serve as an adequate substitute. Under these circumstances surface-correlations have to rely on geomorphological criteria. Subsurface mapping, as far as it has been attempted, relies on degrees of weathering, degrees of compaction and colour. Unfortunately, well drilling is not usually supervised by trained geologists and the available 'drilling logs' lack precision.

For the Christchurch area the following sequence is given by Suggate (1973).

Glacial Advance	Formation
Waimaunga and Porika	Hororata; weathered gravel
Waimea	Woodlands; glacial till and adjoining outwash, partly compacted
Otira	(Windwhistle; moraines and (outwash gravels (Burnham; outwash gravels, (partly compacted
Post-glacial	(Springston; river-gravel and (finer alluvium, not compacted (Christchurch; coastal dune- (sands, marine-estuarine (deposits

Only small outcrops of the older fans and moraines are preserved. Most of the area is covered by the Springston and Burnham formations.

4.2.4. Thickness of Quaternary Strata

Reliable information comes only from three structural boreholes near Leeston, Chertsey and Seafield (ref: Suggate 1973, for locations see fig. 2). Two boreholes encountered bedrock at depths of 1200 and 1460 m. The permeable series of gravels and sand (upper Pleistocene - Post Glacial) is 384 m thick near Leeston, 445 m near Chertsey and 449 m near Seafield. Below these depths mainly impervious strata (clays, gravels embedded in clay etc) were encountered, but in Chertsey an intercalated layer of quicksand yielded brackish artesian water (1650 ppm chlorine-ion) from the depth of 720 m.

Since the boreholes were drilled in a synclinal situation (D. Wilson, pers. comm.) they probably represent thicknesses that are exceeded only around Christchurch. The thickness probably decreases rather rapidly in an inland direction and towards the southern and northern margin of the area. Buried tectonic features of the bedrock may cause considerable local variations of thickness. References: Gage 1969, Suggate 1958, 1963, 1965.

4.3 Climate

The climate is temperate with average summer temperatures of about 15^{o} C and average winter temperatures of about 8 - 9^{o} C. Frosts are frequent during the winter season, April to September, snow is rare in the coastal area but relatively frequent further inland. Short spells of extreme heat up to 40^{o} C may occur during the summer months October to March. The weather is prone to rapid changes. In Canterbury one may experience all the four seasons during 24 hours.

Rainfall is distributed evenly throughout the year. Average annual rainfall amounts to 600 mm around Christchurch, 700 - 800 mm over most of the plain, reaching 1000 mm near the inland edge of the plain. Potential evaporation, as indicated by several raised pans is in the range of 1000 1300 mm/yr (uncorrected pan values). During summer the area has a parched, steppe-like appearance as the ralatively frequent rains are quickly dissipated by high evaporation rates.

(References: Fitzgerald (ed.) 1970, P.E. Consulting Group 1966, N.Z. Meteorological Service Misc. Publ. 110, Tourist and Publ. Dept. 1973/74).

4.4 River Flow

The three major rivers, the Waimakariri, Rakaia and Rangitata, with big catchment areas on the high mountains have a perennial flow. The minor rivers, Ashley, Selwyn, Ashburton, Hinds and Orari are fed mainly from catchment areas in the foothills

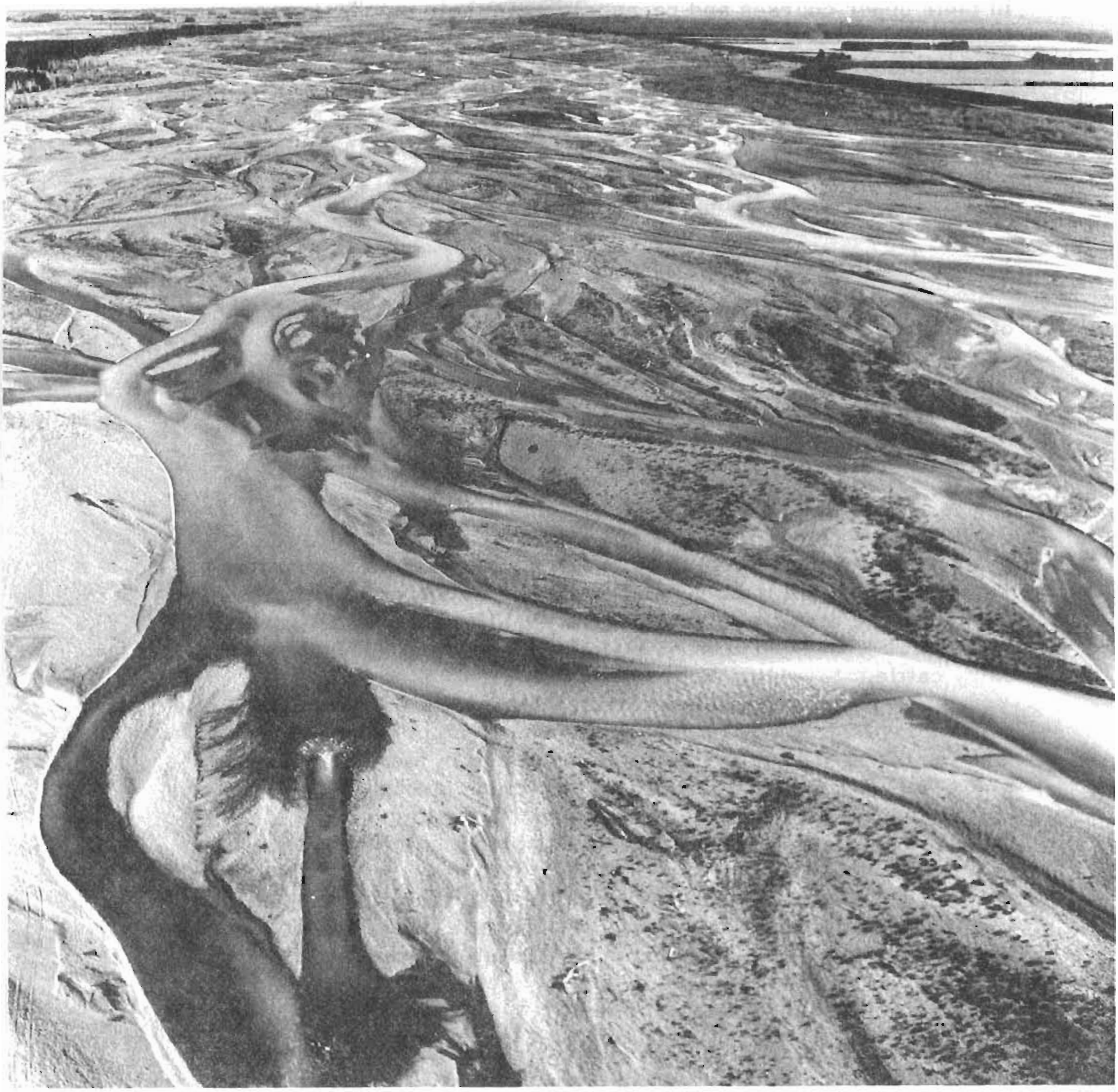


Plate 1: The Waimakariri river. Braided river channel

and in summer their middle courses dry up. Small flows remain in their upper courses and re-appear near their mouths having passed through the river gravels. A few small perennial streams around Christchurch are fed mainly from groundwater.

The total annual discharge of the rivers (excluding the small streams) is about 400 m^3/sec or 12 500 MCM/yr. Low discharges, occuring at a frequency of about once in five years, are approximately 160 m^3/sec or 5 000 MCM/yr.

(Reference: Huber 1973, Heiler and others 1970).

4.5 Demography

The area has a population of about 410 000 souls, almost half of the South Island's population. Seventy-five percent of the population lives in Christchurch (pop. 308 000). Three towns, Timaru (pop. 30 000), Ashburton (pop. 11 000) and Rangiora (pop. 6 000) are situated at focal points of communication. Small service towns such as Darfield, Leeston, Methven, Hororata, dot the countryside.

4.6 Agriculture

The raising of livestock is the main branch of agriculture. There are about 10 million head of sheep (mainly meat sheep are farmed in the area, wool sheep from the hill country spend the winter on the plain), 380 000 head of beef cattle and about 73 500 head of dairy cattle.

Crop farming produces mainly barley, wheat, oats, peas and seeds (clover). About 148 000 ha are under grain crops. Truck farming of vegetables and fruits is practiced in low-lying areas where soil and moisture conditions are more favourable.

In 1972 46 000 ha were irrigated. Irrigation could be expanded over an additional 360 000 ha, bringing the total irrigable area to about 410 000 ha (4100 km^2).

(Reference: Fitzgerald (ed.) 1970, P.E. Consulting Group Ltd 1966, Hamilton 1972, Huber 1973, pers. comm. by Federated Farmers, Cant. Div., Mr Chapman, Statistics Dept., Christchurch).

4.7 Present Water Supplies

A large race (diversion of river water) runs near to the foothills from the Rangitata to the Rakaia river. It has a capacity of 1000 cusecs (almost 30 m^3/sec) and is used for irrigation of about 17 000 ha as well as for power generation by a fall of 110 m at the Rakaia end.

Table 2: DATA ON WELLS*

(For locations see fig. 1. Source: files of the New Zealand Geological Survey)

Location	Depth m	Dia. inches	Disch. m^3/hr	D'Down m	Remarks
Oxford	13.2	8	13.5	1	gravels, loose
Sheffield	12.5	6	13	1	gravels, bound, and sand
Racecourse Hill	12.2	6	2	5	-
Homebush	57.0	6	0.7	25.3	gravel, clay bound
Mayfield	10.3	6	2.3	-	
Springbank	12.7	6	3.3	-	water from 2' of sandy gravel
Halkett	58.8	8	1.3	17	gravels, bound; and sand
Burnham	25	3	11	1	-
Pendarves	48.5	6	3.4	14	deepening was suggested
Fairfield	107	8	38	6	-
Winchmore	29.3	8	2	.6	strata clay-bound
Ashburton	11.3	6	8.4	3	
Tinwald	23.2	6	3.5	2	
Laghmor	10.7	60	55	1.3	dug well
Lismore	10.5	6	3.4	1	
Ealing	22	5	8.1	1	
Windermere	21.2	6	4.5	13	
Waikuku	17.0	6	18.5	1	
Rangiora	24.8	8	4.1	1	
Kaiapoi	22.7	10	100	3.5	
Clarkville	17.7	6	90	-	gravel, loose
Eyreton	16.0	10	95	-	gravel, loose
S. Brighton	170	8	68	1	
Harewood	7.5	6	68	1	
Yaldhurst	25.3	8	80	7	gravel and sand, mainly loose
Christchurch) Waimairi)	24	14	250	4.8	
Christchurch) Hornby	70.6	8	91	-	gravel and sand, partly bound
W. Melton	48	6	1.7	1	gravel and sand, bound
Springston	10.3	6	11.5	1	water from 6 m, gravel, loose
Taumutu	30.7	2	3	-	artesian flow
Selwyn	32.0	8	55	2	gravel and sand loose, some clay
Southbridge	17.0	5	111	10	
Wakanui	10	-	45	4	confined water
Clandeboye	5.6	8	47	2.3	gravels, loose

* Wells with a discharge of less than 1 m^3/hr not represented

Races on the Ashley, Waimakariri, Ashburton, Rakaia and Opihi rivers have a combined capacity of about 750 cusecs (21.5 m^3/sec). From smaller streams irrigation water is abstracted by portable installation.

Groundwater is extensively used for municipal supplies. In the greater Christchurch area about 3 m^3/sec (nearly 100 MCM/yr) are supplied from this resource. Groundwater is also used for irrigation, mainly in the artesian zone around Lake Ellesmere and,

to a smaller extent, elsewhere.
(Reference: Heiler, Taylor and Johnston 1970).

4.8 Wells

The New Zealand Geological Survey keeps files of more than 5 000 wells. They range from dug shafts to smaller-diameter driven pipes, to drilled wells of 8 in. to 14 in. diameter. Discharges of the small to medium wells range from 3 - 10 m^3/hr, larger wells have discharges of 30 - 100 m^3/hr, and a few wells in favourable terrain around Christchurch have discharges of 200 m^3/hr and more. The scant available data makes a meaningful correlation extremely difficult. The impression is gained that most of the wells are far too narrow, too shallow, constructed on a skimpy budget for a small demand and have a much smaller discharge than could be achieved. Pumping equipment ranges from plungers to horizontal centrifugal suction pumps (usually tractor-driven), to modern submersible pump/motor units. Municipal supply wells of the larger townships usually give much higher discharges than farmers' wells in the surrounding countryside.

A sample of representative wells is given in table 2.

5. CHARACTERISTICS OF THE GROUNDWATER SYSTEM

5.1 Properties of the Aquifers

In the heterogeneous Quaternary strata only two groups of aquiferous strata can be distinguished. A younger, highly permeable aquifer formed by unconsolidated sediments and an older, less permeable aquifer formed by partly consolidated sediments (Brown, pers. comm.). For the sake of brevity we shall call them aquifer A (mainly Springston and younger) and aquifer B (mainly Burnham and older). Finer subdivisions are probably possible in the Christchurch area.

In aquifer A, wells have a specific discharge of 30 - 3000 litres/min/m (litres per minute for one metre of draw-down). Near Christchurch specific discharges increase from 30 litres/min/m at West Melton to more than 3000 litres/min/m at Upper Riccarton, probably due to a very pronounced seaward thickening and better grading of the gravels. In aquifer B, wells yield only a few litres/min within a distance of about 35 km from the foothills but further seaward their yield may increase to 800 litres/min (Wilson 1972). Specific discharges depend also on the technical details of well construction, therefore they can serve only as rough indicators of aquifer properties.

On the basis of literature and personal experience the average permeabilities of the aquifers are estimated at about 30 m/day for aquifer A and about 10 m/day to 7 m/day for aquifer B.

Aquicludes are known only in the vicinity of Christchurch although they may also occur over small areas at other locations near the seashore. Lenses of silt, silty sand and the odd clay-lens, as well as the natural orientation of shingles (with the flat side horizontal), render the aquifer strongly anisotropic. Permeability in the vertical direction is probably one tenth or less of horizontal permeability. From this characteristic there follows an important practical conclusion. Shallow wells cannot easily attract water from the deeper parts of the aquifer, deep wells will quickly repay the additional outlay by smaller draw downs (pumping lifts, energy requirements) and larger yields.

5.2 Water Levels

5.2.1. Configuration of Water Levels

The contour map (fig. 2) shows "average characteristic" water levels during the last few years. Large parts of it are based only on a few observations in widely spaced boreholes. In spite of these shortcomings, the following characteristics can be seen.

(a) Gradients are much smaller in the central and seaward part of the aquifer than in its western part. This indicates reduced transmissivities in the east, in conformity with the geological picture.

(b) In the vicinity of Banks Peninsula the seaward part of the contour lines (from about 200 ft elevation down) shows a gradient of around 0.3% whereas southwest and north of Banks Peninsula gradients are of the order of 0.5% - 0.6%. In particular, south of the Ashburton river the contour lines 100 ft and 50 ft are very close to the seashore, but around the Waimakariri river they are about 16 km distant from the seashore. Thick gravel layers were deposited in the shelter of Banks Peninsula, therefore transmissivities are here very large. Thus the configuration of water levels confirms the geological picture.

(c) Pronounced water-level ridges exist along the middle ranges of the major rivers with the exception of the Rangitata, indicating that the rivers feed the groundwater horizon. According to the water-level contours, river water flows not only into the adjacent river gravels but also into the less permeable Burnham formation (see fig. 2, Waimakariri). This is seemingly at variance with the geological picture but is confirmed by geochemical evidence (see 5.3, fig. 4).

Water level maps based on measurements in a network of precisely levelled wells at specified time intervals form an indispensable basis for future groundwater investigations (reference: Wilson 1973).

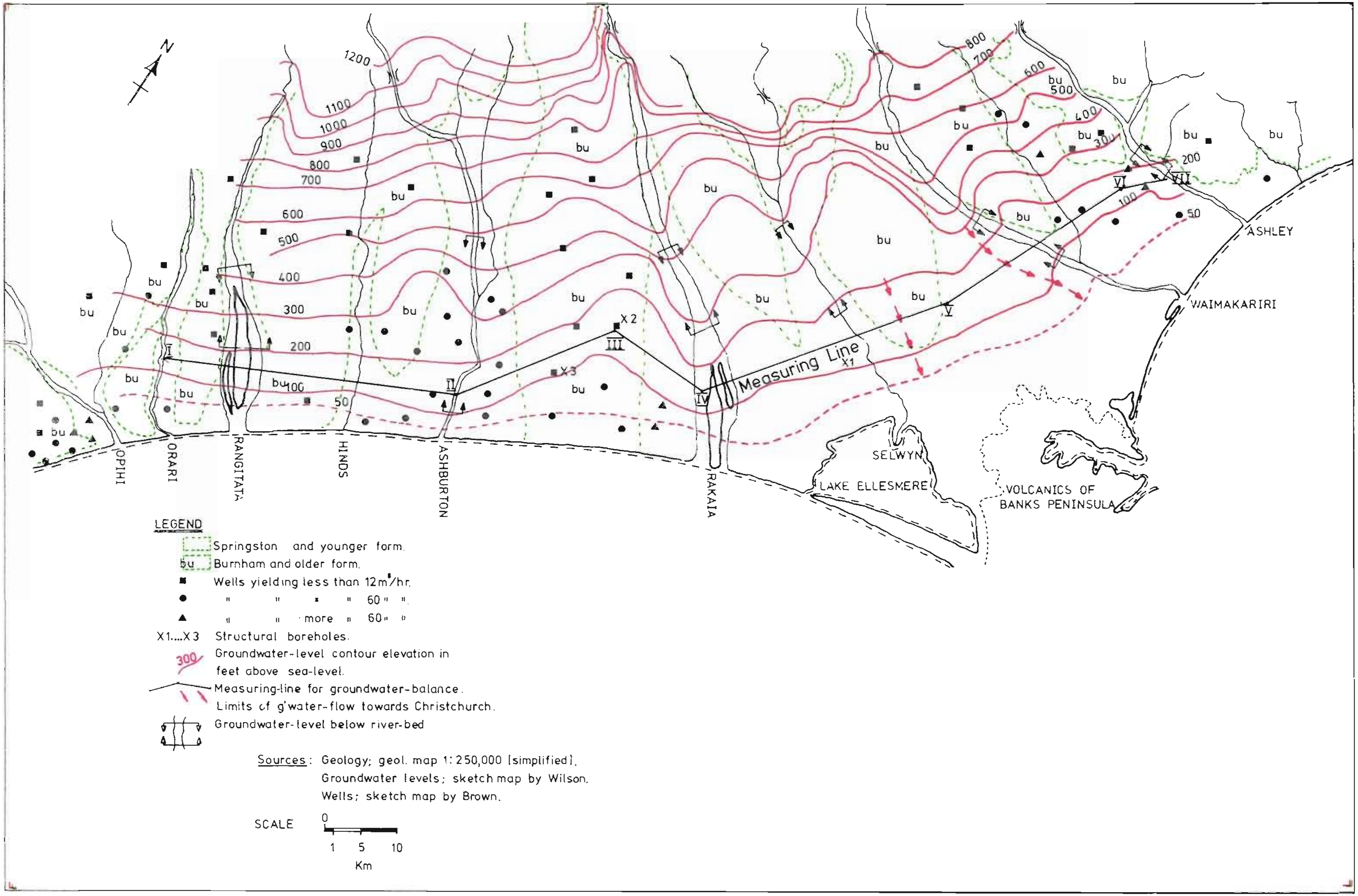


Fig. 2: Water level contour map

5.2.2. Water Level Fluctuations

A record of water levels between the Waimakariri and the Rakaia rivers for the period 1952 - 1960 is given in the Hydrology Annual No. 7 (see fig. 3).

The large fluctuations observed near Kirwee and upstream from Sheffield on the Waimakariri river are strongly attenuated towards the south and east reaching their minimum near Templeton and Hornby. Similarly, large fluctuations of 5 or 6 m in the left bank of the Rakaia river are attenuated towards the Selwyn river, and especially, towards Lake Ellesmere. This pattern indicates the propagation of hydraulic pressure waves from certain locations on the major rivers into the aquifer between them and towards the base level.

A detailed interpretation of the phenomenon taking into account river-stages, rainfall, amplitudes and phase differences cannot be attempted in the present framework. It would probably yield important quantitative characteristics of the natural system and is therefore, recommended for further study.

5.2.3. Dependence of Water Levels on Depth of Wells

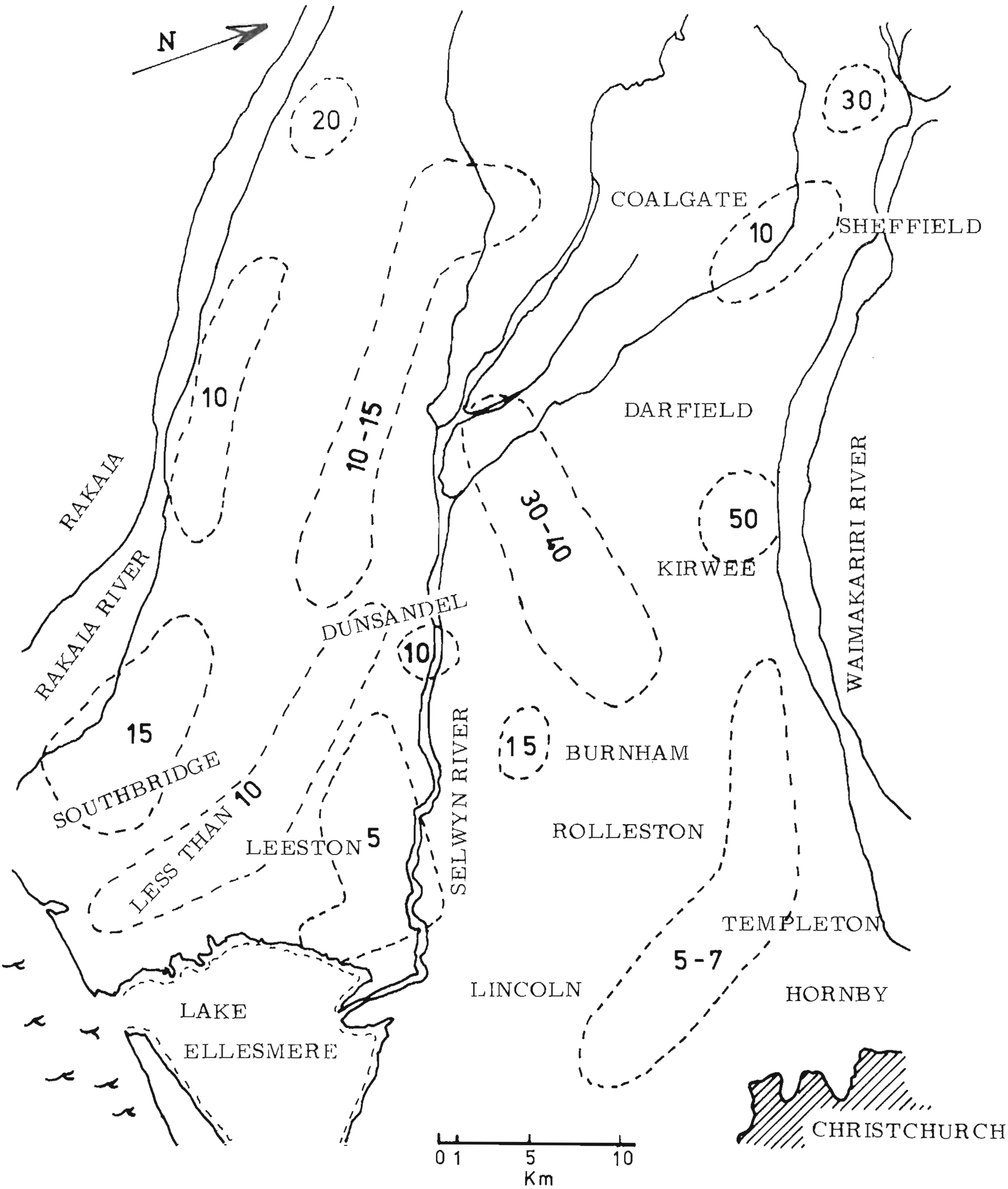
In the Christchurch area water levels rise strongly with the depth of drilling, probably due to the presence of semi-confining layers and/or to the anisotropy of the aquifer. The phenomenon is now being investigated by the New Zealand Geological Survey. In the rest of the area wells are too shallow to discern a significant pattern.

5.3 Geo-Chemical Data

Isotope analyses of tritium, deuterium and oxygen-18 are in the process of being evaluated by the Institute of Nuclear Sciences, Wellington.

The chemical quality of water supplies is checked by the Chemistry Division of the Department of Scientific and Industrial Research (ref: Drummond and Hogan 1965, 1967, and Kingsford 1973). A few analyses give all the major ions, Na, K, Ca, Mg, HCO_3, Cl, SO_4, but most of them give only pH, Cl, total dissolved solids (TDS), total hardness, and ions of special interest such as Fe, NO_3 etc.

Generally, groundwater in the area is suitable for all purposes. The only known exceptions are: (a) slightly ferruginous waters occur near the coast north of Christchurch and around Lake Ellesmere, (b) warm mineral waters occur at the boundary of Banks Peninsula (Motukarara, Lyttelton tunnel, Heathcote Valley) and near Timaru (Centennial park), (c) saline waters, probably due to contamination from the sea, are found in some isolated localities such as Bullivants well near Woodend beach.



Average yearly water-level-fluctuations during 1952-60, feet

Source: Soil conserv. and rivers control council Hydrology Annual No. 7, 1959

Fig. 3: Water level fluctuations

Ferruginous and saline contaminations seem to stem from shallow depths (ancient swamp deposits, recent flooding by the sea), but they are usually eliminated by drilling into deeper, better flushed gravel layers.

Table 3 cites, by way of example, several detailed chemical analyses.

Table 3: DETAILED CHEMICAL ANALYSES

	parts per million						
	pH	Cl	NO_3	TDS	Fe	Hardness	Si
Christchurch, Colombo St. Well 80.3 m deep	7.6	6	0.2	80	Nil	43	12
Christchurch International Airport. Well 10 m deep	7.2	4	0.1	65	0.1	35	4
Lincoln College. Well 33.5 m deep	7.5	10	0.1	90	Nil	55	-
Oxford. Shallow wells	5.5-6.5	5-22	0-10	95-270	0-0.4	30-100	-
Rakaia. Well 13.3 m deep	7.3	3	0.1	55	Nil	40	-
Rolleston. Well 40 m deep	6.6	18	3.6	135	Nil	50	-
Dunsandel. Well 10 m deep	6.5	10	1.2	85	0.4	30	-
Eiffelton. Well 4.3 m deep	6.6	20	Nil	165	0.4	25	-
Ellesmere. Shallow wells	7.2	9	-	115	0-0.8	-	-
Fernside. Well 10 m deep	6.5	8	0.6	100	3	55	-
Fernside. Well 20 m deep	6.2	59	3.2	235	Nil	50	-

Sources: Drummond and Hogan 1965, 67

For a regional correlation chlorine-ion content was selected because it is hardly influenced by processes of ion exchange or adsorption. The wells could not be precisely located,

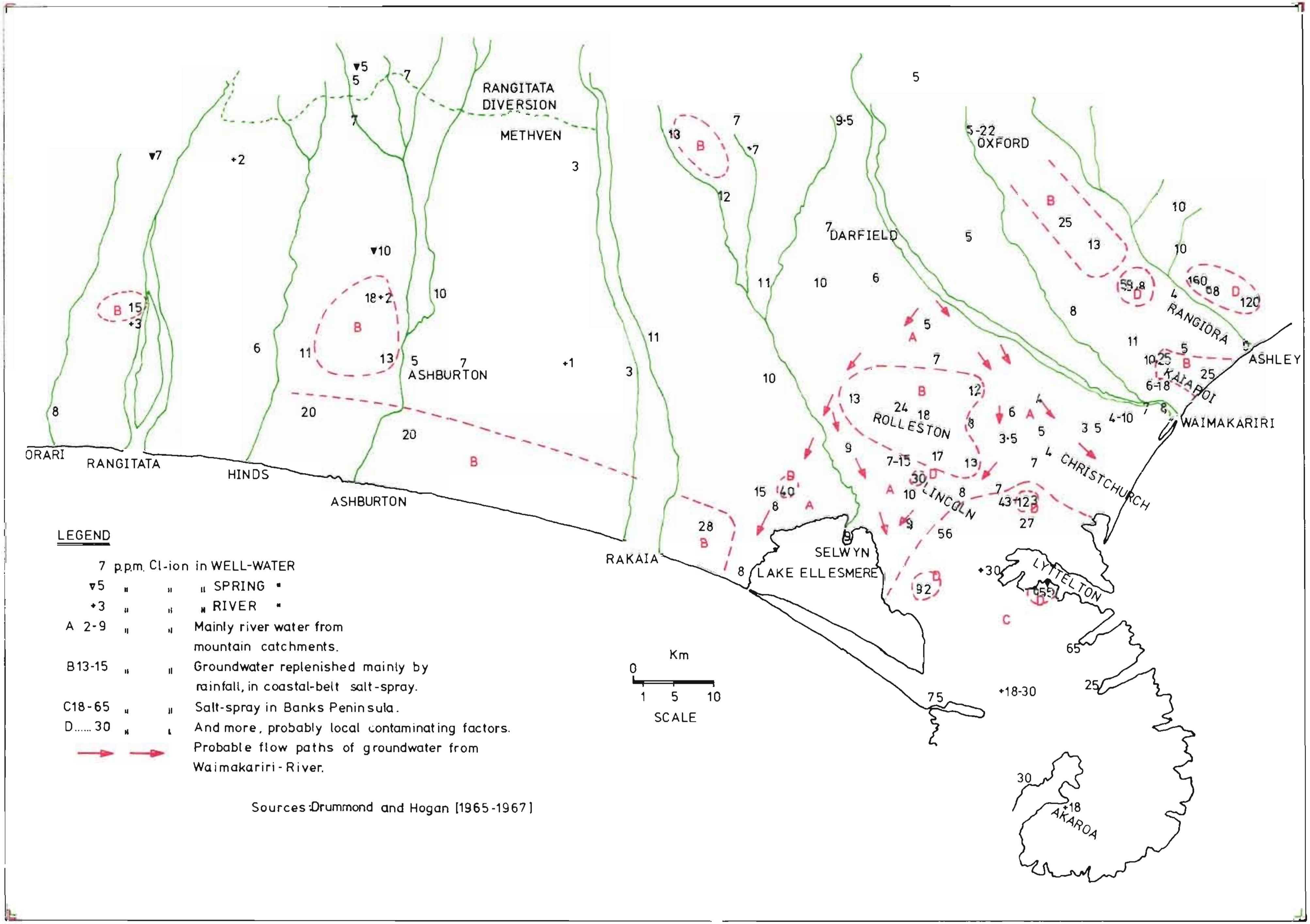


Fig. 4: Chlorine-ion concentrations in groundwater

they are of varying depth, and the determination of low chlorine-ion content may lack in precision as chlorides are not of great practical importance. In spite of these shortcomings the map (fig. 4) yields interesting clues on the hydrology of the area:

(a) In the Banks Peninsula all waters are comparatively rich in chlorine-ion, probably due to salt spray from the ocean. In springs there may also be tidal influences.

(b) Streams from mountain catchments have a very low chlorine-ion content (2 - 8 ppm). On the right bank of the Waimakariri river low chlorine-ion content spreads out towards Christchurch - Lincoln - Lake Ellesmere indicating the preferred paths of groundwater flow from the river through the aquifer.

(c) The "island" of higher chlorine-ion contents around Rolleston (13 - 21 ppm) probably indicates that here groundwater is replenished by direct infiltration from rainfall. The small chlorine-ion content of rainfall is concentrated by evapotranspiration from soils.

(d) In the rest of the area a few data indicate that similar patterns prevail.

(e) Comparatively high chlorine-ion contents (20 - 28 ppm) prevail in the coastal belt south of Lake Ellesmere. They are probably due to salt spray and evapotranspiration from water levels near the surface.

(f) Chlorine-ion contents in excess of 30 ppm are attributed to the influence of local factors (slightly saline strata, man-made contaminations).

For future hydrological studies, complete chemical analysis of all water resources are highly desirable. Interpretation of geochemical data will yield information that can hardly be obtained by any other method. Pollution of water resources can be discovered at an early stage only if the natural state is well known. Measurements of chlorine-ion concentration in rainfall may yield a good estimate of direct infiltration from rainfall and of actual evapotranspiration.

5.4 Infiltration from River Flow

Water level data as well as chemical data clearly show that a great part of the groundwater in the area is replenished by seepage from the major rivers.

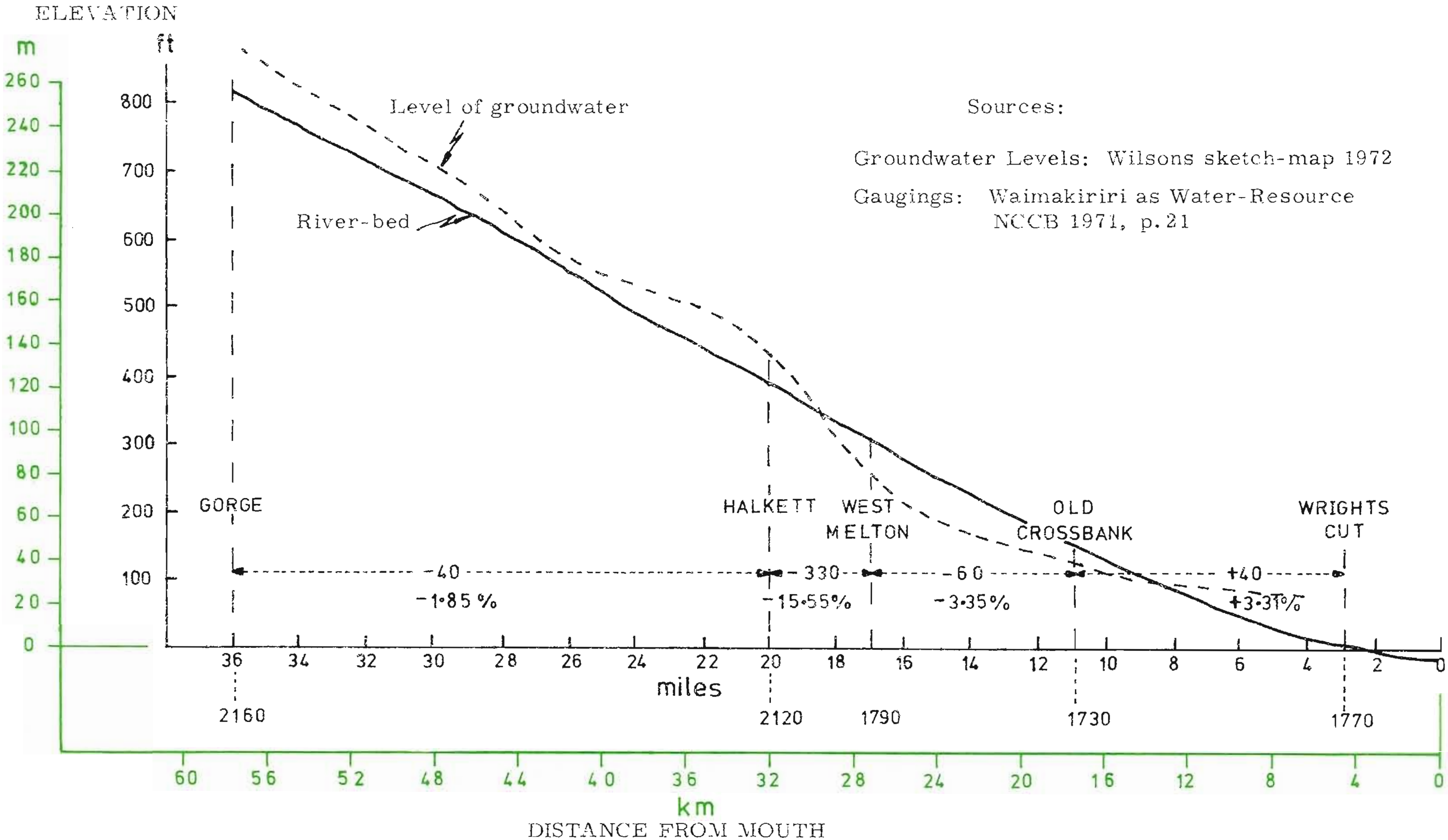


Fig. 5: The Waimakariri river. Longitudinal section

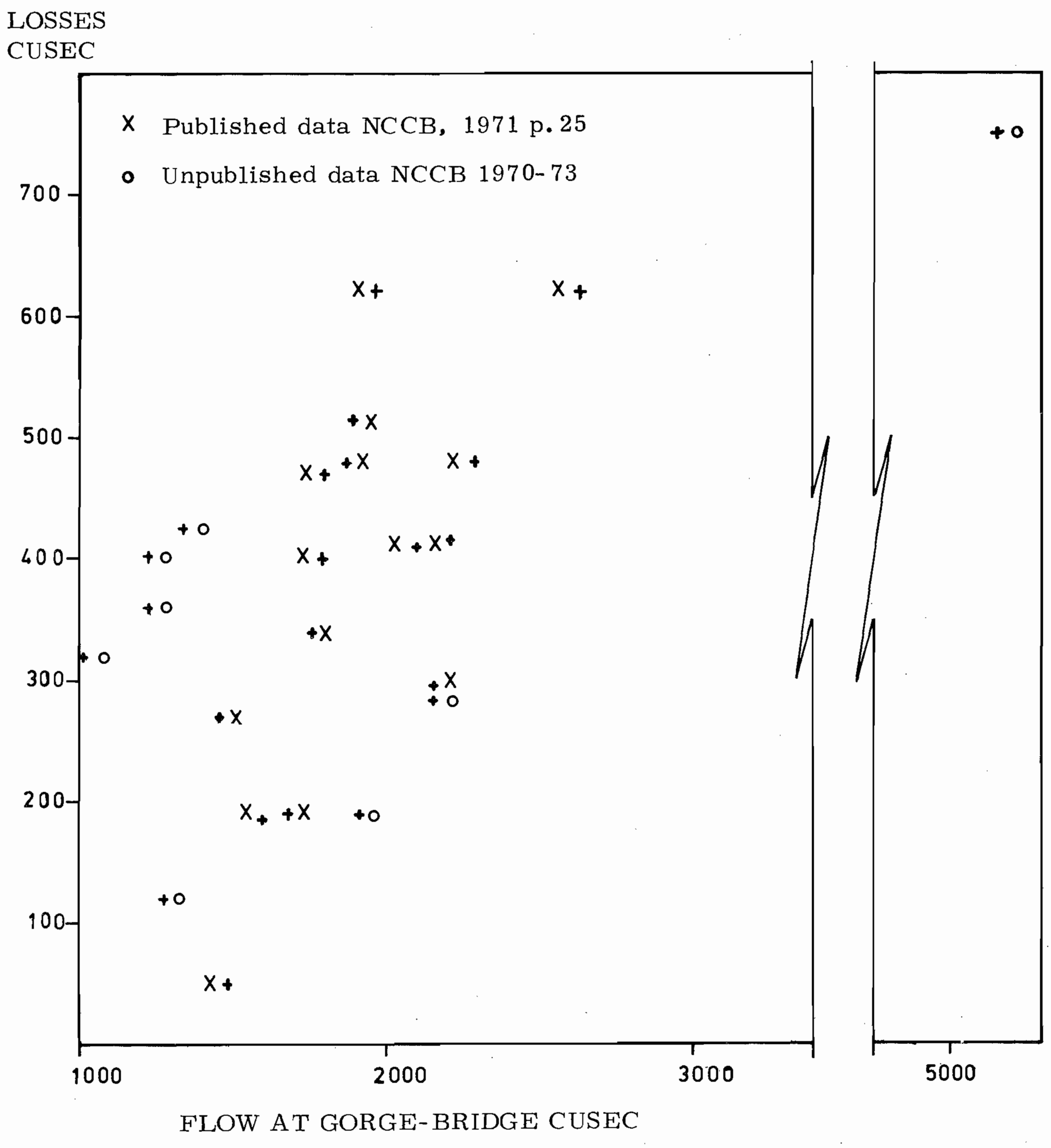


Fig. 6: The Waimakariri river. Stage losses diagram

Each of the major rivers is perched above the adjoining groundwater table over a stretch of its lower course (see fig. 5), where, one may suspect, very considerable river losses occur. The perched river-stretches begin at the apices of roughly triangular fans of younger gravels embedded in older deposits. The length of the perched structures steadily increases from the Waimakariri to the Ashburton river and decreases at the Rangitata, probably reflecting an unknown geological factor.

Quantitative information is provided by a relatively large number of simultaneous gaugings on the Waimakariri river (see figs. 5, 6). Very considerable infiltration takes place over a distance of only about 4 km below West Melton, where the water table dips steeply below the river bed (fig. 5). A comparison of river stages and river losses (fig. 6) shows that losses tend to increase with river stage, but no clear correlation is apparent. The river channels are prone to erratic changes, churning of the gravel, deposition of silt, etc. Groundwater levels may temporarily rise so high that inflow from the river is greatly reduced. Therefore the lack of a clear-cut correlation is hardly surprising. The difficulty of effecting precise gaugings in such a braided river must also be taken into account.

Average river losses were estimated by Heiler, Taylor and Johnston (1970) at 11 m^3/sec, by Huber (1973) at 20 m^3/sec. The more recent gaugings at medium stages (they were not available at the time of Huber's study) indicate about 14 m^3/sec as a rough estimate of average losses from the Waimakariri river.

5.5 Groundwater-fed River Flow

Several small streams draining the coastal belt are almost exclusively fed from groundwater. The discharge of the rivers Styx, Avon, Halswell and Heathcote around Christchurch correlates with losses from the Waimakariri river (Hamilton, pers. comm.). Groundwater "base flow" may occur in the lower reaches of the Ashley, Selwyn, Ashburton, Hinds and Orari but most of the dry-season flow is due to the resurgence of surface water that, further upstream, disappeared into the gravels.

For a detailed investigation of spring fed base-flows meticulous gaugings during the dry season and their analysis by the depletion curve method are suggested. The phenomenon is only of local importance and in the groundwater balance of the area it plays a very minor role.

Plate 2: "Outwash gravels" at the south bank of the Rakaia river. On top of the section, loess

5.6 Underflow

The wide gravelly river beds may carry relatively large groundwater flows in the form of underflow, In the large perennial rivers the quantity of underflow must be much smaller, probably by one or two orders of magnitude, than their mean discharge. In the smaller semi-perennial rivers (Ashley, Selwyn, Ashburton, Hinds) the entire flow occurs as an underflow in the central stretches of the rivers during the dry season.

Underflow constitutes the connecting link between seepage from rivers and groundwater flow proper. Techniques for the quantitative investigation of underflow are very deficient. General suggestions are given in the Appendix. It should be realised that the size of the major rivers will make field investigations very difficult.

5.7 Vein-like Groundwater Flow

Vein-like groundwater flow occurs in ancient, gravel-filled river channels that were created by sudden jumps of the river from gravel-choked beds to another course. It should not be difficult to locate the ancient streams on aerial photographs and to pin-point hidden stretches of river gravel by electrical resistivity measurements. It should also be possible to delineate pronounced directions of vein-like groundwater flow by correlating water level fluctuations in wells (see fig. 3). Many well owners relate water levels in their wells to floods in sometimes distant rivers.

Systematic mapping of vein-like groundwater flow may yield results of considerable practical impact.

5.8 The Position of the Seawater-Freshwater Interface

There are no indications of seawater intrusion into the aquifer. A structural borehole at Chertsey yielded brackish water (1650 ppm chlorine-ion, Wilson pers. comm.) from a layer of quicksand 720 m below ground. This is probably residual salinity from an ancient lagoon, buried at this depth and insulated from the rest of the aquifer by impervious-semipervious layers. The brackish waters that were encountered in the upper part of Bullivants well near Woodend beach probably originate from more recent flooding by the sea. In any case, both occurrences of brackish water are unconnected with the main aquifer.

In the coastal stretch south of Lake Ellesmere water levels are so high that the interface must be situated somewhere offshore. In the artesian zone around Christchurch water-levels are lower. The absence of seawater intrusion into deep wells shows that the interface is still situated offshore, but it may have started to move slowly landwards and upwards (see 5.2, 6.1).

5.9 Delineation of the Groundwater System

The characteristics of the Groundwater System can now be delineated, summing up the above lines of evidence.

(a) Boundaries: An impervious boundary is formed by the outcrops of bedrock greywacke, andesite, etc, to the west of our area. The sea constitutes the only major base level (infinitely pervious boundary).

(b) Aquifers: Only two aquifers can be distinguished on a regional basis: A highly permeable aquifer in unconsolidated gravels, sand and silt. The aquifers are phreatic over most of the area but confined near Christchurch. Horizontal permeability is much larger than vertical permeability. The total thickness of the aquiferous strata reaches a maximum of about 450 m.

(c) Replenishment: Natural replenishment is effected largely by infiltration of river-water and to a lesser extent by infiltration of rainfall.

(d) Drainage: Natural drainage of groundwater is effected mainly by submarine outflow of groundwater into the sea. The seawater-freshwater interface is, at present, situated offshore. Relatively minor amounts of groundwater drain through springs or small rivers.

(e) Underflow, vein-like groundwater-flow: The groundwater-regime of the area is governed to a large extent by these phenomena.

6. NATURAL REPLENISHMENT OF GROUNDWATER

6.1 Estimate of Groundwater Flow

In the Canterbury Plain the natural equilibrium between groundwater replenishment and groundwater outflow has remained almost undisturbed ("steady state of flow"). Under these conditions the flow of groundwater across a section of the geological strata parallel to a waterlevel-contour-line equals the average annual replenishment of groundwater upstream from the section. The seasonal and yearly variations of groundwater flow are very small, "ironed out" as it were by the huge amounts of groundwater in storage, so that a short record of measurements is representative of the average of many years.

The basic equation is:

$$Q = W \cdot T \cdot I$$

where

Q = discharge of groundwater (MCM/yr)

W = width of cross-section (km)

I = slope of water level at right angles to the section (measured in tenths of a percent, dimensionless)

T = transmissivity (m^2/yr)

In a complex, many-layered aquifer T is defined as

$$T = b_1 \cdot k_1 + b_2 \cdot k_2 + \ldots . b_n \cdot k_n$$

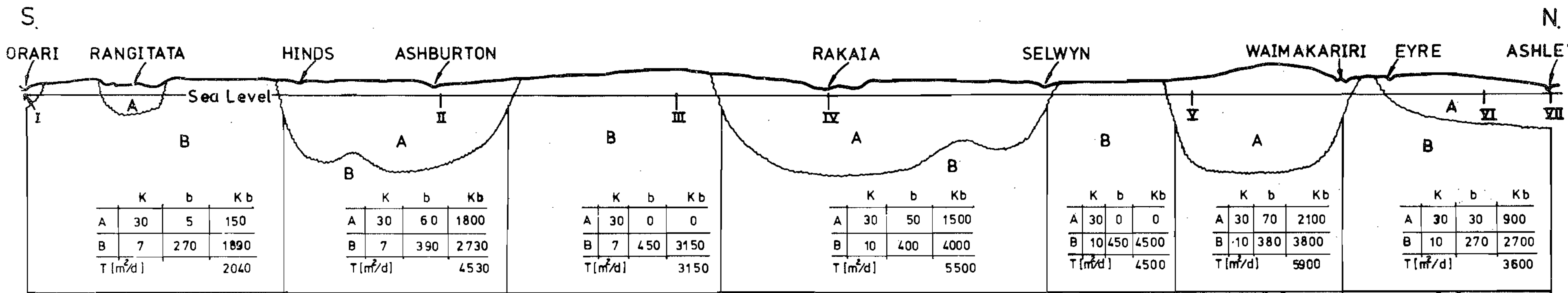
where b is the thickness (m), and k the permeabilities (m/yr) of the respective superimposed layers. (Ref: Todd 1959, De Wiest 1966).

Groundwater flow (Q) was computed across a "measuring section" (see fig. 2) situated between the water level contour lines at 100 and 200 ft. Several considerations dictated the choice of this section: (a) the section must not be too far from the shore so that the amount of groundwater flowing across it represents practically the entire replenishment of groundwater in the Canterbury Plain; (b) nearer to the shore the aquifer is subdivided into a number of vertical units with varying water levels, leading to uncertainties in the contour lines; (c) at the chosen location the contour lines are comparatively well based on actual measurements with comparatively few interpolations.

The slope (I) is read off the map at any desired location, weighted averages of the slope being easily computed for any desired part of the section. Similarly, the width of the section (W) or parts thereof can be measured on the map.

The remaining item to be evaluated is transmissivity (T). The entire thickness of the aquifer is estimated at 450 m except for the southern-most and northern-most part of the section where it is estimated at only about 300 m (see fig. 7). The permeability of aquifer A is estimated at 30 m/day on the average. The average permeability of aquifer B is estimated at 10 m/day north of the Rakaia river and at 7 m/day south of the Rakaia river where it seems to contain a larger percentage of silts and clays (see 9.1).

The hydro-geological cross-section (fig. 7) shows, in a semi-schematic way, the subsurface configuration of two aquifers A and B, based on the structural boreholes (see thickness of Quaternary strata, 4.2.3.) and the geologic map on the scale 1 : 250 000.



	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7
A: K / b / Kb	30 / 5 / 150	30 / 60 / 1800	30 / 0 / 0	30 / 50 / 1500	30 / 0 / 0	30 / 70 / 2100	30 / 30 / 900
B: K / b / Kb	7 / 270 / 1890	7 / 390 / 2730	7 / 450 / 3150	10 / 400 / 4000	10 / 450 / 4500	10 / 380 / 3800	10 / 270 / 2700
T [m²/d]	2040	4530	3150	5500	4500	5900	3600
T	745×10³ m²/yr	165×10³ m²/yr	115×10³ m²/yr	200×10³ m²/yr	164×10³ m²/yr	216×10³ m²/yr	131×10³ m²/yr
I	0·61%	0·49 %	0·45%	0·41%	0·32%	0·32%	0·61%
W	25·0 Km	21·8 Km	21·0 Km	32·0 Km	12·5 km	16·2 Km	20·5 Km
Q	113 MCM/yr	176 MCM/yr	109 MCM/yr	270 MCM/yr	66 MCM/yr	112 MCM/yr	164 MCM/yr

Total Flow of Groundwater ≈ 1000 MCM/yr

LEGEND [See also text]

A B	Aquifers [see text]	T	Transmissivity [m²/d or m²/yr]
b	Thickness [m]	I	Slope of water-level measured on map
K	Permeability [m/d]	W	Width
I II...VII	Match points, see map	Q	G'water-flow

Total thickness of Aquifer: In South and North 300m; In Centre 450m

Fig. 7: Flow of groundwater across a measuring section (for Location of section of map see fig. 2)

Details of the computation are presented in fig. 7. The total flow of groundwater across the measuring section (equalling the total groundwater replenishment in the area) is estimated at 1000 MCM/yr.

It may be objected that only the slopes (I) and the widths (W) were actually measured, the rest of the input data being no more than inferences from slender factual evidence. In particular, it may be doubted whatever permeabilities can be estimated on the basis of experience. However, one should remember that in many fields of applied science and technology average values of 'bulk parameters' derived from literature and personal experience are widely used.

Better information on the sub-surface configuration of the aquifer as well as pumping tests for the determination of permeabilities will make it possible to derive a much more accurate groundwater balance (see 9.2). Methods of theoretical flow-net analysis may also help in refining the groundwater balance, but, in the author's opinion, these methods easily err by substituting highly simplified concepts for the complex natural picture.

6.2 Groundwater Flow Towards Christchurch

Data from the greater Christchurch area seem to indicate an alternative way of calibrating the aquifer without relying on estimated values of permeability and thickness. The argument is as follows:

(a) groundwater exploitation in the greater Christchurch area constitutes a "sink" of known magnitude.

(b) a cursory inspection of more than 30 years of water level records reveals seasonal and yearly fluctuations but no systematic lowering of water levels, in spite of the great volume of exploitation. Therefore steady-state flow prevails in the area.

(c) it is assumed that all the groundwater in the area comes from inland, west of Christchurch.

(d) this amount of groundwater has to flow across part of the measuring section defined by the appropriate flow lines (arrows in fig. 2).

Groundwater exploitation in the greater Christchurch area is estimated at about 100 MCM/yr (Heiler, Taylor and Johnston 1970). The appropriate part of the measuring section is 16.25 km wide and across it there flow 112 MCM/yr (see figs. 2 and 7).

Unfortunately the excellent agreement between the two figures cannot be accepted as "proof" of the groundwater balance. Groundwater also drains through several rivers (Styx, Avon, Heathcote and Halswell). In addition, a groundwater flow several times in excess of actual exploitation must be assumed in order to account for the postulated steady-state condition. When these factors are taken into consideration groundwater flow should be at least five times as much as actual groundwater abstraction at Christchurch i.e. about 500 MCM/yr. It is obvious that this cannot be reconciled with the hydro-geological picture.

The apparent steady-state conditions of flow that lie at the root of the puzzling discrepancy are probably spurious. Perhaps part of the groundwater exploited at Christchurch derives from huge freshwater lenses floating on seawater. If this were the case, the freshwater-seawater interface should move slowly inland and upwards pushing freshwater before it into the pumping wells. Consequently, the lowering of water-levels may remain so small as to be undetectable.

At present there is no evidence of seawater intrusion but this is hardly surprising since the hypothetical freshwater-lenses should be situated somewhere offshore, below the confining layers that jut out into the sea. The actual offshore configuration of the aquifers-aquicludes and the present position of the interface are unknown. The drilling of deep hydrological test holes offshore is so costly that it cannot be recommended at this stage.

The simplest method of finding additional evidence for or against the above hypothesis is sampling for carbon-14. If the hypothesis is true, the deep and the seaward parts of the freshwater lens should be very old, probably of the order of 5000 - 10 000 years. Therefore water samples from deep, seaward wells should be much older than samples from shallow inland wells.

It is suggested that water samples are taken for carbon-14 analysis from several pumping wells representing cross sections from the sea coast inland to the Waimakariri river. If a significant age-gradient is indicated by the carbon-14 method there exists prima facie evidence for the inland movement of seawater and the problem should receive serious attention.

6.3 Estimate by the Water-Balance Method

Input data are daily rainfall and daily potential evaporation as well as field capacity of the soil. A functional relationship between potential evaporation, actual soil moisture and actual evapotranspiration must be found or assumed. The resultant "water crop" must be divided into surface runoff and groundwater respectively. In a heterogeneous area like the Canterbury Plain the computations have to be carried out separately for several small, more or less homogeneous, sub-areas.

Various book-keeping methods are in use for the computation of accurate water-balances. A computer is necessary to handle the large volume of data and the repeated calibration runs they require.

In the present context no good purpose would be served by protracted detailed computations since probably the major part of groundwater replenishment stems from "estimated" river losses. A very simplified estimate of groundwater replenishment from rainfall will, therefore, suffice.

We divide the year into two equal periods: A winter period including the months April - September and a summer period including the months October - March. For each period we compute the difference, rainfall minus potential evaporation, and assume that this represents groundwater replenishment. The area of confined groundwater around Christchurch, areas with a very high water table, and areas on the western margin of the plain where groundwater drains into rivers are excluded from the computations. In the remaining area, three stations record rainfall as well as pan evaporation. The simple computation is shown in the following table:

Table 4: RAINFALL-POTENTIAL EVAPORATION, (AROUND 1970)

Station	Rainfall (mm)		Pot. Evap. (mm)		Rainfall-Pot. Evap. (mm)	
	Winter	Summer	Winter	Summer	Winter	Summer
Highbank[1]	383	449	288	700	95	-251
Winchmore[2]	368	413	176	530	192	-117
Darfield[1]	388	400	200	428	188	-28

Remarks:

1 Measurements in raised pan, multiplied by 0.7

2 Measurements in sunken pan, multiplied by 0.8, several missing months interpolated.

Source: N.Z. Met. Service, Misc. Publ. 110.

During the summer months, October - March, there occurs no groundwater replenishment. Average groundwater replenishment during the winter months, April - September, is about 158 mm. The area over which groundwater replenishment may occur is about 3800 km^2. Total groundwater replenishment from rainfall is, therefore, about 600 MCM/yr.

River losses to groundwater were estimated by Huber (1973) at about 57 m^3/sec (1800 MCM/yr).

In view of the previous findings on the Waimakariri river (see 5.4) this estimate should be reduced by about one half, i.e. to about 900 MCM/yr.

The simplified water balance method yields the following result.

Groundwater replenishment from rainfall	600	MCM/yr
Groundwater replenishment from rivers	900	"
Total groundwater replenishment	1500	MCM/yr

6.4 Discussion of the Groundwater Balance

The two estimates differ by 50%. It would be easy to whittle down these differences by appropriate changes in the assumptions. The result would then be more aesthetically pleasing but not necessarily more correct.

Since it has been proven that there exists a very large, untapped groundwater resource, the exact determination of its size is not of immediate practical importance. Economics will always keep actual groundwater exploitation far below the level of natural groundwater replenishment (see 7.2, 7.3). Patient data collection and interpretation will eventually lead to a much more detailed, accurate picture.

It should be noted that the hydro-geological method relied on less guess work than the water-balance method. In the hydro-geological computations distances and water levels were measured, aquifer configuration and permeabilities were estimated. In the water-balance method rainfall was measured, potential evaporation was based on measured data but included an empirical multiplication factor, soil storage as well as actual evapotranspiration were neglected, the area was estimated, infiltration from rivers was merely guessed. Therefore the result of the hydro-geological balance appears to be more reliable.

Future work should concentrate on more accurate determinations of groundwater flow in well-defined partial areas. An effort must be made to collect reliable geological information from new wells and to correlate the logs of existing wells. Geo-electrical resistivity measurements should be used for the interpolation between boreholes, hydrological pumping tests should be carried out (see 9.2). Water levels should be measured regularly, once monthly, in precisely levelled wells. Chemical analyses may be of great help in elucidating the flow pattern (see 5.3).

River losses must be measured by careful simultaneous gaugings at various river-stages, and the connection between river losses and groundwater must be studied (see 5.4, 5.5). For these difficult gaugings a dye dilution method (see 9.4) may prove to be easier than the presently employed velocity measurements.

Climatic data and hydro-meteorological methods are of limited value for groundwater investigations in this area.

7. THE LIMITS OF GROUNDWATER EXPLOITATION

7.1 General Observations

The uppermost limit of permanently continued groundwater exploitation is at, or somewhere below, average annual replenishment. Apart from that, nature does not offer a criterion for this so called "safe yield", the concepts of "safeness" or "safety" being a human invention. A useful aquifer must hold sufficient water in storage so as to allow seasonal overdrafts, i.e. exploitation of considerable volumes of water during a short period. Reasonably large aquifers can be exploited at rates over and above the rate of average natural replenishment during many years (Mandel, 1967, 1972).

In the Canterbury Plains groundwater will have to compete with abundant surface water supplies. The actual limits of groundwater exploitation will be determined by a combination of hydrological, economic and environmental considerations.

The following discussion attempts to evaluate the impact of the most important limiting factors and to rank them in order of severity.

7.2 Seawater Intrusion

It is necessary to distinguish between seawater intrusion into the aquifer and seawater intrusion into wells. When an aquifer is exploited at a rate commensurate with its average annual replenishment, it is unavoidable that water levels are permanently lowered. If the aquifer is in contact with seawater the freshwater-seawater interface (ref: Tod 1959, De Wiest 1966) will slowly intrude inland and upwards, slowly restricting the outflow of freshwater into the sea. It will assume a stationary equilibrium position when groundwater exploitation plus residual outflow of groundwater into the sea are equal to average annual replenishment of groundwater.

Seawater intrusion into wells must be avoided since even if 3% of seawater is mixed with 97% freshwater the mixture becomes unfit for many uses.

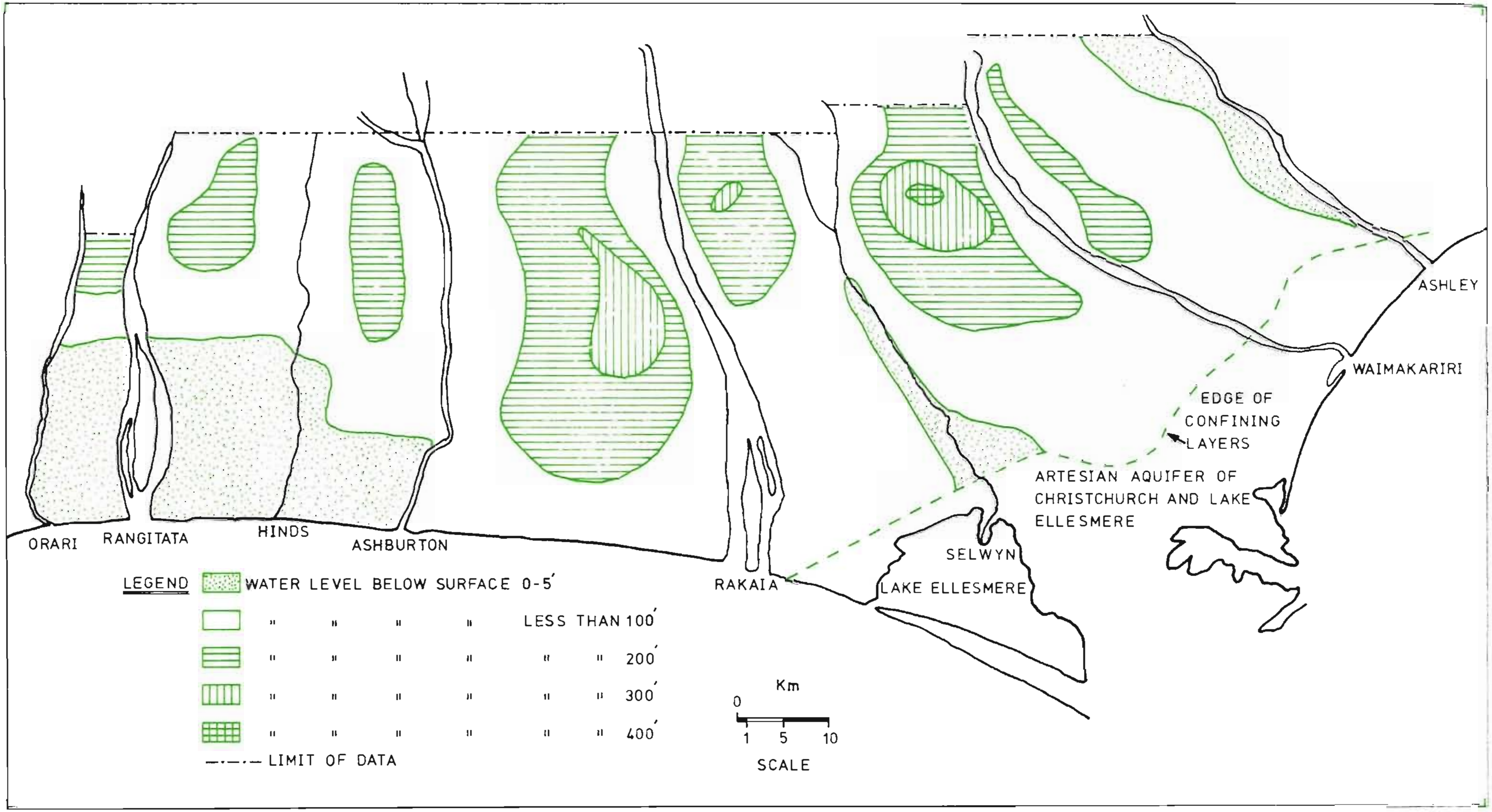


Fig. 8: Depth of water level below the surface

At present the interface is everywhere offshore. In the coastal area south of Lake Ellesmere water levels are about 8.5 m or more above sea level at distances of 2.3 km from the shore. If it is assumed that eventually, after many years of large-scale exploitation, water levels are lowered to, say, 4 m above sea level, the theoretical equilibrium position of the interface will be about 160 m below sea level inside the semipervious lower part of the aquifer. It is to be expected that comparatively shallow wells (say not in excess of 80 m depth) will then still draw freshwater, but, of course, very intensive groundwater exploitation in this coastal strip should be avoided. It is extremely unlikely that further inland seawater intrusion into wells will ever occur. (For the Christchurch area see 6.2).

The chlorine-ion content of water from wells near the seashore should be regularly checked. The drilling of special boreholes for the observation of the interface can be postponed for a long time, perhaps forever. With reasonable precautions, seawater intrusion will not constitute a severe limiting factor of groundwater exploitation, except perhaps in the Christchurch area.

7.3 Energy Requirements for Lifting Water

Energy requirements depend on three parameters:

(a) Distance from water level in the well to surface plus frictional losses in the casing and pump column

(b) Discharge of the well

(c) Efficiency of the pumping system

Additional energy may be required for operating sprinklers etc.

At present, water levels are less than 30 m below ground over most of the area and less than 5 m in a large part of the most productive coastal belt (see fig. 8). If groundwater exploitation is stepped-up, pumping lifts will be greater than the present depths of water levels, depending on the dynamic draw-down in wells during operation, and on the unavoidable general lowering of water levels.

At the present state of our knowledge water level forecasts cannot be made, but it is a reasonable guess that even after many years of intensive groundwater exploitation pumping lifts will be less than 50 m in most of the area and less than 15 m in a large part of the coastal belt.

Only a detailed economic analysis can show whether these pumping lifts are feasible, or where the limits of economic feasibility lie.

Much energy can be saved by the proper construction of boreholes and by the proper selection of pumping systems. For minimum dynamic draw-downs boreholes should be drilled deep into the aquifer and screens should be of at least 8 in. diameter. Screens must have sufficient openings, and the formation around the well should be developed (see 8. 1).

The pumping system must be selected so that it operates at near to maximum efficiency over the entire range of water levels that will be encountered during the seasons and years.

There is reason to believe that the present state of affairs leaves much to be improved. It seems that farmers do not pay attention to these points. Frequently, the performance of the system under actual working conditions, or a suspected deterioration of the pump, cannot even be checked because there is no opening for water level measurements. For the same reason "well losses" due to clogging or to incorrect well construction remain undetected. Large organisations such as municipalities hire expert advice and fare a little better in this respect. Expert advice by qualified engineers and geologists is essential for the economic exploitation of groundwater resources.

7.4 Depletion of Shallow Aquifers

A phreatic (water table) aquifer is termed shallow or "thin" if seasonal water level fluctuations and dynamic draw-downs are of a size comparable to the entire saturated thickness of the aquifer (ref: Todd 1959). To illustrate this definition: a phreatic aquifer of 20 m saturated thickness becomes "thin" as soon as the water table is drawn down by, say, more than 5 m. If the saturated thickness of the aquifer is 100 m it will become "thin" only when draw-downs exceed, say 25 m.

In a thin aquifer, dynamic draw-downs increase very rapidly when the water table is lowered. Eventually, pumps that were thought to be sufficiently submerged start to suck air and their dischrage must be reduced or they have to be operated only intermittently. Although much water remains in the aquifer it can no longer be exploited efficiently. (A theoretical formulation of the problem by a rather intractable, non-linear differential equation, as given in textbooks, is of little practical applicability).

Since in the Canterbury Plain the upper part of the aquifer is, generally, much more pervious than the lower one, this factor may severely limit groundwater exploitation in areas where the upper aquifer is "thin". There are many verbal reports on wells running dry and very great changes of well discharge, but it is difficult to find out whether "thin aquifer" characteristics, poor well construction, or faulty pumping equipment lie at the root of the trouble.

For an evaluation of the problem subsurface mapping of the aquifers and water level measurements in exploited wells are essential.

Remedial measures are: deep drilling wherever possible so as to tap the lower part of the aquifer and artificial replenishment where only a thin aquifer exists (see 9.3).

7.5 The Cost of Well Drilling and of Pumping Equipment

For a rational evaluation of this economic limitation the real social cost of developing groundwater supplies must be compared with the real social cost of bringing comparable surface water supplies to a given location. Because of the many ramifications involved a rational choice cannot be made at the farm level. Economic feasibility studies must be concerned with larger areas or with the whole plain (see 8.2).

Drilling for groundwater always contains an element of calculated risk. Nobody keeps tabs on the percentage of failures in the area but it is hard to avoid the impression that farmers look at well drilling as a kind of "gamble" not subject to cool economic analysis. In view of the deficient geological subsurface information their attitude has a certain justification. Although the aquifer is very complex, patient geological spade-work and scientific procedures of well siting will make it possible to take much of the "gamble" out of water well drilling so that wasted investments are kept to an insignificant minimum (see 8.1).

7.6 Soil Subsidence

Soil subsidence may be caused by compaction of the strata, especially of clay layers, due to dewatering and, to a lesser extent, by the continuous abstraction of fine particles through pumped wells. Only very great differential soil subsidence causes trouble on agricultural areas devoid of high, big buildings. In the Canterbury Plain this factor will probably not play an important role.

7.7 Groundwater Pollution

Groundwater pollution may occur whether the aquifer is exploited or not. It differs from river pollution in two important aspects. (a) Groundwater pollution does not create immediate objection for aesthetic reasons. Therefore it can build-up to dangerous levels before it is detected. (b) It is very difficult to clean-up a polluted aquifer. Many years are required to flush out the polluted volume of groundwater even after pollutants are removed from the surface.

7.7.1. Nitrogen Pollution

In an agricultural area nitrogen pollution from fertilisers and livestock constitutes the biggest problem. Neither the leaching of excess nitrogen from the soil nor the accumulation of nitrates in groundwater can entirely be prevented. The behaviour of nitrogen compounds below ground is imperfectly understood.

Investigations show that nitrates in groundwater tend to play "hide and seek". They are not always found where they should be but sometimes appear where they are not expected (ref: Ronen and Mandel 1973). Nitrates constitute a serious health hazard for infants (methaemoglobinaemia) "blue baby" sickness) but the accepted limit of tolerance, 40 ppm of NO_3, is supported only by very slender evidence. In irrigation, nitrogen compounds create no problem.

As far as the available information goes (Drummond and Hogan 1965, 1967) nitrate concentrations are very low in the groundwater of the Canterbury Plain. There is no reason to believe that they will build up to dangerous levels within the foreseeable future. Nevertheless, the expected build-up of nitrates should be watched by repeated analyses. Drinking water supplies should be drawn from the deeper parts of the aquifer that are less prone to all forms of pollution.

7.7.2 Preventable Forms of Pollution

Even very minute amounts of hydro-carbons give an intolerable taste to drinking water and to irrigated crops. Proper precautions must be taken in the installation of fuel tanks and in fuel transportation.

Small-scale bacterial pollution tends to disappear when the water stays below ground under anaerobic conditions during several months. Boreholes used for drinking water supplies should be cemented or at least back-filled with clay around the casing so that polluted water cannot penetrate through the weakened annular space around the well.

Accidental spillage of chemical material in factories has, reportedly, caused serious groundwater pollution in the Canterbury Plain. Since the sufferers were the factories themselves reliable information is difficult to obtain.

It is hardly necessary to emphasise that groundwater pollution must be prevented as much as possible. However, if reasonable precautions are taken, serious damage to this important resource of clean water can be prevented.

7.8 Ranking of Limiting Factors

It is practically certain that energy requirements, the depletion of shallow aquifers and the capital cost of groundwater development (as compared to surface water supplies) will most severely limit groundwater exploitation in the Canterbury Plain. Seawater intrusion will hardly become operative as a limiting factor with the exception, perhaps, of a very narrow coastal strip and the Christchurch area. Soil subsidence and groundwater pollution may perhaps cause problems of a very local nature.

8. ENGINEERING AND ECONOMIC CONSIDERATIONS IN GROUNDWATER DEVELOPMENT

8.1 Wells for Irrigation

8.1.1. Required Discharges

Irrigation requirements at the peak season (November - February), assuming an irrigation efficiency of 70%, are estimated at 0.33 litres/sec/ha which equals 2.85 m^3/day/ha (van't Woudt 1973). It is assumed that at the peak season wells will operate 16 hours per day. The actual requirement at the well-head will, therefore, amount to about 0.5 litres/sec/ha or 1.8 m^3/hr for the irrigation of 1 ha.

Most new wells will probably have discharges in the range of 30 m^3/hr - 100 m^3/hr, sufficing for the irrigation of 17 ha - 50 ha, provided that drilling techniques and methods of site selection are slightly improved.

Wells with a much smaller discharge than 30 m^3/hr or wells that can be operated for only a few hours at a time ("thin" aquifers) may be useful to individual farmers, but in the development of the area as a whole, they can only play a marginal role.

8.1.2. Well Siting

At present two highly qualified geologists give advice on the location of new wells in the Canterbury area, they are also expected to do all the necessary spade-work and to advise on other economic projects. It is suggested that several junior geologists be engaged (perhaps on a temporary basis) in order to collect data in the field and to keep files and maps up to date. The senior geologists should be able to fully concentrate on scientific data correlation and on advice on well drilling.

Geo-electrical resistivity measurements are at present regarded with a great deal of scepticism although experience is very limited. A change of attitude is suggested. Negative geophysical indications insure against almost certain failure. Positive geophysical indications do not necessarily ensure a successful well. Viewed in this light, the small outlay for a few geophysical measurements in addition to geological advice is amply justified.

8.1.3. Drilling and Development of Wells

In many cases small well-discharges are attributable to the poor construction and development of the boreholes.

As regards well construction the following specifications are suggested:

Drilling technique	-	percussion
Depths	-	all potential aquifers down to a depth of, at least, 100 m should be penetrated
Diameter of casing	-	12 in. - 14 in. down to at least 20 m below present water levels
Diameter of screens	-	8 in. - 12 in. (minimum)
Specification for screens	-	slotted pipes or wound wire
Hole for water level measurements	-	all boreholes must provide access for water level measurements. Otherwise, pump efficiency, deterioration of the screen, etc, cannot be checked.

Several techniques are used for the development of boreholes in non-consolidated strata - backwashing, swabbing, air lifting, etc. All techniques aim at removing the fine sand particles from the portion of the aquifer adjoining the well-screen so that eventually a natural "gravel pack" forms around the well. Discharges from a fully developed well are frequently twice to four times larger than those before development. Working procedures have to be empirically adapted to local conditions, but two general pointers can be given:

(a) well casings and screens must be sturdy enough to withstand rough treatment during well development;

(b) development of the well should be specified as a separate item in the drillers contract and the driller should be given an incentive to spend sufficient time and work on these, rather tedious, procedures.

Before being put into operation the well should be test pumped by a temporary installation for at least 24 hours so that the most suitable pumping system can be specified. This is also the time to carry out a step draw-down and a recovery test (see 9.2).

8.2 The Conjunctive use of Surface and Groundwater Resources

River water is the obvious first choice for irrigation supplies. Groundwater should be used for irrigation only if and where it is cheaper than a comparable quantity of river water, or where it helps to maintain minimum flows in rivers (environmental constraints).

In particular, groundwater can be used to supply part of the peak requirements so that significant savings are effected in the cost of storing and conveying river water. For urban water supplies groundwater has, of course, hygienic advantages. Large-scale groundwater exploitation will have to be confined to the seaward part of the plain, comprising about 30% of the irrigable area. In the rest of the area the aquifer is so poor that only marginal exploitation can be envisaged.

At present it is not possible to estimate the optimal extent of groundwater use even to a valid "first approximation". For meaningful quantitative analysis of the problem the following considerations will have to be pursued:

(a) Determination of the required storage.
The peak of the irrigation season occurs during November to February. Previous studies (Huber 1973, van't Woudt 1973) attempted to show that little or no storage will be required, the "run of the river" being sufficient to satisfy irrigation needs as well as meeting environmental constraints at all times. This conclusion is based on average river flows and average irrigation requirements during the peak season, both expressed in m^3/sec. However "average river discharges" may still incorporate a few days or weeks during which requirements cannot be covered. It is highly probable that seasonal storage will be called for, at least during the not infrequent dry years. Similarly, farmers cannot be content with "average" supplies during the peak season. Efficient irrigation will demand comparatively large water supplies during certain days or hours, depending mainly on weather conditions, interspersed with comparatively slack periods. The additional short time peaks, thus created, may call for operational water-storage. A realistic appraisal of storage requirements should be based on short time-units, days, or, for irrigation schedules, even shorter periods of time.

(b) Environmental constraints.
The above analysis, based on short time-units, will also show whether minimum river flows can be maintained without additional storage for this purpose. Boating facilities can, perhaps, be restricted but aquatic life will seriously suffer if it has to contend with regularly recurring periods of dryness even if they are short.

In an intensively cultivated, more densely populated area, the quality of river water must be expected to deteriorate. An evaluation of this factor, including the smaller rivers, is called for.
In short: at present it is not really known how much river water should be allocated in order to maintain an acceptable "quality of life", or how much groundwater must be used to satisfy the consequent environmental constraints.

(c) Conveyance and distribution of river water. Comparatively large installations will be required if all peak demands have to be covered from diversions near the river gorges. Perhaps small operational storage facilities can be incorporated, further downstream in the distribution system in order to smooth out daily peaks, but this course of action throws the argument back to point (a) discussed above. Groundwater, exploited and used in loco may help in reducing the installations to a more economic size.

(d) Cost of drilling and pumping equipment. An economic evaluation of this factor, per m^3 of water produced, is still outstanding. Considerable savings can probably be effected by improved methods of locating, drilling and developing boreholes as well as by making opportunities for the drillers to organise for work on a larger scale.

(e) Energy expenditure.
The cost of pumping will vary from place to place according to the depths of dynamic water levels. The map, fig. 8, may serve as a general basis. A regional lowering of the water level in heavily exploited locations as well as dynamic draw-downs have to be allowed for. On the other hand it is reasonable to assume that boreholes will be more productive and pumping systems more efficient than they are, on the average, at present. Energy requirements

for pumping may necessitate alterations in the electricity mains, and may even have a significant impact on the national energy situation, if a certain threshold is exceeded. A careful evaluation of these economic factors is needed.
Studies of economic feasibility and of the optimal conjunctive use of surface and groundwater should be carried out as a matter of urgency before there has been too much development.

9. APPENDICES

9.1 Estimates of Permeability

Values of permeabilities for various materials are cited in textbooks, monographs, etc. Engineering materials such as clean sand, clean gravel, etc, are usually tested in permeameters with selected uniform samples being arranged by hand. These values of permeability thus obtained are higher for gravel and sand, and lower for clay when compared with the permeabilities of natural materials tested "in situ" by pumping tests.

A difficulty arises from the use of widely differing units of measurement, and for groundwater investigations the author found it most convenient to use m/day as the unit of permeability (K) since it yields results expressed in m^3/day or MCM/yr when inserted into formulae. Small adjustments for changes of viscosity with temperature or according to the chemical composition of the water can usually be neglected in groundwater work.

On the basis of literature, pumping-tests, and calibration runs by digital models, the following range of values is cited for naturally occurring materials (table 5). The values refer to horizontal permeability. In most sedimentary materials vertical permeability is smaller by about one order of magnitude due to stratified deposition.

Table 5: VALUES OF PERMEABILITIES

Material	Permeability m/day	Remarks
Coarse gravel, Karstic limestone	more than 100	Very high values are suspect as representing flow in well defined channels rather than a porous medium
Gravel, medium-coarse	50 - 100	Range of most useful aquifers
Gravel and sand	20 - 50	
Sand, medium-coarse	10 - 20	
Gravel, sand and silt	about 10	
Gravel, sand, silt and a little clay	about 7	Semipervious "aquitards", marginal wells
Gravel, silt and clay	less than 1	Semipervious confining layers, "leaky" aquifers
Sandy clay	about 0.01 and less	Aquicludes

Ref: Todd, 1959. De Wiest, 1966. Johnson Inc, 1972.
Monographs of the U.S. Geological Survey.
Monographs of "Tahal" Eng. Consultants (Tel-Aviv).

Natural strata frequently occur in the form of thin intercalated often cross-bedded layers such as sandy gravel, sand, silt, lenses of clay, etc. The average regional permeability of such layers is obviously much smaller than the permeability of its coarse constituents. The average regional permeability of aquifer A is probably around 30 m/day judging by the results of well drilling. For the same reason, the regional permeability of aquifer B is probably in the range of 7 - 10 m/day.

9.2 A Note on Pumping Tests

Techniques of pumping tests are treated in textbooks (e.g. Todd 1959), monographs (e.g. Kruseman and De Ridder 1970) and in the voluminous theoretical literature on the subject. Here, only some practical conclusions derived from the author's experience, will be discussed.

9.2.1. Mapping of Transmissivity

Pumping wells that fully penetrate only one of two well-defined aquifer strata should be used to carry out interference tests. At least one observation well at a suitable distance is needed. It is rarely possible to keep the area free from disturbances, changing weather, pumping of neighbouring wells, power failures etc, during more than 48 hours. The distance of observation wells must be determined with this restriction in mind. If observation boreholes do not exist or cannot be drilled a recovery test in the pumping well is the second best choice, but its accuracy is far inferior to an interference test.

From the transmissivities thus measured the values of permeability (K) should be calculated for each of the aquifer strata. With the aid of geological sections values of transmissivity can then be synthesized for other locations from the known thicknesses and the known permeabilities of the constituent strata. In a reasonably well defined rock type the permeability does not vary too much and the extrapolation can be confidently carried out.

9.2.2. Determination of Storativity

It is very difficult to correctly measure the true phreatic storativity of an area (specific yield of a water table aquifer) by pumping tests. Very long interference tests are necessary and even they may give spurious results.

Confined storativities are smaller by at least two orders of magnitude than phreatic storativities. This great contrast makes it possible to map the extent and continuity of confining layers by pumping tests when geological information is deficient. In the Canterbury Plain with its small impervious lenses and unclear subsurface geology this method may prove to be useful.

9.2.3. Step Draw-down Tests

A rough separation of "aquifer losses" and "well losses" is all that can be expected from this type of test. Nevertheless, the method is very useful because it enables actual draw-downs at various discharges (important for the specification of pumps) to be predicted, and shows up faults in well construction (sometimes to the driller's dismay). If trouble arises at a later date a repeated step draw-down test easily shows whether the fault is in the pump, the well, or the aquifer.

After completion and development of a new well a step draw-down test should be made. At the end of the test, recovery of the water level should be observed on the off-chance that the data can be interpreted as recovery tests.

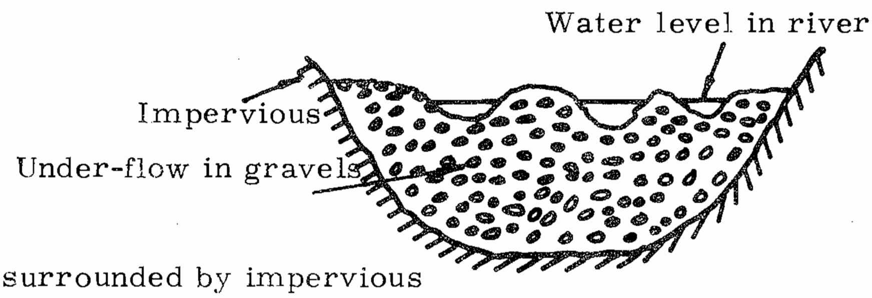
9.3 Artificial Replenishment of Groundwater

Infiltration through spreading grounds is the most commonly used method. Infiltration rates should be of the order of 1 m to 0.3 m per day under a low head, say 10 cm to 50 cm. It is not advisable to speed-up infiltration by higher heads because this may entrain fine particles deep below the surface and irreparable damage may result. The water should have a low turbidity, not in excess of 300 ppm solids in suspension. More turbid water may require treatment prior to infiltration. Infiltration rates normally decline very sharply after several months of uninterrupted operation but they are restored when the ground is left to dry completely. Clogging of the surface can be minimised by allowing deep rooted grasses to grow.

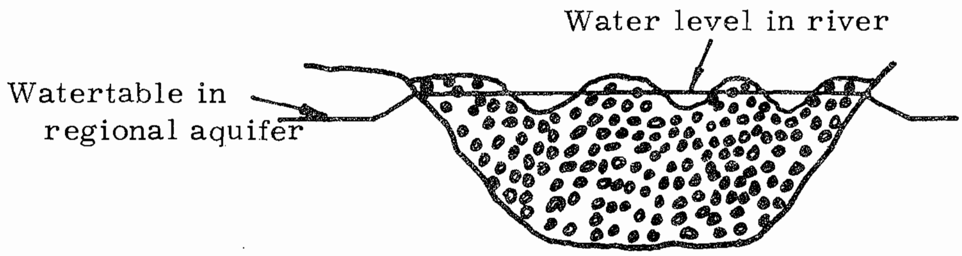
Under suitable conditions the naturally occurring infiltration from river channels may be enhanced by a re-arrangement of the braided channels so as to spread the water over a wider surface. In small rivers it may be possible to construct "underground dams" i.e. a clay filled trench in the gravels so as to retain the underflow and to spread it over a wider area. However it is very difficult to assess the success of such methods except by trial and error.

A quantity of water injected in point A need not necessarily be available for exploitation at point B. A good understanding of the natural groundwater system should precede all attempts to improve it by artificial replenishment.

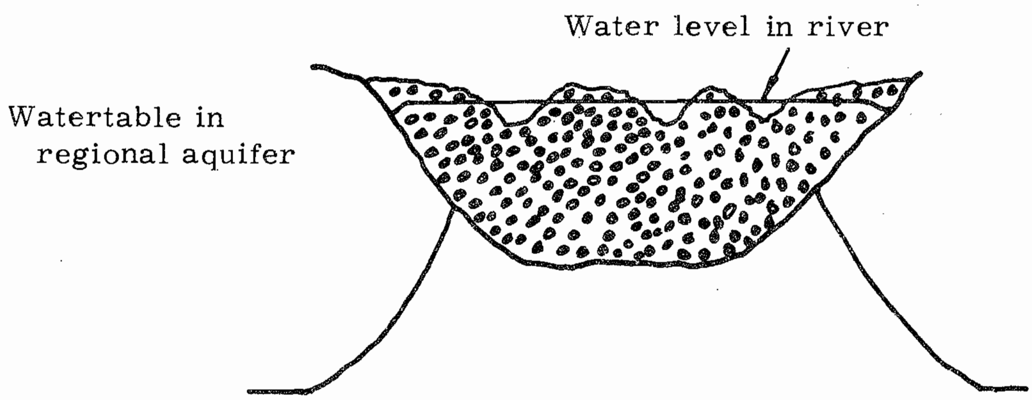
Reference: IASH and UNESCO, Haifa Symposium on artificial replenishment 1967.



(a) River surrounded by impervious rocks. Underflow in gravels



(b) River surrounded by less permeable aquifer. Underflow feeds regional aquifer, or at low stages, regional aquifer may feed underflow.



(c) River surrounded by aquifer with much lower regional watertable. Flow through gravels essentially vertical. No underflow.

Fig. 9: Definition of underflow in river gravels

9.4 Investigations of Underflow

9.4.1. The Definition and Engineering Importance of Underflow

Underflow is defined as the more or less horizontal flow of groundwater in river gravels below and adjacent to a riverbed (see fig. 1). It can be distinguished from regional groundwater occurrence if the river gravels are surrounded by impervious rocks,or, if at least, there exists a strong contrast between the permeability of the river gravels and the surrounding regional aquifer (say by a factor of 5) and if the water table in the regional aquifer intersects the river gravels (see fig. 9).

Underflow is of engineering importance since, in some situations, it can be used as a water resource, especially during periods of drought, or it can be modified so as to increase the replenishment of adjacent aquifers. All engineering uses of underflow depend, of course, on prior quantitative information. The next sections will be devoted to the methodological aspects of this problem.

9.4.2. General Methodological Aspects of Underflow Investigations

The first task is to delineate areas where considerable underflow may occur. This can be done by the interpretation of existing information, e.g. correlation of known water levels in the regional aquifer with the more or less known topography of the riverbeds, correlation of geological data in the vicinity of the river, etc. Where the existence of underflow is proven one may wish to determine: (a) the strength of the underflow (m^3/sec or m^3/day) at any particular time; (b) the place where the underflow is replenished from the river and the quantitative dependence of the replenishment on varying river stages; (c) the location and quantitative characteristics of any connection between underflow and regional aquifers or regional water-veins.

The problems (b) and (c) have to be investigated by standard methods such as river gaugings, water level observation in wells, pumping tests, etc. The central problem (a) measuring the strength of the underflow, can in principle, be investigated by classical hydrological methods: It is "only" necessary to drill a number of boreholes (say, at least six, arranged in three rows of two boreholes each across the river bed), carry out pumping-tests for the determination of transmissivity, determine the gradient of the water-level from measurements in precisely levelled boreholes, determine the width and depth of the river gravels at

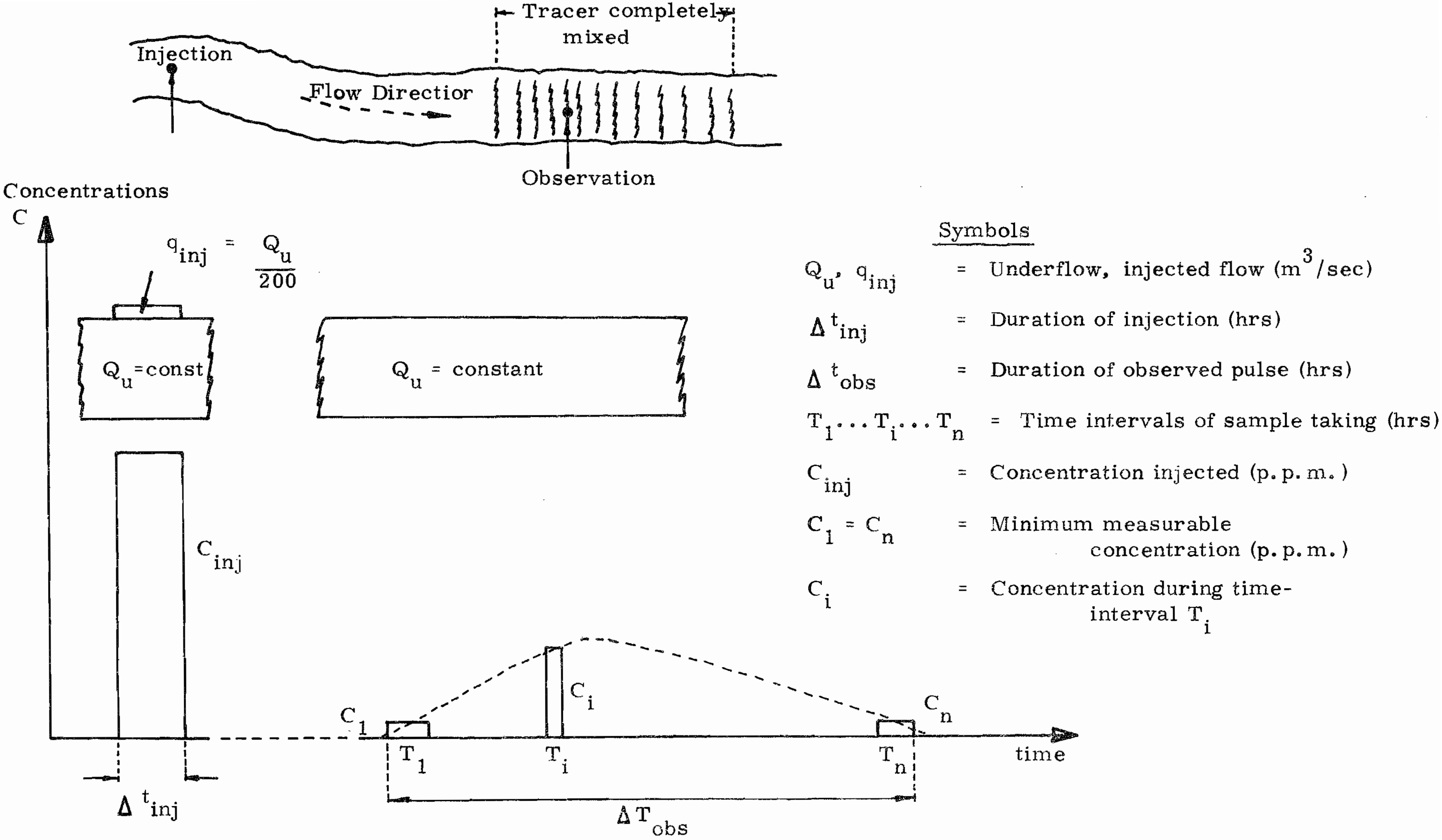


Fig. 10: Theory of tracer methods for measuring underflow

the chosen section (e.g. by geophysical methods) and apply Darcy's Law. In the wide braided rivers of the Canterbury Plain the implementation of such a method will meet with great technical difficulties. It may be considered in the case of some of the smaller, predominantly dry, river courses.

9.4.3. Tracer Methods

It is suggested to adapt the tracer dilution method for sampling river flow (ref: Replogle 1966) to the measurement of underflow and vein-like groundwater flow.

(a) Theoretical principles

A tracer-pulse of measured strength is injected into the gravels at some point and the appearance of the tracer is monitored at another point further downstream (see fig. 10). It is assumed that at the downstream observation point the tracer is completely dispersed over the whole width and depth of the river gravels. If this assumption is not justified, the method will give erroneous results or no results. Prior determination of this complete mixing distance is therefore essential.

The initial 'square-pulse' of injected tracer will be diluted, it will spread out laterally and longitudinally and at the observation point the time-record of tracer concentrations will approximate a Gaussian distribution curve (see fig. 10).

Injection of the square pulse is expressed by

$$V_{inj} = Q_{inj} \times Dt_{inj} \times C_{inj} \qquad (1)$$

where:

V_{inj} = total quantity of tracer injected

Q_{inj} = strength of injection (in say, litres/sec), constant during time Dt_{inj}

Dt_{inj} = duration of tracer injection

C_{inj} = constant concentration of injected tracer (in, say, ppm)

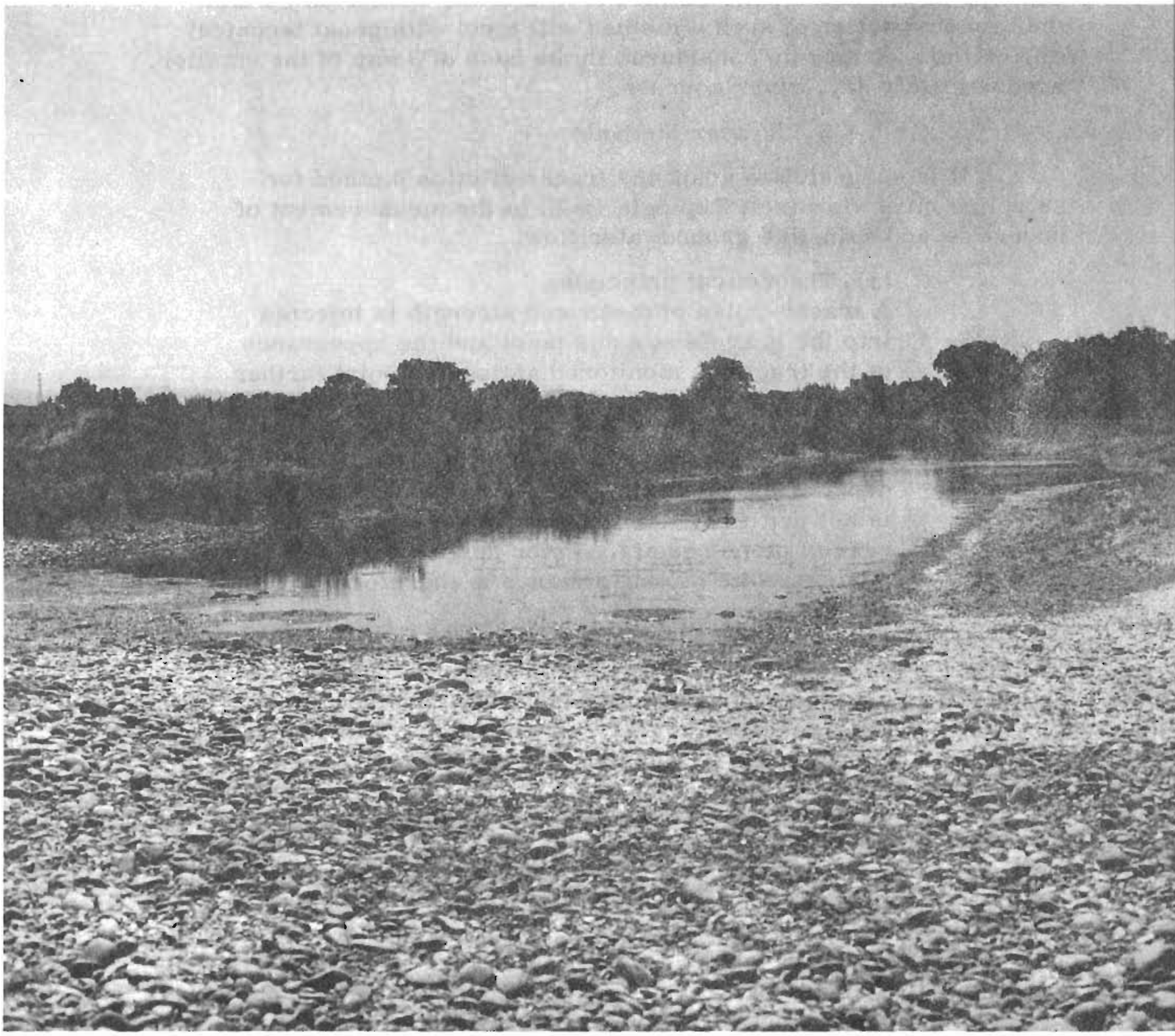


Plate 3: Underflow in the Selwyn River

At the observation point the phenomenon is expressed by:

$$V_{obs} = Q_u \times \text{Sum } C_i \; T_i \tag{2}$$

where:

V_{obs} = total volume of tracer observed

Q_u = underflow (in, say, litres/sec), assumed to be constant during the time of the experiment

C_i = successive concentrations of tracer (in, say, ppm) assuming that C_1 and C_n are the first and last measurable concentrations of tracer respectively

T_i = short but not necessarily equal time intervals at which tracer concentrations are monitored

Sum = summation, i assuming all values from 1 to n

Furthermore, we define the whole time-interval during which measurable tracer concentrations can be observed by:

$$Dt_{obs} = \text{Sum } T_i \tag{3}$$

From the principle of continuity it follows:

$$V_{inj} = V_{obs} \tag{4}$$

Substituting the respective expressions from eq. 1 and 2 and rearranging we obtain:

$$Q_u = \frac{Q_{inj} \times Dt_{inj} \times C_{inj}}{\text{Sum } C_i \times T_i} \tag{5}$$

Here the unknown Q_u is expressed by measureable quantities in the right hand side of the equation.

(NOTE: This reasoning is usually formulated more succinctly and elegantly in integral form. The above formulation stays nearer to experimental procedures).

(b) Considerations of sensitivity

We define the average concentration of the observed tracer by:

$$\overline{C_{obs}} = \frac{\text{Sum } C_i \times T_i}{Dt_{obs}} \quad (6)$$

substitute in (5) and rearrange:

$$\overline{C_{obs}} = \frac{Q_{inj} \times Dt_{inj}}{Q_u \quad Dt_{obs}} \times C_{inj} \quad (7)$$

$\overline{C_{obs}}$ should be much greater than this minimum detectable tracer concentration, or else accuracy will suffer. The stipulation $\overline{C_{obs}} = 10 \times C_1$ is probably justified, but it can be hoped that meaningful results can still be achieved by stipulating:

$$\overline{C_{obs}} \geqslant 5 \times C_1 \quad (8)$$

Substituting in (7) and rearranging one obtains:

$$C_{inj} = \frac{Q_u}{Q_{inj}} \times \frac{Dt_{obs}}{Dt_{inj}} \times 5\ C_1 \quad (9)$$

The ratio $\frac{Q_u}{Q_{inj}}$ is governed by practical experimental considerations. For comparatively small underflows, say $Q_u = 1\ m^3/sec$, it can be about 100 : 1 (i.e. an injection of 36 m^3 during 1 hour). For larger underflows it must be large, of the order of 1000 : 1, or even larger.

For the ratio $\frac{Dt_{obs}}{Dt_{inj}}$ a range of the order of 5 to 50 is estimated.

Therefore we obtain a reasonable range of specifications for C_{inj}:

$$C_{inj} = 2\,500\ C_1 \text{ to } 250\,000\ C_1 \tag{10}$$

i.e. the concentration of the injected solution must be 2 500 to 250 000 times larger than the minimum detectable tracer concentration.

(c) Choice of tracer
The following choices are open in principle:
(i) Electrolyte (ii) Dye (iii) Radio-active tracer

(i) As an electrolyte, rock-salt (NaCl) is the most obvious choice. Its advantages are: comparative cheapness, ease of measurement by conductivity-bridges, absence of environmental danger. Its disadvantages are: high specific gravity and difficult mixing at high concentrations of input tracer, comparatively high threshold of detection, comparatively large 'noise' (salinity) in the natural water. For these reasons it can be considered only for small underflows in the range of $\frac{Q_u}{Q_{inj}} = 100$.

If we assume as threshold of measurement $C_1 = 5 \times 10^{-6}$ (5 ppm chlorine-ion) it follows (for small underflows) $C_{inj} = 12\,500 \times 10^{-6}$ chlorine-ion. Seawater with an estimated salinity of $17\,000 \times 10^{-6}$ chlorine-ion may constitute a useful tracer under very favourable circumstances but even then the quantities to be injected are large and this may cause technical difficulties.

(ii) Dyes have the advantage of comparative cheapness, minimum environmental danger, low threshold of detection and low noise in the natural water. Their disadvantages are the possibility of absorption on clay-particles. If we assume as a practical threshold of detectability $C_1 = 10^{-7}$

(for dyes like Fluorescein or Rhodamine B the threshold can be lowered under good conditions to about $C_1 = 10^{-9}$), we obtain $C_{inj} = 250 \times 10^{-6}$

to 25 000 x 10^{-6}, i.e. 250 to 25 000 ppm. It is comparatively easy to prepare dye solutions of these concentrations. Dyes will work over the entire range indicated in equation 10.

(iii) Radio-active tracers have the advantage of an extremely low threshold of detectability, dilutions of 10^{-12} and more being measureable with gamma-ray tracers. Very accurate and reliable apparatus for their measurement is available. However, many tracer substances are not cheap. If their half-life is short and if no facilities for their synthesis exist near at hand, their price will skyrocket. Against all radio active tracers, there exist environmental objections. Finally, good scintillation counters with the required voltage stabilisers, recorders, etc, need power supplies as well as expert maintenance and handling.

9.4.4. Field Experiments

Preliminary experiments are necessary in order to determine the mixing distance. For this purpose a small quantity of dye is injected into one hole and observed in holes say 20 - 100 m downstream. Simple hand-dug holes can be used.

During the actual experiment it is recommended to use one set of instruments, vessels, personnel, etc., for injection and a different set for observations, the reason being that even a very slight contamination by dye acquired during injection procedures may falsify subsequent observations. For the same reason accidental spillages of dye into the river water or anywhere near the place of injection must be absolutely avoided. The tracer must be injected below water level through a pipe so that air can escape. The last portion of tracer must be flushed out into the aquifer by a small quantity of clean water.

In order to minimise the distance of mixing, injection should be carried out simultaneously in three to four holes across the width of the river.

For observations on the downstream side, one to two holes are enough. The holes should be continuously pumped at a low rate, say about five litres a minute, so that a reasonably integrated sample of the surrounding of the well is obtained. The pumped water, except for small quantities taken for analysis, has to be rejected via a closed pipe at least 20 m further downstream.

In sampling and analysis the big difficulty is the determination of the "first" and the "last" trace of dye. The collection and measurement of many samples by manual methods is too cumbersome and expensive to be of much use. Sensitive, objective, automatic recording instruments should be acquired and adapted for this purpose.

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