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GROUND WATER RESOURCES OF THE TAURANGA GROUP SEDIMENTS IN THE HAMILTON BASIN, NORTH ISLAND, NEW ZEALAND

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ABSTRACT

The Tauranga Group sediments contain the most important and widely distributed aquifers in the Hamilton Basin. Among these sediments the most productive aquifers are well-sorted, coarse sand and gravel deposits. However, poor hydraulic characteristics are common because the sediments are often poorly sorted, and high-yielding zones are interspersed with lenses of less permeable silts, clays and peats. The spatial variation of the regional piezometric surface and the patterns of ground-water flow closely follow the surface topography in the Basin. The depth to the piezometric surface varies, from a few metres below the undissected lowland plains, to a 30 m adjacent to incised stream channels. Vertical piezometric gradients and isotopic analyses suggest most ground water flow is restricted to the upper 30 m of the Tauranga Group sediments.

Recharge occurs from rainfall infiltration over the undissected lowland plains: ground-water discharge is by effluent flow to the incised stream networks. The net variation in aquifer storage observed during this study (9 mm) suggests recharge to the Tauranga Group sediments equals discharge from them and implies no subterranean leakage from the Basin. The implied equilibrium between aquifer recharge and discharge means use of ground water will be associated with a reduction in stream flow. Thus, the availability of water resources in the Tauranga Group sediments depends on the joint management of ground water and surface water resources.

INTRODUCTION

The Hamilton Basin is a large tectonic depression (≃ 2000 km^2) centred on Hamilton City (Fig. 1). The Basin is infilled with a sequence of Pleistocene alluvial sediments, known collectively as the Tauranga Group sediments. The sediments have formed a large area of gently undulating plains on which have developed rich, versatile soils, well suited for many forms of intensive land use. The Tauranga Group sediments also provide the most important and widely distributed system of aquifers in the Hamilton Basin. At present, these aquifers

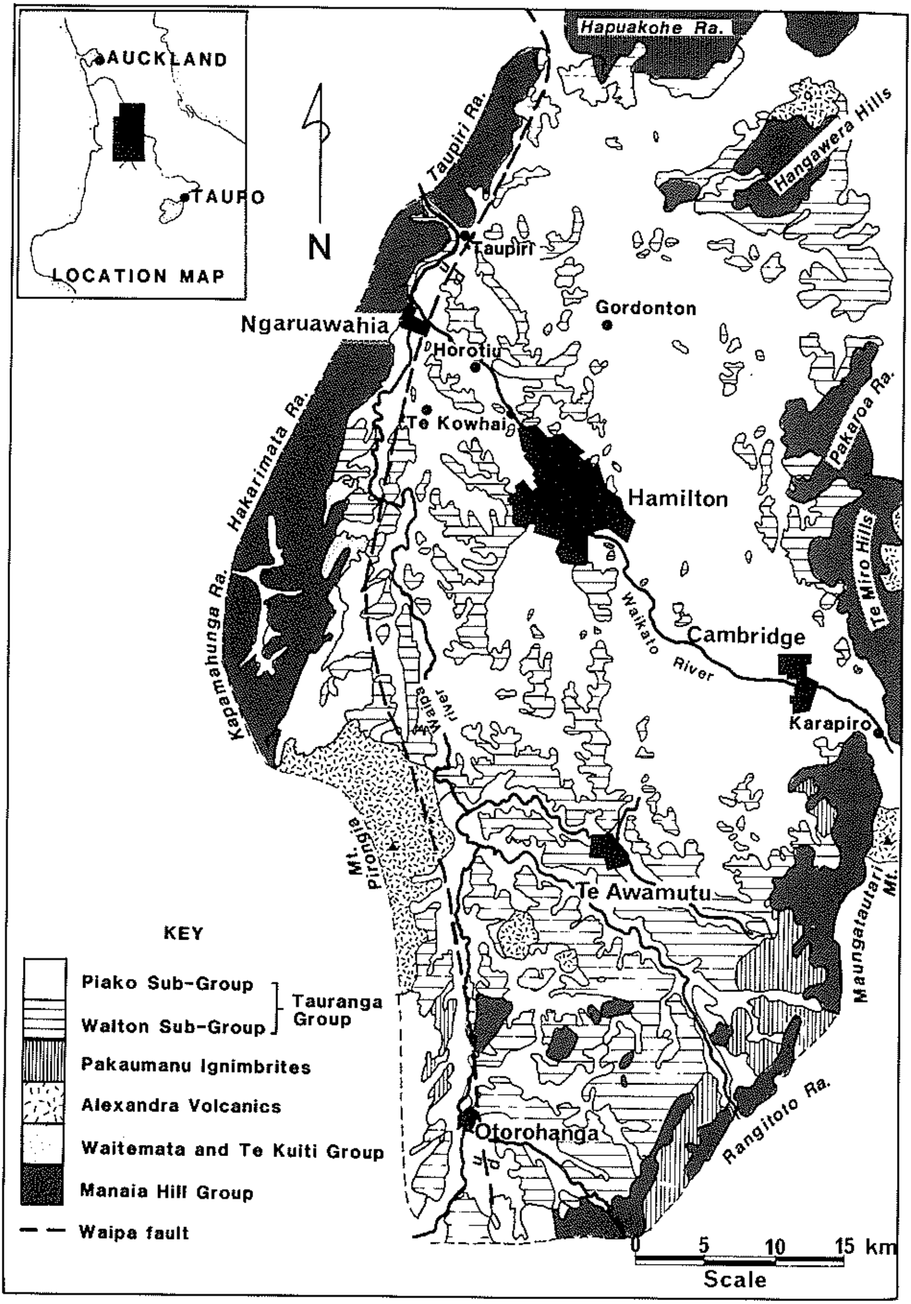

FIG. 1—Location map and surface geology of the Hamilton Basin (after Kear, 1960).

sustain 30% of the total water demand in the Basin (total water demand ≃ 6×10^7 m^3 y^{-1}), although in some catchments they provide more than 80% of the annual water demand (Bird and Lohrey, 1985).

Aspects of the ground-water resources in the Hamilton Basin have been described as part of regional geological mapping programmes and during investigations for ground water supplies (e.g. Taylor, 1935; Schofield, 1956, 1960, 1972). However, additional investigation has been required for water management strategies, particularly given the potential for increased demand for water by intensive land use in the Hamilton Basin.

The Hamilton Basin is one of the few closed alluvial basins in New Zealand, in which the main outlet for ground water is via surface streams or rivers (i.e. the Waikato River at Taupiri). Sensitive relationships between regional climate, surface-water resources and ground-water resources have been shown in basins when inflows and outflows are in equilibrium (assuming a constant climate and no leakage) (Freeze, 1971). In the Hamilton Basin the regional ground-water levels lie above the stream levels. Consequently, uncontrolled use of ground water may lower the regional ground-water levels so that stream flow is reduced, or ceases. These interactions need to be understood to provide integrated management of the ground-water and surface-water resources in the Basin.

REGIONAL GEOLOGY

The Hamilton Basin is a roughly oval depression about 80 km north to south and more than 40 km wide (Fig. 1). The Basin is almost completely surrounded by ranges of low permeability Mesozoic (Manaia Hill Group) and Tertiary (Te Kuiti and Waitemata Groups) sediments. Isolated volcanic centres (Alexandra and Kiwitahi suites) occur along the ranges and in the south of the Basin. Other volcanic material derived from the Taupo Volcanic Zone (Pakaumanu Ignimbrite) occurs in the south-east of the Basin (Kear, 1960).

The Tauranga Group sediments overlie the Waitemata Group and mark the transition from Tertiary marine sedimentation to Quaternary terrestrial deposition. In the Hamilton Basin, most of the Tauranga Group sediments commprise pumiceous and rhyolitic sands, silts, clays and conglomerates derived from the central North Island Volcanic Zone. Three Sub-groups are recognised, (Frankton, Walton and Piako Sub-groups) forming a sequence up to 300 m thick. Sediments of the Frankton Sub-group are known only from deep bores (≃ 250 m) in the Hamilton Basin: accordingly their distribution is poorly defined.

Sediments of the Walton Sub-group are distributed throughout the Hamilton Basin. The oldest of the Walton deposits is the Puketoka Formation which comprises well-sorted, pumiceous clays, sand and breccias, and massive pumice deposits, including distal portions of ignimbrites (Kear and Schofield, 1978). Overlying these sediments is the Karapiro Formation which consists of current-bedded, strongly-weathered, rhyolitic sand and gravels, interspersed with lenses of silt, clay and peat.

The Piako Sub-group represents the most recent period of deposition in the Hamilton Basin and comprises the Hinuera Formation, the Taupo Pumice Alluvium and other minor undifferentiated Holocene sediments. The Hinuera Formation is the most important formation in the Sub-group as it underlies the extensive Hamilton Lowland Plains. These sediments comprise a variable, discontinuous sequence of rhyolitic and pumiceous gravelly sands, interspersed with pumiceous silt and clay and peat. The Hinuera sediments were deposited mainly via the Maungatautari Gorge, into valleys eroded in the Walton sediments, to form a large, low-angled fan extending throughout the Basin. As a consequence of its mode of deposition, the Hinuera Formation is characterised by pronounced vertical and horizontal changes in sediment texture.

POTENTIAL AQUIFERS IN THE TAURANGA GROUP SEDIMENTS

The Hinuera, Karapiro and Puketoka Formations contain the aquifers used most extensively in the Hamilton Basin. On a regional scale, these formations may be considered as a single hydrogeologic unit because of their lithologic and hydraulic similarity (Kear and Schofield, 1978). In these sediments, the most productive aquifers are found in well-sorted coarse sands and gravels, but lithologic variability usually results in many zones of higher permeability, rather than single continuous aquifers (Schofield, 1972).

The spatial and vertical variability of these sediments makes it difficult to intercept single high-producing aquifers and careful construction is required to provide efficient, high-yielding bores. Specific capacities of bores in these sediments vary considerably, usually from 1.25×10^{-5} to 7.0×10^{-4} $m^3 s^{-1}$ per metre drawdown (Schofield, 1972). However, a few continuous aquifers with specific capacities up to 6.2×10^{-3} $m^3 s^{-1}$ per metre drawdown have been located in the Tauranga Group sediments.

DRAINAGE

The drainage network in the Hamilton Basin is dominated by the Waikato and Waipa Rivers and several large tributaries in the south of the Basin. Most other streams are small and spaced widely, especially on the Hinuera Formation, where drainage densities vary from 0.25 to 0.75 $km\ km^{-2}$.

The Waikato and Waipa Rivers are entrenched deeply (up to 60 m) into the Tauranga Group sediments and most tributaries become incised toward their junction with these rivers.

INVESTIGATION STRATEGY

The size of the Hamilton Basin precludes detailed investigation of the ground-water resources of the entire area of the Tauranga Group sediments. Consequently, a two-tiered approach was adopted for this study. First, the general aquifer characteristics were examined on a regional scale. Several falling head tests were completed to estimate the hydraulic conductivity of the Tauranga Group sediments *in situ*. Estimates of transmissivity and aquifer storage were obtained from pumping tests completed throughout the Basin. Some estimates of hydraulic characteristics were also obtained for Tauranga Group sediments located outside the Hamilton Basin.

Piezometric monitoring networks were established in the three areas representative of the Hamilton Basin (Fig. 2). Table 1 presents a summary of characteristics of the three areas. Piezometric levels were monitored fortnightly over the three areas for a four year period (December 1980–December 1984). The regional ground-water studies also included an analysis of Tritium, Oxygen-18 and Deuterium isotopes to provide information on the source of ground water, its residence time and predominant flow directions in the Basin.

TABLE 1—Characteristics of the areas of the Hamilton Basin in which piezometric monitoring networks were established (refer Figure 2).

Locality	Area	No. of Obs. Bores	Characteristics
Area 1 Hamilton Cambridge	135 km²	155	Mainly Hamilton lowland plains underlain by the Hinuera Formation and some peat in the northern sector. An incised, widely spaced stream network. Predominant soils are the Horotiu—Te Kowhai complex.
Area 2 Gordonton	95 km²	31	More varied physiography than in Area 1, including sediments of the Karapiro Formation (low hills), the Hinuera Formation (lowland plains) and large areas of peat (Komakorau peat bog). Hamilton soils predominate on the low rolling hills; Horotiu and Te Kowhai soils on the lowland plains and a variety of organic soils in the peat (e.g. Te Rapa peaty loam). Slightly incised, widely spaced stream network with some artificial drains.
Area 3 Te Kowhai	75 m²	101	Mainly low rolling hills underlain by the Karapiro Formation with valley floors underlain by the Hinuera Formation and some peat. Hamilton soils predominate on the low hills. A greater drainage density than either Area 1 or 2, but the streams are not incised deeply.

DATA SOURCE: McCraw (1967), McLeod (1984)

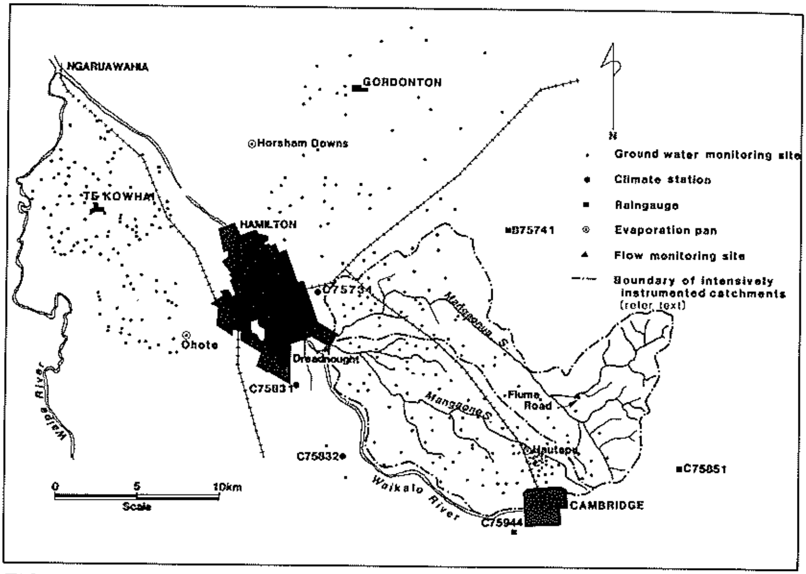

FIG. 2—Location of the hydrometric networks in the representative areas monitored in this study. Water balance components were examined in only the Hamilton — Cambridge area.

In the second part of the study, the water balance of the Tauranga Group sediments was examined in two intensively instrumented, representative catchments located between Hamilton and Cambridge. Estimates of rainfall (P), actual evaporation, stream flow and variation in aquifer storage were obtained from the network (Fig. 2). Actual evaporation (Ae) was estimated from potential evaporation (Pe) (obtained from adjusted evaporation pan estimates (Finkelstein, 1973)) and the calculated soil-moisture deficit, using a function fitted to Ae/Pe ratios observed in Horotiu soils for a range of soil-moisture deficits (McAneney and Judd, 1983). Variation in soil-moisture storage (Δu) was obtained from a simple tank model (P-Ae-Qq) assuming the soil-moisture storage for the predominant soil type in the catchment (102 mm). Net recharge to shallow aquifers was the only unmeasured variable and was assumed to occur when soil-moisture storage was full. The effects of present water use were not considered in this study because the maximum ground-water use is only 2 mm per month during summer, and as little as 0.5 mm during winter. Stream flow was separated into direct runoff (Qq: immediate storm runoff) and delayed flow (Qd: non-storm runoff derived from infiltrated rainfall via shallow aquifers). Variation in aquifer storage (i.e. net recharge: Rn) was estimated from changes in regional mean piezometric level assuming a porosity of 0.1 for shallow aquifers in the Tauranga Group sediments (cf. Schofield, 1972).

The relationships between stream flow, recharge and regional mean piezometric level (used as a measure of aquifer storage) were also examined in the two intensively instrumented catchments, using a mixed auto-regressive, multiple-regression model of the form:

$$Qd_i = a_1Qd_{i-1} + a_2 R_i + a_3R_{i-1} \ldots\ldots + a_8R_{i-6} + a_9W_i + a_{10}W_{i-1} \ldots\ldots + a_{15} W_{i-6} + a_{16} + e_i \qquad (1);$$

where Qd_i is the delayed flow yield in month (i);
R_i is the recharge (P-Ae-Qq) for month (i);
W_i is the regional mean piezometric level in month (i);
$a_{1\rightarrow16}$ are coefficients; and
e_i is the error term for the ith period.

Only 7 terms for recharge (R_i) and regional mean piezometric level (W_i) were included in the model because the two variables are not correlated with delayed flow (Qd_i) for lag times greater than 7 months. The coefficients a_{1-16} are assumed constant with time. Recharge rates may vary non-linearly in response to seasonal soil-moisture variation, but gross departures from the assumption were not detected in the model residuals. Significant variables in the model were selected in a stepwise estimation procedure.

RESULTS AND DISCUSSION

General Hydraulic Characteristics of the Tauranga Group Sediments

Table 2 shows the results from hydraulic conductivity tests completed in the Tauranga Group sediments. A general relationship between hydraulic conductivity and sediment texture is shown. Hydraulic conductivity varies from $\simeq 6 \times 10^{-4}$ cm s^{-1} for silts and fine sands to $\simeq 1.1 \times 10^{-2}$ cm s^{-1} for coarse sands. Similar results have been found for Tauranga Group sediments in the lower Waikato Basin (Fig. 3). However, a large range of hydraulic conductivity values is shown for a given median grain size. Such differences reflect the range of sorting typical of the Tauranga Group sediments. Generally, the sediments are poorly sorted, with a trend for better sorting with smaller grain size (Sherwood, 1972). Observed values of hydraulic conductivity tend to be ten times smaller

TABLE 2—Hydraulic conductivity of the Tauranga Group sediments in the Hamilton Basin.

W.V.A. BORE NO.	HYDRAULIC CONDUCTIVITY (K)		LITHOLOGY
	cm s^{-1}	m d^{-1}	
98	6.65×10^{-4}	0.57	Interlayered sands, clays and peats
101	5.88×10^{-4}	0.51	Silts
102	1.07×10^{-2}	9.24	Coarse gravelly sands
93	1.57×10^{-2}	13.56	Coarse gravelly sands
97	2.95×10^{-4}	0.25	Poorly sorted sands
96	1.74×10^{-3}	1.50	Sands
94	1.55×10^{-3}	1.34	Medium coarse sands
99	5.27×10^{-3}	4.55	Poorly sorted sands

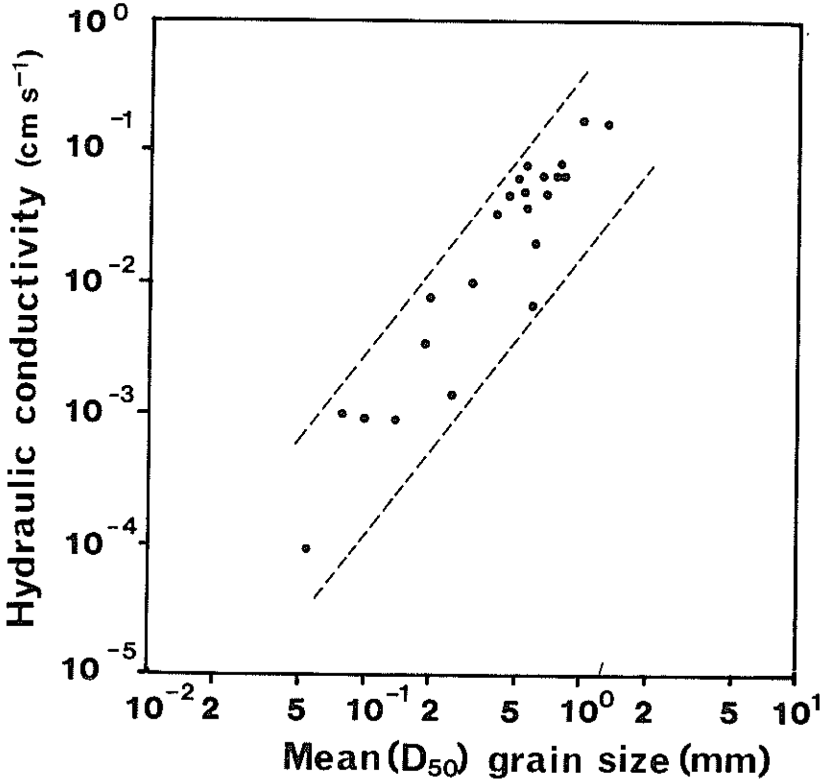

FIG. 3—Graph of the relationship between hydraulic conductivity and median grain size (D_{50}) for the Tauranga Group sediments in the lower Waikato Basin. (Data source: Tonkin and Taylor, 1963).

than those estimated solely on the basis of sediment texture (cf. Todd, 1980). Higher values of permeability have been measured at some sites outside the Hamilton Basin (e.g. 1.0×10^{-1} cm s^{-1}; Heu, 1985) and these values may represent small zones of well-sorted, coarse sediments.

Figure 4 shows estimates of transmissivity obtained from pumping tests in the Tauranga Group sediments. Transmissivity varies from 10 to 1000 m^2 d^{-1} and shows a strongly skewed distribution with a median of 80 m^2 d^{-1}. Geological logs of the bores tested suggest that the low transmissivities result from the thin, lensoidal zones of permeable material that form the effective aquifers and from poor sediment sorting. The few high values of transmissivity recorded in this study are associated with thick, well-sorted sediments. Such zones may represent coarse sediments deposited in paleo-channels of the ancestral Waikato River.

Estimates of aquifer storage obtained from pumping tests vary from $\simeq 4 \times 10^{-3}$ for deep, confined or semi-confined aquifers to 0.1 for shallow, unconfined

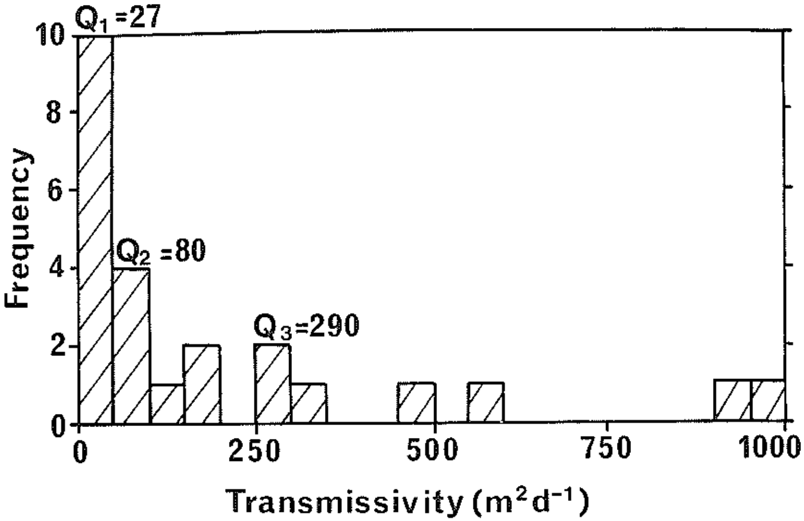

FIG. 4—Distribution of observed transmissivity for the Tauranga Group sediments. Note: $Q_{1...3}$ are distribution quartiles.

aquifers. Similar values have been observed for Tauranga Group sediments in the lower Waikato Basin (Heu, 1985). However, the data obtained for the deep, confined aquifers may underestimate aquifer storage because the estimates were obtained from relatively short-duration pumping tests, in which leakage had no time to develop.

The Tauranga Group sediments appear to have poor hydraulic continuity because of pronounced lateral and vertical changes in lithology. Attempts to correlate borelogs are generally impossible, even over short distances (≃ 20 m). Most aquifers or permeable zones must therefore be relatively small. Some large-scale pumping tests, with multiple piezometers, show an extremely variable and strongly directional distribution of transmissivity in these sediments. Despite such variation in aquifer characteristics, similar seasonal variation in regional piezometric levels suggests that, on a regional scale and over longer time periods, such as a season, the Tauranga Group sediments may be considered hydraulically as a single hydrogeological unit with preferred flow paths defined by zones of permeable sediments.

Regional Piezometric Level and Patterns of Ground Water Flow

Seasonal Variation of Regional Piezometric Level

A similar seasonal variation of regional piezometric level occurs in the three representative areas monitored in the Hamilton Basin (Fig. 5 a, b, c). In each area, the regional piezometric level declines to a seasonal minimum during May to July, followed by a recovery to a seasonal maximum during October to December. The annual range of piezometric level is 1 to 2 m in most bores. The seasonal range of piezometric variation in the Puketoka and Karapiro Formations (e.g. at Gordonton and Te Kowhai) is usually twice that observed

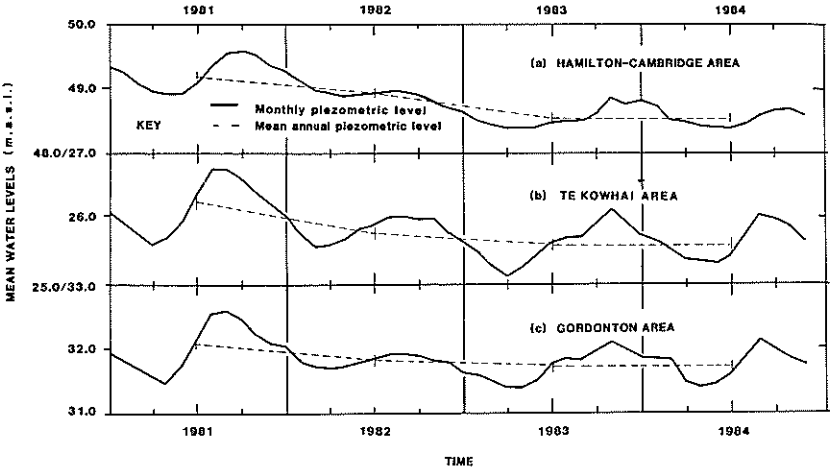

FIG. 5 a, b, c,—Seasonal variation of regional piezometric levels (1981–1984) for the: (a) Hamilton-Cambridge; (b) Te Kowhai; and (c) Gordonton area. Note: the data used in these figures are derived from shallow bores (<10 m) and show variation for shallow aquifers only. Data from deeper aquifers show a similar, but subdued trend.

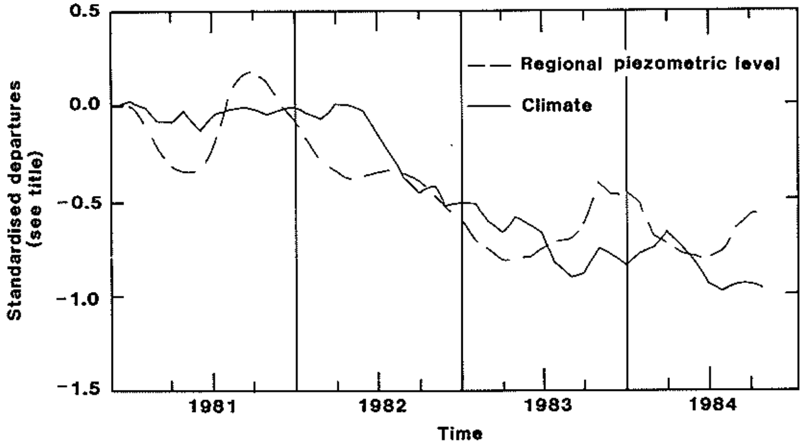

FIG. 6—A comparison of standardised departures from normal climate (P-Ae) and regional piezometric levels observed in the Hamilton-Cambridge area (1981–1984).

in the Hinuera Formation (Marshall and Petch, 1985). The difference is attributed to the lower porosity of the Puketoka and Karapiro sediments, as they are older, more intensely weathered and have a larger proportion of silt and clay compared with the Hinuera sediments.

Figure 5 a,b,c, also shows that the mean annual piezometric level in each

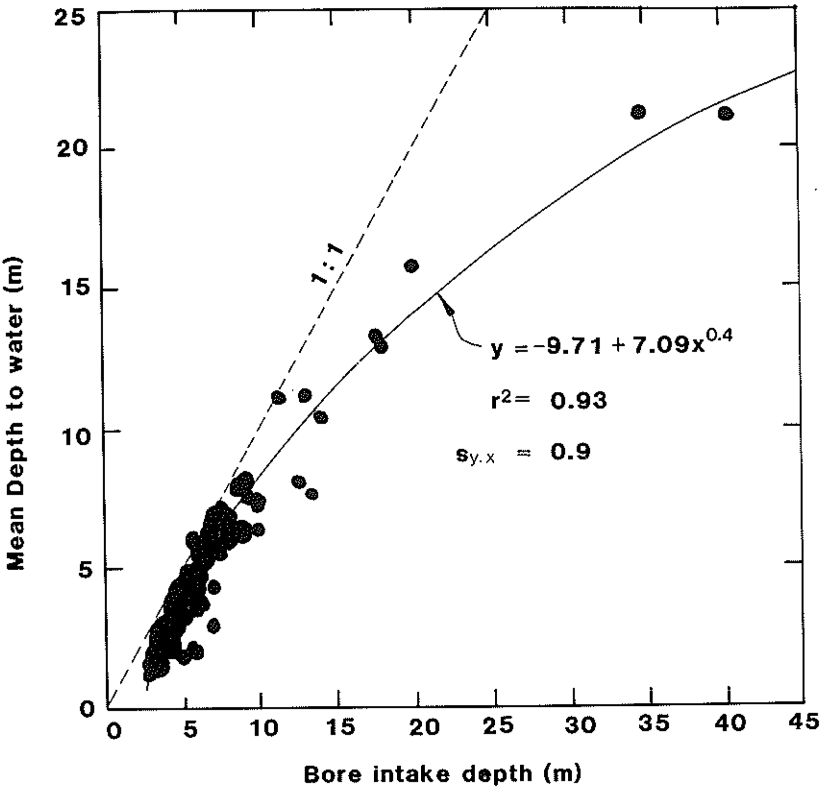

FIG. 7—Variation of piezometric level with depth in the lowland plains (Hinuera sediments). Note the numerous shallow bores. Small, but adequate supplies for stockwater and domestic use can be obtained from shallow aquifers, but larger supplies for irrigation and industry are obtained from deeper bores.

area declined gradually over the period of observation. Such a decline could suggest over-use of ground water, particularly given the large increase in demand for ground water that occurred over the same period (Marshall and Petch, 1985). However, a comparison with cumulative departures from normal climate (i.e. P-Ae) shows that the decline in regional piezometric levels has been caused by a period of less-than-normal net rainfall (Fig. 6). More recent observations show a recovery in regional piezometric levels following a period of greater-than-normal recharge.

Vertical Variation in Regional Piezometric Level

Figure 7 shows the vertical variation of piezometric level observed in the lowland plains (Hinuera Sediments) into which the streams have become incised. Bore-intake depth is used as a surrogate for aquifer depth because it is not usually possible to identify the specific aquifer intercepted. Pronounced downward vertical piezometric gradients are shown, implying potential recharge through

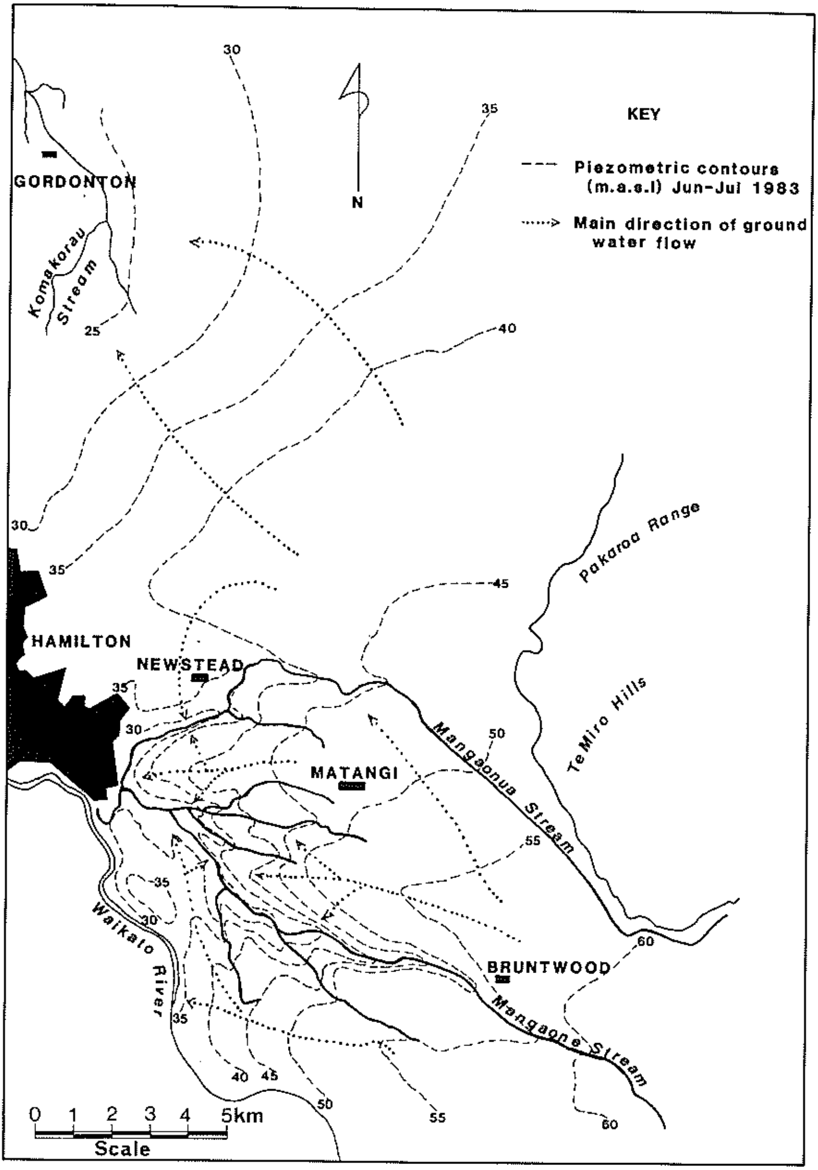

FIG. 8—Piezometric contours and primary ground water flow directions in the Hamilton-Cambridge and Gordonton areas.

the sediments. However, the rate of recharge is likely to be slow as the sediments are anisotropic.

The vertical piezometric gradient shown for the shallow aquifers (<6 m deep) is greater than 1:1 and suggests a sequence of aquifers perched above interbedded silt and clay lenses. Below 6 m depth the vertical piezometric gradient decreases steadily to $\simeq$ 1:3 at 30 m depth. One possible explanation of such a decrease is that the rate of recharge decreases with depth (assuming the Tauranga Group sediments act as a single hydrogeological unit with uniform hydraulic conductivity with depth) and that lateral discharge occurs from the aquifers to the incised stream channels throughout the Hamilton Basin. This explanation is supported by numerous seepages and springs along the stream channels and by the ground-water flow lines implied from regional piezometric levels.

Regional Piezometric Contours and Directions of Ground Water Flow

Figure 8 shows piezometric contours and the direction of ground-water flow in two of the three representative areas chosen for study (Hamilton-Cambridge area and Gordonton). Low piezometric gradients occur under the undissected lowland plains (1.5 m km^{-1}) but they steepen considerably near the incised streams ($\leq$ 50 m km^{-1}). The piezometric surface is close to the surface of the lowland plains, usually between 2 and 6 metres deep. Small mounds in the piezometric surface occur in some areas and are associated with areas of greater topographic relief, often the eroded remnants of higher-level terraces (Puketoka and Karapiro Formation) (Fig. 1). In these areas, the piezometric surface may be up to 40 m below ground.

Ground-water flow is from areas of recharge under the undissected plains to the incised stream channels via numerous springs and seepages that occur along the stream channels and embankments. Greatest discharge is implied for the most incised stream reaches in which the stream channel is clearly below the regional piezometric surface. Measurements of the spatial distribution of surface runoff for the Hamilton-Cambridge area show pronounced increases in flow with increased stream incision (Petch, 1987).

Environmental Isotopes

Specific details of the analysis of environmental isotopes are presented in Marshall and Petch (1985). The results of these studies suggest the Tauranga Group sediments are recharged by rainfall infiltration. However, the ground water in deep aquifers is considerably older, as a separate Carbon_{14} date gives an age of 6500 y B.P. Thus ground-water movement appears to be restricted to the surface zones ($<$ 30 m) of the Tauranga Group sediments and natural circulation in deep aquifers is extremely slow, except where disturbed by abstraction. Induced recharge in deep aquifers is inferred from elevated Tritium concentrations in one deep (90 m), high-yielding industrial bore.

Water Balance Components

Table 3 shows the annual water balance is dominated by input from rainfall and by losses from evaporation and delayed flow. Losses to direct runoff are about 15% of total runoff from the two catchments. Changes in soil moisture usually balance seasonally.

Monthly water balance data (not presented) show soil moisture is maintained at field capacity from May to November, although large soil-moisture deficits occur during summer. Aquifer recharge occurs mainly in winter. Delayed flow shows considerable seasonal variation: flow during winter is usually twice that during summer.

TABLE 3—Estimated average water balance components (mm) for the Tauranga Group Sediments, for the period March 1981–March 1984.

Rainfall (P)		Actual Evaporation (Ae)		Quick Flow (Qq)		Delayed Flow (Qd)		Change In Soil Moisture (Δu)		Net Recharge (Rn)
1055	=	716	+	32	+	288	+	10	+	9

Net recharge (change in aquifer storage) estimated from the water balance is 9 mm for the 3 year period, small compared with the main input and outputs from the water balance. This suggests recharge to the Tauranga Group sediments equals discharge from them and implies no subterranean leakage from the Basin. This inference is supported by the estimate of change in aquifer storage obtained from variation in regional mean piezometric levels over the same period (i.e. only -16.5 mm). Estimates from the two methods differ by up to 50 mm for individual years, but all the differences are considerably smaller than the errors associated with each method (Marshall and Petch, 1985). Both estimates of the change in aquifer storage imply that the Tauranga Group sediments act as a simple storage reservoir. Recharge occurs over the undissected plains: discharge from the aquifers is to the incised stream channels, with changes in aquifer storage being shown as variation in regional piezometric levels.

Relationships Between Recharge, Aquifer Storage and Discharge

The close relationships between ground-water and surface-water resources shown in the previous sections suggest that the ground-water resources cannot be developed without influencing stream flow throughout the Basin. These interactions are presented in more detail in Table 4, which shows the empirical relationships between recharge, aquifer storage and discharge (i.e. Qd: delayed flow) obtained from the auto-regressive, multiple-regression model. Of the variables available for selection in the model, three are important in determining delayed flow: the delayed flow that occurred during the previous month; the recharge during the current month; and the regional mean piezometric level that occurred four months previously.

The variables in Table 4 suggest that monthly yields of delayed flow are a function of processes occurring on two distinct time scales. Short-term variation appears to be determined by the variation of recharge on a monthly interval (R_i), plus a lagged component of the hydrological regime (delayed flow) that occurred one month previously (Qd_{i-1}). The presence of (R_i) in the regression equation may suggest the importance of macropore flow in transmitting a proportion of recharge directly to the stream channel. Alternatively R_i may indicate that shallow, permeable zones of the Tauranga sediments are responding soon after specific recharge events.

The importance of the third variable (W_{i-4}) suggests the short-term variation of delayed flow is also influenced by variation of the regional piezometric level four months previously. This variable may be an index of recharge caused by slower drainage through deeper Tauranga Group sediments.

MANAGEMENT IMPLICATIONS

The results presented provide a basis for developing strategies for water-resource management in the Hamilton Basin. The two catchments examined are considered to represent other catchments in the Hamilton Basin because all catchments in the Basin appear remarkably similar. The Tauranga Group sediments show a high degree of lithological uniformity (Kear and Schofield, 1978). Regional uniformity is supported further by similar drainage densities and soil types (McCraw, 1967) and many aspects of hydrogeology (e.g. seasonal variation of regional piezometric level observed during this study).

Given the relationships between ground water and stream flow and that residual flow is required for instream needs (e.g. to maintain adequate stream quality), the total water resource available for allocation (including instream needs) in the Hamilton Basin is equivalent to the stream-flow yield from each catchment, irrespective of whether the water is taken from shallow aquifers or from the streams. This is because the surface aquifers act only as a reservoir and groundwater discharge provides the delayed flow in the streams. Any use of ground water will be associated with lowered regional piezometric levels and a concomitant

TABLE 4—Regression equation showing the relationships between monthly delayed stream flow, recharge and regional mean piezometric levels for the two intensively instrumented catchments.

$$Qd_i = 0.709\ Qd_{i-1} + 0.091\ R_i + 4.65\ W_{i-4} - 221.75$$

Standard errors of the regression coefficients and the maximum and minimum values observed for each variable.

Variable	Standard error	Max	Min
Qd_{i-1}	0.070 mm	–51	–13
R_i	0.013 mm	148	–70
W_{i-4}	1.760 m	49.4	48.2
intercept	84.90 mm	—	—

r^2 = 0.85
$s_{y.x}$ = 3.54 mm
serial correlation of residuals = 0.07

Qd_i — delayed stream flow for month (i) (mm)
R_i — recharge for month (i) (mm)
W_i — regional mean piezometric level for month (i) (masl)

TABLE 5—Specific discharge (5-year recurrence interval) for the Tauranga Group sediments, tributary catchments in the ranges surrounding the Basin, and the Waikato and Waipa Rivers.

Specific Discharge ($l\ s^{-1}\ km^{-2}$)		
Tauranga Group sediments	Catchments in the ranges surrounding the Hamilton Basin	Waikato and Waipa Rivers
2-4	8-12	8*-18**

* — Waipa at Otorohanga

** — Waikato at Hamilton

reduction in stream flow. Some additional recharge to aquifers may be induced if regional piezometric levels are lowered excessively, thereby reducing seasonal evaporation loss.

The most important critical period for water allocation occurs during January and February when stream flow is at a seasonal minimum, and water demand at a seasonal maximum. As the effects of recharge and ground-water abstraction appear attenuated by the Tauranga Group sediments before influencing stream flow, the development of ground-water resources is preferred. In this way reductions in stream flow caused by ground-water abstraction are likely to be delayed for several months, when demand for stream flow is normally reduced.

The effects of increased abstraction from deep, confined aquifers on the piezometric levels in shallow aquifers are unknown and are the subject of continued investigation. Leakage may be induced from overlying aquifers, but lateral flow from the Waikato and Waipa Rivers may be considerably greater, especially since the Tauranga Group sediments are anisotropic. However, it is clear that conjunctive management of ground water and surface water is required if residual flow is to be maintained in the stream systems as required by most water allocation plans.

Future large-scale horticultural development in the Hamilton Basin may not be sustainable solely by water resources from the Tauranga Group sediments. The total allocatable water yield from these sediments is as little as 2 to 4 $l\ s^{-1}\ km^{-2}$ during drought conditions (5-year recurrence interval) given that some residual flow must be maintained in streams (Marshall and Petch, 1985). In comparison, flow is considerably greater from catchments originating in the ranges surrounding the Hamilton Basin and the Waikato and Waipa Rivers (Table 5). Clearly, these larger sources of water should be considered for water-resource development where they are a viable alternative.

CONCLUSIONS

The Tauranga Group sediments contain the most important and widely distributed aquifers in the Hamilton Basin. The most productive aquifers in these sediments are well-sorted, coarse sand and gravel deposits. More commonly, the sediments are poorly sorted and characterised by lithological discontinuities, which are reflected in the variable, but generally poor aquifer characteristics observed throughout the Basin.

A similar variation of piezometric levels occurs seasonally throughout the Tauranga Group sediments in a pattern that reflects natural seasonal recharge and discharge. No evidence was obtained for a decline in regional piezometric levels caused by over-use of ground water. The spatial variation of regional piezometric levels closely follows the surface topography throughout the Basin. Piezometric levels vary, from a few metres under the undissected lowland plains, to 40 m under low rolling hills or adjacent to the incised stream network.

The regional ground-water flow net reflects the basin topography. Recharge occurs from rainfall infiltration to the undissected plains. Ground-water discharge is dominated by effluent flow to the incised stream network, through many springs and seepage zones along the stream channels. Isotopic analyses suggest ground-water flow is restricted to the shallow zones of the Tauranga Group sediments. Shallow ground water is derived from rainfall: in deep aquifers, ground water is considerably older, recharged slowly by vertical seepage.

Recharge occurs mainly in winter when soil-moisture deficits are satisfied. Discharge from the ground-water system occurs continuously as stream flow and is responsible for approximately 85% of all flow in streams draining from Tauranga Group sediments. For the the data examined, change in aquifer storage is small compared with the main input and outputs from the water balance. This observation suggests recharge to the Tauranga Group sediments equals discharge from them and implies the sediments act simply as a storage reservoir: no subterranean leakage occurs from the Basin.

Three strategies for managing the water resources of the Hamilton Basin are derived from this study. First, as a result of the relationships between aquifer recharge, ground-water storage, and aquifer discharge to streams, the optimal use of water resources in the Tauranga Group sediments depends on the joint management of ground-water and surface-water resources if residual stream flow is to be maintained. Any increase in ground-water use will be associated with a reduction in stream flow, although the full effects of this reduction are unlikely to become apparent for several months. Secondly, future water-resource development in the Tauranga Group sediments should, where possible, be based on ground water rather than surface-water resources, as summer abstractions of ground water will not cause reductions in stream flow until autumn, when water demand is normally reduced and recharge is contributing more to stream flow. Thirdly, flow from the Waikato and Waipa Rivers, and from catchments in the ranges surrounding the Hamilton Basin, should be considered for large-scale water-resource developments because flow is far greater from these sources than that generated from the Tauranga Group sediments.

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