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GROUNDWATER MODELLING AS A TOOL FOR WATER MANAGEMENT: WAIMEA PLAINS, NELSON

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ABSTRACT

A quasi three-dimensional computer model of the groundwater system of the Waimea alluvial basin, Nelson, New Zealand, incorporating the three Waimea aquifers and overlying rivers, was developed and calibrated. Model simulations evaluated the optimal yield of the aquifers given the constraints of preventing sea-water intrusion or excessive water level declines, and maintaining minimum river flows. Other simulations showed the seasonal fluctuations in head when no pumpage is occurring, and the impacts of irrigation scheme proposals. Results of this modelling assisted the Nelson Catchment Board in formulating management policies for the water resources of the Waimea Plains restricting summer water usage.

Keywords: groundwater, computer model, water management, Waimea Plains, Nelson, three-dimensional flow model, alluvial aquifers, Wairoa River, Appleby Gravel, irrigation, safe yield, sea-water intrusion, geohydrology.

INTRODUCTION

Groundwater dynamics are complex and a large amount of data is usually required to understand aquifer behaviour. Computer models of groundwater flow, and to a lesser extent of groundwater contamination, have become widely used for regional aquifer evaluation and management. The models provide a framework for quantifying the resource and testing conceptual ideas of how the groundwater system performs. Their greatest benefit is in simulating the response of the system to different management strategies, to determine optimal yield ('safe yield').

COMPUTER MODELLING OF GROUNDWATER FLOW

Most groundwater models are deterministic, i.e. based on established physical relationships, using Darcy's law and the principle of conservation of mass. Groundwater flow is described by partial differential equations for flow through a porous medium, and the piezometric head distribution is obtained by solving these equations. While analytical solutions such as the Theis equation are available for simple situations such as an aquifer pump test, computer-based numerical methods are needed for more complex problems such as regional aquifer evaluation. Finite difference and finite element methods are the most common iterative solution techniques. Two-dimensional areal representation of an aquifer is the most common application. Computer programs for one-, two- and three-dimensional models are now available for mainframe and micro-computers.

To set up a model a network of nodes (grid points) is defined characterising average values, measured or estimated, for such parameters as aquifer transmissivity, storativity, recharge and pumpage. With this input data, the program produces steady-state or time-dependent heads and flows at model nodes.

After adjusting input parameters so that simulated response matches observed (field) behaviour, the calibrated model can be applied to predict the response of the system to different management strategies. The key to a successful model lies in obtaining an accurate (though not necessarily detailed) concept of how the groundwater system works, and adequately calibrating the subsequent computer model.

Until recently, *regional* groundwater flow modelling has been limited in New Zealand to two areas, the Lower Hutt — Port Nicholson alluvial basin (Donaldson and Campbell, 1977) and parts of the Canterbury Plains e.g. Hunt (1976), Boon and Hunt (1985), Scott and Thorpe (1986). Contaminant dispersion from urban expansion and intensive pasture irrigation was investigated in the Heretaunga Plains aquifers (Thorpe *et al.*, 1982). Some of these models have had limited application for management of the modelled aquifers, because of either lack of a detailed conceptual model or lack of development of the schemes they were simulating.

The Waimea Plains model (Fenemor, 1988) described below is a model of sufficient accuracy to help solve water allocation problems in a water-short area.

THE WAIMEA PLAINS AQUIFERS, NELSON

The Waimea Plains is a 7500 ha area of intensive horticulture and cropping near Nelson (Fig. 1). Its soils have low water-holding capacities, and soil moisture deficits build up rapidly in summer. About 1700 ha are irrigated from groundwater, while the Waimea East Irrigation Scheme will, when fully operational, supply another 1000 ha from the Wairoa River.

Three major alluvial aquifers have been defined beneath the Waimea Plains (Dicker, 1980). The surficial Appleby Gravel Unconfined Aquifer (UA) reaches depths of up to 15 m, and is highest yielding adjacent to the Wairoa and Waimea rivers. UA recharge is from river, rainfall and irrigation seepage. In the summer of 1982–83, assessed from flow records as a 1-in-45 year drought, 83% of Wairoa Gorge flow was lost to this aquifer before the river reached Challies Island (Fig. 1), leaving the lowest-ever gauged flow of 225 ls^{-1} in the Waimea River. Over 1220 ha were irrigated from the UA in 1982–83.

The Upper Confined Aquifer (UCA) and deeper Lower Confined Aquifer (LCA) contain clean river gravel deposited within clay-bound alluvium. Both are recharged north of Wairoa Gorge, partly via river leakage through the UA and partly via summer seepage from shallow aquifer lenses adjacent to the eastern hills.

The UCA ranges from 18 m deep near Wairoa Gorge to 32 m at its discharge zone near Appleby, where it leaks into the overlying UA. During 1982–83, 33 irrigation bores pumped from the UCA, with regional drawdowns averaging 4 m.

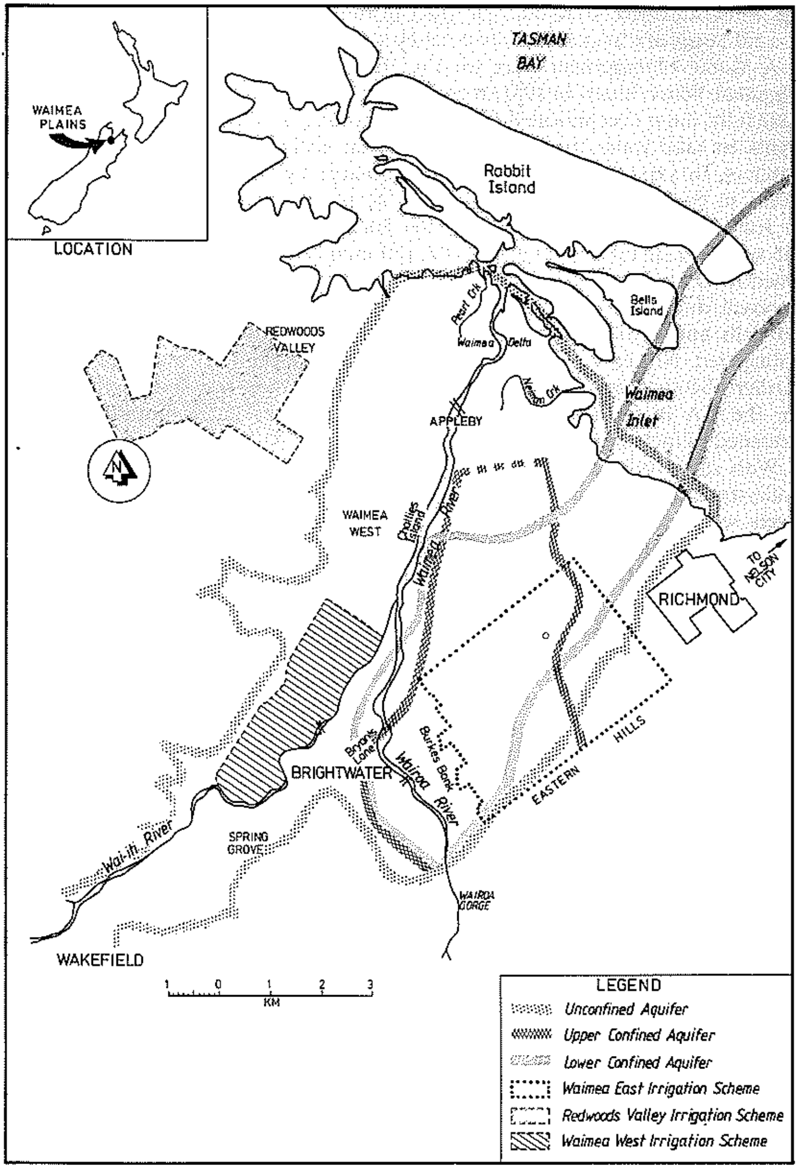

FIG. 1—Rivers and aquifers of the Waimea Plains, Nelson.

The LCA ranges from 30 to 50 m deep, extending beyond the Waimea Inlet. Irrigation pumpage is from 25 bores, and the town of Richmond takes up to 40% of total LCA summer pumpage from a wellfield at the coast. Summer drawdowns exceed 10 m, and sea-water intrusion is considered possible because coastal heads are frequently drawn below sea level.

A Water Management Plan for the Waimea Basin, drafted by the Nelson Regional Water Board in 1981, recognised that parts of the groundwater system were fully, if not over allocated. The Board introduced a moratorium on additional rights to take water in an area covering the recharge zone for the confined aquifers, to safeguard UCA and LCA recharge by maintaining overlying UA heads in this area. Further exploitation of the LCA was also halted because of feared sea-water intrusion in to the Richmond Borough wellfield. During the summers of 1980–81 and 1981–82, rationing was imposed on all LCA users when head at a monitoring well fell below an arbitrary level. No rationing was imposed during 1982–83 because of the discovery of fresh water in the LCA on Bells and Rabbit Island that year, further from the Richmond wells than anticipated. No sea-water intrusion was detected. In the 1981 management plan further abstractions were also banned for rivers during low flow periods, and for the UA in the lower Wai-iti Valley. In 1983, the latter moratorium was extended to include the entire Wai-iti Valley.

With such stress on the groundwater system, including the rivers, a better understanding of aquifer dynamics and the interactions between aquifers and rivers was essential to make water allocation decisions. It was decided that a three-layer areal model of the aquifers would be useful.

WAIMEA GROUNDWATER MODEL

The United States Geological Survey quasi three-dimensional finite difference model (Trescott, 1976) was selected, but it required modification to more adequately model the Waimea system. Modifications included:

- an improved river-aquifer interaction in which residual river flows are calculated sequentially down-river after losses or gains to groundwater.
- the facility for UA nodes to "rewater" when their head has earlier fallen below the base of the aquifer, drying out part of the UA. Parts of the UA are an important winter recharge zone for the confined aquifers, but fail when pumped in summer.
- improvements to data manipulation using time-dependent data from a TIDEDA data base (New Zealand Ministry of Works and Development), and the plotting of simulated heads both spatially and with time. Non-uniform time intervals were used for transient simulations, the minimum being an interval of one day (e.g. for simulating recharge through riverbeds during a flood).

The aquifers were represented in the model by 3 layers of 20 × 46 nodes with uniform grid spacing of 487 m (Fig. 2). Average values of transmissivity and storativity determined from pump tests, measured depths to the base of the

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Abbreviations		
	UA	Unconfined Aquifer
	UCA	Upper Confined Aquifer
	LCA	Lower Confined Aquifer

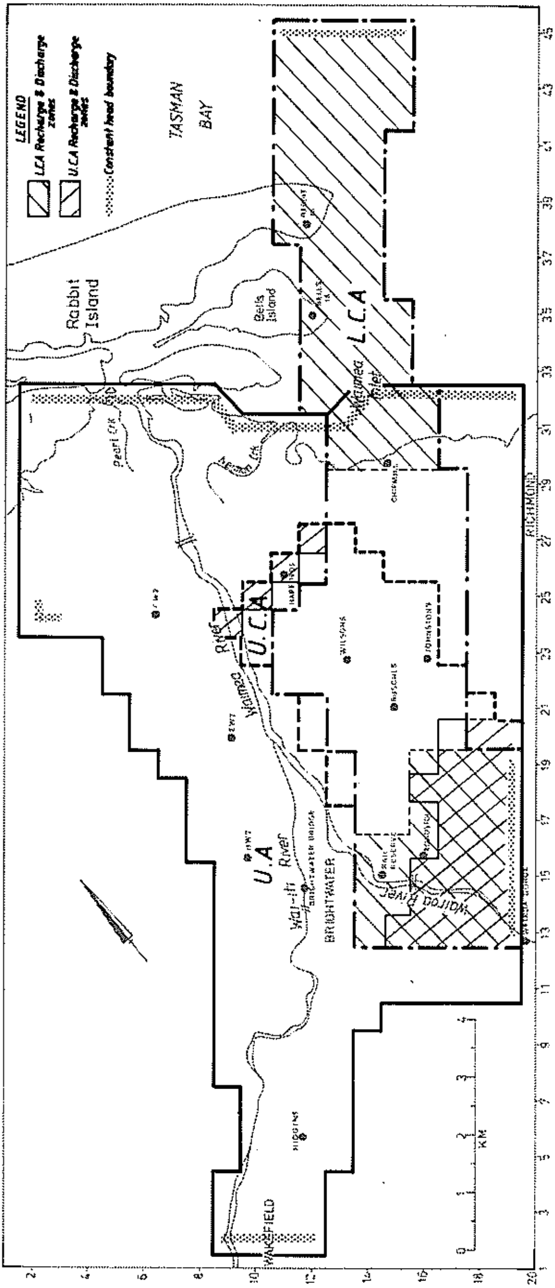

FIG. 2—Spatial discretisation and boundary conditions for the model.

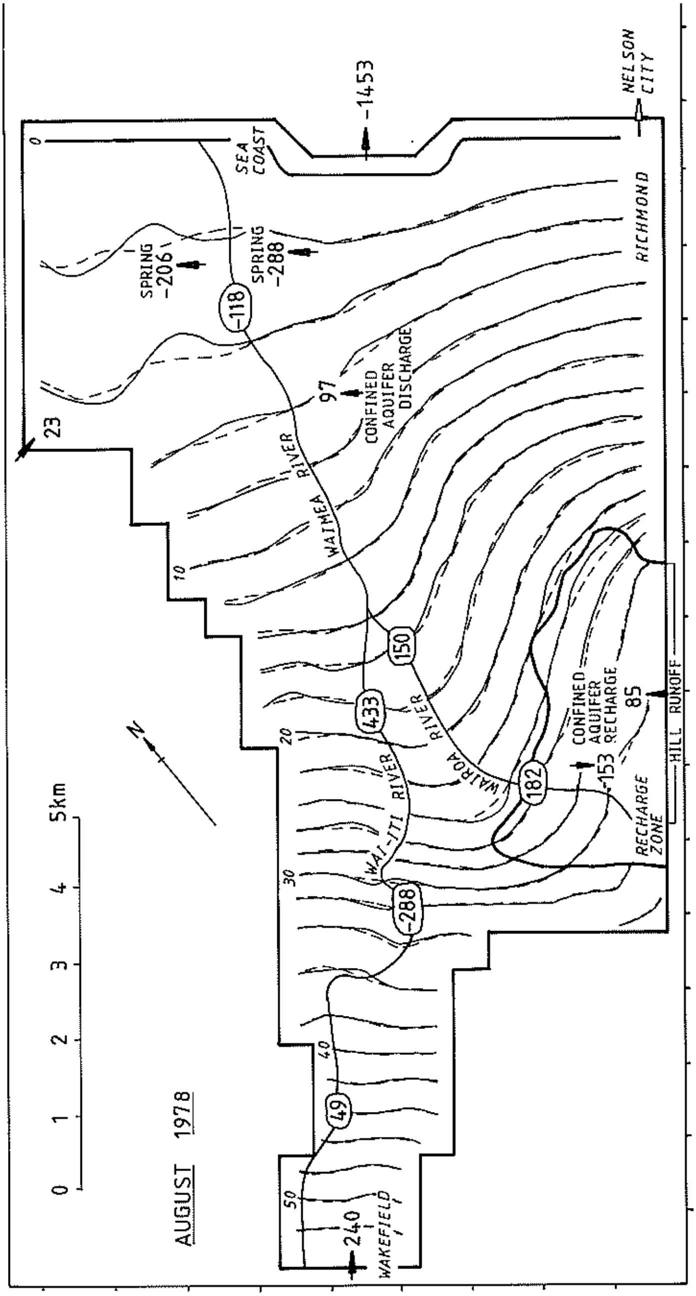

FIG. 3—Unconfined Aquifer steady-state calibration: simulated Unconfined Aquifer heads (dashed contours) are plotted against actual heads (solid contours) above mean sea level. Simulated recharges and discharges are show in ls^{-1}.

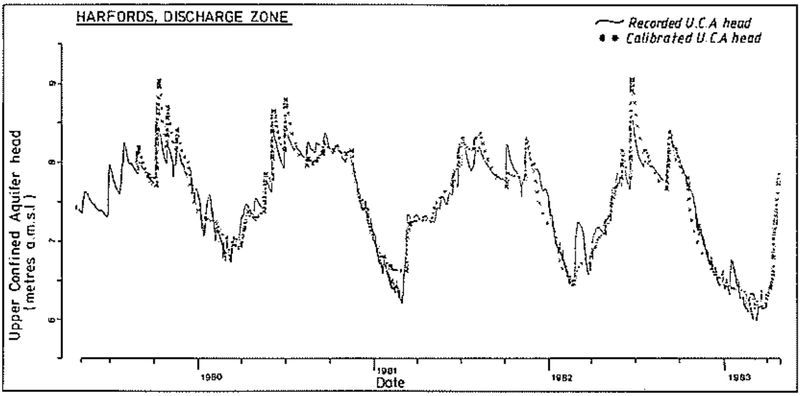

FIG. 4—Example of transient calibration for an Upper Confined Aquifer well, 1979–83.

UA, river-bed reduced levels and estimated river-bed permeabilities were interpolated for each node before model calibration. Submodels were developed to calculate time-dependent rainfall and irrigation recharge using water-balance accounting, and to extrapolate pumpage at each aquifer node from metered usage recorded at LCA wells.

A two-phase approach, comprising steady state then transient calibration was followed. For steady state calibration, Hunt's (1976) method of flow-net analysis was extended to include spatially varying leakage between aquifers. This was used to derive regional distributions of transmissivity and aquitard permeability. These were interpolated in to the nodal grid and further adjusted to achieve a good fit between simulated steady heads and observed winter heads (August 1978). Goodness of fit was calculated as root mean square difference between observed and simulated heads at aquifer nodes — the better the fit, the lower the root mean square. Overall root mean square, using parameters derived from flow-net analysis, was 0.9 m, improving to 0.22 m with trial-and-error parameter adjustment. Simulated aquifer throughflows were within 5% of target flows. The steady-state calibration is illustrated for the UA in Figure 3.

Transient calibration required adjustments to aquifer storativity and to rainfall recharge and river-bed permeabilities, to adequately simulate water level records from 13 wells for 1979–83, and to match river flows from five series of down-river gaugings. Excellent fit was obtained for most wells (Fig. 4). A better fit was obtained for river flows under low-flow conditions than for higher flows.

Calibration required adjustments to the conceptual model of the groundwater system. For example, a good LCA calibration could be obtained only by including a recharge boundary to allow additional recharge from the fractured rocks that form the eastern hills. Vertical leakage within the Waimea Inlet was also required, otherwise LCA transmissitivities measured beneath coastal islands would be ten times too large. UA transient calibration was improved by spreading rainfall recharge over five days following each rain event.

In summary, a well-calibrated model was developed, validated for a wide range of climatic conditions, including flood and drought, and for a wide range of aquifer stress.

MANAGEMENT SIMULATIONS

To test management simulations the transient response of the groundwater system during 1979–83 to various management scenarios was simulated and compared to the recorded behaviour. Particular attention was paid to results for March 1983, the height of a 1-in-45 year drought.

Existing Conditions

A useful summary of system behaviour was obtained by plotting the water-balance components for each aquifer (pumpage, recharge, discharge and change in storage) over the simulation period. Figure 5 shows the LCA water balance under existing 1979–83 stress. LCA inflow (Fig. 5) includes vertical leakage from the UCA, while outflow to the Waimea Inlet is primarily via upward leakage. The LCA is seen to have minimal storage. Pumpage induces increased recharge and reduces outflow to the Waimea Inlet to the extent that outflow reverses, suggesting significant sea-water intrusion for 1981–82 and 1982–83. Although no increase in salinity was detected in the LCA, it is likely that a front of sea-water is being drawn down cyclically through the 40 m of aquitard beneath the inlet.

The UCA was found to be less stressed than the LCA, with greater storage potential. Pumpage induced increased recharge but compared to the LCA, river freshes had a greater effect on recharge, via the UA.

For the UA, flow losses to the confined aquifers were minor compared to river and rainfall recharge. Nett losses of river flow to the UA occurred for more than 90% of the time; nett groundwater leakage *into* rivers occurred only after large winter storms. During the 1982–83 drought, UA pumpage was satisfied more and more by induced river seepage as UA storage stabilised. By the end of March 1983, nett river losses reached 1300 ls^{-1}, and UA discharge to the Waimea Inlet fell from a daily maximum of 2400 ls^{-1} to 970 ls^{-1}.

Unstressed Aquifers

Preliminary simulations were run to evaluate the natural seasonal response

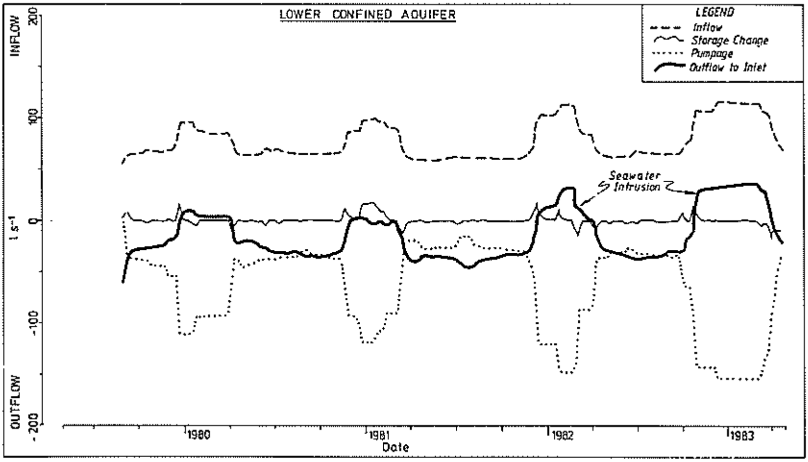

FIG. 5—Simulated weekly water balance for the Lower Confined Aquifer, 1979–83.

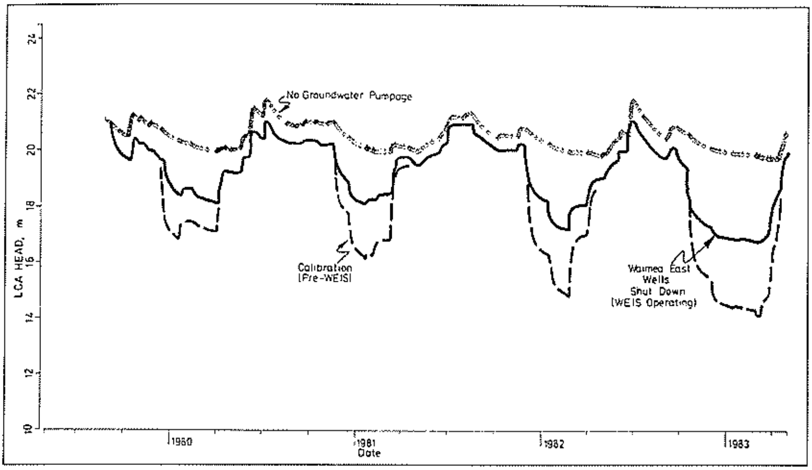

FIG. 6—Simulated LCA head at Rail Reserve monitoring well, comparing recorded (calibrated) head with unstressed and operative Waimea East Irrigation Scheme scenarios.

of the aquifers, with no pumpage from any aquifer. LCA heads were found to rise up to 2 m between summer droughts and winter rains (Fig. 6), but these fluctuations are heavily damped towards the coast. UCA and UA heads are affected more than LCA heads by river freshes and heavy rain. UA pumpage reduces UCA and to a lesser extent LCA heads because of reduced driving heads in the confined aquifer recharge zone.

Waimea East Irrigation Scheme (WEIS)

The Waimea East Irrigation Scheme, commissioned in 1984, will, when fully developed, draw up to 660 ls^{-1} from the Wairoa Gorge. The Nelson Catchment Board has revoked all water rights to irrigate from groundwater within the scheme area (Fig. 1). For March 1983 this would have resulted in a 53% reduction in pumpage from the UCA, and a reduction of 37% from the LCA. The effects of reduced groundwater pumpage and increased river pumpage are illustrated for the LCA in Figure 6. With all wells shut down within the scheme area, and irrigation water supplied instead from the Wairoa River, LCA heads recover by up to 3.3 m and UCA heads by up to 1.6 m in 1982–83. However, sea-water intrusion to the LCA of up to 14 ls^{-1} is still predicted.

For March 1983, simulations also show that river abstractions by the scheme reduce river leakage to the UA by 39%. This results in lower UA heads west of the Waimea River, and minimum river flow is reduced from 200 to 160 ls^{-1}. This confirms the influence of the unconfined groundwater in maintaining a minimal flow in the river channel, but also shows the need for the Nelson Catchment Board to ration river pumping if a higher minimum river flow is to be maintained.

Waimea West Irrigation Scheme (WWIS)

This proposed irrigation scheme covering 370 ha of poor-yielding UA south of Waimea West (Fig. 1) was simulated using five supply options, using water supplied from both within the scheme area and from the higher yielding Waimea Delta, the area surrounding the lower Waimea River. The aim was to determine the impact of pumpage on local UA groundwater and on minimum river flows.

It was found that supplying the WWIS from local groundwater, even from evenly spaced lower-yield wells, would result in at least 25% of the local aquifer being dewatered in a 1982–83 drought. Augmenting the supply from a UA Delta wellfield proved practicable, provided the wellfield is located near the Waimea River and upstream of the river reach affected by sea-water intrusion during spring tides, i.e. near Appleby Bridge.

Redwoods Valley Irrigation Scheme (RVIS)

The possibility of "exporting" UA groundwater from the Waimea Delta to the adjacent 200 ha RVIS (Fig. 1) was simulated. This scheme has recently been implemented for an area of 62 ha. The aim was to check whether the RVIS could be supplied even if the 1400 hectare Waimea Delta area were fully irrigated from the UA. This would be possible, but groundwater supplied uniformly from within the Delta would draw a tongue of sea-water inland along the western edge of the UA, adjacent to Redwoods Valley. Flows from coastal springs would be substantially reduced, and leakage to the UA from the Waimea River would increase. The RVIS could be supplied with least impact if the RVIS wellfield were near the river at Appleby. Such development would reduce UCA heads by 0.2 to 0.3 m in the UCA discharge zone near Appleby, because of the fall in overlying UA heads.

Optimal Aquifer Yields

Finally, a series of simulations was run to determine the "safe yield" of each aquifer, given continuation of the present pattern of irrigation. Domenico (1972) points out the difficulty of defining and evaluating "safe yield", and prefers the more dynamic concept of "optimal yield". Freeze (1983) notes that effective groundwater management requires knowledge of yield at the regional scale; optimal yield must balance the benefits of groundwater pumpage against the undesirable changes that will be induced by such pumpage.

Optimal yield is not unique, because it depends on the spatial and time-dependent pattern of the pumpage. Evaluation of optimal yield from each Waimea aquifer required determination of the major management constraints for each aquifer. These were:

(a) *Lower Confined Aquifer:* preventing sea-water intrusion to coastal wells.
(b) *Upper Confined Aquifer:* optimising summer drawdown versus pumpage.
(c) *Unconfined Aquifer and Rivers:* maintaining a specified minimum low flow in the Wairoa-Waimea river system, set in the Waimea Basin Water Management Plan (Nelson Catchment Board, 1986) as 225 ls^{-1}. Also, localised optimisation of pumpage and drawdown, and prevention of sea-water intrusion into the UA.

Simulations were run to determine the practicality of irrigating, from each aquifer, the area overlying it not already serviced by an irrigation scheme. Irrigation rates were assumed proportional to metered LCA rates, with a peak application rate of 0.58 ls^{-1} ha^{-1} (35 mm wk^{-1}) pumped uniformly from each underlying aquifer node. Results were compared with simulations of other levels of exploitation of each aquifer to interpret optimal yield.

No aquifer was able to supply irrigation to its entire overlying area, even though

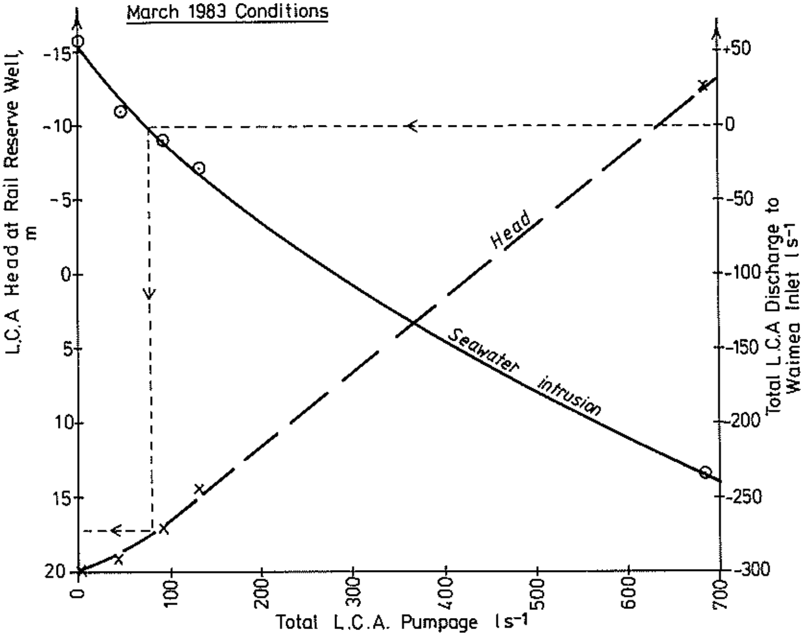

FIG. 7—Head at the Lower Confined Aquifer Rail Reserve well and simulated sea-water intrusion to the Lower Confined Aquifer as related to total Lower Confined Aquifer pumpage.

the Waimea East Irrigation Scheme already services part of the confined aquifer area. Massive sea-water intrusion and dewatering of the LCA aquifer would occur. Figure 7 presents results from five simulations relating LCA sea-water intrusion to total pumpage under the present spatial pattern of wells. Sea-water intrusion occurs if the LCA discharge to the Waimea Inlet becomes negative, through excessive pumping. If the conceptual model for the coastal end of the LCA is correct, pumpage should be limited to a maximum of 80 ls^{-1} and the threshold level for implementing rationing should be raised from the current 15 m to 17 m at the Rail Reserve monitoring well in the LCA recharge zone (Fig. 7).

Over half of the UCA would become unconfined or totally dewatered (Fig. 8) if full irrigation of its overlying area outside the Waimea East Irrigation Scheme were attempted. LCA heads would also be reduced because of reduced recharge from the overlying UCA. UCA transient yield was estimated from the simulations to be around 200 ls^{-1} for the area of UCA outside the irrigation scheme.

Increased pumpage from the UA could be sustained from higher yielding gravels near the rivers, but this would reduce river low flows and water availability elsewhere, especially along the margins of the Wai-iti Valley, around Brightwater and along the western edge of the plains. The impact is least severe in the Waimea Delta. Thus, water management for the UA is best approached by setting allocations for defined sectors of the aquifer, e.g. Wai-iti Valley, Waimea Delta.

The simulations identified a resilience in river low flows. Figure 9 presents

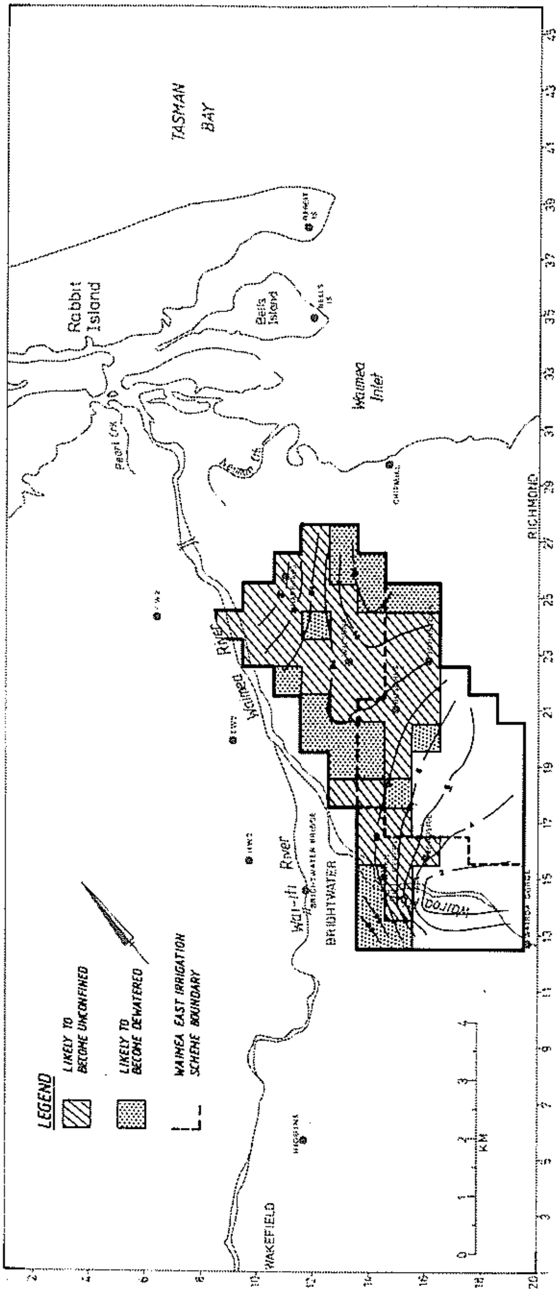

FIG. 8—Simulated additional water level drawdowns in the Upper Confined Aquifer for full irrigation development of its area outside the Waimea East Irrigation Scheme, March 1983.

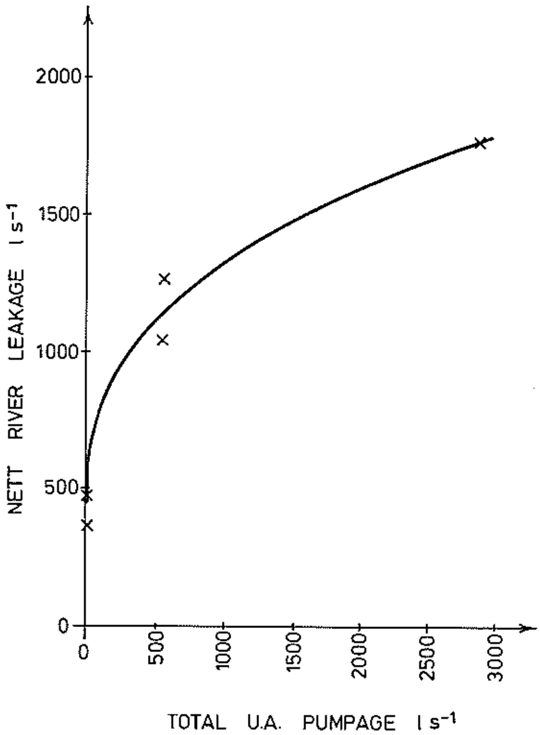

FIG. 9—Nett river leakage to the Upper Aquifer related to total Upper Aquifer pumpage.

the results of five simulations to show that nett river leakage approaches an asymptote as total UA pumpage increases. Some river reaches become perched above the UA water table and leakage therefore becomes independent of UA head. However, comparison of leakages reach by reach indicates that the Waimea river at Challies Island would have been almost dry in March 1983, if the Waimea East Irrigation Scheme were in full operation.

WATER MANAGEMENT PLAN FOR THE WAIMEA BASIN

Waimea Basin Water Management Plan policies (Nelson Catchment Board, 1986) were based to a large extent on the results of this groundwater model. Policies included:

- an extended moratorium on additional water allocation in the LCA because of the possibility of sea-water intrusion;
- rationing of LCA pumpage when the head at the monitoring well falls below 15 m. (Although sea-water intrusion was predicted at this level, there was sufficient uncertainty about the coastal structure of the LCA for the Catchment Board to retain the previous trigger level);
- further water allocation from the UCA up to a maximum pumpage of

150 ls^{-1}, the impact of which will be assessed before extension to the estimated yield of 200 ls^{-1};

- extension of the moratorium on additional UA water allocation to the Waimea West area north to Challies Island;
- metering of water usage in all moratorium zones, both for rationing and for future modelling of aquifer stress and response;
- rationing of Wai-iti catchment water when the Wai-iti River dries up below Brightwater bridge; and
- minimum well spacings of 100 m in the confined aquifers and 50 m in the UA.

This plan has been implemented. All Waimea rights to take water either expired in May 1986 or were cancelled in May 1987. New applications were sought from bona fide users and new irrigation allocations were based on committed usage up to May 1986, calculated at a rate of $350 \text{ m}^3\text{ha}^{-1} \text{ wk}^{-1}$ (35 mm wk^{-1}). Water rights now reflect actual usage and those previously held for speculative purposes such as boosting land value have not been renewed.

The plan acknowledges that groundwater is limited and that means of augmenting the water resource are required. The most economic are likely to be small dams in the Wai-iti foothills and artificial groundwater recharge.

CONCLUSIONS

An integrated groundwater and river model was valuable for evaluating regional water management options and was also a catalyst for the evaluation of the large amount of geohydrological data for the Waimea Plains. The model highlighted areas, such as river-aquifer interaction and the LCA coastal discharge mechanism, which require more intensive data collection.

While computer modelling is indeed useful where large amounts of data are available, as for the Waimea system, it can also be used for testing theories about the behaviour of aquifer systems which are less well characterised.

ACKNOWLEDGEMENTS

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