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UNDERGROUND WATERS OF THE LOWER HUTT —A MODEL STUDY

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ABSTRACT

A two-dimensional time-dependent computer-based model of the Lower Hutt - Port Nicholson groundwater system has been developed and is described briefly in this paper. This model is designed both as a resource and as a management tool in that it has the potential of simulation of this groundwater system under real operating conditions as well as of prediction of drawdown effects under sustained withdrawal conditions of any type likely to be expected in practice.

Computed heads throughout the field over a seven-week period are illustrated and show the quality of this model as a tool in groundwater behaviour simulation.

INTRODUCTION

The waters of the Hutt Valley - Port Nicholson groundwater basin are one of the major sources of water in the Wellington region. Wells tapping the aquifers of this basin supply the municipal needs of Lower Hutt, Petone, and Eastbourne and supplement the Wellington City supply. Other wells supply the needs of many of the major industries of the Lower Hutt Valley. It is thus of considerable importance that the operation of this groundwater system be fully understood and that those responsible for the management of this resource have the means of assessing the effects of various demands on it under a wide range of circumstances. With this in mind it has been suggested that it would be appropriate to develop a suitable model of the system as one means of carrying out such assessments.

In a preliminary study of this system (Donaldson, 1973), the author analysed much of the available data to obtain parameters of the system that are essential in model development, and utilized

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these in setting up a simple 'one-dimensional' model of the main Lower Hutt Valley aquifer. This simple model was set up:

(1) to check and establish the data necessary for more comprehensive model studies;
(2) to determine parameters of the system that cannot be measured directly or obtained by simpler data analysis;
(3) to illustrate the potential of the modelling system;
(4) to assess whether a more comprehensive model study of this system would be either feasible or warranted.

Although this model study was restricted by the simplicity of the model – only variation down the valley and steady conditions being considered in it – it proved extremely satisfactory for the purpose for which it was intended. In particular it showed that a fuller model could be very useful not only in the assessment of the resources of this groundwater system but also as a management tool for determining field behaviour under critical or changing conditions. The basic tests carried out showed that this steady-state model was capable of determining the ultimate drawdown in the system under a wide range of conditions and that it could be useful for the estimation of maximum withdrawal rates that could be sustained by the system for long periods under these conditions. Being steady state, however, the model did suffer from the restraint that transient effects, such as those due to limited periods of heavy withdrawal as might occur during drought conditions, could not be assessed.

Computer runs using this model were carried out for a large number of diverse situations that could arise or be set up in this system. These runs covered situations involving:

(1) river level changes in the infiltration zone;
(2) redistribution of wells and withdrawals along the valley;
(3) alteration of the mean rate of withdrawal from the wells;
(4) modification of the leak pattern beneath the Port Nicholson harbour.

The results showed that the raising of the river level in the infiltration zone by some 2 metres could increase the potential withdrawal rate of the system to about 122 Ml/d, i.e. to approximately twice the present average withdrawal rate of 66 Ml/d or to approximately 1.2 times the present potential average withdrawal rate of 105 Ml/d. They also showed that a significant gain in potential withdrawal rate, to about 140 Ml/d, is possible under present river conditions by resiting the wells about 2 km up the valley from their present positions. As, however, the 'one-dimensional' character of the model implies the averaging of all effects, withdrawals, etc., across the width of the valley, the full effects of well siting and of the withdrawal pattern could not be explored with this model.

In this paper a time-dependent 'two-dimensional' model, incorporating variations both along and across the Lower Hutt Valley, is discussed. This model is at present under development at the Physics and Engineering Laboratory.

Before considering the model in any detail it is useful to have some concept of the system being modelled. In the next two sections therefore is a somewhat brief discussion of the structure of the system and the water flows in it. This is followed by a description of the model and the modelling technique and of some of the preliminary results obtained with it. The paper concludes with a brief consideration of some studies that it is hoped to carry out with this model when all the parameters are set.

STRUCTURE OF THE HUTT VALLEY - PORT NICHOLSON ALLUVIAL BASIN

The Lower Hutt Valley is a delta formation that has developed by the deposition of alluvium carried down by the Hutt River. Meanderings and floodings of this river have built up, eroded away and redistributed these gravels to form extensive layers of permeable material intermingled with lenses of less permeable silts and suchlike. These layers are the aquifers of the groundwater system.

The deposition and distribution of coarse material has been affected from time to time by the periodic inundations of the lower part of the valley by the sea. These inundations have resulted in the deposition of fine, relatively impermeable silt layers between the various permeable ones. These finer beds restrict motion of water from one aquifer to another, and thus channel the water flows in the system; they are the aquicludes of the groundwater system.

The structure of the Lower Hutt - Port Nicholson basin has been described in some detail by Hutton (1965). and reference should be made to his report for fuller information. The overall structural picture that he gives is based on the geological studies of Stevens (1956a,b,c, 1957a,b, 1958) and Grant-Taylor (1959, 1963), the gravity survey by Cowan (1961), the seismic surveys by Garrick (1963, 1964a,b) and on borehole data. This information suggests that the basement rock defining the basin slopes down the valley from near the ground surface towards the north end of Taita Gorge to attain a depth of about 300 m in bore UWA 1 near the western boundary of the basin in Petone. This basement rock then continues

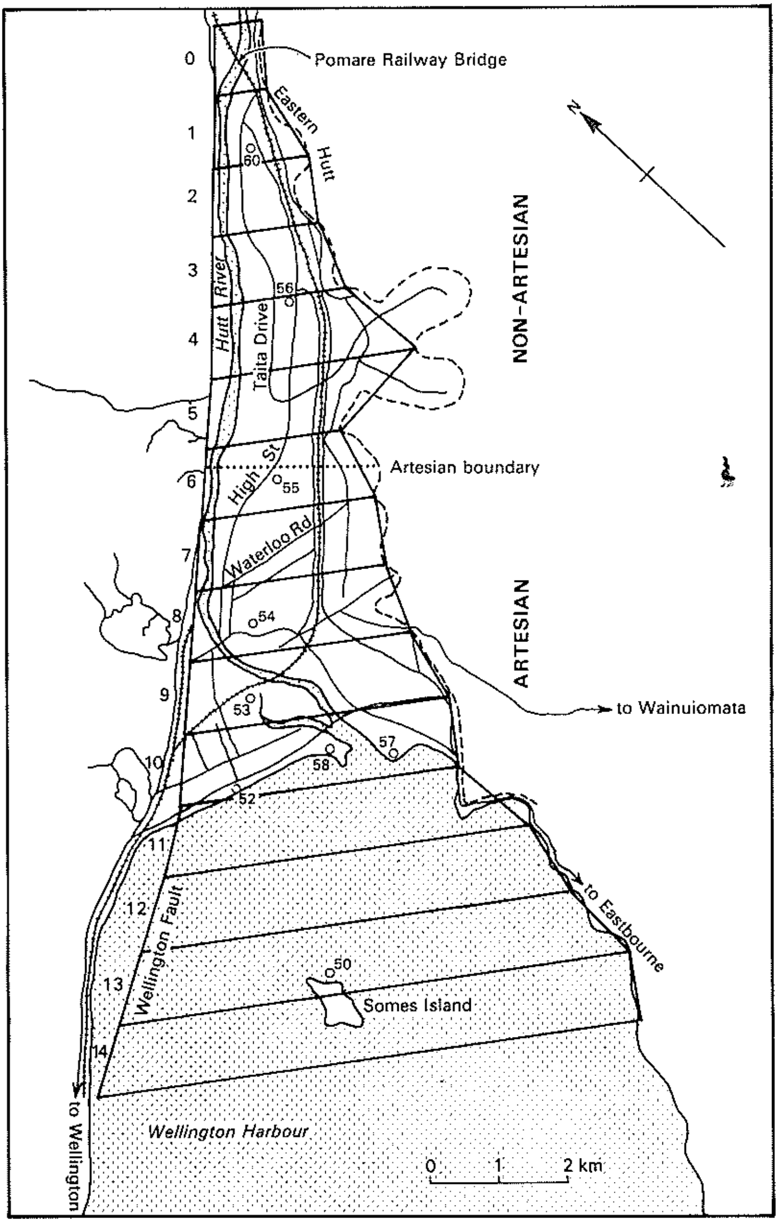


FIG. 1 — Plan of the Hutt Valley showing the underground water system boundaries, the measurement wells (numbered circles) and the 1000-metre grid used down the valley in the model analysis. The artesian and non-artesian sections are separated by the dotted line across the system in section 6.

beneath Port Nicholson harbour. The Upper Hutt basin extending north from Silverstream is a separate system and is not treated in this study.

To the east the basement rock and the basin are defined by the downward continuation of the eastern hills; to the west, however, the available evidence indicates that the groundwater basin is bounded by the Wellington Fault rather than by the physical valley boundary. To the south there appear to be no delineating structures that can be directly assumed to be boundary for the groundwater system structure. Somes Island is basement material but rises sharply on all sides through the covering layers and thus does not indicate any general structural change.

Beneath the harbour and over the southern end of the land section of the valley the permeable beds overlying the basement rock are capped by an impermeable layer. To the south this layer consists mainly of marine silts and clays, but further north the Melling peats become predominant. Hutton (1965) calls this the main or first marine aquiclude. This appears to fade out at about the Hutt Golf Course, and to the north of it, throughout the remainder of the valley, the permeable beds are assumed to be virtually uncapped. This northern section of the Lower Hutt Valley groundwater system is thus non-artesian; the southern section and the section beneath the harbour is artesian in character.

A map of the Lower Hutt Valley - Port Nicholson harbour region illustrating the known boundaries of the groundwater basin and the estimated position of the artesian/non-artesian boundary is shown in Fig. 1. The evenly spaced lines in this figure are 1000 metres apart and are bounding lines used in both the one- and two-dimensional models. The dashed line indicates the base of the bounding eastern hills.

Unfortunately, the various horizons existing beneath the main aquiclude cannot be distinguished beneath the land area by indirect geophysical techniques. Such information that does exist thus comes from a relatively limited number of well records. As drilling for water only requires a well to penetrate a short distance into an aquifer, and almost all the water being drawn from this system comes from the upper or main aquifer, information about the deeper strata is extremely limited. Most of the information concerning the deeper horizons included in Hutton's (1965) report thus comes from the interpretation of data from only four holes. These data do, however, indicate that there are two main freshwater aquifers and that toward the southern end of the land region these overly a series of saline water horizons.

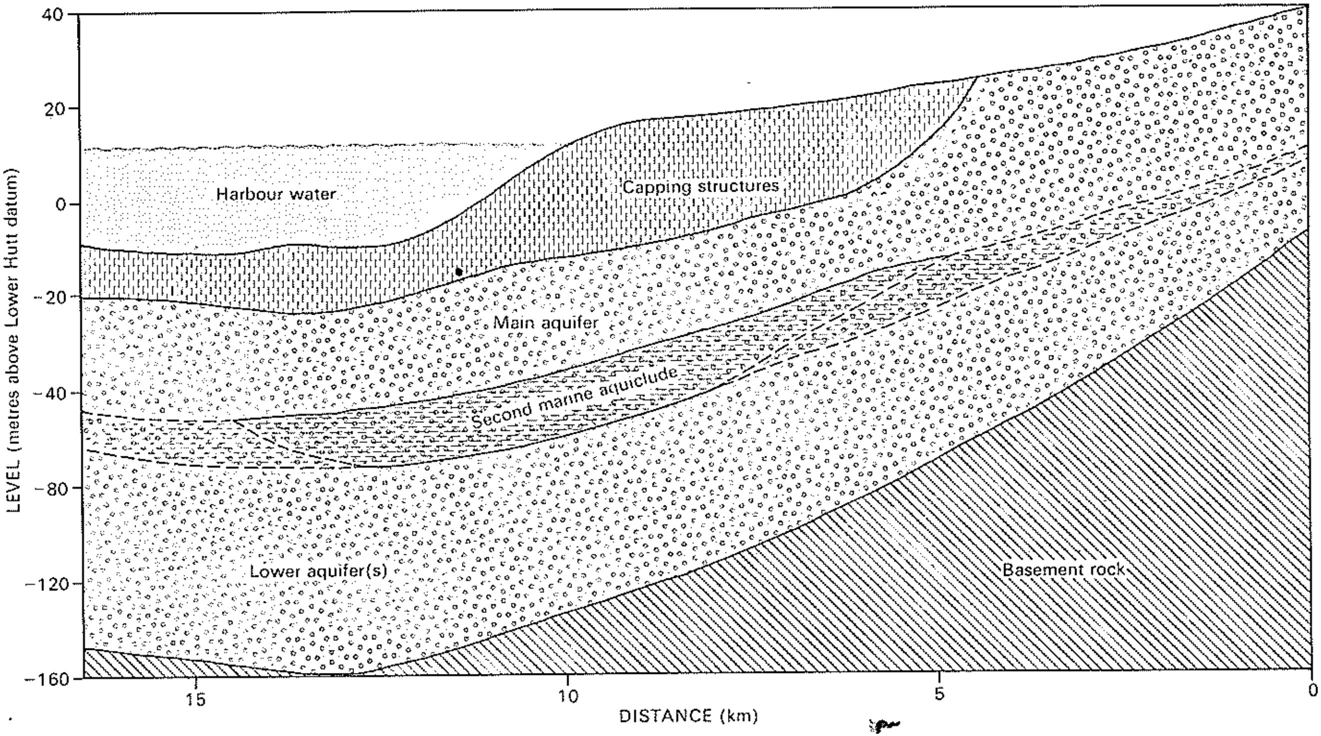


FIG. 2 — A vertical section through the Hutt Valley system to illustrate the pertinent structures in the system. The dashed lines associated with the second marine aquiclude indicate different possible extensions of this structural component.

A vertical section taken along the axis of the valley to show the possible structural form is illustrated in Fig. 2.

GROUNDWATER FLOW IN THE BASIN

As the aquifers all slope down the valley the natural trend of the groundwater flow must be in this direction, i.e. from the non-artesian zone to beneath the harbour.

The Source of Water for the System

With the system as it exists, with effective boundaries to groundwater infiltration from other sources to the north, east and west, the water charging the aquifers must come from within the valley area. Here the only possible sources are rainfall and the Hutt River. Hutt River gaugings by K. J. Mawson in 1939 (Stevens, 1956a) indicate that this river must be the major source for the groundwater and that the infiltration zone extends from the southern end of Taita Gorge to the region of Belmont and the Hutt Golf Course.

The Aquifer System

Flow through the aquifers of the system is controlled by the head of water driving the flow, the pressures downstream, and the resistance of the channels making up the aquifer system. In a simple single aquifer system the pressure would thus be expected to drop continuously along the aquifer from the source to the outlet. Capping of the aquifer and the resultant high resistance to leaks can result in artesian pressures, and this in fact occurs in the Hutt Valley - Port Nicholson system throughout the capped section, i.e. the southern end of the valley and beneath the harbour.

This system, however, consists of at least two aquifers and is affected by both tidal movement in the harbour and withdrawal from the on-shore wells. The natural flow characteristics of the system are thus somewhat obscured by these processes. Nonetheless the study of pressure interactions of wells tapping the various horizons described by Hutton (1965), and the fact that the lower freshwater aquifer and the saline horizons are at significantly higher artesian pressures than the main aquifer, does suggest that the two freshwater aquifers are not directly connected anywhere near the withdrawal zone and that the saline horizons and the lower freshwater aquifer could be a single flow unit. Fig. 2 has been drawn in such a manner as to attempt to illustrate these surmises.

The Outflow of Water from the System

Before the exploitation of this system by withdrawal from wells, all of the water passing into the system must have been escaping from it into Port Nicholson harbour. Even until relatively recently a significant proportion of the water entering must still have been passing right through the system. Nowadays, however, because of increased withdrawals and lowering of the Hutt River bed the amount escaping into the harbour may not be quite so significant.

On the basis of a plot of pressure measurements in wells to the south end of the Hutt Valley, McKillop (1935) suggested that the main outflow into the harbour must occur somewhere to the south of Somes Island. Later similar plots illustrated by Bach (1958) and later workers tend to move the point of discharge further and further south. This suggests that either the change in flow pattern associated with withdrawal and river modification is influencing the pressure profile to a greater and greater extent, or else that the outflow characteristics of the system have changed over the years. As information relating to harbour leaks is relatively sparse the answer to this question must be kept open at this time.

Withdrawal of Water from the System

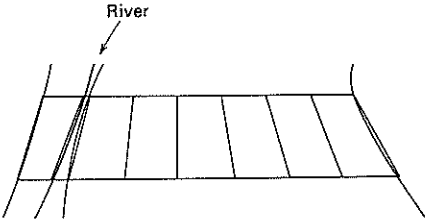
Most of the water withdrawn from wells tapping this system is taken from the upper or main aquifer from wells sited towards the southern end of the valley, i.e. in sections 8, 9 and 10 of Fig. 1. Most of this water is drawn during normal working hours at an average withdrawal rate of 66 Ml/d. This withdrawal rate may, however, drop as low as 36 Ml/d or rise as high as 91 Ml/d.

MODELLING THE GROUNDWATER SYSTEM

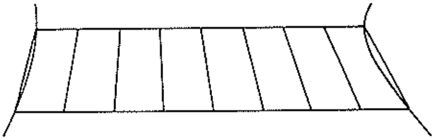
For computer modelling of groundwater systems two approaches are in use at the present time – a finite-difference approach (Pinder and Bredehoeft, 1968; Prickett and Lonnquist, 1971) and a finite-element approach (Pinder and Frind, 1972). Because of his previous experience with the finite-difference technique and because of the known reliability of this technique for the type of equations arising in groundwater problems, the author has opted for this type of approach in this model. It is expected, however, that the finite-element approach would have been just as satisfactory.

The Model

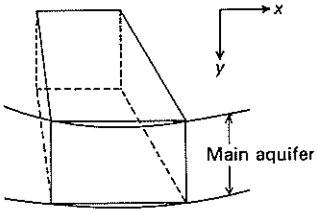
For this model the main aquifer of the Lower Hutt Valley system is divided up into a series of separate elements. In contrast



(a) INFILTRATION ZONE



(b) REMAINDER OF SYSTEM



(c) TYPICAL ELEMENT

FIG. 3 — The cross-valley pattern of elements used in the model and the form of a typical element.

with the usual finite-difference approach, for which such elements are normally rectangular in form, because of the valley shape and the general basic flow down the basin the elements used here have been taken in the form illustrated in Fig. 3. Thus each strip across the valley illustrated in Fig. 1 is divided into eight elements. In those strips into which water is entering from the river, the river itself is taken to be the second element from the left (see Fig. 3a). The six elements to the right of this are then set up by dividing the grid lines into six equal parts. The element to the left of the river is included to allow for the flows along this side. This element may, however, be of zero width in sections of the system in which the river overlies the basin-bounding Wellington Fault. Further down the valley all eight elements are set up by dividing the grid lines into equal units (Fig. 3b).

In the vertical dimension the elements, as illustrated in Fig. 3c, span the full depth of the aquifer. In the artesian zone, where the aquifer is saturated and capped, the vertical water-layer thickness is assumed to correspond with that of the aquifer. In the non-artesian zone the water level must be determined in each element at each step of the computations. In the intermediate zone, allowance must be made for the possibility both of incomplete filling and of saturation of the aquifer in each element, i.e. the computer programme determines where the artesian/non-artesian interface occurs at any time.

The Water Balance of Each Element

The equations used in this model are set up by assuming a full water balance for each element. Thus

The mass of water gained by the element in time Δt
= the mass flowing in from the element immediately to the north
− the mass flowing out to the element immediately to the south
+ the mass flowing in from the element immediately to the west
− the mass flowing out to the element immediately to the east
+ the mass gained from the river (if the element is below this)
− the mass lost by withdrawal from wells
− the mass lost through leaks into the harbour (if the element is below this)
in time Δt.

In setting up the equations from this water balance the only major assumptions made are that physical parameters do not vary over the element and that Darcy's law applies for the flow through the aquifer. Taking these assumptions into account, the terms listed above may all be readily specified. The mass flowing into (or out of) any element from a neighbouring one, for example, may be taken in the form

$$\rho K A_{\mathrm{v}}(\Delta H/\Delta D)\Delta t$$

where K is the permeability normal to the common element boundary at that common boundary; A_{v} is the area of water-saturated material at that boundary; ΔH is the difference in head or water level between the centres of the two elements involved, and ΔD is the distance between these centres; ρ is the density of the water.

The mass gained from the river by an element immediately beneath is taken in the form

$$\rho R A_{\mathrm{H}} \Delta H_{\mathrm{R}} \Delta t$$

where R is a resistance parameter (dimensions equivalent to permeability/length); A_H is the horizontal area of the element; ΔH_R is the difference in head between the river water and that in the aquifer in the element. (An option has been built into the model to permit this element water head to be specified directly by that of the river water if the model user so desires. This option is equivalent to the assumption of zero resistance between river and aquifer.)

The mass withdrawn from wells tapping the aquifer is taken directly from records. In the equations it is specified as a known variable at each time step.

The term representing the mass leaking into the harbour from an element beneath the harbour is taken in the same form as that for flow into an element from the river. In this case, however, ΔH_R is the difference in head between that of the water in the aquifer and the equivalent freshwater level of the seawater at the centre of the element.

The mass gained by an element in time Δt depends upon whether the element is in the artesian or non-artesian zone of the system. In the non-artesian zone any gain in water mass in an element is due to an increase in water level. The term involved thus takes the form

$$\rho \theta A_H (\Delta H_t / \Delta t) \Delta t$$

where θ is the porosity of the aquifer and ΔH_t is the change of water level in the element in time Δt. In the artesian zone this term is controlled by the compressibility of the water and of the matrix material of the aquifer. It takes the same form as above, with the porosity being replaced by S, a storage factor depending on these compressibilities. In this case ΔH_t becomes a head difference.

Boundary Conditions

As the boundaries to this system are clearly defined on three sides, suitable boundary conditions are not difficult to define. For the model, impermeable walls are assumed to the east and to the west of the outer elements in these directions; to the north it is assumed that the river controls the heads in the aquifer across the elements of section 0 (Fig. 1); to the south it is assumed that the head gradient drops to zero when section 16 is reached. These boundary conditions are readily incorporated into the equations.

The Solution of the Equations

Combining the boundary conditions with the equations results in a single equation for each element of the model. Assuming that all structural parameters, withdrawal rates and river and harbour levels can be injected as input information, this set of equations becomes a set of simultaneous equations in the heads or water levels at the centre of each of the elements. This set of equations may thus be solved at each time step.

The method used for the solution of these equations is one developed by Peaceman and Rachford (1955) and used by both Pinder and Bredehoeft (1968) and Prickett and Lonnquist (1971) in their groundwater studies. This is an iterative technique which is improved markedly by reducing the large set of simultaneous equations involved down to a number of small sets which are then each solved directly. By carrying out this reduction first for the elements across each section of the model and solving these equations, and then repeating the exercise for elements in lines down the model, the iterations can be made to converge extremely rapidly and the computation time is significantly reduced. This model study has so far been carried out on a 24K-store Hewlett-Packard 2100A mini-computer, and requires approximately 5 minutes of computer time for each week of real-time simulation.

RESULTS

In most computer-based models of groundwater systems the prime aim of the analysis is to determine the long-term drawdown effects associated with various rates or distribution of withdrawal from the system. In this Lower Hutt model, however, an attempt has been made to simulate the system in sufficient detail to be able to match the day-by-day variations of the system of a significant time period. The potential of long-term evaluation of the system has not, however, been discarded.

The computer programme associated wiht this model has therefore been set up to handle three different modes of operation. In the first mode only the steady-state solution for specific river and withdrawal conditions is computed. This is useful in resource estimation if one is only interested in the effects of or the determination of an ultimate average withdrawal rate. In the second mode the transient solution towards a steady-state condition from any previous condition is computed. The time scale associated with certain changes in the system characteristics (flows or heads) may thus be assessed, and it should be possible to establish the potential of the system to withstand limited periods of overwithdrawal in critical situations. In the third mode the model simulates the actual variations occurring in the real system under varying day-to-day conditions. In this mode the river levels and the withdrawals can be varied at any or all time steps.

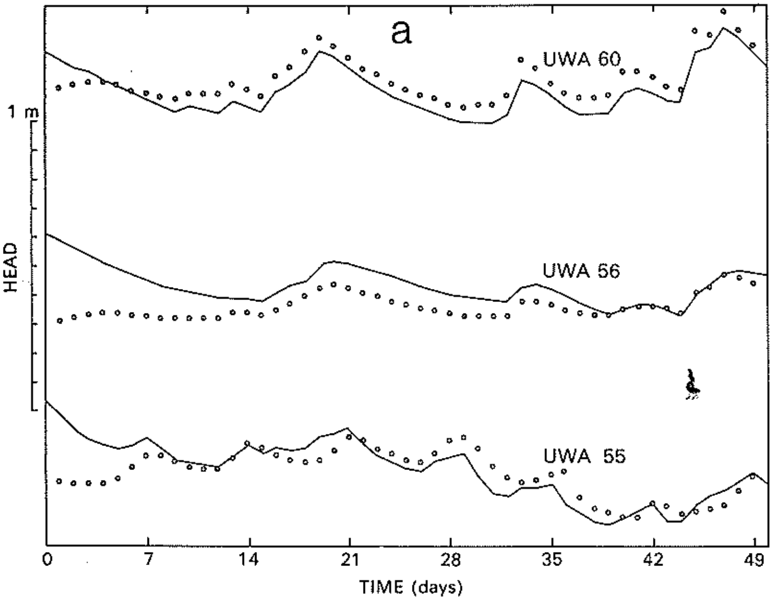
In assessing this system to date, the computer programme has been used in all three modes. Use of the steady-state mode with average river data and average withdrawal data has been invaluable in the establishment of permeability values for the system and in the matching of average head data for the various measurement wells sited throughout this basin (numbered circles, Fig. 1).

In the preliminary study (Donaldson, 1973) an analysis of well pressure variations with time showed that effects associated with tidal movement in the harbour totally obscured all other effects. Elimination of these by averaging over a 12½-hour tidal cycle resulted in a clear relationship between withdrawal rate and drawdown. Use of the third mode with an average week of withdrawal data was therefore the next stage of the programme. Matching of computed and measured amplitude of variation over this week established the storage factors of the system.

All other runs, in either the second or third modes, have used the data established in these earlier runs to determine patterns or trends of the system. Because of the relatively few measurement sites in relation to the number of elements in the model, permeabilities are taken at this time to be constant across any east–west section of the system, i.e. only variation from section to section down the valley is built into the model. It was also found that only two storage factors were necessary for a reasonable match of the system. One of these applies in all artesian-type elements beneath the land sections, the other applies in all elements beneath the harbour.

As a first formal test of the system, data for the 7-week period 26 September to 12 November 1972 was fed into the model. As withdrawals are only recorded on a daily basis, matching of computed and measured data was only carried out at 24-hour intervals (midnight each day). For a selection of measurement wells, these computed and measured values are plotted in Fig. 4a, b and c. The computed values are marked by the small circles. The measured points are joined by straight lines for clarity. It is seen that differences in most cases are only of the order of about 5 cm. Considering that modifications of storage factors can only affect the overall amplitude of the variations, and alteration of permeability only affects the mean head values, it is seen that the model is a remarkably good match of the real system.

The divergence of some results over the first 10 days or so is due to the selected initial head pattern. It has been found that if this pattern is well chosen, the system stabilizes in about this time. Poor patterns take significantly longer. Studies with the model in the second mode suggest that periods of about 1 to 2 months will be


a
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UWA 55
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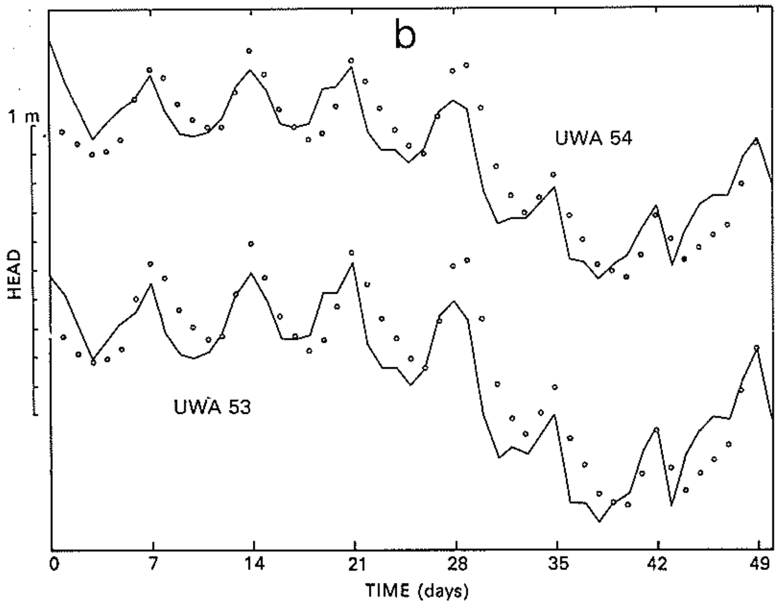
TIME (days)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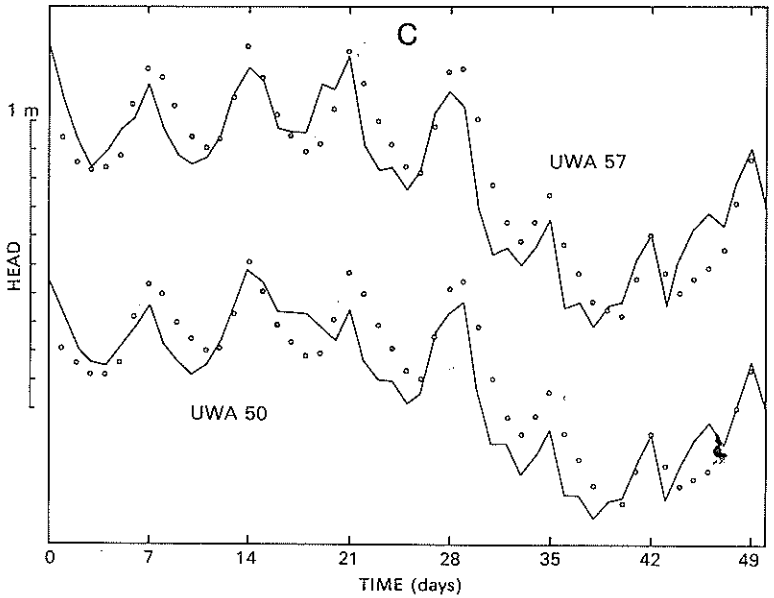

FIG. 4 (*above and opposite*) — Computed and measured heads in wells in the system for the 7-week period 26 September to 12 November 1972.

(a) Wells UWA 60, UWA 56, and UWA 55. Wells UWA 60 and UWA 56 are sited in the non-artesian zone, UWA 55 is just within the artesian section.

(b) Wells UWA 54 and UWA 53.

(c) Wells UWA 57 (Petone foreshore) and UWA 50 (Somes Island).

Relative head changes only are shown.

Solid lines connect measured values, circles indicate computed results.

all that is needed to establish a new basic pattern after a significant change. This, of course, suggests that overwithdrawal of the system will need to be restrained to limited periods. The length of such periods have, however, yet to be assessed. The limits will be set by the approach of conditions under which saline water intrusion into the aquifer could be possible.

FUTURE CONSIDERATIONS

To test this model fully under all conditions, two further periods of data are now in preparation. These are the data for the 7-week period 13 November to 31 December 1972, and for the 14-week period 1 January to 8 April 1973. Each of these periods has a distinctive feature that will be useful as a test of the simulation. At the end of the first period there is the Christmas vacation period with its significant reduction in withdrawal and associated system recovery. During the second period there is a period of fairly severe drought followed by a period of rain and higher river levels, giving both a marked drawdown of the entire system and a good recovery.

After satisfactory matching of measured heads during these periods, the model will be used to assess various possible modifications of the field, e.g. resiting or extended siting of wells, higher withdrawal rates, or raising of river levels in the infiltration zone. It will also be used to predict possible drawdown effects and recovery during and after simulated droughts or other crises, and to assess limits that may need to be set on withdrawals during such drought conditions.

Ultimately, the model could be used as one of the range of tools available to the local regional water authority for its assessment and management of this field.

REFERENCES

Bach, H. R. 1958: Artesian water investigations. Report on pumping test carried out on 8th December 1957. (unpublished).

Cowan, M. 1961: Preliminary report on a gravity survey of the Lower Hutt Valley. Geophysics Division, DSIR. (unpublished).

Donaldson, I. G. 1973: *The Lower Hutt - Port Nicholson Groundwater Basin — Preliminary Model Studies.* Physics and Engineering Laboratory Report No. 416.

Garrick, R. A. 1963: Seismic refraction studies in the Taita Gorge, Silverstream. Geophysics Division, DSIR. (unpublished).

Garrick, R. A. 1964a: Seismic waves refracted along the greywacke basement in the Gracefield region of the Hutt Valley. Geophysics Division, DSIR. (unpublished).

Garrick, R. A. 1964b: Seismic velocity survey in water well at Gracefield. Geophysics Division, DSIR. (unpublished).

Grant-Taylor, T. L. 1959: Geology of the Hutt Valley. *N.Z. Ecological Society Proceedings 6*: 31–35.

Grant-Taylor, T. L. 1963: Geological faults in the Wellington area. *N.Z. Institute of Architects Journal 30* (4) : 68–69.

Hutton, P. R. M. 1965: Report on the hydrology and geology of the Lower Hutt Valley. (unpublished).

McKillop, E. R. 1935: The underground flow of the Hutt River as a source of water supply. (unpublished).

Pinder, G. F.; Bredehoeft, J. D. 1968: Application of the digital computer to aquifer evaluation. *Water Resources Research 4* (5) : 1069–1093.

Pinder, G. F.; Frind, E. O. 1972: Application of Galerkin's procedure to aquifer analysis. *Water Resources Research 8* (1) : 108–120.

Prickett, T. A.; Lonnquist, C. G. 1971: *Selected Digital Computer Techniques for Groundwater Resource Evaluation.* Bulletin 55, State of Illinois Department of Registration and Education.

Stevens, G.R. 1956a: Hutt Valley Artesian System. *N.Z. Journal of Science and Technology B 38* (3) : 149–156.

Stevens, G. R. 1956b: Stratigraphy of the Hutt Valley. *N.Z. Journal of Science and Technology B38* (3) : 201–235.

Stevens, G. R. 1956c: Earth movements in the Wellington area. *N.Z. Geographer 12* (2) :

Stevens, G. R. 1958: The Wellington Fault. *Transactions of the Royal Society of N.Z. 85A* : 633–696.