JOURNAL OF HYDROLOGY
NEW ZEALAND
Published twice annually by the New Zealand Hydrological Society

Volume 24 1985 Number 2

SIMULATING THE EFFECTS OF THE WAIAU IRRIGATION SCHEME ON RECHARGE AND GROUNDWATER LEVELS

M. E. Close

Hydrology Centre, Ministry of Works and Development, PO Box 1479, Christchurch.

ABSTRACT

The Waiau Irrigation Scheme, North Canterbury, commenced operation in late 1980. A water balance approach is used to calculate recharge to groundwater from 1976 to 1984, and assess the effect on recharge estimates of variations in soil water-holding capacity and percolation. Increases in water-holding capacity of 30 mm corresponded to a decrease of approximately 30 mm in mean annual recharge, with increases at low water-holding capacity having a greater effect than at high water-holding capacity. Without irrigation, annual recharge for 1976-84 would have averaged 338 mm with values for individual years ranging between 143 and 548 mm. When full irrigation development of the scheme was simulated for 1977-84, mean annual recharge was 703 and 751 mm for water applications of 80 and 100 mm/irrigation, respectively.

Pre-development groundwater levels were used to identify and calibrate a time-series model which relates groundwater levels to calculated recharge. The effects of the irrigation scheme were estimated by simulating the groundwater levels that would have occurred as a result of rainfall recharge only, and comparing them with the observed groundwater levels for the period 1980 to 1984. The change in water levels has increased from zero in 1980/81 to a 1.4 m rise in the 1983/4 irrigation season, reflecting progressive implementation of the scheme. The mean rise in groundwater levels following full development of the irrigation scheme is predicted to be 0.7 m, with a spatial range of 0.4 to 1.8 m, which would lead to waterlogging in some areas.

INTRODUCTION

In Canterbury and Otago approximately 1500 km^2 of land are currently irrigated, with a further 2100 km^2 under investigation for future irrigation (Chandler and Lewthwaite, 1982). Border strip irrigation is the method most commonly used to improve pasture production. Increased groundwater levels have occurred downstream of two existing irrigation schemes, the Mayfield-Hinds scheme and the Levels scheme (W. Lewthwaite, MWD, Christchurch, pers. comm.). Similar increases were expected for the Waiau Irrigation Scheme, North Canterbury, which commenced the first stage of operation in November 1980. Some drainage problems were anticipated in lower areas of the scheme, as it is in a fault-bounded inland basin where groundwater flow is impeded. Groundwater levels are influenced by recharge, and thus a reasonably accurate estimate of recharge for the area and a prediction of long-term recharge was needed. The objectives of the study were: (a) to determine whether the first stage of irrigation had raised groundwater levels above natural levels and (b) to predict the rise in groundwater levels which would follow full implementation of the scheme.

Smith *et al* (1970), in a study of the Chalk aquifer in England, observing that recharge occurred during a period of soil moisture deficit, postulated that a proportion of the effective rainfall (i.e., rainfall minus evapotranspiration) percolated directly to groundwater, with the remainder reducing the soil moisture deficit. Other workers (e.g., Rushton and Ward, 1979) have varied this approach to obtain a better fit for rainfall/recharge relationships. This paper examines the sensitivity of recharge estimates to the range of water-holding capacities encountered in the study area, and to different assumptions about percolation. Changes in the amounts and distribution of recharge following implementation of an irrigation scheme are estimated, and the estimates used to determine the effects of irrigation on groundwater levels.

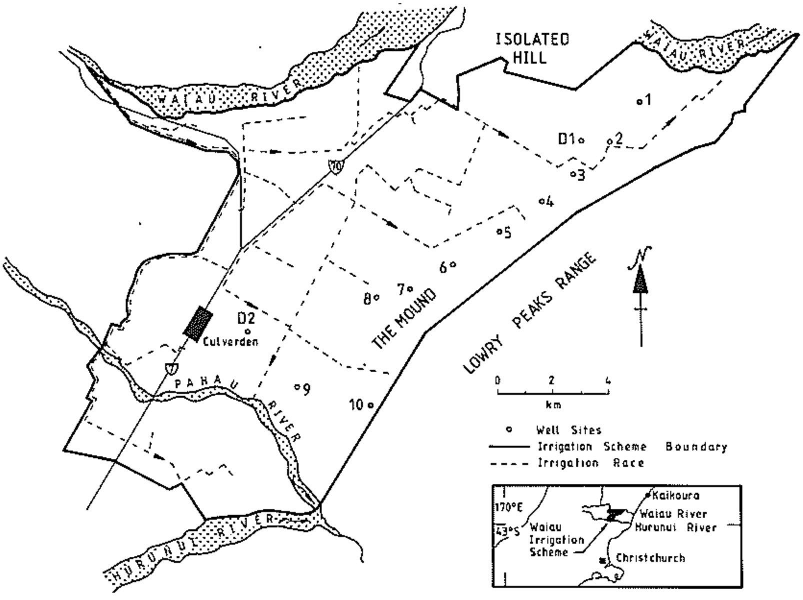

FIG 1 Location of the Waiau Irrigation Scheme and well sites.

DESCRIPTION OF THE STUDY AREA

The Waiau Irrigation Scheme is located approximately 90 km north of Christchurch and 35 km inland (Fig. 1). When completed the scheme will irrigate 170 km², with 80% of this area irrigated using border strips and 20% using spray irrigation. Throughout the study area, thin soils overlie alluvial gravels. Balmoral soils (stony silt loams) are the most widespread, with better and deeper soils such as Chertsey and Hatfield in the north-western section of the plains and a Temuka gley soil along the toe of the Lowry Peaks Range. The available water-holding capacities of these soils vary markedly with depth and type from 30 to 180 mm (T. Webb, Soil Bureau, Lincoln, pers. comm.). The area has a mean annual rainfall of 750 mm (average of Culverden, Lowry Hills and Riverside meteorological stations) with frequent summer droughts. Land use in the area prior to irrigation was approximately 80% sheep grazing, 10% cattle grazing and 10% cropping, the latter mainly to provide winter feed for stock. With the onset of irrigation there has been some diversification into dairying and horticulture.

The study area is in a fault-bounded basin, the south-eastern boundary of which has been uplifted to form the Lowry Peaks Range. It is bounded to the north-west by a range of foothills (Fig. 1). The greywacke bedrock contact is estimated to occur at depths of 500–1500 m (G. Browne, Geological Survey, Christchurch, pers. comm.). Tertiary sediments overlie the greywacke bedrock, and outcrops occur at The Mound, Isolated Hill and west of Culverden. Quaternary gravels above the Tertiary layers probably range from 0 to 100 m in thickness.

METHODS

Water balance

A water balance was calculated for the Waiau Irrigation Scheme from 1976 to 1984 using daily meteorological data to estimate recharge to the groundwater system. The water balance used meteorological parameters to calculate soil moisture changes. Soil moisture was taken as the sum of the initial soil moisture, rain and irrigation, minus evapotranspiration and recharge to groundwater.

Potential evapotranspiration (PET) was calculated using the Priestley-Taylor equation which has been shown to work well in New Zealand conditions (Clothier *et al.*, 1982):

$$\mathrm{PET} = \frac{\alpha\, S\, R_n}{S + Y} \qquad (1)$$

where R_n = nett radiation.
S = vapour pressure slope with respect to temperature.
Y = psychrometric constant (0.66 mb/K)

Nett radiation was calculated using the following equation as set out in Heine (1976):

$$R_n = 0.75.Rm/L \quad 2.0.10^{9}Tk^4\,(0.17+0.83\ n/N)\,(0.47-0.065\ e_a^{0.5}) \qquad (2)$$

where Rm = measured radiation (J/m^2)
L = latent heat of vaporisation ($2.44.10^6 J/kg$)
Tk = temperature in degrees Kelvin
n = actual sunshine hours
N = possible sunshine hours
e_a = vapour pressure (mb)

The $\propto$ is an empirical constant which Priestley and Taylor (1972) estimated to be 1.26. Local calibration of this constant is recommended and a value of 1.35 was used in this study as this was found to be more applicable to Canterbury conditions (P. Jamieson, DSIR, Lincoln, pers. comm.).

Temperature data from Waiau and Balmoral Forest climate stations were averaged; sunshine hours are from the Ashley Forest climate station (40 km southwest) and solar radiation data from Christchurch airport (90 km southwest). Rainfall data are averaged values for Culverden, Lowry Hills, and Riverside rainfall stations.

Actual evapotranspiration (AET) is a function of the potential evapotranspiration rate, soil moisture status and plant development. When potential evapotranspiration is low, actual evapotranspiration may equal potential evapotranspiration, even at relatively low soil moisture levels. At high potential evapotranspiration, actual evapotranspiration may be limited by the transpiration ability of the plant. Actual evapotranspiration decreases as soil moisture levels decrease, with the decrease occurring at higher soil moisture levels as potential evapotranspiration increases. A linear approximation has been developed to describe this relationship (Scott and Thorpe, 1986):

$$\begin{aligned} &AET/PET = 1 \text{ for } SM > WHC\,(1-0.67/PET) \\ &AET/PET = (0.2+SM/WHC)/(1.2-0.67/PET) \text{ for lower SM levels} \end{aligned} \qquad (3)$$

where SM = soil moisture and WHC = water-holding capacity.

The volume of water sold for border strip and spray irrigation was divided by the area being irrigated at the time to obtain a graph of cumulative water applied versus time, which represents the average on many farms. A simulation was carried out for a "typical" farm on which a fixed amount of water was applied approximately every three weeks. The simulation applied water at times when the measured graph indicated that 1/2, 3/2, 5/2, etc. of the fixed amount had been applied, on average, over the scheme area. For example, if the fixed application was 100 mm, this was applied when the scheme average application equalled 50, 150, 250 mm. Two fixed applications, 80 and 100 mm/irrigation, were simulated for the border strip irrigation and the fixed application for spray irrigation was taken as 75 mm. An estimate was made of the volume of water which will be sold when the scheme is fully developed, based on records from similar irrigation schemes and from consideration of scheme capacity (W. Lewthwaite, MWD, Christchurch, pers. comm.).

Field Sampling

An array of shallow wells, each 75 mm in diameter and 6 m deep, with PVC liners slotted over the entire length, was installed in the south-eastern half of the scheme area (Fig. 1) to assess the likelihood of surface flooding or other drainage problems resulting from irrigation. Monthly water-level readings were taken from wells 1–10 from 1977 to 1984. An automatic recorder monitored water level continuously at well 3 for the same period. Two 100 mm diameter, 30 m deep wells (labelled D1 and D2), also with slotted PVC liners, were drilled in 1981 to allow better determination of water quality with depth.

Single borehole dilution tests, as detailed by Klotz *et al.* (1978), were carried out on well 3 and both deep wells (D1 and D2) to calculate groundwater velocity, and a step draw-down pump test was conducted on D1 to estimate transmissivity.

Time Series Modelling

Groundwater levels are highly autocorrelated and exhibit marked seasonal variation; time series modelling is an appropriate method for analysing such data. Rennolls *et al.* (1980) used a first-order autoregressive model to relate groundwater levels to rainfall events. In the Waiau study, drainage from the bottom of the soil layer was used as the recharge instead of direct rainfall. Daily values of recharge were summed to give monthly totals for the model simulation. Without recharge, the water table recedes in an exponential fashion (e.g., Fig. 6, summer periods). This can be represented mathematically by setting the water level equal to a fraction of the previous month's water level. The water levels were adjusted to give zero at a theoretical minimum level of recession by subtracting an amount, X, from the water level data. As this was unknown, a range of values for X was tried until an optimum value, based on minimum variance of the residual (i.e., observed — predicted) water levels, was found. The recharge inputs were multiplied by a coefficient, a_i, which is an index of effective porosity. The coefficients (λ, a_i) were assumed to be constant. Thus, equation (4) was adopted and optimised using an ordinary least-squares procedure (SAS Institute Inc., 1982).

$$W-X = \lambda\,(W'-X) + a_1 R' + a_2 R'' + \ldots \qquad (4)$$

where W = groundwater level at month t.
W′ = groundwater level at previous month, t−1.
X = theoretical minimum level of groundwater recession.
R′, R″ = recharge for month t−1, t−2, etc.
λ = recession coefficient.
a_1, a_2 = recharge coefficient at monthy t−1, t−2, etc.

RESULTS — RECHARGE ESTIMATES

Effect of water-holding capacity on recharge

The effect on estimated recharge of water-holding capacity varying from 30 to 180 mm, both before and after the implementation of irrigation, is shown in Figure 2. The effect of water-holding capacity varied from year to year and was strongly influenced by the distribution of rainfall. Amounts of recharge for lower water-holding capacity were greater than, or equal to, amounts for high water-holding capacity. Mean annual recharges for 1976–80 were 455, 409, 378, 351, 329 and 308 mm for water-holding capacities of 30, 60, 90, 120, 150, and 180 mm, respectively. Following irrigation, recharge values generally increased, with similar relative differences in annual recharge between the different values of water-holding capacity.

The seasonal distribution of recharge also is changing (Fig. 2). Prior to irrigation, the average proportion of annual recharge occurring in winter ranged from 78% for WHC = 30 mm to 94% for WHC = 180 mm. Following irrigation, this changed to between 51 to 54% for all values of water-holding capacity. A water-holding capacity of 60 mm has been used in the following calculations.

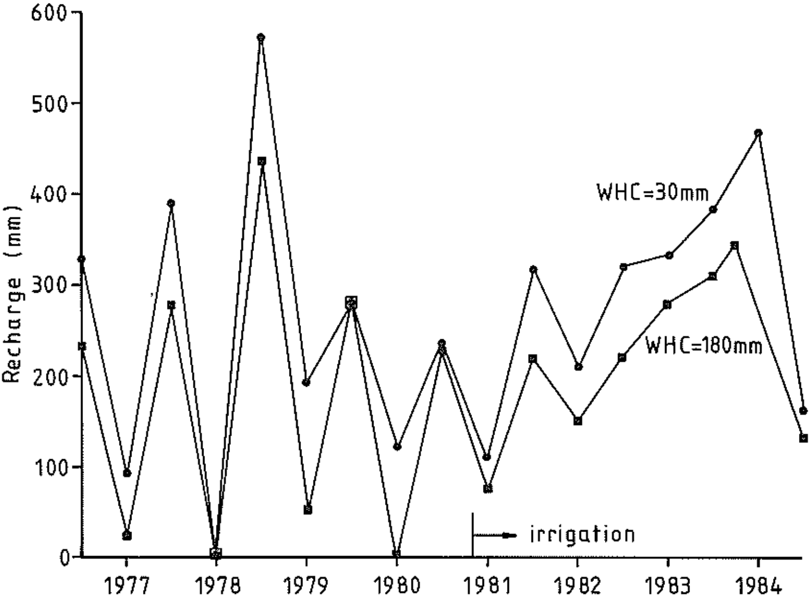

FIG 2 Effect of water holding capacity (WHC) on summer (Oct — Mar) and winter (Apr Sept) recharge, assuming conventional percolation.

Assessment of percolation

Simulations of recharge were carried out assuming a range of percolation modes. These were the conventional approach, which assumes piston flow of soil water; a proportion, ranging from 10 to 50% of the effective rainfall (rainfall minus evapotranspiration) directly percolating through the soil layer; a proportion, ranging from 10 to 50%, of actual rainfall above 10 mm/day directly percolating through the soil layer; and a combination of a proportion of the effective rainfall plus a proportion of actual rainfall above 10 mm/day directly percolating through the soil layer. Where direct percolation occurred, the remainder of the rainfall was treated conventionally. The latter three percolation modes allowed recharge to occur during the summer.

A comparison between the amounts of recharge for the conventional approach and for other percolation modes is given in Figure 3. Direct percolation of rainfall through the soil layer allowed increased recharge during summer, and thus an increased mean annual recharge.

The recharge/groundwater level model described later in the text was used

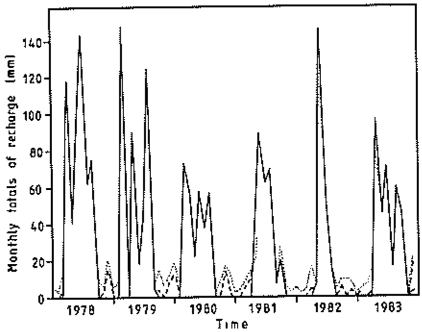

FIG 3—Compairson of monthly totals of natural recharge for different percolation modes: (a) no direct percolation. (b) direct percolation of 30% of actual rainfall > 10 mm/day. (c) direct percolation of 30% of effective rainfall.

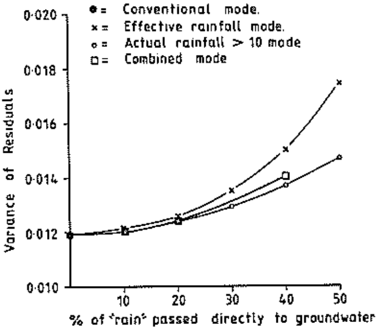

FIG 4—Variance of residual (predicted — observed) pre-irrigation groundwater levels for different percolation modes. The conventional mode does not allow rain to pass directly to groundwater.

to assess the appropriate percolation mode for Waiau by using each set of estimates of pre-irrigation monthly recharge and selecting the best fit with observed groundwater levels (average of 10 wells; Fig. 1). The variance of the residual groundwater levels for each mode (Fig. 4) indicates that the conventional approach is the most appropriate in Waiau.

Predicted recharge for full development of irrigation scheme

As the irrigation scheme is being implemented over a period of 10–15 years, the full impact on groundwater has not yet occurred. To simulate how this impact is proceeding, non-irrigated recharge and fully-irrigated recharge, both for border strip and spray irrigation, have been combined in the ratio of scheme development. The level of on-farm development of the scheme in the first four years is represented by the following equation:

$$\text{Irrigated ha} = 5.52 \times T + 762 \text{ ha } (r^2 = 0.98) \quad (5)$$

where T = days since November 1980.
This is the sum of border strip and spray irrigation as follows:

$$\text{Border ha} = 4.93 \times T + 628 \text{ ha } (r^2 = 0.99) \quad (6)$$

$$\text{Spray ha} = 0.59 \times T + 134 \text{ ha } (r^2 = 0.72) \quad (7)$$

Calculations were made on a daily basis. Monthly and annual totals of recharge to groundwater are given in Table 1. Mean annual recharge before irrigation (1976–1980) was 409 mm, with the recharge being highest during the winter months. Because 1978 and 1979 were very wet, this mean will be larger than the long-term value. If no irrigation were assumed for 1976–84 (which includes some dry years), the mean annual recharge would be only 338 mm, with annual recharge for individual years ranging between 143 and

TABLE 1 Monthly totals of simulated recharge (mm) for a water-holding capacity = 60 mm : Irrigation started in November 1980

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1976	0.0	34.1	0.0	1.2	41.4	54.9	94.2	48.3	65.7	22.9	0.0	0.0	362.7
1977	28.8	0.0	0.0	0.0	16.4	86.1	123.2	81.4	52.7	0.9	0.0	0.0	389.5
1978	0.0	0.0	0.0	118.3	41.0	106.5	143.4	62.6	76.2	0.0	0.0	0.0	548.0
1979	0.0	0.0	148.9	0.0	91.1	18.2	43.9	124.6	5.7	0.0	0.0	0.0	432.5
1980	0.0	0.0	74.2	62.7	22.3	58.1	37.6	57.5	0.0	0.0	0.0	18.0	330.5
1981	17.7	21.7	34.7	10.6	43.9	89.1	62.0	70.5	21.9	44.2	17.8	12.2	446.3
1982	30.4	31.9	41.8	32.7	11.9	146.4	53.7	17.8	35.8	34.7	52.2	50.4	539.5
1983	46.8	49.1	67.2	49.6	99.0	44.4	71.2	15.8	88.1	52.5	53.0	66.7	703.5
1984	55.5	87.1	83.9	3.9	23.5	5.5	82.1	8.9	26.2	71.2	91.4	59.0	598.2

548 mm. Following irrigation, the recharge became more evenly distributed throughout the year, and increased annually as the scheme developed.

The amount of recharge was simulated for 1977–1984 assuming full development of the scheme. Two water application depths, 80 and 100 mm/irrigation, were simulated for the border strip irrigation. The mean annual recharge was 703 and 751 mm for 80 and 100 mm applications, respectively. Recharge for individual years ranged from 578 to 923 mm for 80 mm applications and from 601 to 942 mm for 100 mm applications. This represents an increase of 413 mm, or approximately double the non-irrigated recharge.

GROUNDWATER LEVELS

Groundwater Hydrology

A piezometric contour map for the area, using pre-1980 mean groundwater levels from 37 wells, is shown in Figure 5. Because groundwater moves orthogonally to the piezometric contours, recharge flows from the Waiau River, at the north-west side of the basin, into the centre of the area. There it is split by The Mound and flows down to both the Waiau and Hurunui Rivers. Recharge from the surrounding hills is also indicated by the contours.

Darcy velocities, measured using single borehole dilution tests, ranged with depth from 0.77 to 9.56 m/day in the top 15 m of the water table. Average velocities for D1, D2 and well 3 were 3.97 m/day, 4.92 m/day and 3.09 m/day, respectively. A step draw-down pump test on D1 estimated groundwater transmissivity to be 1690 m²/day.

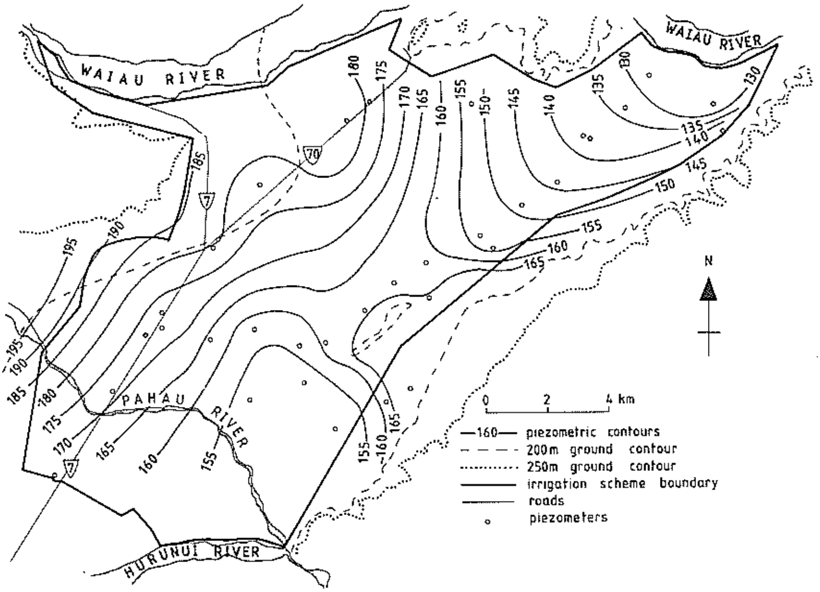

FIG 5 Piezometric contour diagram of the study area.

TABLE 2 — Calibration of mean monthly water levels (8 wells) for 1977–80.

Summary of model parameters and variance (σ^2) of water levels and residuals (observed — predicted)

Calibration Period	X	λ	a_1	σ^2 WL	σ^2 residuals
1977–78	146.1	0.733	5.36	0.247	0.0114
1979–80	145.5	0.838	5.87	0.123	0.0100
1977–80	146.0	0.750	5.59	0.183	0.0122

TABLE 3 – Recharge coefficients and effects of full irrigation (water application depth = 80 mm/irrigation event) for individual sites.

Well No.	Mean pre-irrigation water level (m amsl)	Mean depth of water table below ground level (m)	Variance of water levels (1977–80)	Variance of residuals (1977–80)	Recharge coefficients a_1	Predicted rise following full irrigation (m)			Non-irrigated water level within 0.5 m of ground level (% 1977–80)	Fully irrigated water level within 0.5 m of ground level (% 1977–84)
						Mean annual	Mean summer	Mean winter		
1	134.08	1.19	0.25	0.029	6.4	0.7	1.0	0.2	10	20
2	137.18	2.07	0.47	0.039	8.7	1.3	1.8	0.8	0	12
3	143.24	1.75	0.09	0.015	4.2	0.4	0.6	0.1	0	0
4	147.72	1.26	0.12	0.015	5.2	0.4	0.6	0.1	2	3
5	153.86	0.74	0.16	0.025	5.0	0.5	0.7	0.2	31	51
6	159.59	2.09	0.16	0.025	4.7	0.7	1.0	0.4	0	0
7	163.57	2.99	0.32	0.043	5.4	—	—	—	0	—
8	164.33	4.51	0.86	0.260	8.6	—	—	—	0	—
9	152.70	4.85	0.41	0.031	8.0	1.8	2.3	1.3	0	0
10	147.07	0.64	0.09	0.012	3.5	0.5	0.7	0.3	31	89

Identification of Groundwater Level Model

Continuous 1977-80 water level data for well 3, together with the simulated daily recharge, are shown in Figure 6. Groundwater levels in wells 1-10 varied from 1 to 6 m below the ground level. The seasonal variation in water level before irrigation ranged from 1.12 m in well 3 to 3.16 m in well 8. Analysis of individual well records shows that wells 7 and 8 were subject to different influences than the rest of the wells and these are discussed later. An average of the water levels for the other 8 wells was taken each month and the analysis of these averaged data is reported in detail in Table 2 and Figures 7, 8, 9 and 10. The results of the analysis of individual well records are summarised in Table 3.

The autocorrelation of the averaged water levels (Fig. 7) shows a strong seasonal dependence in the data. Correlograms between water level and simulated rainfall recharge and Waiau River flow (Fig. 7) indicate which inputs had a significant correlation with water levels. Waiau River flow showed no significant correlation with water levels, probably because of the distance between the well array and the recharge area, and was not used in the model. The correlogram between the water levels and recharge showed significant correlations at lags of 1, 2 and 3 months. However, the recharge coefficients in the model equation became very small after the first lag and subsequent lags were dropped from the model. There was no significant autocorrelation of the residual (i.e., predicted — observed) time series, which indicates that the selection of input parameters was appropriate.

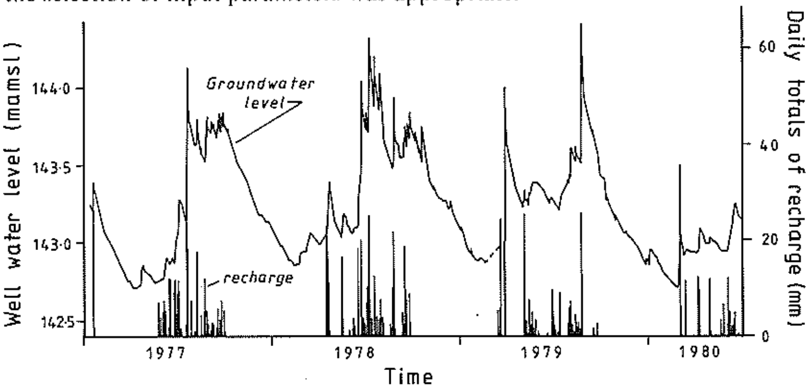

FIG 6 Continuous water-level fluctuation and simulated recharge from rainfall.

Calibration and Confirmation of Model

Four years of pre-irrigation data (1977-80), averaged for eight wells, were split and the model was calibrated on the July 1977 — December 1978 data and confirmed on the January 1979 — December 1980 data, and vice versa. The model was then calibrated on the whole period from 1977-80 for predictive purposes and this is hereafter referred to as the calibrated model. Simulated and observed average water levels for each model are shown in Figure 8.

Figure 8 and Table 2 indicate a generally good fit of the model to the data. There were both wet (1977, 1978) and dry (1980) years in the calibration period, so the model should be applicable to a range of climatic conditions.

A simulation of daily water level for well 3 was carried out using equation

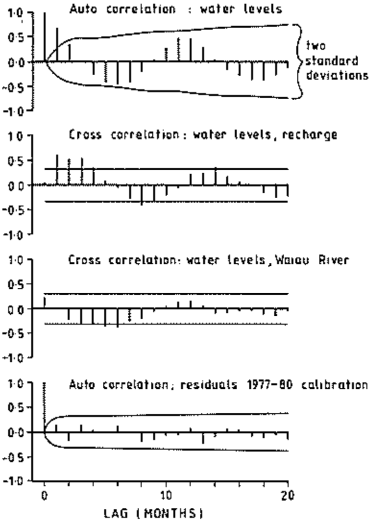

FIG 7 Correlation functions for average monthly water levels for 1977–80.

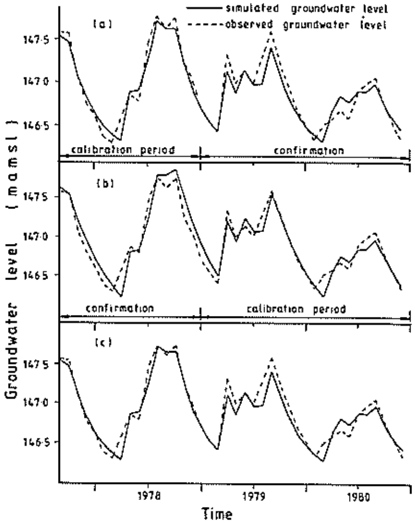

FIG 8 Calibration models for average monthly water-level data.
(a) calibrated for 1977 78;
(b) calibrated for 1979 80;
(c) calibrated for 1977-80.

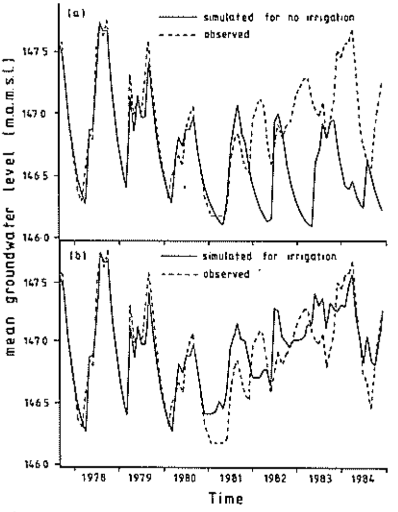

FIG 9 Effect of irrigation on mean groundwater levels. (a) predicted water levels with no irrigation compared with observed water levels. (b) predicted water levels with actual irrigation development compared with observed water levels.

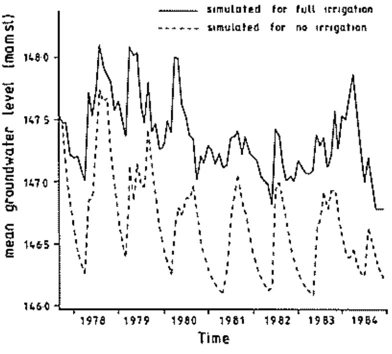

FIG 10 Prediction of impact of full irrigation on mean groundwater levels.

4 and daily input of simulated recharge. Seven lags of daily recharge were assessed. Values of the recharge coefficients obtained (only lags 1 and 3 were significantly different from zero) indicated that most of the recharge reached the groundwater table with 1-3 days. Vertical velocities of 1 m/hour have been measured in similar strata elsewhere in New Zealand (Thorpe *et al.*, 1982). As the water table is about 3 m below ground level at this site, this is consistent with a recharge time of 1-2 days.

Effect of irrigation on groundwater levels

Using the calibrated model, the entire period of 1977-84 was simulated assuming no irrigation. The observed averaged water levels were plotted along with the water levels simulated for no irrigation (Fig. 9a). There is a clear increase in observed water level during the irrigation season: there was no increase in 1980/81, and maximum increases of 0.9 m in 1981/82, 1.2 m in 1982/83 and 1.4 m in 1983/84, reflecting progressive implementation of the irrigation scheme. Irrigation was limited to the north-western half of the scheme in the first season, but subsequent development has occurred over the whole area. The amount of land being irrigated at the end of each season for the same four year period was 16, 36, 62 and 75 km^2, respectively.

Recharge due to precipitation plus irrigation was calculated and used as input for the groundwater level model (Fig. 9b). The observed and simulated water levels were in reasonable agreement, with the simulated water levels tending to oscillate about the observed data. Because the model calibration was based on a uniform distribution of recharge from rainfall, the simulation necessarily assumes a similar areal distribution, whereas irrigation development is not spatially uniform. As a greater area is irrigated, there will be a more uniform application of irrigation which should result in better agreement in the predicted summer water levels. The improvements in drainage works may be the reason that post-irrigation winter water levels are slightly overestimated in Figure 9b.

Prediction of future water levels

Recharge was simulated using climate data for 1977-84, assuming full irrigation over this period, from which groundwater levels were then simulated using the calibrated model. Averaged water levels for non-irrigated and fully-irrigated conditions for a border-strip water application of 80 mm/irrigation are shown in Figure 10. Mean increases are approximately 1.0 m in peak summer levels and approximately 0.4 m in winter, with a mean annual increase of 0.7 m. The mean annual rise varies from site to site, with simulations for individual wells indicating a mean increase ranging from 0.4 to 1.8 m (Table 3). The proportion of time that the water table was within 0.5 m of the surface (Table 3) increased for most wells with shallow water tables, and areas which had experienced occasional drainage problems in the past could expect the frequency of problems to increase.

DISCUSSION

Recharge coefficients (a_1) from individual well simulations ranged between 3.5 and 8.7, with a mean value of 6.0. Because recharge from only one month was used, these recharge coefficients may be interpreted as the reciprocal of effective porosity or specific yield, i.e., for a given water input, a small effective porosity results in a large increase in level. Todd (1959) gives values for effective porosities ranging between 0.15 and 0.3 for sand or gravel aquifers. The values for effective porosity at Waiau, indicated by the recharge coefficients, range from 0.11 — 0.29, with a mean of 0.17, which is within the range, given by Todd. This further increases confidence in the model. The borelogs indicated a mixture of gravel and clay, suggesting a poorly sorted deposit which would result in slightly lower effective porosities.

Wells 7 and 8 had relatively large recharge coefficients at lag 3 (a_3). However, inclusion of this term into the model did not significantly improve the calibration fit for either well. The model fit for these wells, particularly well 8, was poor (Table 3) and attempts at longer term predictions resulted in very high water levels for irrigation and very low levels without irrigation. Optimising the minimum groundwater recession level, X, for these two wells gave a low level compared to those of the other wells, and the variance of residuals did not exhibit the well-defined minimum values of the other wells. These wells were close to a Tertiary outcrop (Fig. 1) which probably affected hydrological behaviour, with the water table banking up behind the outcrop.

The higher groundwater levels in summer resulting from irrigation have significant implications in areas prone to waterlogging. Areas, like those around wells 5 and 10, which have had drainage problems in the past (31% of the period 1977–80 within 0.5 m of the surface) can be expected to have increased problems once irrigation is fully developed. If full irrigation had been in effect between 1977 and 1984, the water table would have been within 0.5 m of the surface for 51% and 89% of the time for sites 5 and 10, respectively (Table 3). Therefore, drainage works may be needed in these areas. As these simulations and predictions are based on pre-irrigation data, no allowance has been made for improved drainage works, some of which have already been constructed and are planned to be further expanded.

SUMMARY AND CONCLUSIONS

Increasing water-holding capacity resulted in less estimated recharge with an increase of 30 mm in water-holding capacity corresponding to a decrease of approximately 30 mm in recharge. Changes at lower water-holding capacity, e.g., 30 to 60 mm, had greater effect than changes at higher water-holding capacity e.g., 150 to 180 mm. Without irrigation, annual recharge for 1976–84 averaged 338 mm with values for individual years ranging between 143 and 548 mm. When full irrigation development of the scheme was simulated for 1977-84, mean annual recharge was 703 and 751 mm for water applications of 80 and 100 mm/irrigation, respectively.

Time-series modelling was used to predict groundwater level changes as a consequence of the Waiau Irrigation Scheme. A model was found which predicted the impact of irrigation on groundwater levels and gave an insight into the groundwater system. Recharge percolated rapidly into the aquifer, with rises in groundwater levels occurring within a few days. Simulated groundwater levels without irrigation were compared with observed data and indicated that levels were increasing as a result of irrigation. Use of the model with synthesised full irrigation data indicates that the groundwater levels could rise by 0.4 to 1.3 m with a mean increase of 0.7 m, and that this would lead to waterlogging in some areas in the lower part of the scheme.

ACKNOWLEDGEMENTS

The author wishes to thank the farmers in the Waiau Irrigation Scheme who allowed installation and sampling of wells on their properties. Thanks are also due to Messrs P. Woods, G. Tod and G. Price for collection of the water level data.

REFERENCES

Chandler, A.; Lewthwaite, W.J. 1982: Water Supplies in the rural sector. In *"Water in New Zealand's Future"*. Proceedings of the fourth National Water Conference, 24-26 August 1982, Auckland, New Zealand. p 223-246.

Clothier, B.E.; Kerr, J.P.; Talbot, J.S. 1982: Measured and estimated evapotranspiration from well-watered crops. *N.Z. Journal of Agricultural Research 25:* 301-307.

Heine, R.W. 1976: "Comparison of methods for estimating potential evapotranspiration in Canterbury". *N.Z. Journal of Science, 19,* p 255-264.

Klotz, D.; Moser, H.; Trimbornn, P. 1978: Single Borehole Techniques. In *"Isotope Hydrology 1978"* International Atomic Energy Agency. p 159-179.

Priestley, C.H.R.; Taylor, R.J. 1972: On the assessment of surface heat flux and evaporation using large scale parameters. *Monthly Weather Review 100:* 81-92.

Rennolls, K.; Carnell, R.; Tee, V. 1980: A descriptive model of the relationship between rainfall and soil water table. *Journal of Hydrology 47:* 103-114.

Rushton, K.R.; Ward, C. 1979: The estimation of groundwater recharge. *Journal of Hydrology 41:* 345-361.

SAS Institute Inc. 1982: SAS/ETS User's Guide, 1982 Edition. SAS Institute Inc., Cary, North Carolina. 398 p.

Scott, D.M.; Thorpe, H.R. 1986: Groundwater resources between the Rakaia and Ashburton Rivers. *Publication No 6 Hydrology Centre MWD Christchurch.* 115 p.

Smith, D.B.; Wearn, P.L.; Richards, H.J.; Rowe, P.C. 1970: Water movement in the unsaturated zone of high and low permeability strata by measuring natural tritium. In *"Isotope Hydrology 1970"* Proceedings of a symposium, Vienna, IAEA, p 73-87.

Thorpe, H.R.; Burden, R.J.; Scott, D.M. 1982: Potential for contamination of the Heretaunga Plains Aquifers. *Water and Soil Technical Publication No 24.* Ministry of Works and Development, Wellington. 149 p.

Todd, D. K. 1959: *Ground Water Hydrology.* John Wiley and Sons, Inc. 336 p.