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STUDIES IN WATER MOVEMENT FROM GROUNDWATER RECHARGE TRENCHES

by

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SUMMARY

The extraction of groundwater for irrigation purposes from the aquifers underlying the delta of the Burdekin River in Northern Queensland is discussed together with the consequent problem of depressed water table levels. The development of an artificial groundwater recharge scheme to ameliorate this condition is then described and details given of four research projects which have been initiated to assist in optimizing the management of the recharge system. The field instrumentation which has been installed for measuring soil water pressures in the sand profile below an off-line recharge trench is outlined and ancillary field equipment described. The use of computer-based numerical solutions for predicting water content and pressure head profiles in a two-dimensional recharge system is then detailed. Finally, results are presented in which the sealing of the recharge surface by silt deposition is simulated in a one-dimensional system by introducing a time-dependent upper boundary condition.

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INTRODUCTION

The onshore portion of the Burdekin Delta in Northern Queensland covers an area of 500 km^2 and is intensively cultivated for agricultural purposes, the predominant crop being sugar cane. Sugar cane requires regular and substantial quantities of irrigation water for efficient year-round crop management; to meet this irrigation need it has been necessary to extract much of the water from groundwater storage. Annual extraction of groundwater is now well in excess of 300×10^6 m^3. Natural recharge, which is supplied partly by seasonal precipitation and partly by bed and bank leakage from the Burdekin River, has been estimated to have a mean annual volume of 210×10^6 m^3. The continual extraction of this water, particularly when paralleled by a succession of low-rainfall years has resulted in periods when there have been depressed water table levels in the deltaic sediments with the consequent danger of sea water intrusion. To alleviate this situation a comprehensive programme of works on the north and south sides of the Burdekin River has resulted in the construction of a regional groundwater recharge system in which water is pumped from the river during times of flow into natural and artificial recharge channels thus inducing seepage into the underlying sediments. Pumpage for artificial recharge is now approaching 100×10^6 m^3 per year. Details of the regional recharge scheme have been presented by O'Shea (1).

Pumping is not carried out when the river carries a heavy sediment load. However, even under favourable conditions when river water which contains a relatively low sediment load is utilized for recharge, thin layers of silt and clay become deposited on the bottom and sides of the recharge trenches with consequent decrease in the seepage flow. In order to study this and related problems of artificial recharge management the Australian Water Resources Council financed in 1971 a group of four research projects. These projects are:

(1) Numerical modelling of the groundwater system with particular emphasis on predicting future aquifer response and improving management practice. Volker and Stark (2) have discussed the modelling approach used in this work.

(2) Experimental and numerical studies of the movement of water from the recharge trenches to the water table and the effect on the seepage flow of the deposition of low permeability surface layers.

(3) Regional studies, along the main recharge channels, of silt deposition and of the longitudinal variation in seepage rates.

(4) Biological studies of the factors involved in the recharge environment and their effect on recharge retardation.

In addition to these funded projects the Australian Atomic Energy Commission has been studying the tritium dating of the groundwaters in the stratified aquifers of the delta to provide data on the age of the groundwater currently being extracted and the age pattern of the water in the different aquifer systems. This work has been discussed by Airey et al (3).

In certain high intake areas of the delta it has been found advantageous to construct artificial recharge trenches of limited length (70-100 m) parallel to the main channels. These trenches also suffer from sealing by the sediment in the recharge water but, due to their off-line location, it is possible for them to be periodically dried out and cleaned. Accordingly, these pits provide excellent experimental sites for studying the requirements of the second of the above projects. The authorities conducting the recharge operations are particularly interested in optimizing the recharge-drying cycle of the trenches to give the most efficient operation. A rational basis for such decisions can only be made following detailed experimental and numerical studies of the movement of water from the trenches to the water table and the manner in which the movement is controlled by the surface sealing. This study is being carried out by the authors for the School of Civil Engineering of the University of New South Wales. At the time of writing the study is not complete and specific conclusions on the physical behaviour of the system cannot be given. However, the project is well advanced and detailed information can now be provided on instrumentation and numerical methods.

EXPERIMENTAL METHODS AND RESULTS

The instrumentation requirements for the successful monitoring in the field of the relevant parameters during the unsteady flow of water in an unsaturated sand profile of the scale encountered in recharge studies are very exacting. The recharge trench (Shands No.2) where the present studies are being carried out has been excavated to a depth of approximately 3 m below natural surface, for it is at this depth that the interface between the fine-grained upper soil horizons and the coarse-grained underlying sand occurs. The trench is approximately 100 m long and runs parallel to a main carrier channel from which water is obtained for the recharge operation. A gated inlet pipe having its invert near bed level and incorporating a flow meter is used to convey the water from the main channel to the recharge trench. The main channel at this location is effectively sealed against significant seepage by long-term sediment deposition and weed growth; any minor seepage which does originate from the main channel does not appear to interfere with the seepage pattern from the recharge trench. The side slopes of the trench are approximately 2:1. An energy dissipator has been constructed at the point where water flows from the inlet pipe into the trench to prevent water turbulence disturbing the fine soil on the side slopes and moving it along the trench where it will eventually settle and form a low permeability surface layer thus reducing the seepage flow.

A characteristic feature of the Burdekin aquifers under the current operating conditions is the pattern of fluctuations to which the water table is subjected. At Shands No. 2 the water table has dropped, in the past, to a level of approximately 6 m below the bottom of the trench although at the time of writing this paper (June 1974) the heavy natural recharge of the 1973/74 summer has resulted in the water table rising to within 3.5 m of the base of the trench. Accordingly, for the monitoring of pressure changes in the profile, when the water table is depressed, pressure sensors are required at depths down to 9 m below natural surface. Since the sand profile is often in an unsaturated condition during the intermittent operation of the trench it has been necessary to use some form of tensiometer for the measurement of the soil water pressure. This has been achieved in the present study by using a tensiometer-pressure transducer unit in which the transducer is mounted near the tensiometer ceramic at the end of a specially constructed probe. The design of this probe is similar to the unit described by Watson (4). The present probe is more robust being made from tubing approximately 33 mm O.D. Providing installation problems can be overcome the probe could be used to depths of 25 m.

The ceramic (which provides the continuity between the bulk water in the measuring system and the water films in the unsaturated material) is of the high flow type with a nominal bubbling pressure of 1 bar. Miniature absolute pressure transducers (Model PA 856, Statham Instruments, Oxnard, California) have been used for the pressure sensors. The range is 0 to 138 kPa absolute (0 to 20 lb/in^2 absolute). The transduction element is a fully active strain gauge bridge; the particular configuration involves the deposition of the strain gauge material on a sensing beam using methods similar to semi-conductor construction techniques. These transducers have proved both reliable and stable during field use. The input voltage of 10 volts D.C. is supplied by a high stability D.C. power supply. The output voltage at maximum range is 4mV/volt. Nineteen tensiometer-pressure transducer probes have been positioned in the profile at the one cross section of the trench to measure the soil water pressure changes occurring during infiltration and drainage. One transducer is kept in the instrument hut with its diaphragm open to the atmosphere so that atmospheric pressure changes can be monitored thus enabling the corrections which must be applied to the other transducers to be determined.

A valuable and almost essential side benefit of using the pressure sensors described above is the ready means by which their outputs can be recorded automatically. This is most necessary in field studies which extend over long time periods. The data acquisition system in use at Shands No. 2 consists of a 1μV digital voltmeter linked with scanning and timing facilities. The voltage output is recorded on punched paper tape for later conversion to real data values by the university computer. An alternative output available in the system is an alphanumerical strip printer; this output is used when immediate readings are needed to check instrument performance and stability. The above system allows a completely automatic scanning and recording of the sensor outputs at preset times.

In addition to the pressure transducers several thermocouples have been connected to the data acquisition system through a thermocouple compensation unit. The thermocouples are installed in the profile at several depths at the one location to provide data on temperature profiles during recharge. Such information is particularly necessary in certain of the biological studies. The data acquisition equipment is installed in an air-conditioned hut at the side of the trench. The air conditioning became necessary because of the high temperatures and humidities which occur during the summer.

The other hydrologic parameter to be measured is the water content of the sand at different depths in the profile. This can be measured conveniently and nondestructively by using a neutron moisture meter. A 400 mCi Am-241/Be source is used as the fast neutron emitter. Water content measurements are made at four locations near the tensiometer units. Other field instrumentation includes three piezometer holes and a water level recorder.

Figure 1 gives details of developing pressure profiles on the trench centreline during infiltration into a profile which had drained for 1 day. At the start of infiltration the water table was at a depth of 4.80 m below the bottom of the trench. The infiltration commenced at 1130 hours on 24 September 1973. Eight tensiometer-pressure transducer probes were installed in the profile on the trench centreline and as close together as possible (approximately 0.3 m). As noted in the figure, pressure profiles are given for the period 1130 to 1346 hours, at which time the wet front was approaching the water table. Due to the coarse nature of the sand the pressure changes are not great although the pattern of wetting is clearly discernible. During continuous infiltration the pressures become positive in the upper part of the profile under the surface ponding of 0.5 to 1 m. At the lower end of the profile a water table mound develops as seepage increases.

NUMERICAL ANALYSIS

The equation describing the two-dimensional, isothermal movement of water in a rigid, homogeneous porous material may be written

$$C(h)\partial h/\partial t = \partial[K(h)\partial h/\partial x]/\partial x + \partial[K(h)\partial h/\partial z]/\partial z + \partial K(h)/\partial z \qquad (1)$$

where h = soil-water pressure (cm of water)

t = time (min)

$K(h)$ = hydraulic conductivity (cm min^{-1})

$C(h)$ = specific water capacity = $d\theta/dh$

θ = voltmetric water content ($\text{cm}^3\ \text{cm}^{-3}$)

x = horizontal ordinate (cm)

z = vertical ordinate, positive upwards (cm)

An equation of similar form was solved by Rubin (5) using numerical methods incorporating ADI techniques. More recently Perrens and Watson (6) have solved equation (1) by finite difference methods using a digital computer and again incorporating ADI techniques. It is this latter computer programme which has formed the basis, with some modifications relating to convergence parameters, of the analysis of the two-dimensional movement of water from a recharge trench to a water table. The programme enables the unsteady infiltration and drainage phases to be analysed as well as the gradual movement towards steady state conditions during prolonged recharge. At this stage the difficult top boundary condition, which is effectively made time dependent by surface flux decrease due to silt deposition, has been simulated on a one-dimensional numerical model only. This will also be discussed briefly later in this section. The details of the computer simulation of the two-dimensional system are extensive and will not be considered in this paper. In equation (1) it should be noted that the K(h) relationship is hysteretic, reflecting the strong hysteresis of $h(\theta)$ during wetting and draining sequences.

The porous material used in the two-dimensional analysis is a uniform silica sand, known as #17 sand. The hydrologic characteristics of this sand have been summarized by Watson and Curtis (7). The recharge system considered in the analysis consists of a trench 2.40 m in width containing 0.3 m depth of ponded water. The depth to the water table is 4.90 m and the initial pressure condition is considered to be that of hydraulic equilibrium. The interface between the fine and coarse material is assumed to occur at the level of the bottom of the trench and, accordingly, in the numerical model, the top boundary at the side of the trench is defined as a zero flux boundary. The computer programme has been written to incorporate, for the infiltration process, a moving side boundary and a moving base boundary so that only those nodes affected, or about to be affected, by the flow process need be considered in the analysis. The node spacing is 100 mm in both horizontal and vertical directions. When the infiltration front is in the vicinity of the water table the number of nodes considered in the solution is approximately 1500.

Figure 2 gives the profiles for the position of the saturated front with time for the area to one side of the trench centreline. Although there is lateral movement of the front at early times this effect tends to a limit as the wet front penetrates deeper into the profile and the developing saturated profile becomes reasonably uniform in width. When the saturated front reaches the water table, mound development will commence and increased lateral movement will be pronounced. Since the lateral spread of the penetrating front is minimal for a sand such as #17 it is reasonable to approximate the flow condition by a one-dimensional solution for the infiltration case,considered to be effective over approximately 1.4 times the trench width.

The surface sealing effect has been simulated for one-dimensional flow by introducing a time-dependent upper boundary condition. The sand used for this analysis is Botany sand, the characteristics of which have been presented by Watson (8). In the analysis a profile of 100 cm is considered; a water table is present at the lower boundary. The initial condition is that of saturation with the initial flux being equal to the K_{sat} value of 0.66 cm min^{-1}. The decrease of surface flux caused by the build-up of silt is simulated in this study by a linear reduction in surface flux from 0.66 to 0.01 cm min^{-1} over a 24 hour period. Since the air entry value of the sand is -38 cm the flux can decrease below the K_{sat} value before drainage commences. Figure 3 gives the h(z) profiles and indicates that drainage does not commence until t = 570 min. The characteristic feature of the profiles is the manner in which a zone of uniform soil water pressure extends downward from the surface at any given time. As the surface flux continues to decrease the zone extends deeper into the profile and the uniform soil water pressure assumes more negative values. These results indicate that during gradual surface flux decline the gravity potential becomes the dominant potential component. Within the zone of constant soil water pressure and hence constant water content the flux will be constant and equal to the hydraulic conductivity value appropriate to the water content established. Similar results have been obtained when the surface flux decrease has been represented by an exponential function.

ACKNOWLEDGEMENTS

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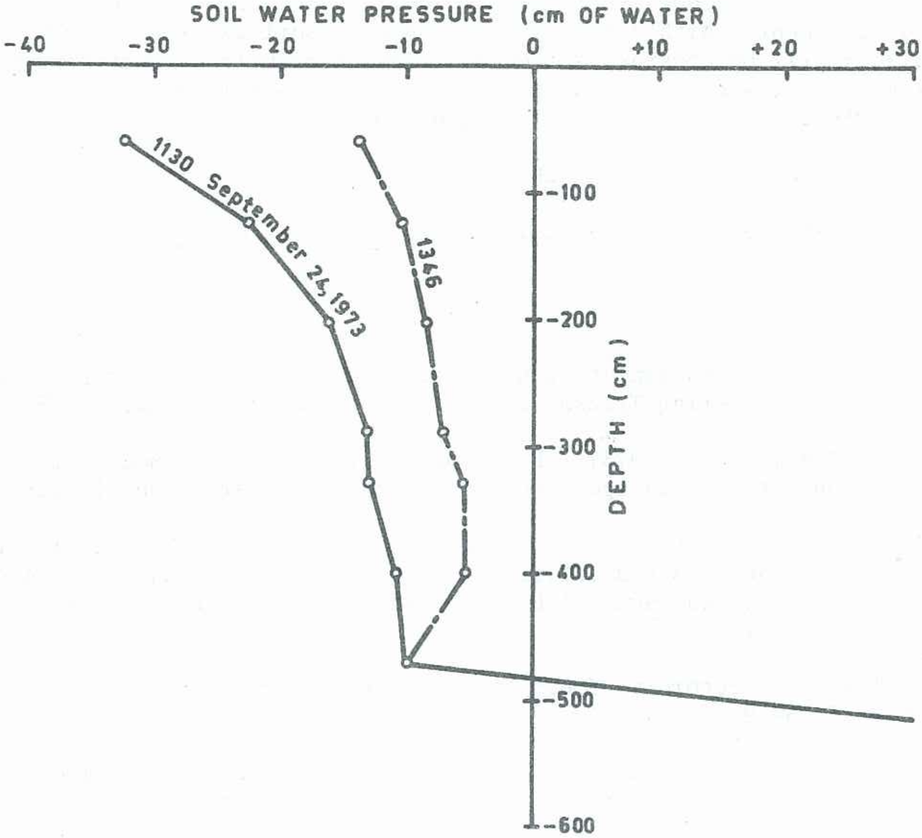

Fig. 1 Pressure profiles at Shands No. 2 trench during infiltration.

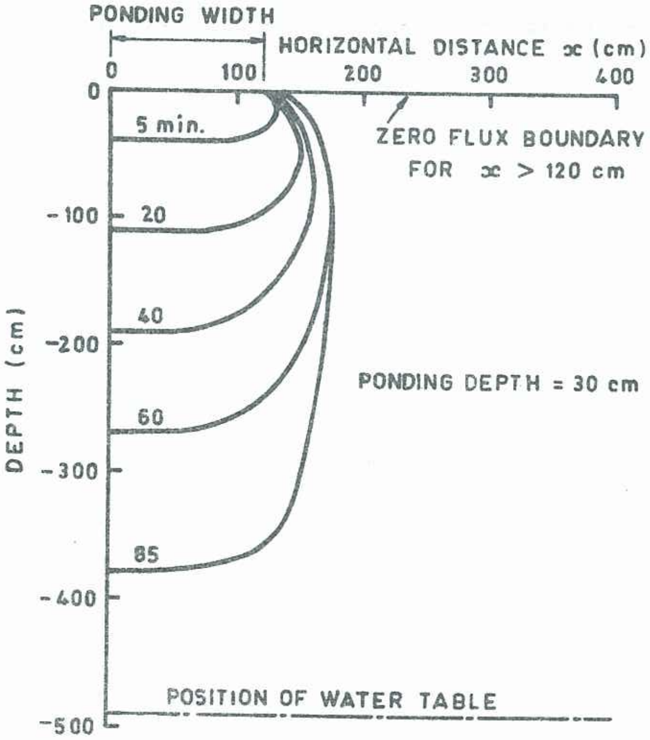

Fig. 2 Position of saturated front with time during infiltration into #17 sand.

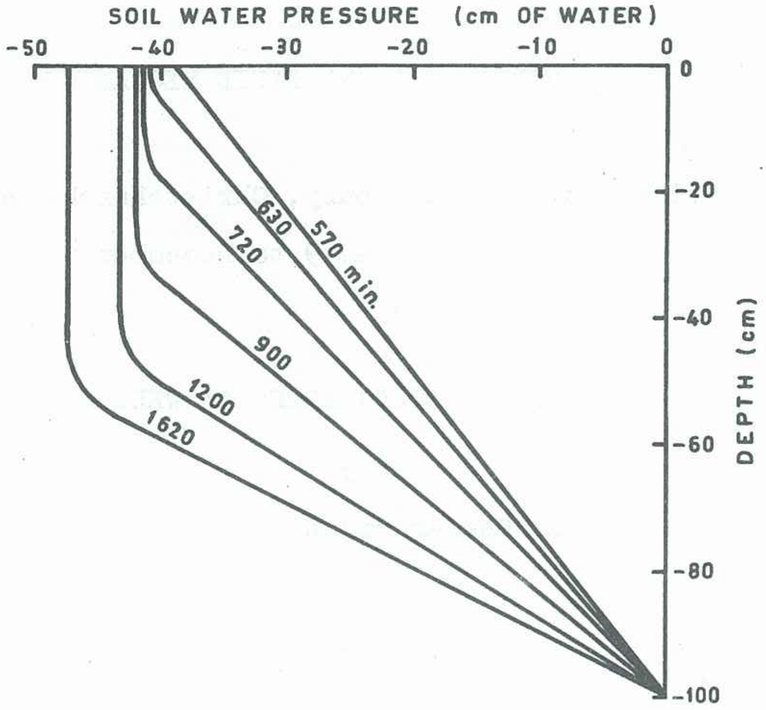

Fig. 3 h(z) profiles during drainage of Botany Sand under a linear reduction in surface flux.