The response of groundwater to drainage in bounded and un-bounded flow conditions

NM Cox[1], **SF Tetlow**[2]
[1]Department of Water, Western Australia
[2]Greenbase Pty Ltd

Introduction

Groundwater drainage is being used increasingly as a tool to lower saline watertables beneath dryland agriculture across the Wheatbelt in Western Australia. Drainage schemes often consist of single open drains up to 3 m deep placed within the lowest part of the catchment valley floors, which are usually the first areas to succumb to land salinisation. The successes of these drainage schemes in preventing or reversing the impacts of salinity have been variable, while planning and prediction of drain effectiveness is limited.

In other parts of the world, drainage schemes consist of parallel drains at 'designed' spacing to adequately control the groundwater conditions that occur between them. A variety of assessment techniques and numerical formulas have been developed to best determine that spacing and predict the impact on groundwater levels (Schwab et al.). However, these formulas are all dependant on the certainty that a boundary to groundwater flow towards one or other drain lies somewhere between the two. This is usually assumed to be at the centre and determines the zone of influence (ZOI) of the drain upon the watertable. A single drain within an 'infinitely' wide landscape has a groundwater catchment that extends far beyond the potential of the drain to exert any degree of control upon it. Under these conditions it could be said that the drain is functioning within an un-bounded groundwater flow condition.

The results of a three-year groundwater monitoring program at the Beynon drainage study site are here used to:

- Identify the different performance characteristics of drains operating within bounded and unbounded groundwater flow conditions.
- Explore the capacity of the Hooghoudt Steady State (steady state) and De-Zeeuw – Hellinga Unsteady State (unsteady state) equations (Ritzema, 1994) to be used as predictive tools in the assessment of the performance of single drains.
- Discuss how the performance of unbounded (single) drains impacts on the ability of the drain to control watertables and therefore surface salinity.

Materials and methods

In December 2002, 4500 m of open groundwater drainage was constructed on mildly to severely saltaffected dryland agricultural land within the catchment of Lake Dumbleyung, 300 km SE of Perth. The scheme consisted of four lateral drains discharging into a collector drain with an outlet into a saline natural watercourse (Fig. 1). Subsequent to a site assessment the design spacing of three of the lateral drains was calculated using the steady-state equation with input values of Ksat = 0.24 m/d, drainage rate of 0.6 mm/d and a depth to confining layer of 8 m. The value for Ksat is a bulk average for the site measured using the Auger Hole Method (Smedema 1983) and bore slug withdraw tests.

The relatively uniform soil profile across the drainage site is described as a gradational loamy earth (Schoknecht, (1997) consisting of sands and silty clays up to 1.4 m thick over medium clay and then heavy clay with a gritty matrix, to more than 3 m depth (Fig. 2). The drains were constructed using a 32 ton excavator to form a 'v' shaped channels of 2 m and 3 m depth with 0.5:1 batters and 0.8 m bottom width. The channels were enclosed within spoil banks to prevent the uncontrolled ingress of surface runoff. Three gauging stations were installed within the scheme, as illustrated in Figure 1:

- Station 609061 measured discharge from a total of 3480 m of 2 and 3 m deep drains within the whole of the scheme.
- Station 609062 measured discharge from a 600 m length of 2 m deep lateral drain.
- Station 609063 measured discharge from 440 m length of 3 m deep lateral drain.

Discharge volume and salinity were measured at each of the stations at 5 minute intervals, pH at 20 minute intervals and rainfall data was continuously collected on site. Groundwater monitoring had commenced in May 2001 with the drilling of 4 transects of 4 m depth bores (fully screened) and 2 deeper bores to 16 m. Groundwater levels from each of the bores and nearby un-drained control sites were measured at frequencies that varied from 6 hourly to monthly.

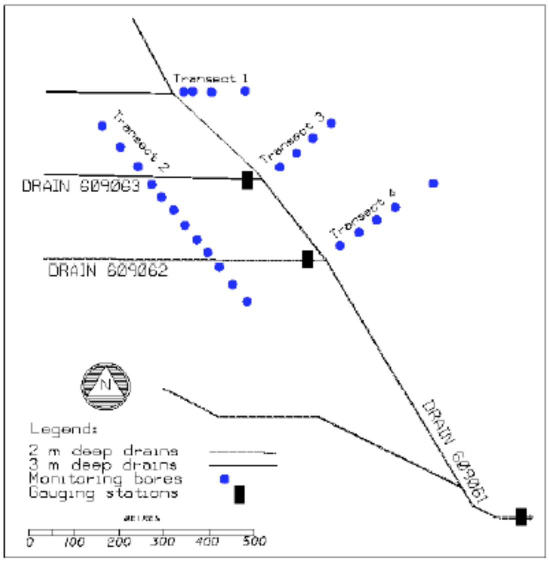


Figure 1 Layout of the scheme showing the position shallow bores and gauging stations

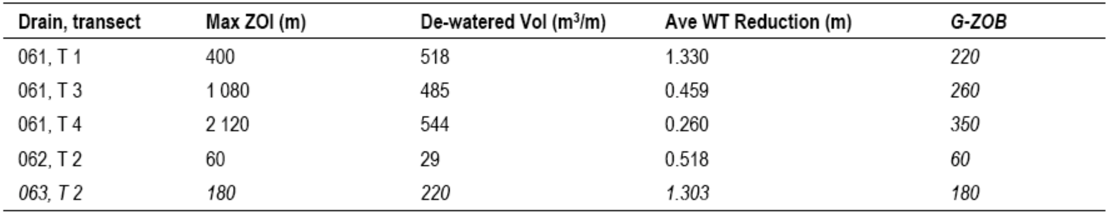
Figure 2 Typical drainage soil profile across the site

Results

Within days of construction the watertable close to the drain fell rapidly. Within a week, watertable reductions of up to 1 m were measured in some bores 50 m from the drains. Within eight weeks of construction the waterlevels in all of the transect 2 bores had fallen to a level within 0.2 m of each other, after reductions of 0.25–1 m. The close waterlevel trend in these bores continued throughout the post-drain monitoring period. The waterlevels within the transect 1, 3 and 4 bores declined by nearly 1 m within 50 m of the drain, 0.5 m at 100 m and 0.3 to 0.2 m and 200 m to 300 m during the eight week period. In all cases the post drainage watertable developed and maintained hydraulic gradients orientated directly towards the drainage channels and remained below its pre-drained levels.

Groundwater hydrograph and profile analysis was used to estimate the maximum extent of the ZOI of the drains on the watertable. The floor level of drain 063, which penetrated to nearly 1 m below that of 062, created a steeper hydraulic gradient towards 063. As a result the groundwater boundary between the drains is located about 190 m from 063 and 60 m from 62. The response of the watertable to drainage measured within the unbounded drain transects 1, 3 and 4 extended to beyond the outer bores. For this reason and because a pre-drainage hydraulic gradient existed towards the drain, potential ZOIs were estimated from log curve analysis of the measured groundwater profiles. The results of the analysis are provided in Table 1.

Table 1 Interpolated (max ZOI) and calculated (G-ZOB) extents of drain groundwater influence



Drain, transect	Max ZOI (m)	De-watered Vol (m^3/m)	Ave WT Reduction (m)	*G-ZOB*
061, T 1	400	518	1.330	*220*
061, T 3	1 080	485	0.459	*260*
061, T 4	2 120	544	0.260	*350*
062, T 2	60	29	0.518	*60*
063, T 2	*180*	*220*	*1.303*	*180*

Further evaluation of the possible ZOIs of the drains was conducted by examining the relationship between the groundwater levels or head in the bores and drain discharge. It was found that a correlation coefficient of 0.5 (approx) existed for this relationship for all of the bores located between the lateral drains (transect 2). For the other transects the values were from 0.5 to 0.7 at 50 m from the drain, uniformly decreasing to 0.2 at 150 to 250 m from the drain. This evaluation has led to the development of the term 'groundwater zone of benefit' (G-ZOB) for unbounded drainage, to reflect the extent to which the drain is having a net positive impact on groundwater levels. While the G-ZOB for the transect 2 (bounded) drains remains the same as the ZOIs in Table 1, for transect 1, 3 and 4, (un-bounded drains) these become 220 m, 260 m and 350 m respectively.

Extrapolation of the G-ZOB of the drains has enabled calculation of their drainage catchment areas: 60.1 ha for 061 (exclusive of 062 and 063), 6.7 ha for 062 and 11.75 ha for 063. 3D groundwater modelling of the pre-drain and 8-week post-drain groundwater levels within the catchment were constructed to calculate the volume of soil that had been de-watered by their respective drains. The results, used in conjunction with the measured groundwater discharge, have been used to calculate bulk soil specific yields. The specific yields are 1.7% for 061, 0.4% for 062 and 2.0% for 063.

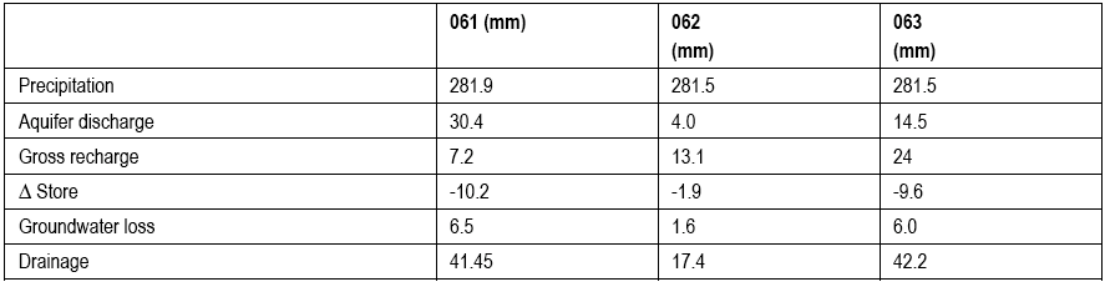
Initial waterbalances calculated from the measured drain discharge highlighted discrepancies in comparison to groundwater fluxes. In summary, these were:

- Observed drain discharge was continuing throughout extensive periods of no or insignificant rainfall and therefore recharge. Under these conditions the expectation is that drainflow would diminish or cease.
- Groundwater levels in transects 1, 3 and 4 displayed upward fluctuations but returned to the same minimum levels which were well above that of the drain base, rather than continuing a steady downward trend. In comparison, those within transect 2 continued to decline to close to or at the drain base.

Flow-net models were used to demonstrate that drain discharge from and waterlevels adjacent to the collector drain (061) are significantly affected by aquifer discharge from the adjacent valley hillside aquifers. The potential for this to occur is highlighted by discrepancies between the ZOI and G-ZOB as in Table 1. The volume of aquifer discharge was estimated from hydrograph analysis and based on the assumption that this source of groundwater is supplied at constant head. According to the Dupit- Forchheimer theory, Darcy's Equation can be applied to describe the flow of groundwater through a vertical plane (Ritzema 1994). Based on this theory, the perimeter of the drainage site was subdivided into sections which presented different surface gradients towards the drains. Assuming that the hydraulic gradient of the watertable corresponds to that of the land surface, average aquifer thickness was 25 m over the granitic basement and Ksat was 0.24 m/d, aquifer discharge to the drains was calculated at 52.6 kL/d. This corresponded closely with the value derived from the hydrograph analysis (55 kL/d) and equated to 65% of the total 31 000 kL discharged from the scheme since construction, to the end of 2003.

Results comparable to those in Table 1 have been calculated using the steady-state equation in unbounded conditions by transposing it to solve for watertable height at X m distances from the drain, rather than directly solving for drain spacing. Using a spreadsheet model allowed the results to be graphed. Model input values differ from those normally used in the equation in that a value for aquifer discharge was incorporated into the drainage rate and the watertable height is that which exists at ∞ distance from the drain rather than the desired height. The extent to which the groundwater levels are controlled at X m distance from the drain were read directly from the chart for various drainage rates.

Table 2 Measured waterbalances for the drains expressed in mm drained



	061 (mm)	062 (mm)	063 (mm)
Precipitation	281.9	281.5	281.5
Aquifer discharge	30.4	4.0	14.5
Gross recharge	7.2	13.1	24
Δ Store	-10.2	-1.9	-9.6
Groundwater loss	6.5	1.6	6.0
Drainage	41.45	17.4	42.2

Calibration between measured (table 2) and unsteady-state modelled data was achieved with gross recharge of 15.5 mm (5.5% of rainfall) in addition to calculated aquifer discharge . The rainfall/recharge relationship was used to develop a recharge model for the period 1980 to 2004, which yielded annual recharge of between 3.6 and 5.6% of rainfall. These are lower than those used at Narembeen (Ali 2003) which are not inclusive of aquifer discharge. The results of the modeling indicated that all of the drains maintained their watertables below pre-drained conditions within their respective G-ZOB. The average modelled drainage rate during the period is 44 mm for 061, 24 mm for 062 and 24 mm for 063. Table 2 shows that aquifer discharge accounted for 73% of the flow from the unbounded drain (061) in comparison to around 30% of that from the bounded drains (062 and 063).

Conclusions

The results of our modelling show that for a single drain:

- Aquifer discharge is a contributor to drainflow and can be significant where aquifers beneath the drain are deep and the hydraulic gradient of the aquifer exists towards the drain floor.
- Recharge to the drainage site can be dominated by aquifer discharge at the expense of draining *insitu* recharge (table 2). This can affect the reduction in watertable level.
- Deeper drains at this site are more likely to intercept the regional aquifer. Discharge from this has been identified as the source of groundwater with higher salinity and lower pH levels.

Groundwater behaviour alongside single drains cannot be 'designed' in the same context as for parallel drains. The only significant design variables available that will affect the performance of single drains are depth and placement. These will determine the relative proportion of recharge verses aquifer discharge that is removed by the drain.

References

Ali, R, Hatton, T, George, R, Byrne, J, Hodgson, G 2004. *Evaluation of the impacts of deep open drains on groundwater levels in the Wheatbelt of Western Australia*, CSIRO Land and Water, Australia.

Smedema, LK 1983, *Land Drainage: planning and design of agricultural drainage systems*, London, UK.

Schoknecht, N 1997, *Soil groups of Western Australia,* Resource Management Technical Report 171*,* Agriculture Western Australia, Western Australia.

Schwab, GO, Frevert, KR, Edminster, TW, Barnes, KK 1981*, Soil and Water Conservation Engineering*, Canada.

Ritzema, HP 1994, *Drainage principles and applications*, International Institute for Land Reclamation and Improvement, Netherlands.