Explaining Trends in Groundwater Depths: Distinguishing Between Atypical Rainfall Events, Time Trends, and the Impacts of Treatments

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Abstract: By 1994, an estimated 1.8 million hectares of cleared land in Western Australia was affected by secondary dryland salinity to some extent. The area affected is likely to double in the coming 20 years. The cause of this salinity is excessive recharge under traditional agriculture, leading to rising groundwater levels. Monitoring changes in groundwater levels is helpful in indicating the degree of threat to agricultural land and public assets. Many researchers have studied groundwater level rises and attempted to explain them statistically. We present an approach for statistically estimating trends in groundwater levels and impacts of treatments on those trends. The approach separates the effect of atypical rainfall events from the underlying time trend and the lag between rainfall and its impact on groundwater is explicitly represented. Rainfall is represented as an accumulation of deviations from average rainfall. Two examples of application of the approach are presented.

Keywords: Groundwater; Monitoring; Treatment; Salinity; Sustainability indicators

1. INTRODUCTION

By 1994, an estimated 1.8 million hectares of cleared land in Western Australia was affected by secondary dryland salinity to some extent, representing 9.4 percent of agricultural land in the state [Ferdowsian et al., 1996]. This area is likely to double in the coming 20 years (to around 3.3 million ha) and may double again before a new equilibrium is reached [Ferdowsian et al., 1996]. The cause of this salinity is excessive recharge under traditional dryland (non-irrigated) agriculture, leading to rising levels of naturally saline groundwater [Wood 1924; Ghassemi et al., 1995]. As water levels come close to the soil surface, saline groundwater will discharge causing soil salinity and contaminating water resources. The rate of rise is not always consistent and increases during years with above average rainfall.

Monitoring changes in groundwater levels in response to management practices is helpful in indicating the degree of threat faced, and the necessary timing and scale of preventative treatments. It can also indicate the impacts of treatments implemented to reduce the rate of groundwater rise. Many researchers have studied groundwater level rises and attempted to explain them statistically. A common approach is to fit a linear time trend to the data or to the annual minima when a strong seasonal response is evident. A potential problem with this approach is that rainfall during the period of observation may not be typical of long-term rainfall levels, so that observed rates of groundwater rise may not be relevant for future projections. Variations in rainfall between years within the sample period will also affect observed groundwater levels and fitted trends.

Other approaches involve fitting different linear trends in different segments of the data [Shao et al., 1999] or analysis of time series data [Box et al., 1994; Larocque et al., 1998]. These approaches are able to explain some of the seasonal variation in groundwater levels if regular and frequent monitoring has occurred. However, they do not explain the variation due to atypical rainfall events or atypical annual rainfall, which are apparent in most data series.

In this paper we present and illustrate a new approach called HARTT (Hydrograph Analysis: Rainfall and Time Trends). The method can differentiate between the effect of rainfall fluctuations and the underlying trend of groundwater levels over time. Rainfall is represented as an accumulation of deviations from average rainfall and the lag between rainfall and its impact on groundwater is explicitly represented. In the following sections, we explain the approach in detail, and present two examples of its application when a treatment has been implemented.

2. DATA AND SITE DETAILS

The Jerramungup and Gnowangerup Districts are located on the south coast of Western Australia (between 117°00′E, 34°30′ S and 119°45′E, 33°30′ S). The basement rocks in the north and central parts of the area are composed of medium and even-grained granites of Archaean origin, intruded by dolerite dykes. The landscape is mostly undulating with well-defined creeks. There are however some broad depressions with poorly defined watercourses. The soils in the area are mostly shallow (A horizon <0.25 m) duplex soils [Northcote, 1979].

The annual rainfall is 550 mm in the south but gradually reduces to 350 mm in the north. The pluviometric regime is characterised by long episodes of widespread and moderate rainfall but occasional short episodes of torrential and localised rainfalls may occur.

The Western Australian Department of Agriculture, a State government agency, has drilled more than 130 bores in this region [e.g. Henschke, 1982; Martin, 1992]. Farmers have monitored the majority of these bores since 1990. The Department of Agriculture is the custodian of the data and provides feedback to individual farmers and catchment groups.

Ferdowsian et al. [2001] analysed data from 49 bores from this data set, excluding any which had some treatment for reducing recharge (e.g. establishment of deep-rooted perennial plants). In this study, we present results from two case studies where recharge treatments were established during the period of monitoring.

The first case located at 119°10′ E, 33°46′ S, is on the mid-slope of a Low Hill landform pattern [McDonald et al., 1990]. It has a local-scale groundwater flow system (slope of land is 3.7%; hydraulic gradient is 2.2%). The paddock was cleared in 1964 and cropped between 1966 and July 1992 when lucerne was planted. Lucerne grew together with annual clover and grasses in winter and on its own in summer until July 1998. Cereals replaced annuals in 1998 and grew together with lucerne until 1999 when lupins replaced both of them. Grazing of lucerne was continuous over winter and rotational over summer (1 week on and 5 weeks off). Bore B1 was drilled approximately 300 m upstream of a saline seep on mid-slope in 1988. Drilling showed 13.5 m of *in situ* weathered material, rich in kaolinite, over fine-grained basement rock (granite) and without any saprolite (permeable layer over basement rock).

The second case located at 117°56′ E, 34°00′ S, is in a broad depression with a poorly defined watercourse. The longitudinal slope of the depression is 0.3% and the side slopes 1%. Drilling showed the profile consists of sediments with heavy clay to 2 m depth and some coarse material below that. The salt-affected area is a strip of land 200 m wide. A bore was drilled in the salt-affected land in September 1993 and had monthly monitoring ever since. A 2.5 m deep drain was constructed in the middle of the salt-affected land in January 1995. The drain passes 20 m away from the bore.

In both cases, the farmers recorded rainfall data.

3. ANALYTICAL METHOD

Based on the pioneering insights of Wenzel [1936] and Jacob [1944], two forms of accumulative residual rainfall were used and compared:

The first was accumulative monthly residual rainfall (AMRR):

$$AMRR_t = \sum_{i=1}^{t} (M_{i,j} - \overline{M}_j) \qquad (1)$$

where $M_{i,j}$ is rainfall (in mm) in month i (a sequential index of time since the start of the data set) which corresponds to the jth month of the year, $\overline{M}_j$ is mean monthly rainfall (in mm) for the jth month of the year, and t is months since the start of the data set.

Figure 1 illustrates an example of the calculated AMRR. The AMRR variable is calculated as the difference between the other two variables shown. The AMRR variable tends to have relatively low within-year fluctuations because, in calculating AMRR, the fluctuations in actual rainfall tend to be offset by seasonal variation in average monthly rainfall.

The second was accumulative annual residual rainfall (AARR):

$$AARR_t = \sum_{i=1}^{t} (M_i - \overline{A}/12) \qquad (2)$$

where $\overline{A}$ is mean annual rainfall (in mm). Because $\overline{A}$ is a constant, the fluctuations in M_i are not moderated as they are for AMRR, so AARR has higher within-year fluctuations. For this reason, it was expected to be well correlated with data from bores with shallow groundwater levels (less than 3 m deep) which typically have seasonally fluctuating watertables.

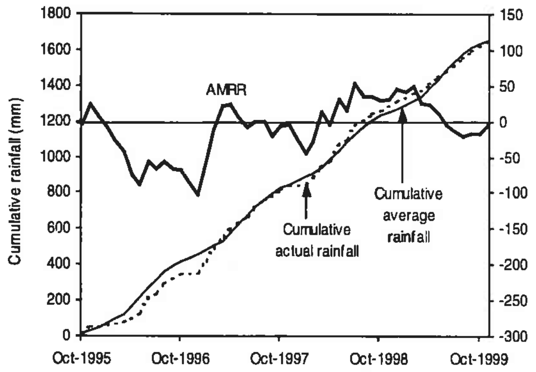

Figure 1. An illustrative example of accumulative monthly residual rainfall (AMRR).

For both AMRR and AARR, construction of the variables was based on data sets pre-dating the earliest recording of depth to groundwater by >8 years. This allowed long lag effects of rainfall on groundwater to be detected, if they occurred. Lags of up to a few years were investigated.

The simplest version of the regression model was:

$$\text{Depth}_t = k_0 + k_1 \times \text{AMRR}_{t-L} + k_2 \times t \qquad (3)$$

where Depth is depth of groundwater below the ground surface, t is months since observations commenced, L is length of time lag (in months) between rainfall and its impact on groundwater, and k_0, k_1 and k_2 are parameters to be estimated. Parameter k_0 is approximately equal to the initial depth to groundwater, k_1 represents the impact of above- or below-average rainfall on the groundwater level, and k_2 is the trend rate of groundwater rise or fall over time.

The rationale for using this model to explain groundwater levels is as follows. Prior to clearing of native vegetation in Western Australia, it is presumed that groundwater tables were in long-run equilibrium, meaning that average rainfall equalled average evaporation and discharge from a catchment. Deviations of rainfall levels from the average level would have resulted in short-term fluctuations in the groundwater level, centred around the stable long-run equilibrium level.

Following clearing of native vegetation, rates of recharge increased, introducing an upward trend to the groundwater level. The t variable in equation (3) captures this upward trend, while AMRR captures the short run fluctuations around that trend.

In cases where it produces models with a higher R^2 (most of which are shallow bores), AARR is substituted for AMRR in the regression model. The value of L was estimated separately for each bore by selecting the value that resulted in the highest R^2 for the regression. Thus L does not necessarily represent the lag until either the first impact or the largest impact of rainfall on watertable depth, but the lag that produces the highest statistical correlation. In many cases, L is longer than the first detectable impact.

This model is appropriate for cases where there is no major change in land use during the period of analysis. If such a change does occur, there are two main ways that it may affect the pattern of groundwater movements: (a) there may be a once-and-for-all shift in the groundwater depth, or (b) there may be a change in the underlying rate of groundwater rise or fall. To include these possible impacts in the model, we define a dummy variable D_t which takes a value of zero in periods of traditional land use and the value 1.0 when the alternative land use is practiced, and a variable S_t which is the cumulative sum of D_t up to time t: ($S_t = \Sigma_{i=1..t} D_i$). The model, then, is

$$\text{Depth}_t = k_0 + k_1 \times \text{AMRR}_{t-L} + k_2 \times t + k_3 \times D_t + k_4 \times S_t \qquad (4)$$

The fourth term represents a shift in the depth during time periods when the alternative land use is in place (with the parameter k_3 representing the extent of the shift) and the fifth term represents a change in the time trend of watertable depth caused by the alternative land use (with k_4 representing the change of slope). Inclusion of the D_t term would be appropriate for a situation where a treatment resulted in a once-and-for-all shift in the groundwater table for the duration of the treatment. Inclusion of the S_t term would be relevant to situations where a treatment reduced the rate of groundwater rise, or increased the rate of groundwater fall.

Depending on the nature of the impacts of the land use change, either or both of the fourth and fifth terms may be included in the model for statistical estimation.

Regressions were made using an Intercooled Stata Statistics Data Analysis software package (Version 6). Durbin and Watson [1950] statistical analysis was used to test for first-order autoregressive errors.

4. RESULTS AND DISCUSSION

4.1 Effect of lucerne on groundwater levels

Figure 2 shows the raw data for the "hydrograph" (groundwater depths over time) for case study 1. Prior to July 1992, the land use at this site was wheat cropping. Lucerne was established in July 1992. Lucerne, a perennial plant, is expected to lower the rate of addition of new water to the groundwater because it has a deeper rooting system and makes use of a greater proportion of the rainfall compared to annual plants such as wheat. After the establishment of lucerne, there was, by chance, a period of below average rainfall. The total rainfall in 1994, 1995 and 1996 were 188 mm, 377 mm and 331 mm compared with an annual average of 395 mm. Therefore, the question arises as to whether the observed fall in groundwaters was due to the lower rainfall or the lucerne. After March 1999, the land use reverted to cropping, and the fall in groundwater apparently ceased.

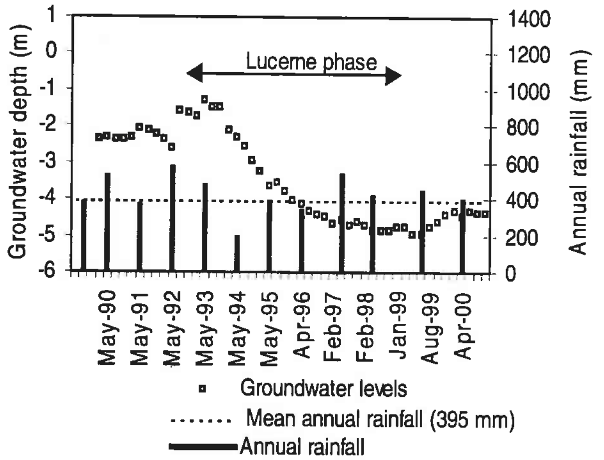

Figure 2. Actual groundwater levels and annual rainfalls for case study 1.

Table 1 shows the statistical regression results for equation 4, including the k_4 term but not the k_3 term. (The parallel shift dummy variable was not statistically significant and was omitted from the final model.) These results are based on the AARR variable, which we have found is often preferred for shallow bores like this one. The *P* values in Table 1 are for *t* tests of whether the parameter estimates are significantly different from zero. Low *p* values indicate a greater degree of statistical significance. The regressions are based on Ordinary Least Squares. The issue of testing and adjusting for serial correlation is discussed in detail by Ferdowsian et al., [2001].

The model fitted the data extremely well, explaining 98 percent of variation in groundwater levels. All three variables were significantly different from zero, with very high levels of statistical significance. As expected, there was a positive relationship between AARR and groundwater level. Every additional mm of rainfall increases groundwater depth by 3.9 mm (which exceeds 1.0 because most of the soil volume is occupied by soil particles). The underlying time trend for groundwater level in the cropping phase is 0.192 m yr^{-1}. This is based on groundwater behaviour both before and after the phase of lucerne. The (S*t*) variable shows that the effect of lucerne was to reduce the rate of rise by 0.687 m yr^{-1}. Therefore, the estimated net trend during the lucerne phase was a 0.495 m yr^{-1} fall.

Earlier, the question was raised about the relative importance of low rainfall and lucerne in determining the fall in groundwater level. Over the course of the 81 months of observations of the lucerne phase, it was estimated that the overall impact of the AARR variable was a fall of 0.08 m, while the impact of lucerne was a fall of 3.34m. Clearly, the lucerne was the dominant factor behind the groundwater fall.

Figure 3 shows the fitted values of groundwater levels from the estimated equation. As expected, given the 98 percent value for R^2, they fit the raw data extremely well. The graph also shows the implied level of groundwaters if lucerne had not been sown. The groundwater would have continued to rise, and late in the period, the predicted level is above the ground surface, implying water discharging at the surface. This would have had extremely adverse impacts on crops grown at this location.

4.2 Effect of drainage on groundwater levels

The second case study concerns the impacts of drainage on a watertable which was initially very shallow. The model and estimation procedure are similar to case study 1, except that the time trend variable is replaced in the model by the drainage dummy variable (D*t*). In periods prior to the installation of drainage (September 93 - January 1995), there was no statistically significant time trend in groundwater level. This is not surprising since the period was short and, with such a shallow watertable, there would be significant discharge at the site (or nearby) to offset any ongoing recharge.

Table 1. Statistical analysis results for case study 1 (lucerne treatment).

Variable	Intercept	AARR	Time trend (m yr^{-1})	Lucerne (m yr^{-1})	R^2
Parameter estimate	-2.27 (m)	0.0039 (m/mm)	0.192 (m yr^{-1})	-0.687 (m yr^{-1})	0.98
Standard Error	0.1	0.0003	0.004	0.005	
P-value	< 0.0001	< 0.0001	0.0003	< 0.0001	

The drainage dummy variable (Dt) was included as the main impact of drainage appeared to be a once-and-for-all shift in the groundwater level (see Figure 4). In addition, the drainage variable (St) was also a significant explanator of groundwater depth.

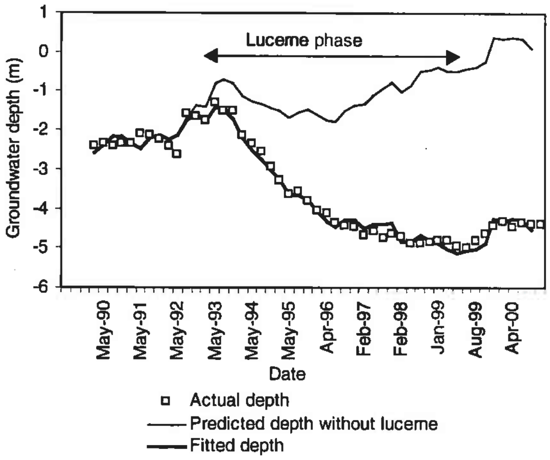

Figure 3. Actual and fitted groundwater levels for case study 1.

Table 2 shows that, once again, all parameters included in the model were different from zero, with very high levels of statistical significance.

Rainfall had a smaller impact than in case study 1 (only 2.2 mm groundwater change per extra mm of rainfall). Drainage had two impacts: a once-and-for-all reduction in groundwater level by 0.566 m, and an ongoing further decline by 0.071 m per year. The overall explanatory power of the model was again high, with an R^2 of 0.90.

Figure 4 shows that the fitted model again captures the actual data well. The predicted watertable depth in the absence of drainage is also shown, indicating that groundwater would have remained at very shallow depths and remained a severe impediment to agricultural production.

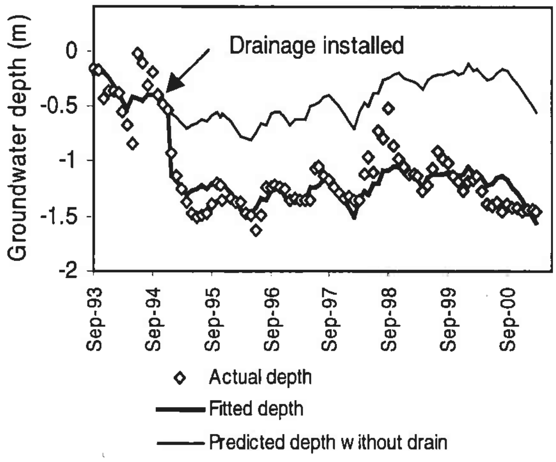

Figure 4. Actual and fitted groundwater levels for case study 2.

Table 2. Statistical analysis results for case study 2 (drainage).

Variable	Intercept	AARR	Drainage dummy (m)	Drainage (m yr^{-1})	R^2
Parameter estimate	-0.312 (m)	0.00219 (m/mm)	-0.566 (m yr^{-1})	-0.071 (m yr^{-1})	0.90
Standard Error	0.0432	0.000338	0.0783	0.00142	
P-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	

5. CONCLUSION

We have presented an approach to statistical modeling of hydrographs that appears to have some considerable strength. The HARTT method is simple to apply with standard regression methods. It provides high quality fits to observed data. It allows the separation of atypical rainfall events from the underlying time trend. Results are highly consistent with hydrological expectations. In two case studies, we have been able to discerne the impacts of treatments on the groundwater rise in the context of fluctuating rainfall and, in one case, an underlying time trend in groundwater depth.

6. ACKNOWLEDGEMENTS

David Pannell acknowledges financial support from Grains Research and Development Corporation.

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