Shallow Groundwater Response to Rainfall and Stream Flow in the Magela Creek Catchment, Northern Territory

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Abstract Water levels have been digitised for three water years of record, in observation bores tapping shallow and deep levels at two sites near Magela Creek, in the vicinity of the Ranger uranium mine. The data show evidence of a minor aquitard at one site, but not at the other. The paper attempts to relate the groundwater hydrographs to rainfall, pan evaporation and stream flows, by using simple models believed to be appropriate at different stages in the water year. The storage in the unsaturated zone at the beginning of the wet season was estimated by considering the cumulative input of rainfall before the start of rise of the water-table. The rate of increase or decrease of water-table level can be related to the difference between input to and output from the groundwater system. Comparison of these results with input early in the wet season, before significant stream base flow was evident, provided an estimate of storage coefficient, while comparison with stream flow late in the wet season led to an estimate of the effective area of the groundwater system which contributes to stream flow. The further decline of the water-table in the dry season has been used to estimate transpiration under stress of the deep-rooted plants, which act as phreatophytes. The results from this site are contrasted with published results for the Howard River catchment, closer to Darwin, where the water balance was estimated by a combination of tracer, micrometeorological and tree sap flow measurements.

1. INTRODUCTION

The hydrology of catchments in northern Australia is distinguished from the rest of the continent by distinct wet and dry seasons in a tropical environment. Under these conditions, streams flow in the wet season, after the initial soil water deficit has been satisfied, and runoff coefficients may be very high during flood events. Water-tables are typically shallow, rising to close to the surface by the end of the wet season, and falling in the dry season under the influence of transpiration by phreatophytic vegetation, and discharge to stream base flow and to regional groundwater flow. In the study described here, an attempt is made to quantify the relative contribution of these factors to the groundwater hydrograph, using simple approximations to the water balance at different periods in the wet and dry seasons. The data used are daily precipitation, pan evaporation, stream flow and groundwater levels, extending over a period of three water years.

The results of this study are contrasted with those from an intensive study on a catchment in the same climatic region, using sophisticated instrumentation to measure groundwater tracers, micrometeorology and tree sap flow.

2. THE MAGELA CREEK CATCHMENT

Magela Creek (Figure 1) is a tributary of the East Alligator, about 250 km east of Darwin. In its upper reaches it drains a sandstone plateau region , then falling through deep narrow gorges into a low plainland characterised by braided sand bed channels and a series of billabongs and connecting channels. It then spreads over a seasonally inundated black clay flood plain before discharging into the East Alligator river.

Most of the catchment is in the Kakadu National Park, and it also contains an active uranium mine and processing plant at Ranger and a projected mine at Jabiluka, a few km to the north. As a result of the environmental issues involved, there has been extensive monitoring of the surface and subsurface hydrology of the catchment, particularly in the neighbourhood of the Ranger site, over a period of about thirty years.

The area of the whole catchment is about 1580 km^2 [Vardavas, 1989], while the area above the main stream gauging station (GS821009) is about 600 km^2. The average annual discharge at this station [Vardavas, 1988] is about 420x10^6 m^3, corresponding to an average depth over the catchment of 700 mm. This may be compared with an annual average rainfall at the gauge site of 1550 mm, and pan and potential evaporations of 2700 and 2000 mm respectively. Figure 2 shows the typical course of the hydrological variables through a water year.

The soils in the lowlands (the focus of the present study) are variable, and support eucalypt woodlands and grassland, with a concentration of dense vegetation near the creek.

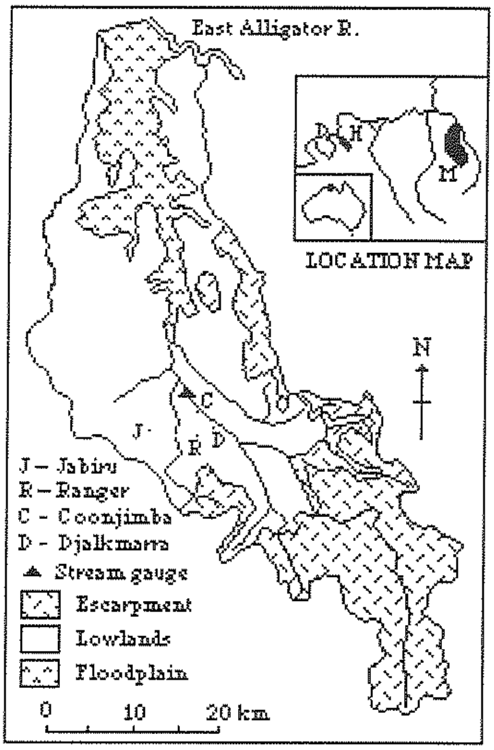

Figure 1. The Magela catchment. Inset shows locations relative to Darwin (D) of the Howard (H) and Magela (M) catchments.

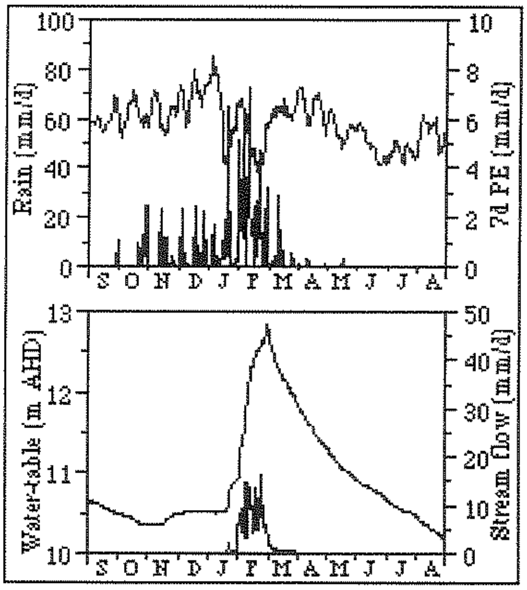

Figure 2. Hydrological variables for the 1986/87 water year, from sources noted in Section 3.

Whitehead [1980] proposed that the hydrogeology of the catchment consisted of a two-aquifer system, with an upper layer in the soil and lateritic profile recharged by rainfall, and separated by an aquitard from an underlying semi-confined aquifer extending to base rock. Both aquifers were assumed to provide a continuous regional flow to the north. While this hypothesis was accepted in several later studies, it was challenged by Salama and Foley [1997], who concluded that no regional shallow aquifer underlies the Ranger mine site. In their model, water infiltrates into the soil to form disjointed saturated areas, which may then discharge downwards or to the surface.

Chapman [1990] found that the water-table contours upstream of Djalkmarra billabong (Figure 1) indicated a flow from north to south, with no evidence of any influence of the creek on the water-table, which was always below the stream bed. This contrasted with the situation further downstream on the floodplain, where the water-table slopes towards the creek and may rise above the surface water level during the wet season.

3. DATA

Groundwater hydrographs for 1986/89 were obtained from two pairs of adjacent bores located near Magela Creek, the upstream pair near Djalkmarra Billabong and the downstream pair near Coonjimba Billabong (Figure 1). One bore in each pair was drilled to a shallow depth and the other was screened to record the head in the lower aquifer (Table 1). The bores were equipped with Stevens A-35 chart recorders, with approximately monthly checking of the chart record against direct depth measurements. Photocopies of the charts were digitised and the information stored by the HYDSYS system[Heweston and Daniell, 1988]. The computer generated plots were checked visually against the recorder charts.

Table 1. Details of groundwater bores. First letter of code refers to location (Djalkmarra or Coonjimba) and the second to depth (Shallow or Deep)

Code	Reg.No.	Surface RL (m AHD)	Screen depth (m)	
			Top	Base
DS	23557	13.53	4.5	5.5
DD	20096	14.17	20	40
CS	23523	10.56	4.4	5.4
CD	9238	11.04	24.6	29.6

Continuous stream flow data from GS821009 were computed as mean daily flows. Daily rainfall data were taken from the pluviograph R821009A, located near the stream gauge. Daily pan evaporation data from the Ranger meteorological site were converted to potential evaporation (PE) by a continuous polynomial fitted to monthly values of lake/pan coefficients [Vardavas, 1987]. For graphical presentation (e.g. Figure 2), these have been smoothed by applying a 7 day moving average.

4. ANALYSIS AND RESULTS

4.1 Groundwater hydrographs

Figure 3 shows a plot of bore levels for the period under study. The levels for the two Coonjimba bores are almost identical, showing that there is no aquitard at that site, but at Djalkmarra the level in the shallow bore is consistently above that in the deep bore, suggesting an aquitard which delays flow from the shallow to the deep layer.

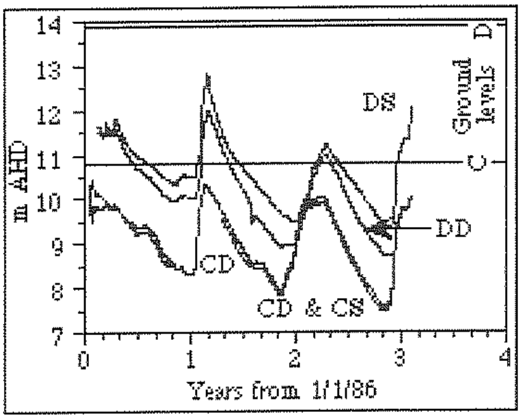

Figure 3. Water-table levels for shallow and deep bores near Coonjimba and Djalkmarra Billabongs.

The levels at the upstream (D) site are always above those for the downstream (C) site, indicating groundwater flow from south to north, in contrast with the plots of water-table contours by Chapman [1990] for an area upstream of Djalkmarra Billabong. These differences support the contention of Salama and Foley [1997] that there is no continuous regional groundwater flow in the lowlands part of the catchment.

Figure 3 also demonstrates that there is greater variability in peak water levels from year to year at the upstream (Djalkmarra) site, while the peak levels are closer to the surface at the downstream (Coonjimba) site.

4.2 Storage in unsaturated zone

At the beginning of the wet season, the unsaturated zone above the water-table has reached a level of dryness where most of the shallow-rooted grasses have died back. As the rainy period begins in October-November, a wetting front moves downwards through the unsaturated zone, while the water-table continues to fall under the influence of transpiration from deep-rooted phreatophytic vegetation. The rainfall that occurs up to the time that the water-table starts to rise can be taken as a measure of the available storage in the unsaturated zone, which could be regarded as the difference in water content between the wilting point and field capacity. Table 2 shows the results of this analysis on the two shallow bores, DS and CS, which give the best measure of the position of the water-table. The appropriate date for this calculation has been taken as the day before the groundwater hydrograph begins its sharp rise (see Figure 2). By using the depth to the water-table on this date, the unsaturated zone storage can be expressed as an increase in volumetric water content.

Table 2. Date of water-table response, depth of water-table, rainfall and corresponding volumetric water content.

Bore	Date	W-T depth (m)	Rainfall (mm)	Water content
DS	17/1/87	3.01	338	0.112
DS	9/1/88	4.02	485	0.121
DS	28/11/88	4.15	281	0.068
DS	Average	3.73	368	0.100
CD	17/1/87	2.62	338	0.129
CS	20/12/87	2.11	262	0.124
CS	23/11/88	2.96	200	0.068
CS	Average	2.56	231	0.107

It will be noted that the water-table started rising appreciably earlier in the 1988/89 wet season than in the other two years under study, with correspondingly lower estimates of storage and water content. Table 2 also shows that the maximum depth of the water-table is consistently greater at Djalkmarra than at Coonjimba, with correspondingly higher storage in the unsaturated zone, but the estimates of water content are very consistent between the two locations.

4.3 Estimates of storage coefficient

When the water-table starts to rise, it can be assumed that the water content in the unsaturated zone remains approximately constant, and the vegetation is freely transpiring, so that the evapotranspiration is measured by the potential evaporation (PE). The rise in the water-table is due to the cumulative input of rainfall less PE, and the slope of the related graph (Figure 4) will be a measure of the storage coefficient. Table 3 shows that there is considerable variability in these estimates between wet seasons, but reasonable consistency between the two locations.

4.4 Area contributing to stream base flow

The interaction between a stream and shallow groundwater in a catchment can be quantified from the nature of the recession limb of the streamflow hydrograph, when the groundwater is the sole source of the surface flow . The classical method of analysis of this period is based on the assumption of the linear relation

$$V = \tau Q \qquad (1)$$

where Q is the stream flow, V is the storage of

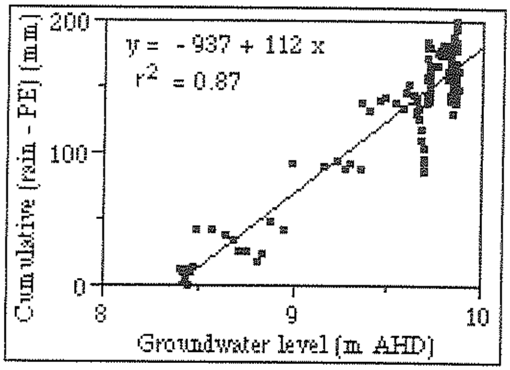

Figure 4. Plot of cumulative (rain-PE) against groundwater level in bore CS for period 15/12/87 to 15/3/88

Table 3. Estimates of storage coefficient S (with coefficient of determination r^2) from plots of cumulative (rainfall less PE) against water-table levels, during the period of rapid groundwater rise.

Bore	DS		CS	
Year	S	r^2	S	r^2
86/87	0.21	0.97	0.27*	0.80
87/88	0.03	0.22	0.11	0.87
88/89	0.11	0.83	0.12	0.90
Mean	0.16		0.17	

*Data from bore CD

groundwater above stream bed level, and τ is the groundwater residence or turnover time. This leads to the exponential relation for the period of base flow:

$$Q_t = Q_0 \, e^{-t/\tau} \qquad (2)$$

where Q_t , Q_0 are the flows at times t and 0. Chapman [1999] showed that a nonlinear relationship fits many streamflow recessions better than (1), but for all but very long recessions, the data are very well fitted by (2) with a biased value of the turnover time.

As noted by Chapman [1990], turnover times for Magela Creek recessions are short, but increase as the wet season progresses. The only recession of significant duration is that which follows the last period of surface stream flow, for which Figure 5 is a typical example.

At this point in the annual cycle, it can be assumed that evapotranspiration losses will be met by occasional showers and depletion of the unsaturated zone. If the bores near the stream can be taken as representative of the groundwater which is feeding the stream flow recession, a balance between the reduction in groundwater storage and the volume of stream flow in this period can be expressed as:

$$\delta V = \tau\,(Q_t - Q_o) = A\,S\,(H_o - H_t) \qquad (3)$$

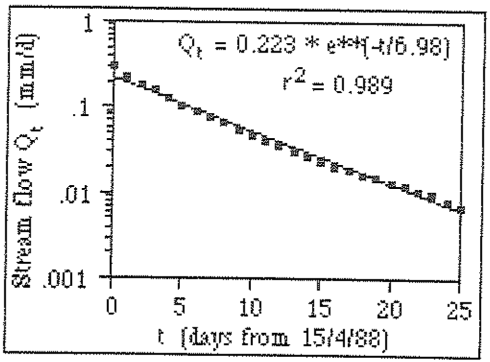

Figure 5. Magela Creek recession at the end of the 1987/88 wet season.

where A is the area of the groundwater system contributing to the stream flow, and H_o , H_t are the water-table levels at the beginning at end of the recession period. In Table 4, the value of the storage coefficient S has been taken as 0.16, and the values of H_o and H_t are averages for all bores with available data.

Table 4. Calculation of area of catchment contributing to final stream flow recession.

	Wet season		
	85/86	86/87	87/88
Start date	2/5/86	28/3/87	15/4/88
Duration (d)	30	12	25
τ (days)	12.73	5.90	6.98
Q_o (mm/d)	0.076	0./328	0.223
δV (mm)	0.88	1.68	1.51
δV (10^3 m^3)	527	1009	909
(H_o - H_t) (m)	0.361	0.231	0.324
A (km^2)	9.1	27.2	17.5

It will be seen that the volume of stream flow in the final recession corresponds to a depth of about 1 mm over the catchment, while the average area A of the part of the catchment contributing to the recession is 18 km^2 or about 3% of the total catchment area.

4.5 Transpiration of phreatophytes under stress

At the end of the dry season, the grasses and other shallow-rooted vegetation have died off, and the only contribution to evapotranspiration is from the phreatophytes which draw their water from the saturated zone. It follows that there will be a balance between reduction in groundwater storage, as measured by the decline in water-table levels, and transpiration from the phreatophytes. If it is assumed that this transpiration will be a constant proportion of PE, a graph of bore water level against cumulative PE should give a straight line, as evidenced in Figure 6.

Assuming a value for the storage coefficient S, the gradients of graphs such as Figure 6 can be converted to a ratio of actual evaporation to potential evaporation, E/PE, as shown in Table 5.

Figure 6 shows that the data would be slightly better fitted by a curve which decreases in gradient as the dry season progresses. Table 6 also shows the values of E/PE at the beginning and end of the period, obtained by fitting a second order curve to the data.

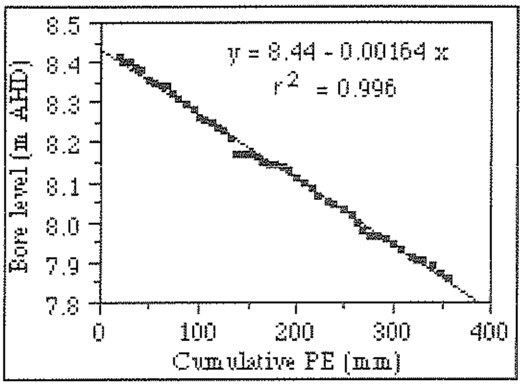

Figure 6. Water level in bore CS plotted against cumulative PE for the period 11/9/87 to 30/10/87.

Table 5. Calculation of E/PE in dry season, assuming storage coefficient S = 0.16

	Date		E/PE		
Bore	Start	End	Mean	Start	End
DS	1/7/86	19/10/86	0.16	0.21	0.12
DS	1/7/87	30/10/87	0.22	0.24	0.17
DS	6/7/88	20/10/88	0.25	0.29	0.21
DD	1/7/86	19/10/86	0.21	0.24	0.17
DD	18/8/87	30/10/87	0.21	0.23	0.18
DD	1/7/88	20/10/88	0.29	0.43	0.12
CS	5/8/86	19/10/86	0.36	0.36	0.36
CS	11/9/87	30/10/87	0.26	0.28	0.19
CS	1/7/88	6/9/88	0.37	0.37	0.37
CD	5/8/86	19/10/86	0.30	0.36	0.24
CD	11/9/87	30/10/87	0.25	0.31	0.18
CD	1/7/88	2/9/88	0.39	0.49	0.30
Mean			0.27	0.32	0.22

5. DISCUSSION

The methods of analysis and results obtained in the last section are best discussed in terms of the approximations that have been made in the water balance of the catchment. For this purpose, the water balance is most clearly described by two equations, one relating to the surface and unsaturated zone, and the other to the groundwater system.

For the surface and unsaturated zone, the water balance for any arbitrary period of time can be written as:

$$P - E_s - Q_s - R = \delta M \qquad (4)$$

where P is the rainfall, E_s is the combination of evaporation from bare soil and transpiration from shallow-rooted plants, Q_s is stream flow from surface runoff, R is recharge to groundwater, and M is the water stored in the unsaturated zone.

For the groundwater system, the water balance is:

$$R - E_g - Q_g - G = \delta V \qquad (5)$$

where E_g is the transpiration from phreatophytes, Q_g is stream flow from groundwater, G is loss of groundwater past the catchment boundaries, and V is the water stored in the groundwater system.

We can now consider the terms in these equations that have been neglected in the calculations.

For the calculation of storage in the unsaturated zone, the terms E_s, Q_s and R in (4) have all been assumed negligible. While there was no surface runoff in the periods considered, there will be some recharge in the last few days of the period, as evidenced by a slowing of the rate of fall of the water-table. Transpiration by shallow-rooted vegetation is probably negligible, but there will be some evaporation from surface soil, particularly towards the end of the period. The values of unsaturated zone storage obtained in Section 4.2 should therefore be regarded as upper bounds.

In all the remaining calculations, the term G has been ignored. This is based on the hypothesis that export of groundwater (except as stream flow) from the catchment is negligible. Woods [1994] used a combination of average water and chloride balances to estimate the net recharge to permanent groundwater on the rehabilitated Ranger uranium mines landform to be 2 - 5% on the average rainfall.. The contrast between the direction of flow (north to south) found by Chapman [1990] for the area upstream of Djalkmarra billabong, and the flow from south to north between Djalkmarra and Coonjimba billabongs found in this study, also suggest that there is no continuous regional groundwater flow, but rather a set of discontinuous systems separated by dykes or other barriers. Omission of the term G is therefore believed to be justifiable.

For the calculation of storage coefficient S, it seems reasonable to take the sum of E_s and E_g as equal to the potential evaporation, and δM to be zero, while Q_g is probably small, but there was some surface runoff Q_s in the periods used in the calculations. Neglect of this term means that the values of S will tend to be overestimates, and this will impact on the subsequent calculations, which use S.

For the calculation of the area A of the groundwater system contributing to stream flow, the quantities R, E_g and G in (5) have been neglected. The error will be minimised if R and E_g have approximately the same magnitude.

In the calculation of E_g in the dry season, the terms R, Q_g and G in (5) have been neglected. These all appear to be reasonable assumptions.

It is instructive to compare the results of this study with those found by Cook et al (1998) in an intensive study of the 126 km^2 Howard River catchment, closer to Darwin (Figure 1) but with the same climate. Figure 7 shows that the water-table in the Howard fluctuates about 4 times as much as that in the Magela, while the Howard stream flow recessions have an average duration of 130 days and a turnover time of 28 days, as compared with 22 and 8 days respectively for the Magela, for the 3 years under study. The contribution of groundwater to stream flow in the recession period is about 14 mm for the Howard and 1 mm for the Magela.

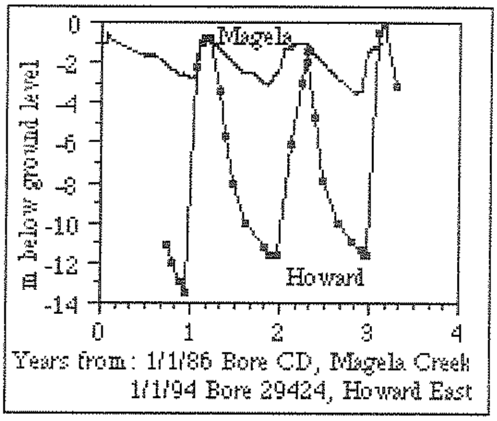

Figure 7. Groundwater hydrograph for one of the bores near Magela Creek, contrasted with a typical bore in the Howard River catchment.

6 CONCLUSIONS

This study has shown that it is possible to obtain useful first estimates relating to the water balance of a tropical catchment, using readily available physical data on groundwater levels, stream flow, rainfall and pan evaporation. The limitations of the approach have been set out in the Discussion.

The specific results for the lowland part of the Magela catchment are:

- Unsaturated zone water content variation of 0.11 between dry and wet seasons (upper bound)
- Average groundwater storage coefficient 0.16 (upper bound)
- Area of groundwater system contributing to stream flow 18 km^2 or 3% of catchment area
- Average ratio of actual to potential evaporation by phreatophytes in dry season is 0.27, falling from 0.32 to 0.22 as the dry season progresses.

These results contrast sharply with those found for another catchment in the same climatic region, showing the necessity of careful studies to determine the water balance of tropical catchments. Such studies shuld be conducted over a longer period than the work described here, which covered only 3 water years, each with below average rainfall.

7 ACKNOWLEDGEMENTS

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