Water level response in fractured rock aquifers underlying irrigated lands – a study in the lower Great Fish River Valley*

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Abstract

During 1982 a study concerned with factors responsible for the mineralization of water in the Great Fish River was undertaken. In particular the irrigation return flow and groundwater seepage components of the mineralization cycle were investigated. A small area of irrigated land in the lower Fish River Valley was chosen for a detailed study of irrigation water input, groundwater and seepage water mineralization. This paper is concerned with the response of deeper groundwater found within the fractured formations to irrigation water input.

Irrigation water and rainfall are the two hydrological inputs into the system, representing on average 70% and 30% respectively, of water reaching the land surface. The major outputs from the system are calculated as evapotranspiration (76%), discharge from fractured sandstones and mudstones (22,4%) and river bank seepage (1,6%). Rapid water level fluctuations, measured in boreholes penetrating both the alluvial and "deeper" fractured rock aquifers, were observed after irrigation. The transmissivity values of the alluvium (1 m^2/d) obtained from controlled aquifer tests, are substantially lower than those of the fractured rock aquifers (38 m^2/d). This latter observation, together with the rapid borehole responses, suggest that the residence time of the irrigation return flow is in the order of months rather than years.

Introduction

In recent years the progressive downstream mineralization of water in the Great Fish River has been the focus of numerous studies; for example Viljoen and Liebenberg (1974), Viljoen and Görgens (1976), and Tordiffe (1978). Much of the research, which has been co-ordinated by a standing Working Group for Mineralization, has concentrated on spatial and temporal variations in river water quality, particularly during irrigation releases from the main storage reservoirs (Van Veelen *et al.*, 1978; Hall and Du Plessis, 1979; Hall, Du Plessis and Hutson, 1980).

One of the major problems associated with irrigation farming worldwide is that the river serves as both the major conveyor of irrigation water as well as the drainage canal for seepage flow returning to the river. In the case of the Great Fish River, mineralized irrigation return flows of the upper schemes are discharged into the river, detrimentally affecting the quality of water abstracted for irrigation further downstream.

During 1982 and 1983 a study was undertaken concerned with the factors responsible for mineralization of water in the Great Fish River, in particular the irrigation return flow and groundwater seepage components (Reynders, 1984). An important aspect of this study was the monitoring of groundwater fluctuations related to irrigation leads. In order to execute this study three section lines of boreholes were drilled (Fig. 1). This paper reports on detailed observations of groundwater levels in boreholes penetrating both alluvial and fractured rock aquifers underlying irrigated lands in the Middleton study area. Inputs, in the form of irrigation leads and rainfall, and outputs, evapotranspiration, river bank seepage and groundwater discharge, are used to derive a simple water balance.

Materials and methods

The Middleton irrigation scheme is situated in the semi-arid Lower Fish River Valley (Figure 1). At present 1 946 ha of land are irrigated, the main crops under cultivation being lucerne, maize and wheat. The whole of the cultivated area is flood irrigated and the irrigation season normally starts in August and lasts till April.

The investigation was restricted to an area comprising 392 ha of irrigated, and 235 ha of non-irrigated land. In this area the fluctuations in groundwater levels were monitored by installing six autographic water level recorders in boreholes penetrating both alluvial and fractured rock aquifers (Figure 1). Rainfall data and daily Class A pan evaporation data were obtained from a weather station situated within the study area (Table 1). The actual evapotranspiration (ETa) for 1982 and 1983 was calculated by multiplying the potential evapotranspiration data with a time dependent set of crop factors supplied by the Soil and Irrigation Research Institute, Pretoria (Table 2). The crop specific ETa data were used to calculate weighted mean ETa values for each hectare of irrigated land by first multiplying each crop's ETa by the fractional area of land covered by that crop, which for the study as a whole was lucerne 0,5, maize 0,4, and wheat 0,1. The irrigation practice used by most farmers of the Middleton area consists of a so-called "pre-leaching" irrigation of 100 mm applied during mid-August. (In 1983, this pre-leaching irrigation was not applied due to the heavy rainfall recorded in July). Following the first irrigation, two applications that vary between 75 and 150 mm each are applied in the period September to October. During the rest of the irrigation season up to January, 75 mm of water is applied at two weekly intervals. From January to April, only infrequent irrigation of lucerne takes place. The total annual amount of water allocated by the local irrigation board to each farm is 1 250 mm ha^{-1}. The actual dates and amounts of water applied to the lands situated within the study area, as calculated from canal diversions, were obtained from local farmers. These latter values were used in the subsequent calculations. The irrigation water is distributed by means of unlined earth canals.

Controlled aquifer pumping tests, using standard procedures (Kruseman and De Ridder, 1970), were used to determine transmissivity values for both the alluvial and fractured rock aquifers. The flow rates within the aquifers were determined with a tracer test using two fluorescent dyes, fluorescein and rhodamine B. The latter test was done by injecting a slug of tracer (400 g of dye dissolved in water) into an injection borehole and then pumping a second hole in order to induce a hydraulic gra-

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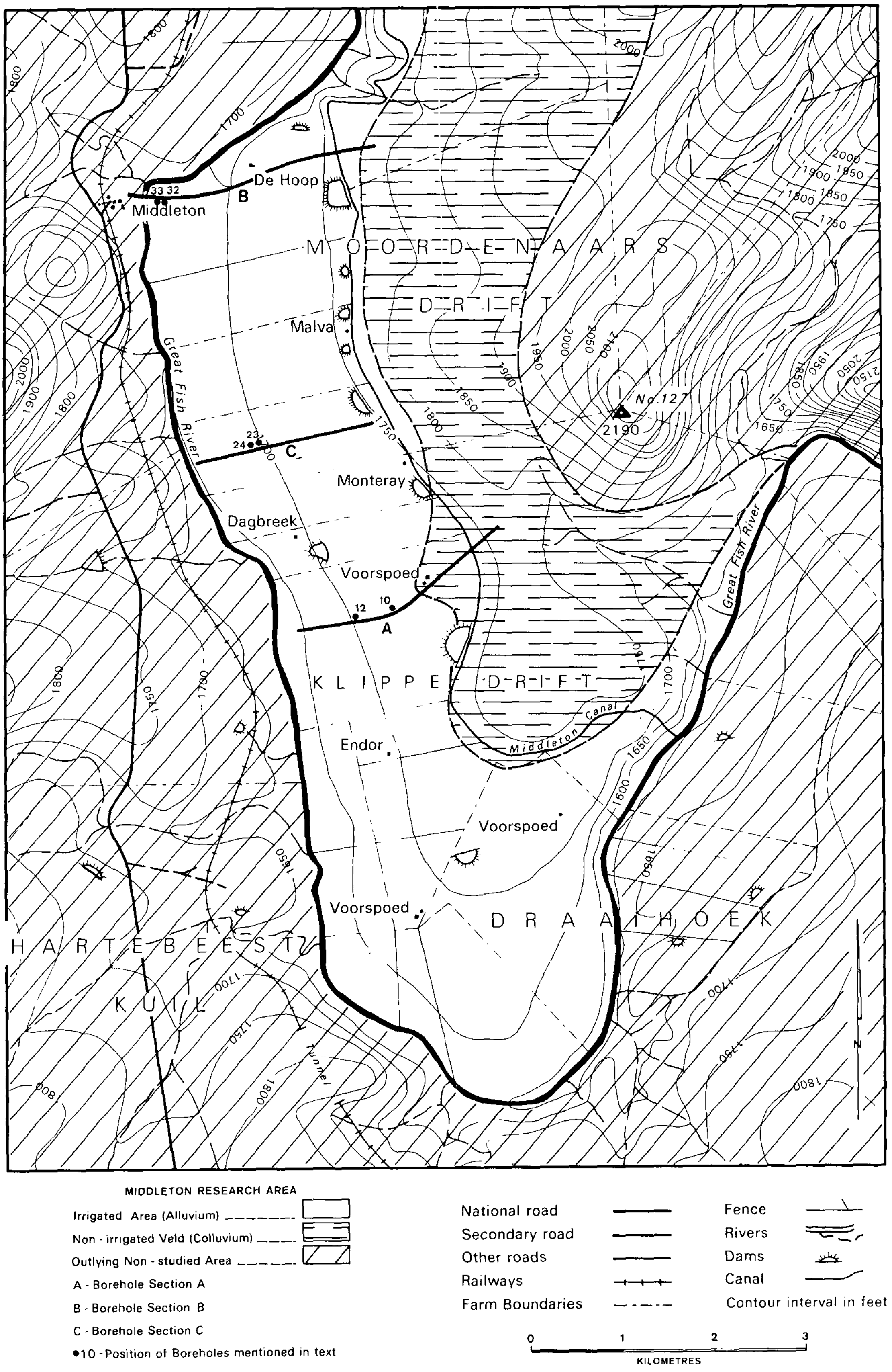

Figure 1
Map of the Middleton research area

TABLE 1
RAINFALL AND CLASS A PAN EVAPORATION DATA FOR THE PERIOD 1980 TO 1983 FOR THE MIDDLETON STUDY AREA

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
1980 Rainfall	30,5	65,9	38,4	27,6	2,8	10,8	5,0	8,5	26,1	14,5	86,2	24,5	340,8
1980 Class A Pan	264,0	204,4	182,4	184,6	132,3	106,8	133,0	130,3	142,8	230,0	212,2	256,5	2 179,3
1981 Rainfall	19,8	62,7	94,9	12,1	57,5	7,0	6,6	39,5	5,0	70,6	48,3	66,5	490,5
1981 Class A Pan	245,3	190,2	166,4	120,6	76,3	63,5	123,1	101,8	173,5	200,1	234,3	254,5	1 949,6
1982 Rainfall	14,9	50,2	31,4	81,9	0,0	46,6	40,5	23,3	29,5	37,4	28,5	10,5	394,7
1982 Class A Pan	282,9	245,2	157,9	120,4	101,0	87,1	78,0	118,3	145,3	217,9	257,0	316,5	2 127,5
1983 Rainfall	8,2	8,5	21,5	5,0	10,8	23,4	129,4	0,0	27,0	21,2	43,0	46,3	344,3
1983 Class A Pan	309,7	241,5	199,5	143,5	117,3	108,9	164,9	146,5	167,0	221,3	208,0	326,3	2 354,4

TABLE 2
CROP FACTORS AND ACTUAL EVAPOTRANSPIRATION DATA FOR 1982 AND 1983

	Crop factors			Actual Evapotranspiration (mm)	
	Maize	Lucerne	Wheat	1982	1983
January	0,40	0,80	0,10	161,3	176,6
February	0,50	0,50	0,10	112,8	111,1
March	0,55	0,50	0,10	75,8	95,8
April	0,55	0,40	0,10	51,8	61,7
May	0,55	0,40	0,10	43,4	50,4
June	0,10	0,30	0,10	17,5	21,8
July	0,10	0,30	0,15	16,0	33,8
August	0,10	0,50	0,30	37,9	46,9
September	0,10	0,50	0,45	48,6	55,9
October	0,13	0,60	0,60	89,8	91,2
November	0,20	0,80	0,55	137,5	111,3
December	0,23	0,80	0,10	158,9	163,8
Total				951,3	1 020,4

dient between the two holes which were situated about 18 m apart. The pumped hole was subsequently sampled until the dye appeared and the travel time and volume of water pumped then recorded.

The hydraulic conductivity of the soils within the root zone of the crops was determined by applying the method of Klute (1965) to undisturbed cores obtained from four soil profiles which were located within the irrigated lands.

Results and discussion

The water balance

In drawing up a water balance for 1982 and 1983 it was assumed that the amount of water passing through the root zone of the irrigated land, is equal to the difference between the total applied water and the water lost by actual evapotranspiration. It was furthermore assumed that because of the contoured nature of the land, no water was lost to overland flows. The amount of irrigation water applied to the land was calculated from the measured canal diversions to each farm. For 1983 this latter figure amounted to approximately 975 mm, while precipitation added a further 344 mm, totalling 1 319 mm of water infiltrating into the irrigated lands. During the same period the actual evapotranspiration was calculated as 1 020 mm. Therefore, the depth of water from the irrigated lands available for percolation to the alluvial and fractured rock aquifers is 299 mm, i.e. 1,17 x 10^6 m^3 from 392 ha (Table 3). In addition, 0,04 x 10^6 m^3 can be added for precipitation falling on the 235 ha of non-irrigated veld situated within the study area, assuming that in non-irrigated areas 5% of the precipitation increments groundwater storage (Tordiffe, 1978). This means that 97% of the deep percolate that recharges the aquifers underlying the study area, comes from the irrigated lands. It can furthermore be calculated that the annual deep percolate from the irrigated lands represents a leaching fraction (LF) of 0,27 and 0,23 for 1982 and 1983 respectively, which is indicative of moderate over-irrigation.

TABLE 3
VOLUMETRIC WATER BALANCE FOR 1982 AND 1983

Irrigated area = 392 ha; Non-irrigated area = 235 ha

	Depth (mm)		Volume (× $10^6 m^3$)	
	1982	1983	1982	1983
Irrigation water applied	914	975	3,58	3,82
Rain on irrigated lands	395	344	1,55	1,35
Rain on non-irrigated veld	395	344	0,93	0,81
ETa from irrigated lands	951	1 020	3,73	3,99
ETa from non-irrigated veld	375	327	0,88	0,77
Deep percolate from irrigated lands	358	299	1,40	1,17
Deep percolate fron non-irrigated veld	20	17	0,05	0,04
Total deep percolate	—	- -	1,45	1,22
River bank seepage through alluvium*	—	—	0,10	
Discharge from fractured rock aquifers*	—	—	1,44	
Total discharge from study area	—	—	1,54	

*Calculated using the equation: $Q = W \times I \times T$
where W = length of river encountered = 8 737 m
I = hydraulic gradient = 1:33,3 for alluvial aquifers and 1:85 for the fractured rock aquifers
T = transmissivity = 1,1 $m^2d^{-1}$for the alluvium and 38,4 m^2d^{-1} for the fractued rock aquifers

Inspection of the individual rainfall events recorded during the study period (data not presented here) indicates that very few events were effective in recharging the aquifers. During the period of intense irrigation, i.e. mid-August to April, the maximum amount of rainfall recorded during any single event was 32 mm which occurred on 20/11/83. During the period of no irrigation, May to mid-August, an individual maximum of 114 mm was recorded on 25/7/83 and 26/7/83. This latter event

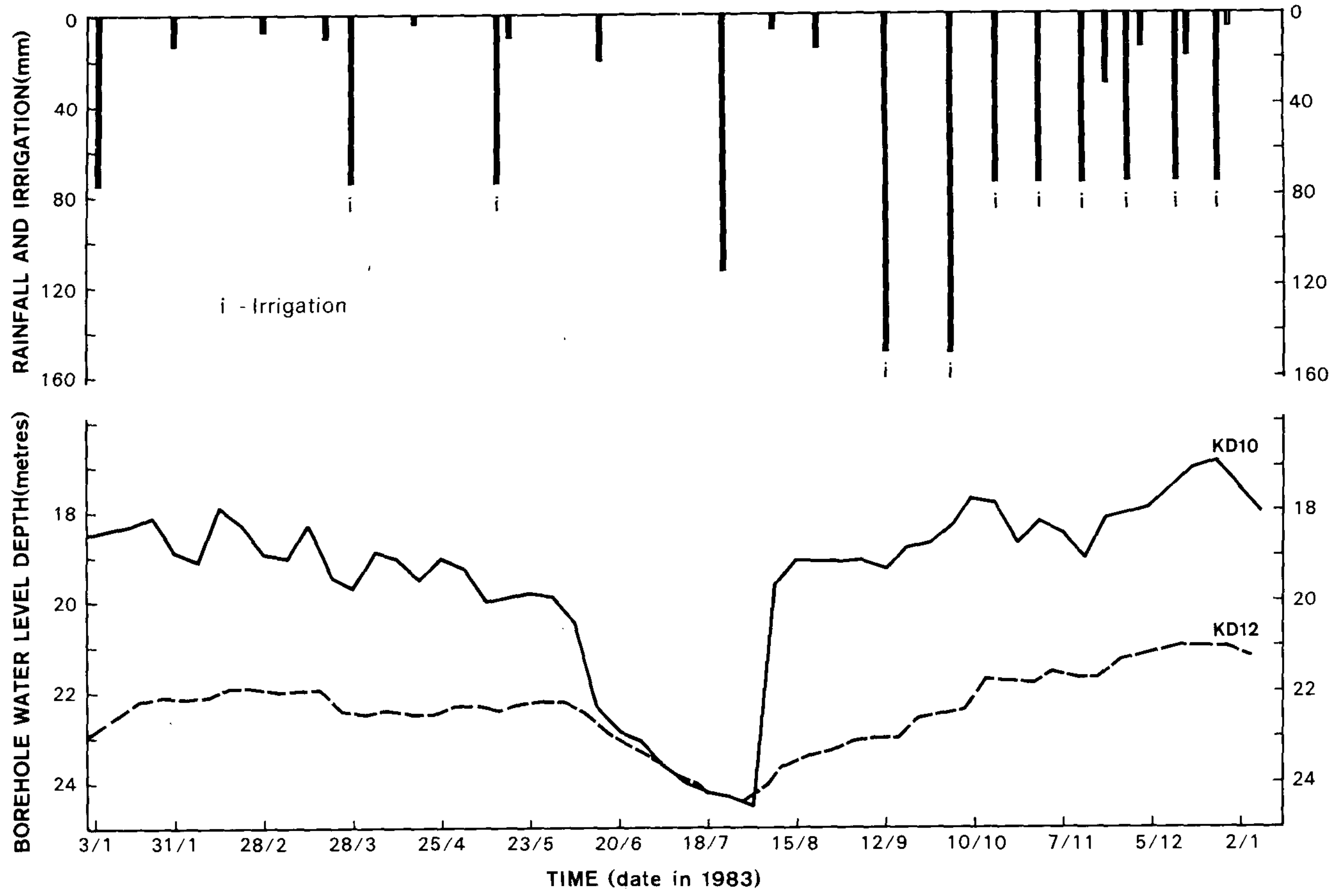

Figure 2
Groundwater level fluctuations as a function of rainfall and irrigation input.

which took the place of the pre-leaching irrigation, apparently did recharge the aquifers as indicated by Figure 2. If the total rainfall is ignored, the ETa exceeds the amount of water applied through irrigation, resulting in water deficits for both 1982 and 1983. However, inspection of the water level fluctuations recorded in boreholes KD10 and KD12 (Figure 2) clearly indicates that deep percolation below the root zone does take place. This anomaly can be explained in part by dividing the 9 month long irrigation season into three-monthly periods and by calculating the LF for each of these periods. This calculation, which ignores the effect of precipitation, yields the following leaching fractions: August – October 0,60; November – January 0,00; February – April 0,00. The pronounced leaching that takes place during the early part of the irrigation season, when the consumptive demand of the crops is still low, is clearly demonstrated and is indicative of inefficient irrigation management. The calculated LF's furthermore indicate that, based on irrigation applications alone, the amount of aquifer recharge during the period November to April will be negligible. This deduction is substantiated by the water level fluctuations for boreholes KD10 and KD12 (Figure 2), both of which experienced increases in their water levels during the first half of the 1983 irrigation season (July – December). The period of significant recharge is followed by a period of continuous discharge, the water levels apparently reaching their lowest levels during July.

The figures derived from this simple water balance are in general agreement with the South African literature. Streutker (1981) reports over-irrigation of on average 42% on the flood irrigated lands at the Vaalhartz Irrigation Scheme. A study conducted in the Breë River Valley on irrigated vineyards also revealed that a substantial amount of water is lost through deep percolation, especially in the early part of the irrigation season, i.e. July to November (Moolman *et al.*, 1983).

The transmissive properties of the aquifers

The results of the pumping tests conducted on 8 boreholes and 2 wells revealed that the transmissivity of the various aquifers within the study area differs by several orders of magnitude. The average transmissivity of the fractured rock aquifers was 38,4 m^{2}d^{-1}, while a value of 1,1 m^{2}d^{-1} was calculated for the alluvial aquifers. The saturated hydraulic conductivities of the root zone soils, as determined in the laboratory using undisturbed soil cores, ranged between 3,61 x 10^{-3} and 69,53 x 10^{-3} md^{-1} and by multiplying by the respective soil depths, could be transformed to transmissivity values (0,03 to 0,56 m^{2}d^{-1}). It is clear that the rate of water movement through the root zone soils and the deeper lying alluvium, is much slower than in the fractured rock aquifers. Consequently it is safe to assume that a major controlling mechanism in determining the travelling time of irrigation return flow back to the receiving river, would be the depth of the alluvium through which it must travel. This assumption is substantiated by the results of the tracer test. A tracer test conducted within the fractured mudstone aquifers of the study area, using boreholes KD33 and KD32 as injection and observation holes respectively, reflected the rapid flow within this type of aquifer. The tracer flow was detected after only two hours of pumping. The alluvial aquifers (boreholes KD23 and KD24) were not suitable for pumping because of very low transmissivities, but even after 6 days of sampling the injection slug was not detected. Although a proportion of the tracer could have been adsorbed within the alluvium, the absence of fluorescein appears to indicate low horizontal flow rates within the alluvial aquifer.

The difference in the transmissive nature of the boreholes penetrating fractured rock only, as represented by KD10, and those which penetrate both alluvium and fractured rock, as is the case with KD12, is illustrated by the water level fluctuations following the rainfall event of 22/7/83 when 114 mm of rain was recorded. Ten days after the event, the water level in KD10 responded and rose by 4,4 m within 48 h and continued to show marked fluctuations during the rest of the irrigation season (Figure 2). In contrast the initial time lag, in the case of KD12, was five days. However, it rose by a mere 1,3 m during the next 1½ months (27/7/83 to 12/9/83), when the first irrigation of the 1983/1984 season was applied. In addition, the variations in the water level of KD12 during 1983 were more subdued due to the damping effect of the alluvial soil overlying the bedrock encountered in this hole (Figure 2).

The difference in the lag times of KD10 and KD12 before responding to the rainfall input of 22/7/84 may be explained in terms of the distance of the boreholes from the recharge areas. In the case of KD10 the recharge area is 100 m to the east (Figure 3), whereas KD12 is situated within irrigated lands.

The average hydraulic gradient, obtained from borehole levelling, for the fractured rock aquifers is 1/85, while for the alluvial aquifer the hydraulic gradient varies between 1/24 and 1/53. It was assumed that all the water passing below the root zone is discharged to the river and to simplify aquifer discharge calculations the average gradient of 1/33,3 was chosen for the alluvial aquifer. Using the transmissivity values, a riverbank seepage (i.e. through the alluvium) of 290 m^3d^{-1} was calculated for the 8 737 m length of river encountered in the study area. Similarly, a groundwater discharge of 3 950 m^3d^{-1} from the deeper fractured rock aquifers was calculated for the same length of river. This means that 93% of the total daily discharge takes place through the fractured rock aquifers, and only 7% through the alluvium. The calculated annual discharge exceeded the total deep percolate from the study area by 6% and 21% for 1982 and 1983 respectively (Table 3).

This large difference for 1983 may be due to the underestimation of the proportion of rainfall of July 1983 (129 mm) which reached aquifers underlying the non-irrigated veld.

Residence time of the irrigation deep percolate within the aquifers

Results presented in the previous two sections have proved that there is a positive relationship between the irrigation applications and the groundwater levels, indicating that appreciable discharge could take place from the irrigated areas to the Great Fish River. The construction of a groundwater level contour map (data not presented here) confirmed the effluent nature of seepage along the river. This particular study could not provide firm conclusions about the actual residence time of the irrigation deep percolate within the aquifers. However, careful inspection of the data presented in Figure 2 provided some clues as to the travelling time of the irrigation return flow through the aquifers to the river. The time interval between the maximum and minimum water levels of both KD10 and KD12 is 23 weeks and can be taken to be the maximum time it takes for the irrigation return flow to reach the river (Figure 2). Further confirmation of this rather short residence time can be found in the transmissivity value of 38,4 m^2d^{-1} for the fractured rock aquifers. Assuming an average fractured rock thickness of 0,5 m within the borehole, a flow velocity of *ca.* 77 md^{-1} is attained. However, it must be

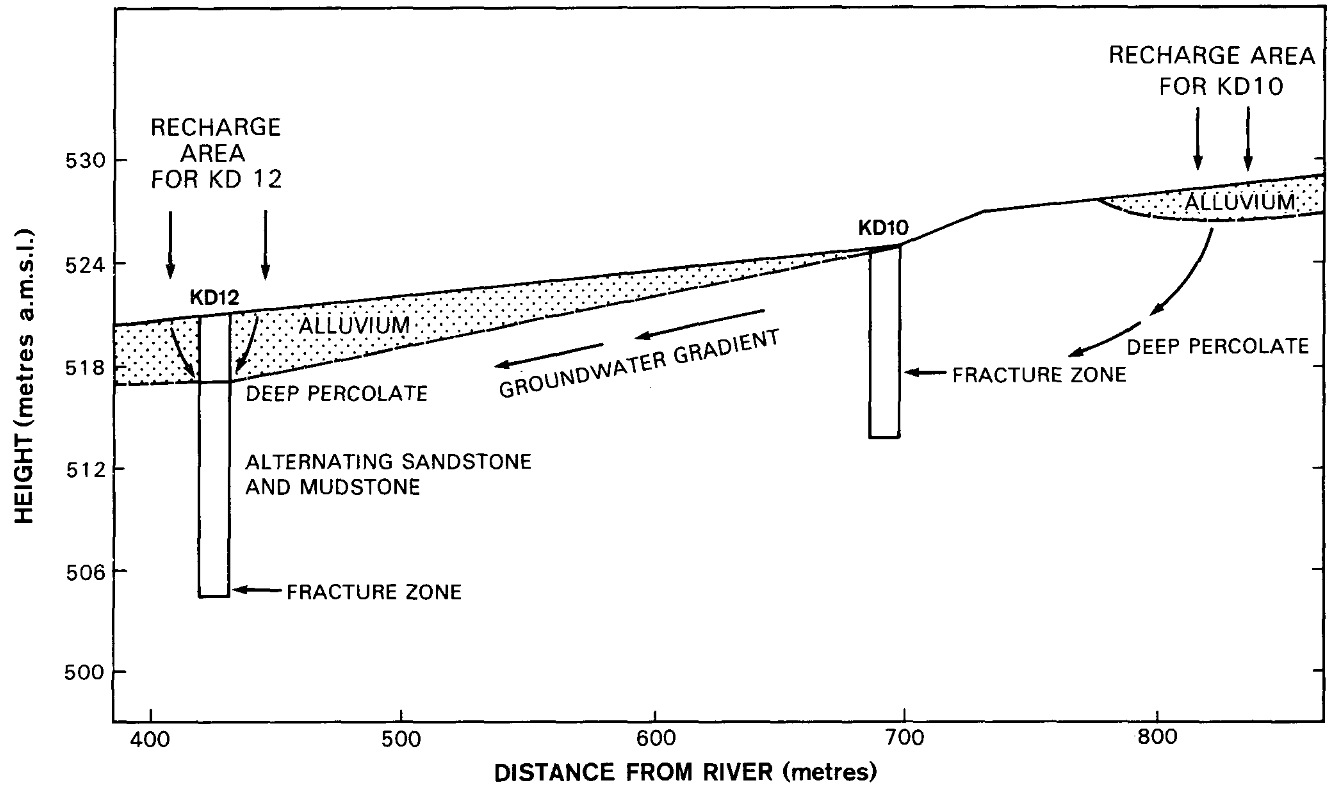

Figure 3
Schematic section of the study area between boreholes KD10 and KD12

born in mind that this latter figure represents a maximum flow rate which was attained by inducing a rather severe hydraulic gradient during irrigation. Despite the uncertainty regarding the precise residence time, the available evidence indicates time intervals in the order of months rather than years. This result is in accordance with that of Moolman *et al.* (1983) who used a travelling time (or time lag) of one month for irrigation return flow to reach the receiving river. However, it is in contrast to data published by Shaffer *et al.* (1977) who calculated a travelling time of up to 52 years for irrigation return flow through an alluvial aquifer.

Conclusion

Analysis of the meteorological and irrigation data, reveals that the prevailing leaching fraction of the Middleton Irrigation Scheme is approximately 0,25. This over-irrigation is reflected in the seasonal recharge pattern observed in borehole water level fluctuations measured during 1983. When related to the potential water use of the crops, the data indicate an imbalance in the temporal distribution of the irrigation applications. This leads to substantial leaching in the early part of the irrigation season and possible water deficits during the period of peak water demand. It is furthermore concluded that, based on the difference in their transmissive properties, most of the irrigation return flow will be discharged through the fractured rock aquifer as opposed to the shallower alluvial aquifer. The rapid response observed, both in the water level fluctuations in the boreholes, and in the travelling times recorded during the tracer study, points towards a relatively short residence time of the irrigation deep percolate within the aquifers. It appears likely that the travelling time back to the receiving river will be in the order of months, rather than years.

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