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Water table fluctuation and recharge in semi-arid climate: some results of the HAPEX-Sahel hydrodynamic survey (Niger)

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Abstract

Groundwater level measurements taken over a 4-year period from an extensive network of wells and boreholes within the HAPEX-Sahel (Hydrologic Atmospheric Pilot Experiment in the Sahel) degree square (south Niger), together with existing data, have provided an insight into infiltration and recharge processes taking place in the porous phreatic aquifer of the Continental Terminal formation. Despite high spatial and temporal variability of aquifer response to rainfall (rises of between 0 and 9 m are recorded), a pattern of recharge can be recognised. Aquifer responses vary from site to site, but the type of response at any single point tends to be consistent from year to year. Recharge is dominated by infiltration from temporary drainage networks (pools and streams) and aquifer response depends to a large extent on aquifer hydraulic characteristics and distance from the nearest infiltrating zone. In many wells, for which data extending back to 1987 is available, water levels show a consistent year by year rise. This is interpreted as a process of aquifer recovery following the severe drought of the 1970s and early 1980s, though part may also be attributable to changing patterns of land management (e.g. woodland clearance). Initial estimates of regional recharge are from 50–60 mm year^{-1}, or in other words about 10% of annual rainfall. The figure is supported by other methods of investigation (hydrochemical analyses; water budgets of pools).

1. Introduction

The HAPEX-Sahel degree square is bounded by latitudes 13°N and 14°N, and longitudes 2°E and 3°E. It covers a 12 000-km^2 area of southern Niger and is traversed by the Niger river.

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The hydrogeological objective of the HAPEX-Sahel experiment was to identify and quantify the processes of groundwater recharge to the underlying phreatic aquifer. To achieve this objective, a detailed piezometric survey covering much of the area was undertaken in conjunction with a number of hydrochemical and soil physics investigations. Hydraulic aquifer characteristics were derived mainly from existing data.

Pre-Cambrian basement gneisses, schists and granites, which are extensively weathered and kaolinised in the upper 8 m, crop out along the Niger valley and lie at shallow depth in the north western part of the degree square. These are overlain by the Continental Terminal formation, a late Tertiary sequence of sandstones, silty sandstones, siltstones and mudstones. Intercalations of hard laterite layers at various levels give rise to flat topped plateaux, which rise up to 100 m above the level of the Niger river. The region lies at the extreme western fringe of the 500-km-wide Iullemeden basin. Overlap of successively younger sediments to the west means that the two lower units of the formation, designated CT1 and CT2 by Greigert and Bernert (1979), may occur at depth to form only one confined aquifer (Schroeter, 1993). On the south bank of the river, at the extreme edge of the basin, where only the upper unit (CT3) is present, the formation crops forms the Say plateau, an isolated outlier covering an area of 4800 km^2. The main aquifer here is an oolitic ironstone, from 0 to 10 m thick, developed at the base of the sedimentary sequence (Fig. 1). In contrast, the main water bearing units on the northern side are generally sands or sandstones, which are sometimes oolitic and rarely silt; the oolitic layers are diachronous and thus have no stratigraphic significance.

There is no hydraulic connection across the Niger river and the hydrogeological conditions are appreciably different on either side. Over the smaller southern region there is only one major aquifer unit recharged directly from rainfall and by infiltration from stream

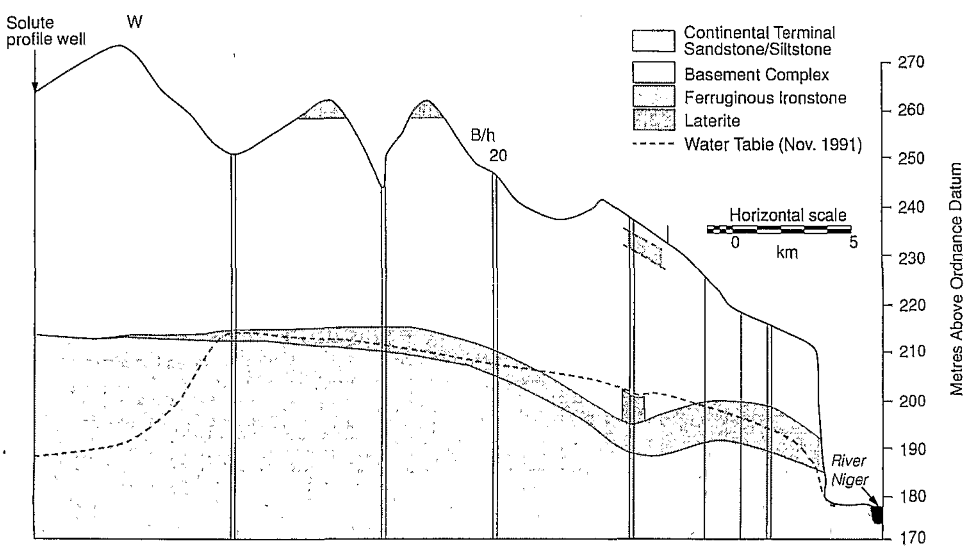

Fig. 1. East–west geological section of the aquifer in the southern bank (see location in Fig. 3).

beds. In the much larger northern area, however, recharge takes place mainly by vertical infiltration from the sandy beds of numerous temporary pools which form a distinctive feature of the landscape during the rainy season. Upward leakage from confined lower aquifer provides an additional source of recharge in some areas, but this tends to be very localised.

Rainfall is highly variable in both space and time throughout the HAPEX-Sahel square; for example in 1991 the Estimation des Pluies par Satellite (EPSAT) raingauge network shows a 100% difference of annual rainfall over a distance of 27 km (Taupin et al., 1993). Average rainfall in the region for the past 5 years has been 419 mm (1990), 522 mm (1991), 511 mm (1992), 460 mm (1993) and 620 mm (1994) (Lebel et al., 1995; J.D. Taupin, personal communication, 1995).

Except for the Niger river, the region possesses no permanent water course, though on the south bank several ephemeral streams, of which the largest is the Damari, flow for a number of days during the rainy season (May to October). On the north side of the river, run-off tends to be concentrated locally within a large number of endoreic pools, where water remains for anything from a few hours to several months (Desconnets, 1994).

2. Experimental set up

Since 1991, groundwater level monitoring has been conducted at quarterly intervals within a network of 270 wells to the north of the river and monthly in 53 wells on the south bank. More frequent readings, however, have been undertaken at selected sites during the rainy season and, at some wells, automatic recorders have been installed. Overall, several thousand measurements have been collected.

The distribution of monitoring sites is very uneven, with cropped areas having better coverage than regions of tiger bush (laterite plateaux). As a result, the network tends to be biased toward agricultural regions (valley bottoms and sandy slopes) and is less representative of natural bush. To the south of the river, work has concentrated within a 17 × 35-km rectangle, between latitudes 13°10′N and 13°17′N (Bromley et al., 1995). The wells used for monitoring are either of the traditional hand dug variety, usually unlined and in a poor state of repair, or lined with concrete and generally in better condition.

Measured levels in the region are the resultant of three factors: a long-term evolution, an annual fluctuation due to the impact of the rainy season and local pumping interferences. This latter influence can be a problem since most of the surveyed wells are used daily by villagers for domestic consumption and cattle watering, and although water is generally drawn by hand, water levels can be lowered by almost 1 m during periods of abstraction in some wells. Despite the uncertainty introduced by this type of erratic abstraction regime, it proved possible to use data from most of the sites monitored (Leduc and Lenoir, 1995).

On the north bank, the elevation of about 100 wells has been established with a precision of a few tens of centimetres using a Global Positionning System (GPS) system; to the south of the river, elevations have been obtained to an accuracy of ± 1 m by altimeter survey.

3. General description of groundwater flow

The depth to water table throughout the region is variable. In some places it is only a few metres below the surface. Such areas include the alluvial flood plain of the Niger river, along the lower reaches of the Damari water course on the south bank, and in the dallol Bosso, a large straight fossil valley on the eastern border of the area. On the other hand, in places below the high laterite plateaux, depths to water can exceed 75 m. Overall water level elevations range from 172 to 215 m a.s.l. (Fig. 2).

On the southern bank, most groundwater movement is eastward from a groundwater divide located in the western half of the study area; smaller flows take place to the west. To the east of the divide, the water table gradients are shallow (1 in 450 to less than 1 in 600) because of relatively high values of oolite transmissivity (average 157 m^2 day^{-1}). On the western side of the divide, water levels drop below the base of the Continental Terminal

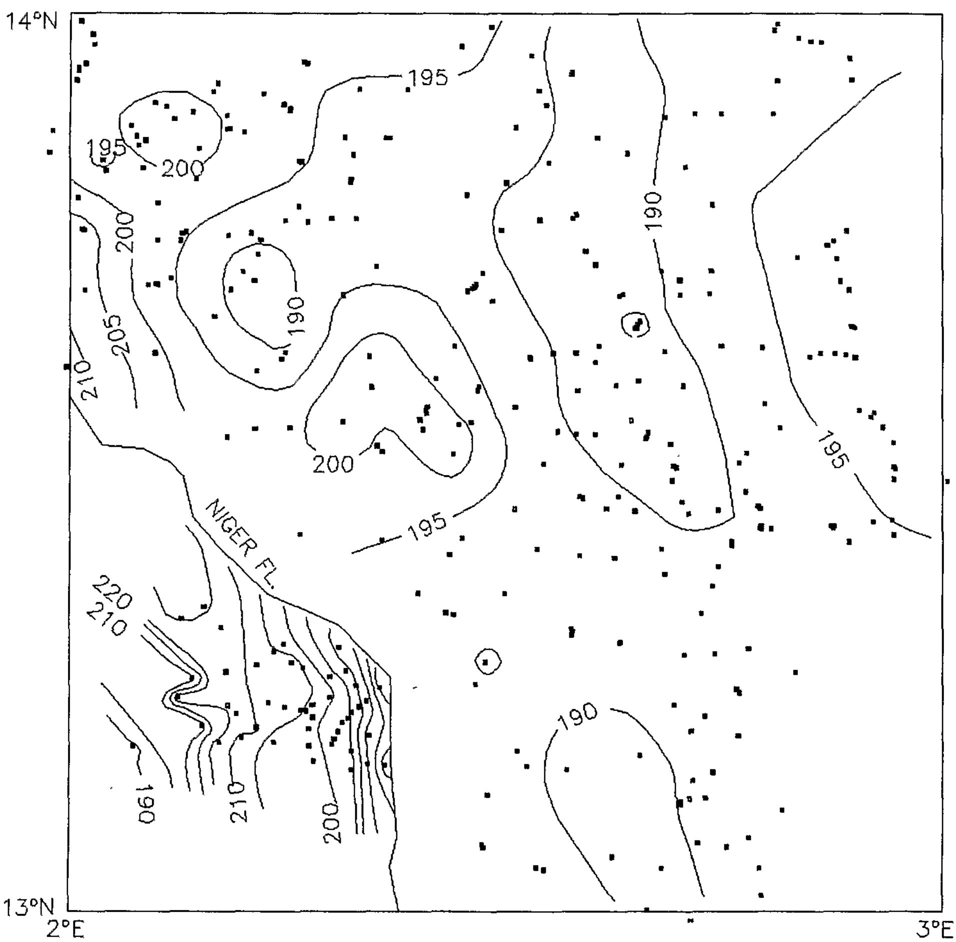

Fig. 2. Monitoring network and piezometric map of the degree square in September 1993 (curve every 5 m).

into the underlying less permeable basement complex (average 50 m^2 day^{-1}). Here gradients initially increase to 1 in 100, but then become less steep further east as water flows toward the valley flanking this side of the plateau.

A notable feature of the water table on the south bank is that the groundwater divide is displaced by about 5 km to the east of the surface watershed. The position of the divide is controlled by geological rather than hydrological factors; it coincides with the line along which the oolite is at its highest elevation and where it begins to pinch out toward the west (Fig. 1).

On the northern bank, the water table is much more complex. There is no regional flow direction, though three hydrodynamic regions can be recognised:

- A north western zone, at the Continental Terminal edge (referenced ''NW'' in Fig. 3), is characterised by a thin aquifer, generally high water table elevations and, in comparison to other areas on the north bank, high gradients, up to 1 in 1000. This heterogeneous region has the two highest water table elevations and one of the two lowest in the region. The drying out of some wells during the dry season,

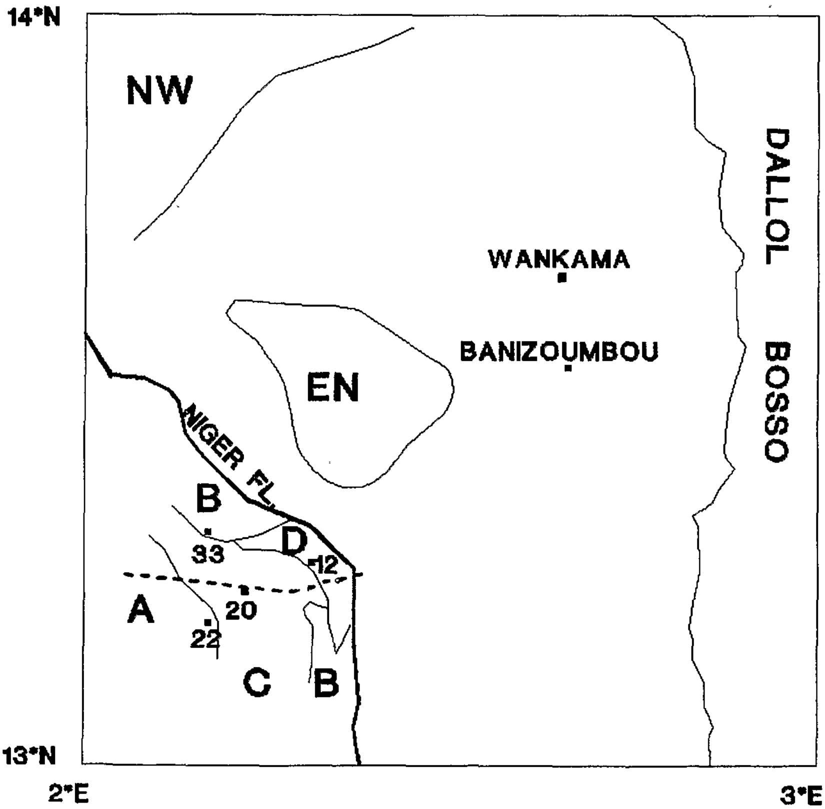

Fig. 3. Main hydrodynamic zones (NW, EN, Dallol Bosso, A, B, C, D), location of the geological section (dotted line) and some observation wells (Banizoumbou, Wankama, 12, 20, 22, 33).

the strong variability of water chemistry and of annual level fluctuation across short distances indicate rapid changes of lithology and possible water transfer with adjacent aquifers.

- A second zone, east of Niamey (''EN'' in Fig. 3) also has high water table elevations, but is much more uniform. Gradients can reach 1 in 1000 and annual fluctuations are large, probably due to poor aquifer characteristics.
- The remainder of the aquifer has very gentle hydraulic gradients, in places as low as 1 in 10 000, and is much larger than the other regions. It is underlain by a deeper, confined Continental Terminal aquifer. The highest water levels are in the dallol Bosso while the lowest are present in a large anomalous depression, aligned with an inactive river bed, the Dantiandou kori. Such anomalies, which are commonplace throughout the Sahel, are generally explained in terms of slight lateral water transfer and evaporation exceeding the rate of infiltration (e.g. Aranyossi and Guerre, 1989).

The phreatic aquifer on the north bank extends far beyond the limits of the HAPEX degree square to the north, east and south east. Long-term water level trends are influenced by the Continental Terminal basin to the east; however, there is no seasonal influence. The Niger river has no impact on either north or south bank water levels since it is cut into the underlying basement complex and thus isolated from the Continental Terminal above. The groundwater flow pattern remains unchanged throughout the year despite the presence of sometimes pronounced annual fluctuation.

Most of the aquifer is phreatic but some points are confined, as shown by the lowest values of storage in Table 1. These singularities are explained by a local change in clay content of the Continental Terminal sediments. Their effective extension is unknown as we have very few reliable data from long-term pumping tests.

4. Annual fluctuations of the water table

Annual water table fluctuations vary from 0 to 9 m in the Continental Terminal, but can be significantly greater in the basement complex.

4.1. The southern bank

From records dating back to 1987 at 18 sites and to 1991 at 49 others, four distinct patterns of hydrograph response can be recognised (Fig. 4):

Table 1
Aquifer properties (transmissivity and storage coefficient) obtained from pumping tests in the southern bank

	Continental terminal			Basement		
	Minimum	Maximum	Median	Minimum	Maximum	Median
T (m^2 day^{-1})	22	1296	259	4.7	657	37
S	3×10^{-4}	0.02	0.01	10^{-9}	3×10^{-4}	2.7×10^{-6}

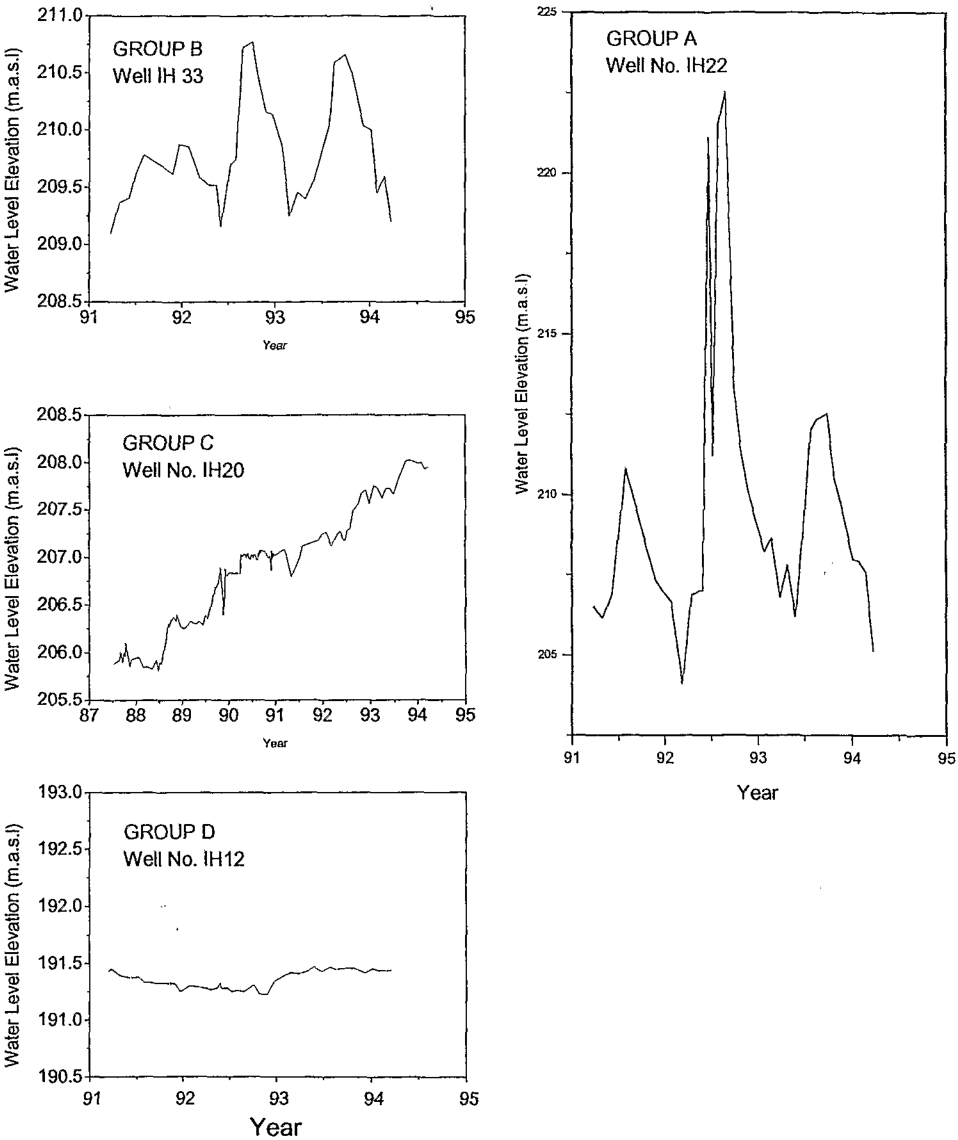

Fig. 4. Selected hydrographs of the Groups A, B, C and D in the southern bank.

- Group A: All the wells in this group are located to the west of the groundwater divide where water levels lie within the basement complex. Hydrographs are characterised by large seasonal responses to rainfall ranging from 5 m to 15 m, this being due to a low storage capacity which is typically an order of magnitude, or more, lower than the overlying sediments. No long-term increase or decrease in water level is apparent, though the combination of large responses and a relatively short period of record makes this difficult to establish with certainty.

- Group B: These wells are concentrated in two areas; at and below the dissected edge of the plateau to the north of the study area, and a smaller group near the lower reaches of the Damari ephemeral stream. The hydrographs show a very pronounced seasonal response ranging from 0.5 m to 2.5 m. As with Group A, there is no obvious long-term water level trend, even for records which extend back to 1987.
- Group C: Most of the wells in the region fall within this group. Hydrographs typically exhibit water levels which rise from year to year with the seasonal fluctuation often, though not always, masked by the long-term trend. Records show that levels have been steadily rising since at least 1988 (Fig. 3), the annual change ranging from about 0.2 m to 0.5 m.
- Group D: Wells within this group are concentrated in a belt along the eastern scarp of the plateau where the water table elevation is below 195 m and where gradients begins to steepen toward the escarpment. The hydrographs show very little seasonal response and either no, or a very small, long-term rise of water level. Annual fluctuations are generally less than 0.2 m.

4.2. The northern bank

Annual water level changes on the northern side of the river are generally smaller than 1 m except in the vicinity of endoreic pools where fluctuation of up to 9 m are recorded.

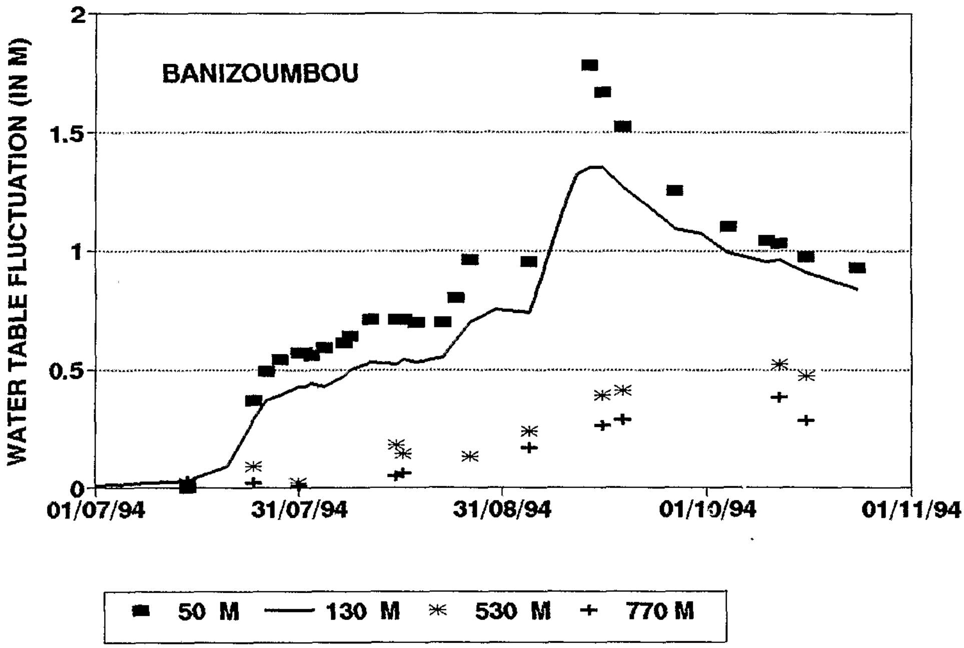

Fig. 5. Piezometric fluctuation in Banizoumbou depending on the distance from the pool (1994).

In 1992 the median response was 0.6 m with only 22 wells having responses in excess of 2 m. Some hydrographs, particularly those from wells near to or on the laterite plateau, show no response to wet season rainfall while others display a sharp rise and fall.

The most pronounced variations are observed in wells concentrated in two zones in the western half of the study area; the north west zone (''NW'' in Fig. 3) and the zone to the east of Niamey (''EN'' in Fig. 3). This variability is explained by the heterogeneous lithology of the Continental Terminal formation in these areas and the resulting rapid changes in hydraulic properties over short distances. In the north west zone, the sedimentary aquifer is sometimes undifferentiated from the basement aquifer.

Over the remainder of the northern area, the largest variations are invariably observed close to the temporary drainage network. In the few places where sufficient monitoring points are available, the seasonal fluctuation decreases with increasing distance from the pool (Fig. 5). There does not, however, seem to be any correlation between the scale of water level response and the thickness of the unsaturated zone; responses are likely to be similar whether the zone is very thick or not. Even where geological and hydraulic conditions appear to be similar, the aquifer response can differ considerably in type and amplitude.

Variability of response with time is also a significant feature of north bank hydrographs. Highest water table elevations and the most rapid response times correspond to the largest rainfall events in wells closest to temporary pools; at more distant sites, the response is usually later and more subdued. The shortest times recorded are no more than a few hours. In some places, the aquifer displays a two phase reaction; no movement during the first weeks of the rainy season, during which time unsaturated zone deficits are replenished, but then a rapid and large response to every significant rainfall event thereafter (details in Desconnets et al., 1997).

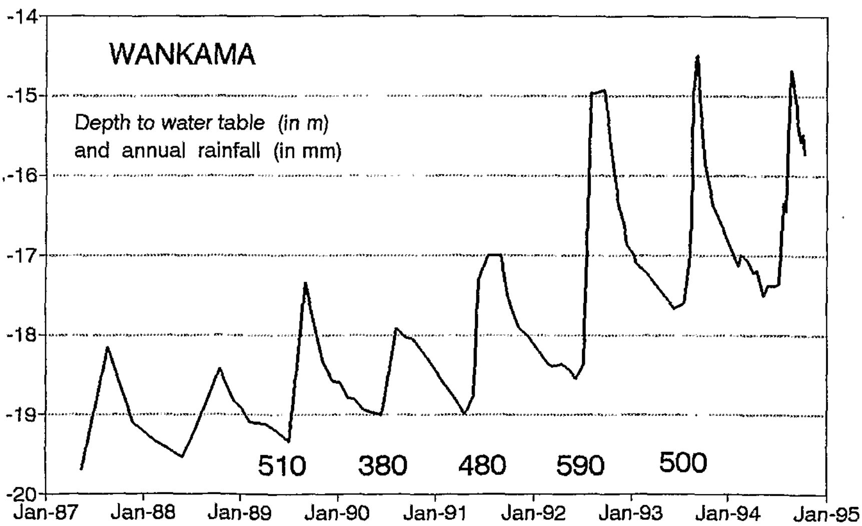

Fig. 6. Piezometric fluctuation in Wankama (1987–1994) with annual rainfall.

The nature of each well hydrograph is determined not by annual rainfall amounts but by local hydraulic characteristics of the aquifer and the distribution and intensity of rainfall events. No matter what the annual rainfall, the most variable zones are the same, and the type of response (none, simple or complex) remains the same for a given well.

Fig. 6 illustrates the lack of correlation between annual rainfall and water level rise at Wankama for the period 1989–1994 (no value of local rainfall is available for 1987 or 1988). While the smallest rise, 1.1 m, corresponds to the lowest rainfall (380 mm), the wettest year 1994 (620 mm) generates a smaller response than the drier years of 1992 and 1993 (590 and 500 mm). Likewise, years with similar rainfall (1989–510 mm, 1991–500 mm and 1993–500 mm) have experienced significantly different levels of water level rise (2 m, 2 m and 3 m, respectively).

5. Recharge processes

The Continental Terminal formation is a water table aquifer recharged by a combination of direct and indirect infiltration and, on the northern bank, by additional local leakage from adjacent aquifers.

The groundwater level survey has highlighted the primary importance of temporary pools and streams in the recharge process. On both sides of the Niger river, the most pronounced and rapid water level responses are observed close to the drainage network. At distance from the network, the responses become delayed and more attenuated. For example, on the south bank two wells, both within 200 m of the Damari stream bed, respond approximately 15 days earlier than a well 1 km further away. Another example is at Wankama: at the end of the rainy season, the response time in a piezometer 30 m from a temporary pool is 2 h, but is 4 h for a well 80 m away.

It is probable that the lower part of the drainage network (in valley bottoms) is providing most of the recharge to the aquifer and that in comparison relatively little infiltration takes place beneath the laterite plateaux. S. Galle (personal communication, 1995, and her information from the HAPEX data base) has observed the advance of a wetting front below a depth of 5 m in the vegetation stripes of tiger bush, but this might simply represent a temporary storage drawn upon and depleted by the vegetation during the dry season. Other evidence of low infiltration rates below plateau areas is provided by the lack of water level response below these regions and direct measurements made by Bromley et al. (1997) which point to average rates of around 13 mm year^{-1}.

In only one place, Samadey, can the recharge not be explained in terms of 'ordinary' flow in porous media. An old hand dug well shows a reaction time of 3 h following flooding of a nearby pool, even though the depth to water table is 45 m. Such rapid response implies the existence of preferential pathways through the silt, even though none can be seen on the sidewalls of the well. Active channels might result from root or termite activity. The same process could be operating at other sites but, however, automatic water level recorders are required to establish its existence.

In most of the surveyed wells, the concomitant rise of both level and electrical conductivity during the rainy season indicates a significant seasonal arrival of water. It confirms the rarity of confined areas in the CT3 aquifer.

Sources of recharge other than rainfall are not thought to be significant. On the north bank, the second and deeper Continental Terminal aquifer, where it occurs, has a higher head and different water chemistry. Intrusion of this chemically different, older water should be hydrochemically detectable if it has taken place. However, only at a few places in the north western zone, has this process been observed. Moreover, the permanence of the head difference, despite limited recharge opportunity for the lower aquifer, implies very limited or no exchange. The Niger river, with a level lower than the water table, can only receive water from the water table aquifer.

6. Long-term evolution

6.1. The southern bank

Long-term rainfall data from Niamey reveals that from 1978 to 1987 the region experienced a succession of years with below average rainfall. This resulted in a severe drought leading to a marked decline of groundwater levels. Because the groundwater table beneath the plateau is in the form of a mound, the largest fall of water level takes place over the highest parts of the mound. At the edge of the mound, close to the fixed head discharge point at the base of the scarp, the fall is inevitably less pronounced.

A return to wetter conditions and increased rates of recharge took place in 1988 at the latest. From this time, the aquifer started to replenish as water levels began to rise back to pre-drought levels. The pattern of this rise mirrors that of the decline, the biggest rise being experienced in the central parts of the mound with a more subdued response toward the discharge point. Examination of the Group C and D hydrographs reveals that this is precisely what is happening. The Group C wells located on higher parts of the mound are characterised by a rapid year by year water level increase. In contrast Group D wells, situated along the escarpment, closer to the discharge point show very little if any long-term increase in water level.

The process of aquifer recovery, however, does not account for the responses displayed by Groups A and B. These are dominated, instead, by local hydrogeological conditions. Wells within Group A are all located in the western part of the area, where the water level lies within the basement complex below the base of the Continental Terminal. The large scale seasonal fluctuations characteristic of this group simply reflect the low storage capacity of the basement, which is several orders of magnitude, or more, lower than the overlying sediments. A combination of a pronounced seasonal response and short records (none of these wells have records extending back beyond 1991) makes it difficult to detect any long-term trend in the group that might be linked to aquifer recovery.

Group B wells are mostly positioned at or close to the dissected edge of the plateau and lie in the vicinity of numerous ephemeral streams (Fig. 3). Concentration of rainfall and rapid indirect infiltration through stream beds results in a very pronounced seasonal response in these wells. There is no long-term water level increase because by and large like Group D, the wells are all at low elevation and close to the discharge level.

6.2. The northern bank

Some long-term water level data are available from 37 wells dating from 1962, 1963 and 1964 (Tirat, 1964; Boeckh, 1965). Though there is uncertainty about some datum levels, it appears that the 1963–64 levels for ten wells are higher than those recorded between 1991–94, in 18 wells they are lower and for the remaining eight are approximately the same. Measurements from hand dug wells confirm this pattern of variable evolution.

Since 1991, most monitored wells, even those below laterite plateau areas, have shown an inter-annual water level rise averaging 5 to 25 cm year^{-1}, though there is considerable variation from year to year (Fig. 6): in average for the HAPEX-Sahel square, 1992 has caused a level rise of about 0.45 m when 1993 had no impact. A monthly water level survey started by the Ministry of Hydraulics in 1987 (Schroeter, 1993) confirms that the inter-annual rise of water level identified from the 1991–94 records, was already established by 1987, its amplitude varying from 0.5 m to 2 m over a 7-year period. As with the south bank, this recovery is explained in terms of water level recovery following the drought of the mid 1970s and 80s. Whether this recovery applies to the entire HAPEX square is uncertain, particularly since the zones where the 1960's levels are thought to above those of the present day lie outside the area covered by the 7-year survey.

There is no obvious relation between inter-annual water level change and seasonal amplitude or annual rainfall. In Wankama (Fig. 6), extreme values of annual rainfall and inter-annual evolution correspond, e.g. the driest year, 1990, has no rise and the very wet year, 1992 has the largest inter-annual rise (0.9 m). However, the rise for 1991 is double that of 1993, despite having comparable rainfalls (Fig. 6). This suggests that the long-term water level trend is influenced by a combination of both local and regional components of recharge. In the case of Wankama, the apparent anomaly for 1993 could be explained by the recorded local rainfall (500 mm) being much higher than rainfall experienced regionally (460 mm); the increased local recharge may not compensate for the much lower regional recharge.

6.3. Interpretation

At the scale of the degree square, the recent 7-year rise seems explicable: the drop of the water table during the 1970s and 80s is known everywhere throughout the Sahel. But the comparison of levels in 1964 and 1994 is more problematic. The end of the 1950s and beginning of the 60s were much wetter than today (646 mm for 1958–1964 and 550 mm for 1986–1992 in Niamey), yet groundwater levels were the same or even lower than they are at present. One possible factor is that increased wood clearing might have contributed to a decreased evapotranspiration rate and increased run-off, and then increased recharge, since the 1960s. In semi-arid Australia, Allison et al. (1990) have clearly shown the increase of groundwater recharge due to the clearing of the native vegetation, up to two orders of magnitude. The first analysis of Landsat images by Finch and Roberts (1994) confirms the diminution of areas covered with forest or tiger bush between 1973 and 1990 in the HAPEX-Sahel degree square.

Finally, it is relevant to note that on both sides of the river, even by 1994, 7 years after the end of the drought, water levels are still rising toward a new equilibrium corresponding to a new environment.

7. Estimate of infiltration

On the northern bank most recharge is contributed by infiltration from the drainage network. Here, calculations of recharge have been made at two scales: single point investigations, often adjacent to preferential sites of infiltration, and regional scale estimates, which provide an integrated figure for the aquifer as a whole.

Single point measurements have been made below the sites of individual pools or temporary streams by using the shape and response of the local water table to derive a value. This technique requires a reasonably accurate estimate of local values for permeability and storage (Table 1 – southern bank). Another approach has been to calculate a complete water budget for individual pools as described by Desconnets (1994) and Desconnets et al. (1997). Both of these methods provide a precise figure for a limited number of representative pools scattered throughout the area.

To obtain regional values for infiltration the same two techniques can be applied to the degree square as a whole. In the first case the configuration and annual fluctuation of the water table over the entire degree square is used to derive a figure, whereas in the second case regional water balance estimates can be extrapolated from point data by geomorphological and hydrogeological analogy.

Other site specific measurements have been made using chloride and soil moisture profiles in the unsaturated zone (Bromley et al., 1997). Also, Peugeot (1995), has used soil moisture data obtained by Galle, to prove the absence of recharge under small parcels of sandy slopes adjacent to areas of Tiger Bush. Maximum values for regional direct recharge from rainfall have been established by the findings of B. Monteny (personal communication, 1995). He has calculated an effective evapotranspiration rate of between 70–80% of total rainfall for a 3-month period during the rainy season (mid-July to mid-October). Based on this data recharge cannot exceed 20–30% of total rainfall. All these methods have given consistent results and also agree with the preliminary output of numerical models for both sides of the river.

On the south bank preliminary analysis suggests that a regional recharge of about 60 mm $year^{-1}$ is sufficient to account for observed water level responses. For the drier northern bank initial results point to a slightly lower recharge of 50 mm $year^{-1}$ (Leduc and Desconnets, 1994). It needs to be stressed, however, that the reliability and accuracy of these figures to a large extent depends on the reliability of current estimates of aquifer properties for the region. Nevertheless, they provide the first reasonable approximation for groundwater recharge in the HAPEX square.

These provisional findings are supported by isotopic (^{3}H and ^{14}C) data from more than 20 sites, which shows that groundwater is of recent age, and has thus been subject to widespread recharge in recent years.

Furthermore, the results are consistent with an earlier recharge estimate made by PNUD (PNUD-DCTD, 1990) for the Continental Terminal aquifer. PNUD estimated an annual recharge of 30 mm $year^{-1}$ to the water table aquifer. However, this estimate applied to an area of 100 000 km^2, which extended far to the north east of the HAPEX square and includes a region of much lower rainfall. This accounts for the lower PNUD estimate.

A recharge figure of 10% of total annual rainfall is also consistent with estimates made in other Sahelian countries. These include:

- Numerical modelling of basement complex areas of a wetter area in Burkina Faso gives average recharge rates of 107 mm (1953–1988: average rainfall 720 mm) and 47 mm (1985–1988: average rainfall 551 mm). This represents from 8 to 15% of rainfall (Milville, 1991).
- Tritium profile studies in a drier area of Senegal produce figures of 22 to 26 mm $year^{-1}$, 6 to 8% of rainfall (Tandia et al., 1993).

However, the concept of 'average' recharge rates must be treated with some caution, because the actual rate at any one site will vary greatly with time, just as the rate between sites will be equally variable. Over the last 5 years, the annual amplitude in wells with rising water levels has varied from 1 to 2 to even 1 to 3; infiltration has probably varied in a similar fashion.

8. Summary and conclusion

The regional groundwater level tends to reflect the influence of both regional and local conditions and is the single parameter that best integrates hydrological processes at the scale of the degree square. The extension of the groundwater level survey for at least 3 years after the end of the HAPEX-Sahel intensive observation period, and the use of earlier data collected from 1987 onward, permits our observations to be placed in a long-term perspective.

Thanks to an intensive campaign of measurements, much more pronounced annual fluctuations of the water table during and after the rainy season have been observed than would have been anticipated from existing literature. The central role of the temporary drainage network (endoreic pools and ephemeral streams) in the recharge process has been demonstrated. Infiltration is thus a distinctly discontinuous phenomenon throughout the HAPEX area.

At a given site the scale of seasonal fluctuation is primarily a function of local permeability and storage, and secondly of the amount of recharge. The Continental Terminal aquifer can be divided into several sub-regions, differing in both hydraulic and hydrochemical characteristics. Based on a range of estimation techniques, regional recharge is about 10% of annual rainfall, but this amount will vary significantly from place to place depending upon the distribution, intensity and frequency of rainfall events. The long-term rise in water levels observed over much of the aquifer for the past 8 years can be attributed to a process of recovery following a prolonged period of below average rainfall from 1978–1987, linked perhaps to increased rates of recharge caused by extensive deforestation over the same time.

Although preliminary values for recharge are now available, much more data and analysis are needed. On the south bank, more precise quantification of direct recharge under three major land use types (millet, fallow and tiger bush) is currently being undertaken from which a more detailed version of the present groundwater model will be developed. For the northern bank indirect infiltration along the course of the Dantiandou kori is still being studied at selected sites, through a series of intensive measurement campaigns. Analysis of the exceptionally wet year of 1994 will help improve present estimates. Work still to be completed includes an analysis of all hydrochemical data and a detailed study of which rainfall characteristics might help explain some of the observed variability of groundwater recharge.

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Water table fluctuation and recharge in semi-arid climate: some results of the HAPEX-Sahel hydrodynamic survey (Niger)

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