MECHANISMS, TIMING AND QUANTITIES OF RECHAGRE TO GROUNDWATER IN SEMI-ARID AND TROPICAL REGIONS

W.M. EDMUNDS
British Geological Survey,
Crowmarsh Gifford, Wallingford,
United Kingdom

Abstract

Groundwater being exploited in many arid and semi-arid regions at the present day was recharged during former humid episodes of the Pleistocene or Holocene and, in contrast, the amounts derived from modern recharge are small generally small and variable. Geochemical and isotopic techniques provide the most effective way to calculate modern recharge and to investigate recharge history, since physically- based water-balance methods are generally inapplicable in semi-arid regions. Examples from Africa (Senegal, Niger, Nigeria, Sudan as well as Cyprus) show that direct recharge rates may vary from zero to around 40% of mean rainfall, dependent primarily on the soil depth and the lithology. Spatial variability presents a real problem in any recharge investigation but results from Senegal show that unsaturated zone profiles may be extrapolated using the chemistry of shallow groundwater. Unsaturated-zone studies show that there are limiting conditions to direct recharge through soil, but that present day replenishment of aquifers takes place via wadis and channels. In the Butana area of central Sudan the regional groundwater was also recharged during a mid-Holocene wet phase and is now in decline. The only current recharge sources, which can be recognised distinctly using stable isotopes, are Nile baseflow and ephemeral wadi floods.

1. INTRODUCTION

Prior to human intervention, groundwater systems had evolved under near steady conditions reflecting hydrodynamic conditions that had remained stable possibly for several thousands of years under modern climatic regimes. Small climatic perturbations at the century todecadal scale such as the little ice age or the prolonged drought of the previous millennium (800-1000BP) whilst having a strong impact locally on water availability probably did not have any long term effects on aquifers. Many aquifers contain evidence of palaeowaters which were recharged during the early Holocene or Pleistocene when the global climates and recharge patterns were significantly different, coinciding with the late Pleistocene glaciation. In coastal regions groundwater movement was also enhanced by the lowering of sea level by up to 130m. With the end of the ice age and the rise to modern sea levels by around 7000 BP some extreme wet periods occurred in the mid-Holocene for example in Africa, which resulted in discrete groundwater recharge. Since that time greater aridity has characterised the modern era (about 4000 years) creating arid or semi-arid regions which may have been much wetter in former times. Well drilling has had the effect of penetrating aquifers which are naturally stratified both in age and in quality. Pumped sampling invariably results in mixed groundwaters.

The development of groundwater resources in semi-arid regions often proceeds without an understanding (or with an over-optimistic interpretation) of the recharge rates and processes. Some of the produced groundwater may therefore not represent that which has been recharged during the modern era. Falling water tables testify to over-development of groundwater, specifically that the rates of groundwater abstraction exceed the rates of natural replenishment from current rainfall or, that a transient condition is produced where water level decline is proportional to the hydraulic diffusivity (transmissivity/storage) of the aquifer (Custodio 1992). In many semi-arid areas the water resources are being mined from recharge from former humid episodes.

Recharge estimates based on empirical formulae are inadequate for low rainfall areas with high evapotranspiration (Gee and Hillel 1988; Allison et al. 1994). One way to overcome this inadequacy is to use the unsaturated zone as a rain gauge. The concentrations of rainfall-derived chloride and other conservative solutes in the unsaturated zone are proportional to the precipitation less evaporation and under favorable conditions may serve as a long term (decadal scale) estimate of recharge rates. The unsaturated zone may also preserve an archive of recharge rates and corresponding climatic events at the decadal scale or better, serving as the only part of the hydrological cycle, excepting ice cores, to provide this function. Inert tracers, especially chloride, can provide a record of oscillating recharge events during wetter or drier periods at time scales up to 500 years or more (Edmunds and Walton 1978; Allison and Hughes 1978; Edmunds et al 1992; Cook et al 1992). Much longer records may be preserved in the unsaturated zone of more arid regions (Allison and Hughes 1983; Phillips 1994; Tyler et al 1996)

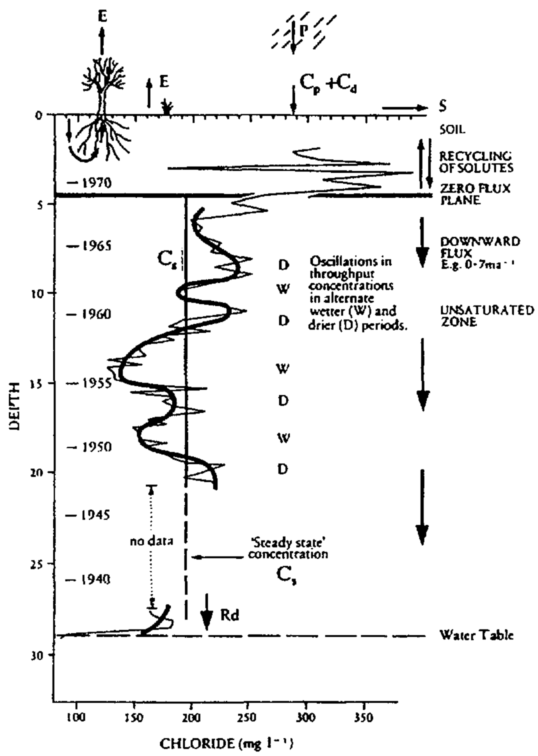
The objective of this present paper is to review recent work relating to arid zone recharge and to demonstrate how geochemical and isotopic methods may be used to measure the mechanisms, timing and amounts of recharge in arid and semi-arid regions. Results are illustrated using examples from three semi arid regions - the Mediterranean (southern Cyprus), west Africa (Senegal) and east Africa (Sudan).

2. METHODOLOGY

Geochemical techniques using chloride contained in unsaturated zone moisture profiles are becoming established as a reliable tool for measurement of direct (or diffuse) recharge rates in semi-arid regions. Until recently tritium has been an important technique for unsaturated zone investigation but it cannot be used as a routine tool and its effectiveness is now limited due to radioactive decay. Tritium has been widely used in temperate zones and less commonly in arid zones (Edmunds and Walton 1980; Allison and Hughes 1978; Gaye and Edmunds 1996) to measure recharge. The position and shape of the tritium peak in unsaturated-zone moisture profiles has provided convincing evidence of the mechanisms of recharge as well as an estimate of the recharge rate.

In contrast to tritium, chloride inputs from atmospheric deposition are conserved in the soil zone and are concentrated due to the loss of moisture by evapotranspitration. The basis of the method has been described elsewhere (Edmunds et al.1988) but a conceptual model and summary of the measurement of recharge and recharge history are given in Figure 1. The chloride balance method has now been successfully used in a range of environments to determine recharge, for example in north Africa and the Middle East: Edmunds and Walton (1980), Suckow et al.(1993), Edmunds and Gaye (1994), Bromley et al.(1996); in Australia: Allison and Hughes (1978), Allison et al. (1994); in India:Sukhija et al.(1988); in southern Africa: Gieske et al.(1990) and in north America: Stone (1987), Phillips (1994), Wood and Sandford (1995).

Samples of moist sand are obtained by augering or other dry drilling techniques at regular intervals through the unsaturated zone. Moisture contents are measured gravimetrically and chloride is determined on samples obtained either by centrifugation (Kinniburgh and Miles 1983) or by elution with distilled water. Rainfall amounts and chemistry (total solute deposition) must be known. In the studies discussed in this paper, an average of the mean rainfall and weighted mean chloride concentrations typically have been obtained over three or more seasons. Errors associated with rainfall measurement and the spatial variability of rainfall are likely to constitute the largest uncertainty in recharge estimation using chloride (up to 25%) and an assumption must be made that the average atmospheric chloride flux has remained constant with time at a given location. It is also assumed that surface runoff is negligible and that homogeneous movement of solutes through the unsaturated zone by piston flow is taking place.



1) **Direct Recharge Estimation.** Assuming no surface runoff rainfall (P) containing a concentration of Cl (C_p) and any dry deposition (C_d) enters the soil. In the soil zone water is lost by evapotranspiration and chloride is recycled and concentrated. Below the "zero flux plane" water is transmitted with variable concentrations depending on the antecedent climatic conditions; the mean concentration (C_s) is proportional to the long term direct recharge (Rd):

Direct Recharge (mm) $\quad \mathbf{Rd = P\,(C_p + C_d)\,/\,C_s}$

2) **Residence Time.** The drainage rate V_w in m yr^{-1} is given by

$$V_w = R_d / \rho . \theta_g$$

where θ_g is the gravimetric moisture content and ρ is the dry bulk density. This enables the transit (residence) time for the water in the unsaturated zone to be calculated.

Figure 1. The use of chloride in unsaturated zone profiles to measure recharge through soils and recharge history.

Groundwater at the water table may also be used to obtain information on recharge and in conjunction with the unsaturated-zone profiles, can provide estimates of the spatial variability of recharge in recent times (Edmunds and Gaye 1994). For the investigation of groundwater recharge to deeper systems, groundwater samples may be obtained from pumping wells. Sampling is restricted by the borehole network. Information on the depth stratification of water quality in aquifers is rare, and the probability is that most pumped samples are mixtures of water from different recharge episodes. It is with these qualifications that some information on the recharge history of palaeowaters may be obtained.

3. PRESENT DAY RECHARGE MEASUREMENT

The data from Cyprus are from the Akrotiri peninsular from Recent dune sediments, and the chloride profiles are shown together with tritium profiles (Figure 2) from the same percussion drilledborehole, and are described in detail in Edmunds et al.(1988). The chloride concentrations below the zero flux plane (around 2m in grass vegetation) oscillate about mean values (C_S) in each profile of 119 and 122 mg l^{-1} respectively. These oscillations have been interpreted in terms of seasonal variations related to periods of wet and dry years. The mean concentrations can be interpreted to give values of recharge (see Fig.1)respectively of 56 and 55 mm a^{-1}, using a three year mean rainfall concentration of 16.4 mm a^{-1} at this coastal site. Tritium profiles serve to confirm the recharge rates given by chloride, the peaks marking the position of the 1963 thermonuclear fallout maximum in the rain; the recharge rates obtained using the amount of moisture above the tritium peak are 52 and 53 mm a^{-1} respectively. The shape of the tritium peaks also confirms that downward movement of moisture (and solutes) is homogeneous with little or no by-pass flow.

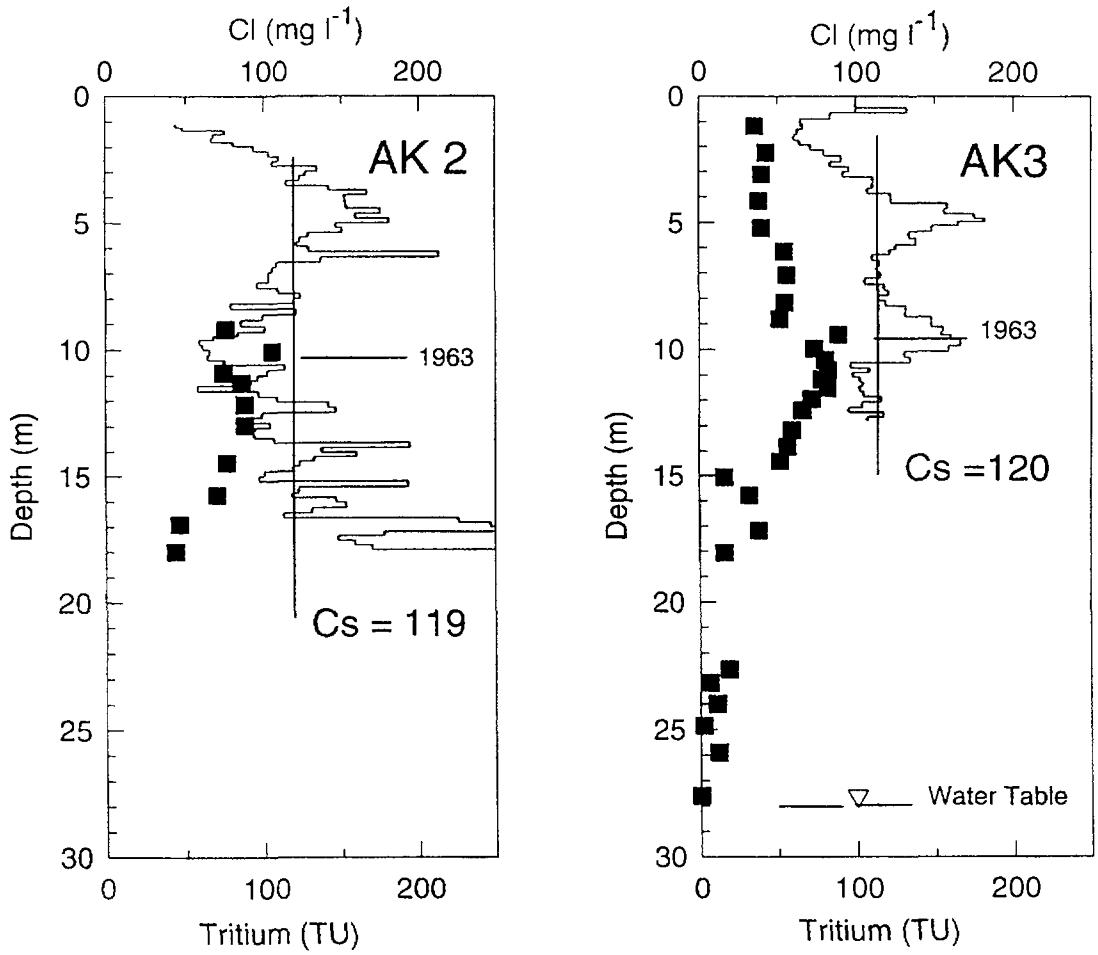


Figure 2. Two profiles (AK2 and AK3) of chloride and tritium in the unsaturated zone from Akrotiri, Cyprus showing the presence of the 1963 thermonuclear peak and the mean concentrations of chloride (C_S) in the unsaturated zone.

Four profiles of chloride from north-west Senegal (Figure 3) illustrate the spatial variability of recharge within one site (of area 0.1m^2). All were obtained from Quaternary dune sands where the water table was at 35m and where the long term (100 year) rainfall is 356 mm a^{-1} (falling by 36% to 223 mm a^{-1} since 1969 during the Sahel drought). The mean concentrations of chloride (C_S) in these four profiles ranges from 28 to 81mg l^{-1} which correspond to a value for mean direct recharge from 10 to 25 mm a^{-1}; as in Cyprus a series of oscillations related to wet and dry years can be found . The average chloride concentration of 7 profiles at this site is 82 mg l^{-1} (13mm a^{-1}). Having established that all the Cl in this region is atmospherically derived, it is possible to extrapolate the unsaturated-zone data to determine the spatial variability of recharge at a regional scale using data from shallow dug wells. Over an area of 1600 km^2 120 shallow wells were used to calculate the distribution of recharge over this area of NW Senegal. The regional recharge varies from 20 to <1mm a^{-1}, corresponding to a renewable resource of between 13 000 and 1100 m^3 km^2 a^{-1} (Edmunds & Gaye 1994).

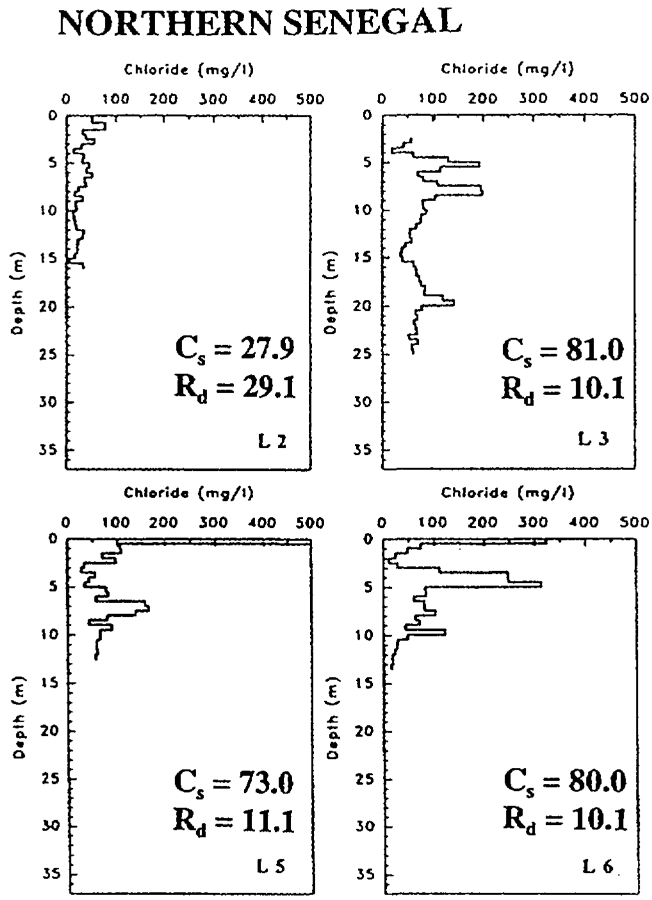


Figure 3. Four profiles (L2, L3, L5, L6) of chloride in the unsaturated zone at Louga, northern Senegal with mean chloride concentrations (C_s) and derived estimates of direct recharge (R_d).

A limiting condition must exist in arid regions where rainfall becomes too low and other factors such as soil type intervene to inhibit any regional or diffuse recharge. The limiting rainfall value will vary widely depending on the local conditions. Under this condition the unsaturated zone will become saline and geochemical reactions will lead to the formation of minerals in the soil zone and the formation of indurated crusts. Data from Sudan (Figure 4) are from the Butana region, north east of Khartoum where, prior to 1969, the mean annual rainfall was 225 mm but for the following 15 years was only 154 mm (Darling et al 1991). The profiles were drilled in interfluve areas comprising sandy colluvial clays of probable Quaternary age overlying Nubian (Cretaceous) sandstone. The four profiles are very similar in their shape with mean chloride concentrations which range from 1357 - 4684 mg l^{-1} corresponding to recharge rates of <0.1 to 0.78 mm a^{-1}. This is effectively zero, and water in the unsaturated zone in this part of Sudan which is 25m thick, must be in storage or have been in transit for around 2000 a. The shapes of the profiles are complex and suggest that in the top 3 m recently recharged water has mixed with water being recycled due to evaporation during drier interludes; in the lower part of the profile, fluctuations of the water table where less saline water is found have probably led to a diffusion gradient. Similar high concentrations of chloride and low recharge rates have been recognised in Australia (Allison and Hughes 1983) and in southern USA (Phillips 1994).

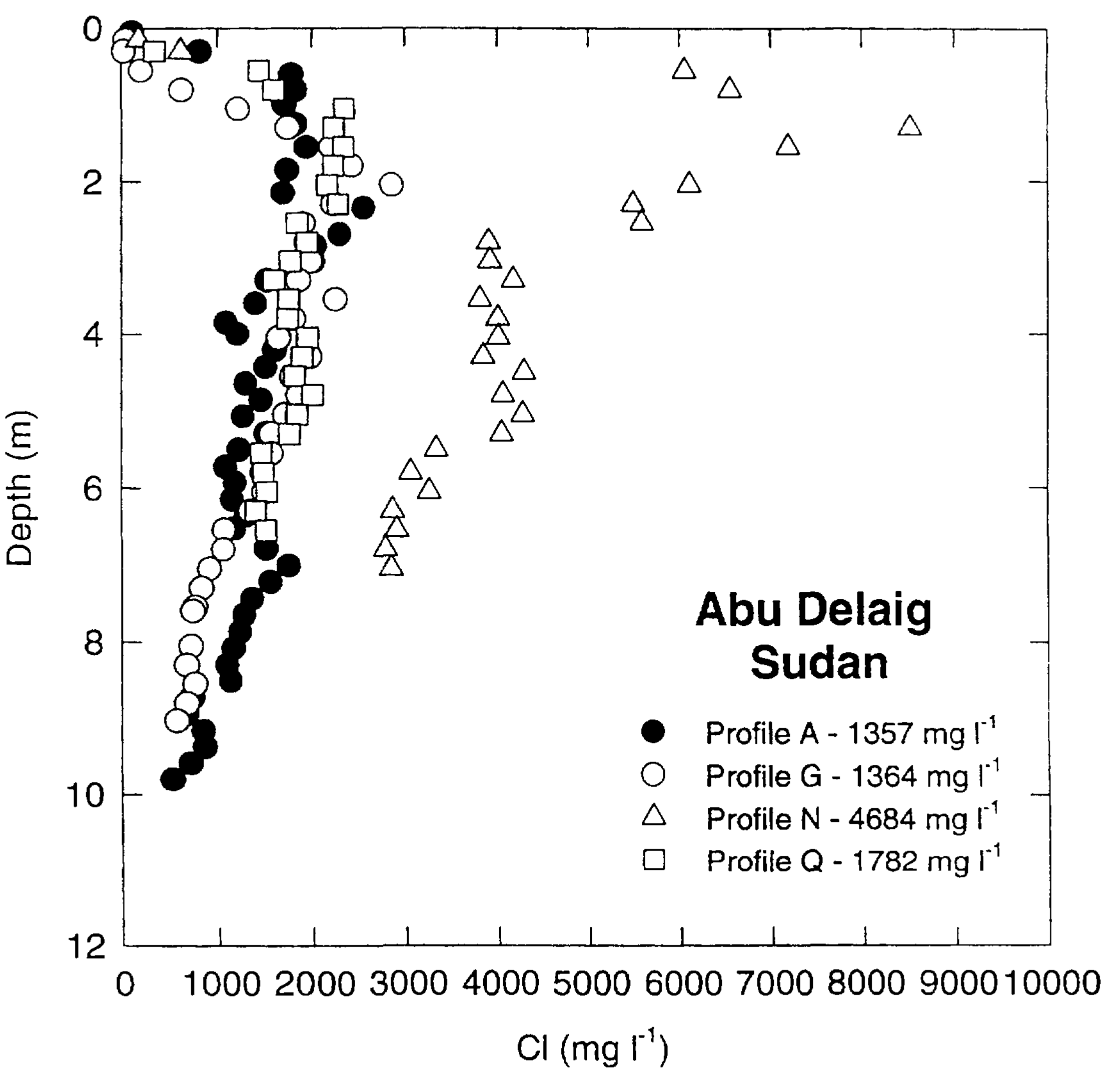


Figure 4. Four profiles of chloride in the unsaturated zone from Abu Delaig, Butana region, Sudan.

4. RECHARGE HISTORY OF PAST 500+ YEARS

Under conditions of piston flow, solute (or tritium) inputs derived from the atmosphere should be displaced at regular intervals from the soil horizon into the unsaturated zone, with higher solute concentrations corresponding to lower recharge. The theory of the movement of solutes through the unsaturated zone and the transmission of solute peaks corresponding to recharge episodes, has been described and critically reviewed by Cook et al (1992). Variations in chemistry will be preserved only if the time scale for hydrological change is large relative to the diffusivetimescale. Using the model developed by Cook et al. (1992), a persistence time may be defined which represents the time that it takes for the relative difference in solute (chloride) concentration to be reduced to 20% of its original value. Thus a 20-year event such as the recent Sahel drought should persist at a recharge rate of 10 mm a^{-1} and at a moisture content of 5% (typical of fine grained sands) for around 800 years. The corresponding isotopic (water) signal will be significantly less due to diffusion also in the gas phase.

Several profiles obtained from N Senegal have been interpreted (Edmunds et al 1992) as archives of recharge, climatic and environmental change for periods up to 500 years. Over the past 100 years, validation is provided by instrumental records for rainfall and river flow. In Figure 5, one profile (L3) has been calibrated using recharge rates and moisture contents. The profile record is 108 years, assuming that recharge over this period is representative of the 3-year average (2.8 mg a^{-1}) measured

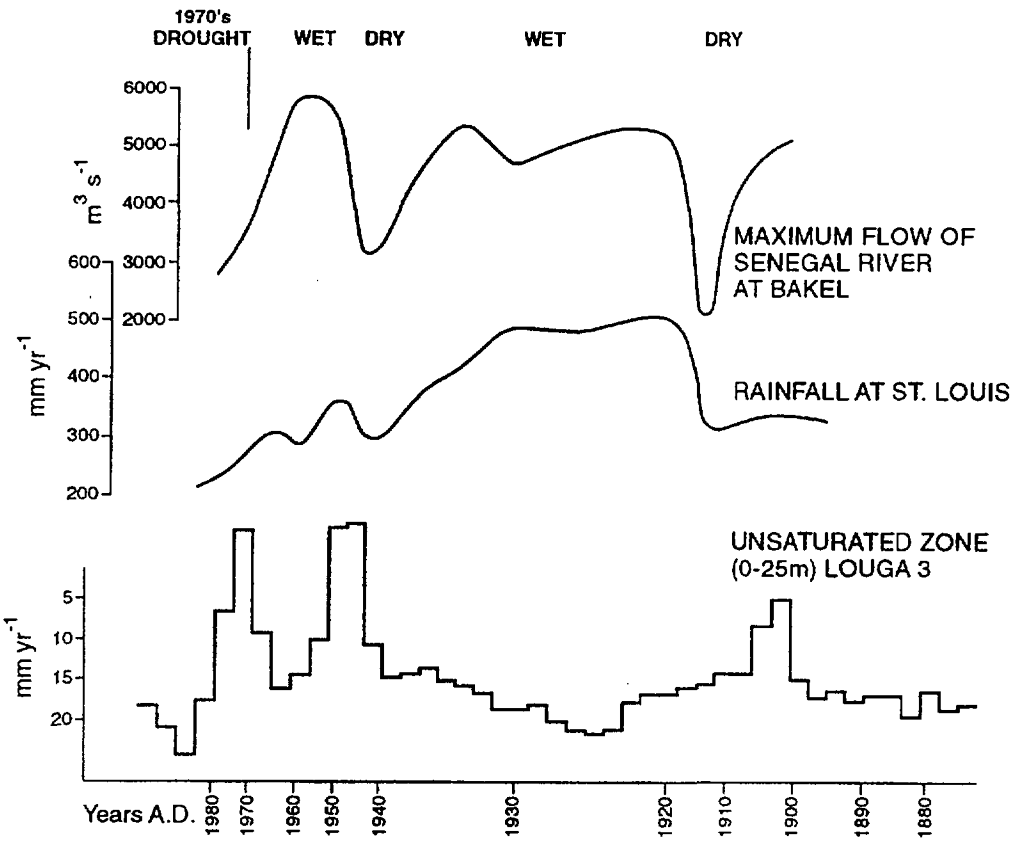


Figure 5. Comparison of the calibrated L3 profile with the climatic record of the last century as given by the rainfall record of St Louis and the flow of the Senegal River at Bakel.

in this study. Assuming that the piston flow model applies, the peaks in Cl at 4-6 m and 6-13 m should correspond to periods of drought from 1970 and also in the 1940's. Another peak in the 1900's also reflects a recorded drought period. The unsaturated-zone profile is compared (Figure 5) with the rainfall record at St Louis (some 80 km from the research site) dating back to the 1890's (Olivry 1983), and with the Senegal River with records over a similar period (Gac 1990). Whereas the correlation with the rainfall records is moderately good, the correlation with the river flow, representing the regional influence is much better. The correspondence with the main wet phase from 1920-1940 is well shown in all sets of data. During the dry episodes the recharge rate reduced to around 4mm a^{-1} but during the wet phases this rose to as high as 20mm at this site. An exact correlation between the various archives would not be expected for reasons stated above, the possibility of some by-pass flow, dispersion of small-scale events and the likelihood that some variation of rainfall chemistry over the long term might be expected. In addition, the rainfall and river flow data also contain possible errors. Nevertheless, similar records are found in other profiles (Cook et al 1992; Edmunds et al 1992) and provide confidence to extrapolate further over longer time scales (over the past 500-2000 years) for which archives are generally scarce.

5. RECHARGE DURING THE HOLOCENE

In north Africa and the Sahel region there is growing evidence from different archive materials (lake deposits, palaeoecology etc) that the early Holocene was characterised by one or more wet periods (Gasse et al 1991) although these were not necessarily synchronous. Evidence is also available from much of north Africa that these wet periods also gave rise to considerable recharge to groundwater which is recorded especially in the phreatic aquifers of arid areas (Edmunds and Wright 1979: Fontes et al. 1993).

In the mainly unconfined Miocene aquifer in central Libya a distinct body of very fresh groundwater (<50 mg l^{-1}) was found which cross-cuts the general NW-SE trend of salinity increase. This feature, around 10km in width may be traced in a roughly NE-SW direction for around 130 km, where the depth to the water table is currently around 30-50 m. Because of the good coverage of hydrocarbon exploration wells (water supply wells) in this region, a three-dimensional impression can be gained of the water quality. It is clear that this feature is a channel that must have been formed by recharge from a former ancient wadi system (Edmunds and Wright 1979). No obvious traces of this river channel were found in this area which had undergone significant erosion, although neolithic artefacts and other remains testified that this region had been settled in the Holocene. Further studies of the different groundwaters were made using stable isotopes (O, H and C) and radiocarbon as well as inorganic chemistry. Whereas the regional, more mineralised, groundwaters gave values of 0.7-5.4% modern carbon, the fresh waters gave values from 37.6-51.2% modern carbon and also were distinctive in their hydrogeochemistry. The younger waters gave 'ages' ranging from 5000-7800 years (uncorrected ages since it was argued that any reaction with the solid phase would have been with active carbonates in the soil zone or with calcretes). Evidence of former extensive soil and vegetation cover over this whole region is also given by the very high nitrate concentrations preserved in the mainly aerobic waters beneath the Libyan desert (Edmunds and Gaye 1997.

Clear evidence of regional replenishment of groundwaters during the Holocene is provided from the Butana area, Sudan (Darling et al 1987; Edmunds et al 1992), where direct recharge through the present day soils in an area with long term average rainfall of 225 mm is close to zero. A detailed study was made of the Wadi Hawad , a former tributary of the Nile and its region. This wadi flows intermittently at the present day yet seldom reaches the Nile, and it represents a good example of hydrological conditions at the boundary between arid and semi-arid conditions. Evidence from tritium shows that current recharge from the rainy season in the headwaters area moves laterally up to 1km from the wadi, but there is no evidence that recharge actually reaches the water table, although it is likely that this is the case. Stable isotopic and radioisotopic evidence together with chemical data provide a good characterisation of the different sources of groundwater (Figure 6).

Groundwater in the Nubian sandstone is abstracted from wide-diameter traditional wells which may be up to 100m deep, and also from boreholes of similar depth. The majority of these groundwaters give uncorrected radiocarbon ages mainly in the range 5500-10000 yr which are probably close to the true ages since active carbonate was probably involved in the formation of the total dissolved inorganic carbon (TDIC). These waters may be mixtures in which any age stratification may have been smoothed out, but they give a distinct mid-Holocene signature across the region. Waters with the youngest ages are found in the more humid southern part of the region, hinting that some modern recharge from the upper courses of the wadi system may be occurring. The regional groundwaters have distinctive light signatures ($\star ^{18}O$ of -9 to -10 1) which contrast with modern waters, including the river Nile. Intermediate waters with $\star ^{18}O$ of -7 to -5 1 may also indicate mixture with modern recharge. The distinctive isotopic signature also implies a different climatic pattern at the time of recharge, probably that the rainfall was derived from the Atlantic or from the Gulf of Guinea rather than from the Indian Ocean as at present (Fontes et al. 1993) who propose a northward shift of the ITCZ (Inter-tropical covergence zone) producing more intense rains to explain the presence of isotopically light rains (after correction for evaporation effects).

6. DISCUSSION AND CONCLUSIONS

The boundary between semi-arid and arid zones (approximately 250mm annual rainfall) is often viewed as the boundary between areas that receive recharge to aquifers and those that do not. An example from the work presented in this paper demonstrates that over the short timespan represented by the prolonged drought in the Sahel region (1969-1989 approx) with a 100 year mean rainfall of 400 mm, where a decrease in mean annual rainfall of up to 38% occurred, the recharge in an area covered by sandy soil decreased from 10mm to 4mm. There must therefore be a threshold value of rainfall for any given set of soil conditions below which infiltrating rainfall is lost entirely by the

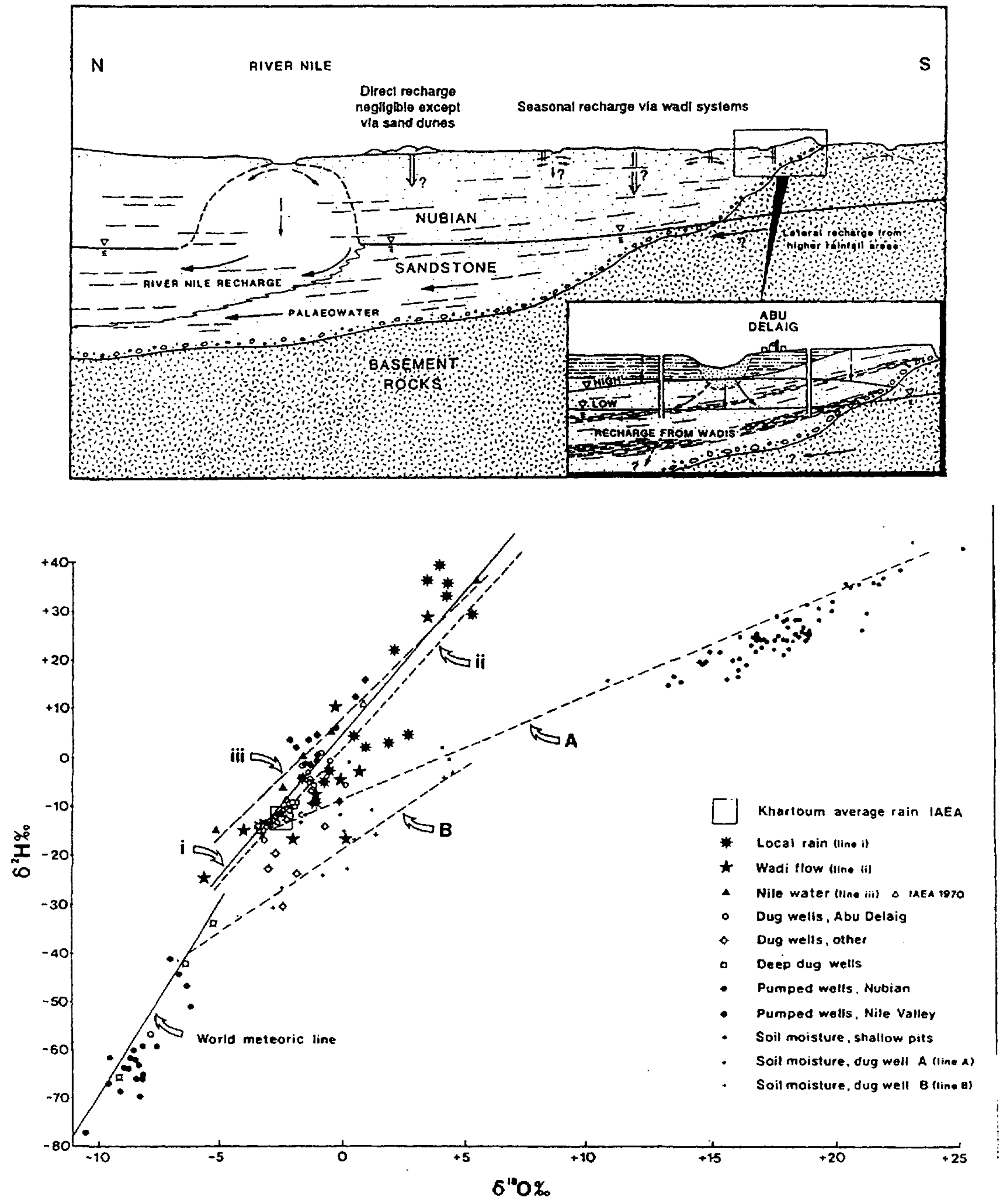


Figure 6. Conceptual model of the Butana region Sudan showing probable sources of recharge and isotopic signatures.

evapotranspiration process and where solutes accumulate giving rise to saline water accumulation and effectively zero movement through the unsaturated zone. This condition is demonstrated with the examples from Sudan, in the extreme situation in N Senegal and elsewhere such as Australia and SW USA.

The soil type and soil thickness are considered to be key variables in controlling recharge. Those semi-arid areas which are overlain by sands and sandy soils are highly favoured as recharge zones. It has been demonstrated at one extreme that sand dune-covered areas may receive significant direct recharge from heavy storms even where, as in Saudi Arabia (Dincer et al 1974), the mean annual rainfall may be as little as 80mm. Thus areas of present day sand dunes and sandy deserts in arid zones need to be closely studied in conjunction with the incidence and intensity of rainfall events to verify the possibility that regional recharge has occurred. In the example given from Senegal, the recharge studies have been carried out in Quaternary dune fields which are typical of much of the Sahel having formed during southward shifts of the arid margin and which now occur in higher rainfall areas. These areas, occurring at desert margins in many parts of the world, are of great importance at the present day since they occur in regions with relatively high populations, acting as buffer zones for migration during drought periods.

It has been shown from studies of the unsaturated zone in Australia discussed above that established vegetation coverage is highly efficient in water usage; on clearance recharge rates increase. This effect is also seen across climatic zones. In northern Senegal, where the mean annual rainfall is around 350 mm, the mean recharge rate is 13 mm (Gaye and Edmunds 1996), but in the south where the vegetation changes from Sahelian to Sudanian and mean annual rainfall increases to around 800 mm a^{-1}, the recharge rates in the same sandy lithology are essentially the same.

During the Holocene, semi-arid regions have witnessed intense changes in their water balance. Areas which at the present day receive 200-400 mm annual rainfall will have oscillated between arid periods when no recharge would have occurred and during which salinity accumulated in the aquifer. However, these same regions would also have undergone periods with active local (but not usually regional) replenishment giving higher water tables leading to spring discharges and lake formation. Further evidence of these changes should be present in the groundwater environment. Careful sampling of the deep unsaturated zones (up to 100 m possibly) for a range of geochemical indicators contained both in the moisture and possibly in the solid phase (resulting from contemporaneous water-rock interaction) should provide indicators of changes of inputs over 2000 a and possibly longer. With the miniaturisation of analytical techniques for isotopic and chemical analysis, notably AMS measurements of ^{14}C (Fontes & Edmunds 1989) it will be possible in well controlled hydrogeological investigations to determine with greater precision the undoubted age (and quality) stratification of unconfined groundwaters.

In terms of groundwater development in arid and semi-arid areas, the methodology described in the present paper, together with representative examples, provide an effective method to determine recharge and the sustainable yield of groundwater. The chloride balance approach is inexpensive to apply and gives results which are applicable to the rates of recharge that apply at the decade or century scale. This methodology is particularly appropriate to areas of desert and desert margins where unconsolidated Quaternary sediments, themselves the products of climate change, are widely-distributed. It is essential to establish a proper water balance before exploitation of a groundwater resource. In many cases this has not been done and the consequences of over-development are all too obvious. In such cases it is still desirable to establish the safe yield of the aquifer, either as a target for reduced but sustainable consumption, or to come to terms with the consequences of mining. In this context it is valuable to have a good understanding of recent variations in recharge history so that management options can include scenarios for any future abrupt climatic change.

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