

Climate change impacts on groundwater recharge in NE Uganda and the potential role of groundwater development in livelihood adaptation and peacebuilding.

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ABSTRACT: The delicately balanced livelihoods of the people of NE Uganda are under increasing pressure due to the dynamic conditions of both the natural and socio-political environments of the region. The climate record for NE Uganda during the 20th century shows patterns of air surface temperature change that mirror those observed in global datasets, with post WW2 cooling giving way to a strong warming trend since the 1960s. While no such trends are observed for precipitation in the record, the latest IPCC report indicates the possibility of future increases in precipitation. Preliminary groundwater recharge simulations are presented which reproduce observed groundwater level fluctuations and give best estimates for groundwater recharge decreasing from 140 mm/a in Teso region to less than 30 mm/a in the semi-arid Karamoja plain. The underlying models and the available data strongly suggest that recharge occurs predominantly through indirect or localised mechanisms. If so, effects caused by higher temperatures may be more than offset by the predicted increase in future precipitation leading, overall, to an increase in the available groundwater resource. Adaptive strategies for the people of NE Uganda may depend on future groundwater use to an increasing extent if current environmental and socio-political trends continue unabated. Thus, further research is essential to confirm the mechanisms of recharge in the region and the sustainability of such developments. Given the role of natural resources within the current conflict dynamics, groundwater science may have a significant role to play in peacebuilding within the region in years to come.

1 BACKGROUND

1.1 Location

The location of the study area in NE Uganda is shown in Figure 1 and extends from Soroti (Teso region) in the southwest to Moroto (Karamoja region) in the northeast.

1.2 Topography, drainage and landcover

The regional topography was determined from a Digital Elevation Model (DEM) (CIAT 2004) and 1:50,000 topographical maps and is dominated by the extensive Karamoja plain (modified 'African Surface') at approximately 1100 to 1200 masl with gentle large scale undulations broken by abrupt topographical highs associated with areas of previous volcanic activity and small inselbergs (Trendall 1965).

The drainage in Moroto District is dominated by deeply incised, sand filled, ephemeral channels flowing from east to west. These 'sand rivers' such as the Omanamani near Kangole, are a locally important source of water during the dry season when water can be found within a few metres of the surface

(Faillace 1973). These channels feed into the southerly flowing Akokorio River via its tributaries, the Okok and Okere Rivers, leading through perennially swampy areas in its lower reaches and eventually draining to Lake Kyoga just to the southwest of the study area.

The regional vegetation, varying according to the distribution of rainfall, soils and land management, comprises grassy plains with variable proportions of scrub, acacia thicket and savanna woodland (Wilson & Rowland 2001, Trendall 1965) with vegetation becoming progressively more sparse to the northeast (Faillace 1973). Only a small percentage of the land is under crops in Karamoja with a much greater proportion in Teso (National Biomass Survey 1996), reflecting the different lifestyles adopted in these regions.

1.3 Geology and soils

An understanding of the local geology and hydrogeology was developed based on existing maps and available borehole records. The solid geology is predominantly Precambrian African 'basement' com-

plex dominated by undifferentiated acid and granitoid gneisses (Faillace 1973). The region is thought to have been subject to cycles of deep weathering and stripping by sub-aerial erosion controlled by both the tectonic and climatic history (Taylor & Howard 1998). A period of volcanic activity in the Miocene saw the formation of a large volcanic center which subsequently collapsed and was eroded leaving the Napak (Fig. 1) peaks in addition to many associated smaller scale features in the landscape.

Based on data from around 400 borehole logs in the study area, the ‘depth to bedrock’ was found to be highly variable and mostly in the range 5 to 40 m. However, since many of the available borehole logs are of insufficient quality to be able to distinguish alluvial material from weathered bedrock, interpretations regarding depths of weathering are in many locations uncertain.

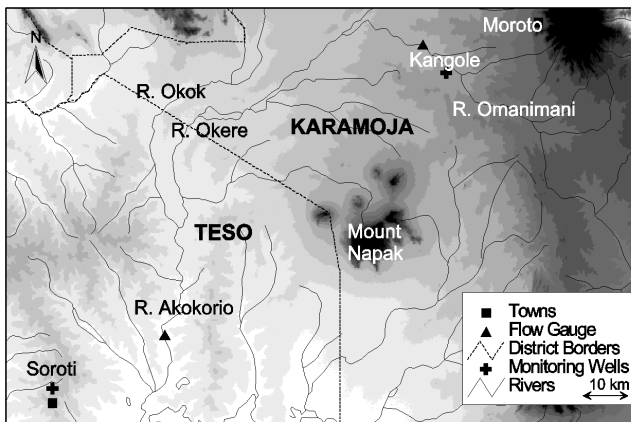


Figure 1. Location map of study area in NE Uganda.

Much of the study area within Karamoja is mapped showing Pleistocene to recent alluvium covering the flat valley bottoms, at least 10 to 15 m thick in some areas, and sometimes coalescing across interfluves (Trendall 1965). More recent alluvium is present along the courses of the main rivers extending into the Teso region. Hard nodular laterites are also present in some interfluve areas and can be up to 2 m thick.

From aerial photography and field mapping, two main soil types can be identified across the study area, the more fertile sandy loams of the interfluves and dark clays of the plains and valleys associated with fine grained alluvium (Wilson & Rowland 2001).

1.4 Hydrology

Data from flow gauges situated on the Omanimani and Akokorio Rivers (Fig. 1) were used for analysis. Flow in the Akokorio River appears to be seasonal and dominated by a baseflow component for much of the year with a pattern of response which correlates strongly with that of groundwater levels meas-

ured in the catchment. Although flow ceases during times of low groundwater levels, standing water is retained in the valley areas by underlying low permeability clay rich soils.

In contrast, the Omanimani River flow gauge, situated near Kangole, shows a very ‘flashy’, run-off dominated response with no indication of any baseflow component, consistent with a deep water table in this area which is well below the base of the river channel. A simple comparison of monthly rainfall (collated from the Tyndall Centre for Climate Research’s CRU TS 2.1 climate model dataset (Mitchell 2004) for the relevant grid square) against monthly river flow, shows that the proportion of rainfall becoming runoff is most often between 2.5 to 15% for the Omanimani catchment. A more rigorous analysis was not possible since higher resolution rainfall data were not available from the local area for this catchment. However, UNDP (1968) suggests that rainfall of less than 12 mm/d is not likely to cause run-off which is consistent with the findings of Taylor & Howard (1996). Furthermore, they note that runoff may be as high as 40% in areas adjacent to the mountains in the north east of the study area.

Based on the available flow data and a UNDP report (UNDP 1968) the following generalizations about the surface flow regime in the study area may be made. In Karamoja, heavy rainfall causes high surface runoff which ends one or two days after rainfall has ceased. In the head waters, river flows commence soon after rainfall starts with peak flows occurring in the afternoon or evening. River flows across the plains of Karamoja occur from around April to August with flow in later months being fed by shallow groundwater flow from adjacent areas. There is a lag time of a month for upland flows to reach the dambos downstream of the Teso-Karamoja border which flow from May to October again supported by shallow groundwater flow long after the main rains have passed. The down stream rivers are then fed for another one or two months after upstream flows have ceased. Total surface outflow is thought to be approximately 5% of the total catchment rainfall.

1.5 Climate

The average rainfall across the study area decreases from around 1300 mm/a in the southwest to less than 650 mm/a in the north and east. This change from sub-humid to semi-arid conditions is reflected in the transition from the settled agrarian lifestyle of the Iteso to the semi-pastoralist ways of life of the Kari-mojong. Rainfall has a bimodal distribution throughout the year with, on average, peaks in May and August and very little rain between December and February. Storms often build up in the afternoon

with velocities of around 8-12 mph with storm diameters of 20 to 30 miles producing highly intense rainfall up to 25 mm/hr in some instances (UNDP 1968).

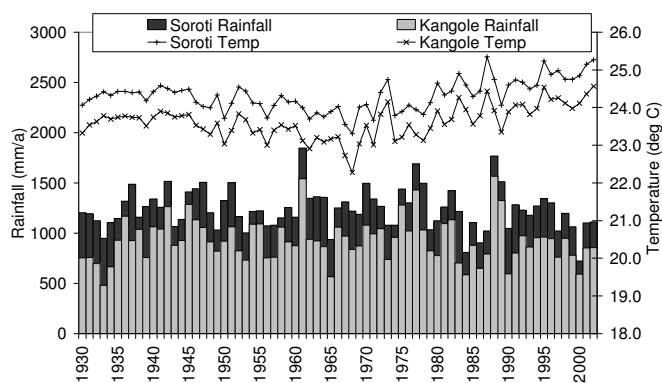


Figure 2. Annual total rainfall and annual average air temperature derived from CRU2.1 data.

Gridded monthly rainfall and air temperature data for the 20th century at 0.5 degree (approximately 50 km) resolution were extracted from the CRU TS 2.1 dataset (Mitchell 2004) for grid squares coincident with groundwater monitoring locations at Soroti and Kangole. Figure 2 shows time-series of annual average temperature and annual total rainfall for both grid squares. Based on the number of nearby data points on which the gridded data are based, data quality was believed to be more reliable from around 1940 onwards. The air temperature record shows a similarity to trends in global temperatures, with post WW2 cooling giving way to a strong warming trend since the 1960s (IPCC 2007). No such clear patterns are seen for annual rainfall totals or for changes in the distribution of rainfall throughout the year.

Sufficient climate data were not available to allow Penman-Montieth, or similar calculations, to derive values for potential evapotranspiration (PET). However, the gridded CRU TS 2.1 temperature data were used to derive a time series for PET using an adapted Thornthwaite method (START 2006). Initially, temperature derived PET values were correlated against available pan evaporation data for Aduku (approximately 75 km west of the study area), giving a correlation factor (k) of 0.76. This was then applied to the Soroti and Kangole situations assuming an evaporation pan factor of 0.9, a reasonable value for Uganda (Taylor & Howard 1999). The resulting values of PET average around 2000 mm/a, which appears reasonable in the Ugandan context (Taylor & Howard 1996).

1.6 Hydrogeology

Available borehole records show that ‘water-strikes’ during drilling are very common within the weathered zone in the southwest of the study area and ex-

ploitable groundwater is often found at less than 10 m below ground level (mbgl) even in interfluvial areas. Hand dug wells are common, often fitted with suction hand-pumps and yielding >1000 l/hr (Harris 1994). The transmissivity (T) of the weathered aquifer has been reported to be 2 to 58 m²/d (but mostly in the lower end of the range) in the western part of the study area (Harris 1994) consistent with values reported for the regolith elsewhere in Uganda (Taylor & Howard 2000). Higher yielding boreholes are also common in Teso, completed within the deeper fractured bedrock, drawing additional storage from the weathered zone above.

Moving northeast, as the ground elevation rises onto and across the Karamoja plain, groundwater is commonly only encountered at greater depths within occasional fractures in fresh crystalline rocks. Failace (1973) reports that valleys present the best locations for siting successful boreholes since there is more likely to be recharge directly to the local fracture system and/or via alluvial storage. The optimal drilling depths for encountering good fractures yielding 2-4 l/s were found to be 30 to 90 mbgl. Furthermore, based on hydraulic and hydrochemical evidence, he reports that the movement of groundwater from any point is thought to be restricted to an area of limited extent and extremely irregular outline and hence the fractured bedrock cannot be considered as a regional aquifer in Karamoja. In this context the concept of transmissivity for the fractured aquifer has little relevance but is reported to be 1m²/d in other parts of Uganda (Taylor & Howard 2000). The specific yield of such a fractured system is likely to be much less than 1% (Howard & Karundu 1992, Clark 1985, Healy & Cook 2002).

Groundwater recharge is thought to be localized and to occur by direct precipitation on exposed joint systems and by the runoff-runon process predominantly through water flowing in river courses feeding the weathered zone and joint systems. Direct recharge is also thought to occur where the soils are relatively permeable, predominantly on the interfluvial areas away from the clayey soils of the plains and valleys. The only estimate of groundwater recharge for Karamoja in available literature is approximately 1 mm/a excluding recharge to sand river beds and is based on analysis of groundwater levels from observation boreholes (unfortunately these data have not been unearthed for this study and may be lost).

1.7 Groundwater levels

The locations of groundwater monitoring sites in the study area for which several years of reasonable quality data are available (3/99 to 12/02) are at Kangole and Soroti as shown in Figure 1.

The observation well at Soroti is situated in a well defined catchment underlain by crystalline basement

rocks weathered to a variable depth of 10 to 30 mbgl and overlain by 6 to 15 m of clay with patchy laterite in the upper few metres. During the monitored period the groundwater level varied between 5 to 8 mbgl within the clayey overburden and showed a clear response to rainfall events with recession in drier periods (Fig. 3(a)).

In contrast, the Kangole observation well is situated close to the Omanimani River, a sand river in which water is commonly held within shallow alluvium for much of the year. It is underlain by crystalline rocks with alluvial and weathered material to depths of up to 20 mbgl. Groundwater levels show seasonal variations between 30 to 31 mbgl within the fractured unweathered zone (Fig. 3(b)). The slow groundwater response to rainfall is likely to be due to the thick unsaturated zone, perhaps with a seasonally saturated upper alluvium feeding deeper fractures monitored by the observation well after periods of prolonged or heavy rainfall.

2 RECHARGE MODELS

2.1 Modelling approach

Quantifying the groundwater resource is a fundamental component for sustainable water resources development in NE Uganda. Furthermore, an understanding of the recharge processes is essential to make sensible predictions of the possible impact of climate change. Hence, numerical models were developed to synthesise the available groundwater hydrographs based on the background understanding of the hydrogeology of the region as described above.

A 'Penman-Grindley' style soil-moisture balance model (SMBM) was developed with a daily time-step to estimate direct recharge for the two groundwater monitoring locations at Soroti and Kangole (Fig. 1). Implemented in a spreadsheet the SMBM requires a daily time series of rainfall and PET. Root constants (C) and wilting points (D) can be defined on a monthly basis throughout the year and an initial value is also needed for soil moisture deficit (SMD). Runoff is given as a fraction of rainfall which can vary with antecedent SMD and rainfall intensity. There is also an option for 'bypass recharge' to enable recharge to occur in the presence of a SMD. This was added to account simply for preferential flow as well as indirect/localised recharge thought to be particularly important in semi-arid areas (Simmers et al. 1997). The user can define a threshold for rainfall above which, and SMD below which, a specified proportion of incident rainfall (less runoff) will become recharge.

Daily rainfall data, collected at sites adjacent to the groundwater monitoring locations, were used as input data. In the few percentage of cases where data were missing, the time series were in-filled using ratio comparisons from the other monitoring stations

based on double-mass plots. A daily time series of PET was derived from the monthly data described above (using temperature data and the adapted Thornthwaite equation) assuming a constant value of PET for each day within a given month.

Prescribed values of C and D ranged from 43 to 76 mm and 74 to 127 mm respectively, depending on the proportion of vegetated cover or bare soil thought to be present through the modeled period. Runoff co-efficients were parameterised based on the correlation between runoff and rainfall observed in available stream flow data for the region. In general it was assumed that runoff fractions would increase with increasing rainfall intensity and decrease with increasing SMD.

The recharge model output was processed to derive a simulated groundwater level according to assumptions about hydraulic processes operating in each location as described below.

2.2 Model implementation and results

2.2.1 Soroti

It was assumed that shallow groundwater in the Soroti catchment drains to the nearby stream and that recession of this baseflow and thus, groundwater levels in the groundwater catchment feeding the stream, will be of an exponential form. Hence, modeled recharge was added to a groundwater store which then drained according to a linear recession constant (d^{-1}).

Methods for estimating groundwater recharge based on groundwater level fluctuations are prone to large uncertainties due to the uncertainty in values for specific yield (S_y) (Healy & Cook 2002). However, a linear recession constant can be related to average aquifer parameters using the aquifer response function (Erskine & Papaioannou 1997) for catchments in which the vertical flow gradients are small. This enables an 'average' catchment groundwater hydrograph response to be modeled using the parameters of S_y , T and a characteristic length parameter (L). This approach was taken for Soroti and a set of non-unique fits for the modeled hydrograph was derived based on a realistic range of values for these three parameters and the recharge model output.

It is clear from a consideration of the rise in groundwater levels after rainfall within the drier parts of the year that preferential/indirect recharge mechanisms must be significant in this area. This was confirmed by the numerical model which showed that without adding a component of bypass recharge, a standard SMBM gave zero recharge for the modeled period. By drastically reducing the root constants and wilting points beyond realistic values some recharge could be simulated but the groundwater hydrograph could not be matched with any degree of realism.

A range of 'best fit' simulated hydrographs were derived using a value for L of 400 m and values of T of 5 to 12 m²/d. The resulting recharge estimates assuming S_y of 1%, 2% and 3% were 70 mm/a, 140 mm/a and 210 mm/a respectively. If S_y was increased much beyond this range, a reasonable model fit could not be made unless T was increased, or L was decreased, out of the expected range. This shows the benefit of using the aquifer response function methodology. The best estimate scenario is shown in Figure 3(a) for the case of $S_y = 2\%$, a reasonable value for the clayey overburden at the site giving an average recharge value of 140 mm/a. Average rainfall and PET for the modeled period were 882 mm/a and 2174 mm/a respectively.

2.2.2 Kangole

Owing to the much thicker unsaturated zone at Kangole (30 m) in comparison with Soroti, an additional store was used to model the groundwater hydrograph in this location. Simulated recharge was added to a first store to represent the temporary storage of focused runoff in superficial alluvium and permeable weathered materials. This store was assumed to drain under a linear recession constant into a second store used to model the groundwater pressure response in the deeper fractured zone in which the monitoring well is located. The recession of the deep groundwater store was controlled by a second linear recession co-efficient.

As for Soroti, to adequately simulate the observed groundwater hydrograph, it was found that bypass flow was needed. Direct recharge was zero for the modeled period. For Kangole, no attempt was made to relate the groundwater hydrograph recession to aquifer parameters since the fractured aquifer in this location is highly complex and unlikely to fit the underlying assumptions inherent in the analysis which utilizes the aquifer response function.

A set of model results for Kangole are shown in Figure 3(b). This simulation results in a recharge of approximately 30 mm/a for the modeled period with rainfall and PET being 654 mm/a and 2072 mm/a respectively. Given that this scenario used a maximum likely value of 1% for the S_y of fractured rock this represents a maximum value of recharge in this location. It should be noted that this value should not be taken as an average for the area as a whole as it is likely that the fracture system monitored by the observation well is fed to some extent by water stored in valley alluvium recharged through focused ephemeral stream flow. Average areal recharge to the wider area is likely to be much lower than this value.

As the fractured rocks in this area are thought not to interconnect and, thereby, not to act as a regional aquifer, the reasonably strong recession seen in the groundwater levels is intriguing. It is unlikely to be caused by local abstraction although this cannot be

ruled out absolutely. Ground surface levels fall below the elevation of the groundwater levels recorded in the Kangole monitoring well only around 10 to 15 km away and discharge to seepage and subsequent evaporation or stream baseflow in such locations is possible. It may be that relatively large recharge in the vicinity of the Omanimani river causes a recharge mound which recedes after periods of rainfall, into a wider fracture network which has natural or artificial outflows over a very wide area. More investigation into possible flow patterns within the fracture system of the area is needed to resolve this uncertainty but it is clear that significant discharge, either natural or artificial, is occurring somewhere in the system.

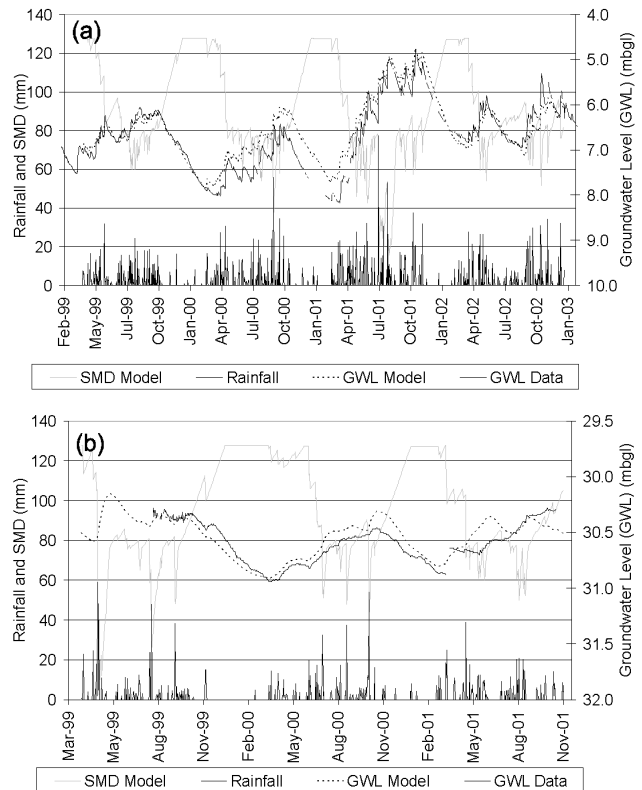


Figure 3. Model results for (a) Soroti and (b) Kangole.

3 DISCUSSION

Unfortunately, recharge estimation by another method is presently impossible until further data are collected to corroborate these results. However, there is clear evidence that significant groundwater recharge occurs in the study area, and is likely to decrease in average terms towards the northeast. Furthermore, it is clear that localized and indirect recharge are the dominant mechanisms for recharge and that standard SMBMs are inappropriate for estimating recharge in the area, even in the relatively humid Soroti area.

This understanding of likely recharge processes enables us to make some general comments about

the likely impact of predicted changes to the climate. The latest IPCC predications (under the A1B scenario) predict a median temperature increase of 3 to 4 °C for East Africa by the end of the century (IPCC 2007). Although the uncertainties are noted regarding how changing CO₂ concentrations may affect plant evapotranspiration, it is likely that overall such a temperature rise will significantly increase the PEt in this region. With rainfall also predicted to increase by several percent, and most strongly in the driest part of the year (IPCC 2007), if direct recharge was dominant then the possible increase in precipitation may, to a great extent, be countered by an increase in PEt (which would lead to greater SMDs needing to be overcome for recharge to result). Obviously, the higher the intensity of the increased rainfall, the less the increase in temperature would offset the increased rainfall. However, given that the recharge processes actually appear to be dominated by indirect and localised mechanisms, any effects caused by higher temperatures may be more than offset by the predicted increase in future precipitation leading, overall, to an increase in the available groundwater resource. Clearly, these results need to be corroborated by further research to confirm these tentative conclusions.

The relevance of such findings, if confirmed, may be vitally important, particularly for Karamoja. Here, a finely tuned system of agro-pastoralism developed over centuries to make the best of the harsh environment, has, in recent years come under increasing pressure through socio-political changes forcing many previously pastoralist people to become more dependent on crop production for survival. If this trend continues, increased development of accessible and sustainable water resources will become increasingly important. The degree to which small-scale groundwater fed irrigation can be developed may be a significant focus for further research. As NE Uganda has seen protracted conflict and ongoing poverty for many decades, and given the role of natural resources within the current conflict dynamics, groundwater science may have a significant role to play in peace-building within the region in the coming years.

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