ENVIRONMENTAL RESEARCH
LETTERS

Rainfall intensity and groundwater recharge: empirical evidence from the Upper Nile Basin

To cite this article: M Owor *et al* 2009 *Environ. Res. Lett.* **4** 035009

IOP PUBLISHING ENVIRONMENTAL RESEARCH LETTERS
Environ. Res. Lett. 4 (2009) 035009 (6pp) doi:10.1088/1748-9326/4/3/035009

Rainfall intensity and groundwater recharge: empirical evidence from the Upper Nile Basin

M Owor[1,2], **R G Taylor**[1], **C Tindimugaya**[3] **and D Mwesigwa**[3]

[1] Department of Geography, University College London, Gower Street, London WC1E 6BT, UK
[2] Department of Geology, Makerere University, PO Box 7062, Kampala, Uganda
[3] Directorate of Water Resources Management, Ministry of Water and Environment, PO Box 19, Entebbe, Uganda

Received 2 June 2009
Accepted for publication 15 September 2009
Published 30 September 2009
Online at stacks.iop.org/ERL/4/035009

Abstract
Changes in the intensity of precipitation as a result of global warming are expected to be especially pronounced in the tropics. The impact of changing rainfall intensities on groundwater recharge remains, however, unclear. Analysis of a recently compiled data set of coincidental, daily observations of rainfall and groundwater levels remote from abstraction for four stations in the Upper Nile Basin over the period 1999–2008 shows that the magnitude of observed recharge events is better related to the sum of heavy rainfalls, exceeding a threshold of 10 mm day^{-1}, than to that of all daily rainfall events. Consequently, projected increases in rainfall intensities as a result of global warming may promote rather than restrict groundwater recharge in similar environments of the tropics. Further monitoring and research are required to test the robustness of these findings, but the evidence presented is consistent with recent modelling highlighting the importance of explicitly considering changing rainfall intensities in the assessment of climate change impacts on groundwater recharge.

Keywords: ground water hydrology, hydroclimatology, regional climate change, climatology in global change

1. Introduction

Global warming is expected to intensify the global hydrological system through a net transfer of freshwater from long-term stores in ice and increased precipitation and evapotranspiration associated with a warmer atmosphere. Considerable uncertainty remains, however, in how a net rise in global freshwater fluxes will be distributed in time and space. Several authors [1–3] contend that very heavy rainfall events (i.e., those in the uppermost quantiles of the rainfall distribution) will increase with the rise in the water-holding capacity of the atmosphere defined by the Clausius–Clapeyron relation ($\sim$6.5% K^{-1} rise in air temperature). This assertion is based on the observation that the heaviest rainfall events tend to deplete air of all of its available moisture. As total increases in global precipitation as a result of warming have been estimated at $\sim$1% K^{-1} [1, 2], the projected rise in very heavy rainfall events is necessarily accompanied by a reduction in the number of low and medium intensity rainfall events or an overall decrease in the frequency of rainfall events.

Increased rainfall intensities are expected to be especially pronounced in the tropics where warmer air temperatures will lead to larger absolute rises in the moisture content of the atmosphere [1–3]. This change in the distribution of rainfall will give rise to more variable river discharges and soil moisture. The former will exacerbate intra-annual freshwater shortages and the risk of flooding whereas the latter threatens food security through reduced crop yields [4]. Groundwater resources, which are better distributed than surface waters and account for over 90% of the world's accessible freshwater [5], are expected to feature prominently in low-cost strategies to adapt to changing freshwater availability and demand throughout the tropics.

The impact of changing rainfall intensities on groundwater recharge in the tropics is unclear. Substantial (70%) declines in groundwater recharge, recently cited in IPCC AR4 [6], have been projected in northeast Brazil and southwest Africa in association with higher air temperatures and lower rainfall [7]. These projections fail, however, to consider changes in the distribution of daily precipitation. Research in the humid tropics of Uganda [8] shows that failure to consider projected changes in rainfall intensities can influence both the direction and magnitude of the climate change signal for groundwater recharge. Projections of groundwater recharge that employ an historical (baseline) distribution of daily rainfall are 55% lower than the baseline period (1961–1990) whereas transformation of the rainfall distribution to account for projected changes in rainfall intensity results in a 53% increase in recharge relative to the same baseline period [8]. Evidence from the application of stable isotope tracers and soil-moisture balance models in tropical Africa [9–13] also highlights the importance of heavy rainfall events (>10 mm day^{-1}) in determining the magnitude and timing of rainfall-fed recharge. To date, no empirical evidence correlating observed rainfall intensities to the magnitude of groundwater recharge deduced from water-level fluctuations in the tropics has been published.

In this paper, we assess the relationship over the past decade (1999–2008) between daily precipitation and groundwater recharge observed in seasonally humid catchments within the Upper Nile Basin of Uganda. Rare as sustained groundwater-level monitoring data are in many areas of the tropics, our observations are exceptional in that observations of groundwater levels and rainfall occur at precisely the same locations and are remote from groundwater abstraction.

2. Methods

Combined rainfall–groundwater monitoring stations were established in the Upper Nile Basin of Uganda by the Ministry of Water and Environment (Uganda) in 1998. Monitoring wells were installed into discrete aquifers that occur within an unconsolidated weathered overburden (saprolite) and underlying fissured bedrock (saprock) across much of the Great Lakes Region of Africa and 40% of sub-Saharan Africa [14–16]. We analysed 10 borehole hydrographs but excluded 6 stations from further analysis due to inconsistencies and excessive gaps in their records. Comparisons between hydrological observations from the 4 stations employed in this study (figure 1) are aided by the fact that all stations occur within a surface of low relief [17] and feature similar soil conditions (i.e., ferallitic sandy loam) [18] and land cover (i.e., bushland and grassland) [19]. Further details of each monitoring well are summarized in table 1. Daily groundwater-level measurements were recorded using a float and chart recorder. Daily rainfall was recorded using a British standard 5-inch diameter rain gauge at each combined rainfall–groundwater monitoring station and meteorological stations (figure 1).

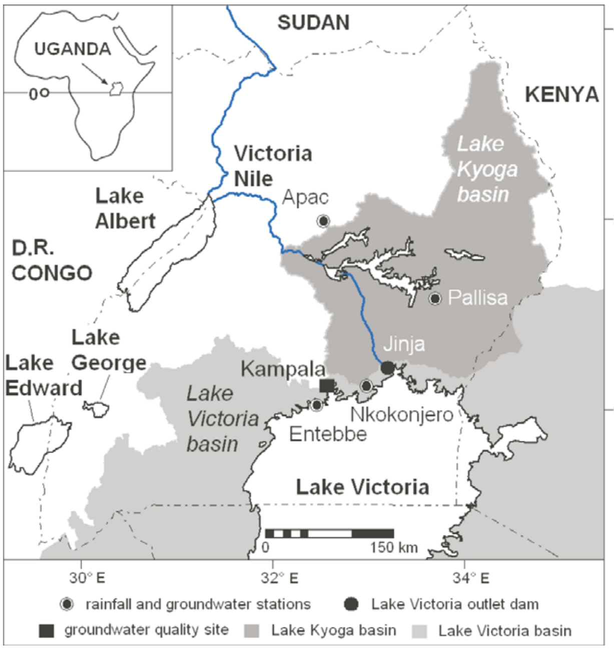

Figure 1. Map of Uganda and drainage basins in Upper Nile Basin showing the location of combined rainfall–groundwater monitoring stations.

Table 1. Local drainage, aquifer conditions, slope and depth of analysed groundwater-level monitoring stations in Uganda.

Station	Basin	Aquifer	Local slope[a] (deg)	Well depth (mbgl)[b]
Apac	R. Victoria Nile	Saprolite	1.4 (0.7)	15
Pallisa	L. Kyoga	Saprock	1.0 (0.4)	61
Entebbe	L. Victoria	Saprock	3.6 (0.8)	48
Nkokonjero	L. Victoria	Saprock	4.6 (1.3)	48

[a] Mean and standard deviation (in parentheses) in surface slope for station and 8 surrounding (90 m) grid cells from the Shuttle Radar Topography Mission (SRTM).

[b] mbgl: metres below ground level.

Saprolite and saprock exhibit considerable heterogeneity laterally and with depth due to the *in situ* weathered origin of each aquifer [14, 20]. Due to uncertainty in aquifer storage co-efficients, recharge events were quantified at each monitoring station according to the magnitude of the water-level rise in response to specific rainfall events [21, 22]. Cross correlations of observed rainfall and recharge at each station provided estimates of the lag time between rainfall and recharge events [22]. The threshold to define ‘heavy rainfall’ is supported by sensitivity analyses in which this threshold was varied from 5 to 25 mm day^{-1} in increments of 1 mm day^{-1}. Highest co-efficients of determination relating heavy rainfall to recharge are realized with a threshold of 10 mm day^{-1} for Apac and Entebbe; marginal improvements in the correlation for Pallisa ($R^2 = 0.72$) are achieved by employing thresholds of 15 mm day^{-1} ($R^2 = 0.74$) and 20 mm day^{-1} ($R^2 = 0.75$). Mean lag times (table 2) indicate average linear (response) velocities through unsaturated saprolite at each station of between 0.9 and 1.2 m day^{-1}. The period of rainfall

Table 2. Summary of results of the linear regression of the observed recharge and both total rainfall depth (ΣP_i) and rainfall depth of events exceeding 10 mm day^{-1} ($\Sigma(P_i - 10)$). N denotes the number of analysed recharge events with complete water-level and rainfall observations; *rmse* represents the root mean square error.

			ΣP_i		$\Sigma(P_i - 10)$	
Station	Mean lag (days)	N (events)	R^2	*rmse* (m)	R^2	*rmse* (m)
Pallisa	11	7	0.54	0.54	0.72	0.44
Entebbe	5	8	0.74	0.60	0.87	0.42
Apac	13	9	0.73	0.20	0.80	0.17

contributing to a recharge event is estimated from the mean lag time and duration of the recharge event indicated by the period of water-level rise.

We relate the magnitude of each recharge event to both the sum of daily rainfall (ΣP_i) and the annual sum of daily rainfall exceeding a threshold of 10 mm day^{-1}($\Sigma(P_i - 10)$). The first correlation assumes that all rainfall events contribute to recharge whereas the second assumes that only heavy rainfall events (>10 mm day^{-1}) contribute to recharge. This latter criterion is consistent with recent modelling of recharge in the tropics [7]. Correlations additionally assume that daily rainfall events contribute proportionally to recharge yet the magnitude of the recharge flux derived from rainfall is influenced not only by antecedent soil-moisture conditions but also intra-annual variability in soil-infiltration capacities and evapotranspiration. In the absence of observations of soil moisture, we directly correlated rainfall and recharge observations in order to avoid the possibility of introducing model bias in relating rainfall intensity to recharge.

3. Groundwater-level fluctuations and recharge in Uganda

Daily groundwater-level and rainfall observations from January 1999 to December 2008 in Lake Kyoga, Lake Victoria and Victoria Nile Basins are presented in figure 2. Bimodal distributions of annual groundwater-level fluctuations are observable in many years and arise from two rainy seasons: 'long rains' from March to May and 'short rains' from August to November [23]. Asymmetry in the response of water tables to bimodal precipitation at northern stations (figures 2(a) and (b)) has previously been observed and attributed to lower soil-moisture deficits that develop during the shorter dry season from June to July and greater intensity of the 'short rains' in the Lake Kyoga and Victoria Nile Basins [10, 11]. For southern stations (figures 2(c) and (d)), greater recharge is often realized from the 'long rains' which, on the north shore of Lake Victoria, are typically greater in magnitude than the 'short rains'. Observed differences in the magnitude of groundwater-level fluctuations (figures 2(a)–(d)) arise from not only different recharge fluxes but also spatial variations in aquifer storage properties.

Groundwater levels on the north shore of Lake Victoria (figures 2(c) and (d)) deviated from their annual bimodal cycle in 2004 and declined sharply from their base (dry season) groundwater levels. These reductions in groundwater levels closely followed a steady decrease in the level of Lake Victoria starting in late 2003 (figure 2(e)). The fall in the level of Lake Victoria is attributed to anomalously low rainfall during the 'short rains' of 2003 and water releases at the Nalubaale and Kiira Dams in Jinja (figure 1) that exceeded the long-term dam release policy known as the 'Agreed Curve' [24, 25]. This temporal association between changes in lake levels and groundwater levels proximate to the lake's north shore reflects the interaction between groundwater and surface water in this basin that has recently been confirmed from evidence gained from newly constructed piezometer networks [26].

Changes in regional water storage were estimated from temporal variations in the gravity field measured under the Gravity Recovery and Climate Experiment (GRACE) [27] and compared with monitored groundwater-level variations. The strength of correlations between GRACE estimates of regional changes (300 km Gaussian radius about 33°30′ E, 0°30′ N) in terrestrial water storage (figure 2(d)) and variations in both lake levels ($R^2 = 0.52$) and groundwater levels at Nkokonjero ($R^2 = 0.61$) suggests that the level of Lake Victoria influences groundwater storage in small catchments along its northern boundary (figure 1). At Entebbe, groundwater levels correlate much less well with both lake levels ($R^2 = 0.20$) and regional storage changes ($R^2 = 0.12$). Substantial lag times in the influence of lake-level changes on groundwater levels may arise from the low lakebed conductance between groundwater and Lake Victoria at Entebbe [26]. Groundwater levels in both Nkokonjero and Entebbe monitoring wells rise in advance of the partial rebound in lake levels from late 2006.

4. Rainfall intensity and groundwater recharge

Mean lag times of 11, 5 and 13 days ($\sigma = 4$ days) derived from significant (95% level) cross correlations were detected at Apac, Entebbe and Pallisa, respectively, but not at Nkokonjero. The absence of a relationship at Nkokonjero is attributed, in part, to the noted influence on groundwater levels of the lake level, which is controlled by a regional, rather than local, climatology and operation of the dams at Jinja. Figure 3 and table 2 summarize the results of a linear regression of observed recharge against both ΣP_i and $\Sigma(P_i - 10)$. Gaps of up to a month or more in daily rainfall records limit the number of recharge events (figure 2) considered in our analyses and thereby constrain the robustness of statistical relationships. Nevertheless, for all three stations in the Lake Kyoga and Victoria Nile Basins, we show that the magnitude of recharge is more strongly correlated to $\Sigma(P_i - 10)$ than ΣP_i. Improved co-efficients of determination (R^2) for the correlation of recharge and $\Sigma(P_i - 10)$, relative to ΣP_i, are also associated with a lower root mean square error (*rmse*) between the regression model and observations. The relationship between heavy rainfall and recharge events has also been observed from high-frequency monitoring of shallow groundwater quality in Kampala (figure 1) where episodic deterioration in bacteriological water quality is associated with recharge from heavy rainfall events [20].

Quantitative inferences can be drawn from observed correlations between rainfall and recharge (figure 3). Differences

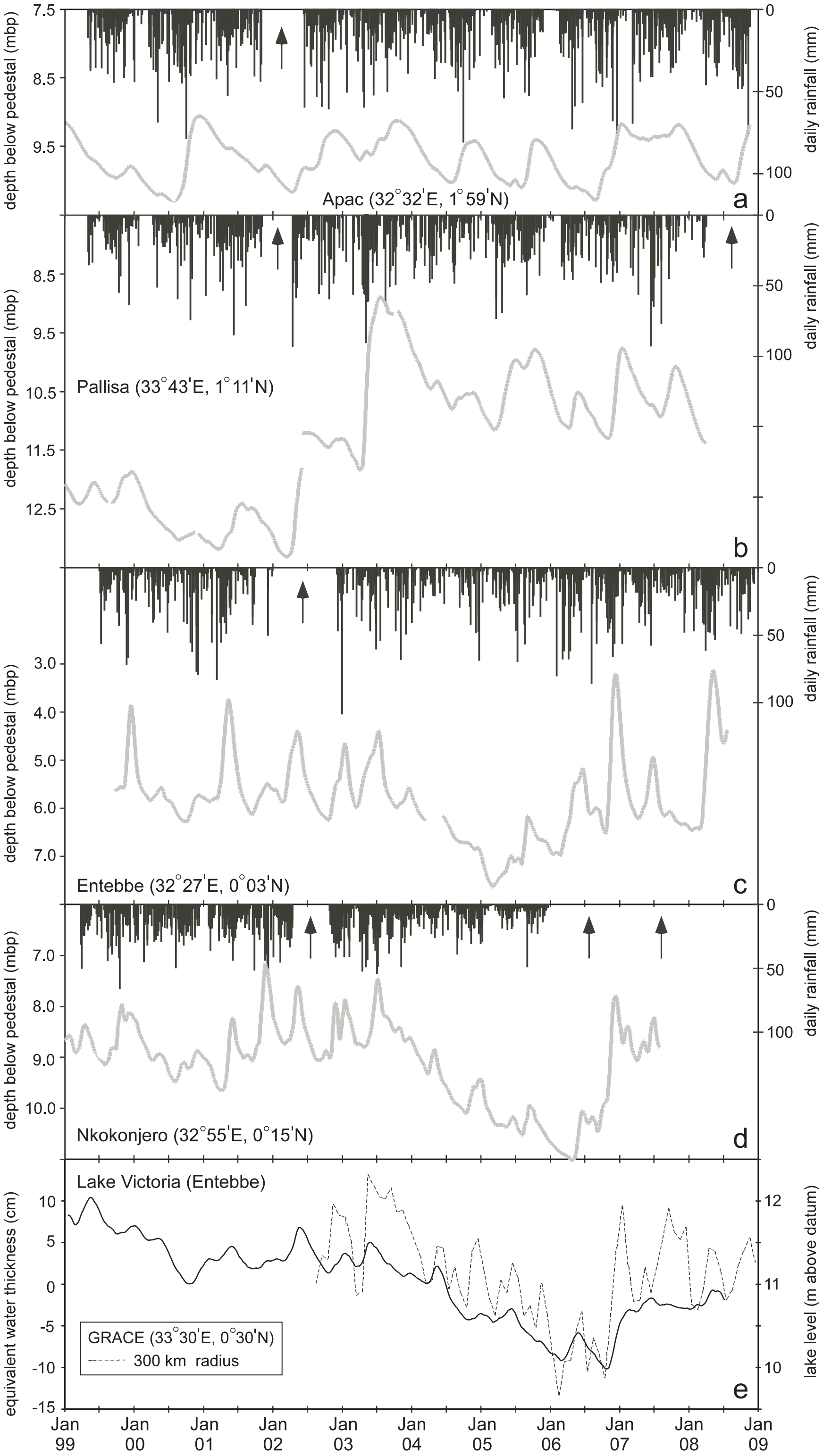

Figure 2. Daily groundwater-level and rainfall observations over the period 1999 to 2008 from (a) Apac and (b) Pallisa in the Victoria Nile and Lake Kyoga Basins, (c) Entebbe and (d) Nkokonjero in the Lake Victoria Basin together with changes in the level of lake Victoria at Entebbe and regional water storage, as an 'equivalent water thickness' (e) indicated by gravity anomalies (GRACE), normalized with respect to monthly means from 2003 to 2008 with Gaussian filter destripped over 300 km [28]. Arrows in plots (a)–(d) indicate gaps in the rainfall record.

in slope, evident from differences axis scales, primarily reflect variations in the storage properties of the monitored aquifer since recharge surface environments (e.g., land cover, relief, soil type) at each station are similar. The lower slope of the correlation between water-level rise (observed recharge) and $\Sigma(P_i - 10)$ at Apac reflects a higher storage co-efficient for

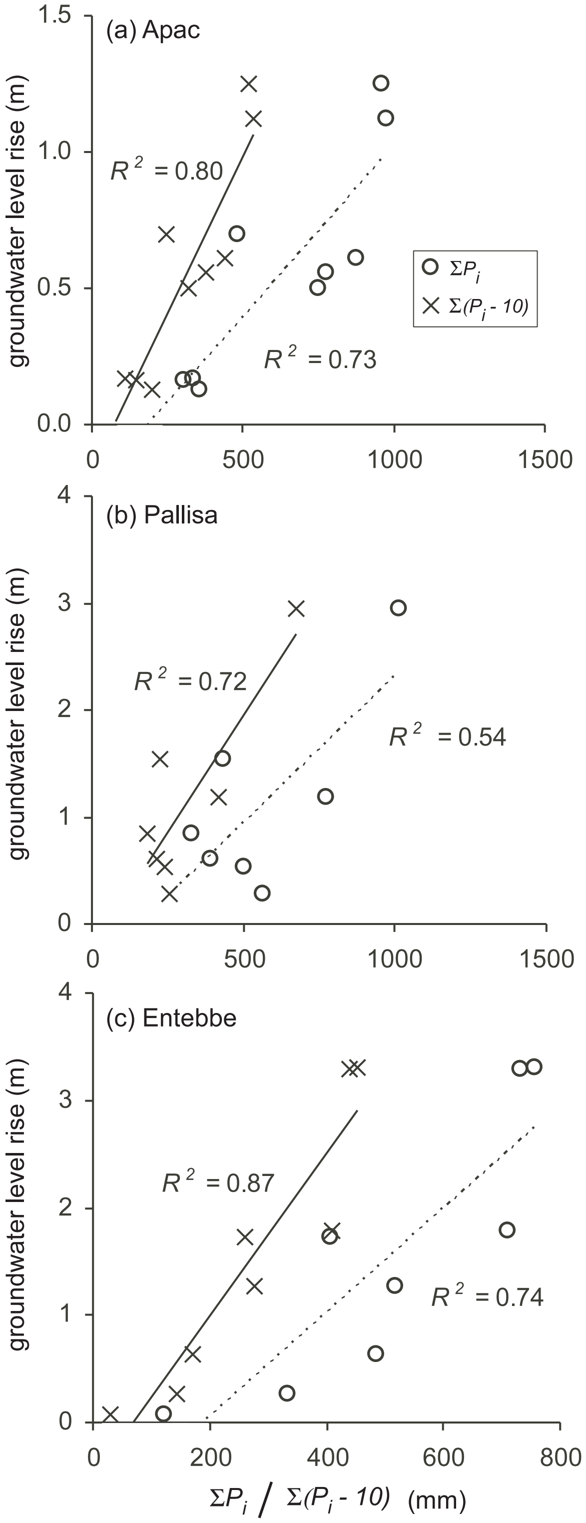

Figure 3. Scatter plots of the relationship between observed recharge events and both daily rainfall (ΣP_i), and daily rainfall exceeding 10 mm day^{-1} ($\Sigma(P_i - 10)$) at (a) Apac, (b) Pallisa, and (c) Entebbe monitoring stations in the Upper Nile Basin. Dashed and solid lines represent the linear regression between observed recharge events and both ΣP_i and $\Sigma(P_i - 10)$ respectively.

the saprolite aquifer [20] compared to the saprock aquifer [29] monitored in Pallisa and Entebbe. The regression of observed recharge and sum of total rainfall (dashed lines) to positive intercepts (158–189 mm) on the x (rainfall) axis in figure 3 supports previous assertions [12] that rainfall exceeding 200 mm in a given year is required for recharge to occur in tropical Africa.

5. Concluding discussion

Using a rare set of coincidental observations of daily rainfall and groundwater levels in a seasonally humid equatorial basin (Upper Nile), we show that the magnitude of groundwater recharge events is better related to the sum of heavy rainfall events exceeding a threshold of 10 mm day^{-1} ($\Sigma(P_i - 10)$) than the sum of daily rainfall (ΣP_i). The limited duration of observations constrains the robustness of observed relationships but our analysis of this rare data set in the tropics is consistent with recent modelling work [8] highlighting the importance of explicitly considering changing rainfall intensities in the assessment of climate change impacts on groundwater recharge. Our results suggest, contrary to previous assertions [7], that a shift to more intensive rainfall may promote rather than restrict groundwater recharge. Substantial uncertainty remains, however, as to whether potential rises in recharge will be offset by increased evapotranspiration associated with warmer atmospheres. Further research that includes enhanced field monitoring is clearly required to refine our understanding of the terrestrial hydrological response to changing rainfall intensities and to inform the simulation of groundwater recharge in the tropics where increases in rainfall intensities are expected to be especially pronounced.

Acknowledgments

Establishment of groundwater-level and rainfall monitoring stations was made possible through investment from DANIDA and the Ministry of Water and Environment (Uganda) under the Water Resources Assessment Project (WRAP). We acknowledge support from the Commonwealth Scholarship Commission (UGCA-2006-141) and the International Foundation for Science (W3428-2) to Owor. Assistance with data collection and analyses from Rashid Kisomoze, Mohammad Shamsudduha and Graham Bradley are greatly appreciated.

References

[1] Allen M R and Ingram W J 2002 Constraints on future changes in climate and the hydrologic cycle *Nature* **419** 224–32
[2] Trenberth K E *et al* 2003 The changing character of precipitation *Bull. Am. Meteorol. Soc.* **84** 1205–17
[3] Pall P, Allen M R and Stone D A 2007 Testing the Clausius–Clapeyron constraint on changes in extreme precipitation under CO_2 warming *Clim. Dyn.* **28** 351–63
[4] Challinor A *et al* 2007 Assessing the vulnerability of food crop systems in Africa to climate change *Clim. Change* **83** 381–99
[5] Shiklomanov I A and Rodda J C 2003 *World Water Resources At the Beginning of the Twenty-First Century* (Cambridge: Cambridge University Press)

[6] Kundzewicz Z W *et al* 2007 Freshwater resources and their management *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contributions of Working Group II to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change* ed M L Parry *et al* (Cambridge: Cambridge University Press) pp 173–210

[7] Döll P and Florke M 2005 Global-scale estimation of diffuse groundwater recharge *Frankfurt Hydrology Paper 03* Institute of Physical Geography, Frankfurt University, Frankfurt AM Main, Germany

[8] Mileham L *et al* 2009 Climate change impacts on the terrestrial hydrology of a humid, equatorial catchment: sensitivity of projections to rainfall intensity *Hydrol. Sci. J.* **54** 727–38

[9] Vogel J C and Van Urk H 1975 Isotopic composition of groundwater in semi-arid regions of southern Africa *J. Hydrol.* **25** 23–6

[10] Taylor R G and Howard K W F 1996 Groundwater recharge in the Victoria Nile basin of East Africa: support for the soil-moisture balance method using stable isotope and flow modelling studies *J. Hydrol.* **180** 31–53

[11] Taylor R G and Howard K W F 1999 The influence of tectonic setting on the hydrological characteristics of deeply weathered terrains: evidence from Uganda *J. Hydrol.* **218** 44–71

[12] Eilers V H M, Carter R C and Rushton K R 2007 A single layer soil water balance model for estimating deep drainage (potential recharge): An application to cropped land in semi-arid North-east Nigeria *Geoderma* **140** 119–31

[13] Mileham L *et al* 2008 Impact of rainfall distribution on the parameterisation of a soil-moisture balance model of groundwater recharge in equatorial Africa *J. Hydrol.* **359** 46–58

[14] Taylor R G and Howard K W F 2000 A tectono-geomorphic model of the hydrogeology of deeply weathered crystalline rock: evidence from Uganda *Hydrogeol. J.* **8** 279–94

[15] Taylor R G, Barrett M H and Tindimugaya C 2004 Urban areas of sub-Saharan Africa weathered crystalline aquifer systems *Urban Groundwater Pollution* (*International Contributions to Hydrogeology* vol 24) ed D N Lerner (Lisse, The Netherlands: A A Balkema) pp 155–79

[16] Tindimugaya C 2008 Groundwater flow and storage in weathered crystalline rock aquifer systems of Uganda: evidence from environmental tracers and aquifer responses to hydraulic stress *PhD Thesis* University College London, London, UK, unpublished

[17] Taylor R G and Howard K W F 1998 Post-palaeozoic evolution of weathered landsurfaces in Uganda by tectonically controlled cycles of deep weathering and stripping *Geomorphology* **25** 173–92

[18] Uganda Government 1967 *Uganda Soils (1:1 500 000) Map*

[19] Drichi P 2003 National Biomass Study *Technical Report 1996–2002* Forest Department, Kampala, Uganda

[20] Taylor R G *et al* 2009 Convergent radial tracing of viral and solute transport in gneiss saprolite *Ground Water* in press doi:10.1111/j.1745-6584.2008.00547.x

[21] Healy R W and Cook P G 2002 Using groundwater levels to estimate recharge *Hydrogeol. J.* **10** 91–109

[22] Lee L J E *et al* 2006 Analysis of water-level response to rainfall and implications for recharge pathways in the Chalk aquifer, SE England *J. Hydrol.* **330** 604–20

[23] Basalirwa C P K 1995 Delineation of Uganda into climatological rainfall zones using the method of principal component analysis *Int. J. Climatol.* **15** 1161–77

[24] Sutcliffe J V and Peterson G 2007 Lake Victoria: derivation of a corrected natural water level series *Hydrol. Sci. J.* **52** 1316–21

[25] Awange J L *et al* 2008 The Falling Lake Victoria water level: GRACE, TRIMM and CHAMP satellite analysis of the Lake Basin *Water Res. Manage.* **22** 775–96

[26] Owor M *et al* Preliminary results on the monitoring of the groundwater—surface water interactions in the Victoria Nile basin of Uganda *Groundwater and Climate in Africa* vol 334, ed R G Taylor *et al* IAHS Publ. in press

[27] Tapley B D *et al* 2004 GRACE measurements of mass variability in the Earth system *Science* **305** 503–5

[28] Chambers D P 2006 Evaluation of new GRACE time-variable gravity data over the ocean *Geophys. Res. Lett.* **33** L17603

[29] Howard K W F and Karundu J 1992 Constraints on the development of basement aquifers in east Africa—water balance implications and the role of the regolith *J. Hydrol.* **139** 183–96