

Groundwater and climate in Africa—a review

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INTRODUCTION

Current assessments of the impacts of historical and projected climate variability and change on water resources commonly exclude groundwater. This omission is of particular concern in Africa, where current usage and future adaptations in response to climate change and rapid population growth place considerable reliance upon groundwater to meet domestic, agricultural and industrial water demands. The *Groundwater and Climate in Africa* Conference (<http://www.gwclim.org/>), held in Kampala, Uganda on 24–28 June 2008, is the first conference in Africa and one of the first globally to focus on the interactions between groundwater and climate variability and change. The conference was organised by the Ministry of Water and Environment (Uganda), University College London (UK) and UNESCO-IHP in order to enable water and climate scientists and policy makers to share knowledge and expertise and thereby improve current understanding of the impact of climate and development on groundwater resources in Africa. The conference featured 96 presentations and was attended by more than 300 water and climate scientists and policy makers from 37 countries, including 23 countries in Africa. This Special Issue of *Hydrological Sciences Journal* comprises a selection of 11 papers whose initial versions were delivered at the conference. Many of the remaining contributions will appear in a forthcoming volume of the IAHS Series of Proceedings and Reports; key policy-relevant outcomes from the conference are summarised in the “Kampala Statement” available from the conference website. Here, we review strategic research issues pertaining to groundwater and climate in Africa, and highlight contributions from the conference.

FRESHWATER AVAILABILITY IN AFRICA

Africa is currently home to nearly a billion (10^9) people. With the highest national rates of population growth (1.6–3.1% per year) in the world (UN, 2007; Carter & Parker, 2009), the continent's population is predicted to grow by more than half billion by 2050. Increased demand for freshwater associated with these trends is expected to be especially intense in rapidly urbanising regions (Taylor *et al.*, 2004) and in the agricultural sector in order to boost food production (Carter & Parker, 2009; MacDonald *et al.*, 2009). In its Fourth Assessment Report, the Intergovernmental Panel for Climate Change (IPCC) projects that Africa will be disproportionately affected by climate change; projected warming in Africa is 1.5 times the global mean (Christensen *et al.*, 2007). Despite general consistency in temperature projections among different general circulation models (GCMs) and emission scenarios, substantial uncertainty remains in the projections themselves and in how preferential warming in Africa will affect the availability of freshwater through changes in precipitation and terrestrial water balances (see section on uncertainty below).

Covering an area of just over 30 million km², Africa is roughly three times the size of Europe and features very diverse hydrological systems. Climates include humid equatorial, seasonally

humid, semi-arid, arid and sub-tropical Mediterranean. The land surface features cropland, scrubland and savannah environments, as well as lowland and montane forests, and deserts. Projected changes in land cover are dominated by the conversion of forest to cropland and increased urbanisation (FAO, 2001). The sub-surface environment in Africa consists primarily of low-transmissivity weathered basement rocks and mudstones (MacDonald *et al.*, 2009), as well as large sedimentary basins primarily in semi-arid and arid regions comprising sandstones and limestones that include some of the largest freshwater reserves in the world (Edmunds, 2009; Scheumann & Alker, 2009). A key characteristic affecting all hydrological systems in Africa is a dearth of observations, particularly in relation to sustained time series data.

Limited observational data in Africa give rise to considerable uncertainty in broad, continental statistics of freshwater availability and withdrawals. Total renewable freshwater resources have been estimated at between 4050 and 4065 km³ year⁻¹ (Shiklomanov, 2000; Döll & Fiedler, 2008) to 4590 km³ year⁻¹ (Braune & Xu, 2009). Although freshwater withdrawals in Africa are considered to represent only a very small proportion (5%) of renewable (annual) freshwater resources (Braune & Xu, 2009), this assertion is supported by very few data and conceals substantial intra-annual variability in freshwater availability (discussed below). As the world's largest accessible store of freshwater, groundwater is often considered a logical resource to turn to when confronted by water shortages associated with low and variable river discharges (Goulden *et al.*, 2009; Kundzewicz & Döll, 2009). Groundwater may also be the only sustained source of water to communities where surface waters are absent. Groundwater is, furthermore, often of potable quality and, thus, does not require expensive treatment, and permits scaled development (upon demand) using infrastructure that is normally of lower cost relative to surface water fed supplies. The generally slow rate of groundwater movement and the storage of aquifers are innate advantages of groundwater resources that make them more resilient to climate variations (including temperature, which impacts water quality) than surface water resources. However, the sustainability of adaptation strategies employing groundwater to alleviate water scarcity brought about by increased demand or climate variability or change is unclear. Uncertainty in the fraction of renewable freshwater resources in Africa that occur as groundwater ranges from 15% (Braune & Xu, 2009; Goulden *et al.*, 2009) to 51% (Döll & Fiedler, 2008). Even estimates of the proportion of the African population that currently depends upon groundwater as its primary source of drinking water, vary from ~50% (Carter & Parker, 2009) to 75% (Goulden *et al.*, 2009).

HYDROCLIMATOLOGICAL VARIABILITY IN AFRICA

Rainfall variability in Africa is high; 95% of annual rainfall totals deviate between 20 and 40% from the mean (Carter & Parker, 2009). Highest absolute variations occur during the wettest months when the contribution of net (P – ET) precipitation (i.e. the proportion of precipitation that produces runoff and groundwater recharge) to the land surface is highest. This variability in African rainfall not only influences freshwater demand but also gives rise to substantial inter-annual and seasonal variability in river discharge (Mahé, 2009). Based on a global survey of 729 river discharge records, McMahon *et al.* (2007) found that annual river discharges in southern Africa demonstrate the highest median coefficient of variation (0.82) of any region in the world, which is substantially greater than the global median coefficient of variation of 0.31. Southern Africa also featured the lowest median annual specific (river) discharge (77 mm), considerably lower than the global average of 354 mm.

The relationship between Africa's highly variable hydroclimatology and groundwater resources is unclear. Although an improved understanding of this relationship is strongly constrained by limited observational data sets (Carter & Parker, 2009; Howard & Griffith, 2009; MacDonald *et al.*, 2009), a nascent but developing knowledge of the interactions between climate and groundwater is emerging and exemplified by contributions to this Special Issue (Mahé, 2009; Mileham *et al.*, 2009; Nyenje & Batelaan, 2009; Olago *et al.*, 2009; Walraevens *et al.*, 2009;).

Strong relationships are observed between negative rainfall anomalies and declining groundwater recharge in the River Niger Basin (Mahé, 2009) and reduced baseflow discharges in the Central Kenyan Rift (Olago *et al.*, 2009). Mahé (2009) shows further that falling water tables in West Africa produce declines in river discharge that are more pronounced than suggested by decreases in rainfall alone. From recent (but few) high-frequency observations in a small catchment in the Ethiopian Highlands, Walraevens *et al.* (2009) provide evidence that monsoonal recharge sustains seepages and spring discharges during the dry season but does not permit inter-annual groundwater storage due to the restricted area and depth of mountain aquifers.

Due to the noted variability in African hydrological systems, inter- and intra-annual contributions of freshwater from storage can be used to strengthen the sustainability of water supplies and maintenance of aquatic ecosystems (Howard & Griffiths, 2009). As recognised in semi-arid and arid environments of Africa (e.g. Eilers *et al.*, 2007; Edmunds, 2009; Olago *et al.*, 2009), rainfall-fed recharge can occur episodically, perhaps in a few years each decade. Considerable inter-annual variability in recharge fluxes has also been estimated and observed in the humid tropics of Africa (e.g. Taylor & Howard, 1999; Mileham *et al.*, 2008). From a water management perspective, balancing highly variable and episodic recharge with groundwater withdrawals over decadal rather than annual time scales would likely prove more instructive but there are currently few long-term studies of recharge in Africa to inform such an approach. Whereas robust evidence has been developed in parts of Africa to explain inter-annual controls on hydrological variability (e.g. Ogallo *et al.*, 1988; Mistry & Conway, 2003; Schreck & Semazzi 2004; Black, 2005), understanding of controls on multi-annual climate variability in Africa (e.g. Sahelian drought) is much less developed. Such controls are, however, expected to determine more forcefully freshwater availability from groundwater resources and in many instances, river discharges (Mahé, 2009). A quantitative understanding of the relationship between climate and groundwater, and the impact of abstraction is severely constrained by the near absence or very few reliable estimates of groundwater storage in Africa whether aquifers are of regional (e.g. Nubian Sandstone Aquifer system) or localised (e.g. saprolite) extent (Taylor *et al.*, 2009). Detection of recent changes in total freshwater storage via the Gravity Recovery and Climate Experiment (GRACE), begun in 2003, has been demonstrated for large basins such as the Congo (Crowley *et al.*, 2006) and Zambesi (Winsemius *et al.*, 2006). However, despite recent advances (Zaitchik *et al.*, 2008), major technical challenges remain in using GRACE data to resolve water storage from groundwater and soil moisture that are able to inform water management and policy.

The chemistry of groundwater within large sedimentary basins with long, well defined flowpaths in semi-arid and arid regions provides an archive of climate variations since the Late Pleistocene (Edmunds & Wright, 1979; Heaton *et al.*, 1986; Guendouz *et al.*, 2003; Rueedi *et al.*, 2005). Inert tracers such as stable isotope ratios ($^{18}\text{O}/^{16}\text{O}$, $^2\text{H}/^1\text{H}$) and noble gases (He) retain information on recharge conditions and thus hydroclimatological changes over time, whereas radiocarbon dating establishes the chronology of these changes. As reviewed by Edmunds (2009), these records reveal that groundwater was largely recharged prior to the Last Glacial Maximum (LGM) in northeastern Africa. An absence of recharge during the LGM reflects aridity which was followed by wetter Holocene climates that sustained river discharge until ~4000 years BP. Today, channels support ephemeral flows in wadis. In contrast, there has been relatively constant recharge over the last 35 000 years BP in the Sahel. Abundant recharge during the Late Pleistocene was followed by aridity during the LGM and then episodic recharge through the Holocene to the Anthropocene.

UNCERTAINTY IN PROJECTIONS OF HYDROLOGICAL CHANGE

Fundamental to assessments of the impacts of climate change on water resources is a quantitative understanding of uncertainty inherent in climate projections generated by GCMs. This important fact is often missed and studies of climate impacts on water resources in Africa (e.g. Kamga, 2001;

Legesse *et al.*, 2006; Messenger *et al.*, 2006), including those in this Special Issue (e.g. Nyenje & Batelaan, 2009), are no exception. For these studies, future climate projections of GCMs are assigned the character of a *reliable forecast*, instead of “*plausible projections of possible futures*” (Kundzewicz *et al.*, 2009). Projected climatic forcing is used to drive hydrological models and the results are subsequently interpreted and used to inform adaptation policies for water resources without assessing the uncertainty associated with the climate projections and the corresponding hydrological response.¹ A “worst” case, if such a case can be defined, is no substitute for a measure of probability.

An in-depth discussion about the uncertainty in the projected climatic forcing and of its propagation to the status of water resources is overdue despite recent advances in this area (New *et al.*, 2007; Vrugt & Robinson, 2007; Vrugt *et al.*, 2008a,b; Lopez *et al.*, 2009). The Technical Report VI of the IPCC, *Climate Change and Water* (Bates *et al.*, 2008), devotes surprisingly little space—about a single page in a total of 210 pages—to the discussion of uncertainty (Box 1.1, on p. 11, and part of subsection 8.2, pp. 135–136). The IPCC gauges uncertainty based on ensembles of projections generated by different GCMs yet this approach has been criticised as lacking mathematical rigour because the probability density function is not conditioned on measured values of the variables (Rougier, 2007). A sharper awareness of the necessity to assess uncertainty in all work related to climate change would improve its credibility. The recent debate between Koutsoyiannis *et al.* (2009) and Kundzewicz *et al.* (2008, 2009) is a step towards remedying that situation.

The undertaking is problematic not only because of long projection timeframes, often decades into the future, and of the breadth of the assumed socio-economic scenarios, but also because water and climate interact (which is but one indication of modelling complexity). We are thus not facing the “simple” uncertainty, for instance, of a short-term weather prediction for flood forecasting in which the weather–water feedback may be safely ignored, implying a unidirectional cause-and-effect relationship between meteo-forcing and hydro-response. Of particular concern to water resources management is the uncertainty of the projected precipitation (admittedly much greater than that of future temperature) at scales below the spatial GCM resolution ($\sim 10^5$ km²) as GCMs “*give a broad, large-scale view of the evolution of global climate*” (Kundzewicz *et al.*, 2009). Therefore, to study the impact of climate change on the management of water resources, the projected precipitation, the principal hydrological forcing, must be commonly downscaled to a basin area of less than 10^5 km². Downscaling, in essence, filters (statistically or dynamically) the uncertain projected data, adding to the uncertainty surrounding the model results. Kundzewicz *et al.* (2009) state, “*quantitative projections in river flow at the basin scale remain largely uncertain*”. Estimating the impact of the climate on the groundwater recharge in a basin is an example of uncertainty propagation, as the recharge is derived from the basin’s hydrological balance, which involves the projected precipitation and the modelled evapotranspiration, surface runoff, infiltration and storages under a changed climate. Uncertainty also derives from land-use changes due to a rapidly evolving demographic and economic environment (both also altering water demand) that modify the physical behaviour of the basin’s surface through changes in its albedo and flow characteristics.

One critical downscaling problem—that of converting monthly to daily rainfall—demonstrates the propagation of uncertainty in projections of recharge in Africa very clearly. As warming amplifies the water-holding capacity of the atmosphere defined by the Clausius-Clapeyron relationship climate change is projected to increase the frequency of very heavy rainfall events (i.e. those in the uppermost quantiles of the rainfall distribution) (Allen & Ingram, 2002; Trenberth *et al.*, 2003; Pall *et al.*, 2007). In the tropics, where warmer air temperatures will lead to larger absolute rises in the moisture content of the atmosphere, increases in rainfall intensities are

¹ Recent, comprehensive analyses of the impact of uncertainty in GCM structure, greenhouse gas emissions, and hydrological model parameterisation on basin-scale hydrological projections in Africa (QUEST-GSI, 2009) provide inconclusive results regarding the magnitude and direction of climate change impacts on monthly river discharge and groundwater recharge.

expected to be especially pronounced. However, recent projections of substantial reductions in recharge in southwestern and northern North Africa (Döll & Flörke, 2005, cited in IPCC AR4: Kundzewicz *et al.*, 2007) fail to account for projected changes in rainfall distributions (Kundzewicz & Döll, 2009). This failure can misrepresent the direction and magnitude of the climate change signal. As demonstrated in a humid equatorial catchment in southwestern Uganda (Mileham *et al.*, 2009), recharge is projected to decrease by 55% under the A2 emissions scenario using the historical (baseline) rainfall distribution, whereas transformation of the rainfall distribution to account for projected increases in rainfall intensity projects a 53% increase in recharge. The implied relationship between heavy rainfall events and the magnitude of recharge in tropical Africa is supported by mounting empirical evidence. Several studies (Taylor & Howard, 1996; Eilers *et al.*, 2007; Owor *et al.*, 2009) show that the sum of heavy rainfall events exceeding a threshold of 10 mm d⁻¹ is better related to the recharge flux than the sum of all daily rainfall events. Episodic deterioration in shallow groundwater quality in Kampala (Uganda) is observed to coincide with heavy rainfall events which produce recharge contaminated by faecal pathogens flushed locally from areas of inadequate community hygiene (Taylor *et al.*, 2009).

GROUNDWATER AND ADAPTATION

On account of substantial uncertainty in projections of hydrological change, Goulden *et al.* (2009) argue that adaptation strategies to water shortages should reduce dependence upon climate projections and focus on plausible futures. Over the next few decades in many parts of Africa, changes in water demand, associated primarily with population growth, are projected to contribute more substantially to imbalances between freshwater availability and demand than climate change (Vörösmarty *et al.*, 2005; Carter & Parker, 2009). However, analyses of the spatio-temporal impacts of development and hydrological change on water scarcity are hindered by current metrics, such as the water stress index (Falkenmark *et al.*, 1989) and relative water demand (Vörösmarty *et al.*, 2005), that are based on mean annual river flow (runoff). These metrics disregard freshwater storage (e.g. groundwater, soil moisture) and systematically misrepresent freshwater availability and demand in sub-Saharan Africa (Taylor, 2009). This is well demonstrated in the production of food.

Globally, the agricultural sector accounts for ~70% of all freshwater withdrawals (~5000 km³ year⁻¹). In sub-Saharan Africa, freshwater withdrawals for agriculture are much less than in Asia, Europe and North America, as <5% of the arable land is under irrigation (Giordano, 2005). Soil water sustains almost all food production but is excluded from measures of freshwater availability based on river flow. In addition, estimates of freshwater demand assume annual withdrawals for irrigated agriculture (and industry) which are 20 times that required for domestic water use. Consequently, current metrics of water scarcity serve to underestimate freshwater availability and inflate freshwater demand in sub-Saharan Africa. It does not follow that water scarcity is necessarily exaggerated in Africa but simply that current metrics do not adequately represent its spatial and temporal dimensions.

Current metrics are also insensitive to projected hydrological change. The projected increase in rainfall intensities as a result of global warming will give rise to more variable (but not necessarily less) river discharge 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 (e.g. Challinor *et al.*, 2007). However, current evidence, highlighted above, suggests that the shift toward more intensive precipitation enhances groundwater recharge. As a result, groundwater in many parts of sub-Saharan Africa can play a strategic role in adapting to changing freshwater availability and improving food production and security through groundwater-fed irrigation (Carter & Parker, 2009; MacDonald *et al.*, 2009). Since small-scale farming accounts for 70% of agricultural production in sub-Saharan Africa (Runge *et al.*, 2004), discrete low-yielding aquifers in weathered crystalline rock and mudstones that underlie more than 50% of

sub-Saharan Africa may prove “fit for purpose” as they are self-regulating, naturally restricting the impacts of local overdevelopment and solving the age-old problem of allocation.

There is a long history of low-intensity groundwater development (e.g. hand-pump abstraction) for domestic rural water supplies in Africa. Low recharge fluxes ($<10 \text{ mm year}^{-1}$) required to sustain such development (Taylor & Howard, 1996; MacDonald *et al.*, 2009), are expected to occur in regions where rainfall exceeds 200 mm year^{-1} (Edmunds, 2009; Owor *et al.*, 2009). In humid regions, there is little evidence of regional water-level decline from such low-intensity abstraction; localised depletion is often due to anomalous geological conditions or faulty infrastructure rather than broad-scale resource depletion. In many arid and semi-arid areas of Africa, however, it must be recognised that substantial recharge has not occurred in modern times so that groundwater resources are essentially non-renewable (Edmunds, 2009).

Intensive development of groundwater for domestic water supplies in Africa began primarily over the second half of the 20th century in association with urbanisation. Groundwater is a common low-cost alternative to surface water for urban water supplies as it is widely distributed and is generally of potable quality, thereby avoiding the expense and management of sophisticated treatment systems. However, despite growing dependency upon groundwater for urban water supplies (Taylor *et al.*, 2004; Mileham *et al.*, 2008; Braune & Xu, 2009), concerns remain over the sustainability of these supplies, in terms not only of the magnitude of abstraction but also their quality. Sub-Saharan Africa is the most rapidly urbanising region in the world with a projected tripling of urban populations from 2000 to 2050 (UN, 2007). This rate of growth presents substantial challenges to the provision of not only safe water supplies but also sanitation (Carter & Parker, 2009; MacDonald *et al.*, 2009). First, few reliable groundwater data exist upon which abstraction policies can be based (MacDonald *et al.*, 2009). Indeed, there has been comparatively limited investment in monitoring infrastructure for groundwater resources relative to surface water resources. Recent research from two well instrumented sites in Uganda highlights the importance of aquifer storage at the borehole catchment scale in determining the sustainability of intensive abstraction for town water supplies (Tindimugaya, 2008). Second, inadequate community hygiene in many rapidly urbanising centres makes urban water supplies derived from shallow groundwater increasingly vulnerable to contamination (Howard *et al.*, 2003). For coastal aquifers (e.g. Senegal, the Niger and Nile deltas), there is the added threat to the quality of abstracted groundwater posed by projected sea-level rise which will decrease the depth (thickness) of the freshwater lens through seawater intrusion (Kundzewicz & Döll, 2009).

At national to regional scales, limited technical and institutional capacities constrain development of groundwater-based solutions to increasing freshwater demand and declining freshwater availability in Africa. Since major gaps exist in current knowledge of groundwater resources in Africa and their relationship to climate variability and change, major investments are required in programmes of applied, interdisciplinary research. As demand for expertise in hydrogeology and climatology rises with increasing groundwater use in Africa, similar investment is also required in training and capacity building in hydrogeology, climatology and allied fields in water policy and management. Such efforts need to recognise that considerable time lags can occur between changes in groundwater resources and their impact on surface water resources (Howard & Griffith, 2009; Scheumann & Alker, 2009), and these complicate integrated water resources management including issues around “cause and effect”.

An added challenge to the development of effective institutions to manage groundwater-based solutions to water scarcity is the transboundary nature of groundwater resources in Africa. Scheumann & Alker (2009) identify 40 transboundary aquifer systems and observe that unilateral, national development and management of these resources currently predominates. This problem is not helped by the fact that surface water catchments are used to define membership to international basin commissions (e.g. the Lake Chad Basin Commission), yet discrepancies exist between surface water and groundwater basins. In light of the often interconnected nature of ground- and surface-water resources, one country's adaptation may impair another country's ability to adapt. For example, international conflict could arise over groundwater use from an aquifer that is not

strictly transboundary—groundwater abstraction that denies baseflow to a river crossing an international boundary.

FINAL REMARKS

This Special Issue represents well the current knowledge of the relationship between groundwater and climate in Africa, and the potential role of groundwater in adapting to both changes in demography and climate over the coming decades. Each contribution provides important new insight into the limitations of this knowledge base, as well as the technical and institutional challenges of improving current understanding. Few offer clear answers. Indeed, a continuing, dominant constraint to an improved knowledge is the limited spatial and temporal coverage of hydrogeological and hydrometeorological observations. Nevertheless, existing data sets show that hydrological variability in Africa is higher than in any other region on the planet. Improving existing capacity to adapt to climate variability in Africa will go a long way to enabling societies in many regions to adapt to climate change.

Often lost in current debates surrounding adaptation to climate change (and this Special Issue is no exception) is the considerable uncertainty associated with current projections of climate change—commonly many decades into the future. Future research on water resources and climate change needs to focus on shorter time scales and consider uncertainty explicitly, providing quantitative probability measures properly conditioned on measured values of the variables. There are compelling arguments that measures for adapting to climate change should reduce their reliance on climate projections and focus on a range of plausible futures (Carter & Parker, 2009; Goulden *et al.*, 2009). Projected impacts of substantial demographic changes on freshwater demand and availability overshadow the impacts of climate change on the availability and, to a lesser extent, the demand for freshwater. High rates of population growth and even higher rates of urbanisation not only increase freshwater demand for domestic and agricultural uses but also threaten the quality of available resources and the maintenance of groundwater-dependent ecosystems.

As highlighted by several contributions to this Special Issue, groundwater is well placed to enable communities to adapt to changes in freshwater demand and availability in many parts of Africa, but substantial uncertainty remains around the development and management of groundwater-based solutions. For example, expansion of small-scale, groundwater-fed irrigation in sub-Saharan Africa could drastically enhance food production and food security, but development and management strategies to avert long-term aquifer depletion associated with the rise in irrigated land in Asia (Keller *et al.*, 2000; Konikow & Kendy, 2005) and the USA (McGuire, 2007) have yet to be advanced. Financial mechanisms to enable the implementation of adaptation strategies have also yet to be developed.

The *Groundwater and Climate in Africa* Conference was organised to stimulate discussion and debate regarding the implications of demographic and hydroclimatological change on groundwater resources in Africa as, for too long, debate has been dominated by discussions by a small group of individuals outside of Africa. In addition to vital informal networking of scientists and policy makers in Africa, and issuance of the *Kampala Statement* (<http://www.gwclim.org/>) outlining policy recommendations derived from conference discussions, the *Groundwater and Climate in Africa* Conference witnessed the establishment of the UNESCO-IHP GRAPHIC (Groundwater Resources Assessment under the Pressures of Humanity and Climate Change) programme in Africa; meetings of the IAH (International Association of Hydrogeologists) Burdon Network of Hydrogeologists in sub-Saharan Africa; and the newly-established Africa Ground Water Commission under the AMCOW (African Ministerial Committee on Water).

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REFERENCES

- Allen, M. R. & Ingram, W. J. (2002) Constraints on future changes in climate and the hydrologic cycle. *Nature* **419**, 224–232.
- Bates, B. C., Kundzewicz, Z. W., Wu, S. & Palutikof, J. P. (eds) (2008) *Climate Change and Water*. Technical Paper of the Intergovernmental Panel for Climate Change, IPCC Secretariat, Geneva, Switzerland.
- Black, E. (2005) The relationship between Indian ocean sea-surface temperature and east African rainfall. *Phil. Trans. Royal Soc. London A* **363**(1826), 43–47.
- Braune, E. & Xu, Y. (2009) The role of ground water in sub-Saharan Africa. *Ground Water* (in press).
- Carter, R. C. & Parker, A. (2009) Climate change, population trends and groundwater in Africa. *Hydrol. Sci. J.* **54**(4), 676–689 (this issue).
- Challinor, A., Wheeler, T., Garforth, C., Craufurd, C. & Kassam, A. (2007) Assessing the vulnerability of food crop systems in Africa to climate change. *Climate Change* **83**, 381–399.
- Christensen, J. H., Hewitson, B., Busiuc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R. K., Kwon, W. -T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C. J., Räisänen, J., Rinke, A., Sarr, A. & Whetton, P. (2007) Regional climate projections. *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor & H. L. Miller). Cambridge University Press, Cambridge, UK.
- Crowley, J. W., Mitrovica, J. X., Bailey, R. C., Tamisiea, M. E. & Davis, J. L. (2006) Land water storage within the Congo Basin inferred from GRACE satellite gravity data. *Geophys. Res. Lett.* **33**, L19402.
- Döll, P. & Fiedler, M. (2008) Global-scale modelling of groundwater recharge. *Hydrol. Earth System Sci.* **12**(3), 863–885.
- Edmunds, W. M. E. (2009) Palaeoclimate and groundwater evolution in Africa—implications for adaptation and management. *Hydrol. Sci. J.* **54**, 781–792 (this issue).
- Edmunds, W. M. E. & Wright, E. P. (1979) Groundwater recharge and palaeoclimate in the Sirte and Kufra basins, Libya. *J. Hydrol.* **40**, 215–241.
- Eilers, V. H. M., Carter, R. C. & 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**, 119–131.
- Falkenmark, M., Lundqvist, J. & Widstrand, C. (1989) Macro-scale water scarcity requires micro-scale approaches: aspects of vulnerability in semi-arid development. *Nat. Resour. Forum* **13**, 258–267.
- FAO (Food and Agricultural Organisation of the United Nations) (2001) Global forest resources assessment 2000. FAO Forest Paper 140, Rome, Italy.
- Giordano, M. (2006) Agricultural groundwater use and rural livelihoods in sub-Saharan Africa: a first-cut assessment. *Hydrogeol. J.* **14**, 310–318.
- Goulden, M., Conway, D. & Persechino, A. (2009) Adaptation to climate change in international river basins in Africa: a review. *Hydrol. Sci. J.* **54** (in press).
- Guendouz, A., Moulla, A. S., Edmunds, W. M. E., Zouari, K., Shand, P. & Marmou, A. (2003) Hydrogeochemical and isotopic evolution of water in the Complexe Terminal aquifer of the Algerian Sahara. *Hydrogeol. J.* **11**, 483–495.
- Heaton, T. H. E., Talma, A. S. & Vogel, J. C. (1986) Dissolved gas palaeotemperatures and ¹⁸O variations derived from groundwater near Uitenhage, South Africa. *Quatern. Res.* **37**, 203–213.
- Howard, G., Pedley, S., Barrett, M. H., Nalubega, M. & Johal, K. (2003) Risk factors contributing to microbiological contamination of shallow groundwater in Kampala, Uganda. *Water Res.* **37**, 3421–3429.
- Howard, K. & Griffith, A. (2009) Can the impacts of climate change on groundwater reserves be studied without the use of transient models? *Hydrol. Sci. J.* **54**(4), 754–764 (this issue).
- Kamga, F. (2001) Impact of greenhouse gas induced climate change on the runoff of the Benue River. *J. Hydrol.* **252**, 145–156.
- Keller, A., Sakthivadivel, R. & Seckler, D. (2000) Water scarcity and the role of storage in development. Res. Report 39, International Water Management Institute, Colombo, Sri Lanka.
- Konikow, L. F. & Kendy, E. (2005) Groundwater depletion: a global problem. *Hydrogeol. J.* **13**, 317–320.
- Koutsoyannis, D., Montanari, A., Lins, H. F. & Cohn, T. A. (2009) Climate, hydrology and freshwater: towards an interactive incorporation of hydrological experience into climate research. Discussion of “The implications of projected climate change for freshwater resources and their management” by Kundzewicz et al. (2008). *Hydrol. Sci. J.* **54**(2), 394–405.
- Kundzewicz, Z. W. & Döll, P. (2009) Will groundwater ease freshwater stress under climate change? *Hydrol. Sci. J.* **54**(4), 665–675 (this issue).
- Kundzewicz, Z. W., Mata, L. J., Arnell, N., Döll, P., Kabat, P., Jiménez, B., Miller, K., Oki, T., Şen, Z. & Shiklomanov, I. (2007) Freshwater resources and their management. *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (ed. by M. L. Parry, O. F. Canziani, J. P. Palutikof, C. E. Hanson & P. J. van der Linden). Cambridge University Press, Cambridge, UK.
- Kundzewicz, Z. W., Mata, L. J., Arnell, N., Döll, P., Jiménez, B., Miller, K., Oki, T., Şen, Z. & Shiklomanov, I. (2008) The implications of projected climate change for freshwater resources and their management. *Hydrol. Sci. J.* **53**(1), 3–10.
- Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döll, P., Jimenez, B., Miller, K., Oki, T. & Şen, Z. (2009) Water and climate projections. Reply to “Climate, hydrology and freshwater: towards an interactive incorporation of hydrological experience into climate research” by Koutsoyannis et al. (2009). *Hydrol. Sci. J.* **54**(2), 406–415.

- Legesse, D., Vallet-Coulomb, C. & Gasse, F. (2006) Hydrological response of a catchment to climate and land use changes in tropical Africa: case study from south-central Ethiopia. *J. Hydrol.* **275**, 67–85.
- Lopez, A., Fung, F. & New, M. (2009) From climate model ensembles to climate change impacts: a case study of water resource management in the south west of England. *Water Resour. Res.* (in press).
- MacDonald, A. M., Calow, R. C., MacDonald, D. M., Darling, G. W. & Dochartaigh, B. E. O. (2009) What impact will climate change have on rural groundwater supplies in Africa? *Hydrol. Sci. J.* **54**(4), 690–703 (*this issue*).
- Mahé, G. (2009) Surface/groundwater interactions in the Bani and Nakambe rivers, tributaries of the Niger and Volta river basins, West Africa. *Hydrol. Sci. J.* **54**(4), 704–712 (*this issue*).
- McGuire, V. L. (2007) Changes in water level and storage in the High Plains aquifer, predevelopment to 2005. *US Geol. Survey Fact Sheet 2007–3029*.
- McMahon, T. A., Vogel, R. M., Pegram, G. G. S., Peel, M. C. & Etkin, D. (2007) Global streamflows, Part 2: Reservoir storage—yield performance. *J. Hydrol.* **347**, 260–271.
- Message, C., Gallee, H., Brasseur, O., Cappelare, B., Peugeot, C., Seguis, L., Vauclin, M., Ramel, R., Grasseau, G., Leger, L. & Girou, D. (2006) Influence of RCM-simulated precipitation on the water discharge over the Sirba basin, Burkina Faso/Niger. *Climate Dynamics* **27**, 199–214.
- Mileham, L., Taylor, R. G., Thompson, J., Todd, M. & Tindimugaya, C. (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.
- Mileham, L., Taylor, R. G., Todd, M., Tindimugaya, C. & Thompson, J. (2009) The impact of climate change on groundwater recharge and runoff in a humid, equatorial catchment: sensitivity of projections to rainfall intensity. *Hydrol. Sci. J.* **54**(4), 727–738 (*this issue*).
- Mistry, V. & Conway, D. (2003) Remote forcing of east African rainfall and relationships with fluctuations in levels of Lake Victoria. *Int. J. Climatol.* **23**, 67–89.
- New, M., Lopez, A., Dessai, S. & Wilby, R. (2007) Challenges in using probabilistic climate change information for impact assessments: an example from the water sector. *Phil. Trans. Roy. Soc. A* **365**, 2117–2131.
- Nyenje, P. M. & Batelaan, O. (2009) Estimating the effects of climate change on groundwater recharge and baseflow in the upper Ssezibwa catchment, Uganda. *Hydrol. Sci. J.* **54**(4), 713–726 (*this issue*).
- Ogalo, L. J., Janowiak, J. E. & Halpert, M. S. (1988) Teleconnection between seasonal rainfall over East Africa and global sea surface temperature anomalies. *J. Met. Soc. Japan* **66**, 807–821.
- Olago, D., Opere, A. & Barongo, J. (2009) Holocene palaeohydrology, groundwater and climate change in the lake basins of the Central Kenya Rift. *Hydrol. Sci. J.* **54**(4), 765–780 (*this issue*).
- Owor, M., Taylor, R. G., Tindimugaya, C. & Mwesigwa, D. (2009) Rainfall intensity and groundwater recharge: evidence from the Upper Nile Basin. *Environ. Res. Lett.* (in review).
- Pall, P., Allen, M. R. & Stone, D. A. (2007) Testing the Clausius-Clapeyron constraint on changes in extreme precipitation under CO₂ warming. *Climate Dynamics* **28**, 351–363.
- QUEST-GSI (2009) Water Resources Workshop of the NERC QUEST-GSI (Global Scale Impacts of Climate Change), 30 March–3 April 2009, <http://www.geog.ucl.ac.uk/research/environmental-modelling/climate-water-research-unit/quest-gsi/quest-gsi-water-resources-workshop>.
- Rougier, J. (2007) Probabilistic inference for future climate using an ensemble of climate and model evaluations. *Climate Change* **81**, 247–264.
- Rueedi, J., Brennwald, M. S., Purtschert, R., Beyerle, U., Hoffer, M. & Kipfer, R. (2005) Estimating amount and spatial distribution of groundwater recharge in the Iullemeden basin (Niger) based on ³H, ³He and CFC-11 measurements. *Hydrol. Processes* **19**, 3285–3298.
- Runge, C. F., Senauer, B., Pardey, P. G. & Rosegrant, M. W. (2004) Ending hunger in Africa prospects for the small farmer. Issue briefs 16, International Food Policy Research Institute, Washington D.C.
- Scheuman, W. & Alker, M. (2009) Cooperation on Africa's transboundary aquifers—conceptual ideas. *Hydrol. Sci. J.* **54**(4), 793–802 (*this issue*).
- Schreck, C. J. & Semazzi, F. H. M. (2004) Variability of the recent climate of eastern Africa. *Int. J. Climatol.* **24**, 681–701.
- Shiklomanov, I. A. (2000) Appraisal and assessment of world water resources. *Water Int.* **25**(1), 11–32.
- Taylor, R. G. (2009) Rethinking water scarcity: the role of storage. *EOS – Trans. Am. Geophys. Union* (in press).
- Taylor, R. G. & 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.
- Taylor, R. G. & 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.
- Taylor, R. G., Barrett, M. H. & Tindimugaya, C. (2004) Urban areas of sub-Saharan Africa; weathered crystalline aquifer systems. In: *Urban Groundwater Pollution* (ed. by D. N. Lerner), 155–179. Balkema, Amsterdam, The Netherlands.
- Taylor, R. G., Tindimugaya, C., Barker, J. A., Macdonald, D. & Kulabako, R. (2009) Convergent radial tracing of viral and solute transport in gneiss saprolite. *Ground Water* (in press).
- 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. Unpub. PhD Thesis, University College London, UK.
- Trenberth, K. E., Dai, A. G., Rasmussen, R. M. & Parsons, D. B. (2003) The changing character of precipitation. *Bull. Am. Met. Soc.* **84**, 1205–1217.
- UN (United Nations) (2007) Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat. World Population Prospects: the 2006 revision and World Urbanization Prospects: the 2005 revision. <http://esa.un.org/unpp>.
- Vörösmarty, C. J., Douglas, E. M., Green, P. A. & Revenga, C. (2005) Geospatial indicators of emerging water stress: an application to Africa. *Ambio* **34**, 230–236.
- Vrugt, J. A. & Robinson, B. A. (2007) Treatment of uncertainty using ensemble methods: comparison of sequential data assimilation and Bayesian model averaging. *Water Resour. Res.* **43**, W00B09, doi:10.1029/2007WR006720.
- Vrugt, J. A., ter Braak, C. J. F., Clark, M. P., Hyman, J. M. & Robinson, B. A. (2008a) Treatment of input uncertainty in hydrologic modelling: doing hydrology backward with Markov chain Monte Carlo simulation. *Water Resour. Res.* **44**, W01411, doi:10.1029/2005/2005WR004838.

- Vrugt, J. A., Stauffer, P. H., Wöhling, T., Robinson, B. A. & Vesselimov, V. V. (2008b) Inverse modeling of subsurface flow and transport properties: a review with new developments. *Vadose Zone J.* **7**(2), 843–864.
- Walraevens K., Vandecasteele, I., Martens, K., Nyssen, J., Moeyersons, J., Gebreyohannes, T., De Smedt, F., Poesen, J., Deckers, J. & Van Camp, M. (2009) Groundwater recharge and flow in a small mountain catchment in northern Ethiopia. *Hydrol. Sci. J.* **54**(4), 739–753 (*this issue*).
- Winsemius, H. C., Savenije, H. H. G., van de Giesen, N. C., van den Hurk, B. J. J. M., Zapreeva, E. A. & Klees, R. (2006) Assessment of Gravity Recovery and Climate Experiment (GRACE) temporal signature over the upper Zambezi. *Water Resour. Res.* **42**, W12201.
- Zaitchik, B. F., Rodell, M. & Reichle, R. H. (2008) Assimilation of GRACE terrestrial storage data into a land surface model: results from the Mississippi River Basin. *J. Hydromet.* **9**, 535–548.