Hydrocomplexity: New Tools for Solving Wicked Water Problems
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Groundwater and global hydrological change – current challenges and new insight

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Abstract As the world's largest accessible store of freshwater, groundwater plays a critical role in enabling communities to adapt to freshwater shortages derived from low or variable precipitation and high freshwater demand. As highlighted by the IPCC in 2001 (TAR) and 2007 (AR4), our knowledge of how groundwater systems respond to changes in climate and abstraction remains severely limited. Although new diagnostic tools such as the global aquifer map (WHYMAP) and satellite monitoring of changes in total water storage under the Gravity Recovery and Climate Experiment (GRACE) have recently been developed, their deployment is greatly constrained by a dearth of reliable and sustained observations of groundwater systems. Land-surface models (LSMs) embedded in general circulation models and offline macro-scale hydrological models continue to employ simplistic characterisations of groundwater systems due, in part, to the absence of global or continental-scale data sets to test or tune these models. Structural modelling challenges, such as the long response times of some groundwater systems to hydrological change and substantial uncertainty in projections of precipitation and evapotranspiration, persist. New insight regarding the relationship between global hydrological change and groundwater systems, including the impacts of intensive abstraction for irrigation on groundwater storage and changing rainfall intensity on groundwater recharge, have recently been developed from basin-scale studies where reliable groundwater observations exist. These studies provide a compelling case for the expansion of groundwater monitoring networks and compilation of a global groundwater archive (IGRAC), comparable to that for other components of the hydrological system (e.g. WMO, GRDC, WGMS), to improve understanding and management of the groundwater system under global hydrological change.

Key words groundwater; climate change; modelling; monitoring; GRACE

INTRODUCTION

Groundwater is the world's largest accessible store of freshwater, estimated to be 10.5 million km^3 in volume (Kozun, 1974, cited in Foster & Chilton, 2003; Shiklomanov & Rodda, 2003). Despite considerable uncertainty in this estimate, this volume is 100 times more freshwater than that stored in lakes and rivers, and approximately half of that residing in the Antarctic ice cap. Although changes in the global hydrological system are one of the major consequences of global warming, groundwater remains peripheral to current analyses and discussions of climate change. Notwithstanding recent efforts (e.g. Bovolo *et al.*, 2009; Taylor *et al.*, 2009), this situation is perplexing and unsatisfactory. Groundwater is the primary source of drinking water for nearly half of the world's population (Coughanowr, 1994; Kundzewicz & Döll, 2009) and is critical to global food security as it is a major source (30%) of water to irrigated land (Foster & Chilton, 2003). As concluded by the Inter-governmental Panel on Climate Change (IPCC) in both their 3rd (2001) and 4th (2007) Assessment Reports:

"*groundwater is the major source of drinking water across much of the world … but there has been very little research on the potential effects of climate change*".

The purpose of this paper is to review some of the key barriers to an improved understanding of the relationship between groundwater and global hydrological change, and to draw attention to emerging insight from recent research. The paper draws from deliberations among climatologists, hydrogeologists, hydrologists, and water managers at a dedicated side event, *Groundwater & Climate*, that was organised by the UNESCO-IHP Groundwater Resources Assessment under the Pressures of Humanity and Climate Change (GRAPHIC) programme[1] at the 3rd World Climate Conference[2] in September 2009.

GROUNDWATER AND CLIMATE PREDICTION

The global hydrological cycle is a central component of the Earth's climate system. Effective representation and quantification of hydrological fluxes are therefore essential to improve climate simulations and prediction, and to quantify impacts of climate change on water resources. At present, groundwater is poorly represented in both land-surface models (LSMs) that are incorporated in general circulation models (GCMs) (Schaller & Fan, 2009), and offline macro-scale hydrological models such as MacPDM (Arnell *et al.*, 1999) and WaterGAP (Alcamo *et al.*, 2003). For a start, simulation of groundwater recharge by these models is poorly constrained due to a lack of information on soil and geological conditions. Other groundwater fluxes operating at a range of spatio-temporal scales are ignored but require consideration. These include: (1) capillary flow from the water table to root zone to sustain evapotranspiration during dry periods; (2) shallow groundwater exchanges with local stream networks and other surface water bodies (lakes, wetlands); (3) deeper regional groundwater discharges to downstream river networks and wetlands; and (4) submarine discharges in coastal areas. Failure to consider groundwater fluxes, particularly (2) and (3) above, can lead to systematic errors in simulated river discharge and soil moisture in LSMs and offline hydrological models.

Land-surface models applied in climate research over the last decade operate with a grid cell of a few hundred kilometres. At such a coarse resolution, it may be argued that groundwater processes can be simulated in a simplistic manner. For example, lateral flows between groundwater cells may only be important at this scale in a few places where substantial regional groundwater flow occurs. In most environments, simple representations of groundwater may prove adequate to improve simulation of hydrological fluxes (e.g. river discharge) and key feedbacks on the land-surface energy budget such as soil moisture in moisture-limited environments. Gedney & Cox (2003) represented shallow groundwater/soil moisture interactions within the UK Met Office GCM (HadCM3) with a version of TOPMODEL (Beven & Kirkby, 1979). Other LSMs incorporate a simple groundwater store (Ngo-Duc *et al.*, 2007; Niu *et al.*, 2007) to represent the deep groundwater. The inclusion of groundwater can result in detectable changes in soil water, evaporation and runoff (Niu *et al.*, 2010). Recent modelling work in the USA also highlights the sensitivity of the land-surface energy budget to shallow (1 to 6 m in depth) groundwater storage (Kollet & Maxwell, 2008; Maxwell & Kollet, 2008) and the importance of irrigation to capture land–atmosphere energy and water feedbacks in managed lands (Ozdogan *et al.*, 2010).

A major constraint to effective simulation of groundwater processes in LSMs is the limited availability of observational data sets both to calibrate models and to test whether the representation of groundwater processes improves model performance. At present, model parameters calibrated for a single region are applied globally since global groundwater data sets are unavailable. This shortcoming is not restricted to groundwater processes as it is well recognised that LSMs are already overparameterised relative to available observations. New types of observations and techniques of multivariate calibration are consequently required to improve these

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[1] http://www.unesco.org/water/ihp/graphic/

[2] World Climate Conference 3 (Geneva, Switzerland), 31 August – 3 September 2009, http://www.wmo.int/wcc3

models. Further research is also warranted at the regional scale where sufficient observations exist to calibrate and validate the simulation of groundwater processes by LSMs. Globally, the extent to which groundwater processes feed back into the atmosphere remains unclear but regionally they are likely to be important. With projected increases in both the resolution and complexity of GCMs and LSMs, it is expected that simulations of climate changes (consequent impacts) will become more sensitive to uncertainty in the representation and parameterisation of groundwater processes.

SATELLITE-DERIVED ESTIMATES OF TERRESTRIAL WATER STORAGE CHANGES

An important new data set to monitor global hydrological change and to constrain simulations of the global hydrological system is that provided by the Gravity Recovery and Climate Experiment (GRACE) (Tapley *et al.*, 2004), a twin satellite mission launched in 2002. Unlike most satellite missions, the two satellites do not carry remote sensing instruments but act as measurement devices themselves. Gravity variations derive from range–rate variations between the two chasing satellites. Schmidt *et al.* (2008) review the characteristics of the GRACE satellites and recovery of hydrological signals. Gravity variations are interpreted as mass changes within Earth fluid envelopes; changes in terrestrial water storage are then derived from GRACE measurements after atmospheric and oceanic mass changes have been removed by numerical modelling (Bettadpur, 2007). These deductions contribute to the overall uncertainty in GRACE measurements of changes in terrestrial water storage (Seo *et al.*, 2006). Scale-dependence in the magnitude of this uncertainty is summarised in Table 1. Due to the satellites' orbit and characteristics, GRACE is sensitive to large-scale mass variations (i.e. >400 km or ~160 000 km^2). This coarse spatial resolution greatly constrains the utility of these data for sub-regional water resources management (Fig. 1); extracting TWS for a specific area of interest such as Bangladesh (Fig. 1) requires specific processing tools (e.g. Horwath & Dietrich, 2009; Longuevergne *et al.*, 2010). GRACE measurements do not therefore preclude the necessity of sustaining and expanding ground-based observational networks.

Table 1 Estimated error in monthly water storage estimates provided by GRACE as a function of spatial scale.

Spatial scale (km)	Equivalent area (km^2)	Error in equivalent water depth (mm)
400	160 000	25
500	250 000	20
700	500 000	15
1000	1 000 000	10

GRACE measurements integrate total water storage (TWS) over surface, unsaturated and saturated zones. Consequently, attribution of changes in water storage to specific components of the hydrological system in equation (1) including groundwater (GW), ice/snow (IS), soil moisture (SM), and surface water (SW), requires independent measurement or, where observational data are unavailable, simulation:

$$\Delta TWS = \Delta GW + \Delta IS + \Delta SM + \Delta SW \tag{1}$$

Use of simple assumptions may be warranted in some locations (e.g. $\Delta IS = 0$ in ice-free environments) but these require careful consideration and, where possible, justification. For example, several studies (Swenson *et al.*, 2006; Rodell *et al.*, 2007; Tiwari *et al.*, 2009) assume that changes in surface water storage (ΔSW) contribute negligibly to changes in TWS (ΔTWS). Though this assumption may be warranted in some basins, Shamsudduha & Taylor (2010) showed in the Bengal Basin that ΔSW accounts for 25% of ΔTWS (Fig. 2, top). Changes in soil moisture

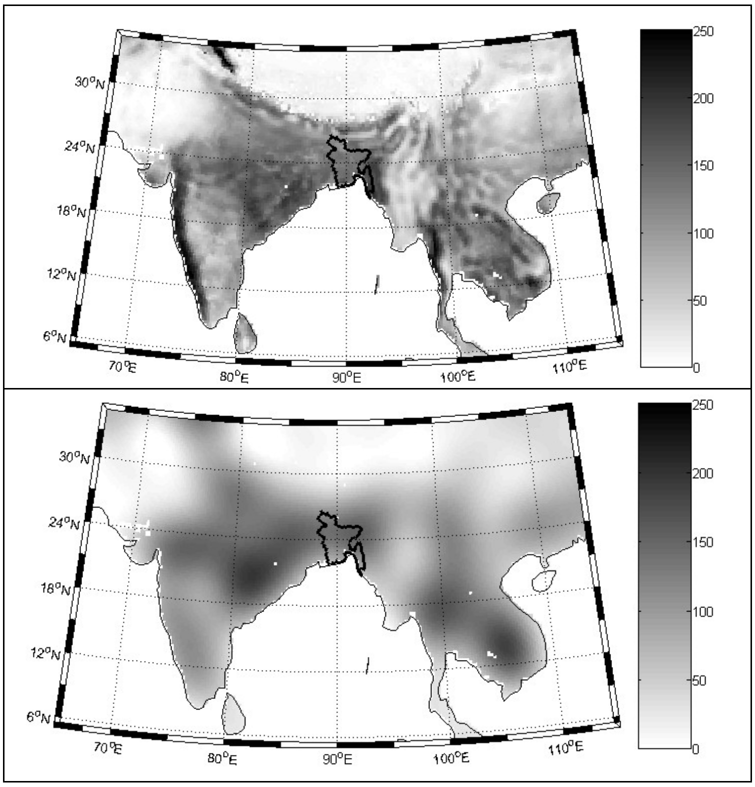

Fig. 1 Maps of the seasonal water storage variations (mm) in South Asia modelled from GLDAS-NOAH: (top) original model output (0.25 degree grid); (bottom) same map considering spatial scales above GRACE resolution (i.e. 333 km, truncation at spherical harmonic degree 60). For reference, the national boundary of Bangladesh is shown in outline.

(ΔSM) are commonly resolved from simulations by one or more LSMs due to the absence of sustained measurements of soil moisture in most environments. Considerable uncertainty remains, however, in the veracity of simulated soil moisture by LSMs. Nevertheless, Ramillien *et al.* (2008) reviewed several studies to show that GRACE-derived ΔTWS compare favourably with ground-based measurements and hydrological models at spatial scales of several hundred km and greater.

Use of GRACE measurements to trace changes in groundwater storage (ΔGW) requires information, be it observed or simulated, of changes in each of the other freshwater stores (equation (1)). There is consequently considerable cumulative uncertainty in GRACE-derived estimates of ΔGW beyond the data themselves (Table 1). Rodell *et al.* (2007) estimated uncertainty of 20 mm when recovering groundwater storage variations in the Mississippi Basin. Several regional studies (Rodell *et al.*, 2007; Swenson *et al.*, 2008; Leblanc *et al.*, 2009; Strassberg *et al.*, 2009; Shamsudduha & Taylor, 2010) report significant correlations between ground-based observations of ΔGW from borehole hydrographs and GRACE estimates (e.g. Fig. 2, bottom). To relate groundwater-level changes to an equivalent water (storage) depth provided by GRACE data requires the application of a storage coefficient. Commonly this calculation employs a specific yield (S_y) which assumes unconfined aquifer conditions persist. There are, however, few reliable measurements of storage for many aquifers (Taylor *et al.*, 2010) and, where these data exist, values are subject to the scale dependency in their derivation that affects other hydrogeological parameters such as hydraulic conductivity and dispersion (Gelhar, 1986; Martinez & Carrera, 2005). A bulk (mean) value for S_y is often applied (e.g. Rodell *et al.*, 2007; Strassberg *et al.*, 2009; Tiwari *et al.*, 2009) but not well constrained. The consequences of this uncertainty are non-trivial. In the Bengal Basin, Shamsudduha & Taylor (2010) estimated a 45% reduction in the magnitude of declining groundwater storage when a spatially distributed S_y, derived from pumping-test data, is applied (-0.75 km^3 year^{-1}) compared to a uniform value (0.10) of S_y (-1.36 km^3 year^{-1}). In

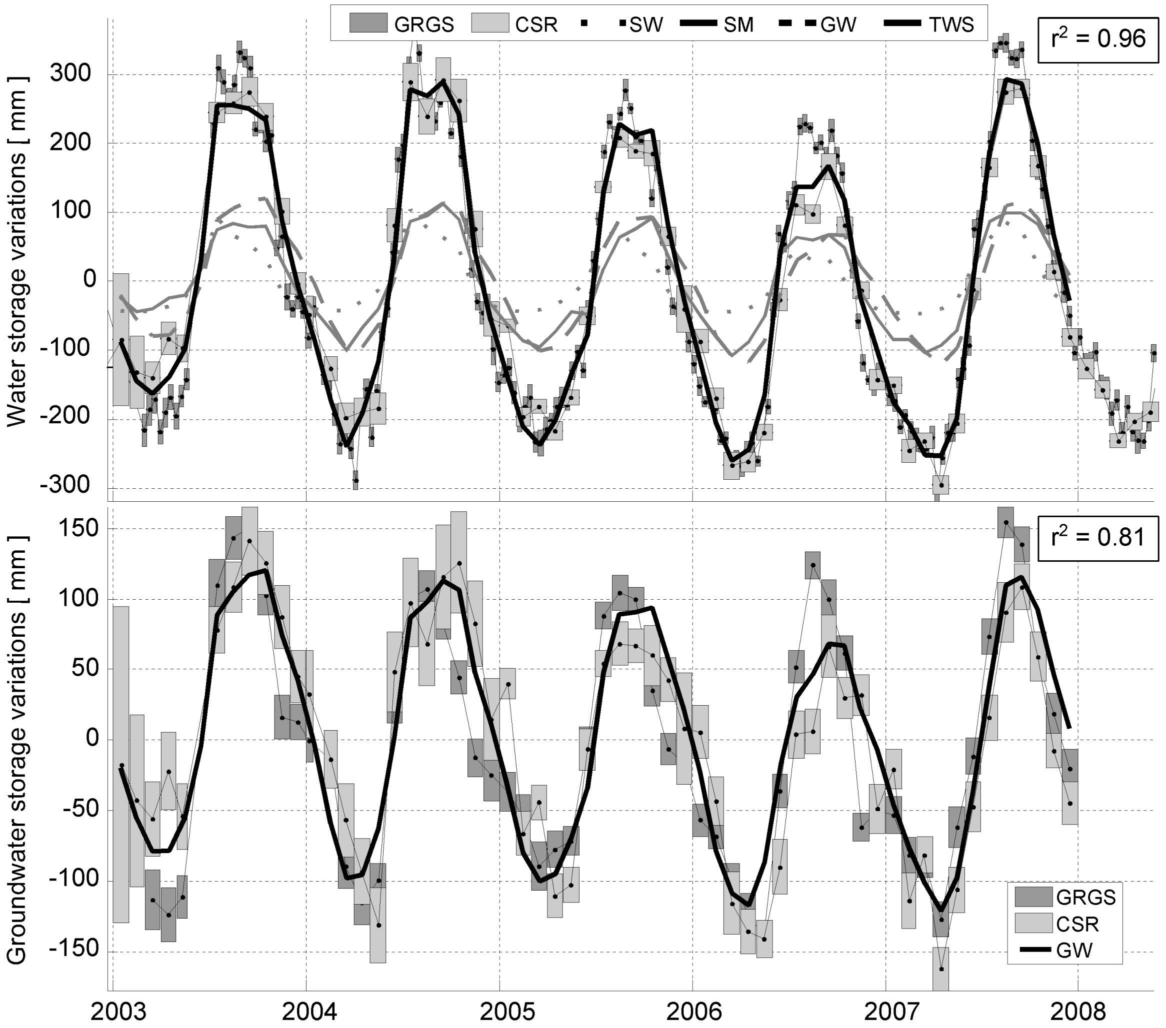

Fig. 2 10-day and monthly time series anomalies from 2003 to 2007 (inclusive) in Bangladesh derived from GRACE CSR and GRGS solutions, ground-based observations of ΔSW and ΔGW, and ΔSM from GLDAS model (adapted from Shamsudduha & Taylor, 2010; processing explained in Longuevergne *et al.*, 2010): (top) comparison of GRACE derived ΔTWS with ΔSM, ΔSW and ΔGW; (bottom) ΔGW derived from GRACE (corrected from ΔSW and ΔSM) and ground-based observations.

contrast, for the High Plains aquifer (USA), a 10% increase in groundwater depletion is calculated using a spatially distributed S_y relative to bulk S_y (Longuevergne, unpublished results). Despite these quantitative uncertainties, favourable comparisons between GRACE and ground-based observations of ΔGW provide a platform for improving global modelling of groundwater resources (Schmidt *et al.*, 2006; Günter, 2008; Zaitchik *et al.*, 2008; Chen *et al.*, 2009; Werth *et al.*, 2009).

In addition to constraining LSMs and global hydrological models, GRACE satellite data have also been used to detect substantial regional changes in groundwater storage on the Indian sub-continent as a result of groundwater abstraction for irrigation (e.g. Rodell *et al.*, 2009; Shamsudduha & Taylor, 2010). These observations follow similar evidence from borehole hydrographs of declining groundwater levels in the USA (McGuire, 2007) and China (Konikow & Kendy, 2006). Such changes are currently ignored in LSMs and global hydrological models that disregard anthropogenic interventions in the hydrological system. It is, however, necessary for these models to explicitly account for large-scale ΔGW as they directly impact terrestrial hydrology (Ozdogan *et al.*, 2010; Wisser *et al.*, 2010). Shamsudduha *et al.* (2010) showed, for example, that rising groundwater abstraction for dry-season Boro rice cultivation in the Bengal

Basin since the 1980s has led to sharp increases in recharge fluxes in several parts of Bangladesh. Groundwater-fed irrigation lowers the water-table in shallow aquifers during the dry season which induces greater recharge by increasing available groundwater storage during the subsequent monsoon. Anomalous decreases in groundwater recharge are, however, observed in areas of intensive groundwater abstraction which feature surface formations with low hydraulic conductivities (e.g. thick clay units) that restrict direct groundwater recharge. The strong influences of abstraction and geology on recharge fluxes observed in the Bengal Basin highlight both the limitations of hydrological models that do not consider geology, and a fundamental flaw in simplistic definitions of the sustainability of groundwater abstraction that are based on mean annual groundwater recharge under static (non-pumping) conditions (e.g. Döll & Fiedler, 2008; Kundzewicz & Döll, 2009).

GROUNDWATER RESOURCES AND CLIMATE CHANGE – *A PROPAGATION OF UNCERTAINTY*

Assessments of the impacts of climate change on terrestrial hydrology require a quantitative understanding of uncertainty inherent in climate projections generated by GCMs (Taylor *et al.*, 2009). Uncertainty in the estimation of climate change impacts on water resources derives primarily from GCM projections of precipitation, the primary forcing of hydrological change. Single-GCM evaluations of climate change impacts are, therefore, likely to be wholly inadequate and potentially misleading as a basis for the analysis of climate change impacts on freshwater resources. Use of GCM ensembles (i.e. multi-model climate projections), however, gives rise to considerable uncertainty in projected changes to basin hydrology (e.g. Chiew *et al.*, 2009; Prudhomme & Davies, 2009; Kingston & Taylor, 2010). Assessing the ability of GCMs to represent key synoptic controls on regional (historical) climatology may provide a reasonable basis for weighting or excluding GCMs in ensemble projections and thereby reducing the magnitude of uncertainty in climate projections applied to basin-scale hydrological models. Such regional evaluations of GCM performance may further help to reduce uncertainty in GCM representations of multi-annual climate variability that is critical to understanding climate impacts on groundwater storage and basin-scale water resources management more generally.

Estimating the impact of the climate change on hydrological fluxes including groundwater recharge involves the propagation of uncertainty from projected precipitation through to modelled evapotranspiration, surface runoff, and infiltration under a changed climate. Kingston *et al.* (2009) show, for example, that the choice of the algorithm for estimating PET in offline hydrological models introduces as much uncertainty as the choice of GCM in the estimation of regional water surpluses (P – PET) and can alter the direction of the climate change signal (e.g. East Africa). As discussed above, constraining parameter uncertainty in hydrological models and their ensembles (i.e. multiple parameterisations) requires sustained hydrological observations for model calibration and validation. Though rarely considered, uncertainty also derives from land-use changes that modify the physical characteristics of the basin through changes in abstraction (discussed above), albedo, and flow characteristics. Descroix *et al.* (2009) and Favreau *et al.* (2009) describe the "Sahelian Paradox" in which river discharge is observed to increase while rainfall decreases due primarily to changes in runoff coefficients associated with substantial increases in the proportion of cultivated land in the Sahelian areas of Niger and Burkina Faso.

Downscaling climate projections to scales below the spatial (~10^5 km^2) and temporal (monthly) resolution of GCMs essentially filters (statistically or dynamically) uncertain climate projections adding to the uncertainty in basin-scale hydrological modelling. One critical downscaling problem – that of converting monthly to daily rainfall – demonstrates the propagation of uncertainty in projections of groundwater recharge very clearly. As global warming amplifies the water-holding capacity of the atmosphere, the frequency of very heavy rainfall events (i.e. those in the uppermost quantiles of the rainfall distribution) is projected to increase (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 expected to be especially pronounced. Coincidental, daily monitoring of rainfall and groundwater levels in the Upper Nile Basin of Uganda since 1998 (Fig. 3) shows that the sum of heavy rainfall events exceeding a threshold of 10 mm day^{-1} is better related to the observed recharge flux than the sum of all daily rainfall events (Owor *et al.*, 2009). A projected shift towards more intensive rainfall in this region therefore favours groundwater recharge (Mileham *et al.*, 2009). Projections of declining recharge in semi-arid areas of the tropics cited in the IPCC AR4 (Kundzewicz *et al.*, 2007) fail, however, to account for projected changes in rainfall distributions.

Strategies to adapt to more variable freshwater resources will, in many environments, increase groundwater abstraction. A growing number of climate impact models (e.g. Allen *et al.*, 2004; Scibek & Allen, 2006; Scibek *et al.*, 2007; Herrera-Pantoja & Hiscock, 2008; Döll, 2009; Mileham *et al.*, 2009; Kingston & Taylor, 2010) explicitly consider how climate change affects groundwater

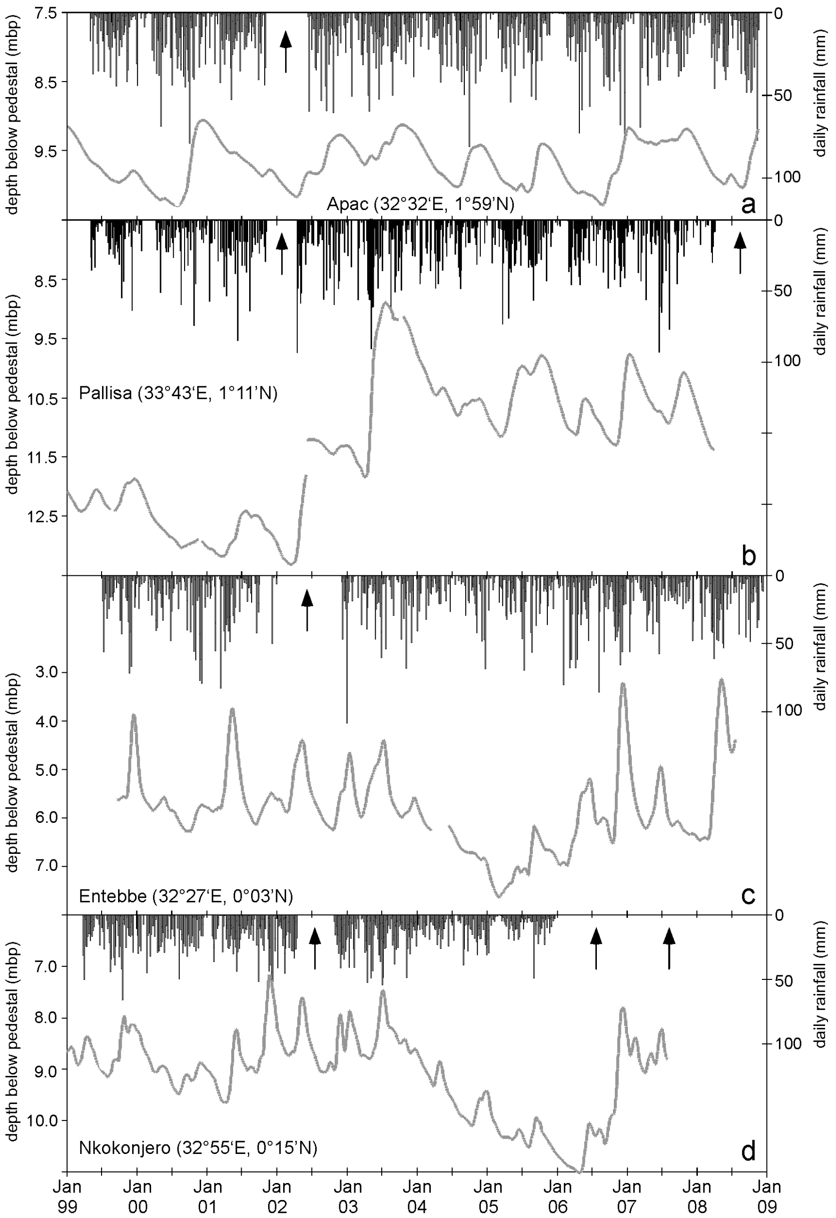

Fig. 3 Coincidental, daily groundwater level and rainfall observations in the Upper Nile Basin of Uganda over the period 1999–2008 from four stations: (a) Apac, (b) Pallisa, (c) Entebbe and (d) Nkokonjero (from Owor *et al.*, 2009). Arrows in plots (a) to (d) indicate gaps in the rainfall record.

recharge. As recognized by the organizers of the 3rd World Climate Conference, there is a need to translate such analyses of climate change impacts into "actionable" information. Döll (2009), for example, represented climate change impacts through a range of new freshwater availability indicators (e.g. ratio of consumptive water use to low, 90th percentile riverflow) and also maps where recharge is expected to decrease or increase. Although the robustness of projections from global models at the basin scale require testing with field observations, Döll (2009) provides a useful model for representing climate change impacts on groundwater recharge for water managers and policy makers.

ACCESSIBLE GROUNDWATER OBSERVATIONS – *A FUNDAMENTAL CONSTRAINT*

As highlighted in each of the sections above, fundamental constraints to both the representation of groundwater fluxes in climate models and analysis of climate impacts on groundwater resources include the limited coverage and duration of groundwater observations. There is also the continued difficulty of accessing available groundwater data. The Global Climate Observing System (GCOS) recognises groundwater as an essential climate variable but notes that historically data from national and regional monitoring networks are neither exchanged nor managed in a centralised manner. The establishment of the *International Groundwater Resources Assessment Centre* (IGRAC)[3] under the auspices of UNESCO and WMO to collate and archive global groundwater data is an important step towards sharing of groundwater information on a global scale (Kukuric & van Vliet, 2009). However, a system for the global collation of groundwater data similar to that of other hydrological parameters, such as precipitation (WMO) and river discharge (GRDC), has yet to be established. In 2006, IGRAC initiated the *Global Groundwater Monitoring Network* (GGMN) which aims to use aggregated information from existing networks in order to represent a regional change of groundwater resources at the scale relevant for global assessments. More than 30 organisations from around the world have agreed to participate and support GGMN but greater cooperation and access to relevant data sets are still necessary. Increased monitoring of groundwater resources is required but efforts need to recognise and address current trends of decreased investment in hydrological monitoring in many parts of the world (Kundzewicz, 1997).

Recent synthesis of groundwater mapping under the *World-wide Hydrogeological Mapping and Assessment Programme* (WHYMAP)[4] has made available, for the first time, low-resolution hydrogeological maps which have the potential for integration into LSMs and global hydrological models. Attribution of quantitative groundwater information such as the transmissivity (T) and storage (S) to geological descriptions remains to be done and is fraught with substantial uncertainty in these parameters for mapped units. Collation and expert review of available evidence from Africa is currently being conducted under a DfID (UK) study, *Groundwater resilience to climate change in Africa*[5] and may provide a model for other continents. It is envisaged that an iterative process whereby improved representations of groundwater processes in regional and ultimately, global LSMs are tested using both satellite and groundwater-based measurements will serve to tune initial parameterisations of T and S. Such efforts, though initially crude, would mark an important step toward an improved understanding of groundwater and global hydrological change at continental and global scales.

CONCLUDING DISCUSSION

As the world's largest accessible store of freshwater, groundwater is strategically placed to play a central role in helping many communities adapt to freshwater shortages derived from low or variable precipitation and high freshwater demand. Current understanding of the relationship

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[3] http://www.igrac.net/

[4] http://www.whymap.org

[5] http://www.bgs.ac.uk/GWResilience/

between groundwater and global hydrological change is, however, limited through simplistic formulations and parameterisations of land-surface models (LSMs) (embedded in general circulation models) and global hydrological models (GHMs), as well as a dearth of sustained, reliable and accessible groundwater observations with which to develop our conceptual understanding and to test hydrological models. Recent developments, such as a global hydrogeological map under WHYMAP and a time series of global changes in total water storage variations under GRACE, provide an opportunity to improve the representation of groundwater processes in LSMs and GHMs. In light of the coarse resolution of both GRACE data and the global aquifer map, there is nevertheless a critical need to expand and integrate ground-based information and monitoring of groundwater into hydrological networks. As highlighted in this paper, ground-based observations form the basis of our understanding of global hydrological change, whether it is ground-truthing satellite measurements such as GRACE, or developing our knowledge of basin-scale responses of hydrological systems to change. Non-intuitive hydrological responses derived from ground-based observations include, for example, increased recharge in response to rising groundwater abstraction in the Bengal Basin, the "Sahelian Paradox" of increasing river discharge and rising groundwater levels in response to declining rainfall in West Africa, and the relationship between rainfall intensity and groundwater recharge in the Upper Nile Basin. Improved knowledge of natural basin storage, particularly groundwater and soil moisture, realised through improved monitoring and modelling, would also enable us to better understand and represent the relationship between freshwater availability and demand (Taylor, 2009). Central to the utility of all new insight regarding the relationship between groundwater and global hydrological change is the translation of research outputs into "actionable" information that directly informs effective adaptation.

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