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A review of aspects of hydrological sciences research in Africa over the past decade

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Abstract This review assesses the potential of the African continent to contribute to the three main targets of the new science decade of IAHS (Panta Rhei): understanding, estimation and prediction, and science in practice. The continent has an extremely diverse climate and physical environment, and is faced with many problems in the interaction between hydrology and society. While inadequate financial and institutional resources often constrain the pursuit of high-level scientific research, there is substantial hydrological research capacity within Africa. The topics covered over the past decade have partly anticipated some of the research themes adopted as part of the Panta Rhei initiative. African hydrological scientists should therefore be in a better position to make future contributions, largely because their research is already grounded in applications linked to societal needs. Some of the papers reviewed and included in the special issue of *Hydrological Sciences Journal* introduced in this paper reflect international partnerships, while others reflect emerging partnerships between institutions within Africa.

Key words hydrological science; Africa; Panta Rhei

Revue de la recherche en sciences hydrologiques en Afrique au cours de la dernière décennie

Résumé Cette revue évalue le potentiel du continent africain à contribuer aux trois principaux objectifs de la nouvelle décennie scientifique de l'AISH (Panta Rhei), à savoir la : compréhension, l'estimation et la prévision, et la pratique de la science. Les climats et les environnements physiques du continent sont extrêmement diversifiés, et il doit faire face à de nombreux problèmes où interagissent l'hydrologie et la société. Bien que des ressources financières et institutionnelles inadéquates limitent souvent l'exercice d'une recherche scientifique de haut niveau, il existe en Afrique une importante capacité de recherche hydrologique. Les sujets abordés au cours de la dernière décennie recoupent en partie quelques -uns des thèmes de recherche adoptés dans le cadre de Panta Rhei. Les hydrologues africains devraient donc être dans une bonne position pour apporter leur contribution, en grande partie parce que leur recherche s'appuie déjà sur les applications liées aux besoins sociétaux. Certains des documents examinés et inclus dans le numéro spécial du Journal des Sciences Hydrologiques considérés dans le présent article font référence à des partenariats internationaux, tandis que d'autres font référence à des partenariats émergents entre institutions africaines.

Mots clefs science hydrologique ; Afrique ; Panta Rhei

1 INTRODUCTION

The end of the International Association of Hydrological Sciences (IAHS) decade on Prediction in Ungauged Basins (PUB: 2003–2012; Hrachowitz *et al*. 2013) provides an appropriate opportunity to review recent contributions from Africa, and to assess the continent's potential for contributing to the new science decade (Panta Rhei: 2013–2022; Montanari *et al*. 2013). This was the main motivation for proposing this special issue of the *Hydrological Sciences Journal* (*HSJ*) that focuses on African hydrology and water resources science research, and has been purposely restricted to contributions that include at least one author from an African institution. The continent is extremely diverse in terms of climate and the physical environment, as well as being faced with many problems with respect to the interactions between hydrology and society. Inadequate financial and institutional resources constrain the pursuit of high-level scientific research (Namuddu 2012). From the perspective of the future development of hydrological research on the continent, there is a need to make some distinctions between all research conducted on African hydrology and research on the same subject by African hydrologists. A Scopus search (17 April 2014) using the keywords "Hydrology" and "Africa" yielded 309 results for the period 1990–2001 and 845 results for the period 2002–2013, and this increase is partly a reflection of the worldwide increase in scientific publication rates, but also indicative of the interest in African hydrology. The search results were further analysed on the basis of affiliation, distinguishing between African and non-African locations. While it is always difficult to analyse these results reliably because of multiple authorship, some trends are apparent. There are 28 African institutions represented in the earlier period, while this number increases to 45 for the second period. Between 2002 and 2010, 14.7% of papers using the same search terms were from special issues of the journal *Physics and Chemistry of the Earth*, which are produced following each of the annual WaterNet symposia (Jonker *et al*. 2012). South Africa continues to dominate in both numbers of institutions and numbers of papers. There are therefore positive signs that more institutions within Africa are publishing research results, but there remains a rather unhealthy regional imbalance. This is also reflected in the origin of publications in the journal *Secheresse*, created in 1990 by l'Agence universitaire de la Francophonie (AUF) which is indexed by Scopus and Web of Science. Many francophone researchers in earth, environment and society topics use this journal and, for the periods 1990–2001 and 2002–2012, the number of papers from Africa increased from 145 (36% of all papers) to 271 (60%). During the 2002–2012 period, 66% of these were from North Africa, 27% from West Africa and 7% from the rest of Africa.

The publication statistics above also emphasize some of the regional distinctions within Africa. There tends to be limited collaboration between institutions across the main regions of Mediterranean North Africa, West Africa, East Africa and southern Africa, although the WaterNet (Jonker *et al*. 2012) programme has fostered recent collaborations between the latter two regions. Central Africa tends to be a neglected sub-region. While there is little evidence of any continent-wide research, there are some indications (based on the affiliations of multi-authored papers) that more regional cooperation is occurring. This is almost certainly a result of relatively large, externally (USA, UK, EU, etc.) funded projects with multiple partners. Unfortunately, there is very little evidence that political developments at the continental scale, such as NEPAD (New Partnership for African Development), AMCOW (African Ministerial Conference on Water) and AMCOST (African Ministerial Conference on Science and Technology), have had any substantial impacts on hydrological science outputs (although see Lane 2004 for a more positive opinion). Part of the problem could be that these bodies have yet to provide readily available funding for hydrological research.

Given the focus of this special issue of *HSJ* on hydrological research in Africa, the vast majority of the citations in this introduction are of publications that include at least one author with an African affiliation, although exceptions are made in some cases to ensure that some key research areas are covered. The citations are also mainly restricted to the period from the start of the PUB decade in 2003. Where possible we have used publications that have been relatively frequently cited; however, the objective of the review was also to be regionally representative. The review is structured to reflect the three main targets of the new Panta Rhei decade of the IAHS. These refer to understanding, estimation and prediction, and science in practice (Montanari *et al*. 2013). The first is about improving our understanding of hydrological systems, how they interact with other systems, and how they respond to change. The second is about improved quantification of hydrological and connected systems, including issues of uncertainty, that continues from one of the PUB (Hrachowitz *et al*. 2013) focal areas, as well as issues related to monitoring. The third is about how science can be implemented in practice to improve policy and decision making. There are clearly a number of overlaps between these topics (e.g. understanding contributes to predictive modelling, and modelling cuts across estimation and implementation of science in practice). This paper is based on the same three target themes, but emphasizes the links between them where appropriate.

2 UNDERSTANDING HYDROLOGICAL AND CONNECTED SYSTEMS

2.1 Hydrological process studies

Resource limitations have constrained the ability of many African hydrologists to contribute to hydrological process studies. Many research organizations on the continent do not have the resources to purchase and maintain the necessary instrumentation for field monitoring, as is evident from the decreasing number of rainfall records in West and Central Africa since the 1980s: by the 1990s the records available were fewer than during the 1940s (Paturel *et al.* 2010). Kongo *et al.* (2010) suggest an approach to collecting additional hydrological data using participatory approaches with rural communities that could be applicable to many parts of the continent. Long-term field observations therefore typically rely on external funding (but with local participation) and perhaps the best example on the continent is the West African programme AMMA-Catch (African Monsoon Multidisciplinary Analysis–Couplage de l'Atmosphère Tropicale et du Cycle Hydrologique) (Lebel *et al.* 2009, Lohou *et al.* 2014). There have been some contributions based on instrumented catchments that have contributed to improved understanding of small-scale runoff generation processes (Uhlenbrook *et al.* 2005), surface runoff (Dlamini *et al.* 2011, Mounirou *et al.* 2012, Orchard *et al.* 2013), interception (Tsiko *et al.* 2012, Bulcock and Jewitt 2012), evapotranspiration (Everson *et al.* 2011), groundwater–surface water interactions (Richard *et al.* 2013) and groundwater storage dynamics (Hector *et al.* 2013). Erosion process studies have been conducted in instrumented basins in southern and northern Africa (Achite and Ouillon 2007, Dlamini *et al.* 2011, Meddi 2013, Morsli *et al.* 2013), and a few in West Africa (Liénou *et al.* 2009, Diallo *et al.* 2013).

The impact of land-use change (Descroix *et al.* 2009, Mango *et al.* 2011, Jewitt and Kunz 2011, Warburton *et al.* 2012) is an important issue throughout Africa. Indeed, this aspect of hydrological research has been a driver of many research initiatives from the well-established forestry catchments of South Africa (Scott and Prinsloo 2008), the East African Kimakia and other catchments (Blackie *et al.* 1981), and in West Africa through older studies during the 1980s in Côte d'Ivoire and Burkina Faso, mainly driven by the French researchers from ORSTOM. Ironically, this type of focused research has declined in the past two decades. However, there have been some important publications arising from land cover-related studies, often associated with multi-partner programmes, with agricultural water management as a driver (Bossio *et al.* 2011, Love *et al.* 2011a).

Modelling studies have been used to investigate hydrological processes in detail (Le Lay *et al.* 2008, Boulain *et al.* 2009, Bulcock and Jewitt 2012, Hughes *et al.* 2014a), or analyse existing data in a modelling conceptual framework (Hughes 2010, Kapangaziwiri *et al.* 2011). While the lack of water chemistry data tends to inhibit the use of hydrochemical tracing studies to understand runoff generation processes, there are some documented studies of this type (Mul *et al.* 2008, Wenninger *et al.* 2008, Munyaneza *et al.* 2012). There has also been a recent trend towards better integration of soil science and hydrology (Van Tol *et al.* 2010a, 2010b, Bossa *et al.* 2012, Nyamadzawo *et al.* 2012, Van Zijl and Le Roux 2014), with the intention of improving the way in which soils information is used to understand processes and parameterize hydrological models.

2.2 Rainfall–runoff variability and change

Many rainfall and climate change studies started after the first drought years struck the Sahel at the beginning of the 1970s, followed by a second drought peak in the 1980s that extended more widely across many regions of Africa, even humid ones. Runoff change studies followed as dramatic decreases occurred in many large river discharge time series, especially in West Africa. There have been attempts to explain these differences based on rainfall and runoff variability, or changes in surface runoff processes and the possible role of groundwater table decreases. Since 2000 these studies have been developed in several countries (Kouassi *et al.* 2012 for the Ivory Coast, for instance), and included human influences on the environment and impacts on surface runoff processes and river regimes (Liénou *et al.* 2008, Beyene *et al.* 2010, Oguntunde and Abiodun 2013), mainly due to agricultural activities and dams (Amoussou *et al.* 2012).

Recent studies have proposed a comprehensive approach to assessing rainfall–runoff variability and changes over Africa (Conway *et al.* 2009, Mahé *et al.* 2013, Roudier *et al.* 2014a), showing the specific variability from one region to another, and confirming that the 1970s and 1980s droughts were not evident in all regions, while in other regions river regimes were still actively changing, including in Central Africa (Liénou *et al.* 2008) and the Sahel (Karambiri *et al.* 2011, Sighomnou *et al.* 2013). The most recent topics studied by African researchers are linked to (a) climate projections for Africa and their impact on rainfall, runoff and water resources regimes; (b) impact of climate change on agriculture, economy and hydropower; and (c) adaptation strategies of populations to climate change impacts. The first of these is discussed below, while the other two are covered in the next section on connected systems.

There is a strong demand from civil society for predictions of future rainfall and runoff at local to regional scales. Given the evidence of continuous climate change, it is not sufficient to use statistical approaches to predict possible future values, but local to regional climate model outputs should be used to predict the availability and variability of water resources in the future (e.g. Shongwe *et al*. 2009). Sylla *et al*. (2013) used the Famine Early Warning System, Global Precipitation Climatology Project and Tropical Rainfall Measuring System rainfall grids to assess the performance of the RegCM3 regional climate model in simulating daily precipitation characteristics over Africa. They highlight the uncertainty in observations as a key factor preventing a rigorous and unambiguous evaluation of climate models. Improving the quality and consistency of predicting current climatic conditions is essential for an improved understanding of the response of African climate to global warming. The regional studies of Li *et al*. (2013) dealing with forcing a hydrological model with future rainfall in southern Africa, Saeed *et al*. (2013) examining the representation of extreme rainfall in the Congo basin from different climate models, and Anyah and Qiu (2012) about characteristic precipitation and temperature pattern changes over the Greater Horn of Africa, have reached similar conclusions about improved predictions.

2.3 Connected systems

A number of different research topics fall under this heading, including linking environmental systems to hydrology and water quality (Love *et al*. 2004) and ecology (McClain *et al*. 2014), surface water–groundwater interactions (Hughes 2010, Tanner and Hughes 2013), and linkages between environmental, agricultural and human systems (Bola *et al*. 2013). However, many of these overlap with the “estimation and prediction” or “hydrology and practice” topics and are covered in more detail in later sections.

The issue of the possible economic impacts of climate change overlaps with the third Panta Rhei target. However, we need to understand the relationships between hydrological change and local and global economic activities. Blanc and Strobl (2013) demonstrated significant reductions in cropland productivity in the future based on satellite data. Sissoko *et al*. (2011) showed that in the West African Sahel, early warning systems including an operational agro-meteorological information system are already providing farmers with crucial information. Hamatan *et al*. (2004) have established that such information is rarely used due to poor reliability at the local scale at which farmers make their decisions. Noufé *et al*. (2011) in Ivory Coast and Traore *et al*. (2013) in Mali concluded that climate changes had the potential to cause changes in crop production although other human related causes had significant effects on production. Agronomic models forced with climate data and calibrated with local information have been used to predict future agronomic indicators (Gerardeaux *et al*. 2013, Roudier *et al*. 2014b), while Makurira *et al*. (2010, 2011) used plot- and field-scale water balance studies to enhance understanding of water resource allocation in semi-arid environments. Several authors have established potential negative effects of climate change on hydro-power production (Barbier *et al*. 2009, Yamba *et al*. 2011, Hamududu and Killingtveit 2012).

Warburton *et al*. (2012) discussed the ability of models to adequately represent the links between climate variability and land-use change responses, and raised the question about whether these models can realistically simulate future climate change conditions. There have been some studies that have assessed the risk arising from future conditions (Ben Mohamed 2011, Ghile *et al*. 2014). Some studies have investigated how local populations perceive climate change, the associated impacts (Zaré *et al*. 2013), and the possible adaptation strategies to be adopted (Sturdy *et al*. 2008, Fosu-Mensah *et al*. 2012, Antwi-Agyei *et al*. 2014). These studies have been aimed at developing generalized solutions to climate change and variability. Some of the practical applications of these developments are referred to in Section 4.

3 ESTIMATION AND PREDICTION

Within Africa, hydrological data are generally sparse and of low quality, often difficult to access from the relevant agencies, and frequently contain long periods of missing data. Estimation and prediction methods to overcome the limitations in the monitoring data are therefore essential, and consequently a high proportion of the hydrological literature deals with modelling and prediction, either from a science perspective (developing and testing models) or from a practical perspective (see Section 4: Science in practice). The use of data derived from Earth observation technology has also featured quite strongly in the literature, although, in the past, the resources required to access and apply these methods constrained the wide use of these data sources.

3.1 Remote sensing to improve monitoring data

The use of remote sensing in hydrological applications and research has a particularly large potential in Africa, where the scarcity of traditional hydrological measurements is commonly combined with large spatial scales and high spatial variability of climate and land cover. African research on remote sensing in hydrology has expanded over recent years, with an increasing number of publications per year facilitated by initiatives such as the ESA Tiger programme aimed at developing Earth observation applications for water resources management in Africa (Achache *et al*. 2004, Fernandez-Prieto and Palazzo 2007). There are about 60 research papers dealing with the application of data derived from remote sensing in hydrology authored or co-authored by African scientists, with all but one published after 2000 and half during the past 4 years. The published remote sensing applications in hydrology fall into four categories: precipitation estimation, estimation of surface water fluxes and states, wetland monitoring and hydrological modelling. The use of Earth observation data for precipitation estimation (Dinku *et al*. 2008) and improved interpolation of sparse raingauge networks (Frezghi and Smithers 2008) is common for both long-term assessments (Hughes 2006, Habib *et al*. 2012) and real-time applications (Li *et al*. 2009, Sinclair and Pegram 2010, De Coning 2013). Estimation of hydrological surface states and fluxes has been investigated for soil moisture (Friesen *et al*. 2008, Vischel *et al*. 2008a) and, more recently, for evapotranspiration (Kongo *et al*. 2011, Kiptala *et al*. 2013, Marshall *et al*. 2013). The numerous large and inaccessible wetlands of Africa have led to several applications of remote sensing-based mapping and monitoring schemes (Munyati 2000, Kashaigili *et al*. 2006, Rowberry *et al*. 2011) of these systems (De Roeck *et al*. 2008). Finally, Earth observation data have been used widely in hydrological modelling studies for either mapping land use (Mango *et al*. 2011), estimating driving variables (Mahé *et al*. 2008, Sawunyama and Hughes 2008, Li *et al*. 2013), or quantifying internal fluxes (Marshall *et al*. 2013).

3.2 Hydrological modelling

Some parts of the region, and specifically South Africa, have a long history of research in hydrological modelling (Mendas *et al*. 2008, Warburton *et al*. 2010, Hughes 2013), which has included the development of new models, testing a wide variety of existing models that have been developed elsewhere (Dye and Croke 2003, Mutua and Klik 2007, Ndomba *et al*. 2008, Vischel *et al*. 2008b, Githui *et al*. 2009, Hamlat *et al*. 2013, Sinclair and Pegram 2013), parameter estimation (Nyabeze 2005, Kapangaziwiri and Hughes 2008) and regionalization (Love *et al*. 2011a), problems of data scarcity (Mekonnen *et al*. 2009) and the assimilation of new data types into hydrological models (Milzow *et al*. 2011), as well as assessing uncertainty in modelling (Katambara and Ndiritu 2009, Kapangaziwiri *et al*. 2012). Models have also been applied at different spatial scales from the catchment scale (Hamlat *et al*. 2013 and many others) to large rivers (Tshimanga and Hughes 2014) and continental scales (Alemaw and Chaoka 2003, Trambauer *et al*. 2013). Apart from catchment water balance modelling, progress has also been made in the use of models for flood (Yawson *et al*. 2005, Ngongondo *et al*. 2013, Smithers *et al*. 2013) and drought assessments (Nyabeze 2004), as well as hydraulic modelling of floodplains (Birkhead *et al*. 2007, Unami *et al*. 2009).

3.3 Groundwater modelling

Groundwater is a key resource in many rural parts of Africa (Braune and Xu 2010), especially in the arid regions where surface water resources are scarce and unreliable (Murray *et al*. 2012). Even more so than with surface water modelling, groundwater estimation approaches are constrained by limited data (Van Camp *et al*. 2013, Candela *et al*. 2014). The estimation of recharge is clearly of critical importance (Harris *et al*. 2010, van Wyk *et al*. 2012, Waswa *et al*. 2013, Sun *et al*. 2013), while the links between groundwater and surface water have also received a great deal of attention (Ayenew *et al*. 2008b, Le Maitre and Colvin 2008, Mahé 2009, Pfeffer *et al*. 2013, Tanner and Hughes 2013). Of particular interest in arid zones with ephemeral rivers is the amount of groundwater stored within alluvial aquifers (Quilis *et al*. 2009, Love *et al*. 2011b), while traditional numerical modelling studies of different aquifer types have occurred in various parts of the region (Banoeng-Yakubo *et al*. 2008, Ayenew *et al*. 2008a, El-Bihery 2009).

3.4 Estimating water quality

There are many important water quality issues in Africa that are linked to aridity and agricultural production, especially irrigation, as well as urban and industrial pollution. Some contributions have concentrated on the health and economic issues of deteriorating water quality, but the main focus in this review is on understanding and estimation. One of the major constraints is the lack of quality observations that are available to develop and validate models and, therefore, relatively simple approaches have often been used (Malan *et al*. 2003, Deksissa *et al*. 2004, Omo-Irabor *et al*. 2008, Askri *et al*. 2010). Documented studies span the issues of groundwater quality (Fetouani *et al*. 2008, Hajhamad and Almasri 2009), eutrophication (Nyenje *et al*. 2010), impacts of land-use change (Ngoye and Machiwa 2004, Kulabako *et al*. 2007), erosion and sediment modelling (Defersha *et al*. 2012, Tilahun *et al*. 2013), designing monitoring systems (Chilundo *et al*. 2008), and determining options for water quality management (Deksissa *et al*. 2003).

4 SCIENCE IN PRACTICE

There are many overlaps between the first two Panta Rhei targets and the third, which is orientated towards the practical implementation of hydrological science to benefit society. One area of research that has inevitably received a great deal of attention is the impact of *climate change* and the potential for contributions from the hydrological sciences (see also Section 2.2). Hydrological models have been used to simulate impacts (Wolski and Murray-Hudson 2008, Githui *et al*. 2009, Graham *et al*. 2011, Hughes *et al*. 2011, Ruelland *et al*. 2012, Wolski *et al*. 2012, Faramarzi *et al*. 2013) and develop scenarios of future possible water resources availability. A common thread is the large amount of uncertainty inherent in forcing hydrological models with different climate model projections, and the general conclusion is that this is largely associated with the differences in the climate model outputs. There are a large number of papers that address a range of other topics associated with climate change impacts on water resources (Ngcobo *et al*. 2013). Some have compared the potential impacts of climate change (Kusangaya *et al*. 2014) with impacts related to land cover (Zhao *et al*. 2010), land use (Warburton *et al*. 2010), population dynamics (Reenberg *et al*. 2013) or economic development (Mahé *et al*. 2013). Connections between hydrology and social systems have been made by investigating the vulnerability and adaptation of communities to environmental and development change (Jury 2002, Sturdy *et al*. 2008, Lankford *et al*. 2011, Mwang'ombe *et al*. 2011, Fraser *et al*. 2013, Pasquini *et al*. 2014). Many studies deal with agriculture and agronomy (Adimo *et al*. 2012, Traore *et al*. 2014), including runoff harvesting (De Winnaar and Jewitt 2010, Mwenge Kahinda and Taigbenu 2011), while others deal with more general water resources management issues under climate change.

Another practical focus area in which hydrological modelling has been linked with ecological systems is the quantification of *environmental water requirements* (King and Brown 2006, Mazvimavi *et al*. 2007, Hughes and Louw 2010, McClain *et al*. 2013). One of the problems has always been linking water quantity and quality in integrated assessments of the ecological status of aquatic systems (Palmer *et al*. 2005, Hughes 2009). A clear indication of the interest in environmental flows is illustrated by the number of papers from African institutions in the recently published special issue of *Hydrological Sciences Journal* (Adams 2014, Duvail *et al*. 2014, King *et al*. 2014, McClain *et al*. 2014, Riddell *et al*. 2014, Hughes *et al*. 2014b).

4.1 Integrated water resources management

Research on integrated water resources management (IWRM) in Africa has been dominated by studies focusing on the policy and institutional issues related to translating IWRM into practice (Swatuk 2005, Jonker 2007, Merrey 2008, Mazvimavi *et al*. 2008, Anderson *et al*. 2009, Mehta *et al*. 2014). A considerable number of studies have been carried out by members of WaterNet, which is a network of over 70 institutions in East and southern Africa that promotes training and research on IWRM. This network is running a regional master's degree programme with special emphasis on IWRM, and, since 2000, has been holding an annual symposium during which papers on IWRM related themes are presented. Some of the major conclusions of the policy and institutional related studies have been the lack of political will to implement IWRM (Swatuk 2005), ineffective participation of stakeholders (Manzungu 2002, Dungumaro and Madulu 2003, Kujinga and Jonker 2006, Akpabio *et al*. 2007, Ako *et al*. 2010), mismatch between river basins upon which water resource management is based, and the administrative units used by other sectors. Problems of institutional overlap, lack of understanding and capacity for implementing IWRM were identified by Swatuk and Rahm (2004) and by Mkandawire and Mulwafu (2006). The feasibility of implementing IWRM has also been questioned (Merrey 2008).

Hydrology related studies on IWRM have mainly focused on impacts of various land-use options on elements of the water cycle, largely reflecting the early emphasis of the role of the catchment and the "integrated catchment management" approach. The growing population in sub-Saharan Africa necessitates increasing food and fibre production. Various rainwater harvesting techniques have been proposed, particularly in the semi-arid regions of sub-Saharan Africa, in order to increase food production (Mwenge Kahinda and Taigbenu 2011). Several studies have examined how rainwater harvesting techniques will influence upstream and downstream linkages of river flows. Hydrological modelling has shown that various rainwater harvesting techniques will reduce downstream river flows (Mugabe *et al*. 2011), but De Winnaar and Jewitt (2010) showed that, when restricted to domestic use, the impact is likely to be minor. Increasing abstractions of water for supplemental irrigation can reduce downstream flows and compromise the provision of environmental flow requirements (Sengo *et al*. 2004, Mugabe *et al*. 2011). Effects of upstream expansion of cultivated lands and urban areas on downstream flows have also been investigated (Sengo *et al*. 2004, Palamuleni *et al*. 2011, Warburton *et al*. 2012). The effects of land-use change can be complex and location specific, with impacts being detectable at the local scale, but in some cases not noticeable at the catchment level (Jewitt and Kunz 2011, Mugabe *et al*. 2011, Warburton *et al*. 2012). However, most studies suggest that large-scale upstream land-use changes have significant effects on downstream peak flows and dry season flows, as in the case of the Niger River (Descroix *et al*. 2009, Sighomnou *et al*. 2013).

Studies that attempt to use a holistic approach by linking land uses to hydrological responses and the subsequent effects on livelihoods and attainment of environmental objectives, such as satisfying environmental flow requirements, have also been carried out (Hope *et al*. 2004, Magombeyi and Taigbenu 2011). Hope *et al*. (2004) found that downstream water-dependent livelihood activities were adversely affected by upstream commercial forests. Magombeyi and Taigbenu (2011) developed an integrated modelling framework comprising a semi-distributed rainfall–runoff model, a crop yield model and a socio-economic model to explore impacts of rainwater harvesting on river flows, sediment yield and household incomes. Rainwater harvesting decreased river flows and sediment yield, while crop yields increased. Further studies are needed to examine the effects of human activities in a holistic manner and provide information necessary for implementing IWRM.

Groundwater resources management (Braune and Xu 2010), and its role as a stable water supply under high climate variability and change, has been a research topic of increasing focus (Taylor *et al*. 2009). There is a huge potential for groundwater development in Africa (Altchenko and Villholth 2013), and several studies have explored this in relation to sustainability (Lutz *et al*. 2009), integrated water resources management (Benito *et al*. 2010) and agricultural development (Forkuor *et al*. 2013).

5 CONCLUSIONS

This review has demonstrated that there is substantial hydrological research capacity within Africa and that the topics covered over the past decade have been partly aligned to international trends in the field. However, African understanding of hydrological processes has not led to a cohesive hydrological theory for the conditions pertinent to the continent. The general trend has been to apply and test temperate zone theories and models (developed largely in Europe and the USA) rather than developing new approaches based on the uniqueness and diversity of African conditions. While there were some contributions to the IAHS PUB decade from Africa, the level of participation was therefore relatively small. In contrast, much of the recent research on the continent has anticipated, and arguably already applied, the research themes adopted by IAHS as part of the new Panta Rhei decade of science (Montanari *et al*. 2013). African hydrological scientists should therefore be in a better position to make significant contributions to the new IAHS scientific decade, largely because their research is already grounded in applications linked to societal needs.

One of the positive conclusions of this review is that there exist quite strong partnerships between African and European research teams, particularly within francophone Africa, and as part of the WaterNet organization in southern and eastern Africa, as evidenced by the papers published in *Physics and Chemistry of the Earth* (19 citations in this paper) based on their annual symposia that have been held since 2000.

A single special issue can hardly do justice to the full extent of active hydrological research in a continent the size of Africa. The initial invitation to submit papers was designed to cover the continent as a whole, and was especially directed at emerging researchers to encourage them to make their research more visible internationally (Hughes *et al*. 2014c). The abstracts that were selected for development into full papers were chosen to get regional representation and to cover as broad a range of research topics as possible. Unfortunately, not all of those selected were submitted before the deadline. The final result includes papers that investigate hydrological processes (Tanner and Hughes 2015), hydrometeorological data issues in data-scarce environments (Slaughter *et al*. 2015, Stisen and Tumbo 2015), climate variability and change (Bayissa *et al*. 2015, Kenabatho *et al*. 2015), climate change impacts (Ayeni *et al*. 2015, Noufé *et al*. 2015, Ouermi *et al*. 2015), as well as several that address various issues of modelling hydrological systems (Kollongei and Lorentz 2015, Tekleab *et al*. 2015, Tumbo and Hughes 2015). Some of the papers reflect similar international partnerships evident in the review of existing published papers and referred to in the previous paragraph. Others reflect some emerging partnerships between institutions within Africa.

Some of the papers in this special issue, as well as many of those cited in this paper, are based on relatively localized case studies that are not always considered favourably by the editors and reviewers of international journals, partly because they do not attract many citations. However, local case studies can be used to illustrate more widespread scientific and practical issues. Perhaps what is necessary is for papers submitted on the basis of local case studies to further highlight the more generic outcomes and strengthen the regional and international context of the results (Hughes *et al*. 2014c).

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