PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

rsta.royalsocietypublishing.org

Water security, global change and land–atmosphere feedbacks

Simon Dadson[1], Michael Acreman[2] and Richard Harding[2]

[1]School of Geography and the Environment, University of Oxford, South Parks Road, Oxford, UK

[2]Centre for Ecology and Hydrology, Maclean Building, Crowmarsh Gifford, Wallingford, UK

Review

Cite this article: Dadson S, Acreman M, Harding R. 2013 Water security, global change and land–atmosphere feedbacks. Phil Trans R Soc A 371: 20120412.
http://dx.doi.org/10.1098/rsta.2012.0412

One contribution of 16 to a Theme Issue 'Water security, risk and society'.

Subject Areas:
hydrology, atmospheric science, meteorology

Keywords:
water security, climate change, land use, feedbacks, global hydrological models, uncertainty

Author for correspondence:
Simon Dadson
e-mail: simon.dadson@ouce.ox.ac.uk

Understanding the competing pressures on water resources requires a detailed knowledge of the future water balance under uncertain environmental change. The need for a robust, scientifically rigorous evidence base for effective policy planning and practice has never been greater. Environmental change includes, but is not limited to, climate change; it also includes land-use and land-cover change, including deforestation for agriculture, and occurs alongside changes in anthropogenic interventions that are used in natural resource management such as the regulation of river flows using dams, which can have impacts that frequently exceed those arising in the natural system. In this paper, we examine the role that land surface models can play in providing a robust scientific basis for making resource management decisions against a background of environmental change. We provide some perspectives on recent developments in modelling in land surface hydrology. Among the range of current land surface and hydrology models, there is a large range of variability, which indicates that the specification and parametrization of several basic processes in the models can be improved. Key areas that require improvement in order to address hydrological applications include (i) the representation of groundwater in models, particularly at the scales relevant to land surface modelling, (ii) the representation of human interventions such as dams and irrigation in the hydrological system, (iii) the quantification and communication of uncertainty, and (iv) improved understanding of the impact on water resources availability of multiple use

through treatment, recycling and return flows (and the balance of consumptive and conservative uses). Through a series of examples, we demonstrate that changes in water use could have important reciprocal impacts on climate over a wide area. The effects of water management decisions on climate feedbacks are only beginning to be investigated—they are still only rarely included in climate impact assessments—and the links between the hydrological system and climate are rarely acknowledged in studies of ecosystem services. Nevertheless, because water is essential not only for its direct uses but also for the indirect functions that it serves (including food production, fisheries and industry), it is vital that these connected systems are studied. Building on the examples above, we highlight recent research showing that assessment of these trade-offs is particularly complex in wetland areas, especially in situations where these trade-offs play to the advantage of different communities.

1. Introduction

(a) Biophysical drivers of water security

Understanding the biophysical drivers of water security requires a detailed knowledge of the future distribution of water in the Earth system under uncertain environmental change. The need for a robust, scientifically rigorous evidence base for effective policy planning and practice has never been greater [1], but several key challenges remain in our understanding of the representation of interactions between climate, ecological processes, land use and water availability for human activities. Evidence from field observations, Earth observation and models accumulated over the past 20 years points to the operation of key feedback processes in the Earth system, which complicate any attempt to understand the impact of one isolated change in climate, land use or water management. A change in the distribution of water caused by any one of these processes may have a subsequent impact on the other processes. Through a series of recent examples, we consider the consequences of these findings for water management and water security.

One of the greatest challenges faced by water managers is the need to secure the sustainability of supply under climate scenarios that involve changes in the relative frequency of rainfall events of different magnitude [2]. Uncertainties associated with the rainfall response to climate change are widely acknowledged [3–5]. These uncertainties are compounded when predictions of river flow are required, because the land surface adds complexity through its control on evaporation, soil moisture and groundwater recharge. The loss due to evaporation is often equally uncertain because of its reliance on proper characterization of the land surface and the processes through which vegetation modulates the water vapour flux to the atmosphere, especially under conditions of climate change [6]. The resulting difference represents the surface water balance, i.e. the amount of water remaining after the evaporative demands of the vegetated land surface have been taken into account.

There is wide recognition that the Earth's natural ecosystems deliver important goods and services to mankind [7,8]. While the literature includes some contradictory conclusions on the precise nature of regulatory services of ecosystems on the hydrological cycle, particularly forests [9,10] and wetlands [11], there is broad agreement on the importance of maintaining sufficient water to these ecosystems (generally termed environmental flows) to sustain biodiversity and ecosystem integrity [12,13]. There is thus an important feedback loop between ecosystems and the water cycle that needs to be understood and quantified to ensure water security (figure 1).

(b) Integrated data and model analyses

Knowledge of the components of the global water cycle is an essential prerequisite of any analysis of water security. Such information is required on a range of time and space scales. For a global

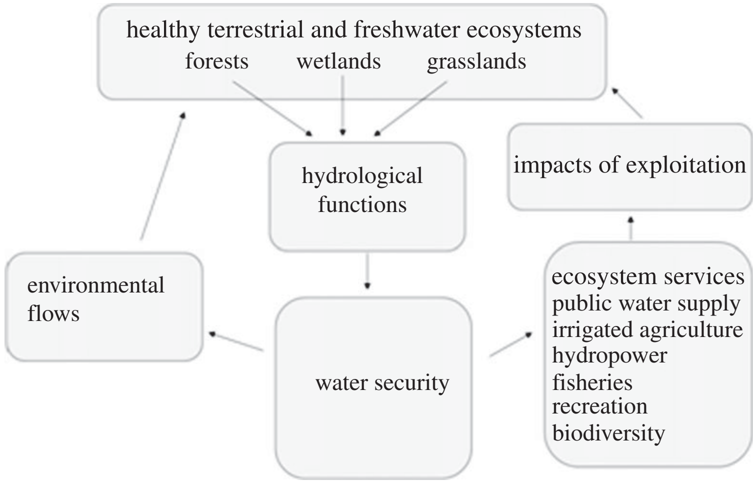

Figure 1. Feedback between ecosystems and water security.

or continental basin scale, a 50 km (or 0.5°) scale is a useful compromise to provide large-scale resource assessment and to link with climate models for analyses of the future. Nevertheless, a number of uncertainties are associated with this choice of model resolution: such a scale cannot capture features such as localized flooding and local interventions but can capture large-scale flooding and droughts. Daily information is of great value to assess flooding and droughts and to feed into hydrological and land surface models, but sub-daily data would be required in order to assess local and regional features.

Of the main components of the water cycle only precipitation and run-off are measured and collated systematically at a global scale, and even then there are many gaps. Other components and stores, such as evaporation, soil moisture and groundwater, are measured only sporadically, often using inconsistent techniques. One of the most comprehensive sets of precipitation data is that from the Global Precipitation Climatology Centre[1] (GPCC; [14]). These gridded data are provided monthly on a 0.5° or 1.0° grid. Two datasets are provided: first, the monitoring product is available for the period 1986 to present, based on quality-controlled data from 7000 stations; second, the full data product is available for the period 1951–2004 and is based on quality-controlled data from a larger number of stations (up to 43 000) with irregular coverage in time. The reliability of these global gridded datasets has been questioned, especially over the tropics, deserts, mountain ranges and large parts of the Asian continent because of the sparse spatial distribution of measurement stations, exacerbated by their decreasing number in recent decades [15]. Some of these gaps are being filled with satellite data arising from the Global Precipitation Climatology Project [16] but there remain significant problems, particularly in mountainous areas.

The Global Runoff Database held at the Global Runoff Data Centre[2] (GRDC) contains river discharge data collected at daily or monthly intervals from more than 8000 stations in 157 countries. This adds up to around 320 000 station-years with an average record length of 40 years. The monthly datasets have a good global coverage, although many datasets are not current and finish prior to 1980. These data are also available as a global interactive map at the Global Water System Project (GWSP) water atlas map.[3] Stahl *et al.* [17] collated a daily streamflow dataset from over 400 small, semi-natural basins from the European Water Archive and elsewhere, specifically to investigate changes in extremes across Europe; and even within Europe there were significant difficulties in accessing data from some countries.

[1]See http://www.esrl.noaa.gov/psd/data/gridded/data.gpcc.html.

[2]See http://www.bafg.de/GRDC.

[3]See http://atlas.gwsp.org.

Estimates of global average land evapotranspiration range between 1.1 and 2.0 mm d^{-1}, with an ensemble mean of approximately 1.5 mm d^{-1}. Thus, there is considerable variability both within the observationally based estimates and between these estimates model-based reanalyses, and Intergovernmental Panel on Climate Change (IPCC) AR4 climate simulations [18]. The best estimates of evapotranspiration are made using eddy covariance techniques, but these are available only at a limited set of stations. The FLUXNET[4] project gathers over 500 such stations, but the geographical coverage is patchy, and many stations have records covering only a few years. A number of initiatives have produced global land evapotranspiration maps based on FLUXNET data, Earth observations, models or a combination of these sources.[5]

Soil moisture plays a critical role in land–atmosphere interactions, both as a store of water and as a control on both evaporation and run-off. While there are a few regions with substantial *in situ* soil water observations [19], the coverage of these observations is patchy, and there is no consistency over methodology or depth. Global coverage is possible with microwave satellite sensors (e.g. AMSR-E, SMOS and ASCAT); however, the measurements cover only the top few centimetres of soil, and the influence of vegetation cover poses additional difficulties in interpretation [20]. Soil moisture levels can be calculated from land surface and hydrological models, although every model treats soil moisture differently, and so interpretation and comparison are difficult.

Groundwater is the world's largest accessible store of freshwater and contributes 42% of the water used for irrigation, 36% of household water consumption and 27% of water demand for manufacturing [21]. A number of studies have estimated groundwater recharge and depletion globally [22,23] using hydrological models, demonstrating the continuing depletion of groundwater resources. These estimates contain many uncertainties, not least the uncertainties in evaporation estimates discussed above and difficulties in modelling ground water recharge in semi-arid regions [23], highlighting the continuing need for regional observations of groundwater to validate these estimates. The World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP) initiative has provided global maps of aquifer properties and the Global Groundwater Archive is an important initiative to collect groundwater data; however, progress is slow in collecting data [24]. Meanwhile, the Gravity Recovery and Climate Experiment (GRACE) satellite has provided considerable insights into dynamic changes in groundwater globally at large scale, highlighting rapid depletion in groundwater storage in India, the USA and elsewhere [25,26].

Land surface and global hydrology models provide an alternative approach to the global estimation of components of the terrestrial water cycle [27]. The WATCH Forcing Data provide a single global dataset of the climate variables required to drive hydrological models, which covers the period 1901–2001. It has been produced by combining the Climatic Research Unit's monthly observations of temperature, 'wet days' and cloud cover with the GPCCv4 monthly precipitation observations and the ERA40 reanalysis products (with the addition of corrections for varying atmospheric aerosols to adjust the solar radiation). The WATCH Driving Data cover the period 2001–2100 and have been generated using three well-established climate models that have been downscaled and bias corrected. Each model was run for two different IPCC scenarios, giving six data subsets within the driving data. All of the forcing and driving datasets cover the land surface of the Earth on a 0.5° grid [28].

(c) Anthropogenic interventions in the water cycle

While physical science can provide important information on the availability of water in the future, the role of changing anthropogenic intervention is often as critical in developing scenarios of change in freshwater systems [29,30]. Anthropogenic interventions that form part of natural resource management include the regulation of river flows using dams, artificial abstraction

[4]See http://fluxnet.ornl.gov/.

[5]See http://www.iac.ethz.ch/groups/seneviratne/research/LandFlux-EVAL.

from surface or groundwater stores and the use of water from a range of sources for irrigation. The sustainability of anthropogenic demands on water resources under scenarios of climate and land-use change is a serious question for water managers and decision-makers.

Several recent studies have indicated that anthropogenic water demand is often equivalent in magnitude to the natural components of the water balance [31,32]. The consequences of this situation are particularly acute in river basins where a considerable fraction of the renewable flow of the river is abstracted for human use (e.g. Colorado, Murray–Darling [31]) and also in locations where the rate of groundwater abstraction exceeds the rate of recharge (e.g. United States High Plains Aquifer [33]; northwestern India [25]). The increasing importance of abstraction raises two questions: (i) what are the consequences of large-scale geophysical changes in climate and land use on the sustainability of anthropogenic modifications to the water budget, and, conversely, (ii) what are the consequences of large-scale alterations to the management of the land surface on the climate system?

(d) Water security and global environmental change

The scope of environmental changes that have driven the availability of water resources in the past is broad. Recent debate has stressed that, while the evidence for anthropogenic climate change is unequivocal, the effect on precipitation, especially precipitation extremes, is less certain. Overall, precipitation is expected to increase with increasing temperatures [4]. There will, however, be large regional variations, with the subtropics becoming drier and high latitudes wetter—a feature widely observed in recent decades [3,5,34]. Precipitation extremes are also likely to increase and increasing extreme rainfall is observed in most regions of the world [6]. Many regions of the world, however, do not have sufficiently long or detailed records to support definite conclusions. This is particularly true of sub-daily records [5].

Nevertheless, while climate change is an important driver of global change, it is not the only factor in play. Land-cover change, sea-level shifts and anthropogenic interventions have in the past influenced water resource availability either because they directly affect the availability of water at the surface or because they control the quality of available water supplies. The role played by complex spatial heterogeneity in land-cover change also remains a key unknown in quantifying the local response to environmental change (e.g. changes in latent heat flux owing to altered tropical vegetation [35,36] and the direct effects of vegetation on albedo in northern latitudes [37]). These drivers of global change have received global attention through initiatives equal in scope and in profile to the IPCC [38–40], including the United Nations Environment Programme GEO-5 Assessment [41], the Millennium Ecosystem Assessment (MEA) [42] and the International Geosphere–Biosphere Programme [35]. The emphasis on joint drivers of change in different spheres of the Earth system has prompted calls for multi- and interdisciplinary evaluations of the joint, interacting effects of changes in components of the Earth system [43–46].

(e) Uncertainty

The quantification of uncertainty has received much attention across a range of geophysical academic disciplines and in wider discussion with social researchers and policy-makers [38–40]. This engagement with uncertainty has a long tradition that has developed from a straightforward evaluation of the range of outcomes predicted by different climate models to a series of designed model experiments designed to span the range of possible radiative forcing and model formulations [47–49]. The more recent use of perturbed physics ensembles has permitted a focus on the key processes that contribute most clearly to uncertainty in model predictions [50–52]. Improved knowledge of these processes is widely expected to yield reductions in model uncertainty [53]. It is true, however, that increasing the number of processes within models also tends to increase the uncertainty range.

Model uncertainty exists alongside internal variability and scenario uncertainty. The relative importance of particular sources of uncertainty varies in important ways with the time scale of

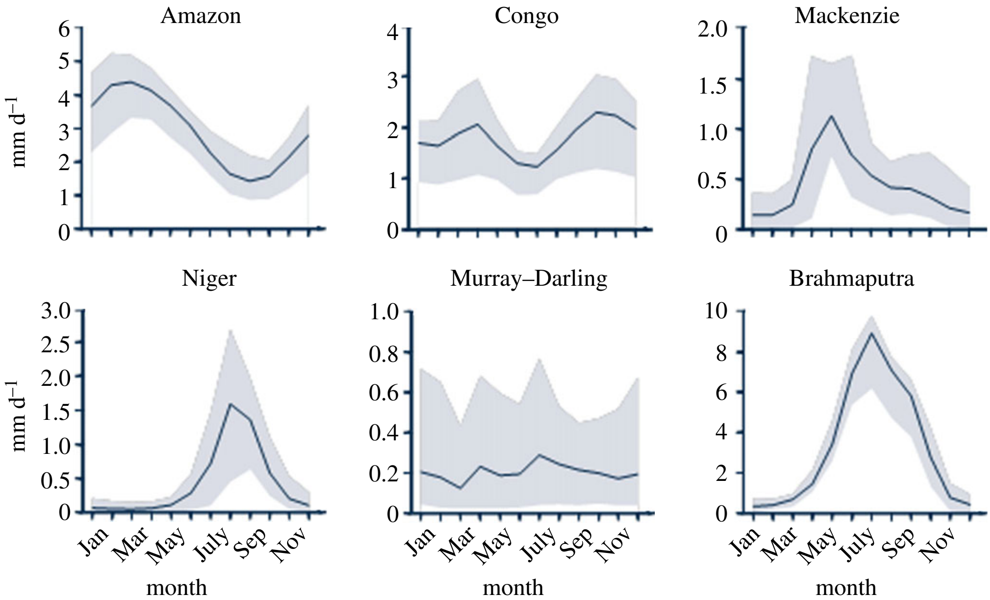

Figure 2. Multi-model total run-off for six of the world's major river basins for the period 1985–1999. Ensemble mean (solid line) and range (shaded area) of 13 hydrological and land surface models, from the WaterMIP inter-comparison [29,54]. (Online version in colour.)

prediction required. Weather forecasts and seasonal predictions are influenced to a great extent by internal variability and initial condition uncertainty. By contrast, multi-decadal predictions (out to 2100, for example) are dominated by scenario uncertainty, with decadal climate predictions controlled by a balance of model and scenario uncertainty [53].

While model inter-comparisons have been commonplace in climatology (e.g. Coupled Climate Carbon Cycle Model Intercomparison Project (C4MIP) and Project for Intercomparison of Land-surface Parameterization Schemes (PILPS)), recent work under the auspices of the Water Model Intercomparison Project (WaterMIP) has brought a similar approach to the study of hydrological responses to climate change. The WaterMIP used the WATCH Forcing Data to provide a consistent comparison of 11 land surface and hydrology models [54]. All models were run for a 15 year period (1985–1999). Simulated global terrestrial evapotranspiration, excluding Greenland and Antarctica, ranged from 415 to 586 mm yr^{-1} (1.2–1.6 mm d^{-1}) and simulated run-off from 290 to 457 mm yr^{-1}. Both the mean and median run-off fractions for the land surface models were lower than those of the global hydrological models. Significant differences between land surface and global hydrological models were attributed to differences between the snow schemes, which are typically physically based energy balance models in land surface simulations but which in large-scale hydrology models are usually based on a more empirical degree-day approach. Some differences in simulated run-off and evapotranspiration can be explained by model parametrizations, although the processes included and parametrizations used are not distinct to either land surface models or global hydrological models. The results of this study show that differences between models are a major source of uncertainty (figure 2), and climate change impact studies require not only multiple climate models but also some other measure of uncertainty (e.g. multiple impact models). It is also clear that the significant improvements in process representation could improve model results and reduce uncertainty.

A comparison of WaterMIP simulations against a dataset of European streamflows [17] revealed large uncertainties in the individual models' abilities to simulate the amplitude and timing of the mean run-off cycle; however, the ensemble mean yielded rather more robust results [55]. Some serious variations and shortcomings were revealed in the ways the models handled the timing of snow accumulation and melt. In a subsequent study, using the same data

to simulate high- and low-flow events, a subset of three models (Joint UK Land Environment Simulator (JULES), MPI-HM and WaterGAP) reproduced the broad spatio-temporal evolution of hydrological extremes in Europe, but the reproduction of variability and spatial coherence of low and high flows was found to be variable [56]. Some systematic weaknesses emerged in all models, in particular for high flows, which could be a product of poor spatial resolution of the input climate data (e.g. where extreme precipitation is driven by local convective storms or topography). In addition to model uncertainties, there are considerable uncertainties associated with input variables, particularly rainfall, which can be substantial [57,58].

There are many uncertainties within our assessment of the physical water system, including our understanding of past changes, our simulation of the components of the water cycle and our predictions of the future. The Global Energy and Water Cycle Experiment (GEWEX) has recently identified four Grand Science Challenges—covering observations and predictions of precipitation, global water resource systems, changes in extremes, and the water and energy cycles—to focus the efforts of the science community.[6] It is clear that improvements will come with better data and enhanced integration of models and data. It is also clear from the inter-comparison studies that there is considerable scope to improve land surface and global hydrological models, particularly with better representation of snow and storages, such as groundwater and soil water.

2. Hydrological feedbacks in the Earth system

Internal feedbacks frequently arise within complex, interconnected environmental systems (see [59] for some recent examples). The presence of feedbacks alongside external drivers adds an extra set of scientific questions to those that are usually considered in impacts assessments, because models of systems that include feedbacks must include an explicit representation of the connections between the hydrosphere, lithosphere and biosphere.

Feedbacks between the land surface and the atmosphere occur at many scales. At the local or patch scale (1–10 km), a patch of irrigated land or forest may influence the local temperature and humidity through changes in water availability and roughness, which will, in turn, feed back on the evaporative demand. At a regional scale (up to a few hundred kilometres), changes in the land surface may not only influence local temperature and humidity but also change local cloud amounts (hence radiation inputs [60]) and generate local atmospheric circulations, with the possibilities of the initiation of convective rainfall systems [61,62]. At continental scales, a changing land surface can, in principle, change large-scale atmospheric circulation, such as the monsoon [63]. The influence of land surface depends not only on scale but also on the hydro-climatology of a region, thus Koster *et al.* [64] found geographical hotspots of the interaction between soil moisture and rainfall concentrated in semi-arid regions where the contrasts in soil moisture are likely to be large.

While large numbers of studies suggest a strong interaction between the land surface and climate the majority of these studies rely on numerical models. The LUCID project [35] has addressed the robustness of estimates of biogeophysical impacts of historical land-use change. An analysis of seven coupled land surface/climate models generally showed a significant reduction in available energy and cooling in regions where forest cover had been replaced by agriculture but few significant or consistent changes in precipitation [35]. This result mirrors that of Koster *et al.* [64], who found a considerable variation in the strength of land surface coupling in the climate models used.

In the following, we present a number of recent examples to illustrate emerging evidence for the control exerted by land–atmosphere feedbacks on water availability.

(a) Feedbacks from irrigation

Looking more deeply at the impact of anthropogenic demands on water, evidence has emerged in the past decade pointing towards the considerable impact that anthropogenic interventions in the

[6]See http://www.gewex.org/pdfs/grand_challenges_7-2012.pdf.

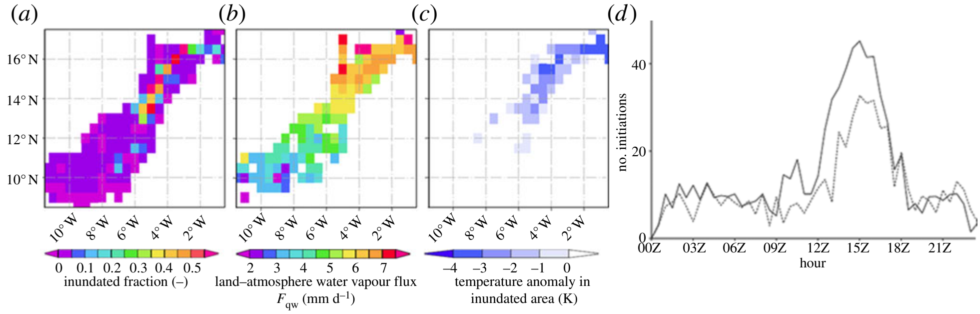

Figure 3. Role of seasonal inundation in land surface evaporation and associated heat flux in the inland delta of the Niger River, Mali. Spatial pattern of model predictions. (*a*) Inundated fraction. (*b*) Land–atmosphere water vapour flux. (*c*) Temperature anomaly in inundated regions, measured as the difference between the inundated open-water tile and grid box mean over all tiles. (*d*) Diurnal cycle of storm initiations over the region 3–6.5° W, 14–15.5° N for wet (solid line) and dry (dashed line) periods. (Adapted from [67,68].)

water cycle such as irrigation, groundwater abstraction and surface water management can have on regional climatological patterns. A recent historical evaluation of the effect of representing irrigation in a climate model has demonstrated that in the twentieth century irrigation has led to a significant reduction in temperature trends in the boreal summer over irrigated regions, with consequent increases in precipitation as a result of the additional water vapour flux to the atmosphere [65]. A striking example of this effect is the finding that the extra water added to the land surface as a result of widespread irrigation in India has reduced the land–sea temperature gradient and altered the circulation pattern of the South Asian summer monsoon itself [63]. The consequences of these connections between water resource management and global climate suggest hitherto unexplored possibilities that water management strategies in one region might affect climate in another and motivate an urgent need to represent water management in Earth system models [21,32,66].

(b) Wetland inundation and cloud feedbacks

The availability of water at the surface has the potential to alter fluxes of heat and moisture to the atmosphere and, in areas where convection is limited by water availability such as the transition zones between semi-arid and wetter climates, can be an important control on mesoscale convection [6,64]. The role of land–atmosphere feedbacks in modifying the climate and in climate impacts is particularly evident in the Niger inland delta, where observed river gauging data show significant evaporative losses from the land and water surface [67]. Adding a subgrid-scale parametrization of overbank inundation to the JULES land surface model enables the salient features of the observed inundation pattern to be reproduced, and reveals that significant evaporative losses from the inundated region account for a doubling in the total land–atmosphere water flux during periods of greatest flooding. Moreover, the suppression of sensible heat flux establishes a hypothesized 'wetland breeze' effect, which promotes the daytime initiation of convective storms and generates a series of long-lived mesoscale convective systems, which have the possibility of impacting on the rainfall in the surrounding region (figure 3; [68]).

(c) Heat waves and drought

Spatial and temporal patterns of water availability greatly affect the resilience of water resource systems [1]. The global spatial synchronicity of drought, shown for summer 1976 in figure 4 [69], alters the ways in which water managers, insurers and civil contingencies planners might respond given that events such as the ensuing 1976 drought are not isolated in space nor independent

Figure 4. Synchronicity of global drought for August 1976. Red areas indicate where the simulated run-off is lower than 5 of 100 year run-off (95%); orange areas indicate run-off lower than 10 of 100 year run-off (90%); blue areas indicate run-off lower than 15 of 100 year run-off (85%); and light blue areas indicate run-off lower than 20 of 100 year run-off (80%) [29].

in time. The majority of recent European summer heat waves (1976, 1994, 2003 and 2005) have been linked to negative soil moisture anomalies during the preceding spring, which led to reduced latent heat fluxes and therefore greater surface warming in the subsequent summers [70]. The interactions between soil moisture and temperature are thought to account for over half of the days with extreme temperatures during these periods [70], and one recent estimate, made using a large ensemble of simulations, suggests that the risk of such heat waves has been doubled as a result of anthropogenic emissions of carbon dioxide [71].

Taken together, the examples cited above that document the importance of climate feedbacks between soil moisture and persistence of low rainfall demonstrate that changes in the distribution of water at the surface as a result of human interventions could, in fact, have important reciprocal impacts on climate over a wide area. The effects of water management decisions on climate feedbacks are only beginning to be investigated—they are still only rarely included in climate impact assessments—and the links between the hydrological system and climate are rarely acknowledged in studies of ecosystem services. It is clear that interactions between hydrology and climate occur on many space and time scales, involve a whole range of processes and are incompletely represented within land surface and climate models. Nevertheless, because water is essential not only for its direct uses but also for the indirect functions that it serves (including food production, fisheries and industry), it is vital that these connected systems are studied.

3. Water security, ecosystem services and environmental flows

The previous sections have focused on the importance of feedbacks in land–atmosphere interactions for water security. A further crucial feedback process occurs across the landscape between ecosystems (terrestrial, wetland and aquatic) and water resources. Figure 5 depicts the role of ecosystems influencing the hydrological cycle to support water security on which many ecosystem services are based, and emphasizes the importance of maintaining environmental flows to conserve ecosystem functions. The exploitation of ecosystem services presents an additional feedback loop. For example, wise use of wetland resources [73] such as sustainable fisheries supports food security without degrading the ecosystem. By contrast, exploiting water resources to generate hydropower by building a dam can negatively impact on the river ecosystem and loss of fisheries, presenting a trade-off as demonstrated in the River Mekong [74].

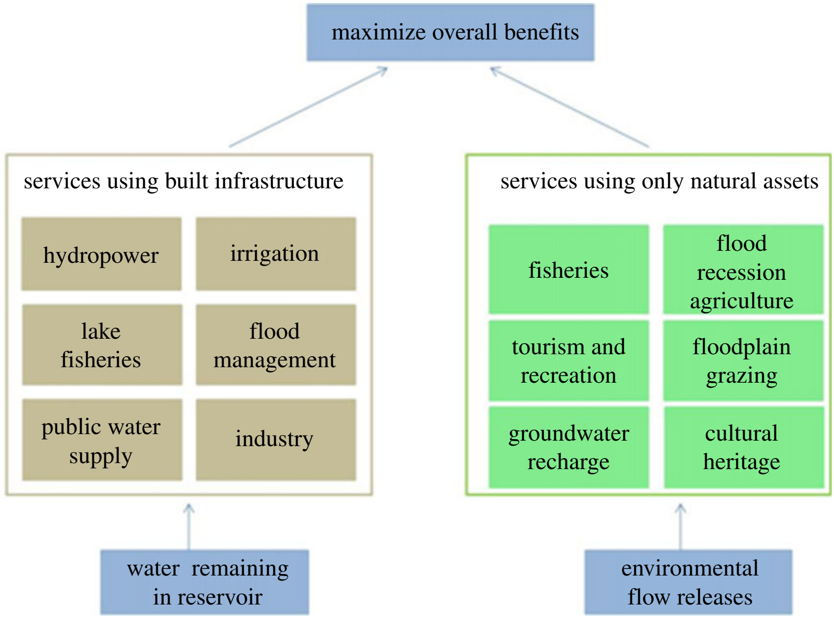

Figure 5. Developing world trade-off. (Adapted from Acreman & McCartney [72].) (Online version in colour.)

(a) Ecosystem services

The United Nations Conference on Environment and Development (UNCED) held in Rio in 1992 was an important turning point in modern thinking; it raised to a global political level the view that the lives of people and the environment are profoundly interlinked. Ecological processes keep the planet fit for life, providing our food, air to breathe, medicines and much of what we call 'quality of life' [75]. Freshwater ecosystems provide economic security (e.g. fish, plant foods and medicines, timber); social security (e.g. protection from natural hazards, such as floods); and ethical security (e.g. upholding the rights of people and other species to water; [75]). Water used for economic growth (i.e. for drinking, growing food, generating power and supporting industry) has been viewed as water directly for people, whereas water for ecosystems has been considered as water indirectly for people through the goods and services they deliver [76]. This idea attempted to counter the notion of conflict in water resource allocation that water was either for people or for Nature. Despite this, the MEA [42] showed that many ecosystems were being degraded or lost, with aquatic systems suffering particularly from abstraction or diversion often associated with dams [32,74,77,78]. The MEA used the concept of ecosystem services, which developed largely through wetland research [73], to demonstrate the value of Nature and its contribution to social and cultural well-being [8].

(b) Environmental flows

The idea for environmental water needs began in the 1940s, in the western USA [79] with rapid methodological development during the 1970s [80–82] in parallel with changes in legislation. The UK Water Resources Act 1963 stated that minimum acceptable flows were required to maintain natural beauty and fisheries, and the Clean Water Act in the USA in 1972 set the objective of restoring and maintaining the chemical, physical and biological integrity of the nation's waters. However, it is in South Africa that the law most explicitly recognizes that the highest priority for water should be for the environment, after basic human needs [83]. In particular, South Africa recognized the crucial feedback between water and wetlands. Many countries, including Tanzania and Costa Rica, now have similar legislation.

Under the European Water Framework Directive, the general aim for all river water bodies is to achieve good ecological status, and flow requirements to meet this aim have been defined

[84]. The concept of flow required for natural ecosystems has evolved from the initial idea of minimum flow, which assumed that the river ecosystem would be protected if flow was maintained above a low threshold value, to whole flow regimes. The term 'environmental flows' is now widely used and describes the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems.[7] The concept of environmental flows is now a key element in many international policies (such as the Convention on Biological Diversity, signed by 168 countries, and the International Convention on Wetlands, signed by 132 countries).

To manage ecosystems and water in the integrated manner required, the concept of environmental flows needs to be incorporated within hydrological models. Although there are technically more than 200 methods available to assess environmental flows, they fall broadly into two types. The first type is based on the natural flow paradigm [12,85], which proposed that river species or communities are dependent on multiple aspects of the flow regime. This view encompasses the concept of the flood pulse [86], wherein flooding is considered to be important for linking river and floodplain ecosystems. Thus, any alteration from the natural flow regime will lead to some ecosystem degradation and possible loss of ecosystem services, with too much flow at the wrong time being as detrimental as too little flow. The application of this approach is most evident in the protection of natural rivers, such as in protected areas, e.g. national parks. Using the natural flow paradigm for setting environmental flows can be thought of as a 'top-down' approach [13] in that the full reference flow regime provides the baseline point of reference and elements are removed, such as certain flood events that are not essential to meet a particular desired ecological state.

The second type of method recognizes that much of the Earth's surface has been managed intensively for many millennia, as human populations have expanded, and that major infrastructure, such as dams, provides essential water, food and energy security [87]. The premise here is to identify specific species, communities, functions or ecosystem services required and to attempt to design the river's flow regime to deliver these objectives. This is essentially a 'bottom-up' approach that starts, at least conceptually, with no flow (the situation below a dam with outlet gates closed) and builds up a flow regime by adding low flows, high channel flows and floods at different times, of different magnitude and duration, until the specified objectives are met. The most well known is the building block methodology [88]. This can be a particularly useful concept where decisions have already been made over the broad allocation of water resources. Attention is then focused on using the environmental water allocation to best meet the objectives of society for the river. The approach is amenable to heavily managed rivers where specific reservoir flow releases are likely to be used to deliver particular objectives, e.g. fish breeding or natural floodplain irrigation. The downstream response to imposed flow transformations (DRIFT) method [89] incorporates an optimizing routine to help design the most effective flow regime where various scenarios of flow regime alteration are specified in relation to dam operations [90,91]. Currently, these methods are not directly linked to hydrological processes models and tend to be applied separately in sequence. There is great potential for linking hydrological models and environmental flow models to establish the important feedback between water security and ecosystem processes.

(c) Trade-offs in water management for ecosystem services

Ecosystem services provide a useful framework, because exploitation of the ecosystem, for example its water, for public supply and intensive irrigation can be seen as ecosystem services that require input of built infrastructure (such as dams and pipes) alongside services that rely more exclusively on natural assets [92], such as fisheries. Water allocation can be considered in terms of a trade-off in the ecosystem services. Water held in a dam can be for direct use, whereas water released as an environmental flow will support indirect use (figure 5).

[7] See http://www.flownet.org.

Building on the examples given in §3*b*, we highlight recent research showing that assessment of hydrologically based ecosystem trade-offs is particularly complex in wetland areas, especially in situations where trade-offs in the biophysical system play to the advantage of different communities [73]. We suggest that improvements in the modelling of coupled climate feedbacks will create new opportunities for more thorough assessments of ecosystem trade-offs that arise in response to environmental and water management decisions. For example, building of the Fomi Dam in Guinea will allow expansion of irrigation in southern Mali, but the resulting reduction in flood extent in the Inner Niger Delta [93] may alter patterns of grazing and could also reduce rates of evaporation and rainfall in surrounding areas. The resulting trade-offs in food provision (and between the people of northern and southern Mali) can only be understood using coupled models.

In many African river systems (e.g. Senegal, Logone and Kafue), development is focused on poverty alleviation, and environmental flows aim to deliver simple annual flood-dominated hydrographs that are required for flood recession agriculture, fisheries and cattle grazing and directly support local rural livelihoods [94]. Appropriate balancing of the management of dams has had benefits for natural services as well as created services. For example, environmental flow management on the Logone River in northern Cameroon using infrastructure of the Lake Maga reservoir has produced regular inundation of the Logone floodplain and production of constant ecosystem services that were otherwise highly variable under extremes of droughts and large floods generated by a natural flow regime [95]. At the same time, sufficient water has been retained in Lake Maga to support intensive rice irrigation downstream of the dam. Reservoirs are not necessarily without ecological value. For example, in 2012, the government of Tunisia designated six reservoirs as wetlands of international importance under the Ramsar Convention, including the Barrage de Sidi El Barrak, which stores irrigation water and provides a supply of potable water to the city of Tunis but supports the threatened Eurasian otter (*Lutra lutra*).

With any allocation of resources, there will inevitably be winners and losers. The Manantali Dam in Mali was constructed to supply hydroelectricity to cities in Senegal, Mauritania and Mali, thus benefiting the urban elite, commerce and industry, at the expense of the rural poor downstream who had little electrification and who lost ecosystem benefits of floodplain inundation, including fisheries, flood-recession agriculture [96,97].

4. Conclusion

The prospects for using coupled land surface hydrology models to understand the role of human water management decisions in the global hydrological cycle are compelling [98] and raise the possibility that land surface models could themselves be used to inform water allocation decisions. Many of the improvements to land surface models that we advocate require a corresponding improvement to the observed data available to build and test the models themselves. There is still a need to improve global fields of components of the global water cycle, both for assessment of existing resources and to benchmark and improve coupled models. In particular, precipitation data are scarce in sparsely populated and mountainous regions, where coverage is limited, but evaporation and soil moisture data are also problematic because they are not measured using standardized techniques, nor are such measurements routinely collated. In many regions of the world, measurement networks are degrading and, in others, there are institutional barriers to the free exchange of data. Remote Earth observations help to fill some gaps, but *in situ* data are still essential to validate and calibrate satellite products.

There remains an urgent need to improve (i) the representation of groundwater, particularly at the scales relevant to land surface modelling; (ii) the storage of water in snow—in a manner both that is physically realistic and that maintains the energy balance at the surface; (iii) the representation of human interventions such as land-cover changes, dams and irrigation in the hydrological system; (iv) the quantification and communication of uncertainty in a way that is accessible to stakeholders and that uses metrics defined by and of importance to end-users and decision-makers; (v) the recognition and quantification of a wide range of ecosystem services

provided by the river corridor and the linkage to environmental flow provision; and (vi) the definition and quantification of multiple use as this is important for quantifying the true supply of the resource.

Feedbacks can be extremely important, particularly where water fluxes are limited by soil moisture. However, given the diversity and complexities of both the physical feedbacks and interactions between water management and the hydrological cycle, it is impossible at present to identify hard and fast rules to determine when and how coupled models should be used. It is suggested that the continued collection of individual case studies, such as those presented here, should ultimately provide guidance on coupled modelling and the incentive to improve the realism of Earth system models.

Acknowledgements. We thank Chris Taylor and Douglas Clark for their contributions to figures 2 and 3. This paper was presented as a contribution to the Oxford Water Security, Risk and Society Meeting in April 2012 and thanks are due to the other panellists and discussants for their valuable feedback. We thank two anonymous reviewers for their feedback, which substantially strengthened the manuscript.

Funding statement. Financial support for this work was provided to S.D. by the UK Natural Environment Research Council (NE/E011969/1 and NE/I01277X), and to R.J.H. and S.D. via the European Commission Water and Global Change (WATCH) Integrated Programme (contract no. 036946).

References

1. Grey D, Garrick D, Blackmore D, Kelman J, Muller M, Sadoff C. 2013 Water security in one blue planet: twenty-first century policy challenges for science. *Phil. Trans. R. Soc. A* **371**, 20120406. (doi:10.1098/rsta.2012.0406)
2. Milly PCD, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz ZW, Lettenmaier DP, Stouffer RJ. 2008 Climate change: stationarity is dead: whither water management? *Science* **319**, 573–574. (doi:10.1126/science.1151915)
3. Allan RP, Soden BJ. 2008 Atmospheric warming and the amplification of precipitation extremes. *Science* **321**, 1481–1484. (doi:10.1126/science.1160787)
4. Allen MR, Ingram WJ. 2002 Constraints on future changes in climate and the hydrological cycle. *Nature* **419**, 224–232. (doi:10.1038/nature01092)
5. Trenberth KE. 2011 Changes in precipitation with climate change. *Clim. Res.* **47**, 123–138. (doi:10.3354/cr00953)
6. Seneviratne SI, Corti T, Davin EL, Hirschi M, Jaeger EB, Lehner I, Orlowsky B, Teuling AJ. 2010 Investigating soil moisture–climate interactions in a changing climate: a review. *Earth Sci. Rev.* **99**, 125–161. (doi:10.1016/j.earscirev.2010.02.004)
7. Assessment ME. 2005 *Ecosystems and human well-being*. Washington, DC: Island Press.
8. Fischer B, Turner RK, Morling P. 2009 Defining and classifying ecosystem services for decision making. *Ecol. Econ.* **68**, 643–653. (doi:10.1016/j.ecolecon.2008.09.014)
9. Andréssian C. 2004 Waters and forests: from historical controversy to scientific debate. *J. Hydrol.* **291**, 1–27. (doi:10.1016/j.jhydrol.2003.12.015)
10. Chappell NA. 2005 Water pathways in humid forests: myths vs observations. *Suiri Kagaku (Water Sci.)* **48**, 32–46.
11. Bullock A, Acreman M. 2003 The role of wetlands in the hydrologic cycle. *Hydrol. Earth Syst. Sci.* **7**, 358–389. (doi:10.5194/hess-7-358-2003)
12. Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997 The natural flow regime: a paradigm for river conservation and restoration. *Bioscience* **47**, 769–784. (doi:10.2307/1313099)
13. Arthington AH, Lloyd R (eds). 1998 *Logan river trial of the building block methods for assessing environmental flow requirement: workshop report*. Queensland, Australia: Centre for Catchment and Instream Research and Department of Natural Resources.
14. Schneider U, Becker A, Finger P, Meyer-Christoffer A, Ziese M, Rudolf B. 2013 GPCC's new land surface precipitation climatology based on quality-controlled *in situ* data and its role in quantifying the global water cycle. *Theor. Appl. Climatol.* (doi:10.1007/s00704-013-0860-x)
15. Lorenz C, Kunstmann H. 2012 The hydrological cycle in three state-of-the-art reanalyses: intercomparison and performance analysis. *J. Hydrometeorol.* **13**, 1397–4120. (doi:10.1175/JHM-D-11-088.1)

16. Adler RF *et al*. 2003 The version-2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979–present). *J. Hydrometeorol.* **4**, 1147–1167. (doi:10.1175/1525-7541(2003)004<1147:TVGPCP>2.0.CO;2)
17. Stahl K, Hisdal H, Hannaford J, Tallaksen LM, van Lanen HAJ, Sauquet E, Demuth S, Fendekova M, Jódar J. 2010 Streamflow trends in Europe: evidence from a dataset of near-natural catchments. *Hydrol. Earth Syst. Sci.* **14**, 2367–2382. (doi:10.5194/hess-14-2367-2010)
18. Mueller B *et al*. 2011 Evaluation of global observations-based evapotranspiration datasets and IPCC AR4 simulations. *Geophys. Res. Lett.* **38**, L06402. (doi:10.1029/2010GL046230)
19. Dorigo WA *et al*. 2011 The International Soil Moisture Network: a data hosting facility for global in situ soil moisture measurements. *Hydrol. Earth Syst. Sci.* **15**, 1675–1698. (doi:10.5194/hess-15-1675-2011)
20. Wanders N, Karssenberg D, Bierkens M, Parinussa R, de Jeu R, van Dam J, de Jong S. 2012 Observation uncertainty of satellite soil moisture products determined with physically-based modeling. *Remote Sens. Environ.* **127**, 341–356. (doi:10.1016/j.rse.2012.09.004)
21. Döll P, Hoffmann-Dobrev H, Portmann FT, Siebert S, Eicker A, Rodell M, Strassberg G, Scanlon BR. 2012 Impact of water withdrawals from groundwater and surface water on continental water storage variations. *J. Geodyn.* **59–60**, 143–156. (doi:10.1016/j.jog.2011.05.001)
22. Wada Y, van Beek LPH, van Kempen CM, Reckman JWTM, Vasak S, Bierkens MFP. 2010 Global depletion of groundwater resources. *Geophys. Res. Lett.* **37**, L20402. (doi:10.1029/2010GL044571)
23. Doll P, Fiedler K. 2008 Global-scale modeling of groundwater recharge. *Hydrol. Earth Syst. Sci.* **12**, 863–865. (doi:10.5194/hess-12-863-2008)
24. Taylor R *et al*. 2010 Groundwater and global hydrological change – current challenges and new insight. In *Hydrocomplexity: new tools for solving wicked water problems, Proc. 10th Kovacs Colloquium* (eds S Khan, H Savenije, S Demuth and P Hubert), pp. 48–58. IAHS Publication no. 338. IAHS: Wallingford.
25. Rodell M, Velicogna I, Famiglietti JS. 2009 Satellite-based estimates of groundwater depletion in India. *Nature* **460**, 999–1002. (doi:10.1038/nature08238)
26. Rodell M, Chen J, Kato H, Famiglietti J, Nigro J, Wilson C. 2006 Estimating ground water storage changes in the Mississippi River basin (USA) using GRACE. *Hydrogeol. J.* **15**, 159–166. (doi:10.1007/s10040-006-0103-7)
27. Harding R *et al*. 2011 WATCH: Current Knowledge of the Terrestrial Global Water Cycle. *J. Hydrometeorol.* **12**, 1149–1156. (doi:10.1175/JHM-D-11-024.1)
28. Weedon GP *et al*. 2011 Creation of the WATCH Forcing Data and its use to assess global and regional reference crop evaporation over land during the twentieth century. *J. Hydrometeorol.* **12**, 823–848. (doi:10.1175/2011JHM1369.1)
29. Harding RJ, Warnaars TA. 2011 *Water and global change: the WATCH project outreach report*. Wallingford, UK: Centre for Ecology and Hydrology.
30. Alcamo J, Flörke M, Märker M. 2007 Future long-term changes in global water resources driven by socio-economic and climatic changes. *Hydrol. Sci. J.* **52**, 247–275. (doi:10.1623/hysj.52.2.247)
31. Gleick PH, Palaniappan M. 2010 Peak water limits to freshwater withdrawal and use. *Proc. Natl Acad. Sci. USA* **107**, 11 155–11 162. (doi:10.1073/pnas.1004812107)
32. Vörösmarty CJ *et al*. 2010 Global threats to human water security and river biodiversity. *Nature* **467**, 555–561. (doi:10.1038/nature09440)
33. Scanlon BR, Faunt CC, Longuevergne L, Reedy RC, Alley WM, McGuire VL, McMahon PB. 2012 Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proc. Natl Acad. Sci. USA* **109**, 9320–9325. (doi:10.1073/pnas.1200311109)
34. Zhang X, Zwiers FW, Hegerl GC, Lambert FH, Gillett NP, Solomon S, Stott PA, Nozawa T. 2007 Detection of human influence on twentieth-century precipitation trends. *Nature* **448**, 461–465. (doi:10.1038/nature06025)
35. Boisier JP, de Noblet-Ducoudré N, Pitman AJ, Cruz FT, Delire C, van den Hurk BJJM, van der Molen MK, Müller C, Voldoire A. 2012 Attributing the impacts of land-cover changes in temperate regions on surface temperature and heat fluxes to specific causes: results from the first LUCID set of simulations. *J. Geophys. Res.* **117**, D12116. (doi:10.1029/2011JD017106)
36. Lawrence PJ, Chase TN. 2010 Investigating the climate impacts of global land cover change in the community climate system model. *Int. J. Climatol.* **30**, 2066–2087. (doi:10.1002/joc.2061)

37. Betts RA. 2000 Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature* **408**, 187–190. (doi:10.1038/35041545)
38. Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) 2007 *Climate change 2007: impacts, adaptation and vulnerability*. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.
39. Bates BC, Kundzewicz ZW, Wu S, Palutikof JP. 2008 *Climate change and water*. Geneva, Switzerland: IPCC Secretariat.
40. Kundzewicz ZW, Mata LJ, Arnell NW, Döll P, Kabat P, Jiménez B *et al*. 2007 Freshwater resources and their management. In *Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds ML Parry, OF Canziani, JP Palutikof, PJ van der Linden, CE Hanson), pp. 173–210. Cambridge, UK: Cambridge University Press.
41. UNEP. 2012 *Global environmental outlook 5*. Nairobi, Kenya: United Nations Environment Programme.
42. Hassan R, Scholes R, Ash N (eds). 2005 *Ecosystems and human well-being: current state and trends. Findings of the Condition and Trends Working Group*. Washington, DC: Island Press.
43. Slaymaker O, Spencer T, Dadson S. 2009 Landscape, and landscape-scale processes as the unfilled niche in the global environmental change debate: an introduction. In *Geomorphology and global environmental change* (eds O Slaymaker, T Spencer, C Embleton-Hamann), pp. 1–36. Cambridge, UK: Cambridge University Press.
44. Dadson S. 2010 Geomorphology and Earth system science. *Prog. Phys. Geogr.* **34**, 385–398. (doi:10.1177/0309133310365031)
45. Rockstrom J *et al*. 2009 A safe operating space for humanity. *Nature* **461**, 472–475. (doi:10.1038/461472a)
46. Steffen W, Grinevald J, Crutzen P, McNeill J. 2011 The Anthropocene: conceptual and historical perspectives. *Phil. Trans. R. Soc. A* **369**, 842–867. (doi:10.1098/rsta.2010.0327)
47. Meehl GA, Covey C, McAvaney B, Latif M, Stouffer RJ. 2005 Overview of the coupled model intercomparison project. *Bull. Am. Meteorol. Soc.* **86**, 89–93. (doi:10.1175/BAMS-86-1-89)
48. Taylor KE, Stouffer RJ, Meehl GA. 2011 An overview of CMIP5 and the experiment design. *Bull. Am. Meteorol. Soc.* **93**, 485–498. (doi:10.1175/BAMS-D-11-00094.1)
49. Meehl GA, Covey C, Taylor KE, Delworth T, Stouffer RJ, Latif M, McAvaney B, Mitchell JFB. 2007 The WCRP CMIP3 multimodel dataset: a new era in climate change research. *Bull. Am. Meteorol. Soc.* **88**, 1383–1394. (doi:10.1175/BAMS-88-9-1383)
50. Collins M, Chandler RE, Cox PM, Huthnance JM, Rougier J, Stephenson DB. 2012 Quantifying future climate change. *Nat. Clim. Change* **2**, 403–409. (doi:10.1038/nclimate1414)
51. Murphy JM, Sexton DMH, Barnett DN, Jones GS, Webb MJ, Collins M, Stainforth DA. 2004 Quantification of modelling uncertainties in a large ensemble of climate change simulations. *Nature* **430**, 768–772. (doi:10.1038/nature02771)
52. Stainforth DA *et al*. 2005 Uncertainty in predictions of the climate response to rising levels of greenhouse gases. *Nature* **433**, 403–406. (doi:10.1038/nature03301)
53. Hawkins E, Sutton R. 2009 The potential to narrow uncertainty in regional climate predictions. *Bull. Am. Meteorol. Soc.* **90**, 1095–1107. (doi:10.1175/2009BAMS2607.1)
54. Haddeland I *et al*. 2011 Multi-model estimate of the global terrestrial water balance: setup and first results. *J. Hydrometeorol.* **12**, 869–884. (doi:10.1175/2011JHM1324.1)
55. Gudmundsson L, Wagener T, Tallaksen LM, Engeland K. 2012 Evaluation of nine large-scale hydrological models with respect to the seasonal runoff climatology in Europe. *Water Resour. Res.* **48**, W11504. (doi:10.1029/2011WR010911)
56. Prudhomme C, Parry S, Hannaford J, Clark DB, Hagemann S, Voss F. 2011 How well do large-scale models reproduce regional hydrological extremes in Europe? *J. Hydrometeorol.* **12**, 1181–1204. (doi:10.1175/2011JHM1387.1)
57. Biemans H, Hutjes R, Kabat P, Strengers B, Gerten D, Rost S. 2009 Impacts of precipitation uncertainty on discharge calculations for main river basins. *J. Hydrometeorol.* **10**, 1011–1125. (doi:10.1175/2008JHM1067.1)
58. Fekete BM, Vörösmarty CJ, Roads J, Willmott C. 2004 Uncertainties in precipitation and their impacts on runoff estimates. *J. Clim.* **17**, 294–304. (doi:10.1175/1520-0442(2004)017<0294:UIPATI>2.0.CO;2)

59. Lenton TM, Held H, Kriegler E, Hall JW, Lucht W, Rahmstorf S, Schellnhuber HJ. 2008 Tipping elements in the Earth's climate system. *Proc. Natl Acad. Sci. USA* **105**, 1786–1793. (doi:10.1073/pnas.0705414105)
60. Harding RJ, Blyth EM, Tuinenburg AA, Wiltshire A. 2013 Land atmosphere feedbacks and their role in the water resources of the Ganges basin. *Sci. Total Environ.* (doi:10.1016/j.scitotenv.2013.03.016)
61. Clark DB, Taylor CM, Thorpe AJ, Harding RJ, Nicholls ME. 2003 The influence of spatial variability of boundary-layer moisture on tropical continental squall lines. *Q. J. R. Meteorol. Soc.* **129**, 1101–1121. (doi:10.1256/qj.02.122)
62. Taylor CM, Gounou A, Guichard F, Harris PP, Ellis RJ, Couvreux F, De Kauwe M. 2011 Frequency of Sahelian storm initiation enhanced over mesoscale soil-moisture patterns. *Nat. Geosci.* **4**, 430–433. (doi:10.1038/ngeo1173)
63. Saeed F, Hagemann S, Jacob D. 2009 Impact of irrigation on the South Asian summer monsoon. *Geophys. Res. Lett.* **36**, L20711. (doi:10.1029/2009GL040625)
64. Koster RD *et al*. 2004 Regions of strong coupling between soil moisture and precipitation. *Science* **305**, 1138–1140. (doi:10.1126/science.1100217)
65. Puma MJ, Cook BI. 2010 Effects of irrigation on global climate during the 20th century. *J. Geophys. Res.* **115**, D16120. (doi:10.1029/2010JD014122)
66. Pokhrel Y, Hanasaki N, Koirala S, Cho J, Yeh PJF, Kim H, Kanae S, Oki T. 2012 Incorporating anthropogenic water regulation modules into a land surface model. *J. Hydrometeorol.* **13**, 255–269. (doi:10.1175/JHM-D-11-013.1)
67. Dadson SJ, Ashpole I, Harris P, Davies HN, Clark DB, Blyth E, Taylor CM. 2010 Wetland inundation dynamics in a model of land surface climate: evaluation in the Niger inland delta region. *J. Geophys. Res.* **115**, D23114. (doi:10.1029/2010JD014474)
68. Taylor CM. 2010 Feedbacks on convection from an African wetland. *Geophys. Res. Lett.* **37**, L05406. (doi:10.1029/2009GL041652)
69. Corzo Perez GA, van Huijgevoort MHJ, Voß F, van Lanen HAJ. 2011 On the spatio-temporal analysis of hydrological droughts from global hydrological models. *Hydrol. Earth Syst. Sci.* **15**, 2963–2978. (doi:10.5194/hess-15-2963-2011)
70. Fischer EM, Seneviratne SI, Lüthi D, Schär C. 2007 Contribution of land-atmosphere coupling to recent European summer heat waves. *Geophys. Res. Lett.* **34**, L06707. (doi:10.1029/2006GL029068)
71. Stott PA, Stone DA, Allen MR. 2004 Human contribution to the European heatwave of 2003. *Nature* **432**, 610–614. (doi:10.1038/nature03089)
72. Acreman MC, McCartney MP. 2000 Framework guidelines for managed flood releases from reservoirs to maintain downstream ecosystems and dependent livelihoods. In *International Workshop on Development and Management of Floodplains and Wetlands*. Beijing, China 5–8 September, 2000, pp. 155–164.
73. Maltby E, Acreman MC. 2011 Ecosystem services of wetlands: pathfinder for a new paradigm. *Hydrol. Sci. J.* **56**, 1341–1359. (doi:10.1080/02626667.2011.631014)
74. Ziv G, Baran E, Nam S, Rodriguez-Iturbe I, Levin SA. 2012 Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin. *Proc. Natl Acad. Sci. USA* **109**, 5609–5614. (doi:10.1073/pnas.1201423109)
75. Acreman MC. 2001 Ethical aspects of water and ecosystems. *Water Policy J.* **3**, 257–265. (doi:10.1016/S1366-7017(01)00009-5)
76. Acreman MC. 1998 Principles of water management for people and the environment. In *Water and population dynamics* (eds AD de Shirbinin, V Dompka). Washington, DC: American Association for the Advancement of Science.
77. Rosenberg D, McCully P, Pringle C. 2000 Global-scale environmental effects of hydrological alterations: introduction. *Bioscience* **50**, 746–751. (doi:10.1641/0006-3568(2000)050[0746:GSEEOH]2.0.CO;2)
78. Nilsson C, Reidy CA, Dynesius M, Revenga C. 2005 Fragmentation and flow regulation of the world's large river systems. *Science* **308**, 405–408. (doi:10.1126/science.1107887)
79. Tharme RE. 2003 A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Res. Appl.* **19**, 397–441. (doi:10.1002/rra.736)
80. Tennant DL. 1976 Instream flow regimens for fish, wildlife, recreation, and related environmental resources[1]. In *Proceedings of the Symposium and Speciality Conference on Instream*

Flow Needs II (eds JF Orsborn, CH Allman), pp. 359–373. Bethesda, Maryland: American Fisheries Society.

81. Stalnaker C, Arnette S. 1976 Methodologies for the determination of stream resource flow requirements: an assessment. US Fish and Wildlife Services, Office of Biological Services Western Water Association.
82. Trihey E, Stalnaker C. 1985 Evolution and application of instream flow methodologies to small hydropower developments: an overview of the issues. In *Proc. Symp. on Small Hydropower and Fisheries* (eds FW Olson, RG White, RH Hamre), pp. 176–183. Bethesda, MD: American Fisheries Society.
83. Rowlston WS, Palmer CG. 2002 Processes in the development of resource protection provisions on South African water law. In *Proceedings of the International Conference on Environmental Flows for River Systems and Fourth Ecohydraulics Symposium* (*Environmental Flows*) *Cape Town*. Cape Town: Southern Waters.
84. Acreman MC, Ferguson A. 2010 Environmental flows and European water framework directive. *Freshw. Biol.* **55**, 32–48. (doi:10.1111/j.1365-2427.2009.02181.x)
85. Richter BD, Baumgartner JV, Powell J, Braun DP. 1996 A method for assessing hydrological alteration within ecosystems. *Conserv. Biol.* **10**, 1163–1174. (doi:10.1046/j.1523-1739.1996.10041163.x)
86. Junk WJ, Bayley PB, Sparks RE. 1989 The flood pulse concept in river-floodplain systems. *Can. J. Fish. Aquat. Sci.* **106**, 110–127.
87. Grey D, Sadoff CW. 2007 Sink or swim? Water security for growth and development. *Water Policy J.* **9**, 545–571. (doi:10.2166/wp.2007.021)
88. King JM, Tharme RE, de Villiers MS. 2000 Environmental flow assessments for rivers: manual for the building block methodology. Report TT 131/00. Water Research Commission, Pretoria, South Africa.
89. King JM, Brown CA, Paxton BR. 2004 *Development of DRIFT: a scenario-based methodology for environmental flow assessments*. Pretoria, South Africa: Water Research Commission.
90. Richter BD, Thomas GA. 2007 Restoring environmental flows by modifying dam operations. *Ecol. Soc.* **12**, 12.
91. Konrad CP *et al*. 2011 Large scale flow experiments for managing large rivers. *Bioscience* **61**, 948–959. (doi:10.1525/bio.2011.61.12.5)
92. Barbier EB. 2009 Ecosystems as natural assets. *Found. Trends Microecon.* **4**, 611–681. (doi:10.1561/0700000031)
93. Zwarts L *et al*. 2005 *The Niger: a lifeline. Effective water management in the upper Niger Basin*. Lelystad, The Netherlands: RIZA.
94. Acreman MC. 2003 *Case studies of managed flood releases environmental flow assessment, part III*. World Bank Water Resources and Environmental Management Best Practice Brief no. 8. Washington, DC: World Bank.
95. Loth P. 2010 *The return of the water: restoring the Waza–Logone floodplain in Cameroon*. Gland, Switzerland: IUCN.
96. Acreman MC. 1996 Environmental effects of hydro-electric power generation in Africa and the potential for artificial floods. *Water Environ. Manage.* **10**, 429–434. (doi:10.1111/j.1747-6593.1996.tb00076.x)
97. Adams WM. 1992 *Wasting the rain: rivers, people and planning in Africa*. London, UK: Earthscan.
98. Wood EF *et al*. 2011 Hyper-resolution global land surface modeling: meeting a grand challenge for monitoring Earth's terrestrial water. *Water Resour. Res.* **47**, W05301. (doi:10.1029/2010WR010090)