Anthropogenic Influences on the Global Water Cycle—Challenges for the GEWEX Community

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Water and energy are fundamental for life on Earth. Freshwater is a major pressure point for society owing to increasing demand and the vagaries of climate. The role of human activities in modifying and controlling the continental water cycle has been recognized by the World Climate Research Programme (WCRP) as one of its Grand Challenges and also underlies the GEWEX Science Questions. To better understand the mechanisms behind this challenge, the GEWEX Hydroclimatology Panel (GHP) and the GEWEX Global Land/Atmosphere System Study (GLASS) Panel have begun the joint effort presented here.

Water Security in the 21st Century

Water security is widely recognized as one of the major challenges for human society in the 21st century. Water resources are limited in many of the populous areas of the world and water scarcity is likely to increase in the coming decades as population increases and climate change alters rainfall and evaporation. Sir John Beddington (until recently the Chief Scientific Advisor to the UK Government) identified a "perfect storm" of global events where the world will need to produce 50% more food and energy, together with 30% more freshwater, by 2030, while at the same time adapting to a changing climate and reducing greenhouse gas emissions (Beddington 2009). These pressures are set in a context of unprecedented human impacts on the Earth system. Man's activities are changing the land surface, river flows and groundwater storage, with largely unknown feedbacks to the climate system. There is thus a social and scientific imperative to understand and predict the impacts of anthropogenic influences on the water cycle.

Water Consumption Representation

Globally, man uses only a small fraction (about 3%) of freshwater runoff. However, in the more populated regions of the world, this proportion can be much larger; for example, in India, 40% of potential water resources are used, and in certain basins, much more. In fact, it has been estimated that in India nonrenewable extraction of water is 68 km^3 per year (Wada et al., 2010). In California and the midwestern United States, the Mediterranean, Pakistan, India and China, water is being extracted at a faster rate than it is replenished, leading to the rapid reduction of groundwater levels and decreasing river flows. We know that 80-90% of the world's consumptive use of water is for irrigation, and that the enhanced evaporation induced by irrigation can feed back on the atmosphere at local and mesoscales (although the impact on regional and global climates is uncertain). There are also indications that the reduced freshwater discharge from continents can affect processes in certain oceans or coastal regions. Still, there is no strategy for systematically monitoring these manmade interventions within the global water cycle or for including them in the models we use to predict climate variability and change.

Land-Surface Component in Models

The land-surface component of our climate and Earth system models has improved considerably over the last two decades. Representations of physically realistic runoff generation and river routing are now the norm within most climate models. These representations, however, still describe the "natural" system and there have only been sporadic attempts at the inclusion of anthropogenic influences on evaporation, water storage, runoff generation and flow. Few of these additions have found their way into the routine versions of climate models. In addition to the land surface models (LSMs), recent decades have seen the development of stand-alone global hydrology models (GHMs). These have been developed by the hydrological community and tend to have a very different structure; they are typically simpler and focus on representing water resources, rather than the full range of land surface processes. They may also make some use of local calibration; however, calibrated models need to be used with caution in climate scenarios where flow regimes may be radically different. Many of the GHMs have a more explicit representation of man-made features, such as dams, water extraction and diversions. Currently both LSMs and GHMs are imperfect and incomplete and simulations rarely match available hydrological observations (e.g., Haddeland et al., 2011).

Water Resource Management

The issue of water resource management can be divided into two interdependent elements—water demand and water supply (and allocation) (Nazemi and Wheater, 2015a). Global water demand is dominated by agriculture, which accounts for approximately 90% of total global water consumption and 70% of all water withdrawals from surface and groundwater. Other demands, such as domestic and industrial use and energy-related requirements, are smaller but increasing, and often are of major local importance. There is considerable regional variation in domestic and industrial use of water, which is a constraint on development in many high population regions of the world. Crop irrigation is primarily a consumptive water use while the non-irrigative demands often return water to the system, although these uses will impact the timing and quality of the resulting river flows.

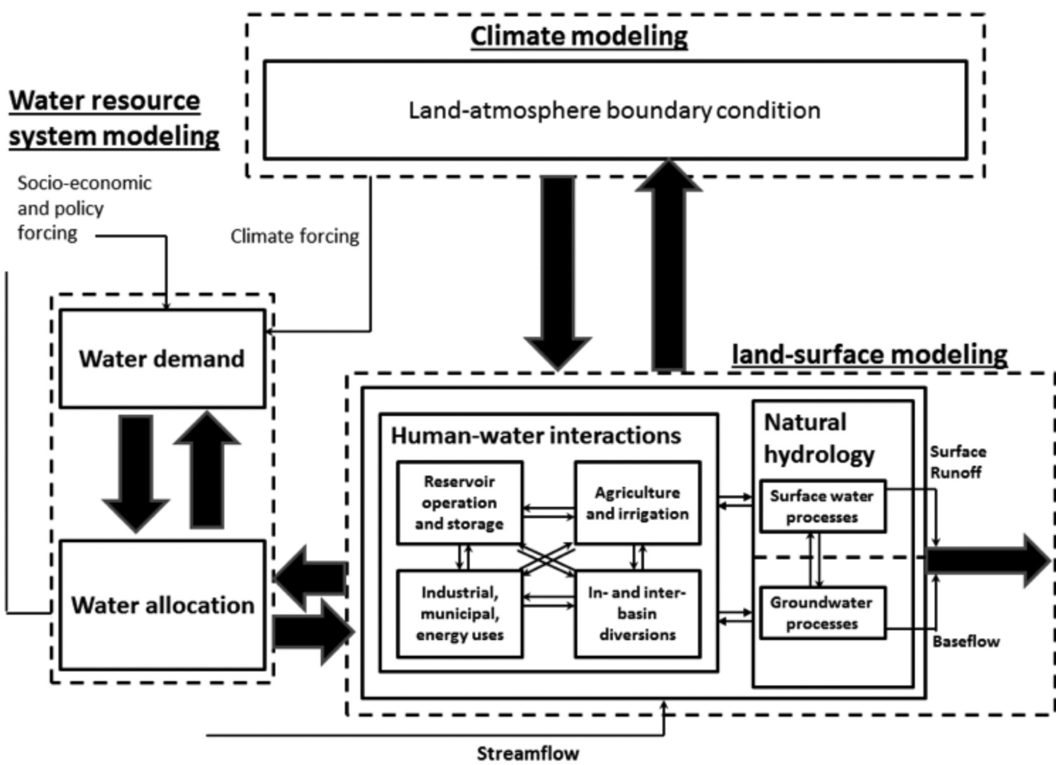
Irrigated areas have been included in a large number of offline LSMs and GHMs (Nazemi and Wheater, 2015a, Table 1) and a smaller number of online simulations (mostly regional models), but with very different levels of complexity. The simplest irrigation algorithms allow evaporation at a potential rate and keep the soil layer topped up with water at the expense of water conservation. More complex representations use published estimates of water requirements for crops and information on the irrigation techniques used and their efficiency. Very few algorithms link water demand to water constraints and ensure water conservation. Projecting forward requires an estimation of future agricultural development, and thus needs to be conditioned by socio-economic and technological factors. These factors can be included using integrated assessment models; however, the current state-of-the-art versions of these models poorly represent the water constraints on agricultural development.

While surface water is the primary supplier of irrigation water, nearly 40% is derived from groundwater. It is essential, therefore, when considering supply constraints, that both surface water reservoirs and groundwater be included in land surface descriptions. Reservoirs can be represented within the routing algorithms of large-scale models but, unlike natural lakes, their dynamics will be controlled by downstream demand and management decisions (further complicated by the multi-functional nature of many reservoirs). Regionally, interbasin transfers may also need to be considered, and local management decisions (as well as infrastructural constraints) will determine their nature and extent.

In principle, a physical 3-dimensional gridded groundwater model can be linked to climate models, but computational constraints (and detailed knowledge of global aquifer properties) limit this approach to a few regional examples. Simpler approaches, such as a conceptual linear groundwater reservoir (parameterized using local topography and lithology), have been proposed and implemented in a small number of regional instances. Groundwater recharge is often a fine balance between rainfall and evaporation, although in semi-arid regions lateral redistribution of surface water may determine recharge, and is imperfectly modeled in LSMs. Overlaid on this physical description is the need for estimates of groundwater withdrawals.

The simplest allocation schemes assume grid-based demands can be supplied within the model grid cell. There is a need to parameterize grid-to-grid transfer and rules for water allocation (complicated by the multiple and conflicting demands on reservoirs; for example, flood prevention in the winter and supply in the summer). In principle, local operating rules could be applied, but an alternative approach is to find release scenarios, which minimize the costs and use economic theories to derive the most likely allocation strategies.

Major gaps remain in representing water resource management in LSMs. The first is to fully couple the various components to provide water and energy conservation (often violated in irrigation and groundwater algorithms) and provide true water constraints on agricultural use (for example, as proposed by Nazemi and Wheater, 2015b, in the figure below). The second is the problem of scale. Much water resource management takes place at finer resolution than current GCM grids. Future global or regional models with finer grids will have an increased need for a representation of these processes as they matter for spatial contrasts and establish resolved land surface



A fully coupled framework for inclusion of water resources management in a typical land surface model grid.

structures. This will bring difficulties of increasing complexity, computational burden and data requirements. Thirdly, many current algorithms require local knowledge and parameterization. How algorithms developed for offline analyses can be generalized and used in coupled models and how this might be used in future scenarios is a complex issue. Finally, we need to address the considerable uncertainties in our estimations of the components of the global water cycle in our current models. To these must also be added the uncertainties in demand, reservoir operation and groundwater withdrawals.

The need to include water management in the coupled climate and Earth system models to provide a realistic assessment of the current and future terrestrial water cycle is clearly urgent. To advance, we need high performance computing, improved data sources (for example, remote sensing) and improved data sharing, calibration algorithms and continued improvements in process representation and parameter identification. It is clear that with limited resources the various communities need to increasingly share algorithms, data and experience to ensure the development of the best models for the future.

New GHP/GLASS Crosscut to Include Water Management in Models

In order to address these issues, GHP and GLASS are creating a crosscutting project focused on the inclusion of water management in large-scale models. This project will be launched with a workshop in late 2016 at the Ebro River Basin in Spain. The location was chosen because it is within the area of the GEWEX Regional Hydroclimate Project (RHP) called the Hydrological Cycle in the Mediterranean Experiment (HyMeX). The Elbro River Basin has lost two-thirds of its discharge in the past 50 years due to irrigated agriculture in the catchment. Plans for the new GEWEX crosscutting project include: (1) defining a program of research that addresses the four key gaps identified above; (2) developing a coherent action plan that integrates the current rather disparate activities in this area; and (3) linking modeling development to regional case studies through the RHP projects.

References

Beddington J., 2009. Food, energy, water and the climate: A perfect storm of global events? In-conference presentation given to the Sustainable Development UK Annual Conference, QEII Conference Centre, London, March 19, 2009. See *http://www.bis.gov.uk/assets/goscience/docs/p/perfect-storm-paper.pdf.*

Haddeland, I., et al., 2011. Multimodel Estimate of the Terrestrial Global Water Balance: Setup and First Results. *J. Hydrometeorol.*, 12, 869–884, doi: 10.1175/2011JHM1324.1.

Nazemi, A., and H.S. Wheater, 2015a. On inclusion of water resource management in Earth system models–Part 1: Problem definition and representation of water demand. *Hydrol. Earth Syst. Sci.*, 19, 33–61.

Nazemi, A., and H.S. Wheater, 2015b. On inclusion of water resource management in Earth system models–Part 2: Representation of water supply and allocation and opportunities for improved modeling, *Hydrol. Earth Syst. Sci.*, 19, 63-90.

Wada, Y., L.P.H. Van Beek, Ch.M. Van Kempen, J.W.T.M. Reckman, S. Vasak, M.F.P. Bierkens, 2010. Global depletion of groundwater resources. *Geophys. Res. Lett.*, 37, L20402, doi:10.1029/2010GL044571.