Recent progresses in incorporating human land-water management into global land surface models toward their integration into Earth system models

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ABSTRACT

The global water cycle has been profoundly affected by human land-water management especially during the last century. Since the changes in water cycle can affect the functioning of a wide range of biophysical and biogeochemical processes of the Earth system, it is essential to account for human land-water management in Earth system models (ESMs). During the recent past, noteworthy progress has been made in large-scale modeling of human impacts on the water cycle but sufficient advancements have not yet been made in integrating the newly developed schemes into ESMs. This paper reviews the progresses made in incorporating human factors in large-scale hydrological models and their integration into ESMs. The paper focuses primarily on the recent advancements and existing challenges in incorporating human impacts in global land surface models (LSMs) as a way forward to the development of ESMs with humans as integral components, but a brief review of global hydrological models (GHMs) is also provided. The paper begins with the general overview of human impacts on the water cycle. Then, the algorithms currently employed to represent irrigation, reservoir operation, and groundwater pumping are discussed. Next, methodological deficiencies in current modeling approaches and existing challenges are identified. Further, light is shed on the sources of uncertainties associated with model parameterizations, grid resolution, and datasets used for forcing and validation. Finally, representing human land-water management in LSMs is highlighted as an important research direction toward developing integrated models using ESM frameworks for the holistic study of human-water interactions within the Earths system.

INTRODUCTION

Humans have historically modified the Earth's landscape as a consequence of the exploitation of natural resources[1, 2]. Human impacts on the natural environment now rival global geophysical processes[3-5] transforming our planet into a new geological epoch termed as the Anthropocene[6, 7]. Evidences are overwhelming that these human forces have been fundamentally altering the natural patterns of freshwater flows and storages over a broad range of spatio-temporal scales[2, 5, 8-10]; Figure 1 shows a schematic of the present-day global water cycle depicting the major human factors that are affecting the large-scale flow and storage of water. Some of the plainly visible manifestations of the human impacts on the water cycle are diminishing river flows due to impoundment by large dams and long-distance water transport[9, 11, 12], especially during reservoir filling, aquifer storage depletion due to over-exploitation of groundwater resources[13-22], altered groundwater recharge due to change in land use and irrigation[23], and desiccation of inland water bodies such as the Aral sea as a consequence of large-scale river diversion and irrigation[24, 25].

These evidences indicate that human footprint on freshwater and ecosystem services is widening across the planet at an alarming rate[3, 10, 18, 26, 27]. Increasing demand for water and food associated with future population and economic growths[28-32] combined with the adverse climate impacts on water availability[29, 33-35] will further exacerbate the current scale of human footprint, heighten water scarcity[35, 36], and increase hydrologic extremes such as floods and droughts[37-40] in many regions. Coping with these enormous challenges and providing reliable predictions of freshwater occurrence, circulation, and distribution requires a broad understanding of the continually changing water cycle as well as the dynamic and often complex human-water interactions[27, 41-43].

Earth system models (ESMs) are the tools used for studying the past evolution and potential future changes of these intricately intertwined Earth system processes and the interactions and feedback within them. ESMs integrate various—physical, chemical, and biological—aspects of the Earth system on land and in the atmosphere and ocean into a single, consistent modeling framework and simulate the interactions and feedback among them[44]. The land water cycle in ESMs is represented by land surface models (LSMs) which simulate the soil and vegetation processes and provide the lower boundary conditions to the atmospheric processes simulated by global climate models (GCMs) within ESM frameworks. Because of their crucial role within ESMs, LSMs have been significantly advanced over the last several decades through intensive improvements in schemes representing soil and vegetation processes[45, 46]. However, despite the widely recognized fact that the changes in water cycle due to human land-water management are now of global significance, as discussed above, most global LSMs do not yet account for human impacts on the water cycle. There has been increased attention in this line of research and noteworthy progress has been made during the last two decades, but the majority of these studies have focused on representing human impacts into offline global hydrological models[47, 48] (GHMs) developed to assess water resources availability and use. As such, the advancements made so far have not been able to meet the urgent need to develop holistic and integrated models by representing human impacts into ESMs.

This review presents the recent advances made in representing human land-water management into global LSMs as a way forward to the development of ESMs with humans as integral players within the Earth system. The emphasis is on reviewing current practices to model irrigation, reservoir operation, and groundwater pumping and identifying methodological deficiencies and existing challenges pertaining to the inclusion of these human factors into LSMs, but the progresses made in GHM development are also highlighted because some schemes developed for GHMs have been employed in LSMs and vice versa. Light is also shed on the sources of uncertainties associated with model parameterizations and grid resolution, as well as with the datasets used for forcing and validation, and the need for incorporating human land-water management in ESMs is highlighted as an important research direction for the future. We put less emphasis on the review of GHM developments because such reviews can be found in previous studies (e.g., *Nazemi and Wheater*[42, 43]; *Sood and Smakhtin*[48]).

Nazemi and Wheater[42, 43] provide a comprehensive review of various approaches currently employed to model human impacts on the water cycle; while they discuss the current state of representing human impacts in both online and offline models, particular emphasis was placed on reviewing and comparing the schemes used especially by various GHMs. The present paper expands on these previous reviews and provides further details and insights on the integrated impacts of human land-water management on various Earth system components which were not covered in the previous reviews. The paper focuses more on the technicalities of modeling human impacts in LSMs and discusses the current challenges and opportunities in integrating the new LSM developments into ESMs. The purpose of the paper is therefore not to review the findings of the literature published on human impact modeling but to characterize the current state of large-scale hydrologic modeling in the context of simulating the coupled human-water-climate interactions using consistent modeling frameworks. Specifically, the paper discusses how human factors interact with various hydro-climatic components of the Earth from the standpoint of Earth system modeling as shown in Figure 2. The figure depicts how the human and natural components are interlinked, and the possible pathways whereby human land-water management practices can affect various hydrologic, atmospheric, and oceanic processes within the Earth system. In the rest of this review, we first provide an overview of the human impacts on the water cycle in general, then discuss the current modeling approaches, and finally identify current gaps and challenges related to data availability and modeling strategies.

HUMAN WATER MANAGEMENT AND ITS IMPACTS ON THE GLOBAL WATER CYCLE

Exploitation of freshwater resources has brought astounding socio-economic benefits; however, the benefits have come with an unprecedented scale of negative environmental consequences[49]. Contemporary global water withdrawals, estimated to be ~4,000 km^3/yr[31, 50], account for only ~10% of the total annual continental runoff (40,000-45,000 km^3) to oceans[31] (Figure 1) and even a very small fraction of the total freshwater available on Earth[51-54]. However, the high spatial and temporal variability in both the availability and use of water has caused water scarcity in many regions around the world[29, 55, 56]. In an attempt to make this unevenly distributed resource available across space and time, humans have radically altered the natural patterns of freshwater flows and storages through impoundment and large-scale diversion[2, 28, 29, 57]. Since safe limits for surface water use have already reached in many regions[58], groundwater resources have also been extensively exploited to meet the soaring water demands especially during the last several decades[14, 16, 18, 22, 59].

As such, freshwater systems are now among the most extensively exploited and altered ecosystems on Earth[10]. The most prominent and palpable impacts of such management and exploitation of freshwater resources are altered flow regimes and dwindling storages as discussed earlier. These are, however, only a few examples of the profound influence that mankind is exerting on the Earth system as a whole. The potential impacts on various other Earth system processes are, in fact, far-reaching and exceedingly complex as the changes in freshwater systems can affect a wide range of biophysical processes and biogeochemical cycles on Earth and can in turn be affected through important feedbacks. For example, irrigation can alter regional precipitation patterns[60, 61] as well as global climate[62, 63], which in turn can affect water resources availability. Reservoir impoundments and groundwater pumping over long times have been found to have a measurable impact on sea level change[17, 64-67] and can substantially alter regional precipitation patterns[68-70].

The significance of various land-water management practices can be different at different spatial and temporal scales. Here, we identify agricultural irrigation, flow regulation, and groundwater use as the three major factors which are known to have affected the water cycle at global level and are important from large-scale hydrological modeling standpoint. In the following sub-sections, we first provide an overview of the direct impacts of these three factors on flows and storages of water and then highlight their combined effects on various Earth system processes in relation to the need for representing them in global LSMs.

Agricultural Land Use Change and Irrigation

Human land management practices have largely transformed the terrestrial biosphere in the recent past[8, 71-73]. The primary mode of the alteration of natural landscape has been the conversion and modification of natural ecosystems for agriculture[74-76]. It is estimated that ~40% of the planet's ice-free land surface has now been used for agriculture much of which replaced forests, savannas, and grasslands[71, 77]. Global cropland and pasture areas increased from 3 million km^2 and 3.24 million km^2, respectively, in 1700 to 15.32 million km^2 and 34.29 million km^2 in 2000 [*Klein Goldewijk et al.*[78]]. The intensification in land use change associated with agriculture particularly began during the early 20th century during which the global cropland and pasture areas were still 8.5 million km^2 and 12.93 million km^2 (Figures 3a-3c).

Changes in land use can alter the biophysical properties of land surface such as its albedo, roughness, leaf area index, and rooting depth consequently affecting various hydrologic processes such as evaporation from land and transpiration from leaf stomata[72, 79, 80]. The changes in evapotranspiration (ET) can in turn influence the climate over a range of spatio-temporal scales through alterations in the exchange of water, energy, and momentum between land surface and atmosphere[81-87]. Land use change can also affect the hydrologic functioning of the land surface as a result of changes in the partitioning of precipitation into ET and runoff and the alterations in soil water movement and root uptake[80]. Studies have suggested that change in land use, expansion of irrigated areas, and the associated effects on biophysical processes on land may have resulted in significant changes in the long-term global terrestrial water balance[88-90].

Irrigation further intensifies the perturbations in land surface water and energy balances due to agricultural activities. Irrigation consumes the largest share of total global water withdrawals accounting for ~70% of total and ~90% of consumptive water use globally[91, 92]. Irrigated agriculture currently contributes to 40-45% of global food production[93, 94]. Therefore, irrigation is an important component of global water use and food production as well as that of the terrestrial water balance. Irrigation, through increased soil water content, affects land surface water and energy balances[95-98] which can directly influence regional as well as global climate[60, 62, 63, 81, 83, 99-109]. While irrigation has been used since the beginning of cultivation, rapid expansion in irrigated areas occurred during the 20th century[110, 111]. In 2005, 3.1 million km^2 of land was irrigated globally[94, 111, 112] which is about three and five times of that in 1950 (1.1 million km^2) and 1900 (0.6 million km^2), respectively (Figures 3d-3f). The increased food demand driven by economic and population growths will likely result in further expansion of croplands and extension of irrigation facilities in the future, further accelerating the impacts on freshwater systems and climate[55, 113].

Large Dams and Flow Regulation

Globally, about 50,000 large dams—defined as >15m in height—were built during the last century with a major proliferation during its latter half[11, 57] (Figure 4). Globally, the water impoundment on these dams has been estimated as 7,000-8,300 km^3 [*ICOLD*[114], *Chao et al.*[65], *Lehner et al.*[57]] which represents about one-sixth of the annual continental discharge to global oceans[31]. If millions of small dams[115-119], which have not been well documented, are accounted for the global total impoundment may even exceed 10,000 km^3 [*Chao et al.*[65]]. Therefore, water stored in large reservoirs accounts for a significant portion of the terrestrial water balance.

Flow regulations by these dams have fragmented most of the large river systems around the world[2, 9, 119, 120], adversely affecting the natural flow regimes[121] and ecological integrity of freshwater-dependent ecosystems[26]. While the impacts of reservoir impoundments on freshwater ecosystems, land use, sediment transport, and human settlement as well as the effects on sea level change have been relatively well documented[11, 17, 64-67, 117, 122], their impacts on climate have remained underemphasized and largely unexamined. Studies suggest that large dams can alter regional precipitation patterns, particularly affecting extreme precipitation in surrounding regions, with potential implications on the safety of dams[68-70]. It is likely that rising global temperatures will further intensify these climate impacts as a result of increased evaporation rates from reservoirs. Therefore, the importance of incorporating reservoirs and their operation into large-scale hydrological model will continue to grow in the future.

Groundwater Use

Increased use of groundwater—the readily available and generally high-quality source of freshwater—has facilitated improvement in livelihoods, increase in agricultural productivity, food security, economic growth, and human adaptability to climate variability in many regions[14, 123]. Today, at least one-fourth of world's population relies heavily on groundwater[59, 124], and it is likely that the dependence on groundwater will continue to rise in the future as demands for water will increase and surface water sources will likely diminish in many regions[12, 29-31]. Therefore, groundwater will play an increasingly important role in water resources and agricultural sustainability in the future[18, 58, 125] but will also be adversely affected by global climate change[126, 127]. Recent studies have shown that aquifer storages have already been declining at an alarming rate in many regions[15-17, 21, 128-130] as a result of groundwater overexploitation at the rate exceeding its natural replenishment and stream discharge[14, 123]. This has caused unanticipated negative environmental consequences such as streamflow and aquifer storage depletion, water quality deterioration, and degradation of ecosystems[13, 14, 123, 131-133].

Groundwater also plays a crucial role in global water circulation. It often regulates surface runoff in humid climates and also interacts with regional climate especially in areas where water table is shallow[134-139]. It can also strongly modulate the seasonal cycle of terrestrial water storage and buffer soil water stress potentially increasing vegetation resilience during long dry spells[140, 141]. Studies have suggested that groundwater-supplied moisture contributes to ~9% of global ET[142] and the direct groundwater discharge to oceans accounts for ~10% of river discharge[143]. Therefore, alterations in groundwater dynamics can profoundly influence regional climate with important implications on global atmospheric circulations.

Despite the critical role that groundwater plays in securing global water supplies and driving regional climate, it has received less research attention than surface water and therefore remains as a poorly understood component of the global water balance[22]. Moreover, the lack of global groundwater monitoring networks, reliable models, and geological data required to constrain large-scale models limits our current understanding of the dynamic relationship between human water use, groundwater, and the hydrologic cycle[124, 125], which are all changing continually in response to global climate change and increase in human pressure. Contemporary global groundwater withdrawals have been estimated to be within 600-1000 km^3/yr (Table 1) based on country-level statistics[14, 123, 144-147]. These estimates provide the upper and lower bounds of total groundwater use but they may not be fully reliable as the country statistics obtained from different sources contain inherent uncertainties and are not always complete and accurate[123]. A number of hydrological models have also been used to estimate global groundwater withdrawals[16, 19, 92, 148-151]. The global total values simulated by different models fall within an even larger range of 500-1700 km^3/yr (Table 1; see *Wada et al.*[152] for details). Such large disagreements among different estimates suggest that reliable approaches and robust models to estimate global groundwater use are yet to be developed. Nonetheless, global models provide a large picture view with a generally good agreement in the broad spatial patterns of high groundwater withdrawals and depletion (Figure 5). The highest withdrawals are in the regions such as the northwest India, High Plains aquifer, and Central Valley Aquifer that are intensively irrigated using groundwater (Figure 5).

Integrated Effects of Irrigation, Flow Regulation, and Groundwater Use

As discussed in the preceding sections, human factors arising from land-water management exert profound influence on various hydro-climatic processes at varying spatial and temporal scales, but their combined effects have even broader implications on the changes in the overall system behavior and characteristics of the hydrologic cycle. Therefore, it is crucial to study their effects in an integrated manner and characterize the interactions and feedback among natural and human systems. Figure 2 shows different pathways whereby human-impacted landscape and water systems can potentially alter various atmospheric and oceanic processes. As indicated in the figure, the key underlying processes in the context of large-scale modeling include the changes in surface water and energy balances and the alteration in water drainage to global oceans. For instance, evidences indicate that irrigation can significantly alter precipitation patterns and the overall regional climate variability and change[60, 61]. Such changes in regional climate characteristics can directly influence water availability and use which can further perturb the overall system balance. Regional climate variability is also linked to increased evaporation from large artificial reservoirs[68-70] which can be expected to further accelerate with increase in global temperature, potentially affecting reservoir operation rules.

Groundwater, another crucial component of the total terrestrial balance and human water use, can also directly influence near-surface climate as well as the long-term balance in terrestrial and ocean water stores. Of particular interest is the use of deep fossil groundwater which once pumped to the surface (primarily for irrigation) enters into a complex cycle of utilization, recharge, and long-rage transport through atmospheric and land surface hydrological processes. Offline modeling studies have demonstrated that use of deep and non-renewable groundwater has contributed to significant sea level rise over the past century[17, 67] but the impacts of groundwater pumping on the overall system behavior still remains largely unexamined as groundwater is either ignored altogether or accounted rather crudely in many global LSMs and ESMs. This calls for the need to study these human systems as integral players within the Earth system as a whole, which requires the development and use of models that account for human factors and operate within the framework of ESMs. Such a holistic analysis will also promote a better understanding of various components of human-natural systems and the interaction and feedback among them under changing conditions of land use, water resources management, and climate variability in the future.

MODELING HUMAN IMPACTS ON THE WATER CYCLE

The way we model the global water cycle has been changing over the past few decades. It has been increasingly recognized that it no longer makes sense to model only natural hydrological cycles without considering human land-water management[31]. Consequently, there have been emerging efforts in representing human factors in large-scale hydrological models. However, majority of these modeling efforts have been focused on incorporating human activities into GHMs with the primary objective of assessing global water resources availability and use. As such, less attention has been paid in incorporating human factors into global LSMs, and particularly in integrating them into ESMs. In general, both LSMs and GHMs simulate the hydrological processes on land but they differ significantly in terms of their intended use and the details of parameterizations they employ to represent soil and vegetation processes. An extensive review of various GHMs and the current state of available methodologies and applications for the representation of water availability and use within these GHMs can be found in *Nazemi and Wheater*[42, 43]. Here, we provide a brief overview of GHMs in order to facilitate a clear distinction between modeling concepts in GHMs and LSMs.

GHM[47, 48, 153] developments have traditionally been focused more on water resources assessment[154-156]. They have a comprehensive representation of various hydrological processes but are typically simple in structure compared to the LSMs. While most GHMs are process-based, many treat soil and vegetation processes rather conceptually[43, 46]. GHMs typically are water balance models operating at a daily time scale without solving land surface energy balance. Since GHMs were traditionally designed to assess water resources availability, the primary goal in their development remains the accurate simulation of river discharge at the relevant scales. To achieve this, most GHMs typically employ a few parameters which can be tuned to match the simulated discharge with observations[149, 156, 157]. The underlying assumption is that since the models are tuned to capture the observed discharge, other variables such as ET are also simulated with reasonable accuracy. GHMs have been widely used to assess water resources availability and use at global to regional scales[149, 150, 152, 154, 158-161] as well as to examine the human-induced changes in river flows[149, 161, 162]. However, they are designed to be used in an offline mode, i.e., they simulate the water cycle on land with given climate information as an external input and are not coupled with GCMs, and hence are not the integral components of ESMs. Therefore, while the advancements in GHMs have led to the improved understanding and estimation of water resources availability and use, these progresses are not directly in line with the need to develop holistic models for the integrated study of human-natural systems using ESM frameworks.

LSMs, on the contrary, simulate the terrestrial water cycle within ESMs. Specifically, they provide the lower boundary conditions required to simulate atmospheric processes in GCMs. LSMs can operate both in offline and online modes, and typically run on a sub-daily time scale solving both water and energy balances on land; solving energy balance in LSMs is vital to the simulation of diurnal patterns of temperature variations required in the parent GCMs. As such, LSMs simulate the water cycle on land and provide a dynamic linkage between land and atmosphere through continuous exchange of moisture, energy, and momentum. As opposed to the parameter tuning-based water balance approach used in typical GHMs, LSMs simulate soil and vegetation processes on a physical basis with less involvement of tuning. Parameter tuning in LSMs may not also be always feasible as there are multiple parameters involved, and also because the evaporative fluxes are determined based on surface energy balance in advance of the estimation of runoff or river discharge. As such, accurate representation of state variables such as soil moisture and surface temperature is important for the realistic estimation of the land surface hydrologic fluxes which play crucial role in land-atmospheric interaction as well as for the estimation of water resources availability. It is, however, important to note that some LSMs employ parameter tuning, especially for runoff parameterizations. Such tuning can have important implications on land-atmosphere interactions and carbon cycle as runoff parameterizations in LSMs are tightly coupled with surface energy balance calculations[163, 164].

Because land surface hydrological processes exert profound influence on the overlying atmosphere[165, 166] and can potentially affect the biological and geochemical cycles simulated within ESMs, LSMs have been advanced through intensive improvements in many aspects of model parameterizations though concerted efforts across hydrological, atmospheric, and Earth system modeling communities (see *Sellers et al.*[45], *Pitman*[167], *Overgaard et al.*[46]). These efforts have led to the development of a family of advanced LSMs that employ sophisticated parameterizations of soil, water, and vegetation, processes including carbon exchange by plants[168, 169]. However, very few efforts have been made to represent human impacts in global LSMs[170, 171]. Advances have certainly been made during the past two decades but significant challenges and opportunities still remain in representing anthropogenic factors in global LSMs and integrating them into ESMs[27, 171, 172].

RECENT ADVANCES IN REPRESENTATING HUMAN IMPACTS IN HYDROLOGICAL MODELS

During the last two decades there has been a surge of interests and efforts in modeling human impacts on the global water cycle. The early efforts were led by water resources modeling communities with the primary objective of assessing the impacts of human activities on the terrestrial water cycle and providing better estimates of global water resources availability and use. Therefore, the early studies used GHMs as the core of the modeling framework and incorporated various human water management schemes within them. For example, *Alcamo et al.*[155] developed a global water resources model called the Water-Global Analysis and Prognosis (WaterGAP) by integrating together a global water use model, hydrology model[156], and an irrigation model[93]. A number of subsequent studies have since then advanced the model substantially through improved representation of human water use[150, 162]. *Haddeland et al.*[173] implemented reservoir operation and irrigation schemes into the Variable Infiltration Capacity (VIC) model[174] and examined the effects of reservoir operation and irrigation water withdrawal on surface water fluxes at the continental scale.

Hanasaki et al.[175] developed a new global reservoir operation model for a global river routing model called the Total Runoff Integrating Pathways[176] (TRIP). They further developed an integrated water resources assessment model H08[157, 159] by incorporating the reservoir operation model[175] and various other human water use modules into a bucket-model[177] based global hydrology model. Adding to the continuing efforts in modeling human water management in GHMs, *Wisser et al.*[149, 178] simulated irrigation water use and the effects of global reservoirs on continental water fluxes to oceans by using WBM_{Plus}. More recently, *van Beek et al.*[160] and *Wada et al.*[161] incorporated various water management practices including water allocation and use, irrigation, and reservoir operation in the macro-scale global hydrological model PCR-GLOBWB[160].

With the increased recognition of the need to account for human land-water management not only in water resources modeling but also in the broader context of modeling human-natural systems and the interactions and feedback within them, there have been concerted efforts in recent years from hydrological, climate, and Earth system modeling communities in incorporating human factors into LSMs and GCMs. The goal of these efforts is to inform the development of ESMs with human as integral players within the Earth system. Therefore, the objective is not only to improve land surface hydrologic simulations but also to explore and understand the dynamic pathways whereby human land-water management activities can affect various hydrologic and atmospheric processes and the mutual interactions and feedback among them over a range of spatio-temporal scales. Here, we review some of the major developments and advancements made in the development of LSMs with the representation of human land-water management. *de Rosnay et al.*[179] incorporated an irrigation scheme into the Organizing Carbon and Hydrology in Dynamics Ecosystems (ORCHIDEE[180]) LSM and examined the regional impacts of irrigation on the partitioning of energy between sensible and latent heat fluxes. *Tang et al.*[181] investigated the natural and anthropogenic heterogeneity, including irrigation, on the simulation of land surface hydrologic processes using a distributed biosphere hydrological model. *Rost et al.*[92] enhanced the dynamic global vegetation model (DGVM) LPJmL[182] through the representation of irrigation, river flow routing, and reservoirs and lakes. They used the model to examine agricultural blue and green water consumption in the context of changing land use and irrigation extents. *Ozdogan et al.*[96] integrated satellite-derived irrigation data into the NOAH LSM and examined the role of irrigation on the simulation of land surface hydrologic fluxes and states within the LSM.

More recently, *Pokhrel et al.*[97] incorporated various water use modules into an LSM called the Minimal Advanced Treatment of Surface Interactions and Runoff (MATSIRO[183]). Their model accounted for reservoir regulation, environmental flow requirements, as well as domestic and industrial water withdrawals which were unrepresented in the previous LSM studies; however, the model still lacked the inclusion of groundwater pumping. In a recent study[19], they further enhanced the model through the incorporation of a dynamic groundwater scheme[134, 142] and an explicit groundwater pumping scheme, resulting in a new model called the HiGW-MAT which was of its first kind in terms of explicitly simulating groundwater withdrawal and depletion within a global LSM. This area of research has therefore been evolving with increasing number of studies in recent years.

Some of the latest developments include those by *Leng et al.*[98] and *Leng et al.*[184] who integrated a simple groundwater pumping scheme into the interactive irrigation scheme (http://www.cesm.ucar.edu/models/cesm1.0/clm/CLMcropANDirrigTechDescriptions.pdf) in CLM4[169] to examine the effects of irrigation, including groundwater use, over the conterminous United States at a relatively high spatial and temporal resolution. *Voisin et al.*[185, 186] also examined the regional impacts of water resource management using an integrated model designed for integration into ESM. A number of other studies [e.g., *Faunt*[187], *Ferguson and Maxwell*[188], *Condon and Maxwell*[189]] have developed integrated models which simulate human water management within the models that fully resolve surface water and energy balances while also accounting for groundwater flows, but these models have been particularly designed for catchment to regional scale applications.

Even though the LSM-based models summarized above have been developed for potential integration into ESMs, they were mostly used for offline applications. Some other studies have directly incorporated water management, particularly irrigation, into GCMs or regional climate models (RCMs) for online applications. The early studies of this category investigated the climate effects of irrigation and the associated feedbacks on land water cycle at global[62, 63, 99, 101, 102, 107] and regional[81, 83, 100, 103-106, 190, 191] scales. They differ primarily with the offline LSMs described above in that the model grid resolution, in general, is relatively coarse and many of these models employ rather simplified algorithms to represent irrigation processes without accounting for water withdrawals from man-made reservoirs and groundwater, as well as the temporal dynamics of crop growth. The volume of annual irrigation water in many of these studies is commonly fixed at a mean value based on the available data [e.g., *Döll and Siebert*[93], *Wisser et al.*[149]], soil moisture in irrigated areas is set at saturation throughout the year without considering crop growing season, or the ET from irrigated areas is grossly set at the potential rate. Therefore, the temporal dynamics of irrigation water requirements is largely ignored. Such model configurations with highly simplified irrigation schemes may result in improper description of soil hydrological processes such as overestimation of soil moisture and deep-soil percolation which may lead to the overestimation or underestimation of the irrigation impacts on climate[192]. Therefore, while these studies have, in general, suggested that irrigation can affect climate by surface cooling and enhanced ET, there are large disagreements in the quantification of the magnitude of these impacts[193].

More recently, various studies have used improved schemes to investigate regional climate impacts of irrigation. For example, *Sorooshian et al.*[192] incorporated a "more realistic" irrigation scheme based on actual irrigation practices in California[194] into the NCAR/PENN STATE mesoscale model MM5. The model, which has recently been enhanced further[109, 193], was used to study climate impacts due to irrigation in the California Central Valley. *Lo and Famiglietti*[108] also studied the irrigation-induced climate impacts in California using the Community Land Model (CLM) but they prescribed the amount of annual irrigation from surface water and groundwater based on the available estimates. Numerous other studies have also incorporated irrigation, and in some cases groundwater withdrawal schemes, into various climate models to study the regional climate impacts of irrigation[195-200].

As discussed above, the advances in representing human impacts in GHMs and LSMs have been made by isolated efforts from different modeling groups. However, there are methodological similarities between the algorithms employed by different models, and the schemes originally developed for GHMs have been implemented into LSMs and vice versa. Therefore, in the following, we present an overview of the current practices in representing the three major human activities discussed earlier in large-scale water cycle models without making a clear distinction between GHMs and LSMs. Nonetheless, the aim here is to review the schemes compatible with global LSMs and identify the major shortcomings in these schemes and existing challenges in further integrating them into ESMs.

Irrigation Schemes

The primary purpose of irrigation is to increase root-zone soil water content to reduce moisture stress and ensure optimal crop growth and productivity. From modeling perspective, when to irrigate (timing), how to irrigation (method), and how much to irrigate (amount) are the three key aspects of irrigation[96]. Since various irrigation practices are used in different regions, and farmers use different methods to determine the timing and amount of irrigation and may act rationally, it is difficult to represent the actual irrigation practices in large-scale models. Nevertheless, certain guidelines can be used to capture some of these complex irrigation mechanisms. These guidelines can be established by using the information on cropping pattern, soil texture, and climate conditions. Once the amount of irrigation water requirement is estimated based on these guidelines, the next step is to realistically determine the source of water and the method and timing of irrigation. The amount of water used consumptively by crops can vary with the irrigation method used and this can largely alter surface water energy balances. Therefore, realistically representing irrigation practices is crucial for accurate representation of irrigation and its effect on land surface hydrology and the interaction with the atmosphere through the exchange of moisture and heat.

While some studies use the available estimates of annual irrigation water requirements [e.g., *Döll and Siebert*[93]*, Wisser et al.*[149]] as model input[62, 63, 102, 104, 107, 108], others calculate the net irrigation water requirements within the models[19, 92, 93, 95-98, 109, 157, 161, 178]. Assuming that crops evapotranspire at the potential rate under irrigated conditions, irrigation water requirement can be estimated as the difference between potential evapotranspiration (PET) and the actual ET under unirrigated conditions[93]. It can also be estimated as the difference between crop-specific PET and the effective rainfall reaching the soil[179]. These approaches are generally useful only in GHMs because ET in most LSMs is estimated by solving energy balance at the land surface without calculating PET. Therefore, the method commonly employed in most LSMs, as well as in some GHMs, is the soil moisture deficit approach, in which the net irrigation water requirement is calculated as the difference between the target soil moisture content (θ_T) and the simulated actual soil moisture, as described in *Pokhrel et al.*[97], as,

$$I = \frac{\rho_w}{\Delta t} \sum_{k=1}^{n} \{max[(\theta_T - \theta_k), 0] D_k\} \qquad (1)$$

Where θ_T is given as $\alpha\theta_s$, I [kg m^{-2} s^{-1}] is the net irrigation demand; ρ_w [kg m^{-3}] is the density of water; Δt is model time step; θ_s and θ_k [m^3 m^{-3}] are the field capacity and simulated actual volumetric soil moisture content, respectively; and D_k [m] is the thickness of k_{th} soil layer from the land surface. The *n* represents the number of soil layers considered in the calculation (usually those in the top-meter), and α is the parameter that defines the upper soil moisture limit which has been used varyingly[96-98, 109, 200] from 0.5 to 1.

While this method has been widely used and yields plausible results of regional (e.g., country-scale) irrigation water demand (Figure 6**;** also see *Pokhrel et al.*[97] for detailed evaluation and comparison of results from different models), it may not be suitable for finer-scale studies. Recent studies have therefore begun to account for actual irrigation practices especially for regions where reliable data are available. For example, *Sorooshian et al.*[109] reflected the irrigation practices in California into their model and also used additional factors such as solar radiation and soil temperature to trigger irrigation. In the early studies, use of groundwater was ignored altogether or implicitly accounted for by withdrawing groundwater unlimitedly from an imaginary source representing fossil groundwater[92, 97, 148, 159]. Recent studies have, however, begun to account for groundwater withdrawals as well as irrigation return flows which can be substantial in some regions[19, 21, 152].

A tile approach is typically employed to represent sub-grid variability of irrigated areas. Each grid cell is divided into two tiles and calculations are performed for irrigated and non-irrigated conditions with no interactions between the tiles. Grid-averaged values of all relevant fluxes and states are then calculated by using the fractional weights of irrigated and non-irrigated areas. Crop types and their planting and harvesting dates are either simulated with the model or taken from available global database[201-203]. Regardless of the regional differences in actual irrigation practices used, the estimated irrigation demand in most models is added to the soil either as throughfall or rain (sprinkler irrigation) at a specified time each day[96, 97]. It is suggested that the effects of irrigation on the fluxes and states may not differ significantly with different irrigation methods, but the estimated irrigation water requirements may vary to some extent due to the difference in efficiency[96]. Irrigating uniformly between 0600 and 1000 local time has been suggested to be the optimal irrigation period to reduce evaporation losses[96], but irrigation at every time step has also been commonly used[198]. Owing to such methodological differences, the estimated irrigation water requirements vary greatly among different models (Table 2).

Reservoir Operation Schemes

Even though the role of reservoirs in modulating the temporal dynamics of surface water flows is well known[9, 11, 57, 204] and their regional climate impacts have also been recognized[68, 69], representation of reservoir operation in large-scale models has received less attention compared to other human water managements such as irrigation and groundwater withdrawals. A few schemes that have been developed during the last decade have mainly been used for offline water resources assessments and there have been no online studies on the impacts of reservoirs on climate. Early studies incorporated simple parameterization into large-scale models to study the effects of reservoir operation on river flows at regional scales, for example, in eastern and southern Africa[205] and in the Parana river basin[206]. *Döll et al.*[156] modified the parameterizations of *Meigh et al.*[205] and applied the model to simulate the effects of reservoirs on river flows and water use, but they treated global reservoirs as lake owing to the lack of information on their management.

Hanasaki et al.[175] *and Haddeland et al.*[173] carried out the pioneering works in representing reservoir operation in large-scale hydrological models. The model of *Hanasaki et al.*[175] was originally developed to simulate reservoir regulation within a global river routing model but has subsequently been incorporated into various GHMs[157, 185] and LSMs[97]. The model sets operating rules for individual reservoirs based on the information on reservoir storage capacity, intended purpose, simulated inflow, and water demand in the lower reaches. Reservoirs are categorized into irrigation and non-irrigation (hydropower, water supply, flood control, recreation and others), and the operating rules are determined in three steps. First, once each year, the annual total release for the following year is provisionally targeted to reproduce the inter-annual fluctuations in release. Second, monthly release is provisionally targeted, considering the simulated storage, inflow, and water demands within the reach of the reservoir; this reproduces the monthly variations in release. Third, the targeted annual and monthly releases are combined to determine the actual monthly release. The monthly release for non-irrigation reservoirs is fixed at the mean annual inflow, except during the time of overflow and storage depletion. Despite being generic and retrospective, this algorithm has been found to substantially improve river discharge simulations in the highly regulated global river basins (Figure 7).

The model of *Haddeland et al.*[173] is based on an optimization scheme in which the information regarding the inflow, storage capacity, and downstream demands is used to calculate optimal releases. The model simulates operation of reservoirs for different purposes such as irrigation, flood control, hydropower, water supply, and navigation by employing different objective functions. Irrigation demand is taken into account by estimating irrigation water requirements in the downstream of reservoirs and the optimization scheme attempts to optimize power production for hydropower dams. This model is also retrospective in a sense that the release for the next operational year is targeted at the beginning of the operational year based on the known information on long-term mean inflow and storage.

A number of subsequent studies have incorporated the models of *Hanasaki et al.*[175] *and Haddeland et al.*[173] into other models and have improved them to some extent[97, 160, 162, 207-209]. For example, *Adam et al.*[207] incorporated reservoir filling, storage-area-depth relationships, and minimum storage criteria into the scheme of *Haddeland et al.*[173]. *Biemans et al.*[208] combined the key aspects of the two modeling approaches[173, 175] and added some new functionalities including the representation of the influence of upstream reservoirs in setting the beginning of operational year and sharing of irrigation demand between multiple reservoirs. *Döll et al.*[162] adopted the parameterizations of *Hanasaki et al.*[175] but, in addition to the long-term mean inflow, they also used the difference between precipitation and evaporation over the reservoir to determine monthly release.

van Beek et al.[160] enhanced the scheme of *Haddeland et al.*[173] particularly by adding the functionality to prospectively target the future release by taking into account both the gradual changes in long-term expectancies of demand and inflow as well as the short-term variations. Their model determines the target storage over a defined period ensuring its proper functioning given the forecasts of inflow and downstream demands. Notwithstanding these continuing efforts, there have not been sufficient advancements in terms of representing realistic and adaptive operation rules and especially in integrating them into ESM frameworks. The available schemes also lack the representation of water temperature and evaporation from reservoir surface, which becomes crucial if the schemes are to be used within ESM frameworks. Seepage from reservoirs to groundwater and associated changes in other components of the terrestrial water balance as well as the changes in ocean water should also be accounted for in a consistent manner.

Groundwater Pumping Schemes

Groundwater pumping and its effects on surface and sub-surface hydrological processes and the potential implications on climate are either ignored altogether in many large-scale hydrological models or represented rather crudely. Realistically simulating the effects of pumping requires the representation of both the water table dynamics and allocation of water withdrawn from surface and groundwater resources. Despite the growing interest in incorporating water table dynamics[134, 135, 138, 142, 210-215] as well as human water withdrawals[19, 92, 96-98, 149, 150, 152, 155, 157, 160, 186] in large-scale hydrological models, there is still lack of models that integrate both factors within a single and consistent modeling framework.

In most models that account for human water use but do not explicitly represent water table dynamics, the amount of non-sustainable water use, termed as the non-local, non-renewable blue water (NNBW[92]), is estimated as the difference between total demand of a grid cell and water availability from near-surface sources. Due to the lack of rigorous modeling approach, particularly applicable for global studies, this method has subsequently been adopted by many other studies[97, 148, 149]. The approach is useful in estimating the non-renewable portion of human water use but the model configuration may result in improper description of certain hydrological processes such as recharge to deep groundwater and soil moisture variation, which in turn can alter ET and irrigative demands.

To circumvent the deficiencies in the NNBW approach, recent studies have used improved representation of groundwater withdrawal and storage change. For example, *Döll et al.*[150] added a sub-module into the WaterGAP model to account for water withdrawn from surface water and groundwater and estimated the net storage depletion using withdrawals and recharge including irrigation return flows. They modeled groundwater as a linear reservoir by setting a globally-constant outflow coefficient or 0.01. While new functionalities such as recharge from surface water bodies have been added in their recent study[21], the model still lacks the explicit representation of water table dynamics. *Wada et al.*[152] simulated groundwater withdrawals and storage depletion by adding a deep groundwater layer to their previously developed model[161]. They used the daily baseflow and long-term mean discharge as a proxy of groundwater availability and also accounted for irrigation return flows. More recently, *Pokhrel et al.*[19] implemented explicit water table dynamics and pumping schemes into an LSM which accounts for various human activities such as irrigation and reservoir operation. Their model therefore explicitly simulates both groundwater withdrawal and depletion within a consistent modeling framework while also accounting for the dynamic interaction between soil moisture and groundwater, an important mechanism for sustaining summertime ET, which has been confirmed by various previous studies [e.g., *Miguez-Macho and Fan*[216], *Koirala et al.*[142]]. The model however lacks the representation of lateral groundwater flow and any physical constraints on groundwater pumping. Despite these limitations, the model simulates the rate of change in global groundwater storage and regional water table fairly well (Figure 8; see *Pokhrel et al.*[19] for the evaluation of results with observations). A number of other studies have developed integrated hydrological models with more comprehensive representation of groundwater-surface water interactions and human water use, but their global application has not yet been tested[187-189].

EXISTING GAPS AND CHALLENGES

Despite the significant efforts that have been made during the last two decades to incorporate human impacts in large-scale hydrological models, significant gaps and major challenges still remain. First, an increasing number of studies have incorporated various human land-water management practices into large-scale hydrological models but there is still lack of coordinated efforts in integrating the patchwork of these individual studies into common modeling framework using ESMs to examine the integrated effects of human factors in various Earth system processes and the interactions and feedback among them. While the early modeling studies were oriented more on the development of integrated GHMs for accurate assessment of global water availability and use, recent years have seen emerging efforts in incorporating human impacts also in global LSMs. Nonetheless, most of these LSMs have been used for offline studies and their use within ESMs is yet to be tested. Even though the model advancements using LSM frameworks can be integrated into ESMs, the integration can be challenging because of the increased complexities and added uncertainties in online simulations. This is particularly so due to the varying level of complexities at which various biophysical and biogeochemical processes are represented in ESMs and human land-water management practices, which can potentially alter these processes, are simulated in the human impacts modules. Satisfactorily closing land surface water and energy balances could also become challenging due to increased level of model complexities when human water management schemes within LSMs are integrated into ESMs. Therefore, it is crucial to rigorously test the new schemes in offline mode before integrating them into ESMs. Moreover, future efforts should focus on developing robust modeling frameworks which can be used at varying spatial and temporal resolutions as required for different purposes such as global climate impacts studies and regional water management. This will also help identify and incorporate various human land-water management practices at their relevant spatio-temporal scales. It will also be an important exercise to examine the extent to which the uncertainties in human impacts schemes propagate through various systems in the ESM framework especially when these coupled models are used for extended future simulations.

Second, there are important methodological deficiencies in current approaches to represent various water resources management practices. For example, as discussed earlier in the paper, irrigation has been represented rather crudely in many LSMs. As a consequence, there are large disagreements among models both in estimating irrigation water use and quantifying the potential impacts on climate. Studies have begun to incorporate actual irrigation practices but the dearth of global database poses enormous challenges in using the new schemes for global applications. There is also lack of efforts to consider both natural and anthropogenic sources for nutrients, as well as to couple them with agricultural and irrigation models that simulate crop growth and yield. In addition, future models should also account for seasonal crop growth dynamics as well as the inter-annual variations in cropping patterns.

Some models account for flow regulation by dams but the currently employed schemes use generic algorithms for all global reservoirs and are not able to fully capture the timing and magnitude of peak and low flows in some river basins (Figure 7). Moreover, reservoirs are typically considered as a part of river flow routing and their dynamic interactions with the underlying soil and overlying atmosphere are not accounted for. In addition, the hydrologic and climate impacts of lakes and wetlands also remain largely unrepresented in most models and hence unexamined. Groundwater pumping, which was traditionally ignored altogether in global modeling, has now been represented in some models but the existing schemes are highly simplified. The NNBW concept that has been employed by many studies enables the estimation of unsustainable water use but involves inconsistencies in the representation of various hydrologic processes associated with groundwater withdrawal and recharge. Recent studies have used improved and explicit representation of groundwater withdrawals and recharge, and simulate aquifer storage change within the models but groundwater is still modeled as an unlimited resource without setting any physical constraints on its availability in space and time.

Third, as argued by *Wood et al.*[172], in order to adequately address critical water cycle science questions global hydrological models should be implemented at much higher spatial resolution (~1 km, referred to as "hyper-resolution") than the 10-100 km typically employed in current models. The use of such high-resolution models, however, still remains as a challenge due to data gaps as well the limitations in computational resources, and hence is yet to be fully assessed. The increase in spatial resolution alone will, however, not solve the grand challenges of predicting the past and projecting the future of hydrology because there are many physical processes (both natural and human-induced) which are not represented in current models and can become increasingly important as model grid resolution becomes finer. For example, lateral groundwater flows can be insignificant within ~100 km grid cells but may become a significant portion of the overall water budget as grid resolution increases to ~10 km (see *Krakauer et al.*[217]). *Beven and Cloke*[218] consequently argue that representing scale-dependent physical processes is crucial because there will still be inherent subgrid heterogeneities even within 1 km grids. In addition, it is also important to reduce the gap between the grid resolutions of GCMs and LSMs in order to be able to consistently use current LSM developments for online simulations. This implies that model parameterizations and spatial resolution must improve in parallel in both LSMs and GCMs such that the future model developments can become promising tools both to study the large-scale patterns of human-induced changes in the Earth system as well as to provide basic information for decision making in integrated water resources management at regional to local scales.

Fourth, there is a lack of common and standardized framework for the advancement of LSMs and characterization of modeling uncertainties. Lack of such coordinated efforts have resulted in a wide range of models which differ significantly in many aspects of model parameterizations to account for various biophysical processes and human land-water management. Community-governed efforts are therefore required to develop common frameworks for the assessment of global LSMs and to pave pathways for future model improvement and their integration into ESMs. Recent years have seen significant progress in evaluating the performance of GHMs under standardized modeling protocols but there is a lack of such intercomparison of global LSMs, especially in relation to human water management. For example, the Water Model Intercomparison Project[47] and Inter-sectoral Impact Model Intercomparison Project[219] brought together a number of GHMs to characterize the uncertainties arising from both the forcing data and model parameterizations. Results from these intercomparisons have demonstrated that the spatial agreement among models in simulating human water use is rather small for many regions and that the disagreement further increases for future simulations[220]. Therefore, it is essential that community-driven efforts are made to develop common frameworks for LSMs development and set standardized approaches for their integration into ESMs.

Fifth, there are no comprehensive datasets required to adequately constrain and evaluate hydrological models. The data gaps limit our ability to fully assess model accuracy for the past and hence to develop more reliable models to predict the future. While relatively more reliable data for some hydrologic variables such as precipitation, air temperature, and river discharge are available for many regions, data on groundwater and human water use are particularly lacking. Regional groundwater datasets are now becoming increasingly available[23, 137] but significant challenges still remain in collecting and synthesizing the data with global coverage because even the available data for most regions are not easily accessible. Vast amounts of soil and aquifer analyses and measurements have been made but the data remain dispersed and unstructured in the scientific literature, government archives, and online repositories. It is therefore essential to make community-driven efforts to compile these scattered data into a synthesis of comprehensive database easily accessible to the modeling community[221]. Some of the available global datasets on human water management and use include the Food and Agriculture Organization's AQUASTAT (http://www.fao.org/nr/water/aquastat/main/index.stm) database of water use and agricultural management, the groundwater database of the International Groundwater Resources Center (IGRAC: http://www.un-igrac.org/) and global reservoir database developed by the International Commission on Large Dams (ICOLD: http://www.icold-cigb.org/). Hydrologic modeling community has hugely benefited from such coordinated data collection and distribution efforts but it may be time to revise these datasets to meet the growing need for more comprehensive, spatially explicit, and time-varying data on human interactions with the hydrological cycle[171].

Recently, use of remote sensing has provided an unprecedented opportunity to fill the spatial and temporal gaps in ground-based observations. For example, the data obtained from the Advanced Very High Resolution Radiometer, the Landsat mission, and the Moderate-Resolution Imaging Spectroradiometer (MODIS) have provided a unique opportunity to derive global land cover and land use data which have been widely used in global hydrologic and climate modeling. MODIS data have been utilized to derive global ET at very high spatial resolution[222-224] which are used for the evaluation of global and regional hydrological models. The Shuttle Radar Topography Mission (SRTM) provides a high resolution topography data useful for global and regional water transport modeling. Satellite radar altimetry and laser altimetry have provided measurements that can be used to derive water surface elevation of lakes and reservoirs[225]. Precipitation has also been measured from space by recent satellite missions such as the Tropical Rainfall Monitoring Mission (TRMM) that delivers rainfall data for mid- and low-latitude regions.

The Gravity Recovery and Climate Experiment (GRACE) satellite mission has provided the measurements of the changes in Earth's gravity field at an unprecedented accuracy. GRACE data have been used to infer the changes in terrestrial water storage over large regions and have been widely used to study human-induced changes in surface and groundwater storages[15, 128-130, 226]. The Global Precipitation Measurement (GPM), Soil Moisture Active Passive (SMAP), and Surface Water and Ocean Topography (SWOT) mission are expected to provide comprehensive data on global precipitation, near-surface soil moisture, and ocean and terrestrial surface waters respectively. Satellite observations have therefore enabled us to better constrain and evaluate hydrological models and monitor the Earth's water cycle. However, there are inherent uncertainties and limitations in satellite-derived products. Satellite data usually provide global coverage filling the spatial gap in ground-based observations, but their temporal coverage may be limited. In addition, satellite-derived products can contain significant uncertainties because certain algorithms are used to derive the desired geophysical product as satellites typically measure the surface characteristics of Earth rather than the geophysical variables themselves. Therefore, it is important to expand ground-based observational networks in parallel with the advancements in remote sensing technology because even the satellite-derived products need to be verified with independent observations.

And finally, there are a number of other factors that still remain largely ignored in large-scale hydrological models. Some of the processes that are either ignored completely or represented crudely include lateral groundwater flow between grid cells, long-distance water transfer, temporal evolution of land cover, and vegetation dynamics among others. Future studies should also account for water quality in large-scale models, particularly in relation to the adverse effects of human activities such as irrigation, flow regulation, and groundwater exploitation which can radically alter and deteriorate water quality in the affected regions. Most global water resources and climate studies are currently confined to understanding the occurrence, flow, and distribution; there are very limited studies that deal with water quality issues especially at the global-scale[227-229].

CONCLUDING REMARKS

Human activities have fundamentally altered the patterns of global freshwater flows and storages. Therefore, anthropogenic factors can no longer be neglected in large-scale hydrological modeling. In particular, it is essential to account for human factors in global LSMs as a way forward to integrate them into Earth system models because the changes in water cycle as a consequence of human land-water management can affect a wide range of geophysical and biogeochemical processes of the Earth system. Significant advances have been made during the last two decades in incorporating human land-water management in large scale hydrological models; however, these efforts have primarily been focused on the development of GHMs for water resources assessment and less attention has been paid in developing global LSMs with the inclusion of human factors and integrating them into ESMs. Therefore, the progresses made so far have not been able to meet the urgent need to develop holistic models for integrated study of the impacts of human activities on the Earth system and the essentially complex interactions and feedbacks between human and natural systems. Human impacts have been incorporated in some global LSMs, but majority of these models have been used for offline applications and their integration into ESMs has not yet been fully assessed. Therefore, we emphasize that coordinated efforts are required to integrate the existing model developments into ESMs and further advance them by improving the currently employed schemes. We also corroborate with the conclusion of various earlier studies[27, 80, 171, 172] that it is essential to change the way we conduct hydrologic research today by considering humans as the integral driver of the global environment; the importance of dealing with human factors will further heighten in the future as the growing demand for water and food compounded by negative climate impacts will significantly expand the current scale of human footprints on Earth.

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Tables

Table 1. Global estimates of groundwater abstraction ($km^3\ yr^{-1}$)

Reference	Total/Nonrenewable Groundwater abstraction[1]	Year	Sources
Data based estimates			
Postel[144]	-/~200	Contemporary	Literature and country statistics
IGRAC-GGIS	~750/-	2000	Literature and country statistics
Shah et al.[123]	750-800/-	Contemporary	FAO AQUASTAT
Zekster and Everett[145]	600-700/-	Contemporary	Country statistics
Model based estimates			
Vörösmarty et al.[146]	-/391$^{Irr.}$ -/830$^{Tot.}$	Avg. 1995-2000	Simulated by WBM (0.5°)
Rost et al.[92]	-/730	Avg. 1971-2000	Simulated by LPJmL (0.5°)
Döll[126]	1100/-	2000	IGRAC-GGIS and WaterGAP (0.5°)
Wisser et al.[149]	1708/1199	Contemporary	Simulated by WBM_{plus} (0.5°)
Hanasaki et al.[148]	-/703	Avg. 1985-1999	Simulated by H08 (1.0°)
Siebert et al.[147]	545/-	2000	15,038 national/sub-national statistics (irrigation)
Wada et al.[16]	734(±82)/283(±40)	2000	IGRAC-GGIS and PCR-GLOBWB (0.5°)
Pokhrel et al.[97]	-/455(±42)	2000	Simulated by MATSIRO (1.0°)
Döll et al.[150]	~1500/-	Avg. 1998-2002	IGRAC-GGIS and WaterGAP (0.5°)
Wada et al.[152]	952/304	2010	IGRAC-GGIS and PCR-GLOBWB (0.5°)
Pokhrel et al.[19]	570(±61)/330(±49)	Avg. 1998-2002	Simulated by HiGW-MAT (1.0°)

[1]Some model based studies also include the estimate of nonlocal water abstraction (e.g., water supplied from cross-basin water diversions)

Table 2: Global Total Irrigation Water Withdrawals

Reference	Crop Types	Crop Calendar	Year	Irrigation Water ($km^3\ yr^{-1}$)	
				Consumption	Withdrawal
FAO	-	-	2000	-	2660
Döll and Siebert[93]	Rice, Non-Rice	Optimal growth	2000	1257	3256
Rost et al.[92]	11 Crops, Pasture	Simulated	1971-2000	1364	2555
Hanasaki et al.[148]	*Monfreda et al.*[201]	Simulated	2000	1598	3755
Siebert et al.[147]	*Portmann et al.*[202]	*Portmann et al.*[202]	2000	1277	-
Wisser et al.[149]	*Monfreda et al.*[201]	Optimal growth	2002	-	2997
Pokhrel et al.[97]	*Monfreda et al.*[201]	Simulated	2000	1021 ± 55	2462 ± 130
Döll et al.[150]	Rice, Non-Rice	Simulated	1998-2002	1231	3185
Wada et al.[152]	*Portmann et al.*[202]	*Portmann et al.*[202]	2000	1098	2572
Pokhrel et al.[19]	*Monfreda et al.*[201]	Simulated	1998-2002	1238 ± 67	3028 ± 171

Figure captions

Figure 1: A schematic of global water cycle depicting the major natural processes and human land-water management. The three major human factors discussed in the paper are shown in boldface. The fluxes and river storage are taken from *Oki and Kanae*[31], reservoir storage from *Lehner et al.*[57], and groundwater withdrawals from *Wada et al*.[16]. The total withdrawals (agricultural, domestic, and industrial) sum up to ~3810 km^3/yr of which ~730 km^3/yr comes from groundwater (see Table 1 and 2).

Figure 2: A schematic representation of various pathways whereby human land-water management practices interact with and affect various land-atmosphere-ocean processes simulated by Earth System Models. Blue color indicates storages and green indicates temperature.

Figure 3: Global cropland[78] (a,b,c) and irrigated[111] (d,e,f) areas in 1900, 1950, and 2005 shown as the percentage of the area within 5 arc minute grid cells. The insets show the temporal changes in global total values from 1900 to 2005.

Figure 4: Global distribution of large reservoirs (storage capacity > 0.5 km^3) from GRanD database[57]. The inset shows the cumulative change in global total storage capacity from 1900 to 2010.

Figure 5: Groundwater withdrawals per 0.5 degree grid cell for circa 2000, compiled by *Wada et al.*[16] based on the groundwater database of the International Groundwater Resources Assessment Centre (IGRAC). The inset depicts the time series of global total withdrawals from 1900 to 2010.

Figure 6: Simulated global irrigation water withdrawals[19] in million km^3 (MCM) per year.

Figure 7: Comparison of the seasonal cycle of river discharge simulated with and without considering human impacts[97] with observations obtained from the Global Runoff Data Center (GRDC).

Figure 8: Global groundwater depletion around 2000 simulated by HiGW-MAT model[19] (a), and the anomaly of water table depth averaged over the High Plains (b) and Central Valley (c) aquifers also simulated by HiGW-MAT.

Further Reading/Resources

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