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**Water resource
management in Earth
System models –
Part 2**

A. Nazemi and
H. S. Wheater

**On inclusion of water resource
management in Earth System models –
Part 2: Representation of water supply
and allocation and opportunities for
improved modeling**

A. Nazemi and H. S. Wheater

Global Institute for Water Security, University of Saskatchewan, 11 Innovation Boulevard,
Saskatoon, SK, S7N 3H5, Canada

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Correspondence to: A. Nazemi (ali.nazemi@usask.ca)

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Abstract

Human water use has significantly increased during the recent past. Water allocation from surface and groundwater sources has altered terrestrial discharge and storage, with large variability in time and space. Water supply and allocation, therefore, should be considered with water demand and appropriately included in large-scale models to address various online and offline implications, with or without considering possible climate interactions. Here, we review the algorithms developed to represent the elements of water supply and allocation in large-scale models, in particular Land Surface Schemes and Global Hydrologic Models. We noted that some potentially-important online implications, such as the effects of large reservoirs on land-atmospheric feedbacks, have not yet been addressed. Regarding offline implications, we find that there are important elements, such as groundwater availability and withdrawals, and the representation of large reservoirs, which should be improved. Major sources of uncertainty in offline simulations include data support, water allocation algorithms and host large-scale models. Considering these findings with those highlighted in our companion paper, we note that advancements in computation, host models, system identification algorithms as well as remote sensing and data assimilation products can facilitate improved representations of water resource management at larger scales. We further propose a modular development framework to consider and test multiple datasets, algorithms and host models in a unified model diagnosis and uncertainty assessment framework. We suggest that such a framework is required to systematically improve current representations of water resource management in Earth System models. A key to this development is the availability of regional scale data. We argue that the time is right for a global initiative, based on regional case studies, to move this agenda forward.

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1 Introduction

The water cycle is fundamental to the functioning of the Earth System and underpins the most basic needs of human society. However, as noted in our companion paper (hereafter Nazemi and Wheater, 2014a), the current scale of human activities significantly perturbs the terrestrial water cycle, with local, regional and global implications. Such disturbances affect both hydrological functioning and land-atmospheric interactions, and therefore, should be explicitly represented in Land Surface Schemes (LSSs), whether coupled with climate models (i.e. online) for integrated Earth System modeling, or uncoupled (i.e. offline) for large scale impact assessment, similar to Global Hydrologic Models (GHMs). In this pair of papers we focus on the large-scale representation of water resources management. We considered this as a 2-stage problem. We noted that while historically the effects of water management have largely been neglected in LSSs and GHMs, there has been increasing interest in recent years in their inclusion and a common first step is to estimate the demand for water, in particular associated with irrigation. However, in practice water resource systems are often complex, and associated infrastructure may have competing functional requirements and constraints (e.g. flood protection, water supply, environmental flows, etc.), exacerbated during drought. In this paper, we turn to the issues around water supply and allocation and associated representations in large-scale models.

Major implications are associated with water supply from surface and ground water sources. For instance, large dams and reservoirs can significantly modify downstream streamflow characteristics (e.g. Vörösmarty et al., 2003, 2004; Oki and Kanae, 2006; Wisser et al., 2010; Tang et al., 2010; Tebakari et al., 2012; Lai et al., 2013; Lehner and Grill, 2013) with large regional variability (see e.g. Pokhrel et al., 2012a). Considering that almost all major river systems in the Northern Hemisphere (except for the arctic and sub-arctic regions) are dammed (e.g. Meybeck, 2003; Nilsson et al., 2005), it can be argued that accurate simulation of global runoff is impossible without considering the effects of reservoirs. Such hydrologic impacts and associated environmental

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consequences can be studied through offline LSSs or GHMs (see e.g. Döll et al., 2009). There are, however, important implications that require online models. For instance, it has been argued that large dams can have important footprints on surface energy (Hossain et al., 2012), with associated effects on land-surface boundary conditions and potential interactions with local and regional climate (MacKay et al., 2009).

Groundwater resources have been also exploited during the “Anthropocene”. Every year, a large amount of groundwater is pumped to the land-surface for both irrigative and non-irrigative purposes (e.g. Zektser and Lorne, 2004; Siebert et al., 2010), which has already caused large groundwater depletions in some areas (Rodell et al., 2007, 2009; Gleeson et al., 2010, 2012) and changed the surface water balance due to return flows from demand locations to river systems and ultimately to oceans (e.g. Lettenmaier and Milly, 2009; Wada et al., 2010; Pokhrel et al., 2012b). In parallel, a considerable proportion of the surface water diverted into the irrigated lands may recharge groundwater (Döll et al., 2012). Also, from a broader perspective groundwater aquifers (particularly shallow groundwater) can be also an important control on soil moisture and wetlands, and thus influence atmospheric surface boundary conditions (e.g. Maxwell et al., 2007, 2011; Fan and Miguez-Macho, 2011; Dadson et al., 2013). These online effects are widely unquantified at the global scale, as the sub-surface processes below the root zone have been generally assumed to be disconnected from the atmosphere (Taylor et al., 2013).

In addition to the importance for simulations of terrestrial runoff and storage as well as regional and global climate, representing water allocation practice in large-scale models is urgently required to address various emerging water security concerns. Currently, the most densely-populated parts of the globe suffer from extremely fragile water security (e.g. Grey et al., 2013; Falkenmark, 2013; Schiermeier, 2014) and this will be amplified under global warming and population growth (e.g. Arnell, 2004; Wada et al., 2013; Rosenzweig et al., 2013). Yoshikawa et al. (2013) argued that current sources can only account for 74 % of the global net irrigation requirements of the 2050s and supply/demand imbalance will cause a major increase in global water scarcity (Alcamo

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et al., 2007; Hanasaki et al., 2008a, b, 2013a, b; Schewe et al., 2013). Current impact assessment studies, however, focus mainly on measuring the annual difference between natural water availability and projected demand as an indicator of water scarcity. This is a narrow interpretation as in water-scarce conditions, competition for water resources becomes increasingly important and the details of water allocation practice play a key role in the spatial and temporal distribution of water stress. Moreover, climate change is expected to result in greater seasonal and inter-annual variability with increase in the risk of extremes (e.g. Dankers et al., 2013; Prudhomme et al., 2013). Improving the accuracy of water allocation algorithms is therefore required for examining alternative management strategies to mitigate the effects of water stress and extreme conditions.

Representation of water allocation practice introduces a set of issues associated with management and societal preferences, local and regional differences in decision making, complexity of water resources systems (particularly at larger scales), as well as lack of enough data support. At local and basin scales, water allocation practice is mainly defined as an optimization problem and the aim of search is to minimize the adverse effects of water shortage and/or to maximize the economic benefits of the water resource system. The advent of search algorithms such as Linear Programming (Dantzig, 1965), Dynamic Programming (Bellman, 1952) and Genetic Algorithms (Goldberg, 1989) has resulted in a wide variety of operational models for water resource management at small basin-scale (e.g. Rani and Moreira, 2010; Hossain and El-shafie, 2013; see Revelle et al., 1969 for the early developments). These small-scale water allocation models, however, typically do not include processes related to water supply and demand and receive these variables as prescribed inputs. Moreover, small-scale operational models often require detailed information about policy constraints and operational management. This information is not generally available over larger regions and at the global scale. Even if all related information were to be available, the level of complexity within small-scale operational models cannot be supported globally due to high dimensionality in decision variables and computational burdens. These

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restrictions have gradually resulted in the development of macro-scale algorithms to represent water allocation practice and competition among demands at regional and global scales.

The main objective of this paper is to overview the current literature and to identify the state of available methods and applications for representing water supply and allocation in LSSs and GHMs. Section 2 addresses the representation of water sources. Section 3 discusses the linkage between available sources and prescribed demands through macro-scale allocation algorithms. Section 4 reviews current large-scale modeling applications and discusses the quality of available simulations. Section 5 merges the findings of Nazemi and Wheater (2014a) with those obtained in Sects. 2 to 4, and highlights current gaps and opportunities from an integrated water resources, hydrology and land-surface modeling perspective. This is finalized by suggesting a systematic framework for model development and uncertainty assessment to guide future efforts in inclusion of water resource management in large-scale models. Section 6 close our survey and provides some concluding remarks.

2 Available representations of water sources in large-scale models

2.1 Reservoir storage

There are more than 16 million reservoirs worldwide (Lehner et al., 2011), retaining around 10 % of the annual runoff and 5 % of the total volume of the world's freshwater lakes (Meybeck, 2003; Wood et al., 2011). Reservoirs are important water supply for supporting global irrigation. Yoshikawa et al. (2013) estimated that 500 km³ was allocated for irrigation by reservoirs during the year 2000. The basic data availability for larger reservoirs is relatively good. For instance, databases of International Commission of Large Dams (ICOLD; <http://www.icold-cigb.net/>) and Global Reservoir and Dam (GRanD; <http://www.gwsp.org/products/grand-database.html>) contain information about the location, purpose and capacity of 33 000 and 7000 large dams, globally.

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However, more specific physical characteristics, such as storage-area-depth relationships, are required for the parameterization of evaporation as well as reservoir storage and release. These data are not available at the global scale and parametric relationships have been used for approximating these properties based on some assumptions (e.g. Takeuchi, 1997; Liebe et al., 2005). Nonetheless, at this stage of model development, reservoir simulations cannot be directly verified, due to the lack of observations for reservoirs' level and storage globally (Gao et al., 2012). These data limitations may be largely solved in the relatively near future by upcoming satellite missions – see the discussion of Sect. 5.3 below.

From the large-scale modeling perspective, reservoirs introduce heterogeneity into land-surface parameterizations, with both offline and online implications. Depending on their size, reservoirs can be represented within channel or sub-grid routing components of host large-scale models. While large reservoirs are normally represented within the river routing component and regulate the channel streamflow, small reservoirs are mainly considered within sub-grid parameterizations as an additional pond (Wisser et al., 2010). If human management is neglected, reservoir releases can be parameterized similar to natural lakes using simple parametric equations that link the reservoir release to reservoir storage (or level) (e.g. Meigh et al., 1999; Döll et al., 2003; Pietroniro et al., 2007; Rost et al., 2008). Lake algorithms, however, have limited success in highly regulated basins (Döll et al., 2003). This is rather intuitive: for natural lakes, the dynamics of lake storage (and hence discharge) are regulated by climate and inflow variability, whereas the dynamics of reservoir discharge (and hence storage) are mainly controlled by pressures of downstream demands and management decisions. Moreover, reservoirs are often multi-functional and deal with competing demands with varying priority in time; therefore, simple lake routing algorithms are unable to fully describe reservoirs' functionality. Alternatively, macro-scale algorithms for reservoir operation are suggested, which attempt to link reservoirs' releases to inflows, storage and prescribed human demands considering water allocation objectives – see Sect. 3.3.

Considering online implications, the effects of dams on near surface energy and moisture conditions and hence land-atmospheric feedbacks can be important for large reservoirs (Hossain et al., 2012). Addressing this issue using coupled LSSs is currently a major gap in the literature and exhibits a challenging problem at the grid scale, since the contribution of dams on the local climate can be masked by regional climate variability and surrounding land cover (e.g. Zhao and Shepherd, 2011).

2.2 Streamflow diversions and inter-basin water transfers

Streamflow diversions of any magnitude require dams or barrages. At small scale these include in-basin water transfers from local streams to nearby demands. In-basin diversions are often represented in large-scale models by instantaneous abstractions (e.g. Hanaski et al., 2008a, 2010; Döll et al., 2009). Hydrologic routing can be alternatively considered for improved representation (e.g. Wisser et al., 2010). It should be noted that a proportion of the diverted flow returns to the river systems. Heuristic algorithms have been advised to mimic the mechanism of diversion based on returning the excess water to the river with some lag. Biemans et al. (2011) for instance represented the dynamics of diverted/return flows for irrigated areas by making water available for consumption for 5 days; if not used, it is released back to the river.

Inter-basin water transfers normally involve major infrastructure and can significantly perturb the regional streamflow regime. For instance, proposed South to North water transfer schemes in China (see Liu and Zheng, 2002; Liu and Yang, 2013) would divert 44.8 billion m³ of water annually (<http://www.internationalrivers.org/>). The associated hydrological impacts are estimated to be as, or more significant than, land-use and/or land-cover changes (Liu et al., 2013). Inter-basin water transfer can be adequately represented by hydrologic routing. Examples are available for some regional applications (e.g. Nakayama and Shankman, 2013a, b; Ye et al., 2013); however, efforts to represent long-distance diversions at the global scale are limited. This is mainly due to data issues regarding the location and specification of diversion channels globally. This could

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be largely resolved in future due to improvements in remote sensing observations – see the discussion of Sect. 5.3 below.

2.3 Groundwater

Even large-scale models with detailed water resource management schemes have limited representation of groundwater availability (see Table 1), largely due to the limitations in data related to groundwater storage, withdrawals and sub-surface properties as well as computational difficulties. There have been some efforts to include groundwater in LSSs to describe the aquifer dynamics, land-atmospheric feedbacks and watershed responses mainly at basin and small regional scales (e.g. Maxwell and Miller, 2005; Maxwell et al., 2005, 2007, 2011; Kollet and Maxwell, 2008; Ferguson and Maxwell, 2010; Miguez-Macho and Fan, 2012). These studies consider a physically-based groundwater store, which can be updated at each modeling time step using a 3-D representation of groundwater movement, and linked to land-surface calculations through soil moisture dynamics. Such representations are computationally expensive and limited at the global scale, since temporal and spatial domains should be finely gridded for accurate representations of groundwater movement and soil-moisture interactions, particularly in online studies. To the best of our knowledge, no online study characterizing the feedback effects between groundwater management and climate is available at the global scale. Offline representation of groundwater management has mainly been performed in the context of GHMs and involves estimation of available groundwater storage, sub-grid groundwater recharge and groundwater withdrawals. In this section we focus on groundwater availability and recharge and leave the discussion related to groundwater abstractions to Sect. 3.2.

In current representations, often groundwater availability is assumed as an unlimited local source (e.g. Rost et al., 2008; Biemans et al., 2011; Pokhrel et al., 2012a, b). This can cause major uncertainties in estimation of actual withdrawals (see Sect. 3.2). Efforts have been made to improve this assumption. For instance, Strzepek et al. (2012) bounded the groundwater availability by considering a threshold

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for groundwater allocation. Wada et al. (2014) proposed a conceptual linear groundwater reservoir, parameterized globally based on lithology and topography, to estimate the groundwater availability at the grid-scale using the baseflow proxy. Although this conceptual representation provides an efficient scheme for global simulations, it ignores inter-grid lateral groundwater movement, which is an important contributor of water availability across various scales. Although lateral groundwater movement is widely studied in aquifer studies at smaller basin and regional scales (Ye et al., 2013), it is currently a key missing process representation at larger regions and global scales (Taylor et al., 2013).

Groundwater recharge includes the movement of water from the unsaturated zone to a saturated groundwater body. There are a number of approaches to represent the vertical water movement in large-scale models, including heuristic methods (e.g. Döll et al., 2003), conceptual “leaky-buckets” (e.g. Wada et al., 2010), or numerical solutions of the physically-based Richards’ equation (Best et al., 2011; D. B. Clark et al., 2011). These approaches are based on various assumptions and are subject to large uncertainties. Heuristic schemes relate the recharge rate to surface runoff, using a set of parameters based on catchment, soil and aquifer characteristics. These representations are often simplistic and may result into large estimation errors, particularly in arid and semi-arid regions (Polcher et al., 2011). Conceptual approaches widely assume a steady-state condition and use the unsaturated hydraulic conductivity to represent groundwater recharge with or without considering capillary rise (van Beek and Bierkens, 2008; Wada et al., 2010, 2014; van Beek et al., 2011; Ye et al., 2013). In a global study, Wada et al. (2012) used this approach to account for additional recharge from irrigated lands based on the unsaturated hydraulic conductivity at the field capacity. Although conceptual representations are efficient for large-scale studies, still limitations remain in these schemes due to large heterogeneities in soil characteristics, a common assumption of steady-state recharge rate, as well as the inherent uncertainty associated with soil hydraulic properties. The physically-based approaches remove the steady-state assumption; nonetheless as discussed above, they require

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a detailed numerical scheme for solving a highly non-linear partial differential equation. This is subject to various computational difficulties at larger scales, and invariably there is a gap between the scale for which Richards' equation was developed and the scale at which it is implemented in groundwater and hydrologic models (Beven, 2006a; Gentine et al., 2012).

2.4 Desalination and water reuse

Water reuse and desalination are currently minor water resources at the global scale and have been widely ignored in large-scale models. Nonetheless, it should be noted that these water sources have local relevance and are important in several water limited regions (Wade Miller, 2006; Pokhrel et al., 2012a). Wada et al. (2011) estimated that annual desalinated water use is around 15 km³ globally, of which Kazakhstan uses 10% of the total volume. Desalinated water availability can be estimated using a bottom-up approach based on the information available about treatment and water reuse capacity at the grid-scale (Strzepek et al., 2012). These data, however, are limited and uncertain globally. Alternatively, top-down approaches try to downscale the countrywide water reuse data. Wada et al. (2011, 2014), for instance, downscaled the countrywide data on water reuse and desalination using a gridded population map. Considering that water reuse and desalination will likely be more important in future due to increased water scarcity at the global scale, we suggest more effort in representing these sources, including data collection to support future algorithm developments.

3 Available representations of water allocation in large-scale models

Water allocation distributes the available water sources among competing demands and should typically include a set of management decisions to systematically (1) link the prescribed demands to available sources of water; (2) determine allocation objectives as well as priorities in case of water shortage; and (3) withdraw the available water

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based on operational objectives and management constraints. At this stage of model development, there are limited examples for representation of water allocation at larger scales. These studies are offline and have multiple sources of uncertainty. Table 1 summarizes some examples from the recent literature. In this section, we briefly discuss the main requirements and available algorithms for representing the water allocation in large-scale models.

3.1 Main requirements

The first basic requirement is to identify which sources are available to supply the water demands within each computational grid (or basin). The majority of current allocation schemes assume that grid-based demands can be supplied from the sources available within the grid locally. This assumption is intuitive and easy to implement, however, it naturally ignores long distance water transfers. Various modifications have been proposed to overcome this limitation. Relative elevation and travel time of water from source to demand have been used to condition demands to the sources. For example, Hanaskai et al. (2006) assumed that large reservoirs can supply all downstream demands within 1100 km (based on a travel time of 1 month) and with lower elevation. Similarly, Wada et al. (2011) considered a criterion of approximately 600 km and Biemans et al. (2011) 250 km. These rules are evidently simplistic but can be easily implemented. They also generally assume steady-state conditions, so that the allocated water can be simply abstracted from the source and added at the demand location at the same time step. Alternatively, routing schemes can provide a more accurate basis for representing the water delivery and avoid this limitation – see the discussion of Sect. 5.5 below.

The second important issue is to determine objectives and priorities of water allocation, particularly during shortage. In the absence of access to local operating rules, this requires defining a set of generic rules to assign the relative preference of each demand and to define the purpose of water allocation. Irrigation has often been given the highest priority (e.g. Hanasaki et al., 2008a; Rost et al., 2008; Döll et al., 2009;

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Wada et al., 2014) but this not always the case (e.g. Strzepek et al., 2010, 2012; Blanc et al., 2013). In cases where multiple demands with the same priority are derived from a unique source of water, the deficit is typically shared proportionately to the demands (e.g. Hanasaki et al., 2008a, 2013b; Biemans et al., 2011). Based on priorities and assumptions made regarding water availability, several allocation objectives have been used (see Table 1). It should be noted that water resource management is commonly multi-purpose and allocation objectives and priorities can change within a typical operational year. For example, many reservoirs are designed for two conflicting objectives, i.e. irrigation supply and flood control. To account for this, Voisin et al. (2013a) varied the operational objective seasonally, to drop the reservoir level before snowmelt for accommodating peak flow and to retain water during the snowmelt period for the growing season, when irrigation is the main allocation purpose. They showed that this modification can improve the simulation of regulated flow and maintain the spatiotemporal consistency of reservoir levels.

Finally, allocation algorithms are required to estimate groundwater abstractions and reservoir releases at each simulation time step based on allocation objectives and priorities. Groundwater abstraction algorithms are generally limited, due to significant gaps in information about groundwater availability and actual groundwater withdrawals at the global scale. Although current data availability for reservoir levels and storages is also poor, runoff data are relatively available regionally and globally, which can be used for algorithm development and performance assessment through comparison of simulated and observed discharges downstream of reservoirs. Apart from local or national data, data of the Global Runoff Data Centre (GRDC; <http://www.bafg.de/GRDC/>) have been widely used for calibration and validation of macro-scale reservoir operation algorithms.

3.2 Grid-based groundwater abstractions

Groundwater abstractions include both sustainable and unsustainable water uses. While sustainability of groundwater withdrawals is a complex issue, in particular related

to environmental impacts of abstraction, the distinction between these for large scale applications is generally based on the grid-based groundwater recharge, as any abstraction exceeding recharge rate results in groundwater depletion, and therefore, can be considered as unsustainable. So far, groundwater withdrawals have been estimated through bottom-up and top-down algorithms, both subject to large uncertainty.

In bottom-up procedures, the groundwater abstraction is identified using grid-based estimations of surface and groundwater availability as well as the water demand. If the groundwater is considered as an infinite local source (Rost et al., 2008; Hanasaki et al., 2010; Wisser et al., 2010; Pokhrel et al., 2012a, b), then the groundwater abstraction is equal to estimated demand minus estimated surface water availability. In this case, priorities are not inherently considered. If the groundwater availability is bounded at the grid or basin scale, then the maximum groundwater withdrawal cannot exceed the local groundwater availability (e.g. Strzepek et al., 2012; Wada et al., 2014); however still, errors in estimations of surface water availability and water demands can directly propagate into estimation of groundwater withdrawals.

Top-down approaches are based on using recorded regional groundwater withdrawals or downscaling national groundwater abstractions data to finer spatial scales. Siebert et al. (2010) created a global data for irrigation water supply from groundwater abstractions based on FAO-AQUASTAT (<http://www.fao.org/nr/water/aquastat/main/index.stm>) and other census and sub-national data. In an another effort, Wada et al. (2010, 2012) used the data of the International Groundwater Resources Assessment Center (IGRAC; <http://www.igrac.net>) to estimate the countrywide groundwater use for year 2000. These estimates were further downscaled to $0.5^\circ \times 0.5^\circ$ grids, based on a global map of yearly total water demand. In a countywide study, Blanc et al. (2013) used the groundwater withdrawal data of the USGS for the year 2005 (USGS, 2011) and repeated the data for every year of simulation. These approaches are also limited by the fact that the actual groundwater pumping might be considerably more than the recorded data (e.g. Foster and Loucks, 2006; Wada et al., 2012) and groundwater withdrawals can have considerable inter-annual variability. Current and upcoming remote

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sensing technologies can address some of the issues around groundwater data availability – see Sect. 5.3 below.

3.3 Macro-scale reservoir operation

Current macro-scale reservoir operation algorithms are designed for offline applications and included in large-scale models for characterizing the impacts of reservoirs on terrestrial water storage, runoff and water security. These algorithms can be roughly divided into two general categories based on either simulating the reservoir release using a set of prescribed operational rules or using search algorithms to find optimal reservoir release. In brief, simulation-based schemes are based on a set of functional rules that use initial storage as well as inflows and demand pressure during a typical operational period to simulate releases during the operational period. In contrast, optimization-based algorithms search for optimal releases at each time step given an ideal storage at the end of the operational year, storage at the beginning of the year and forecast inflows and demands during the year. Naturally, optimization-based algorithms are more computationally expensive; nonetheless, they are more suitable for evaluating competition among water demands and effects of policy change, due to the ability to explicitly include multiple allocation objectives to guide the search for optimal releases. In contrast, simulation-based algorithms are more efficient and can be modified to support online simulations – see Sect. 5.4. Table 2 summarizes some representative examples from the current literature.

3.3.1 Available simulation-based algorithms

Current simulation-based algorithms are heavily influenced by the work of Hanasaki et al. (2006), which was initially proposed for global routing models but extended to GHMs (Hanasaki et al., 2008a, 2010) and LSSs (Pokhrel et al., 2012a, b). The algorithm distinguishes between operational rules for irrigation and non-irrigation purposes. The algorithm also accounts for both inter-annual variability and seasonality in

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reservoir releases. In simple terms, the total release in a typical operational year is first determined based on the reservoir capacity, initial storage and the annual mean natural inflow to the reservoir. Second, the monthly fluctuations in the reservoir release are parameterized based on annual mean natural inflow, mean annual demand and the prescribed monthly demand. Note that demands are considered as total water withdrawals rather than consumptive uses. Finally, monthly fluctuations are corrected based on inter-annual variability in total reservoir releases (estimated during the first step) to provide actual monthly reservoir releases. The correction, depending on the purpose and size of reservoir, is based on the ratio of initial reservoir storage to total capacity, the ratio of reservoir capacity to annual mean inflow, and/or the monthly mean natural inflows to the reservoir – see Hanasaki et al. (2006) for related formulations.

Hanasaki et al.'s algorithm has been widely used in the recent literature as it provides a generic and flexible framework to represent reservoir operation. Döll et al. (2009) implemented this algorithm for representing operation of large reservoirs within the framework of WaterGAP (Alcamo et al., 2003). They considered some modifications to accommodate losses from the reservoir and to characterize the dynamics of demand pressure on reservoirs based on consumptive uses rather than total water withdrawals. Biemans et al. (2011) modified Hanasaki et al.'s algorithm by extracting the reservoir releases using annual and monthly mean regulated inflows (rather than corresponding natural flows), limiting the demand pressure only to irrigation and changing the release rules during high demand periods. These modifications were further added to the Joint UK Land Environment Simulator (JULES; Best et al., 2011; D. B. Clark et al., 2011) for offline simulations (Polcher et al., 2011). Voisin et al. (2013a) made a regional inter-comparison between various simulation-based algorithms in the Columbia River Basin and concluded that deriving releases based on withdrawals rather than consumptive uses results in improved simulations of downstream flows. They also indicated that the choice of natural or regulated inflows depends on the severity of the demand pressure and water allocation: if the overall water demand is high with respect to mean annual inflow, it would be better to drive the algorithm with mean monthly regulated inflow;



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otherwise it is better to use the natural flow, due to large uncertainties associated with water demand estimates, and therefore, regulated flows. Although this study is limited to one region, it provided an assessment of uncertainties in estimating the reservoir releases due to uncertainties in estimating both inflows and water demand – see the discussion of Sect. 4.1.

Existing simulation-based schemes are not limited to above algorithms. Efforts have been made to simulate the reservoir releases using parametric functions, in which the parameters can be calibrated using observed downstream flows. For example, Wisser et al. (2010) advised a set of functional rules to parameterize the release from large reservoirs using the actual inflow and the long-term mean inflow to the reservoirs. More recently, Wu and Chen (2012) proposed a new algorithm by explicit consideration of operational rule curves, locally specified for each reservoir. In brief, rule curves are a set of pre-defined reservoir levels that divide the total reservoir capacity into different storage zones. These storage zones can be further associated with demands conditioned on the reservoir using various assumptions. The algorithm considers the reservoir operation at a given day as a deviation from mean releases at that day and represents this by a weighted sum of individual variations as the result of allocation for each individual water demand. Demand-specific allocations can be therefore characterized based on rule curves, the available storage, total capacity as well as the history of inflow to the reservoir. Accordingly the total release at any given day can be defined as a parametric function, in which the parameters can be tuned using observed downstream flows. Although, they noted that the operational parameters are inherently time-varying, as the purpose of dam can change with time, a systematic scheme for dealing with non-stationary parametric estimation has not been provided. This remains for future efforts – see Sect. 5.4.

3.3.2 Available optimization-based algorithms

Optimization-based schemes were initially proposed by Haddeland et al. (2006a) and implemented further in Haddeland et al. (2006b, 2007). These algorithms are heavily

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inspired by small-scale reservoir operation algorithms within the engineering literature, particularly Dynamic Programming (see Voisin et al., 2013a), and strongly rely on estimates of future inflow and demand. Therefore, they are not suitable for online simulations. In brief, the calculation starts by targeting the reservoir storage at the end of a typical operational year based on forecast demands, but without considering forecast inflows. Then, the minimum release at each daily time step is defined based on the natural streamflow at the dam's location to maintain a minimum flow requirement downstream of the reservoir. Accordingly, the maximum allowable daily release is determined based on simulated daily inflow, minimum release, reservoir storage at the beginning of the day and the targeted storage at the end of operational year. Minimum and maximum releases introduce a feasible release range, where a search algorithm can be used to find the optimal monthly releases that provide the minimum deficit during the year and the least violation from the target storage at the end of the year. Adam et al. (2007) slightly changed this algorithm by considering new thresholds for allowable release and storage and used maximization of hydropower revenue as the objective function for reservoir operation.

There are two main issues with the proposed scheme. First, feasible reservoir releases are determined based on forecasts of natural flow at dam location; therefore, the algorithm essentially requires estimating both natural and regulated flow at each simulation time step. Second, a high dimensional search (e.g. 12 releases in the case of a monthly release simulation) must be performed for each operational year, and given the uncertainty in prognostic inflows, this can result in considerable uncertainty in the optimality of actual releases. These issues were noted by van Beek et al. (2011), who modified Haddeland et al.'s (2006a) algorithm to decrease the complexity and uncertainty associated with the algorithm. Most importantly, they defined the expected inflow for each month prospectively as a function of the flow in the same month of the previous years; therefore, they omitted using prognostic natural flow forecasts. In order to reduce the dimensionality of search, they considered reservoir release as a harmonic function; therefore, only release at beginnings of the release and the discharge

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periods needed to be determined. As the actual inflow values become available, the release can be consequently updated so that the final storage at the end of release period can meet the predefined target storage. With respect to determining the reservoir inflow based on naturalized or regulated flows, van Beek et al. (2011) noted that either set-ups can be used, depending on how the observed discharge is simulated at the large-scale. This is due to large uncertainties in simulating the regulated runoff.

4 Current large-scale modeling applications

Water supply and allocation schemes reviewed in Sects. 2 and 3 have been used in a wide range of applications, including estimation of human impacts on the terrestrial water cycle as well as water security studies under current and future conditions. These simulations, however, are highly uncertain due to major limitations in methods and data support. The efficiency of available water allocation algorithms can be diagnosed by comparing the streamflow obtained from simulations with observations. Here, we first summarize the performance of current runoff simulations in regulated catchments and highlight the main sources of uncertainty. Then we turn to discuss the main findings and research needs for impact assessment and water security studies.

4.1 Quality of regulated streamflow simulations

Despite important developments, current macro-scale water allocation schemes cannot fully describe the dynamics of regulated streamflows and there can be major disagreements between the regulated discharges obtained from different reservoir algorithms (Voisin et al., 2013a). It has been shown that calibration can improve the quality of reservoir operation algorithms (e.g. Wu and Chen, 2012); however, calibration is also associated with uncertainty and can potentially hinder model applications for future projections due to possible temporal and spatial variations in optimal parameters. Hanasaki et al. (2006) as well as Döll et al. (2009) showed that simulation-based

algorithms can generally provide improved discharge simulations compared to lake routing algorithms for both irrigative and non-irrigative applications; however, simulations remain substantially biased in highly regulated catchments (e.g. San Francisco River, US; Syr Darya, Central Asia) and in cold regions (e.g. Saskatchewan and Churchill Rivers in Canada), particularly during high flows (e.g. Hanasaki et al., 2008a; Biemans et al., 2011; Pokhrel et al., 2012a). The simulation algorithm of Wu and Chen (2012) was found to be more accurate in simulating both storage and release compared to simple multi-linear regression and the target-release scheme embedded in SWAT (Arnold et al., 1998); however, it was tested only at the local scale and it is not clear how the algorithm can perform in other regions with different climate, level of regulation and allocation objectives. Very similar conclusions were obtained for optimization-based algorithms. Discharge simulations are generally improved compared to the no reservoir condition (e.g. Haddeland et al., 2006a); however, there are still significant deficiencies in simulating highly regulated flows, particularly in mountainous and cold regions such as Colorado River in the US as well as Yukon and Mackenzie Rivers in Canada (e.g. Haddeland et al., 2006b; Adam et al., 2007). This majorly relates to prognostic reservoir inflows, which remain highly uncertain in these environments and this uncertainty contributes to the uncertainty in assigning optimal reservoir releases, often in dynamic and complex manners (Nazemi and Wheater, 2014b).

From a broader perspective, the current performance of reservoir operation and water allocation algorithms must be seen in the context of the hydrological performance of the host large-scale models. Currently, there are large biases in modeling hydrological processes at the continental and global scales (e.g. Wisser et al., 2010) and runoff estimates remain widely divergent at global and continental scales (see Hejazi et al., 2013b). More clearly, it has been shown that current simulations systematically underestimate streamflow in the arctic and sub-arctic regions and overestimate the observations in dry catchments; and reservoir operation algorithms mainly improve the timing of the flow, but not the volume (van Beek et al., 2011). While there are many potential reasons for this, one key source of this limitation is the quality of gridded precipitation

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products (Biemans et al., 2009, 2011). Rost et al. (2008) used different precipitation products to simulate the regulated river discharge and found substantial variations in simulated discharge due to the choice of precipitation data. Moreover, they showed that sometimes the total precipitation estimate can be less than the total observed discharge after abstraction and regulation. Upcoming satellite missions can address some of the issues regarding historical forcing (see the discussion of Sect. 5.3); however, uncertainty in future precipitation (and other climate variables) should be dealt systematically using multiple climate forcing options using various combinations of concentration pathways, climate models and downscaling procedures.

4.2 Impacts assessment and water security studies

Despite modeling uncertainties and disagreements between different simulation results, the current literature agrees that the effects of water allocation are more pronounced at finer spatial and temporal scales. For example, Haddeland et al. (2007) studied the impacts of reservoir operation coupled with irrigation on continental runoff and argued that water allocation has resulted in 2.5 and 6 % increase in annual runoff volume in North America and Asia, respectively. This is almost canceled out by increased evaporation due to irrigation. Nonetheless, as the analysis moves from global and continental to regional and large catchment scales, the effects of water allocation become more profound. For instance, while the mean annual runoff decreased in the western US by around 9 % during a historical control period, the rate of decrement is around 37 % in the Colorado River during the same period (Haddeland et al., 2006b). Similarly, the effects of water allocation are more significant at finer time scales. For instance, Adam et al. (2007) noted that reservoirs have a minor effect on annual flows in Eurasian watersheds but have significant seasonal effects by changing the flow timing and seasonal amplitudes (see also Döll et al., 2009; van Beek et al., 2011; Biemans et al., 2011). This has an important implication for water security studies, particularly under climate change conditions with large seasonal impacts. Accordingly, measuring regional water stress on the annual basis (e.g. Strzepek et al., 2012; Blanc et al., 2013)

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can be misleading due to seasonality of demand pressure and climate change effects (see Hanasaki et al., 2008b; Wada et al., 2011).

Turning from surface water to groundwater issues, almost all available global studies agree on a significant increasing trend in groundwater withdrawal from the late 20th century onward. As an example, Wada et al. (2014) argued that from 1990 to 2010, the rate of global groundwater withdrawal increased by around 3% a year. Although the results of current simulations are relatively in good agreement with major observed depletions in some regional aquifers (see Gleeson et al., 2012), various quantified assessments and further conclusions regarding the groundwater-induced sea-level rise (e.g. Wada et al., 2010; Pokhrel et al., 2012b) remain highly uncertain due to crude representation of groundwater availability, recharge and withdrawal, as discussed in Sects. 2.3 and 3.2. This highlights an urgent necessity for improving the representation of human-groundwater interactions at larger scales.

5 Towards an improved representation of water resource management in large-scale models

5.1 Current gaps and the ideal representation

Throughout this paper, we highlighted the importance of including water supply and allocation in large-scale models. This has both online and offline implications. We have noted that all currently available efforts in including water supply and allocation in large-scale models are offline and have been made mainly in the context GHMs. Although GHMs provide an efficient platform for algorithm development and testing given the relative lack of computational constraints, online effects of large reservoir storage and large-scale groundwater pumping at the global scale are currently unknown. As limitation in online simulations was also noted in Nazemi and Wheater (2014a) for irrigation, we argue that improving the inclusion of water resource management in Earth System

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models requires more model development efforts in LSSs, particularly towards coupled simulations.

From an integrated water resource management and land-surface modeling perspective, water demands can be considered as functions of climate, vegetation and soil-moisture as well as socio-economic and policy variables (see Nazemi and Wheater, 2014a). As shown in this paper, water supply is mainly controlled by natural surface and ground water availability but water demands remain as the key driver of water allocation. Therefore, water demand and water allocation should be systematically linked through a feedback loop. Also, as noted in Sect. 3.1, various human–water interactions are coupled and linked to available water sources through water allocation practice. This integrated water resource system should be then linked to natural land-surface processes at the grid scale. This is rather intuitive: when considered in a typical grid, water allocation perturbs hydrological and land-surface variables within the grid. In parallel, the combined effects land-surface and hydrological processes govern the variations in surface and ground water availability, which consequently determines water allocation in the next simulation step. Figure 1 shows a simplified schematic for this integrated modeling framework, in which grid-based calculations of natural and anthropogenic land-surface are further coupled with climate through grid-based land-atmospheric feedbacks.

Major gaps remain in representing water resource management in LSSs in a way defined above. Essentially, water resource management often takes place at the sub-grid resolution of current LSSs used for simulations over large region and global scales (i.e. 10 km and more). Including the elements of water resource management therefore requires moving towards a “hyperresolution” scale (a few kilometers or less) for explicit representation (see Wood et al., 2011) and/or adding new sub-grid parameterizations related to human–water interactions, as illustrated in Fig. 1. However, as the time-space resolutions become finer or more sub-grid parameterization are added, computational burdens and data requirements increase significantly, in particular for online simulations. On important example is online representation of groundwater processes at the

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global scale. Moreover, current algorithms originally designed for offline applications might not be suitable for online implementations. An important example is reservoir operation a both optimization- and simulation-based algorithms have some levels of prognosis that hinder their application in coupled simulations.

5 From offline perspective, major limitations are associated with representing water resource management at larger scales due to uncertainties in (1) data support, particularly with respect to precipitation and actual water use; (2) water demand, supply and allocation algorithms, particularly with respect to irrigation demand estimation, reservoir operation and groundwater withdrawals; as well as (3) host large-scale models, particularly with respect to those calculations that determine surface and ground water availability. It should be noted that here we only focus on epistemic sources of uncertainty, which needs to be addressed, quantified, communicated and possibly reduced (see Beven and Alcock, 2012). Table 3 summarizes various aspects of uncertainty related to data support, algorithmic procedures and host models, identified for estimation of water demand (see Nazemi and Wheeler, 2014a) and surface water allocation (see Sects. 2 to 4). It is often quite difficult to identify the exact source of uncertainty due to complex interconnections between various elements; and currently, a formal framework to test and validate the water resource management components in the face of various sources of uncertainty is not available (see also Beven and Cloke, 2012).

20 In the remainder of this section, we briefly highlight the opportunities to address the gaps and uncertainties noted above and to move towards the integrated representation proposed in Fig. 1 by suggesting few directions for future development.

5.2 Computational complexities

25 Online simulations and groundwater modeling are generally computationally expensive (e.g. Hill et al., 2004). Moreover, capturing online effects of water resource management requires appropriate resolution of process representation (Sorooshian et al., 2011a), which is generally unknown in advance. Implicit schemes therefore require research into appropriate scales of resolution. Explicit consideration of land-surface

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processes using hyperresolution schemes can in principle overcome this issue; however, such representations require large computational resources. Wehner et al. (2008) suggested opportunities to address computational burdens, including hardware design (i.e. building enhanced computer processors for a specific application) and use of distributed and grid systems. A wide range of applications exists for grid and cloud computing systems (see Schwiegelshohn et al., 2010; Lecca et al., 2011), for example in running coupled LSS runs as well as sensitivity analysis and ensemble predictions (Fernández-Quiruelas et al., 2011). This can also provide a basis to explore various model resolutions to identify critical scales for process representations (see Gentine et al., 2012) and to support computationally expensive offline calculations, such as groundwater processes, dynamic crop growth, river routing and model calibration (e.g. von Bloh et al., 2010; Rouholahnejad et al., 2012; Wu et al., 2013).

5.3 Data support

As noted through our survey, major data limitations exist in representing various aspects of water resource management, which are related to forcing, parameterization, calibration and validation of water demand, supply and allocation algorithms (see also Table 3). At this stage of research, major gaps noted in spatial and temporal data quality and coverage related to climate, hydrology, socio-economy, policy and water resource management that are required to drive or to support large-scale models (see Wood et al., 2011; Gleick et al., 2013; Oki et al., 2013).

One important opportunity to improve data support is the use of remote sensing technology, which can provide a synoptic view of the state of land-surface and atmospheric variables (see Sorooshian et al., 2011b; Asrar et al., 2013) and a reliable data support for dynamic forcing, parameter estimation as well as evaluation of large-scale models (see van Dijk and Renzullo, 2011; Trenberth and Asrar, 2012). For instance, Landsat missions (<http://landsat.gsfc.nasa.gov>; see Williams et al., 2006) have captured long-term variations in global land-cover with a temporal resolution of 16 days and spatial resolution of up to 30 m, which can help to parameterize anthropogenic activities

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such as crop growth and reservoir area. More recently, passive MODerate Resolution Imaging Spectroradiometer (MODIS; <http://modis.gsfc.nasa.gov>; see Savtchenko et al., 2004) provide a wide range of land-surface information and have already been applied for various large-scale modeling studies, including validation of online models (Sorooshian et al., 2011a), high resolution parameterization (Ke et al., 2012) and monitoring storage in large reservoirs (Gao et al., 2012). Assimilation of MODIS land measurements with meteorological data and the Penman–Monteith equation has also provided 8 day, monthly and annual evapotranspiration estimates at 1 km resolution globally (Mu et al., 2007, 2011). This can provide a basis to evaluate simulated evapotranspiration over land-surface (see Sect. 5.4). Another important product is the Gravity Recovery and Climate Experiment (GRACE; <http://www.csr.utexas.edu/grace/>; see Tapley et al., 2004), measuring changes in the total terrestrial water storage at rather coarser resolutions. GRACE data have already been used in studies related to regional groundwater depletion (e.g. Rodell et al., 2007, 2009), model calibration (Sun et al., 2012) and validation of large-scale simulations (Pokhrel et al., 2012a, b).

Upcoming satellite missions can further support representation of water resources management. For instance, precipitation is a key limitation in hydrological modeling in general, but is also important for irrigation demand and scheduling. The upcoming Global Precipitation Measurement mission (GPM; <http://gpm.nasa.gov>) will collect data at 10 km resolution, every 3 h, globally. The upcoming Soil Moisture Active Passive mission (SMAP; see Entekhabi et al., 2010) will provide improved global soil moisture measurements every 24 h without sensitivity to cloud cover. This can be considered as an important data support for irrigation demand algorithms. Another upcoming remote sensing mission is the Surface Water and Ocean Topography mission (SWOT; see Fu et al., 2009; Biancamaria et al., 2010; Durand et al., 2010), which will provide fine-scale measurements of various surface water stores, including reservoirs as well as natural and man-made channels. Such information at the global scale has the potential to revolutionize representation, calibration and validation of algorithms related to estimation of inflow to reservoirs, reservoir releases and inter-basin water transfers.

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There are also important improvements in sharing ground-based data and simulation results, including some inspiring grass-root data collection efforts. For example, the International Groundwater Resources Assessment Centre (IGRAC; <http://www.un-igrac.org>) assigns an associate expert to each one-degree grid cell to submit monthly groundwater levels. Such data can be a critical source for testing groundwater withdrawal algorithms. Similar grass-root efforts could be made to record other water resource management data, particularly with respect to actual (rather than licensed) water uses, local management policies and water technologies. We also note that sharing of gridded climate forcing and simulation results is important and provides a basis for consistent model intercomparison efforts. One example is the recently finished EU-WATCH program (<http://www.eu-watch.org/>), which provides forcing and simulation results of WATCH's Model Intercomparison Project (WaterMIP; <http://www.eu-watch.org/watermip>).

5.4 Water resource management algorithms

Computational algorithms for representing the elements of water resource management have various sources of uncertainty (see Table 3) and improving the related representations and reducing the modeling uncertainty can be considered as an important avenue for future development. Some important opportunities include enhancing the simulation-based reservoir operation algorithms for online applications and various applications of calibration, data assimilation and system identification techniques.

- One crucial limitation, as noted above, is in current reservoir operation algorithms for online applications. Simulation-based schemes provide a basis to move forward, however, modifications are required to (1) implement the operation at finer temporal resolution (sub-hourly to few hours rather than daily and monthly); (2) relax the need to forecast demand; and (3) represent the thermal and evaporative functions of reservoirs for online applications. Modeling schemes developed for representing energy balance of natural lakes at sub-grid scale (e.g. MacKay,

2011; MacKay and Seglenieks, 2013) can be merged with improved simulation-based reservoir operation algorithms to simultaneously characterize reservoir release and storage as well as land-atmospheric feedbacks.

- Calibration using observed, simulated or assimilated system behavior can be used to implicitly represent management and sub-grid heterogeneity. One example would be to address diversity in irrigation demand by finding “representative parameters” that match the assimilated evaporation over a typical irrigated grid. Calibration with ability to identify time-varying parameters could also be used to improve the performance of reservoir operation algorithms and provide a basis to account for variations in water allocation practice in time and potentially in space by considering functioning of multiple reservoirs.
- Another opportunity is to improve functional mappings of system response and demand through system identification techniques. These techniques can range from statistical regression models to more sophisticated machine-learning techniques such as artificial neural networks (e.g. Nazemi et al., 2006a) and genetic symbolic regression (e.g. Hassanzadeh et al., 2014). One example would be building functional relationships for estimation of irrigative or non-irrigative water demands and/or uses. Another would be to represent reservoir operations through transfer functions and enhanced rule-based models. This can provide an interesting prospect to extract operational rules from observed data and to incorporate soft variables such as social values and expert insights into modeling water resource management (e.g. Nazemi et al., 2002). Having such an improved modeling capability might provide an opportunity to guide representation of adaptive management and may provide a basis to regionalize management policies and operational practices.

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5.5 Host models

Limitations in host models can introduce a wide range of uncertainties (see Table 3). This is due to the fact that water resource management algorithms are fully embedded within the host models and interact with calculations related to land-surface process at the grid scale (see Fig. 1). For instance, estimation of antecedent soil moisture affects estimation of irrigation demand. Similarly, estimates of the natural inflows to reservoirs govern the calculations related to reservoir releases and storage. Currently, there are major limitations in representing soil moisture, snow cover, permafrost, evapotranspiration, deep percolation and runoff in large-scale models and they cannot be represented without large uncertainty (Lawrence et al., 2012; Trenberth and Asrar, 2012; Oki et al., 2013). Moreover, host models often contain missing processes. For instance, current host models often ignore the effects of increased CO₂ concentration on irrigation demand. This may result in large uncertainties under climate change effects (see Wada et al., 2013).

While an extensive review of these issues goes beyond the scope of this paper, we note that substantial efforts continue to be made to include missing processes and to improve current parameterizations of natural and anthropogenic processes in large-scale models, particularly in the context of LSSs. For instance, the Community Land Model (CLM; Oleson et al., 2004, 2008; Lawrence et al., 2011) has been recently improved by new algorithms for representing permafrost (Swenson et al., 2012), agriculture (Drewniak et al., 2013) and irrigation (Levis and Sacks, 2011; Levis et al., 2012). Another important development is the vector-based river routing algorithms (e.g. Li et al., 2013; Tesfa et al., 2013) that can improve the representation of natural and anthropogenic channel processes such as reservoir stores, streamflow diversions and inter-basin water transfers (see Lehner and Grill, 2013). Another key opportunity is the application of data assimilation and/or calibration techniques to reduce parametric uncertainty and to improve prediction capability. Some systematic frameworks for calibration and parameterization of land-surface processes are suggested (Rosolem

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et al., 2012, 2013). We expect improvements in process representations and parameterizations related to LSSs will increase in near future due to the need that has been already recognized (e.g. Wood et al., 2011; Lawrence et al., 2012; Trenberth and Asrar, 2012; Gleick et al., 2013; Oki et al., 2013; Dadson et al., 2013).

5.6 A framework to move forward

As noted through our survey, a variety of modeling options for representing key elements of water resource management at larger scales is currently available. Nonetheless, major limitations exist in current data, algorithms and host models. At this juncture, a primary task for model development should be to test and compare different data and modeling alternatives with respect to accuracy, identifiability and capability for generalization. Guidelines are available for (1) considering multiple working hypotheses for supporting and representing relevant sub-processes and modeling component; (2) constructing different simulations based on various combinations of the considered options and (3) rejecting them if they fail to describe new data, violate their underlying assumptions and/or can be equally described by simpler models (M. P. Clark et al., 2011; see Popper, 1959). Modular systems, such as the recently released WRF-Hydro (NCAR, 2013), are particularly suitable for building such a framework as they provide a tool for constructing/falsifying different hypotheses for process representations, parameterizations and data support in a unified computational platform.

To address this and to move towards the integrated representation of water resource management in LSSs, suggested in Fig. 1, we propose a systematic framework for improving the incorporation of water resource management through building, testing and falsifying various modeling options. Figure 2 shows this framework. In brief, Fig. 2 divides the model development into six components, related to (A) modeling set-up and data configuration, (B) climate modeling, (C) land-surface modeling, (D) water resource management representation, (E) calibration and parametric identification, as well as (F) testing and falsification. The framework starts with prior knowledge (A), coming from the modeling purpose, current modeling capabilities and limitations and

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the knowledge obtained from previous modeling attempts. According to the prior knowledge and emerging advancements, a range of modeling scales can be selected and multiple working hypotheses can be configured to represent the data and modeling options in (B) to (E). Depending on the mode and period of simulation, climate data or more generally climate models (B) are required to force or to be coupled with land-surface processes. The land-surface component (C) includes relevant sub-modules related to natural processes, water supply and allocation and irrigative and non-irrigative withdrawals. The anthropogenic activities are controlled by the water resource management component (D), which requires inputs from land-surface and climate components to determine water availability and to estimate various demands with the aid of these and/or other proxies (priori knowledge). Rules for prioritizing, partitioning and allocating water demands are reflected in a management decisions sub-module that further drives water allocation in the land-surface modeling component. Sub-modules within (C) and (D) often contain unknown parameters that need to be identified through prior knowledge or calibration. As a result, calibration and parameter identification algorithms (E) with capability for further uncertainty assessment are a key requirement. Population-based optimization algorithms are particularly suitable for parameter identification as they provide a range of behavioral parameters, which can be analyzed through advanced visualization schemes and provide valuable insights into modeling uncertainty, identifiability and multiple performance measures (e.g. Nazemi et al., 2006b, 2008; Pryke et al., 2007). Moreover, population-based algorithms can provide methodological linkage to uncertainty assessment through various diagnostic tests. Guidelines are provided to test and falsify models through various evaluation criteria such as parametric identifiability (e.g. Beven, 2006b), Pareto optimality (Gupta et al., 1998), predictive uncertainty (Wagener et al., 2004) and limits of acceptability (Beven and Alcock, 2012).

A key requirement for implementing the suggested framework is the availability of suitable data, at an appropriate scale, for algorithm development and intercomparison. Although global studies are important to improve our knowledge of the Earth System

and water security, our ability to conduct a comprehensive global study as proposed in Fig. 2 is currently limited due to methodological, computational and funding barriers. We argue that a network of regional case studies, however, could provide access to local data, and a sample of comparative examples to support algorithm intercomparison and further development. We note, for example, the success of model intercomparison projects such as MOPEX (Duan et al., 2006) for hydrological modeling, and suggest that the time is right to develop a similar initiative for the incorporation of anthropogenic effects in hydrological models. One possibility is to draw on the resources of the set of Regional Hydroclimate Projects (RHPs) supported by the Global Energy and Water Exchanges (GEWEX) initiative of the World Climate Research Program (WCRP). As an example, our home river basin in western Canada, the 340 000 km² trans-boundary Saskatchewan River Basin (SRB), is a GEWEX RHP, embodies a complex large scale water resources system (Nazemi et al., 2013), and poses globally-relevant science and management challenges (see Wheeler and Gober, 2013). These require improved representation of water resource management at larger scales to diagnose the changes in the regional discharge, climate and water security as the result of current and future water resource management and climate change. Such RHPs could provide a basis for model development and intercomparison to support inclusion of water resource management in Earth System models for fully coupled global simulations.

6 Summary and concluding remarks

Human water supply and allocation have intensively perturbed the water cycle. We noted that the inclusion of these anthropogenic activities in Earth System models poses a new set of modeling challenges and progress has remained incomplete. Despite some major developments, we noted that current limitations can significantly degrade the capability for large-scale water security assessment and resource management, particularly with respect to future conditions, and neglects potentially-significant sources of change to land surface systems. We highlighted important deficiencies

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related to representing groundwater stores and withdrawals as well online implications of large reservoirs. We also noted that current water allocation algorithms have considerable limitations in representing streamflow in regulated catchments. We argued that these limitations are attributed to uncertainties in data support, water allocation algorithms and host models and proposed that future water security and impact assessment studies should aim to improve current representations and move to finer spatial and temporal resolutions.

We identified four opportunities for improvements. These are advancements in (1) high performance computing; (2) remote sensing, data collection and data sharing; (3) calibration algorithms, system identification techniques and assimilation products; and (4) ongoing improvements in host models including both process representation and parameter identification. As there are several options available for data support, water resource management algorithms and host models, we proposed a modular framework for testing various modeling and data options, which can be configured by multiple working hypotheses and implemented in a unified and fully integrated modeling framework. The selected working hypotheses can be tested and falsified on the basis of available information, intercomparison and/or various model diagnosis frameworks. Similar to other recent commentaries (e.g. M. P. Clark et al., 2011; Beven et al., 2012), we believe that such a systematic framework is essential for improving current modeling capability in both offline and online modes and can be pursued using regional case studies, before aiming for fully coupled global simulations. WCRP RHPs are one source of suitable examples to move this agenda forward.

It should be noted that filling current gaps in the inclusion of water resource management in Earth System models requires substantial efforts across a wide range of disciplines, from social and policy sciences to economics and water management, from natural sciences to engineering and mathematical modeling, and from remote sensing to hardware technology and computer science. Interdisciplinary research efforts, therefore, are important. Moreover, for various reasons including funding limitations, the community needs to fully recognize the role of collaboration and explore various



opportunities to share data and resources for efficient model developments and for consistent intercomparisons.

Finally, it should be indicated that our survey considered water resource management from a water quantity perspective. Water quality concerns are increasingly associated with growing human water demand and can also impact water supply and allocation. Coupling water quality and quantity in Earth System models is however very much in its infancy and much future effort will be required to fill this gap. We hope that our survey will trigger more attention towards the necessity for improving current Earth System modeling capability to respond to the needs and challenges of the “Anthropocene”.

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Table 1. Examples for available representations of water supply and allocation in large-scale models.

Reference	Water supply				Water allocation		
	Diversions	Reservoirs	Groundwater store	Desalination and reuse	Demand-supply dependency	Priorities in demands	Operational objectives
Haddeland et al. (2006b)	In- and inter-grid abstraction	Macro-scale operation ^a	N/A	N/A	Grid and 5 grids upstream ^b	Irrigation, flood control, hydropower, others	Minimize deficit, maximize hydropower
Hanasaki et al. (2008a)	In- and inter-grid abstraction	Macro-scale operation	N/A	N/A	Grid and 10 grids upstream	Irrigation, non-irrigation	Allocate available water, share deficit
Rost et al. (2008)	Local abstraction	Lake routing	Unlimited local source ^c	Unlimited source	Local grid	Irrigation only	Meet total demand using unlimited groundwater
Döll et al. (2009)	In- and inter-grid abstraction	Macro-scale operation	N/A	N/A	Grid and 5 grids upstream	Irrigation, non-irrigation	Meet total demand ^d
Hanasaki et al. (2010)	Local abstraction	Macro-scale operation/local abstraction	Unlimited local source	N/A	Local grid	Irrigation and livestock only	Meet total demand using unlimited groundwater
Strzepek et al. (2010)	Local abstraction	Macro-scale operation ^e	Countrywide estimates	N/A	Local basin	Domestic, industry, livestock, irrigation	Maximize profitability
Wisser et al. (2010)	In-grid hydrologic routing	Macro-scale operation	Unlimited local source ^f	N/A	Local grid	Irrigation only	Meet total demand using unlimited groundwater
Biemans et al. (2011)	Local abstraction, Heuristic routing	Macro-scale operation	Unlimited local source ^g	Unlimited source	Grid and 5 grids upstream	Irrigation only	Proportional allocation of available water
Wada et al. (2011)	In- and inter-grid abstraction	Macro-scale operation	Countrywide estimates	Countrywide estimates	Grid and sources 600 km upstream	Irrigation, flood control, hydropower, others	Minimize deficit, maximize hydropower
Pokhrel et al. (2012a)	Local abstraction	Macro-scale operation	Unlimited local source	N/A	Local grid	Irrigation, non-irrigation	Meet total demand using unlimited groundwater
Strzepek et al. (2012)	Local abstraction	Macro-scale operation ^h	Basin-scale threshold	Function of capacity	Local basin	Non-agricultural, Agricultural	Minimize groundwater use and spill
Blanc et al. (2013)	Local abstraction, Heuristic routing	Macro-scale operation ^e	Basin-scale threshold	N/A	Local basin	Non-agricultural, Agricultural	Minimize groundwater use and spill
Hanasaki et al. (2013b)	Local abstraction	Macro-scale operation	N/A	N/A	Local grid	Municipal, industrial, irrigation	Allocate available water, share deficit
Voisin et al. (2013a, b)	In- and inter-grid abstraction	Macro-scale operation	N/A	N/A	Grid and 200 km upstream	Dynamic priority in operation	Allocate available water, share deficit
Wada et al. (2014)	In- and inter-grid abstraction	Macro-scale operation	Conceptual reservoir	Countrywide estimates	Grid and 600 km upstream	Irrigation, non-irrigation	Allocate available water, share deficit

^a Simultaneous operation of multiple dams in a river basin was not considered.

^b See Haddeland et al. (2006a).

^c Simulations without assuming unlimited groundwater store were also performed.

^d Demand that cannot be allocated in any given day is allocated later in the year or in the next year, when water is available.

^e A virtual reservoir is considered for each basin.

^f Shallow groundwater is represented as a runoff retention pool, which delays runoff before it enters streams.

^g Simulations with considering only surface water availability were also performed.

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Table 2. Representative examples for available macro-scale reservoir operation algorithms implemented in large-scale models.

Reference	Host model	Routing algorithm	Type of operation	Reservoir data	Discharge data
Hanasaki et al. (2006)	N/A	TRIP (Oki and Sud, 1998)	Simulation-based	WRD98 (ICOLD)	GSWP (Dirmeyer et al., 1999; Oki et al., 2001)
Haddeland et al. (2006a, b, 2007)	VIC (Liang et al., 1994)	Linearized Saint-Venant (Lohmann et al., 1996, 1998)	Optimization-based	ICOLD (Vörösmarty et al., 1997, 2003)	USGS (http://waterdata.usgs.gov) USBR (http://www.usbr.gov) GRDC (http://www.bafg.de/GRDC/)
Adam et al. (2007)	VIC (Liang et al., 1994)	Unit hydrograph and Linearized Saint-Venant (Lohmann et al., 1996, 1998)	Optimization-based	ICOLD (Vörösmarty et al., 1997, 2003)	Adam and Lettenmaier (2008)
Hanasaki et al. (2008a)	H07 (Hanasaki et al., 2008a, b)	TRIP (Oki and Sud, 1998)	Simulation-based	WRD98 (ICOLD)	GRDC (http://www.bafg.de/GRDC/)
Döll et al. (2009)	WaterGAP (Alcamo et al., 2003)	HBV (Bergström and Smith, 1995)	Simulation-based	GRanD (Lehner et al., 2008)	GRDC (http://www.bafg.de/GRDC/)
Wisser et al. (2010)	WBMplus (Vörösmarty et al., 1998)	Muskingum-Cunge (Ponce and Changanti, 1994)	Simulation-based	ICOLD	UNH-GRDC (Fekete et al., 1999, 2002)
Biemans et al. (2011)	LPJmL (Gerten et al., 2004; Rost et al., 2008)	Linear reservoir model (Huggins and Burney, 1982)	Optimization-based	GRanD (Lehner et al., 2011)	GRDC (http://www.bafg.de/GRDC/)
Van Beek et al. (2011)	PCR-GLOBW (van Beek and Bierkens, 2009)	Kinematic Saint-Venant (Chow et al., 1988)	Optimization-based	GLWD1 (Lehner and Döll, 2004)	GRDC (http://www.bafg.de/GRDC/)
Wu and Chen (2012)	SWAT (Arnold et al., 1998)	SWAT (Arnold et al., 1998)	Simulation-based	Wu et al. (2007)	Chen and Wu (2008)
Pokhrel et al. (2012a)	MASTIRO (Takata et al., 2003)	TRIP (Oki et al., 2001)	Simulation-based	WRD98 (ICOLD)	GRDC (http://www.bafg.de/GRDC/)
Voisin et al. (2013a)	VIC (Liang et al., 1994)	MOSART (Li et al., 2013a, b)	Simulation-based	GRanD (Lehner et al., 2011)	Source of data is not indicated

Table 3. Uncertainties in current offline representations of surface water resource management in large-scale models.

Component	Type of activity	Specification	Data uncertainty	Algorithm uncertainty	Host model uncertainty ^a
Water demand (Nazemi and Wheeler, 2014a)	Irrigative demands	Irrigation	Climate forcing; soil, crop, land-use and land management including sub-grid heterogeneities; actual diversions; socio-economy and technological variables; agricultural management.	Characterizing the potential evapotranspiration and crop water demand; representing the sub-grid crop diversity, irrigation expansion, crop change.	Estimation of actual evapotranspiration, soil water movement, runoff and canopy losses; considering CO ₂ effects
	Non-irrigative demands	Industrial uses	Location, diversity and capacity of uses; actual diversions; downscaling proxies; socio-economy and technological variables.	Seasonal variations in industrial water needs; structural and parametric uncertainty in estimation and projection of industrial demand.	N/A
		Energy-related uses	Location, diversity and capacity of uses; actual diversions; downscaling proxies; socio-economy and technological variables.	Seasonal variations in energy-related water needs; structural and parametric uncertainty in estimation and projection of industrial demand.	N/A
		Municipal Uses	Population; diversity in uses; actual diversions and uses; downscaling proxies; socio-economy and technological variables.	Seasonal variations in municipal water needs, structural and parametric uncertainty in estimation and projection of municipal demand.	N/A
	Livestock uses	Heads; socio-economy	Seasonal variations in livestock water need; return flows	N/A	
Water allocation (see Sects. 2 to 4)	Water supply	River diversion	Location of diversion; capacity, slope and other properties of diversion networks	Diversion losses, return flows	Channel routing
		Reservoirs storage ^b	Precipitation; reservoir location and characteristics; actual storage; small dams	Crude representation of reservoir releases using representations of natural lake, losses from reservoir	Hydrological processes upstream of dams, channel routing
		Inter-basin transfer	Location of diversion; capacity, slope and other water transfer properties; management policies; actual water transfer.	Diversion losses, simplicity of heuristic algorithms	Channel routing, calculation of demands
		Reused water	Location, capacity and actual desalinated water supply	Limited representations	N/A
	Water allocation practice	Operational objectives	Management policies and local constraints	Limitations of common objective functions; Temporal and spatial variations in operational objective	Estimation of water demand and supply
		Demand-Supply dependency	Management policies and local constraints, topography, diversion channels	Steady-state assumption	Estimation of water demand and supply
	Priorities	Management policies and local constraints	Temporal and spatial variations in priorities	Estimation of water demand and supply	
	Reservoir operations	Management policies and local constraints	Simplicity of operational rules in simulation-based approaches, complexity of optimization-based algorithms, prognosis of both approaches	Operational objectives, inflow to reservoirs, water demand	

^a Uncertainties from host-model also include the uncertainties that can extend from other algorithms, related to water resource management, embedded in host models (see Fig. 1).

^b See also reservoir operations.

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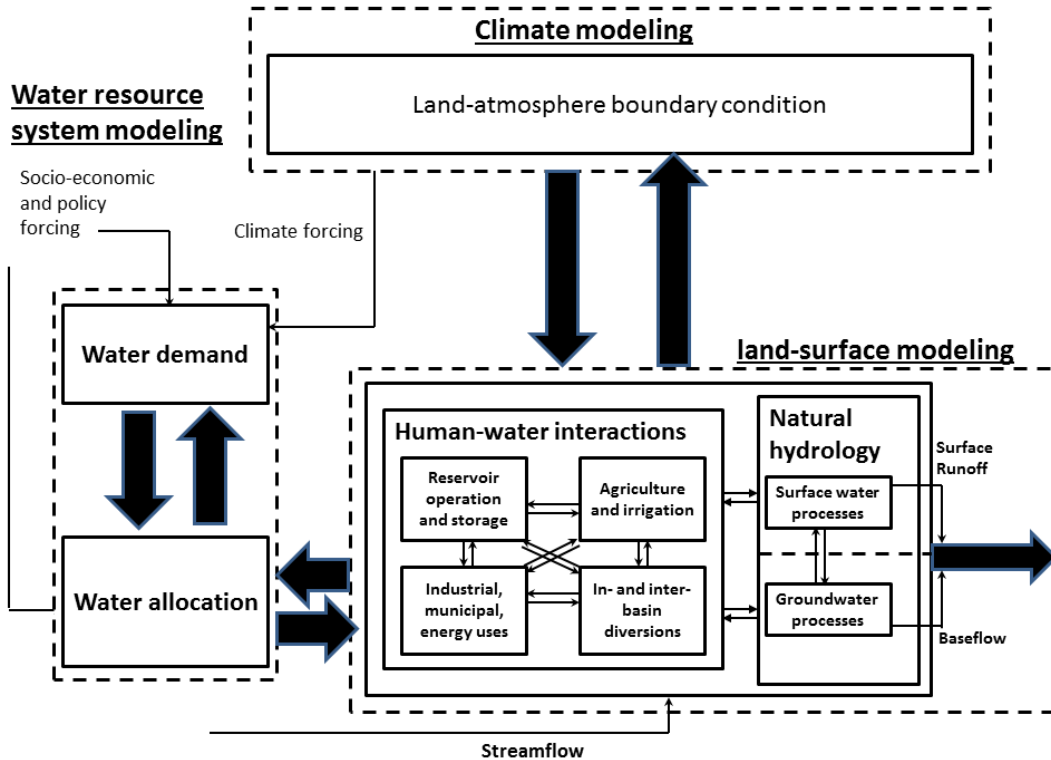


Figure 1. A fully coupled framework for inclusion of water resources management in a typical LSS grid.

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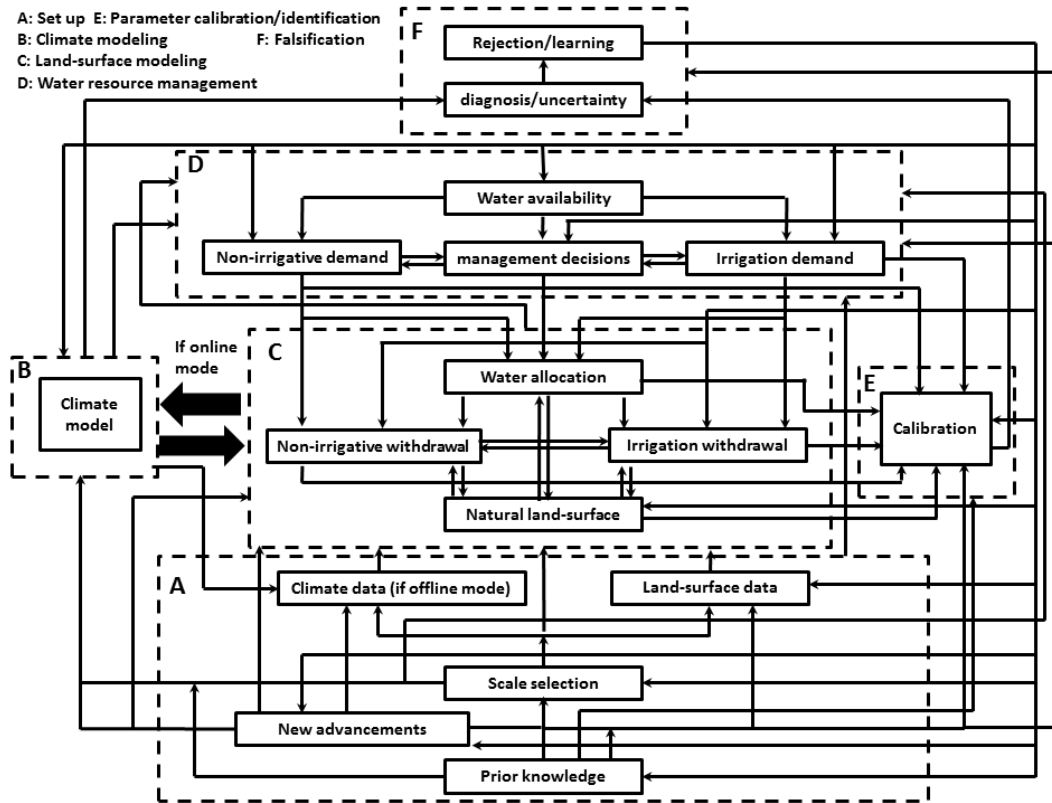


Figure 2. A modular framework for improving the inclusion of water resource management in LSSs through building, testing and falsifying multiple working hypotheses.

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