

1 On inclusion of water resource management in Earth System 2 models - Part 1: Problem definition and representation of 3 water demand

4
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9 10 **Abstract**

11 Human activities have caused various changes to the Earth System, and hence, the interconnections
12 between human activities and the Earth System should be recognized and reflected in models that
13 simulate Earth System processes. One key anthropogenic activity is water resource management,
14 which determines the dynamics of human-water interactions in time and space and controls human
15 livelihoods and economy, including energy and food production. There are immediate needs to
16 include water resource management in Earth System models. First, the extent of human water
17 requirements is increasing rapidly at the global scale and it is crucial to analyze the possible
18 imbalance between water demands and supply under various scenarios of climate change and
19 across various temporal and spatial scales. Second, recent observations show that human-water
20 interactions, manifested through water resource management, can substantially alter the terrestrial
21 water cycle, affect land-atmospheric feedbacks and may further interact with climate and
22 contribute to sea-level change. Due to the importance of water resource management in
23 determining the future of the global water and climate cycles, the World Climate Research
24 Program's Global Energy and Water Exchanges project (WRCP-GEWEX) has recently identified
25 gaps in describing human-water interactions as one of the grand challenges in Earth System
26 modeling (GEWEX, 2012). Here, we divide water resource management into two interdependent
27 elements, related firstly to water demand and secondly to water supply and allocation. In this paper,
28 we survey the current literature on how various components of water demand have been included

29 in large-scale models, in particular Land Surface and Global Hydrological Models. Issues of water
30 supply and allocation are addressed in a companion paper. The available algorithms to represent
31 the dominant demands are classified based on the demand type, mode of simulation and underlying
32 modeling assumptions. We discuss the pros and cons of available algorithms, address various
33 sources of uncertainty and highlight limitations in current applications. We conclude that current
34 capability of large-scale models to represent human water demands is rather limited, particularly
35 with respect to future projections and coupled land-atmospheric simulations. To fill these gaps,
36 the available models, algorithms and data for representing various water demands should be
37 systematically tested, intercompared and improved. In particular, human water demands should be
38 considered in conjunction with water supply and allocation, particularly in the face of water
39 scarcity and unknown future climate.

40

41 **1 Background and scope**

42 **1.1 Large-scale modeling – an introduction to Land-Surface and Global** 43 **Hydrological Models**

44 The Earth System is an integrated system that unifies the physical processes at the Earth's surface.
45 These processes include a wide range of feedbacks and interactions between and within the
46 atmosphere, land and oceans and cover the global cycles of climate, water and carbon that support
47 planetary life (e.g., Schellnhuber, 1999; Kump et al., 2010). From the advent of digital computers,
48 Earth System models have been a key tool to identify past changes and to predict the future of
49 Planet Earth. These models normally include sub-models that represent various functions of the
50 land, atmosphere and oceans (Claussen et al., 2001; Schlosser et al., 2007). A crucial sub-model
51 in Earth System models is the Land-Surface Models (LSM) that represents the land portion of the
52 Earth System. LSMs contain interconnected computational modules that characterize physical
53 processes related to soil, vegetation and water over a gridded mesh, and account for their influences
54 on water, energy and, increasingly, carbon exchanges. A wide range of LSMs is currently
55 available, and these can be differentiated based on how, and to what extent, different land-surface
56 processes are represented; nonetheless, a LSM should explicitly or implicitly include the dynamics

57 of these processes, and account for their drivers at various temporal and spatial scales (see
58 Trenberth, 1992; Sellers, 1992).

59 The importance of representing the terrestrial water cycle in LSMs is well-established (see Pitman,
60 2003 and references therein) and there has been progressive development of LSMs in representing
61 various components of the hydrologic cycle, such as soil moisture, vegetation, snowmelt and
62 evaporation. In early LSMs, hydrology was conceptualized as a simple lumped bucket model
63 (Manabe, 1969), but this representation has progressively been improved by including more
64 complexity and explicit physics in canopy, soil moisture and runoff calculations (see Deardorff,
65 1978; Dickinson, 1983, 1984; Sellers et al., 1986, 1994, 1996a; Nicholson, 1988; Pitman et al.,
66 1990). Despite these improvements, major limitations and uncertainties remain in the hydrological
67 simulations, causing systematic bias in water and energy balance calculations. These deficiencies
68 have been attributed (in part) to unrealistic assumptions and incomplete parameterizations of
69 catchment response in LSMs (Soulis et al., 2000; Music and Caya, 2007; Sulis et al., 2011). Further
70 attempts, therefore, have focused on including catchment scale runoff generation and routing
71 processes (e.g. Miller et al., 1994; Hagemann and Dümenil, 1997; Oki and Sud, 1998; Oleson et
72 al., 2008; Lawrence et al., 2011). These components determine the hydrological response at the
73 larger scales and have been frequently used in large-scale hydrological models, so called Global
74 Hydrologic Models (GHMs). Similar to LSMs, GHMs are gridded large-scale models; however,
75 they are typically simpler in structure and focus on representing the water cycle rather than other
76 land-surface processes (such as the energy and carbon cycles). LSMs have been applied frequently
77 in regional and global modeling (e.g., Liang et al., 1994; Pietroniro et al. 2007; Adam et al., 2007;
78 Livneh et al., 2011) and compared to GHMs (see Haddeland et al., 2011). At this stage of research,
79 however, both LSMs and GHMs are still imperfect and incomplete, as current simulations cannot
80 match recent hydrological observations (see Lawrence et al., 2012).

81 **1.2 Modeling human-water interactions**

82 While external forcing, mainly the energy flux from the Sun, is the main driver of the Earth System,
83 internal disturbances such as volcanic eruptions, wildfires and human activities can substantially
84 affect the natural Earth System cycles (Vitousek et al., 1997; Trenberth and Dai, 2007; Bowman
85 et al., 2009). In particular, post-industrial human activities, from the mid-20th century onwards,
86 have severely perturbed the Earth System (Crutzen and Steffen, 2003; Crutzen, 2006). This has

87 initiated a new geological epoch, informally termed the “Anthropocene”, in which it is recognized
88 that the natural processes within the land surface system are highly controlled and regulated by
89 humans (see McNeil, 2000; Steffen et al., 2007, 2011). Accordingly, Earth System models should
90 address feedbacks and interactions between the natural Earth System and the anthroposphere,
91 which includes human cultural and socio-economic activities (Schellnhuber, 1998, 1999;
92 Claussen, 2001). The terrestrial water cycle is one set of Earth System processes that is greatly
93 perturbed by human activities; it also is of critical importance in determining human health, safety
94 and livelihoods, as well as local, regional and global economies (e.g., Nilsson et al., 2005).
95 However, although some anthropogenic effects, such as the emission of greenhouse gases and
96 land-use change, have been incorporated in LSMs (e.g., Lenton, 2000; Zhao et al., 2001; Karl and
97 Trenberth, 2003; Brovkin et al., 2006; Solomon et al., 2009), less effort has been made to represent
98 human-water interactions (e.g., Trenberth and Asrar, 2012; Lawrence et al., 2012; Oki et al., 2013).
99 This can be a major reason for current deficiencies in hydrological performance of large-scale
100 modes (i.e., LSMs and/or GHMs). In fact, large-scale models still widely assume that human
101 effects on the terrestrial water cycle can be ignored. This assumption is highly questionable and
102 can result in the neglect of important hydrologic processes (see Gleick et al., 2013).

103 Human-water interactions include a wide spectrum of anthropogenic interventions, including land-
104 use change and water resource management. During the past century, human water consumption
105 has increased more than 6-fold, with around 5, 18 and 10 times increase in agricultural, industrial
106 and municipal consumption, respectively (see Shiklomanov, 1993, 1997, 2000). Supplying such
107 intensive demands has required large changes in the natural water cycle – which can be even more
108 than the effects of warming climate (see Haddeland et al., 2014), and is associated with major
109 environmental water stress at the global scale. Smakhtin et al. (2004) concluded that over 1.4
110 billion people currently live in river basins with high environmental water stress and this number
111 will increase as water withdrawals grow. For instance, surface water withdrawals for supplying
112 human needs decrease downstream flows, often substantially, and result in seasonal decline in
113 flows of major rivers such as the Colorado River (e.g., Cayan et al., 2010). Similarly, dam
114 operations considerably change the timing, volume, peak and the age of natural streamflow and
115 reduce inputs to wetlands, lakes and seas (e.g., Vörösmarty et al., 1997, 2005; Vörösmarty and
116 Sahagian 2000; Meybeck, 2003; Tang et al., 2010). This is associated with some extreme effects,
117 such as the death of the Aral Sea (e.g., Precoda, 1991; Small et al., 2001). In parallel, groundwater

118 abstractions are associated with declining groundwater levels, reduced baseflow contributions and
119 loss of wetlands. For instance, current assessments reveal significant groundwater depletion in
120 some areas of the globe, such as Indian peninsula, the US mid-west, and Iran (Giordano, 2009;
121 Rodell et al., 2009; Gleeson et al., 2012; Döll et al., 2014). Without considering human
122 withdrawals, these changes in surface- and ground- water availability cannot be captured by large-
123 scale models. It should be noted that human activities have large effects on water quality as well.
124 For instance, extensive groundwater pumping is also associated with potential long-term
125 contamination, for example by salt-water intrusion (Sophocleous, 2002; Antonellini et al., 2008),
126 and nutrient pollution of surface and groundwater is an outstanding global challenge. These water
127 quality impacts, however, remain beyond the scope of this survey.

128 As human life and water availability are tightly interconnected (see Sivapalan et al., 2012), current
129 and future changes in the water availability are not only important for Earth System modeling, but
130 are also of major importance to human society, and these issues can be explored to a large extent
131 with large-scale models. Although human water use still accounts for a small proportion of total
132 water on and below the surface (see Oki and Kanae, 2006), total human withdrawals currently
133 include around 26 percent of terrestrial evaporation and 54 percent of the accessible surface runoff
134 that is geographically and temporally available (Postel et al., 1996). There are already major water
135 scarcity issues across highly populated regions of the globe (e.g., Falkenmark, 2013; Schiermeier,
136 2014), which raise fundamental concerns about how future demand should be supplied,
137 particularly considering climate change (e.g., Arnell, 1999, 2004; Tao et al., 2003; Döll, 2009;
138 Taylor et al., 2013, Hanasaki et al., 2013a, b; Wada et al., 2013b; Milano et al., 2013; Mehta et al.,
139 2013; Schewe et al., 2014). Such important threats to water security necessitate a detailed
140 understanding of water availability and demand in time and space; and therefore large-scale
141 models are required for impact assessments.

142 Apart from the hydrologic and water security relevance discussed above, human-water interactions
143 can have broader implications for the water cycle and affect climate, although these issues are yet
144 to be fully explored, and remain in some cases controversial. For instance, irrigation can disturb
145 the “natural” atmospheric boundary conditions (e.g., Sacks et al., 2009; Destouni et al., 2010;
146 Gerten et al., 2011; Pokhrel et al., 2012; Hossain et al., 2012; Guimberteau et al., 2012; Dadson et
147 al., 2013). At this stage of model development, the available quantitative understanding of these
148 land-atmospheric implications is limited. To explore these issues it is necessary to include these

149 processes in coupled land-atmospheric models, and this requires explicit representation of relevant
150 human-water interactions within LSM computational schemes. Moreover, the return flows from
151 human usage, entering the seas and oceans, can affect salinity and temperature and consequently
152 impact their circulation patterns (e.g., Rohling and Bryden, 1992; Skliris and Lascaratos, 2004;
153 Vargas-Yañez et al., 2010). This is of particular concern for closed oceans and the polar
154 environment, where a change in fresh water input can modify the oceanic circulations and thus
155 feedback on continental rainfall (Polcher, 2014). However as noted above, issues related to water
156 quality remain beyond the scope of our survey.

157 **1.3 Aim and scope of this survey**

158 The aim of our survey is to consider the associated scientific and data challenges, the state of
159 current practice, and directions for future research around including human effects on the terrestrial
160 water cycle. In this paper and a companion paper (hereafter Nazemi and Wheeler, 2014), we focus
161 on human-water activities manifested through water resource management and note that this is
162 subject to operational and policy constraints. We only consider water quantity aspects of water
163 resource management, which we define as a suite of anthropogenic activities related to storage,
164 abstraction and redistribution of available water sources for various human demands. Although a
165 fully coupled representation of water resource management in Earth System models is not
166 currently available, important progress is being made, and more generally a body of literature is
167 gradually shaping around describing different aspects of water resource management in large-scale
168 models, in particular within the context of GHMs. Nonetheless, there are still fundamental
169 obstacles in including water resource systems within large-scale models.

170 First, a fundamental principle in Earth System models as well as LSMs and GHMs is the
171 conservation of water. To represent water resource management, therefore, it is necessary to fully
172 capture water in a coupled human-natural system. To achieve this i) modeling complexity should
173 be increased, ii) process representations related to both natural and anthropogenic systems should
174 be improved and iii) modeling capability should be extended to new domains (see Polcher, 2014
175 for an in-depth discussion). For instance, a large proportion of human demand is supplied by
176 groundwater, which is often absent or crudely represented in both LSMs and GHMs and is widely
177 considered disjoint from other elements of the Earth System such as climate.

178 Second, multiple factors affect water resource management at the larger scales, such as climate,
179 hydrology, land-cover and socio-economy as well as land and environment management.
180 Moreover, real-world management decisions often include cultural values and political concerns
181 (Gober and Wheeler, 2014). These various influences are so far considered in isolation and the
182 interactions among them are widely unseen (e.g., Beddington, 2013).

183 Third, there is considerable lack of regional and global data concerning the actual use and operation
184 of water resources systems, and therefore, large-scale models cannot be properly tuned or
185 validated. This major limitation, for instance, has led the research community to use estimated
186 demand as a surrogate for actual use. Lack of data about human operations can also introduce large
187 uncertainty into simulations of terrestrial storage and runoff. For instance Gao et al. (2012) noted
188 that the "...results from global reservoir simulations are questionable" as "there are no direct
189 observations of reservoir storage".

190 Fourth, there is a major gap between the scope of local operational water resource models and
191 large-scale applications and research needs. Essentially, the scale at which local water resource
192 management takes place is often within the sub-grid resolution of current large-scale models,
193 which requires narrowing the resolution in large-scale models for explicit representation (see
194 Wood et al., 2011) or adding more sub-grid heterogeneity into grid calculations for implicit
195 parameterization. In addition, there is (and will increasingly be) competition between various
196 water demands which requires allocation decisions. At this stage of model development, however,
197 it is still unclear how operational policies should best be reflected at larger scales. At the local
198 scale, detailed information on physical and operational systems as well as climate and water supply
199 conditions are available (or can be generated as scenarios; see e.g., Nazemi et al., 2013) and the
200 competition between demands is often reflected as an optimization problem. As the simulation
201 scale moves from local and small basin scales to regional and global scales, the data availability
202 degrades considerably and the high level of calculations within optimization algorithms cannot be
203 maintained, due to computational barriers as well as data availability issues.

204 Conceptually, water resource management at larger scales can be seen as an integration of two
205 fully interactive elements, related to water demand as well as water supply and allocation: Water
206 demand is constrained by water availability and drives water allocation, which results in extraction
207 from water sources and determines the extent of change in hydrological elements of the land-

208 surface. Moreover, as noted briefly above, perturbations in the terrestrial water cycle due to water
209 resource management can further interact with other elements of the Earth System, particularly
210 with climate (see Figure 1). To assess the impacts of water resource management on land-surface
211 processes and associated feedbacks with climate, the elements of water demand and water
212 allocation should be described using computational algorithms and included in large-scale models.
213 For the purpose of our survey, and reflecting the state of algorithm development and data
214 availability, we focus in this paper only on the representation of water demand, and in the Nazemi
215 and Wheeler (2014) on water supply and allocation. Here, we classify human-water demands under
216 two general categories, namely irrigative and non-irrigative, and further divide non-irrigative
217 demands into municipal, industrial, environmental, energy-related, and livestock water needs. This
218 is useful to put current algorithms and modeling applications into context. Accordingly, we discuss
219 how these demands are characterized using various computational algorithms. As will be shown
220 later in this paper, human demands are mainly quantified either using downscaling (i.e. top-down
221 approaches) or through direct modeling at the grid scale (i.e., bottom-up approaches). Depending
222 on the type of application, the algorithms can be included in a wide range of large-scale models.
223 Throughout our review, we consider both offline and online implications of water demand. Offline
224 simulations assess the effects of water demand on land-surface processes without considering the
225 associated feedbacks to the climate system, but can be linked to atmospheric driving variables to
226 simulate land-surface and/or hydrological responses to climate and water resource management.
227 Online models also account for the effects of water demand on land-atmospheric feedbacks and
228 are further coupled with climate models. This is done by considering the effects of water demand
229 on the dynamics of land-surface variables and updating the surface boundary conditions in climate
230 models (Verseghy, 1991, 2000; Verseghy et al., 1993). Online applications are also termed in the
231 LSM community as coupled land-atmospheric simulations (e.g., Entekhabi and Eagleson, 1989;
232 Noilhan and Planton, 1989) and are more computationally demanding comparing to offline
233 simulations. While off-line models include both LSMs and GHMs, it should be noted that GHMs
234 cannot be used for online applications as they do not account for the energy balance and therefore
235 cannot fully represent land-atmosphere feedbacks.

236 The structure of this paper is as follows: In Section 2 we highlight the impacts of irrigative and
237 non-irrigative water demands on the terrestrial water cycle and land-atmospheric feedbacks.
238 Sections 3 and 4 provide an overview of available representations of irrigative and non-irrigative

239 demands at larger scales, respectively. In section 5, we briefly explore state-of-the-art applications
240 and highlight current limitations and uncertainties in estimating current and future water demand
241 and associated online and offline impacts. We further discuss current gaps in Section 6 and provide
242 some suggestions for future developments. Finally, Section 7 summarizes this first part of our
243 survey and outlines our main findings with respect to representing human water demand.

244

245 **2 Types of human demand and their impacts on the water cycle**

246 Human water demands can be divided into irrigative and non-irrigative categories. Irrigation is the
247 dominant human water use and has significantly intensified since the 1950s, due to population
248 growth and technological development (Steffen et al., 2011). This has major importance for global
249 food security, as it produces approximately 40 percent of the world’s food (Abdullah, 2006).
250 Currently, around 25 percent of harvested crop area is irrigated (Portmann et al., 2010). This
251 accounts for some 90 percent of water consumption at the global scale (Döll et al., 2009; Siebert
252 et al., 2010), which is around 70 percent of the total water withdrawals from surface and
253 groundwater resources (Wisser et al. 2008; Gerten and Rost, 2010). Clearly supplying such a large
254 water demand can severely disturb the “natural condition” by decreasing streamflow volume (e.g.,
255 Meybeck, 2003; Gaybullaev et al., 2012; Lai et al., 2014) and groundwater levels (e.g., Rodell et
256 al., 2009; Gleeson et al., 2012; Wada et al., 2010; 2012, 2013a; Döll et al., 2014). Currently, surface
257 water is the main supplier of global irrigative needs, accounting for 57 percent of the total
258 consumptive irrigation use at the global scale (Siebert et al., 2010).

259 Apart from driving hydrological changes, irrigation-induced changes in soil-moisture can affect
260 land surface-atmosphere feedbacks (see Eltahir, 1998). Pokhrel et al. (2012) showed that increased
261 soil water content through irrigation substantially enhances evapotranspiration, and therefore
262 transforms the surface energy balance. Evapotranspiration due to irrigation leads to cooling of the
263 land surface (e.g., Haddeland et al., 2006; Saeed et al., 2009; Destouni et al., 2010), as well as
264 enhanced cloud cover and chance of convective precipitation (e.g., Moore and Rojstaczer, 2001;
265 Douglas et al., 2009; Harding and Snyder, 2012a, b; Qian et al., 2013). Irrigation may also alter
266 regional circulation patterns due to temperature difference between irrigated areas and neighboring
267 regions (e.g., DeAngelis et al., 2010; Wei et al., 2013). Over highly irrigated regions, this can mask

268 important climate change signals. Gerten et al. (2011), for instance, showed that the irrigation in
269 South Asia has offset the increasing temperature in the region.

270 Non-irrigative water demands include municipal and industrial uses, energy-related withdrawals,
271 other agricultural uses, such as livestock, as well as designated environmental water uses, which
272 can be an important constraint on water management. Non-irrigative demands contribute a lesser
273 proportion to total human water use at the global scale. This proportion, however, has significant
274 spatial variability (Vassolo and Döll, 2005; Flörke et al., 2013) as regional differences in
275 population, income, life style and technological developments can alter the extent of non-irrigative
276 demand significantly (e.g., Alcamo et al., 2003; Flörke and Alcamo, 2004; Hejazi et al., 2013a).
277 However, while irrigation is predominantly a consumptive water use, only a small portion of the
278 non-irrigative withdrawal is consumptive (e.g., Hanasaki et al., 2013a). Non-irrigative
279 withdrawals, therefore, partially or totally return to surface water or groundwater systems with
280 varying degrees of time lag. Still, this can considerably perturb the streamflow regime (e.g.,
281 Maybeck, 2003; Förster and Lilliestam, 2010). Non-irrigative water demands are currently on a
282 rapid incline due to growing population and industrial development. This can increase water stress
283 in both time and space (Hejazi et al. 2013a,b,c,d). As non-irrigative demands are mainly non-
284 consumptive, they are less likely to change the energy balance and/or perturb the atmospheric
285 moisture condition significantly and therefore they are less relevant to land-atmospheric
286 interactions. However, changing timing of flows can have significant local effects, for example on
287 wetland inundation. Similarly, for some large-scale mining activities in which the extent of water
288 withdrawals is considerable, the associated changes in soil moisture and land-cover can be
289 potentially relevant to land-atmospheric feedbacks. To the best of our knowledge, such online
290 considerations for non-irrigative withdrawals have not yet been explored in the literature.

291

292 **3 Available representations of irrigative demand in large-scale models**

293 Irrigation is an important element of water resource management and has been explored more in
294 depth than non-irrigative demands. To simplify our presentation, we classify current
295 representations with respect to the scale (regional vs. global) and/or mode of simulation (offline
296 vs. online). Tables 1 and 2 summarize representative examples of offline simulations at both
297 regional (Table 1) and global (Table 2) scales. Table 3 presents some online examples. In brief,

298 current online applications have mainly been performed at rather fine temporal and spatial
299 resolutions with shorter simulation periods than offline representations. In contrast, a wide
300 spectrum of host models (i.e. large-scale models in which the irrigation algorithm is embedded),
301 as well as forcing and land-use data, has been used in current offline examples (see Tables 1 and
302 2). Model resolutions in offline applications can vary in time from 1 hour (e.g., Leng et al., 2013)
303 to 1 day (e.g., Haddeland et al., 2007) with a grid size ranging from a few kilometers (e.g., Siebert
304 and Döll, 2010; Nakayama and Shankman, 2013) to a few hundred kilometers (e.g., Gueneau et
305 al., 2012) in space. Moreover, offline irrigation demand calculations have already been performed
306 globally under future climate conditions.

307 **3.1 Framework and general procedure**

308 Irrigated lands normally introduce heterogeneity into the computational grids of LSMs and GHMs.
309 Such sub-grid heterogeneity can be represented as an additional “tile,” similar to forested land,
310 bare soil and snow cover (Polcher et al., 2011). Essentially, irrigation algorithms are required to
311 estimate the irrigation demand, and accordingly irrigative water use, at the grid scale. Here we
312 refer to the irrigation demand as the water required for ideal crop growth in addition to the available
313 water from precipitation. To simulate the grid-based irrigation demand, crop type and the extent
314 of irrigated regions and growing seasons should be first identified. The location and area of
315 irrigation districts and the associated crop types can be extracted from regional and global data
316 sets (e.g., USDA, 2002; 2008; Siebert et al., 2005, 2007; Portmann et al., 2010) and/or remotely
317 sensed data (e.g., Adegoke et al. 2003; Qian et al., 2013). There are two general approaches for
318 identifying growing seasons. The choice of these options depends on the level of detail in the host
319 model. In simpler models, where no energy-balance calculation is available (i.e. GHMs), crops
320 can grow when and where simple temperature- and precipitation-based criteria are met (e.g., Döll
321 and Siebert, 2002). In more detailed models (i.e. LSMs) the optimal growing season can be
322 identified based on biophysical conditions of crop growth and/or soil water, canopy and energy
323 balance conditions to estimate the cropping period that is necessary to obtain mature and optimal
324 plant biomass (e.g., Rost et al., 2008; Pokhrel et al., 2012). Both approaches are subject to
325 uncertainty. On one hand, models with fixed crop calendars ignore inter-annual variability in
326 growing seasons. On the other hand, even models with fully dynamic crop growth algorithms may
327 misrepresent the seasonality. After the growing season is identified, the irrigation demands (and

328 under some assumptions, actual irrigation withdrawals) at each simulation time step can be
329 calculated. A variety of top-down and bottom-up procedures are available for calculating the
330 irrigation demand in large-scale models and are reviewed further below. If the irrigation demand
331 is completely fulfilled, then the actual evapo(transpi)ration would be equal to crop-specific
332 evapo(transpi)ration under standard conditions (see Allen et al., 1998). In offline applications, the
333 irrigation rate can perturb soil moisture content, evaporation, deep percolation and runoff in
334 irrigated tiles (e.g., Hanasaki et al., 2008a,b; Wada et al., 2011, 2012, 2013a). In online
335 applications, the vertical vapor and heat fluxes need also to be considered. The total fluxes for each
336 grid can be then calculated as the sum of the flux contributions from irrigated and non-irrigated
337 portions of the grid (e.g., Haddeland et al., 2006; Pokhrel et al., 2012), and can be further
338 introduced to climate models as coupled surface boundary conditions (e.g., Sorooshian et al., 2011;
339 Harding and Snyder, 2012a,b).

340 **3.2 Top-down algorithms for calculating irrigation demand**

341 In top-down approaches, the irrigation demand is not directly calculated, but estimated based on
342 downscaling information available at coarser scales, often at national or geopolitical scales. Such
343 information is based on census-based inventories (e.g., Sacks et al., 2009) or socio-economic
344 model outputs (e.g., Voisin et al., 2013). Top-down approaches are highly influenced by the
345 availability of global data on water use, such as FAO's Information System on Water and
346 Agriculture (AQUASTAT; <http://www.fao.org/nr/water/aquastat/main/index.stm>), which
347 provides annual inventory data on national (and in some cases also sub-national) scales, and has
348 been further extended to include socio-economic model outputs. An example of such a model is
349 the Global Change Assessment Model (GCAM; Wise et al., 2009a,b; Wise and Calvin 2011),
350 which estimates agricultural production based on socio-economic variables, from which the
351 irrigation water use is indirectly calculated using the water required for each crop per unit of land.
352 Downscaling is performed mainly using land-use, technological and/or socio-economic proxies.
353 There are various sources of uncertainty associated with top-down algorithms. First, both
354 inventory and model-based products have major limitations due to their spatial and temporal scales
355 as irrigation practices are highly variable within a country and a typical year. Moreover, the quality
356 of both census and model-based products is poor. For instance, there are inconsistencies between
357 census data and data quality varies from country to country (see Portman et al. 2010 for a detailed

358 discussion). Also, socio-economic models widely ignore water availability constraints (Hejazi et
359 al., 2013d). As a result, calculation of irrigation demand is mainly pursued through bottom-up
360 schemes.

361 **3.3 Bottom-up algorithms for calculating irrigation demand**

362 In contrast to top-down schemes, bottom-up approaches estimate the irrigation demand directly at
363 the grid scale by mimicking the optimal crop growth for irrigated tiles. Despite major limitations
364 due to the heterogeneity in soil and crops, bottom-up algorithms have been widely used in the
365 literature. These algorithms include a range of modeling assumptions; however, they are all
366 centered around estimation of an ideal crop water requirement, i.e. where there is no water deficit.
367 This requirement is based on estimation of “potential evapo(transpi)ration”, which characterizes
368 the atmospheric moisture deficit (Hobbins et al. 2008). There are multiple approaches to estimate
369 the potential evapo(transpi)ration, and the estimates obtained may vary considerably. LSMs
370 typically include detailed energy balance calculations and resolve the diurnal cycle; therefore, they
371 can directly calculate potential and actual evaporations (see Milly, 1992; Barella-Ortiz et al., 2013
372 for a detailed description). Alternative approaches adopt a variety of methods, are heavily
373 influenced by FAO’s guidelines for calculating irrigation water requirements (see Allen et al.,
374 1998) and are mainly used in GHMs, where the evapotranspiration is calculated for a reference
375 crop and corrected as a function of crop type and development stage using a set of empirical
376 coefficients. Various methods are used to characterize the reference evapotranspiration, such as
377 FAO Penman-Monteith (Allen et al., 1998), Priestley and Taylor (1972) and modified Hargreaves
378 (Farmer et al., 2011) to name a few (see McKenney and Rosenberg, 1993 for more examples). The
379 choice of appropriate formulation for reference evapotranspiration is rather arbitrary and depends
380 largely on the data availability as well as the level of detail supported in the host model. It should
381 be noted that due to the difference in estimation of evaporation, incorporating FAO’s guidelines
382 for estimation irrigation demand in LSMs can introduce inconsistencies with the evaporation
383 estimated by the model at various time scales, particularly over dry regions where the irrigation is
384 likely to occur (Polcher, 2014).

385 Here we briefly explain the currently available bottom-up algorithms, from the more simple to the
386 more comprehensive algorithms, and highlight their strengths and weaknesses.

387 In the most simple bottom-up representations, the irrigation demand at every time step is the water
388 required to bring the soil moisture at the root zone to saturation (e.g., Lobell et al., 2006; Harding
389 and Snyder, 2012a,b), which describes an extreme demand condition and clearly overestimates the
390 actual irrigation water requirement (Sacks et al., 2009). In a more realistic but still naïve
391 representation, the soil moisture requirement during the growing season is considered to be the
392 field capacity (e.g., Nakayama and Shankman, 2013); therefore, the irrigation water need is the
393 water required to bring the soil moisture to field capacity. The description of the irrigation demand
394 based on the field capacity can also overestimate the actual water requirements, as the evaporation
395 often reaches potential level before the soil reaches field capacity. The threshold at which the
396 evaporation reaches potential evaporation is crop-dependent, but often considered as a constant
397 value in large-scale models. As an offline example, Hanasaki et al. (2008a) assumed that paddy
398 and non-paddy crops require soil moisture content of 100 or 75 percent of the field capacity at the
399 root zone with constant depth at the global scale. Yoshikawa et al. (2013) later updated the
400 assumption for non-paddy soil moisture requirement and used 60 percent of field capacity,
401 referring to the requirement for wheat. This is again rather unrealistic as (1) by assuming a constant
402 percentage of the field capacity for all crop types, the diversity in crop water requirement is
403 ignored; and (2) a constant root zone depth at the global scale can result in misestimating the
404 irrigation demand. There are attempts to address these limitations. For instance, Sorooshian et al.
405 (2011) assumed that the required soil moisture content can change for each grid based on the
406 dominant crop. Leng et al. (2013) and Qian et al. (2013) implemented root growth in their irrigation
407 demand algorithm to avoid overestimation of demand due to a constant root zone. It should be
408 noted that calculating the root growth is also subject to uncertainty; however, associated limitations
409 remain beyond the scope of this paper.

410 More realistic definitions of irrigation water demand are based on the difference between the crop-
411 dependent potential evapotranspiration and available crop water. This definition has been widely
412 used in global irrigation demand projections (see Table 2). In earlier examples (e.g., Döll and
413 Siebert, 2002; de Rosnay et al., 2003), crop development is described by constant monthly
414 multipliers for potential evapotranspiration and the effective rainfall is used as a surrogate for
415 available crop water. In more advanced algorithms, the correction factors are considered as
416 functions of daily climate, stage of vegetation and root growth. Moreover, actual
417 evapotranspiration or soil moisture content can be used instead of effective rainfall (Haddeland et

418 al., 2006, 2007; Gueneau et al., 2012). There are two key limitations associated with this approach
419 to simulation of irrigation demands. First, FAO's definition of irrigation water requirement
420 considers both transpiration from crop and evaporation from soil. It has been noted that this
421 quantification may result in overestimating the irrigation demand and may not properly represent
422 the dynamics of vegetation (Polcher et al., 2011). Second, it is assumed that crop growth is a
423 function of water availability only; therefore, the effects of other drivers such as CO₂ on
424 photosynthesis are wholly ignored.

425 Some efforts try to overcome these limitations by defining irrigation demand based on potential
426 transpiration instead of potential evapotranspiration (e.g., Wada et al., 2011, 2012), in conjunction
427 with models that have more comprehensive vegetation schemes. Potential transpiration is the
428 transpiration that would occur if the crop is not water stressed. Potential transpiration takes into
429 account CO₂ fertilization effects and can represent the adaptation of the plants to climatic
430 conditions and/or crop growth cycles, if the host model is equipped with relevant calculations
431 (Guimberteau et al., 2012); therefore, this approach is mainly used in LSMs with detailed
432 consideration of vegetation growth. As an example, Rost et al. (2008) coupled a transpiration
433 deficit algorithm with the Lund-Postdam-Jena managed Land scheme (LPJmL; Bondeau et al.,
434 2007), which has a detailed vegetation growth module based on carbon and water availability (see
435 Sitch et al., 2003; Gerten et al., 2004). The crop water limitation was calculated based on the
436 atmospheric water deficit, soil moisture, plant hydraulic states as well as the CO₂ effects.
437 Considering the effects of both carbon and water in vegetation can provide a basis for explicit
438 linkage between CO₂ emission, crop growth and irrigation water requirement. This would be
439 important for future predictions under increasing CO₂ effects. Moreover, some recent simulations
440 showed that the irrigation requirement changes if a dynamic growth model is used; and this can
441 improve the partitioning of latent heat flux, which is relevant to online applications (e.g., Lu,
442 2013). Nonetheless, it should be noted that the success of potential transpiration algorithm depends
443 strongly on the way various tiles are treated at the grid scale. Normally, LSMs can define multiple
444 crops at the grid scale and can distinguish the various water needs across different tiles within a
445 grid. If potential transpiration is implemented consistently with sub-grid soil moisture divisions,
446 then the water taken from the irrigated tiles optimizes photosynthesis and is only evaporated by
447 the crops and not used by other surface types (e.g. bare soil, non-irrigated crops etc.). In contrast,

448 if all tiles share the same soil moisture reservoir at the grid scale, irrigation will increase the soil
449 moisture and evaporation and therefore reduce water stress over the whole grid.

450 **3.4 Projection of irrigative demand**

451 From water and food security perspectives, particularly under various global change scenarios, it
452 is crucial to investigate future irrigation demand and assess various possibilities for irrigation
453 deficit. Climate model projections under IPCC emission scenarios (IPCC, 2000) have been widely
454 used to force bottom-up irrigation demand algorithms (e.g.; Arnell, 1999; Wada et al., 2013b;
455 Rosenzweig et al., 2014). Efforts have been also made to include intermediate socio-economic
456 scenarios that can be matched to current climate change scenarios (see e.g., Arnell, 2004; Fischer
457 et al., 2007; Alcamo et al., 2007). For irrigation, intermediate scenarios describe changes in
458 irrigated areas, irrigation efficiency and crop type, using empirical approaches. For example,
459 Hanasaki et al. (2013a) recently proposed intermediate scenarios based on newly developed Shared
460 Socio-economic Pathways (SSPs; Kriegler et al., 2012; see also Moss et al., 2010), which are
461 consistent with Representative Concentration Pathways (RCPs; Meinshausen et al., 2011; K. E.
462 Taylor et al., 2012). Constructing intermediate scenarios using empirical procedures, however, is
463 uncertain as mechanisms that link irrigation expansion to socio-economic factors are not fully
464 known and current empirical relationships can contain large uncertainties. More dynamic linkage
465 between irrigation expansion and socio-economic drivers can be provided by coupled socio-
466 economy-energy-carbon models. One emerging model of such a kind is GCAM, which has been
467 recently implemented for simulating the future expansions in irrigation areas and demands (Hejazi
468 et al., 2013b,c,d) as well as policy implications for irrigation water requirements (e.g., Chaturvedi
469 et al., 2013a,b). Although these models can represent the dynamic effects of various drivers on
470 irrigation, they remain uncertain as their simulations are rather coarse and do not incorporate water
471 availability constraints. There are emerging efforts to avoid this limitation by linking the irrigation
472 demand to climate, economy and water management constraints. This can result in prediction of
473 regions in which irrigation can be developed and sustained considering changing climate, water
474 availability, water price and water management infrastructure (see Nassopoulos et al., 2008, 2012).
475 Such approaches however have not been applied at larger regional and global scales.

476

477 **4 Available representations of non-irrigative demand**

478 **4.1 Forms and drivers of non-irrigative demand**

479 Non-irrigative water demands relate to a wide range of environmental, municipal, industrial and
480 energy-related uses, as well as other agricultural water needs (e.g., livestock), and include both
481 consumptive and non-consumptive withdrawals. Among these, livestock water demand is assumed
482 fully consumptive, and can be estimated by livestock number and demand per livestock head (e.g.,
483 Wada et al., 2011; Strzepek et al., 2012b; Hejazi et al., 2013d). Wada et al. (2013a) made a further
484 improvement by estimating daily livestock requirements at $0.5^{\circ} \times 0.5^{\circ}$ spatial resolution using
485 livestock data of Steinfeld et al. (2006). Daily demand was considered as a function of daily
486 temperature.

487 In contrast to livestock water demand, environmental flow needs can be considered as a fully non-
488 consumptive need, required to protect rivers' health and aquatic life. Considering the extent of
489 environmental degradation at the global scale, accounting for environmental flow needs becomes
490 more and more relevant and should be considered as an integral part of water resource management
491 at larger scales. Tharme (2003) made an extensive review of available methodologies for
492 estimating environmental flow needs and identified more than 200 methodologies based on various
493 hydrological, hydraulic rating, habitat simulation and holistic guidelines at the river basin scale.
494 There are also some recent trends to involve scientists, water-resource managers and stakeholders
495 to analyze available hydrological information and convert them into ecologically based and
496 socially acceptable goals for estimating the environmental flow needs (see Poff et al., 2009). Such
497 procedures however are widely dependent on the availability of relevant information, and
498 therefore, cannot be easily implemented in large-scale models. Currently, implementation of
499 environmental flow needs in large-scale models remains rather limited and simplistic and these
500 needs are often calculated based on generic rules. For instance, Smakhtin et al. (2004) assigned
501 thresholds for fair (Q90), natural (Q50) and good (Q75) natural flow conditions. Shirakawa (2004,
502 2005, referenced from Hanasaki et al., 2008a) distinguished between two factors, i.e. minimum
503 and perturbation flow requirements, which can also accommodate transient streamflow conditions.
504 Currently, the perturbation flow requirements are often ignored in large-scale models and the
505 environmental needs are estimated as a minimum flow threshold (often Q90 or 10 percent of mean
506 annual), which should be maintained in the river reaches (e.g. Hanasaki et al., 2008a; Döll et al.,

507 2009; Strzepek et al., 2010, 2012b; Blanc et al., 2013). Other rules have been also suggested. For
508 instance, Haddeland et al. (2006) considered a seven-day consecutive low flow with a ten-year
509 recurrence period as the environmental flow requirement. Although these rules are easily
510 implementable for larger regions and global scales, they widely ignore natural system complexity
511 and the local policy context and can contribute to misunderstanding of the extent of environmental
512 water stress (Arthington et al., 2006).

513 At this stage of model development, municipal, industrial and energy-related water demands are
514 the most dominant forms of non-irrigative uses, and can be considered as complex functions of
515 socio-economic and technological factors, with high variability in time and space. Population is
516 the most significant factor driving these withdrawals (e.g., Alcamo et al., 2003; Hanasaki et al.,
517 2008a; Wada et al., 2013a). National Gross Domestic Product (GDP) is also a strong factor (e.g.,
518 Gleick, 1996; Cole, 2004; Wada et al., 2011). Although higher GDP may trigger more municipal
519 water use per capita (Alcamo et al., 2007), Hughes et al. (2010) showed that, in general, water uses
520 per capita are greater in developing than developed countries due to low-tech water delivery and
521 industrialization. Strzepek et al. (2010) argued that industrial water use increases with the level of
522 resource industry and decreases when a country moves toward the service sector. Industrial
523 technology is another important factor for non-irrigative use as the extent of both consumptive and
524 non-consumptive uses can significantly change based on the type of technology. Macknick et al.
525 (2011), for instance, provided estimates of total water withdrawals and consumption for most
526 electricity generation technologies within the US. Comparing to recirculating cooling technology,
527 they noted that once-through cooling requires 10 to 100 times more water withdrawal per unit of
528 electric generation. However, the latter consumes less than half of the water consumed by
529 recirculating cooling technology. Climate can be another important factor controlling both
530 consumptive and non-consumptive withdrawals (e.g., Wada et al., 2011, 2013a, Hejazi et al.,
531 2013a, Voisin et al., 2013), but has often been ignored as an explicit driver of non-irrigative water
532 demand.

533 **4.2 Top-down algorithms for estimation of grid-based non-irrigative withdrawals**

534 Unlike irrigation demand, top-down approaches have been widely used for non-irrigative
535 withdrawals to transfer national or geopolitical data to basin or grid scales. Various downscaling
536 procedures have been suggested, based on different proxies (see Table 4). These top-down

537 schemes are heavily influenced by the availability of national and global datasets and the
538 downscaling algorithms within the Water – Global Assessment and Prognosis scheme, which is a
539 global water budget and use model (WaterGAP; Alcamo et al., 1997, 2003, 2007). Currently, the
540 availability of different global information sources has provided the opportunity to generate
541 gridded products from different sources. As an example, Hanasaki et al. (2008a) merged the FAO-
542 AQUASTAT data with population distributions and national boundary information from
543 Columbia University (CIAT, 2005) and the consumptive ratios of Shiklomanov (2000) to come up
544 with gridded industrial and municipal water withdrawals and uses at the global scale. More detailed
545 information on various industrial uses resulted in breaking down the industrial withdrawals into
546 their components. For instance, Vassolo and Döll (2005) distinguished between industrial water
547 uses related to thermoelectric power generation and manufacturing production. Temporal
548 disaggregation of annual withdrawals, however, has received much less attention. Recently Wada
549 et al. (2011, 2013a) and Voisin et al. (2013) developed simple algorithms to disaggregate annual
550 data to monthly and daily estimates (see Table 5).

551 **4.3 Projection of non-irrigative demand**

552 Characterizing the past and future evolution of non-irrigative demands is required to understand
553 the mechanisms controlling water use and water allocation. Current projections have coarse
554 temporal and spatial resolution and describe non-irrigative demands as functions of socio-
555 economic and technological developments (e.g., Davies et al., 2013; Blanc et al., 2013; Hejazi et
556 al., 2013b,d; Voisin et al., 2013). These changes can be characterized by intermediate socio-
557 economic and technological scenarios, as briefly explained above for irrigation expansion (see
558 Section 3.4). The projected demands can be further downscaled using various proxy variables, as
559 explained in Section 4.2. Table 6 summarizes some representative efforts, which can be classified
560 as explicit and implicit algorithms. In explicit algorithms, changes in water withdrawals are
561 directly described as functions of changes in socio-economy, technology and water price using
562 simple parametric structures (e.g., Strzepek et al., 2012b; Flörke et al., 2013; Hanasaki et al.,
563 2013a; Hejazi et al., 2013a). The parameters can be assigned using the available global and
564 regional data. In implicit procedures, first the production (or population) is estimated based on
565 integrated economy and population models or prescribed scenarios. By considering the amount of

566 water withdrawal per unit of production (or population) and accounting for technological and/or
567 socio-economic shifts, water withdrawals are consequently projected.

568

569 **5 State of large-scale modeling applications**

570 The algorithms reviewed in Sections 3 and 4 have had a wide range of online and offline
571 applications. In comparison to offline applications, online simulations are still at a relatively early
572 stage of development; they typically only include irrigation, mainly implemented at regional scale
573 and under current conditions, and present rather contradictory results. Offline applications in
574 contrast include both irrigative and non-irrigative demands, performed under current and future
575 conditions, and provide relatively more consistent results. Here, we briefly summarize recent
576 applications and highlight the limitations in current simulations.

577 **5.1 Online representation**

578 Recent studies have shown that including irrigation in coupled land-surface schemes can generally
579 improve climate simulations. With respect to regional temperature, for instance, Saeed et al. (2009)
580 showed that representing irrigation activities over north-western India and Pakistan can reduce
581 climate model simulation bias by 5 degrees. It should be noted, however, that there are still large
582 disagreements in quantifying the effects of irrigation on regional and global temperature (see e.g.,
583 Boucher et al., 2004 vs. Lobell et al., 2006), mainly attributed to the difference in the implemented
584 irrigation demand calculations. Sacks et al. (2009) tried to overcome the limitations in demand
585 algorithms by downscaling the AQUASTAT irrigative water use data to the grid scale. They
586 concluded that irrigation has significant importance for regional temperature, but at global scale
587 the temperature cooling in some regions due to irrigation is cancelled by temperature warming in
588 some other areas due to climate, land-cover and circulation changes. There are, however, some
589 limitations in their study, as the irrigation demand did not vary between years and they applied
590 irrigation only when the LAI is around 80% of the annual LAI. These assumptions can result in
591 large uncertainty.

592 Irrigation-induced precipitation has been studied for quite some time and irrigation has been shown
593 to have a significant effect on local and regional precipitation patterns (e.g., Barnston and
594 Schickedanz, 1984; Moore and Rojstaczer, 2001). For instance despite regional decline,

595 Tuinenberg et al. (2011) found a positive precipitation trend in climate stations located in the
596 irrigated regions of the Southern Asia. Lucas-Picher et al. (2011) tested four climate models and
597 argued that lack of representation of irrigation is the main reason for precipitation bias over the
598 Indian Monsoon area. Guimberteau et al. (2012) showed that irrigation can also affect the onset of
599 mean monsoon date over the Indian peninsula, leading to a significant decrease in precipitation
600 during May to July. Nonetheless, there are still large disagreements in (1) identifying the dominant
601 mechanisms that drive the irrigation-induced precipitation; and (2) estimating the amount and
602 spatial extension of change in precipitation. DeAngelis et al. (2010) noted that the growing season
603 precipitation increased in the Great Plains of the U.S. during the 20th century as a result of
604 intensive irrigation. Using vapor tracking analysis, they indicated that evaporation from irrigated
605 lands adds to downwind precipitation, which increases as the evaporation increases. Harding and
606 Snyder (2012a,b), however, noted that the extent of effects on precipitation also depend on the
607 antecedent soil moisture. They argued that in low soil moisture conditions, further irrigation can
608 result in suppression of regional precipitation. Guimberteau et al. (2012) argued that these
609 contrasting results might be due to differences in local moisture, where the irrigation is applied.
610 Based on a 30-year simulation, they showed an increase in summer precipitation over the arid
611 western region of the Mississippi river basin in association with enhanced evapotranspiration.
612 However, a decrease in precipitation was identified over the wet eastern part of the basin. These
613 results, however, are based on only one set of models and the coarse grid resolution might degrade
614 the quality of simulations – see the discussion below. With respect to the scale of disturbance,
615 Sorooshian et al. (2011) showed that irrigation over California’s Central Valley significantly
616 decreases local temperature and increases local precipitation; however, they argued that the effects
617 of irrigation do not expand far from the place where irrigation takes place. In contrast, Lo and
618 Famiglietti (2013) argued that irrigation in California’s Central Valley intensifies the water cycle
619 in the southwestern US and can increase the flow in the Colorado River.

620 There are two main limitations associated with available simulations of irrigation-induced rainfall
621 discussed above. First, in most of the online studies, water availability is not a constraint. As a
622 result, the water balance is not closed and they simply analyze whether evaporation increase can
623 enhance atmospheric moisture convergence or not. This can be considered as a major limitation as
624 the available water can control the extent of irrigation (and consequently evaporation) and stabilize
625 the associated feedback processes. Second, it is known that sharp landscape contrasts (i.e.

626 transitions between wet and cool as well as dry and hot areas) critically affect rainfall formation
627 (e.g., Taylor 2009; C. M. Taylor et al., 2012). Although irrigation can create such transitions due
628 to enhanced evaporation and decreased surface temperature, current LSMs are generally unable to
629 generate the atmospheric perturbations due to these transitions (Polcher, 2014). Due to these
630 limitations, the results of current sensitivity analyses should be considered with caution.

631 Online simulations under future climate change are limited and have been performed mainly at
632 regional scales. Gerten et al. (2011) used a nested regional climate model to dynamically
633 downscale the future simulations of a global climate model over Southern Asia and considered
634 two modes of simulation, with or without irrigation. They concluded that including irrigation can
635 result in roughly half of the temperature increase predicted without representing irrigation. With
636 respect to future precipitation, simulation with and without irrigation both showed a decrease in
637 precipitation over northern India and increase in precipitation over the southern peninsular; the
638 latter was enhanced with irrigation. They noted that the increase in precipitation cannot be seen if
639 the global scale simulations are not dynamically downscaled. This highlights the importance of
640 including irrigation schemes in regional climate models for dynamic downscaling of future climate
641 change scenarios.

642 In summary, despite current limitations and differences in the host climate and LSM models,
643 irrigation demand algorithms and simulation settings, significant feedback effects are associated
644 with irrigation. Large uncertainties, however, exist in current coupled irrigation-land-surface-
645 climate modeling, which emphasizes the need for more research in this area.

646 **5.2 Offline representation**

647 Offline representation of water demands is more common and a wide variety of GHMs and LSMs
648 in conjunction with different demand algorithms have been used to simulate the dynamics of water
649 demand under both current and future conditions. The available global simulations under current
650 conditions are compared and summarized in Wada et al. (2013a) and Chaturvedi et al. (2013a,b)
651 for irrigative demands and in Alcamo et al. (2003) and Hejazi et al. (2013b) for total water
652 consumption. Although incorporating water demand calculations can generally result in more
653 realistic river discharge simulations (see Ngo-Duc et al., 2005a, b, 2007), current simulations
654 exhibit large differences in estimates of water demand and use at countrywide, continental and

655 global scales. This can be referred to the differences in data support, demand calculation schemes
656 and host models – see the discussion of Section 6 below.

657 Normally, future projections of water demands include more uncertainty than simulation of current
658 conditions as they are also conditioned on uncertain climate futures and/or socio-economic and
659 technological scenarios. Considering future climate projections, with or without considering
660 irrigation expansion, irrigation demand algorithms have mainly projected increase in irrigation
661 demand under climate change scenarios. As an early example, Fischer et al. (2007) estimated
662 irrigation water requirement as a function of both projected irrigated land and climate change from
663 1990 to 2080. They showed that the impact of climate change on increasing irrigation water
664 requirement could be nearly as large as the changes initiated by socio-economic developments.
665 There are, however, two sets of uncertainty associated with future projections of irrigation demand.
666 First, gridded climate products have significant deficiencies in representing current and future
667 climate, particularly with respect to precipitation (e.g., Lorenz and Kunstmann, 2012; Grey et al.,
668 2013). This can further propagate to estimation of irrigation demand at the sub-grid scale. Second,
669 there are large disagreements between irrigation demand projections with respect to different
670 climate model simulation, irrigation algorithms and host large-scale models. One possible
671 approach to account for these uncertainties would be using a multi-model approach, as
672 recommended by Gosling et al. (2011) and Haddeland et al. (2011, 2014) and implemented to
673 some extent by Wada et al. (2013b) and Rosenzweig et al. (2014). Based on the latest IPCC climate
674 scenarios (K. E. Taylor et al., 2012), these studies generally concluded that a significant increase
675 in future demand is likely, with possibly one-month or more shift in the peak irrigation demand in
676 mid-latitude regions (Wada et al., 2013b), but large uncertainties are associated with the
677 predictions (see Rosenzweig et al., 2014). Moreover, both studies noted that CO₂ increases might
678 have beneficial effects on crop transpiration efficiency, if other factors are not limiting (see also
679 Gerten et al., 2011; Konzmann et al., 2013). Nonetheless, it still remains unclear whether increased
680 transpiration efficiency is cancelled out by increased transpiration due to increasing biomass and
681 plant growth. More studies, therefore, are required in this direction (see Gerten, 2013). This is a
682 context for which LSMs can offer an ideal platform as they have the explicit modules required for
683 considering dynamic interactions of carbon, vegetation and water – see the discussion of Section
684 6.

685 Similar conclusions were obtained with respect to non-irrigative demands. Alcamo et al. (2007)
686 and Hejazi et al. (2013d) showed that increasing domestic and industrial water uses, if not
687 controlled, can be a major threat for water supply. There are, however, large discrepancies between
688 different projections of non-irrigative demands (Gleick, 2003), in which the divergence between
689 modeling results becomes more highlighted as the projection horizon increases (see Davis et al.
690 (2013) for electrical demand and associated water use). These uncertainties can be referred to
691 limitations in current data availability for supporting robust and reliable projections, differences in
692 socio-economic and technological scenarios, as well as some underlying assumptions in demand
693 calculation algorithms, which can limit their efficiency in future simulations.

694 As the current global potential for expanding water demand is rather limited (Rost et al., 2009;
695 Gerten and Rost, 2010), adaptation and mitigation strategies are required to moderate human water
696 demands. In such cases prescribed “policy” scenarios can be introduced into large-scale models
697 for impact assessment. Using this approach, it has been shown that mitigation can significantly
698 decrease future global water demand. For example, Hanasaki et al., (2013a) showed approximately
699 7-fold and 2.5-fold variation in industrial and municipal demands, depending on the SSP
700 considered. The effects of mitigation, however, have large regional variation. For irrigative
701 demands, Fischer et al. (2007) showed that some regions may be negatively affected by mitigation
702 actions, which depend on specific combinations of CO₂ changes that affect crop water requirement
703 and projected precipitation and temperature changes. Kyle et al. (2013) showed that applying CO₂
704 mitigation policies can result in high deployment of other high-tech solutions for electrical
705 generation (e.g., solar power) that have low water requirements. Hejazi et al. (2013c) further
706 showed that taxation can be an important factor in mitigating the effect of water scarcity by
707 regulating more water efficient options for irrigation. Hejazi et al. (2013a) further showed the
708 possibility of a slight decrease in municipal withdrawals in the year 2100 under a high-tech
709 scenario, despite significant population growth. Davies et al. (2013) showed similar results for
710 electricity water withdrawals if high-tech solutions are employed. Large-scale models also showed
711 that promoting international trade can be a strong adaptation option for controlling regional
712 demand, in which water-limited regions can import water-expensive products from other areas
713 (e.g., Siebert and Döll, 2010; Hanasaki et al., 2010; Konar et al., 2013). Assessment of trade
714 scenarios and water footprinting, however, needs detailed tracking of the water cycle (see
715 Chenoweth et al., 2013) and is highly dependent on how reasonable the human demands and

716 production, as well as water availability and water allocation, are described in time and space.
717 Such a level of accuracy is currently not available and therefore the assessments remain widely
718 uncertain.

719 In summary, current offline projections agree on large impacts of future change in climate, socio-
720 economy and technology on water demands and the importance of adaptation and mitigation
721 strategies for managing future water security threats. Available projections, however, are rather
722 limited and suffer from major sources of uncertainty, which is revealed by large discrepancies
723 between different simulation products under current and future conditions. We now turn to discuss
724 these gaps in more detail and identify the research needs and priorities.

725

726 **6 Discussion**

727 Major gaps remain in the current capability in modeling water demands and understanding their
728 online and offline impacts on the terrestrial water cycle and human livelihoods. These gaps are
729 partially due to inherent complexity in modeling Earth System processes, which is more significant
730 in coupled simulation modes. Apart from various computational barriers, one main challenge in
731 online simulations is the uncertainty associated with coupling land and atmospheric models, as
732 given a unique land-surface boundary condition, the simulations obtained by different climate
733 models can be divergent (Koster et al., 2004; Pitman et al., 2009; Dadson et al., 2013). Another
734 major challenge for coupled irrigation-land-surface-climate simulations is the choice of
735 appropriate temporal and spatial resolutions, at which the relevant physical processes and
736 feedbacks between land and atmosphere should be represented and described. Ideally, the optimal
737 modeling resolution should be identified based on physical realism; nonetheless, the choice of
738 resolution in coupled simulations is mainly constrained by computational resources, data
739 availability and the complexity supported by the LSMs. If these are not limiting factors, it has been
740 shown that finer temporal and spatial resolutions can improve online representation of irrigation.
741 For instance, using six different combinations of temporal/spatial resolutions, Sorooshian et al.
742 (2011) concluded that spatial and temporal resolution in coupled irrigation-land-climate models
743 can significantly change both temperature and precipitation simulations over irrigated grids and a
744 fine level of detail is required for representing the physical processes controlling the feedbacks
745 between irrigation and atmosphere. However, these findings remain regionally and seasonally

746 dependent and are closely linked to the level of complexity supported in the considered irrigation
747 parameterization and host model. It should be noted that by increasing the spatial resolution, more
748 processes need to be included in order to ensure water conservation within the model and that can
749 further complicate the issues related to water availability – see the discussion below. The effects
750 of fine modeling resolution seem to be in general less significant in offline runs, as far as the
751 evaporation calculation is consistent with estimation of crop water requirements and each crop is
752 supplied by a unique moisture reservoir. Compton and Best (2011) conducted offline global
753 simulations and showed that fine spatial resolution has little importance on long-term modeling of
754 evaporation and runoff; however, the temporal resolution does change the mean
755 evaporation/runoff balance. The issues around modeling resolution are explored further in Nazemi
756 and Wheeler (2014).

757 Large uncertainties are also associated with offline human water demand simulations under current
758 and future conditions. Lissner et al. (2012), for instance, noticed significant difference in terms of
759 water demand per capita between the simulated products of WaterGAP and reported AQUASTAT
760 data. These uncertainties are mainly related to (i) available data support, (ii) demand calculation
761 algorithms and (iii) host models. These sources are widely connected and cannot be easily
762 addressed and quantified independently. Here we briefly discuss these sources and propose few
763 directions for future developments.

764 (1) Uncertainty in current data support: Primarily, there are considerable uncertainties
765 across the input and forcing data required for executing large-scale models. Generally,
766 large-scale models discussed in this paper are forced and initialized using various data
767 sources that are developed and maintained independently. This results in major
768 inconsistencies, particularly at the grid scale, where it is often the case that information
769 coming from different sources does not match each other (e.g. soil properties do not fit
770 to land use etc.). Typically, modelers fix these issues by applying simple rules or
771 assumptions; however, these inconsistencies can highly affect the quality of simulations
772 at the local and regional scales. Major uncertainties are also associated with the data
773 required for executing demand calculation algorithms. Siebert et al. (2005) noted that
774 even the locations of irrigation districts are uncertain in many regions and sub-grid
775 variability of crops within irrigated areas is not generally available. Wisser et al. (2008)
776 argued that major uncertainties are associated with forcing, irrigation and crop maps

777 and this can result in large differences between simulations of irrigation water
778 requirement. Another source of data uncertainty is the generally sparse information on
779 irrigation techniques. This can be important for understanding the amount of water
780 losses and thus estimating the actual irrigation use and evaporation. The issues around
781 data support apply to non-irrigative demands as well. For the case of water use for
782 electricity generation in the US, Macknick et al. (2011) noted that “federal data sets on
783 water use in power plants have numerous gaps and methodological inconsistencies”.
784 Data uncertainty can propagate into structural and parametric identification during
785 model development and can further extend to future projections. The availability of
786 different sources of global and regional data has resulted in emergence of various
787 datasets, with varying degrees of quality, which can potentially support demand
788 calculation algorithms. At this stage of research, the various datasets have not been
789 systematically compared with respect to their uncertainty and the associated effects on
790 demand simulations. This is a major need for future exploration.

791 (2) Uncertainty in demand calculation algorithms: This includes both irrigative and non-
792 irrigative demands.

793 a) Irrigative demand: Limitations in current algorithms mainly include the uncertainty
794 in describing the crop moisture requirements in time and space and constraining the
795 irrigation to water availability. If the irrigation is limited by the water available at
796 the grid scale, then the quality of simulation is hindered by the ability of the host
797 model to describe water allocation from surface and groundwater resources (see
798 Nazemi and Wheeler, 2014). In addition, current bottom-up algorithms do not
799 appropriately consider plant-specific water requirements at the sub-grid scale due
800 to missing soil and crop diversity. This can result in misestimating the irrigation
801 demand. In the best situation, where the same assumption is used for the calculation
802 of the crop evaporation and the irrigation demand, the uncertainty of the irrigative
803 demand is the same as evaporation, but this can still vary greatly across various
804 host models. Considering future simulations, widely-used irrigation demand
805 estimates based on FAO guidelines often require several input variables (see e.g.,
806 Farmer et al., 2011 and Hejazi et al., 2013b for simplifications), and given the need
807 for downscaling of climate variables for future simulations, these can be

808 outperformed by simpler models (e.g., Vörösmarty, 1998; Wisser et al., 2010). At
809 the current stage of research, different methods for calculating irrigative demand
810 have not yet been fully intercompared to identify appropriate algorithms with
811 respect to region, climate and type of crops. This can be considered as an important
812 need for further research. Another avenue for future development is improving the
813 demand simulations using data assimilation and model calibration. These
814 opportunities will be discussed further in Nazemi and Wheeler (2014).

815 b) Non-irrigative demand: The current off-line modeling capability is generally
816 temporally coarse and available downscaling and projection algorithms mainly do
817 not account for seasonal variations in water demand. There are also parametric and
818 structural uncertainties in functional mappings that link water demand to socio-
819 economic and technological proxies due to limitations in available data as well as
820 the diversity and spatiotemporal variability in non-irrigative demands. At this stage,
821 it is not fully understood how these uncertainties propagate into future projections
822 considering additional uncertainty in future climate and socio-economic scenarios.
823 Developing robust downscaling and projection algorithms for estimation of non-
824 irrigative demands therefore is an important need for future development.

825 (3) Uncertainty in host models: Host models can add substantial uncertainty to demand
826 simulations, particularly for irrigation. As noted in Section 3, the calculation of
827 irrigation demand involves solving the soil water balance at every simulation time step
828 and this is determined by how the relevant natural processes, such as actual
829 evapotranspiration and soil moisture, are parameterized in the host model. Haddeland
830 et al. (2011) showed major differences in the global simulations obtained from six
831 LSMs and five GHMs due to differences in underlying assumptions, process
832 representations, and related parameterizations. It is also shown that considering
833 feedback effects between irrigation and atmosphere can considerably change potential
834 evaporation (e.g., Blyth and Jacobs, 2011; Lu, 2013); therefore offline irrigation
835 demand simulations based on GHMs might be biased as they inherently ignore climate
836 feedbacks. Moreover, GHMs often cannot represent important processes such as the
837 effects of increased carbon concentration on irrigation demand. This limitation may
838 result in major deficiencies in simulating climate change scenarios as CO₂ increases

839 can significantly change vegetation dynamics (e.g., Prudhomme et al., 2014), which
840 can further alter the evaporation and runoff regimes (Gerten et al., 2004). From this
841 perspective, it can be concluded that online LSMs are superior to GHMs with respect
842 to simulations under increasing CO₂ concentration and future water stress, as they often
843 include many of the required computational components for investigating interactions
844 between climate, carbon, vegetation and water cycles. Efforts are however needed to
845 transfer recent demand calculation algorithms developed in the context of GHMs into
846 LSMs. In addition, although it has been argued that the uncertainties in host models are
847 more significant than in climate forcing (e.g., Wada et al., 2013b), uncertainties in
848 irrigation algorithms and large-scale host models have not been fully disaggregated and
849 distinguished. This requires a “mix and match” of multiple demand algorithms with
850 multiple host models to conduct a systematic intercomparison and sensitivity analysis.
851 This can be considered as an important research direction – see Nazemi and Wheeler
852 (2014).

853

854 **7 Summary and concluding remarks**

855 The terrestrial water cycle has been greatly affected in time and space by human activities during
856 the recent past, to the extent that the current geological era has been named the “Anthropocene”.
857 Anthropogenic activities, therefore, are required to be represented in models that are used for
858 impact assessments, large-scale hydrological modeling and land-atmosphere feedback
859 representations. Current human-water interactions are mainly manifested through water resource
860 management, which can be further broken down into two interacting components, related to water
861 demand as well as water supply and allocation. In this paper we considered the representation of
862 water demand in large-scale models. Water demand was further divided into irrigative and non-
863 irrigative categories. We summarized current demand calculation algorithms based on type of
864 demand, modeling procedure and underlying assumptions. Current applications were overviewed;
865 and limitations in knowledge were identified and discussed. Considering current gaps in
866 representing the anthropogenic demands in large-scale models, three main directions are suggested
867 for future developments. These include (1) systematic intercomparisons between different
868 datasets, demand algorithms and host models and associated uncertainties with respect to different

869 geographic regions as well as various socio-economic and climate conditions; (2) developing
870 improved algorithms for calculating both irrigative and non-irrigative demands in time and space
871 considering data limitations as well as diversity and spatiotemporal variability in human demand;
872 and finally (3) transferring the algorithms developed in the context of GHMs to LSMs for (a)
873 improved irrigation demand calculation under increasing CO₂ effects; and (b) further coupled
874 studies with climate models to address various scientific questions with respect to interactions
875 between carbon, irrigation and climate under climate change conditions. Apart from these
876 immediate research needs, efforts are also required to link with socio-economic and energy models
877 to have a full understanding of the dynamic interactions between natural and anthropogenic drivers
878 of human water availability, demand and consumption (Calvin et al., 2013). This seems to be more
879 of a long-term development due to the limitations in current demand algorithms, LSMs as well as
880 socio-economic and energy models.

881 As a final remark, it must be noted that the effects of water demand on both the terrestrial water
882 cycle and water security cannot be fully studied unless considered in conjunction with water supply
883 and allocation, which determine the extent of human intervention in water cycle. This is
884 particularly important for future predictions, as increasing water scarcity is a major limiting factor
885 for water demand and can substantially increase competition over available water sources. In
886 Nazemi and Wheeler (2014), we review how water supply and allocation have been represented
887 at larger scales and been integrated with various water demands and natural land-surface processes
888 at grid and sub-grid scales.

889

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896

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Table 1. Representative examples including regional irrigation in large-scale models (offline mode)

Reference	Irrigation data	Irrigation demand	Region	Host model	Forcing	Temporal resolution	Spatial resolution
Haddeland et al. (2006)	Döll and Siebert (2002)	Difference between current soil moisture content and minimum of FAO Penman-Monteith crop-specific evapotranspiration and soil moisture content at field capacity.	Colorado (USA) and Mekong (east Asia)	VIC (Liang et al., 1994)	Adam and Lettenmaier (2003); Maurer et al. (2002)	3hr	0.5°×0.5°
Haddeland et al. (2007)	Siebert et al. (2005)	Haddeland et al. (2006)	North America and Asia	VIC (Liang et al., 1994)	Maurer et al. (2002)	24hr	0.5°×0.5°
Gueneau et al. (2012)	GAEZ (IIASA/FAO, 2012); FRIS (USDA, 2008)	Difference between actual and potential evapotranspiration based on Farmer et al. (2011). Crop growth and irrigation losses included.	USA	CLM3.5 (Oleson et al., 2004, 2008)	NCC (Ngo-Duc et al., 2005b)	6hr	2.5°×2.5°
Leng et al. (2013)	MODIS (Ozdogan and Gutman, 2008); NASS (USDA, 2002)	Difference between current and ideal soil moisture content based on CLM4CNcrop crop growth model of CLM4 (Levis and Sacks, 2011; Levis et al., 2012).	Conterminous USA	CLM4 (Lawrence et al., 2011)	NLDAS (Cosgrove et al., 2003)	1hr	0.125°×0.125°
Nakayama and Shankman (2013)	Liu et al. (2010)	Difference between current soil moisture content and soil moisture at the field capacity.	Changjing, Yellow River basins (China)	NICE (Nakayama, 2011)	ECMWF (http://www.ecmwf.int/en/forecasts/datasets)	6hr	10 ^{km} ×10 ^{km}
Voisin et al. (2013)	Crop area projections in Chaturvedi et al. (2013a,b).	Downscaling GCAM model estimations (Wise and Calvin, 2011; Wise et al., 2009a) using methods of Hejazi et al. (2013a), Siebert and Döll (2008) and Hanasaki (2013a,b).	US mid-west	SCLM-MOSART (Lawrence et al., 2011; Li et al., 2013a,b)	CASCaDE (http://cascade.wr.usgs.gov)	1hr	0.125°×0.125°

Table 2. Representative examples including global irrigation in large-scale models (offline mode)

Reference	Irrigation data	Irrigation demand	Host model	Forcing	Temporal resolution	Spatial resolution
Döll and Siebert (2002)	Döll and Siebert (2000)	Difference between Smith (1992) effective rainfall and Priestley and Taylor (1972) crop specific potential evapotranspiration and Allen et al. (1998) multipliers.	WaterGAP (Alcamo et al., 2003)	CRU TS 1.0 (New et al., 1999, 2000)	24hr	0.5°×0.5°
de Rosnay et al. (2003) ¹	Döll and Siebert (2002)	Difference between effective rainfall and FAO potential evapotranspiration (Allen et al., 1998) without considering irrigation efficiency.	ORCHIDEE (Ducoudré et al., 1993)	ISLSCP-I (Sellers et al., 1996b)	24hr	1°×1°
Hanasaki et al. (2006)	Döll and Siebert (2000)	Similar to Döll and Siebert (2002). Reference evaporation is based on FAO Penman Monteith.	TRIP (Oki and Sud, 1998)	ISLSCP-I (Sellers et al., 1996b)	24hr	0.5°×0.5°
Wisser et al. (2008)	Siebert et al. (2005, 2007); GIAM (Thenkabail et al., 2009)	Similar to Haddeland et al. (2006) using Allen et al. (1998) procedure.	WBM (Vörösmarty et al., 1998)	CRU TS 2.1 (Mitchell and Jones, 2005); NCEP (Kalnay et al., 1996)	24hr	0.5°×0.5°
Rost et al. (2008, 2009)	Siebert et al. (2007)	Difference between available plant-moisture and an updated Priestley and Taylor (1972) potential evaporation based on potential canopy conductance of carbon and water (Sitch et al., 2003).	LPJmL (Bondeau et al., 2007)	CRU TS 2.1 (Mitchell and Jones, 2005)	24hr	0.5°×0.5°
Hanasaki et al., (2008a,b)	Döll and Siebert (2000)	Difference between current and 75% of field capacity. Irrigation applied 30 days prior to planting. Detailed crop growth representation based on SWIM (Krysanova et al., 1998).	H08 (Hanasaki et al., 2008a,b)	NCEP-DOE (Kanamitsu et al., 2002); GSWP-2 (Zhao and Dirmeyer, 2003)	24hr	1°×1°
Siebert and Döll (2010)	MIRCA2000 (Portmann et al., 2010)	Difference between actual and crop-dependent reference evapotranspiration computed according to Priestley and Taylor (1972). Crop coefficients obtained from Allen et al., (1998).	GCWM (Siebert and Döll, 2008)	CRU TS 2.1 (Mitchell and Jones, 2005)	24hr	0.08°×0.08°
Wada et al. (2011, 2012)	MIRCA2000 (Portmann et al., 2010)	Difference between actual and potential transpiration according to van Beek et al. (2011), using Priestley and Taylor (1972) crop-specific and transpiration (Allen et al., 1998).	PCR-GLOBWB (van Beek et al., 2011)	CRU TS 1.0 (New et al., 1999, 2000)	24hr	0.5°×0.5°
Pokhrel et al. (2012)	Siebert et al. (2007)	Procedure of Hanasaki et al. (2008a,b). Crop calendar is based on Potential evapotranspiration (Allen et al., 1998).	MASTIRO (Takata et al., 2003)	Kim et al. (2009); GPCC (Rudolf et al., 2005)	6hr	1°×1°
Wada et al. (2013a)	MIRCA2000 (Portmann et al., 2010)	Constant 50mm surface water depth for paddy irrigation until 20 days before harvesting. For non-paddy areas, the difference between current and ideal plant available moisture at field capacity with dynamic root zone	PCR-GLOBWB (van Beek et al., 2011)	ERA-Interim (Dee et al., 2011); MERRA (http://gmao.gsfc.nasa.gov/merra/)	24hr	0.5°×0.5°

¹ The simulation is performed globally but the results are analyzed only over the Indian Peninsula.

Table 3. Representative examples including irrigation in coupled land-surface models (online mode)

Reference	Irrigation data	Irrigation demand	Region	Host LSM	Climate model	Temporal resolution	Spatial resolution
Adegoke et al. (2003)	LandSat (http://landsat.gsfc.nasa.gov/)	Target soil moisture deficit (difference between actual and saturated Soil moisture).	High Plains (USA)	LEAF-2 (Walko et al., 2000)	RAMS (Pielke et al., 1992)	30sec nested in 1 min	10 ^{km} ×10 ^{km} nested in 40 ^{km} ×40 ^{km}
Sacks et al. (2009)	FAO-AQUASTAT (http://www.fao.org/nr/water/aquastat/main/index.stm)	AQUASTAT irrigated water uses applied at constant rate when LAI exceeds 80% of the maximum annual value.	Global	CLM3.5 (Oleson et al., 2008)	CAM (Collins et al., 2004, 2006)	20min	2.8°×2.8°
Sorooshian et al. (2011)	CIMIS-MODIS (http://www.cimis.water.ca.gov/)	Target soil moisture deficit (irrigation starts when the soil moisture drops below a maximum depletion threshold beyond which the plant is stressed (a percentage of field capacity, depending on the crop) and continues to field capacity)	California Central Valley (USA)	Noah (Ek et al., 2003)	NCAR-MM5 (Chen and Dudhia, 2001a,b)	30min 1hr	4 ^{km} ×4 ^{km} 12 ^{km} ×12 ^{km} 36 ^{km} ×36 ^{km}
Harding and Snyder (2012a,b)	MODIS (Friedl et al., 2002; Ozdogan and Gutman, 2008); NASS (USDA, 2002)	Target soil moisture deficit (difference between actual and saturated soil moisture to depth of 2m).	Great Plains (USA)	Noah (Ek et al., 2003)	WRF (Skamarock et al., 2005)	30s and 25s	10 ^{km} ×10 ^{km}
Guimberteau et al. (2012)	Döll and Siebert (2002)	Difference between potential transpiration and the net water amount kept by the soil (i.e. the difference between precipitation reaching the soil and total runoff).	Global	ORCHIDEE (Ducoudré et al., 1993)	LMDZ4 (Hourdin et al., 2006)	30 min	2.5°×1.25°
Qian et al. (2013)	MODIS (Ozdogan and Gutman, 2008; Ozdogan et al., 2010)	Similar to Sorooshian et al. (2011). Based on Ozdogan et al., (2010), moisture threshold is fixed at 50% of field capacity. Roots grow based on the greenness index.	Southern Great Plains (USA)	Noah (Ek et al., 2003)	WRF (Skamarock et al., 2005)	3hr	12 ^{km} ×12 ^{km}

Table 4. Representative examples calculating grid-based non-irrigative demands using downscaling of coarse scale estimates

Reference	Estimated demand	Downscaling procedure	Data support	Targeted resolution
Alcamo et al. (2003)	Domestic	Distributing country-level withdrawals based on population, ratio of rural to urban population (constant for each country) and percentage of population with access to drinking water	Population (van Woerden et al., 1995); access to drinking water (WRI, 1998)	0.5°×0.5° (Global)
	Industrial	Downscaling county-wide industrial withdrawals based on proportion of urban population	Population (van Woerden et al., 1995)	
Vassolo and Döll (2005)	Thermoelectric cooling	Calculating the gridded data for power production based on downscaling global estimates. Allocating constant flow to each unit of production according to type of cooling system.	World Electric Power Plants Data Set (http://www.platts.com).	0.5°×0.5° (Global)
	Manufacturing	Estimating country-wide sectoral production volumes along with water intensity for each unit of production in each sector. Downscaling total demand to the grid-scale based on city nighttime light.	Industrial production volumes (UN, 1997; CIA, 2001); sectoral intensity (Shiklomanov, 2000; WRI, 2000); night city light pollution (US Air Force, www.ngdc.noaa.gov/dmsp)	
Hanaskai et al. (2008a)	Domestic and industrial	Countrywide data downscaled to grid scale by weighting population and national boundary information, further converted to water consumption estimates.	AQUASTAT countrywide withdrawals, population and national boundaries (CIAT, 2005); ratio of consumption to withdrawal (Shiklomanov, 2000).	1°×1° (Global)
Hejazi et al., (2013b)	Municipal and industrial	Demand estimates of GCAM model (http://wiki.umd.edu/gcam) downscaled as a function of population. Population density assumed static in time.	Global population density data based on WWDR-II and methodology of Wada et al. (2011, 2013a)	0.5°×0.5° (Global)

Table 5. Representative examples for disaggregating annual non-irrigative demand into monthly estimates

Reference	Estimated demand	Disaggregation procedure	Data support
Wada et al. (2011, 2013)	Municipal and livestock	Downscaling annual demand to monthly fluctuations as a function of temperature	CRU (New et al., 1999; 2000)
Voisin et al. (2013)	Electrical	Dividing electrical use into industry, transportation and building sectors. Assuming uniform distribution for industry and transportation uses and capturing the monthly fluctuations in building use based on heating/cooling degree days.	CASCaDE (http://cascade.wr.usgs.gov)

Table 6. Representative examples for projection of non-irrigative water demands using socio-economic variables

Reference	Simulated demands	Simulation procedure	Temporal resolution	Spatial resolution
Alcamo et al. (2003a)	Domestic and industrial	Explicit simulation of change in industrial and domestic withdrawal as functions of usage intensity and technological change. Usage intensities are functions of GDP.	Annual	Countrywide
Strzepek et al. (2012b)	Municipal and industrial	Explicit simulation of change in municipal water use as a function of population and per capita income. Industrial water use considered as a function of water use per capita and GDP considering growth rate and climatic and water availability factors.	Annual	Assessment sub-regions (global)
Flörke et al. (2013)	Domestic and industrial	Explicit simulation of domestic demand using Alcamo et al. (2003) with parameterization based on HYDE (http://themasites.pbl.nl/tridion/en/themasites/hyde/) and UNEP (http://www.unep.org/) datasets. Technological change influenced electrical demand. Manufacturing water use computed as a function of baseline structural intensity and rates of manufacturing gross value and technological change.	Annual	Countrywide (global)
Davies et al. (2013)	Electrical	Implicit simulation – changes in regional cooling system shares estimated based on shift from wet to dry cooling technologies. Reductions in water withdrawal and consumptions estimated based on level of technological change.	Annual	Geopolitical regions (global)
Hanasaki et al. (2013a)	Industrial and municipal	Explicit simulation of industrial withdrawal as a function of electricity production and water intensity which decreases linearly in time. Municipal water use calculated as a function of population and change in municipal intensity, varying based on GDP.	Five-year interval	countrywide
Blanc et al. (2013)	Electrical, domestic, industrial and mining	Electrical demand projected implicitly using ReEDS (Short et al., 2009) and integration with USREP model (Rausch and Mowers, 2013). Water withdrawal and consumption to meet electrical demand estimated using Strzepek et al. (2012a). Other demands categorized into three groups: public supply, self-supply and mining supply and simulated explicitly. Public supply considered as a function of population and GDP per capita. Self-supply considered as function of sectoral GDP. Mining supply considered as a function of mining's GDP.	Annual	Assessment sub-regions (US)
Hejazi et al. (2013a)	Municipal	Withdrawal per capita explicitly determined as a function of GDP per capita, water price and technological development. Technological development considered as a function of operational efficiency, which further determines extent of water use.	Annual	Geopolitical regions (global)
Hejazi et al., (2013b,d)	Industrial	Manufacturing water demand is explicitly simulated based on population and GDP. Water demand for primary energy scaled by amount of fuel production and water demand for secondary energy.	Annual	Geopolitical regions (global)
Wada et al. (2013a)	industrial and municipal	Industrial and municipal withdrawal taken from WWDR-II dataset (Shiklomanov, 1997; Vörösmarty et al., 2005) and backcasted explicitly using economic and technological proxies. Net municipal water demand calculated as a function of fraction of urban to total population and recycling ratio.	Annual	Countrywide (global)

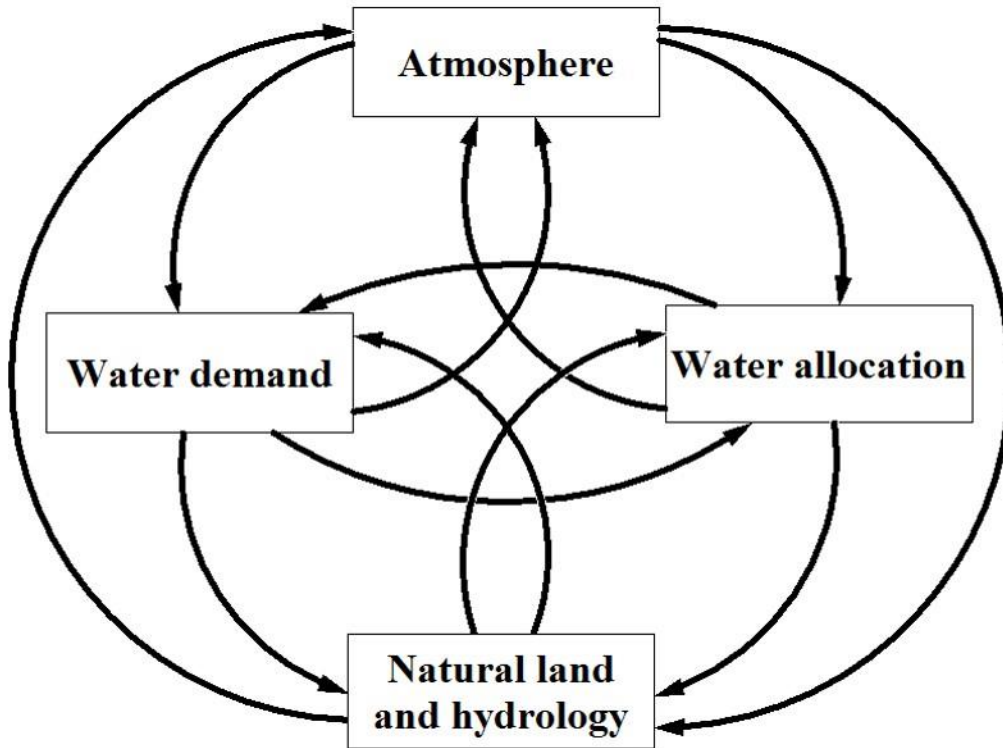


Figure 1. Water resource management as an integration of water demand and water allocation and its interactions with natural land-surface and climate.