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# 1 Groundwater and climate change: recent advances and a 2 look forward

3  
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10  
11 As the world's largest distributed store of freshwater, groundwater plays a central role in  
12 sustaining ecosystems and enabling human adaptation to climate variability and change.

13 The strategic importance of groundwater to global water and food security will intensify  
14 under climate change as more frequent and intense climate extremes (droughts, floods)  
15 increase variability in soil moisture and surface water. Here we critically review recent  
16 research assessing climate impacts on groundwater through natural and human-induced  
17 processes as well as groundwater-driven feedbacks on the climate system.

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18 Groundwater is a near ubiquitous source of generally high quality freshwater. These  
19 characteristics promote its widespread development which can be scaled and localised to  
20 demand obviating the need for substantial infrastructure<sup>1</sup>. Globally, groundwater is the  
21 source of one third of all freshwater withdrawals supplying an estimated 36%, 42% and 27%  
22 of the water used for domestic, agricultural and industrial purposes, respectively<sup>2</sup>. In many  
23 environments, natural groundwater discharges sustain baseflow to rivers, lakes and  
24 wetlands during periods of low or no rainfall. Despite these vital contributions to human  
25 welfare and aquatic ecosystems, a paucity of studies of the relationship between climate  
26 and groundwater severely restricted the ability of the Intergovernmental Panel on Climate  
27 Change (IPCC) to assess interactions between groundwater and climate change in both its  
28 third<sup>3</sup> and fourth<sup>4</sup> assessment reports. There has since been a dramatic rise in published  
29 research applying local- to global-scale modelling as well as ground-based and satellite  
30 monitoring that has substantially enhanced understanding of interactions between  
31 groundwater and climate<sup>5,6</sup>. We examine these recent advances that include emerging  
32 knowledge of direct and indirect (through groundwater use) impacts of climate forcing  
33 including climate extremes on groundwater resources as well as feedbacks between  
34 groundwater and climate such as groundwater depletion on global sea level rise. Further, we  
35 identify critical gaps in our understanding of direct and indirect interactions between  
36 groundwater and climate, and groundwater-based strategies to adapt to climate variability  
37 and change.

38

### 39 **Influence of climate variability and change on groundwater systems**

40 *Palaeohydrological evidence.* Long-term responses of groundwater to climate forcing, largely  
41 independent of human activity, can be detected from palaeohydrological evidence from

42 regional aquifer systems in semi-arid and arid parts of the world (Fig. 1). Groundwater  
43 flowing in large sedimentary aquifers of central USA (High Plains Aquifer), Australia (Great  
44 Artesian Basin), Southern Africa (Kalahari Sands) and North Africa (Nubian Sandstone Aquifer  
45 System) was recharged by precipitation thousands of years ago<sup>7-10</sup>. As evaporation and plant  
46 transpiration consume soil moisture but leave chloride behind, substantial accumulations of  
47 chloride in unsaturated soil profiles within these basins indicate that little or no recharge has  
48 since taken place<sup>11</sup>. Stable isotopes of oxygen and hydrogen together with noble gas  
49 concentrations suggest that recharge occurred under cooler climates ( $\geq 5^{\circ}\text{C}$  cooler) before  
50 and occasionally during Late-Pleistocene glaciation with further local additions during the  
51 Early Holocene. Groundwater recharged during cooler, wetter climates of the Late  
52 Pleistocene and Early Holocene ( $\geq 5$  ka B.P.) is commonly referred to as 'fossil groundwater'.  
53 As current groundwater recharge rates are responsible for at most a tiny fraction of total  
54 groundwater storage, fossil aquifers are storage dominated rather than recharge flux  
55 dominated<sup>12</sup>. As such, their lifespan is determined by the rate of groundwater abstraction  
56 relative to exploitable storage. In these systems, robust estimates of groundwater storage  
57 estimates and accurate records of groundwater withdrawals are of critical importance.  
58 Although fossil aquifers provide a reliable source of groundwater that is resilient to current  
59 climate variability, this non-renewable groundwater exploitation is unsustainable and is  
60 mined similar to oil<sup>13</sup>.

61

62 *Direct impacts.* Current, natural replenishment of groundwater occurs from both diffuse  
63 rain-fed recharge and focused recharge via leakage from surface waters (i.e. ephemeral  
64 streams, wetlands or lakes) and is highly dependent upon prevailing climate as well as land  
65 cover and underlying geology. Climate and land cover largely determine precipitation (P) and

66 evapotranspiration (ET) demand whereas the underlying soil and geology (Fig. 1) dictate  
67 whether a water surplus (P-ET) can be transmitted and stored in the subsurface. Modelled  
68 estimates of diffuse recharge globally<sup>14,15</sup> range from 13,000 to 15,000 km<sup>3</sup> year<sup>-1</sup>, equivalent  
69 to ~30% of the world's renewable freshwater resources<sup>16</sup> or a mean per capita groundwater  
70 recharge of 2,100 to 2,500 m<sup>3</sup> year<sup>-1</sup>. These estimates represent potential recharge fluxes as  
71 they are based on a water surplus rather than measured contributions to aquifers. Further,  
72 these modelled global recharge fluxes do not include focused recharge which, in semi-arid  
73 environments, can be substantial<sup>11,17</sup>.

74         Spatial variability in modelled recharge is related primarily to the distribution of  
75 global precipitation<sup>14,15</sup>. Over time, recharge is strongly influenced by climate variability  
76 including climate extremes (i.e. droughts and floods) that often relate to modes of climate  
77 variability such as El Niño Southern Oscillation (ENSO) at multiyear timescales and Pacific  
78 Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO) and others at longer  
79 timescales<sup>18,19</sup>. During the recent multi-annual Millennium Drought in Australia,  
80 groundwater storage in the Murray-Darling Basin declined substantially and continuously by  
81 ~100 ± 35 km<sup>3</sup> from 2000 to 2007 in response to a sharp reduction in recharge<sup>20</sup>. Heavy  
82 rainfall has been found to contribute disproportionately to recharge observed in borehole  
83 hydrographs from tropical Africa<sup>18,21</sup>. Further, recharge in semi-arid environments is often  
84 restricted to statistically extreme (heavy) rainfall<sup>14,22</sup> that commonly generates focused  
85 recharge beneath ephemeral surface water bodies<sup>17,18,23</sup>. Recharge from heavy rainfall  
86 events is also associated with microbial contamination of shallow groundwater-fed water  
87 supplies and outbreaks of diarrhoeal diseases in both low and high-income countries<sup>24</sup>.  
88 Wetter conditions do not, however, always produce more groundwater recharge. Incidences  
89 of greater (x 2.5) winter precipitation in the SW USA during ENSO years, give rise to

90 enhanced evapotranspiration from desert blooms that largely or entirely consume the water  
91 surplus<sup>25</sup>.

92 At high latitudes and elevations, global warming changes the spatial and temporal  
93 distribution of snow and ice. Warming results in lower snow accumulation and earlier  
94 snowmelt as well as more winter precipitation falling as rain and an increased frequency of  
95 rain-on-snow events. The aggregate impact of these effects on recharge is not well resolved  
96 but preliminary evidence<sup>26,27</sup> indicates that they serve to reduce the seasonal duration and  
97 magnitude of recharge. Aquifers in mountain valleys that are strongly coupled to adjacent  
98 rivers exhibit shifts in the timing and magnitude of: (1) peak groundwater levels due to an  
99 earlier spring melt, and (2) low groundwater levels associated with longer and lower  
100 baseflow periods<sup>28,29</sup> (Fig. 2). Summer low flows in streams may be exacerbated by declining  
101 groundwater levels so that streamflow becomes inadequate to meet domestic and  
102 agricultural water requirements and to maintain ecological functions such as in-stream  
103 habitats for fish and other aquatic species<sup>29</sup>. The impacts of receding alpine glaciers on  
104 groundwater systems are also not well resolved yet the long-term loss of glacial storage is  
105 estimated to similarly reduce summer baseflow<sup>30</sup>. In glaciated watersheds of the Himalayas,  
106 the impacts of large reductions in glacial mass and increased evaporation on groundwater  
107 recharge are projected to be offset by a rise in precipitation<sup>31</sup>. In permafrost regions where  
108 recharge is currently ignored in global analyses<sup>14</sup>, coupling between surface water and  
109 groundwater systems may be particularly enhanced by warming<sup>32</sup>. In areas of seasonal or  
110 perennial ground frost, increased recharge is expected even though the absolute snow  
111 volume decreases<sup>33</sup>.

112

113 *Human and indirect climate impacts.* Linkages between climate and groundwater in the  
114 modern era are complicated by Land-Use Change (LUC) that includes most pervasively the  
115 expansion of rain-fed and irrigated agriculture. Managed agro-ecosystems do not respond to  
116 changes in precipitation in the same manner as natural ecosystems. Indeed, LUC may exert a  
117 stronger influence on terrestrial hydrology than climate change. Under multi-decadal  
118 droughts in the West African Sahel during the latter half of the 20<sup>th</sup> century, groundwater  
119 recharge and storage rose rather than declined due to a coincidental LUC from savannah to  
120 cropland that increased surface runoff through soil crusting and focused recharge via  
121 ephemeral ponds<sup>34</sup>. Much earlier in the 20<sup>th</sup> century, LUC from natural ecosystems to rain-  
122 fed cropland in SE Australia and SW USA similarly increased groundwater storage through  
123 increased recharge but also degraded groundwater quality through the mobilisation of  
124 salinity accumulated in unsaturated soil profiles<sup>11</sup>. In both regions, recharge rates under  
125 cropland increased by about an order of magnitude<sup>35-37</sup>.

126 Humans have also exerted large-scale impacts on the terrestrial water system  
127 through irrigation (Fig. 2). In 2000, irrigation accounted for ~70% of global freshwater  
128 withdrawals and ~90% of consumptive water use<sup>2</sup>. This large-scale redistribution of  
129 freshwater from rivers, lakes and groundwater to arable land (Fig. 2) has led to: (1)  
130 groundwater depletion in regions with primarily groundwater-fed irrigation; (2) groundwater  
131 accumulation as a result of recharge from return flows from surface-water fed irrigation; and  
132 (3) changes in surface-energy budgets associated with enhanced soil moisture from  
133 irrigation. Irrigation has depleted groundwater storage in several semi-arid and arid  
134 environments including the North China Plain<sup>38</sup>, NW India<sup>39</sup>, US High Plains<sup>40,41</sup> but also in  
135 humid environments of Brazil<sup>42</sup> and Bangladesh<sup>43</sup> (Fig. 1) where abstraction is especially  
136 intense. During a recent (2006 to 2009) drought in the California Central Valley (Fig. 1), large-

137 scale groundwater depletion occurred when the source of irrigation water shifted from  
138 surface water to mostly groundwater. GRACE (Gravity Recovery and Climate Experiment)  
139 satellite data and ground-based observations revealed that groundwater storage declined by  
140 between 24 and 31 km<sup>3</sup>, a volume that is equivalent to the storage capacity of Lake Mead,  
141 the largest surface reservoir in the USA<sup>44,45</sup>. These observations show that indirect effects of  
142 climate on groundwater through changes in irrigation demand and sources can be greater  
143 than direct impacts of climate on recharge. Global-scale modelling<sup>2</sup> highlights areas of recent  
144 (1998 to 2002) groundwater accumulation through irrigation return flows from surface-  
145 water fed irrigation in the Nile Basin of Egypt, Tigris-Euphrates basin of Iraq, Syria and  
146 Turkey, the lower Indus basin in Pakistan, and southeastern China (Fig. 3). In parts of the  
147 California Central Valley, surface water irrigation since the 1960s has increased groundwater  
148 recharge by a factor of ~7 replenishing previously depleted aquifers and raising groundwater  
149 levels by up to 100 m<sup>46</sup>. Increased recharge may also serve not only to degrade groundwater  
150 quality through the mobilisation of salinity in soil profiles (discussed above) but also to flush  
151 natural contaminants such as arsenic from groundwater systems<sup>47,48</sup>.

152

153 *Future climate impacts on groundwater systems.* As irrigation dominates current  
154 groundwater use and depletion, the effects of future climate variability and change on  
155 groundwater may be greatest through indirect impacts on irrigation water demand.  
156 Substantial uncertainty persists in climate change impacts on mean precipitation from  
157 General Circulation Models (GCMs)<sup>49</sup> but there is much greater consensus on changes in  
158 precipitation and temperature extremes, which are projected to increase with intensification  
159 of the global hydrological system<sup>50,51</sup>. Longer droughts may be interspersed with more  
160 frequent and intense rainfall events. These changes in climate may affect groundwater

161 initially and primarily through changes in irrigation demand, in addition to changes in  
162 recharge and discharge. A global analysis of climate change impacts on irrigation demand  
163 suggests that two thirds of the irrigated area in 1995 will be subjected to increased water  
164 requirements for irrigation by 2070<sup>(ref. 52)</sup>. Projected increases in irrigation demand in  
165 southern Europe will serve to stress further limited groundwater resources<sup>53</sup>. Persistent  
166 droughts projected in the California Central Valley over the latter half of the 21<sup>st</sup> century are  
167 predicted to trigger a shift from predominantly surface water to groundwater supply for  
168 agriculture<sup>54</sup>. Increased groundwater abstraction combined with reduced surface water  
169 flows associated with intermittent droughts during the first half of the 21<sup>st</sup> century may,  
170 however, induce secondary effects (e.g. subsidence) that severely constrain this future  
171 adaptation strategy.

172         Projections of the direct impacts of climate change on groundwater systems are  
173 highly uncertain. The dominant source of uncertainty lies in climate projections derived from  
174 GCMs which typically translate the same emissions scenarios into very different climate  
175 scenarios, particularly for precipitation<sup>49</sup>. Nevertheless, GCM projections of global  
176 precipitation for the 21st century broadly indicate a 'rich get richer' pattern in which regions  
177 of moisture convergence (divergence) are expected to experience increased (decreased)  
178 precipitation<sup>50,55</sup>. At the global scale, there are no published studies applying a large  
179 ensemble of GCMs and greenhouse-gas emissions scenarios to generate recharge  
180 projections. Global simulations employing output from two climate models (ECHAM4,  
181 HadCM3) under two emissions scenarios (A2, B2) project: (1) decreases in potential  
182 groundwater recharge of more than 70% by the 2050s in NE Brazil, SW Africa and along the  
183 southern rim of the Mediterranean Sea; and (2) increases in potential recharge of more than  
184 30% in the Sahel, Middle East, northern China, Siberia and the western USA<sup>16</sup>. Baseline

185 recharge rates in many of these areas are, however, very low so that small changes in  
186 projected recharge can result in large percentage changes. For most of the areas with high  
187 population densities and high sensitivity to groundwater recharge reductions, model results  
188 indicated that groundwater recharge is unlikely to decrease by more than 10% until the  
189 2050s<sup>16</sup>.

190 Groundwater recharge projections are closely related to projected changes in  
191 precipitation. Regional simulations employing 16 GCMs in Australia project potential  
192 recharge decreases in the west, central and south, and increases in the north based on the  
193 ensemble median<sup>55</sup>. In Europe, potential recharge projections derived from an ensemble of  
194 four GCMs under the A1FI emissions scenario demonstrate strong latitudinal dependence on  
195 the direction of the climate change signal<sup>56</sup>. Substantial reductions in potential groundwater  
196 recharge are uniformly projected in southern Europe (Spain and northern Italy) whereas  
197 increases are consistently projected in northern Europe (Denmark, southern England,  
198 northern France). Current uncertainty in climate change impacts on recharge derives not  
199 only from the substantial uncertainty in GCM projections of precipitation but also from the  
200 cascade of uncertainty associated with the downscaling of GCM projections and employed  
201 hydrological models<sup>57</sup>. For a chalk aquifer in England, for example, application of an  
202 ensemble of 13 GCMs resulted in projected changes in groundwater recharge for the 2080s  
203 of between -26% and +31%<sup>58</sup>. In southern British Columbia, recharge projections for the  
204 2080s range from -10 % to +23 % relative to historical recharge<sup>59</sup>. At three Australian sites,  
205 the choice of GCMs was found to be the greatest source of uncertainty in future recharge  
206 projections followed by that of downscaling and, in turn, the applied hydrological model  
207 amounting to 53, 44 and 24% of historical recharge, respectively<sup>60</sup>. Uncertainty from

208 downscaling can be greater than uncertainty due to the choice of applied emissions  
209 scenarios<sup>61,62</sup>.

210 Current projections of groundwater recharge under climate change commonly do not  
211 consider the intensification of precipitation and CO<sub>2</sub>-physiological forcing. Although  
212 precipitation intensity is of critical importance to recharge, historical daily rainfall  
213 distributions are typically used to downscale monthly rainfall projections to a daily timestep.  
214 Evidence from the tropics<sup>63</sup> where the intensification of precipitation is expected to be  
215 especially strong, reveals that failure to consider changes in daily rainfall distributions may  
216 systemically underestimate future recharge. Transformation of the rainfall distribution to  
217 account for changes in rainfall intensity reversed a projected 55% decline in potential  
218 recharge to a 53% increase. Recent multi-model simulations that account for precipitation  
219 intensification<sup>64,65</sup> represent a critical advance in assessing climate change impacts on  
220 groundwater recharge and terrestrial water balances. Under higher atmospheric CO<sub>2</sub>  
221 concentrations, terrestrial plants open their stomata less; this response is projected to  
222 reduce evapotranspiration and increase continental runoff<sup>66</sup>. Recent analyses in Australia<sup>67</sup>  
223 highlight that: (1) greater plant growth (i.e. greater leaf area) can offset reductions in  
224 evapotranspiration through stomatal closure; (2) reduced leaf area due to unfavorable  
225 climate conditions can result in an increase of groundwater recharge even with slightly  
226 decreased rainfall; and (3) changes in rainfall intensity can have a greater impact on recharge  
227 fluxes than rising atmospheric CO<sub>2</sub> concentrations.

228

## 229 **Groundwater Impacts on the Climate System**

230 *Impact of groundwater-fed irrigation on soil moisture.* Groundwater primarily influences  
231 climate through contributions to soil moisture. Irrigation can transform areas from water

232 (soil moisture) -limited to energy-limited evapotranspiration thereby influencing water and  
233 energy budgets. A modeling study<sup>68</sup> showed that during the growing season and averaged  
234 over the continental United States, irrigation increases evapotranspiration by 4%.  
235 Simulations show that rising groundwater-fed irrigation in the High Plains (Fig. 1) over the  
236 20th century increased downwind precipitation by  $\leq 15$  to 30 % in July<sup>69</sup> with associated  
237 increases in groundwater storage and streamflow observed from August to September<sup>70</sup>.  
238 Irrigation in California's Central Valley is shown to strengthen the southwestern U.S.  
239 monsoon increasing precipitation by 15% and discharge of the Colorado River by 30%<sup>71</sup>.  
240 Similar impacts of groundwater-fed irrigation on evapotranspiration and downwind  
241 precipitation have been demonstrated in the Indian monsoon region using a regional climate  
242 model<sup>72</sup>.

243

244 *Representation of groundwater in land-surface models.* Land surface models (LSMs),  
245 embedded in GCMs, have long neglected hydrological processes below the root zone such as  
246 lateral groundwater flow as these have been assumed to be disconnected from the  
247 atmosphere. LSMs were subsequently retrofitted with a simplified formulation of  
248 unconfined groundwater storage changes<sup>73,74</sup>. There have also been attempts to better  
249 represent subsurface processes in LSMs<sup>75</sup> or to couple more complete groundwater models  
250 to LSMs<sup>76</sup>. These efforts led to the discovery of a critical zone of water table depths from 2  
251 to 7 m where groundwater exerts the most influence on land-energy fluxes<sup>77</sup>. Coupling of an  
252 integrated hydrological model to mesoscale atmospheric models<sup>78</sup> revealed clear  
253 connections between water-table depth and development of the atmospheric boundary  
254 layer<sup>79</sup>. Representing groundwater flow in atmospheric models at larger scales and longer  
255 time frames affects land surface moisture states that feed back into regional climate where

256 water tables are relatively shallow<sup>80</sup>. Without a prognostic groundwater reservoir and  
257 explicit groundwater-surface water exchanges in LSMs, we remain unable to represent the  
258 integrated response of the water cycle to human perturbations and climate change. One key  
259 groundwater process missing from LSMs is lateral groundwater flow from high to low  
260 regions. This flow occurs at multiple spatial scales<sup>81</sup> but is fundamentally important at  
261 hillslope (or small model grid) scales in a humid climate or at basin scales in semi-arid and  
262 arid climates with regional aquifers where discharges can be remote from sources of  
263 recharge<sup>82</sup>. Lateral groundwater flow supports persistently wetter river valleys in humid  
264 climates and regional wetlands and oases in arid climates<sup>80</sup> affecting land surface moisture  
265 states and ET fluxes. Groundwater also acts as an important store and vehicle for carbon  
266 though studies accounting for groundwater interactions and feedbacks in the global carbon  
267 budget are still in their infancy<sup>83</sup>.

268

269 *Groundwater and Sea Level Rise.* Coastal aquifers form the interface between the oceanic  
270 and terrestrial hydrological systems and provide a source of water for the more than one  
271 billion people in coastal regions<sup>84</sup>. Global sea-level rise (SLR) of 1.8 mm yr<sup>-1</sup> over the second  
272 half of the twentieth century<sup>85</sup> is expected to have induced fresh-saline water interfaces to  
273 move inland. The extent of seawater intrusion into coastal aquifers depends on a variety of  
274 factors including coastal topography, recharge, and critically groundwater abstraction from  
275 coastal aquifers<sup>86-88</sup>. Analytical models suggest that the impact of SLR on seawater intrusion  
276 is negligible compared to that of groundwater abstraction<sup>89</sup>. The impacts of seawater  
277 intrusion have been observed most prominently in association with intensive groundwater  
278 abstraction around high population densities (e.g. Bangkok, Jakarta, Gaza)<sup>89,90</sup>. Coastal  
279 aquifers under very low hydraulic gradients such as the Asian Mega-Deltas are theoretically

280 sensitive to SLR but, in practice, are expected in coming decades to be more severely  
281 impacted by saltwater inundation from storm surges than SLR<sup>89</sup>.

282 Groundwater depletion contributes to SLR through a net transfer of freshwater from  
283 long-term terrestrial groundwater storage to active circulation near the earth's surface and  
284 its eventual transfer to oceanic stores. The contribution of groundwater depletion to SLR  
285 has, however, been subject of debate. In the IPCC AR4<sup>91</sup>, the contribution of non-frozen  
286 terrestrial waters including groundwater depletion to sea-level variation is not specified due  
287 to its perceived uncertainty. Recently, there has been a series of studies estimating the  
288 contribution of groundwater depletion to SLR<sup>15,92-94</sup>. Current estimates of global  
289 groundwater depletion derived from flux-based (year 2000) and volume-based (period:  
290 2001-2008) methods are summarised in Table 1. Global groundwater depletion ( $204 \pm 30$   
291  $\text{km}^3 \text{ year}^{-1}$ ) estimated by the flux-based method<sup>92</sup>, is based on the difference between grid-  
292 based simulated groundwater recharge and net abstraction (i.e. groundwater withdrawals  
293 minus return flows). This approach overestimates depletion as it does not account for  
294 increased capture due to decreased groundwater discharge and long-distance surface-water  
295 transfers. The volume-based method<sup>93</sup> combines evidence of groundwater storage changes  
296 for the US and another five aquifer systems (Indo-Gangetic Plain, North China Plain, Saudi  
297 Arabia, Nubian Sandstone and North West Sahara) (Fig. 1) and then extrapolates  
298 groundwater depletion elsewhere using the fixed ratio of depletion to abstraction observed  
299 in the US. This approach produces a lower global estimate of groundwater depletion ( $145 \pm$   
300  $39 \text{ km}^3 \text{ year}^{-1}$ ) than the flux-based approach but assumes that the average relationship  
301 between groundwater depletion and abstraction is reasonably approximated by the known  
302 ratio in the US. Both methods reveal that groundwater depletion is most pronounced in Asia  
303 (China, India) and North America (Table 1). The different estimates of global groundwater

304 depletion produce variable estimates of its current contribution to SLR (34% or  $0.57 \pm 0.09$   
305  $\text{mm year}^{-1}$  versus 23% or  $0.4 \pm 0.1 \text{ mm year}^{-1}$ ). Direct observations of groundwater depletion  
306 continue to be hampered by a dearth of ground-based observations that not only limits  
307 understanding of localised groundwater storage changes but also our ability to constrain  
308 evidence from GRACE satellite observations at larger scales ( $\geq 150\,000 \text{ km}^2$ ).

309

### 310 **A look forward**

311

312 Groundwater can enhance the resilience of domestic, agricultural and industrial uses  
313 of freshwater to climate variability and change. As the only perennial source of freshwater in  
314 many regions, groundwater is of vital importance to the water security of many communities  
315 including most critically rural dwellers in low-income countries. Groundwater-fed irrigation  
316 provides a buffer against climate extremes and is consequently essential to global food  
317 security. Further, it serves to alleviate poverty in low-income countries by reducing crop  
318 failure and increasing yields<sup>95</sup>. The value of groundwater is expected to increase in coming  
319 decades as the temporal variability in precipitation, soil moisture and surface water  
320 increases under more frequent and intense climate extremes associated with climate  
321 change<sup>51</sup>. Rises in both absolute groundwater abstractions and groundwater abstractions as  
322 a ratio of total water abstraction threaten to overexploit groundwater resources. This risk is  
323 particularly acute in semi-arid regions where projected increases in the frequency and  
324 intensity of droughts, combined with rising populations and standards of living as well as the  
325 projected expansion of irrigated land, will intensify groundwater demand. To sustain  
326 groundwater use under these conditions will require careful aquifer management<sup>96</sup> that: (1)  
327 is informed by integrated models able to consider the range of interactions between

328 groundwater, climate and human activity summarised here (Fig. 2); and (2) exploits  
329 opportunities for enhanced groundwater recharge associated with less frequent but heavier  
330 rainfall events.

331 A comprehensive management approach to water resources that integrates  
332 groundwater and surface water may greatly reduce human vulnerability to climate extremes  
333 and change, and enable sustainable increases in supply for global water and food security.  
334 Conjunctive uses of groundwater and surface water that employ surface water for irrigation  
335 and water supply during wet periods and groundwater during drought<sup>46</sup>, are likely to prove  
336 essential. Managed aquifer recharge wherein excess surface water and treated wastewater  
337 are stored in depleted aquifers could also supplement groundwater storage for use during  
338 droughts<sup>41,97</sup>. Use of aquifers as natural storage reservoirs avoids many of the problems of  
339 evaporative losses and ecosystem impacts associated with large, constructed surface water  
340 reservoirs. In South Asia for example, intensive groundwater abstraction for dry season  
341 irrigation has induced greater recharge in areas with permeable soils by increasing available  
342 groundwater storage during the subsequent monsoon<sup>98</sup>.

343 Two fundamental impediments to employing the adaptation strategies discussed  
344 above are: (1) availability of groundwater observations to inform them; and (2) existence of  
345 robust integrated models to evaluate their impact. Although we report above on progress  
346 toward the latter, there remains no global programme for the collation of groundwater data.  
347 As a result, the ability in many environments to evaluate fully the responses of groundwater  
348 to climate variability and change, to estimate directly groundwater replenishment, and to  
349 constrain models and satellite observations, is severely impaired. There is, for example, a  
350 profound lack of knowledge regarding the quantity of exploitable groundwater storage in  
351 most aquifers. The equivalent depth of groundwater storage, determined primarily by

352 geology, can vary substantially from regional sedimentary aquifers (>50 m) to small,  
353 discontinuous aquifers in deeply weathered crystalline rock (<1 m) that underlie 40% of sub-  
354 Saharan Africa<sup>99</sup>. Due, in part, to this lack of data globally, groundwater resources continue  
355 to be disregarded in current metrics defining water stress and scarcity despite their strategic  
356 role in ensuring water security.

357

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359

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- 604

605 **Table 1.** Flux-based and volume-based estimates of global and continental-scale  
 606 groundwater depletion ( $\text{km}^3 \text{ year}^{-1}$ ) and their contributions to global sea-level rise ( $\text{mm year}^{-1}$ ).  
 607  
 608

region	flux-based method (ref. 92)*		volume-based method (ref. 93)^	
	gw depletion	sea-level rise	gw depletion	sea-level rise
World	$204 \pm 30$	$0.57 \pm 0.09$	$145 \pm 39$	$0.40 \pm 0.11$
Asia	$150 \pm 25$	$0.42 \pm 0.07$	$111 \pm 30$	$0.31 \pm 0.08$
Africa	$5.0 \pm 1.5$	$0.014 \pm 0.004$	$5.5 \pm 1.5$	$0.015 \pm 0.004$
N. America	$40 \pm 10$	$0.11 \pm 0.03$	$26 \pm 7$	$0.07 \pm 0.02$
S. America	$1.5 \pm 0.5$	$0.0042 \pm 0.0014$	$0.9 \pm 0.5$	$0.002 \pm 0.001$
Australia	$0.5 \pm 0.2$	$0.0014 \pm 0.0006$	$0.4 \pm 0.2$	$0.001 \pm 0.0005$
Europe	$7 \pm 2$	$0.02 \pm 0.006$	$1.3 \pm 0.7$	$0.004 \pm 0.002$

609 *\*year 2000; ^period of 2001 to 2008*  
 610  
 611

612 **FIGURE CAPTIONS:**

613

614 **Figure 1.** Global hydrogeological map simplified from ref. 100 highlighting the locations of  
615 cited regional aquifers systems.

616

617 **Figure 2.** Conceptual representation of key interactions between groundwater and climate.

618

619 **Figure 3.** Anthropogenic groundwater recharge in areas with substantial irrigation by surface  
620 water estimated from the difference between the return flow of irrigation water to  
621 groundwater and total groundwater withdrawals ( $\text{mm yr}^{-1}$ ) for the period 1998 to 2002<sup>(ref. 2)</sup>.

622 Note that in areas with predominantly groundwater-fed irrigation or significant water

623 withdrawals for domestic and industrial purposes, no anthropogenic groundwater recharge

624 occurs; a net abstraction of groundwater leads to groundwater depletion in regions with

625 insufficient natural groundwater recharge.





