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R.G. Taylor, Bridget R. Scanlon, Petra Doll, Matt Rodell, Rens van Beek,
Yoshihide Wada, Laurent Longuevergne

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

3
4 Richard G. Taylor^{1*}, Bridget Scanlon², Petra Döll³, Matt Rodell⁴, Rens van Beek⁵, Yoshihide
5 Wada⁵, Laurent Longuevergne⁶, Marc LeBlanc⁷, James S. Famiglietti⁸, Mike Edmunds⁹,
6 Leonard Konikow¹⁰, Tim Green¹¹, Jianyao Chen¹², Makoto Taniguchi¹³, Marc F.P Bierkens⁵,
7 Alan MacDonald¹⁴, Ying Fan¹⁵, Reed Maxwell¹⁶, Yossi Yechieli¹⁷, Jason Gurdak¹⁸, Diana
8 Allen¹⁹, Mohammad Shamsudduha²⁰, Kevin Hiscock²¹, Pat Yeh²², Ian Holman²³ and Holger
9 Treidel²⁴

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.

¹ Department of Geography, University College London, London, UK * email: r.taylor@geog.ucl.ac.uk

² Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, USA

³ Institute of Physical Geography, University of Frankfurt, Germany

⁴ Hydrological Science Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

⁵ Department of Physical Geography, University of Utrecht, Utrecht, The Netherlands

⁶ Géosciences Rennes, Université de Rennes 1, Rennes, France

⁷ Hydrological Sciences Research Unit, James Cook University, Cairns, Australia

⁸ UC Center for Hydrologic Modelling, University of California, Irvine, California, USA

⁹ School of Geography and the Environment, Oxford University, Oxford, UK

¹⁰ U.S. Geological Survey, Reston, Virginia, USA

¹¹ Agricultural Systems Research Unit, USDA, Fort Collins, Colorado, USA

¹² School of Geography and Planning, Sun Yat-sen University, Guangzhou, China

¹³ Research Institute for Humanity and Nature, Kyoto, Japan

¹⁴ British Geological Survey, Edinburgh, United Kingdom

¹⁵ Department of Earth and Planetary Sciences, Rutgers University, New Jersey, USA

¹⁶ Department of Geology and Geological Engineering, Colorado School of Mines, Golden, Colorado, USA

¹⁷ Geological Survey of Israel, Jerusalem, Israel

¹⁸ Department of Geosciences, San Francisco State University, San Francisco, California, USA

¹⁹ Department of Earth Sciences, Simon Fraser University, Burnaby, British Columbia, Canada

²⁰ Institute for Risk and Disaster Reduction, University College London, London, UK

²¹ School of Environmental Sciences, University of East Anglia, Norwich, UK

²² International Centre for Water Hazard and Risk Management (ICHARM), UNESCO, Tsukuba, Japan

²³ Environmental Science and Technology Department, Cranfield University, Milton Keynes, UK

²⁴ Division of Water Sciences, UNESCO-IHP, Paris, France

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 infrastructure¹. 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, respectively². 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 third³ and fourth⁴ 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^{5,6}. 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 ago⁷⁻¹⁰. 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 place¹¹. 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 (≥ 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 dominated¹². 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 oil¹³.

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^{14,15} range from 13,000 to 15,000 km³ year⁻¹, equivalent
69 to ~30% of the world's renewable freshwater resources¹⁶ or a mean per capita groundwater
70 recharge of 2,100 to 2,500 m³ year⁻¹. 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^{11,17}.

74 Spatial variability in modelled recharge is related primarily to the distribution of
75 global precipitation^{14,15}. 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^{18,19}. 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 km³ from 2000 to 2007 in response to a sharp reduction in recharge²⁰. Heavy
82 rainfall has been found to contribute disproportionately to recharge observed in borehole
83 hydrographs from tropical Africa^{18,21}. Further, recharge in semi-arid environments is often
84 restricted to statistically extreme (heavy) rainfall^{14,22} that commonly generates focused
85 recharge beneath ephemeral surface water bodies^{17,18,23}. 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 countries²⁴.
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 surplus²⁵.

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^{26,27} 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^{28,29} (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 species²⁹. 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 baseflow³⁰. 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 precipitation³¹. In permafrost regions where
108 recharge is currently ignored in global analyses¹⁴, coupling between surface water and
109 groundwater systems may be particularly enhanced by warming³². In areas of seasonal or
110 perennial ground frost, increased recharge is expected even though the absolute snow
111 volume decreases³³.

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 20th 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 ponds³⁴. Much earlier in the 20th 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 profiles¹¹. In both regions, recharge rates under
125 cropland increased by about an order of magnitude³⁵⁻³⁷.

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 use². 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 Plain³⁸, NW India³⁹, US High Plains^{40,41} but also in
135 humid environments of Brazil⁴² and Bangladesh⁴³ (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 km³, a volume that is equivalent to the storage capacity of Lake Mead,
141 the largest surface reservoir in the USA^{44,45}. 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 modelling² 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 m⁴⁶. 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^{47,48}.

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)⁴⁹ 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^{50,51}. 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^(ref. 52). Projected increases in irrigation demand in
165 southern Europe will serve to stress further limited groundwater resources⁵³. Persistent
166 droughts projected in the California Central Valley over the latter half of the 21st century are
167 predicted to trigger a shift from predominantly surface water to groundwater supply for
168 agriculture⁵⁴. Increased groundwater abstraction combined with reduced surface water
169 flows associated with intermittent droughts during the first half of the 21st 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 precipitation⁴⁹. 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^{50,55}. 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 USA¹⁶. 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 2050s¹⁶.

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 median⁵⁵. 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 signal⁵⁶. 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 models⁵⁷. 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%⁵⁸. In southern British Columbia, recharge projections for the
204 2080s range from -10 % to +23 % relative to historical recharge⁵⁹. 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, respectively⁶⁰. Uncertainty from

208 downscaling can be greater than uncertainty due to the choice of applied emissions
209 scenarios^{61,62}.

210 Current projections of groundwater recharge under climate change commonly do not
211 consider the intensification of precipitation and CO₂-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 tropics⁶³ 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^{64,65} represent a critical advance in assessing climate change impacts on
220 groundwater recharge and terrestrial water balances. Under higher atmospheric CO₂
221 concentrations, terrestrial plants open their stomata less; this response is projected to
222 reduce evapotranspiration and increase continental runoff⁶⁶. Recent analyses in Australia⁶⁷
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 CO₂ 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 study⁶⁸ 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 ≤ 15 to 30 % in July⁶⁹ with associated
237 increases in groundwater storage and streamflow observed from August to September⁷⁰.
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%⁷¹.
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 model⁷².

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^{73,74}. There have also been attempts to better
249 represent subsurface processes in LSMs⁷⁵ or to couple more complete groundwater models
250 to LSMs⁷⁶. 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 fluxes⁷⁷. Coupling of an
252 integrated hydrological model to mesoscale atmospheric models⁷⁸ revealed clear
253 connections between water-table depth and development of the atmospheric boundary
254 layer⁷⁹. 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 shallow⁸⁰. 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 scales⁸¹ 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 recharge⁸². Lateral groundwater flow supports persistently wetter river valleys in humid
264 climates and regional wetlands and oases in arid climates⁸⁰ 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 infancy⁸³.

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 regions⁸⁴. Global sea-level rise (SLR) of 1.8 mm yr⁻¹ over the second
272 half of the twentieth century⁸⁵ 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 aquifers⁸⁶⁻⁸⁸. Analytical models suggest that the impact of SLR on seawater intrusion
276 is negligible compared to that of groundwater abstraction⁸⁹. 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)^{89,90}. 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 SLR⁸⁹.

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 AR4⁹¹, 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^{15,92-94}. 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 ± 30
291 $\text{km}^3 \text{ year}^{-1}$) estimated by the flux-based method⁹², 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 method⁹³ 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 ± 0.09
305 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 yields⁹⁵. 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 change⁵¹. 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 management⁹⁶ 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 drought⁴⁶, 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^{41,97}. 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 monsoon⁹⁸.

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 Africa⁹⁹. 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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- 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 (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 ± 30	0.57 ± 0.09	145 ± 39	0.40 ± 0.11
Asia	150 ± 25	0.42 ± 0.07	111 ± 30	0.31 ± 0.08
Africa	5.0 ± 1.5	0.014 ± 0.004	5.5 ± 1.5	0.015 ± 0.004
N. America	40 ± 10	0.11 ± 0.03	26 ± 7	0.07 ± 0.02
S. America	1.5 ± 0.5	0.0042 ± 0.0014	0.9 ± 0.5	0.002 ± 0.001
Australia	0.5 ± 0.2	0.0014 ± 0.0006	0.4 ± 0.2	0.001 ± 0.0005
Europe	7 ± 2	0.02 ± 0.006	1.3 ± 0.7	0.004 ± 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.

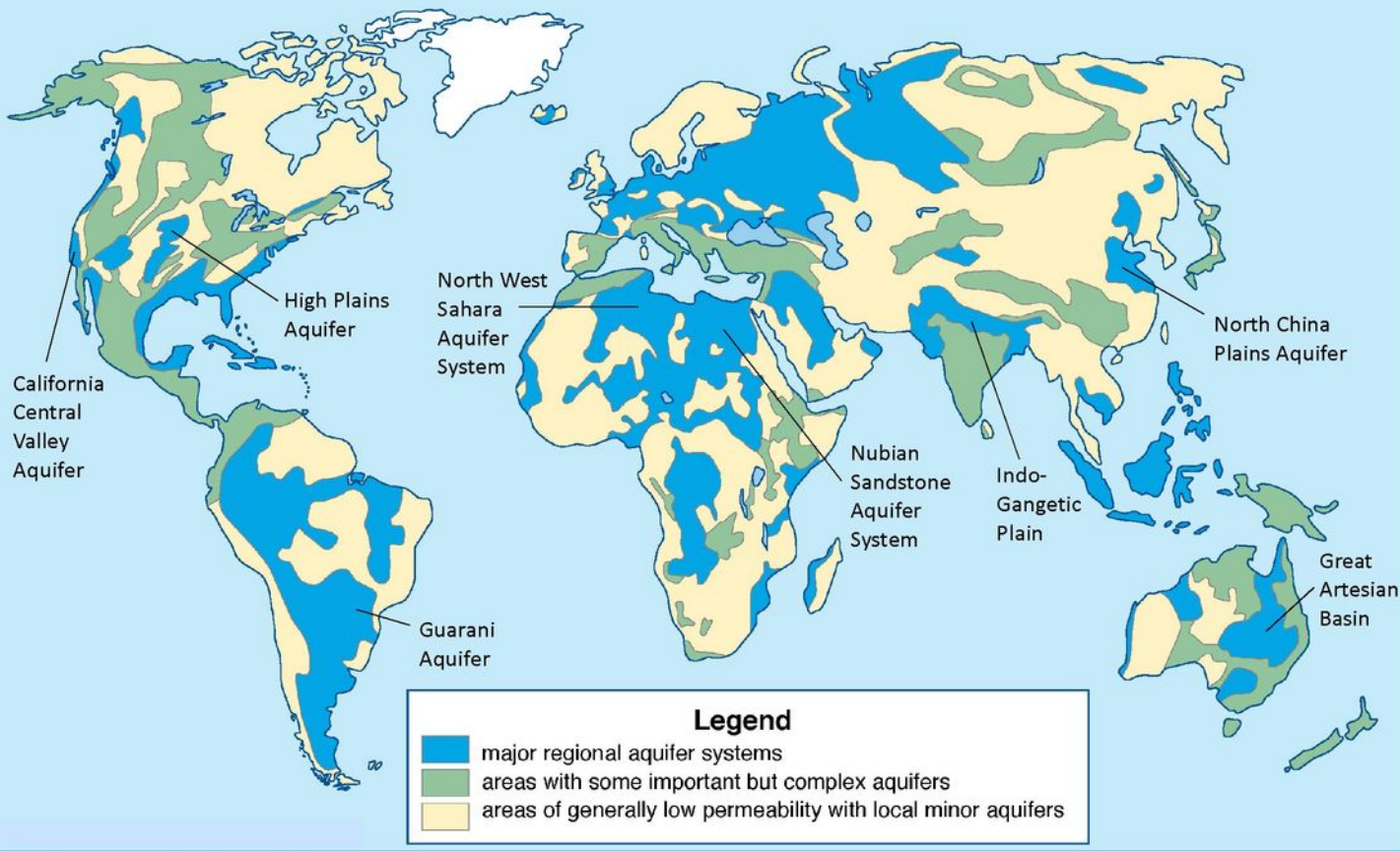
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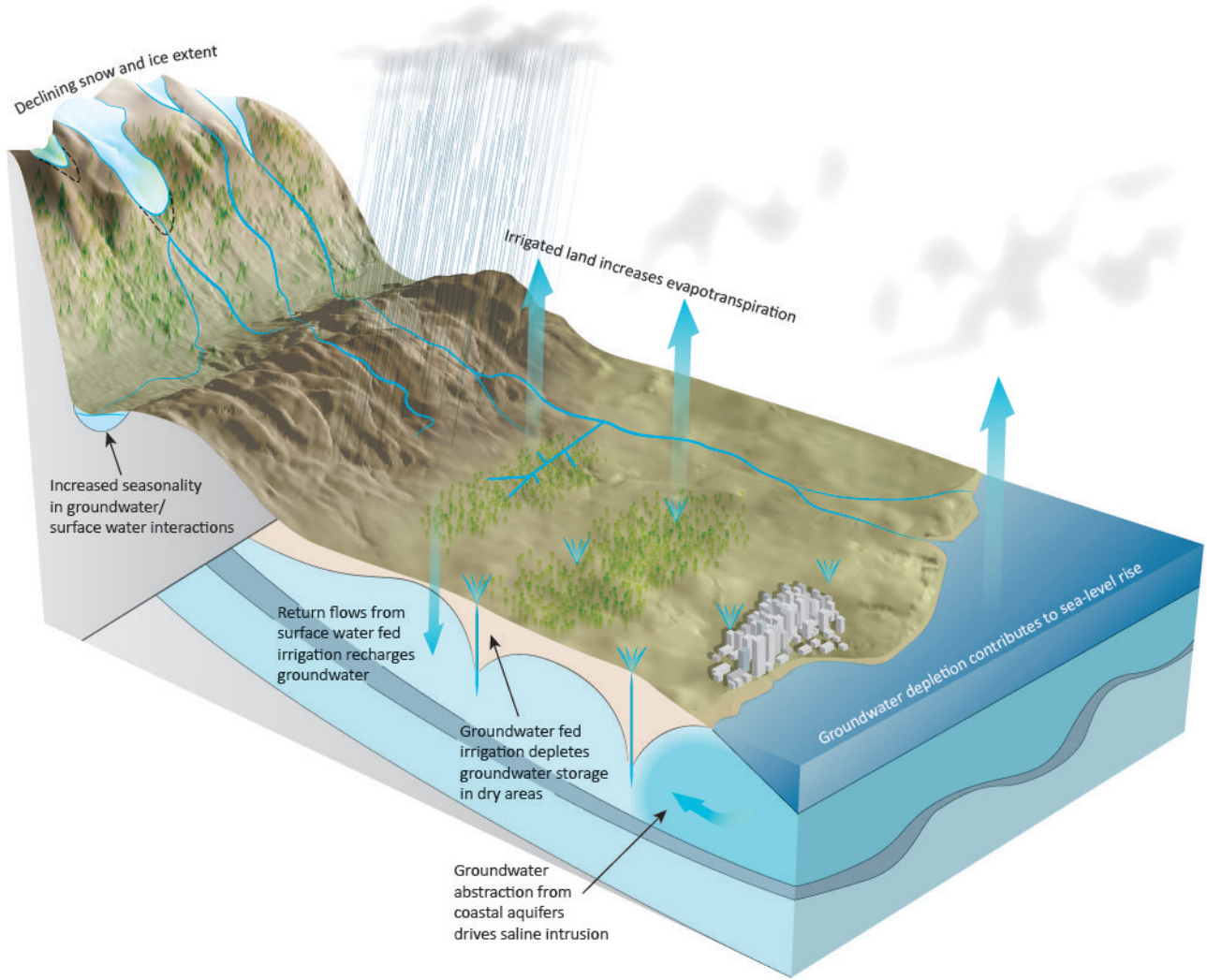
617 **Figure 2.** Conceptual representation of key interactions between groundwater and climate.

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 (mm yr^{-1}) for the period 1998 to 2002^(ref. 2).

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.





Declining snow and ice extent

Irrigated land increases evapotranspiration

Increased seasonality in groundwater/surface water interactions

Return flows from surface water fed irrigation recharges groundwater

Groundwater fed irrigation depletes groundwater storage in dry areas

Groundwater abstraction from coastal aquifers drives saline intrusion

Groundwater depletion contributes to sea-level rise

