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1 Water Security, Global Change and Land-Atmosphere Feedbacks

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5 Summary

6 Understanding the competing pressures on water resources requires detailed knowledge of the future
7 water balance under uncertain environmental change. The need for a robust, scientifically rigorous
8 evidence base for effective policy planning and practice has never been greater. Environmental
9 change includes, but is not limited to, climate change; it also includes land-use and land-cover
10 change, including deforestation for agriculture, and occurs alongside changes in anthropogenic
11 interventions which are used in natural resource management such as the regulation of river flows
12 using dams, which can have impacts which frequently exceed those arising in the natural system.

13 In this paper we examine the role that land-surface models can play in providing a robust scientific
14 basis for making resource management decisions against a background of environmental change. We
15 provide some perspectives on recent developments in modeling in land-surface hydrology. Amongst
16 the range of current land-surface and hydrology models there is a large range of variability, which
17 indicates that the specification and parameterization of several basic processes in the models can be
18 improved. Key areas which require improvement in order to address hydrological applications
19 include: (i) the representation of groundwater in models, particularly at the scales relevant to land-
20 surface modelling, (ii) the representation of human interventions such as dams and irrigation in the
21 hydrological system, and (iii) the quantification and communication of uncertainty, (iv) improved

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3 22 understanding of the impact on water resources availability of multiple use through treatment,
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5 23 recycling and return flows (and the balance of consumptive and conservative uses).
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9 24 Through a series of examples, we demonstrate that changes in water use could have important
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11 25 reciprocal impacts on climate over a wide area. The effects of water management decisions on
12
13 26 climate feedbacks are only beginning to be investigated – they are still only rarely included in
14
15 27 climate impact assessments – and the links between the hydrological system and climate are rarely
16
17 28 acknowledged in studies of ecosystem services. Nevertheless, because water is essential not only for
18
19 29 its direct uses but also for the indirect functions that it serves (including food production, fisheries,
20
21 30 and industry), it is vital that these connected systems are studied. Building on the examples above,
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23 31 we highlight recent research showing that assessment of these trade-offs is particularly complex in
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25 32 wetland areas, especially in situations where these trade-offs play to the advantage of different
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27 33 communities.
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32 34 **Keywords** water security, climate change, land use, feedbacks, global hydrological models,
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35 35 uncertainty
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38 36 **1 Introduction**

39 37 **1.1 Biophysical drivers of water security**

40 38 Understanding the biophysical drivers of water security requires detailed knowledge of the future
41
42 39 distribution of water in the Earth system under uncertain environmental change. The need for a
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44 40 robust, scientifically rigorous evidence-base for effective policy planning and practice has never
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46 41 been greater (Grey *et al.*, this volume), but several key challenges remain in our understanding of the
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48 42 representation of interactions between climate, ecological processes, land-use, and water availability
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50 43 for human activities. Evidence from field observations, Earth observation and models accumulated
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3 44 over the past twenty years points to the operation of key feedback processes in the Earth system,
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5 45 which complicate any attempt to understand the impact of one isolated change in climate, land use or
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7 46 water management. A change in the distribution of water caused by any one of these processes may
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10 47 have a subsequent impact on the other processes. Through a series of recent examples, we consider
11
12 48 the consequences of these findings for water management and water security.

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15 49 One of the greatest challenges faced by water managers is the need to secure the sustainability of
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17 50 supply under climate scenarios that involve changes in the relative frequency of rainfall events of
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19 51 different magnitude (1). Uncertainties associated with the rainfall response to climate change are
20
21 52 widely acknowledged (2-4). These uncertainties are compounded when predictions of river flow are
22
23 53 required because the land-surface adds complexity through its control on evaporation, soil moisture,
24
25 54 and groundwater recharge. The loss due to evaporation is often equally uncertain due to its reliance
26
27 55 on proper characterization of the land-surface and the processes through which vegetation modulates
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29 56 the water vapour flux to the atmosphere, especially under conditions of climate change (e.g., 5). The
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31 57 resulting difference represents the surface water balance: i.e., the amount of water remaining after
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33 58 the evaporative demands of the vegetated land-surface have been taken into account.

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39 59 There is wide recognition that the Earth's natural ecosystems deliver important goods and services to
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41 60 mankind (6, 7). Whilst the literature includes some contradictory conclusions on the precise nature of
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43 61 regulatory services of ecosystems on the hydrological cycle, particularly forests (8, 9) and wetlands
44
45 62 (10), there is broad agreement on importance of maintaining sufficient water to these ecosystems
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47 63 (generally termed environmental flows) to sustaining biodiversity and ecosystem integrity (11, 12).
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49 64 There is thus an important feedback loop between ecosystems and the water cycle that needs to be
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51 65 understood and quantified to ensure water security (Figure 1).
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66 1.2 Integrated data and model analyses

67 The knowledge of the components of the global water cycle is an essential prerequisite of any
68 analysis of water security. Such information is required on a range of time and space scales. For a
69 global or continental basin scale a 50 km (or 0.5 degree) scale is a useful compromise to provide
70 large-scale resource assessment and to link with climate models for analyses of the future.
71 Nevertheless a number of uncertainties are associated with this choice of model resolution: such a
72 scale cannot capture features such as localised flooding and local interventions but can capture large
73 scale flooding and droughts. Daily information is of great value to assess flooding and droughts and
74 to feed into hydrological and land surface models, but sub-daily data would be required in order to
75 assess local and regional features.

76 Of the main components of the water cycle only precipitation and runoff are measured and collated
77 systematically at a global scale and even then there are many gaps. Other components and stores,
78 such as evaporation, soil moisture and groundwater are measured only sporadically, often using
79 inconsistent techniques. One of the most comprehensive sets of precipitation data is that from the
80 Global Precipitation Climatology Centre¹ (GPCC; 13). These gridded data are provided monthly on a
81 0.5 or 1.0 degree grid. Two datasets are provided; first, the monitoring product is available for the
82 period 1986–present, based on quality-controlled data from 7,000 stations; second, the Full Data
83 Product is available for the period 1951–2004 and is based on quality-controlled data from a larger
84 number of stations (up to 43,000) with irregular coverage in time. The reliability of these global
85 gridded datasets has been questioned, especially over the tropics, deserts, mountain ranges, and large
86 parts of the Asian continent because of the sparse spatial distribution of measurement stations,
87 exacerbated by their decreasing number in recent decades (14). Some of these gaps are being filled

¹ http://www.esrl.noaa.gov/psd/data/gridded/data_gpcc.html

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3 88 with satellite data arising from the Global Precipitation Climatology Project (GPCP; 15) but there
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5 89 remain significant problems, particularly in mountainous areas.
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8 90 The Global Runoff Database held at the Global Runoff Data Centre² (GRDC) contains river
9
10 91 discharge data collected at daily or monthly intervals from more than 8,000 stations in 157 countries.
11
12 92 This adds up to around 320,000 station-years with an average record length of 40 years. The
13
14 93 monthly data sets have a good global coverage although many data sets are not current and finish
15
16 94 prior to 1980. These data are also available as a global interactive map at the GWSP water atlas map
17
18 95 ³. Stahl *et al.* collated a daily stream flow data set from over 400 small, semi-natural basins from the
19
20 96 European Water Archive and elsewhere specifically to investigate change in extremes across Europe
21
22 97 and even within Europe there were significant difficulties in accessing data from some countries
23
24 98 (16). Estimates of Global average land evapotranspiration range between 1.1 and 2.0 mm day⁻¹, with
25
26 99 an ensemble mean of approximately 1.5 mm day⁻¹. Thus there is considerable variability both within
27
28 100 the observationally-based estimates and between these estimates model based reanalyses, and IPCC
29
30 101 AR4 climate simulations (17). The best estimates of evapotranspiration are made using eddy
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32 102 covariance techniques, but these are available only at a limited set of stations. The FLUXNET⁴
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34 103 project gathers over 500 such stations but the geographical coverage is patchy and many stations
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36 104 have records covering only a few years. A number of initiatives have produced global land
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38 105 evapotranspiration maps based on FLUXNET data, Earth observations, models, or a combination of
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40 106 these sources⁵.
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47 107 Soil moisture plays a critical role in land-atmosphere interactions, both as a store of water and as a
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49 108 control on both evaporation and runoff. Whilst there are a few regions with substantial *in situ* soil
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53 ² <http://www.bafg.de/GRDC>

54 ³ <http://atlas.gwsp.org>

55 ⁴ <http://fluxnet.ornl.gov/>

56 ⁵ <http://www.iac.ethz.ch/groups/seneviratne/research/LandFlux-EVAL>

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3 109 water observations (18), the coverage of these observations is patchy and there is no consistency over
4
5 110 methodology or depth. Global coverage is possible with microwave satellite sensors (e.g., AMSR-E,
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7 111 SMOS and ASCAT) however the measurements cover only the top few centimetres of soil and the
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9 112 influence of vegetation cover poses additional difficulties in interpretation (19). Soil moisture levels
10
11 113 can be calculated from land surface and hydrological models although every model treats soil
12
13 114 moisture differently and so interpretation and comparison are difficult.

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18 115 Groundwater is the world's largest accessible store of freshwater and contributes 42% of the water
19
20 116 used for irrigation, 36% of household water consumption and 27% of water demand for
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22 117 manufacturing (20). A number of studies have estimated groundwater recharge and depletion
23
24 118 globally (21, 22) using hydrological models, demonstrating the continuing depletion of groundwater
25
26 119 resources. These estimates contain many uncertainties, not the least the uncertainties in evaporation
27
28 120 estimates discussed above and difficulties in modelling ground water recharge in semi-arid regions
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30 121 (22), highlighting the continuing need for regional observations of groundwater to validate these
31
32 122 estimates. The WHYMAP initiative has provided global maps of aquifer properties and the Global
33
34 123 Groundwater Archive an important initiative to collect groundwater data, however progress is slow
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36 124 in collecting data (23). Meanwhile the GRACE satellite has provided considerable insight into
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38 125 dynamic changes in groundwater globally at large scale, highlighting rapid depletion in groundwater
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40 126 storage in India, USA and elsewhere (24, 25).

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46 127 Land surface and global hydrology models provide an alternative approach to the global estimation
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48 128 of components of the terrestrial water cycle (26). The *WATCH Forcing Data* provides a single global
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50 129 data set of the climate variables required to drive hydrological models, which covers the period
51
52 130 1901–2001. It has been produced by combining the Climatic Research Unit's monthly observations
53
54 131 of temperature, 'wet days' and cloud cover, plus the GPCCv4 monthly precipitation observations,
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56 132 and the ERA40 reanalysis products (with the addition of corrections for varying atmospheric
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3 133 aerosols to adjust the solar radiation). The *WATCH Driving Data* covers the period 2001–2100 and
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5 134 has been generated using three well-established climate models that have been downscaled and bias
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7 135 corrected. Each model was run for two different IPCC scenarios, giving six data subsets within the
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10 136 driving data. All of the forcing and driving data sets cover the land surface of the Earth on a 0.5
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12 137 degree grid (27).

138 **1.3 Anthropogenic interventions in the water cycle**

139 Whilst physical science can provide important information on the availability of water in the future,
140 the role of changing anthropogenic intervention is often as critical in developing scenarios of change
141 in freshwater systems (28, 29). Anthropogenic interventions that form part of natural resource
142 management include the regulation of river flows using dams, artificial abstraction from surface or
143 groundwater stores, and the use of water from a range of sources for irrigation. The sustainability of
144 anthropogenic demands on water resources under scenarios of climate and land-use change is a
145 serious question for water managers and decision makers.

146 Several recent studies have indicated that anthropogenic water demand is often equivalent in
147 magnitude to the natural components of the water balance (30, 31). The consequences of this
148 situation are particularly acute in river basins where a considerable fraction of the renewable flow of
149 the river is abstracted for human use (e.g., Colorado, Murray-Darling (30)) or in locations where the
150 rate of groundwater abstraction exceeds the rate of recharge (e.g., United States High Plains Aquifer
151 (32); north-western India (24)). The increasing importance of abstraction raises two questions: (i)
152 what is the consequence of large-scale geophysical changes in climate and land-use on the
153 sustainability of anthropogenic modifications to the water budget; and conversely (ii) what are the
154 consequence of large scale alterations to the management of the land-surface on the climate system?

155 **1.4 Water security and global environmental change**

156 The scope of environmental changes that have driven the availability of water resources in the past is
157 broad. Recent debate has stressed that whilst the evidence for anthropogenic climate change is
158 unequivocal, the effect on precipitation, especially precipitation extremes, is less certain. Overall
159 precipitation is expected to increase with increasing temperatures (3). There will, however, be large
160 regional variations, with the sub-tropics becoming drier and high latitudes wetter – a feature broadly
161 observed in recent decades (see e.g., 2, 4, 33). Precipitation extremes are also likely to increase and
162 again increasing extreme rainfall is observed in most regions of the world (5). Many regions of the
163 world, however, do not have sufficiently long or detailed records to come to definite conclusions.
164 This is particularly true of sub daily records (e.g., 4). Nevertheless, whilst it is an important driver of
165 global change, climate change is not the only factor in play. Land cover change, sea level shifts, and
166 anthropogenic interventions have in the past influenced water resource availability either because
167 they directly affect the availability of water at the surface (for example changes in latent heat flux
168 due to altered tropical vegetation (34, 35) and the direct effects of vegetation on albedo in northern
169 latitudes (36)) or because they control the quality of available water supplies. The role played by
170 complex spatial heterogeneity in land-cover change also remains a key unknown in quantifying the
171 local response to environmental change.

172 These drivers of global change have received global attention through initiatives equal in scope and
173 in profile to the IPCC (37-39), including the United Nations Environment Programme GEO-5
174 Assessment (40), the Millennium Ecosystem Assessment (41), and the International Geosphere-
175 Biosphere Programme (IGBP; 34). The emphasis on joint drivers of change in different spheres of
176 the Earth system has prompted calls for multi- and inter-disciplinary evaluations of the joint,
177 interacting effects of changes in components of the Earth system (42-45).

178 1.5 Uncertainty

179 The quantification of uncertainty has received much attention across a range of geophysical
180 academic disciplines and in wider discussion with social researchers and policymakers (37-39). This
181 engagement with uncertainty has a long tradition that has developed from a straightforward
182 evaluation of the range of outcomes predicted by different climate models to a series of designed
183 model experiments designed to span the range of possible radiative forcing and model formulations
184 (46-48). The more recent use of perturbed-physics ensembles has permitted a focus on the key
185 processes that contribute most clearly to uncertainty in model predictions (49-51). Improved
186 knowledge of these processes is widely expected to yield reductions in model uncertainty (52). It is,
187 true however, that increasing the number of processes within models also tends to increase the
188 uncertainty range.

189 Model uncertainty exists alongside internal variability and scenario uncertainty. The relative
190 importance of particular sources of uncertainty varies in important ways with the time-scale of
191 prediction required. Weather forecasts and seasonal predictions are influenced to a great extent by
192 internal variability and initial condition uncertainty. By contrast, multi-decadal predictions (out to
193 2100, for example) are dominated by scenario uncertainty, with decadal climate predictions
194 controlled by a balance of model and scenario uncertainty (52).

195 Whilst model inter-comparisons have been commonplace in climatology (for example C4MIP and
196 PILPS), recent work under the auspices of WaterMIP has brought a similar approach to the study of
197 hydrological responses to climate change. The WaterMIP project used the WATCH Forcing Data to
198 provide a consistent comparison of eleven land surface and hydrology models (53). All models were
199 run for a 15-yr period (1985–99). Simulated global terrestrial evapotranspiration, excluding
200 Greenland and Antarctica, ranged from 415 to 586 mm yr⁻¹ (1.2 to 1.6 mm d⁻¹) and simulated runoff

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3 201 from 290 to 457 mm yr⁻¹. Both the mean and median runoff fractions for the land surface models
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5 202 were lower than those of the global hydrological models. Significant differences between land
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7 203 surface and global hydrological models were attributed to differences between the snow schemes,
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9 204 which are typically physically-based energy balance models in land-surface simulations but which in
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11 205 large-scale hydrology models are usually based on a more empirical degree-day approach. Some
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13 206 differences in simulated runoff and evapotranspiration can be explained by model parameterizations,
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15 207 although the processes included and parameterizations used are not distinct to either land surface
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17 208 models or global hydrological models. The results of this study show that differences between
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19 209 models are a major source of uncertainty (Figure 2) and climate change impact studies need to use
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21 210 not only multiple climate models but also some other measure of uncertainty (e.g., multiple impact
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23 211 models). It is also clear that significant improvements in process representation could improve
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25 212 model results and reduce uncertainty.
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31 213 A comparison of WaterMIP simulations against a dataset of European stream flows (16) revealed
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33 214 large uncertainties in the individual models' abilities to simulate the amplitude and timing of the
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35 215 mean runoff cycle however the ensemble mean yielded rather more robust results (54). Some serious
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37 216 variations and shortcomings were revealed in the ways the models handled the timing of snow
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39 217 accumulation and melt. In a subsequent study using the same data to simulate high and low flow
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41 218 events a subset of three models (JULES, MPI-HM and WaterGap) reproduced the broad spatio-
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43 219 temporal evolution of hydrological extremes in Europe, but the reproduction of variability and spatial
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45 220 coherence of low and high flows was found to be variable (55). Some systematic weaknesses
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47 221 emerged in all models, in particular for high flows, which could be a product of poor spatial
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49 222 resolution of the input climate data (e.g., where extreme precipitation is driven by local convective
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51 223 storms or topography). In addition to model uncertainties there are considerable uncertainties
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53 224 associated with input variables, particularly rainfall, which can be substantial (56, 57).
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3 225 There are many uncertainties within our assessment of the physical water system including our
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5 226 understanding of past changes, our simulation of the components of the water cycle and our
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7 227 predictions of the future. The Global Energy and Water Cycle Experiment (GEWEX) has recently
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9 228 identified four Grand Science Challenges covering: observations and predictions of precipitation,
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11 229 global water resource systems, changes in extremes and the water and energy cycles to focus the
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13 230 efforts of the science community⁶. It is clear that improvements will come with better data and
14
15 231 enhanced integration of models and data. It is also clear from the inter-comparison studies that there
16
17 232 is considerable scope to improve land surface and global hydrological models, particularly with
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19 233 better representation of snow and storages, such as groundwater and soil water.
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24 234 **2 Hydrological feedbacks in the Earth system**

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28 235 Internal feedbacks frequently arise within complex, interconnected environmental systems (see (58)
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30 236 for some recent examples). The presence of feedbacks alongside external drivers adds an extra set of
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32 237 scientific questions to those that are usually considered in impacts assessments, because models of
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34 238 systems that include feedbacks must include explicit representation of the connections between the
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36 239 hydrosphere, lithosphere and biosphere.
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40 240 Feedbacks between the land surface and the atmosphere occur at many scales. At the local or patch
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42 241 scale (1 to 10 km) a patch of irrigated land or forest may influence the local temperature and
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44 242 humidity through changes in water availability and roughness which will in turn feedback on the
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46 243 evaporative demand. At a regional scale (up to a few hundred kilometers) changes in the land
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48 244 surface may not only influence local temperature and humidity but may also change local cloud
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50 245 amounts (hence radiation inputs, (59)) and generate local atmospheric circulations, with the
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52 246 possibilities of the initiation of convective rainfall systems (60, 61). At continental scales a changing
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57 ⁶ http://www.gewex.org/pdfs/grand_challenges_7-2012.pdf
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3 247 land surface can in principle change large-scale atmospheric circulation, such as the monsoon (e.g.,
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5 248 62) The influence of land surface not only depends on scale but also the hydro-climatology of a
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7 249 region, thus Koster *et al.* found geographical hotspots of the interaction between soil moisture and
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9 250 rainfall concentrated in semi-arid regions where the contrasts in soil moisture are likely to be large
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11 251 (63).

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15 252 While large numbers of studies suggest a strong interaction between the land surface and climate the
16
17 253 majority of these studies rely on numerical models. The LUCID project (34) has addressed the
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19 254 robustness of estimates of biogeophysical impacts of historical land use change. An analysis of seven
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21 255 coupled land surface/climate models generally showed significant reduction in available energy and
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23 256 cooling in regions where forest cover had been replaced by agriculture but few significant or
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25 257 consistent changes in precipitation (34). This result mirrors that of Koster *et al.* who found a
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27 258 considerable variation in the strength of land surface coupling in the climate models used (63).

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32 259 Below we present a number of recent examples illustrate the emerging control exerted by land-
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34 260 atmosphere feedbacks on water availability.

35 36 37 38 261 **2.1 Feedbacks from irrigation**

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42 262 Looking more deeply at the impact of anthropogenic demands on water, evidence has emerged in the
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44 263 past decade pointing towards the considerable impact that anthropogenic interventions in the water
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46 264 cycle such as irrigation, groundwater abstraction, and surface water management can have on
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48 265 regional climatological patterns. A recent historical evaluation of the effect of representing irrigation
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50 266 in a climate model has demonstrated that in the twentieth-century irrigation has led to a significant
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52 267 reduction in temperature trends in the Boreal summer over irrigated regions, with consequent
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54 268 increases in precipitation as a result of the additional water vapour flux to the atmosphere (64). A
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56 269 striking example of this effect is the finding that the extra water added to the land surface as a result
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3 270 of widespread irrigation in India has reduced the land-sea temperature gradient and altered the
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5 271 circulation pattern of the south Asian summer monsoon itself (62). The consequences of these
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7 272 connections between water resource management and global climate suggest hitherto unexplored
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10 273 possibilities that water management strategies in one region might affect climate in another and
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12 274 motivate an urgent need to represent water management in Earth system models (20, 31, 65).

13 14 15 275 **2.2 Wetland inundation and cloud feedbacks**

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19 276 The availability of water at the surface has the potential to alter fluxes of heat and moisture to the
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21 277 atmosphere and, in areas where convection is limited by water availability such as the transition
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23 278 zones between semi-arid and wetter climates, can be an important control on meso-scale convection
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26 279 (5, 63). The role of land-atmosphere feedbacks in modifying the climate, and climate impacts is
27
28 280 particularly evident in the Niger inland delta, where observed river gauging data show significant
29
30 281 evaporative losses from the land and water surface (66). Adding a sub-grid-scale parameterization of
31
32 282 overbank inundation to the JULES land-surface model enables the salient features of the observed
33
34 283 inundation pattern to be reproduced, and reveals that significant evaporative losses from the
35
36 284 inundated region account for a doubling in the total land-atmosphere water flux during periods of
37
38 285 greatest flooding. Moreover, the suppression of sensible heat flux establishes a hypothesized
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40 286 “wetland breeze” effect, which promotes the daytime initiation of convective storms and generates a
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42 287 series of long-lived meso-scale convective systems, which have the possibility of impacting on the
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44 288 rainfall in the surrounding region (Figure 3; (67)).

45 46 47 48 49 289 **2.3 Heat waves and drought**

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53 290 Spatial and temporal patterns of water availability greatly affect the resilience of water resource
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55 291 systems (Grey et al., this volume). The global spatial synchronicity of drought, shown for summer
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57 292 1976 in Figure 4, (68), alters the ways in which water managers, insurers and civil contingencies

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3 293 planners might respond given that events such as the ensuing 1976 drought are not isolated in space
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5 294 nor independent in time. The majority of recent European summer heat waves (1976, 1994, 2003,
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7 295 2005) have been linked to negative soil moisture anomalies during the preceding spring which lead
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9 296 to reduced latent heat fluxes and therefore greater surface warming in the subsequent summers (69).
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11 297 The interactions between soil moisture and temperature are thought to account for over half of the
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13 298 days with extreme temperatures during these periods (69) and one recent estimate, made using a
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15 299 large ensemble of simulations, suggests that the risk of such heat waves has been doubled as a result
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17 300 of anthropogenic emissions of carbon dioxide (70).
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22 301 Taken together, the examples cited above which document the importance of climate feedbacks
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24 302 between soil moisture and persistence of low rainfall demonstrate that changes in the distribution of
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26 303 water at the surface as a result of human interventions could in fact have important reciprocal
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28 304 impacts on climate over a wide area. The effects of water management decisions on climate
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30 305 feedbacks are only beginning to be investigated – they are still only rarely included in climate impact
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32 306 assessments – and the links between the hydrological system and climate are rarely acknowledged in
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34 307 studies of ecosystem services. It is clear that interactions between hydrology and climate occur on
35
36 308 many space and time scales, involve a whole range of processes, and are incompletely represented
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38 309 within land surface and climate models. Nevertheless, because water is essential not only for its
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40 310 direct uses but also for the indirect functions that it serves (including food production, fisheries, and
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42 311 industry), it is vital that these connected systems are studied.
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48 312 **3 Water security, ecosystem services, and environmental flows**

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52 313 The previous sections have focused on the importance of feedbacks in land-atmosphere interactions
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54 314 for water security. A further crucial feedback process occurs across the landscape between
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56 315 ecosystems (terrestrial, wetland and aquatic) and water resources. Figure 5 depicts the role of
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3 316 ecosystems influencing the hydrological cycle to support water security on which many ecosystem
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5 317 services are based, and emphasizes the importance of maintaining environmental flows to conserve
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7 318 ecosystem functions. The exploitation of ecosystem services presents an additional feedback loop.
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9 319 For example, wise use of wetland resources (71) such as sustainable fisheries supports food security
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11 320 without degrading the ecosystem. In contrast, exploiting water resources to generate hydropower by
12
13 321 building a dam can negatively impact on the river ecosystem and loss of fisheries, presenting a trade-
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15 322 off as demonstrated in the River Mekong (72).

323 3.1 Ecosystem services

24 324 The UNCED Conference in Rio in 1992 was an important turning point in modern thinking; it raised
25
26 325 to a global political level the view that the lives of people and the environment are profoundly inter-
27
28 326 linked. Ecological processes keep the planet fit for life providing our food, air to breathe, medicines
29
30 327 and much of what we call “quality of life” (73). Freshwater ecosystems provide economic security
31
32 328 (e.g., fish, plant foods and medicines, timber); social security (e.g., protection from natural hazards,
33
34 329 such as floods); and ethical security (e.g., upholding the rights of people and other species to
35
36 330 water;(73)). Water used for economic growth (i.e., for drinking, growing food, generating power and
37
38 331 supporting industry) has been viewed as water directly for people, whilst water for ecosystems has
39
40 332 been considered as water indirectly for people through the goods and services they deliver (74). This
41
42 333 idea attempted to counter the notion of conflict in water resource allocation that water was either for
43
44 334 people or nature. Despite this, the Millennium Ecosystem Assessment (MEA; 41) showed that many
45
46 335 ecosystems were being degraded or lost, with aquatic systems suffering particularly from abstraction
47
48 336 or diversion often associated with dams (31, 72, 75, 76). The MEA used the concept of ecosystem
49
50 337 services, which developed largely through wetland research (71), to demonstrate the value of nature
51
52 338 and its contribution to social and cultural well-being (7).

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3 339 **3.2 Environmental flows**
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6 340 The idea for environmental water needs began in the 1940s, in the western USA (77) with rapid
7
8 341 methodological development during the 1970s (78-80) in parallel with changes in legislation. The
9
10 342 UK Water Resources Act 1963 stated that minimum acceptable flows were required to maintain
11
12 343 natural beauty and fisheries and the Clean Water Act in the USA in 1972 set the objective of
13
14 344 restoring and maintaining the chemical, physical, and biological integrity of the nation's waters.
15
16 345 However it is in South Africa that the law most explicitly recognises that the highest priority for
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18 346 water should be for the environment, after basic human needs (81). In particular, South Africa
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20 347 recognised the crucial feedback between water and wetlands. Many countries, including Tanzania
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22 348 and Costa Rica now have similar legislation.
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28 349 Under the European Water Framework Directive the general aim for all river water bodies is to
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30 350 achieve good ecological status, and flow requirements to meet this aim have been defined (82). The
31
32 351 concept of flow required for natural ecosystems has evolved from the initial idea of minimum flow,
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34 352 which assumed the river ecosystem would be protected if flow was maintained above a low threshold
35
36 353 value, to whole flow regimes. The term 'environmental flows' is now widely employed and
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38 354 describes the quantity, quality and timing of water flows required to sustain freshwater and estuarine
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40 355 ecosystems and the human livelihoods and well-being that depend on these ecosystems⁷. The concept
41
42 356 of environmental flows is now a key element in many international policies (such as the Convention
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44 357 on Biological Diversity signed by 168 countries and the International Convention on Wetlands,
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46 358 signed by 132 countries).
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51
52 359 To manage ecosystems and water in the integrated manner required, environmental flows needs to be
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54 360 incorporated within hydrological models. Although there are technically more than 200 methods
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57 ⁷ www.flownet.org
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3 361 available to assess environmental flows they fall broadly into two types. The first type is based on
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5 362 the natural flow paradigm (11, 83), which proposed that river species or communities are dependent
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7 363 on multiple aspects of the flow regime. This view encompasses the concept of the flood pulse (84),
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9 364 wherein flooding is considered to be important for linking river and floodplain ecosystems. Thus any
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11 365 alteration from the natural flow regime will lead to some ecosystem degradation and possible loss of
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13 366 ecosystem services, with too much flow at the wrong time being as detrimental as too little flow. The
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15 367 application of this approach is most evident in the protection of natural rivers, such as in protected
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17 368 areas e.g., National Parks. Using the natural flow paradigm for setting environmental flows can be
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19 369 thought of as a 'top-down' approach (12) in that the full reference flow regime provides the baseline
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21 370 point of reference and elements are removed, such as certain flood events that are not essential to
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23 371 meet a particular desired ecological state.
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28
29 372 The second type of method recognises that much of the Earth's surface has been managed
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31 373 intensively for many millennia, as human populations have expanded and that major infrastructure,
32
33 374 such as dams, provides essential water, food and energy security (85). The premise here is to identify
34
35 375 specific species, communities, functions or ecosystem services required and to attempt to design the
36
37 376 river's flow regime to deliver these objectives. This is essentially a 'bottom-up' approach that starts,
38
39 377 at least conceptually, with no flow (the situation below a dam with outlet gates closed) and builds-up
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41 378 a flow regime by adding low flows, high channel flows and floods at different times, of different
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43 379 magnitude and duration until the specified objectives are met. The most well-know is the Building
44
45 380 Block Methodology (86). This can be a particularly useful concept where decisions have already
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47 381 been made over the broad allocation of water resources. Attention is then focused on utilising the
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49 382 environmental water allocation to best meet the objectives of society for the river. The approach is
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51 383 amenable to heavily managed rivers where specific reservoir flow releases are likely to be employed
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53 384 to deliver particular objectives, e.g. fish breeding or natural floodplain irrigation. The DRIFT method
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55 385 (87) incorporates an optimising routine to help design the most effective flow regime where various
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3 386 scenarios of flow regime alteration are specified in relation to dam operations (88, 89). Currently
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5 387 these methods are not directly linked to hydrological processes models and tend to applied separately
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7 388 in sequence. There is great potential for linking hydrological models and environmental flows
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9 389 models to establish the important feedback between water security and ecosystem processes.
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12 13 390 **3.3 Trade-offs in water management for ecosystem services** 14 15

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17 391 Ecosystem services provides a useful framework because exploitation of the ecosystem, for example
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19 392 its water, for public supply and intensive irrigation can be seen as ecosystem services that require
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21 393 input of built infrastructure (such as dams and pipes) alongside services that rely more exclusively on
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23 394 natural assets (90), such as fisheries. Water allocation can be considered in terms of a trade-off in
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25 395 ecosystem services. Water held in a dam can be for direct use, whilst water released as an
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27 396 environmental flow will support indirect use (Figure 5).
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32 397 Building on the examples given in the previous section, we highlight recent research showing that
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34 398 assessment of hydrologically-based ecosystem trade-offs is particularly complex in wetland areas,
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36 399 especially in situations where trade-offs in the biophysical system play to the advantage of different
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38 400 communities (71). We suggest that improvements in the modeling of coupled climate feedbacks will
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40 401 create new opportunities for more thorough assessments of ecosystem trade-offs that arise in
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42 402 response to environmental and water management decisions. For example, building of the Fomi dam
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44 403 in Guinea will allow expansion of irrigation in southern Mali, but the resulting reduction in flood
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46 404 extent in the Inner Niger delta (91) may alter patterns of grazing and could also reduce rates of
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48 405 evaporation and rainfall in surrounding areas. The resulting trade-offs in food provision (and
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50 406 between the people of northern and southern Mali) can only been understood through the use of
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52 407 coupled models.
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3 408 In many African river systems (e.g., Senegal, Logone and Kafue) development is focused on poverty
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5 409 alleviation, and environmental flows aim to deliver simple annual flood-dominated hydrographs that
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7 410 are required for flood recession agriculture, fisheries and cattle grazing and directly support local
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9 411 rural livelihoods (92). Appropriate balancing of the management of dams has had benefits for natural
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11 412 services as well as created services. For example, environmental flow management on the Logone
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13 413 River in northern Cameroon using infrastructure of the Lake Maga reservoir has produced regular
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15 414 inundation of the Logone floodplain and production of constant ecosystem services that were
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17 415 otherwise highly variable under extremes of droughts and large floods generated by a natural flow
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19 416 regime (93). At the same time sufficient water has been retained in Lake Maga to support intensive
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21 417 rice irrigation downstream of the dam. Reservoirs are not necessarily without ecological value. For
22
23 418 example, in 2012 the government of Tunisia designated six reservoirs as wetlands of international
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25 419 importance under the Ramsar Convention including Barrage de Sidi El Barrak, which stores
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27 420 irrigation water and provides a supply of potable water to the city of Tunis, but supports the
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29 421 threatened Eurasian otter (*Lutra lutra*).
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35 422 With any allocation of resources, there will inevitably be winners and losers. The Manantali dam in
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37 423 Mali was constructed to supply hydro-electricity to cities in Senegal, Mauritania and Mali, thus
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39 424 benefiting the urban elite, commerce and industry, at the expense of the rural poor downstream who
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41 425 had little electrification and who lost ecosystem benefits of floodplain inundation including fisheries,
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43 426 flood recession agriculture (94, 95).
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48 427 **4 Conclusion**

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52 428 The prospects for using coupled land-surface hydrology models to understand the role of human
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54 429 water management decisions in the global hydrological cycle are compelling (96) and raise the
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56 430 possibility that land-surface models could themselves be used to inform water allocation decisions.
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3 431 Many of the improvements to land-surface models that we advocate require a corresponding
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5 432 improvement to the observed data available to build and test the models themselves. There is still a
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7 433 need to improve global fields of components of the global water cycle, both for assessment of
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9 434 existing resources and to benchmark and improve coupled models. In particular precipitation data are
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11 435 scarce in sparsely populated and mountainous regions, where coverage is limited, but evaporation
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13 436 and soil moisture data are also problematic because they are not measured using standardised
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15 437 techniques, nor are such measurements routinely collated. In many regions of the world
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17 438 measurement networks are degrading and in others there are institutional barriers to the free
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19 439 exchange of data. Remote Earth observations help to fill some gaps, but *in situ* data are still essential
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21 440 to validate and calibrate satellite products.
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27 441 There remains an urgent need to improve: (i) the representation of groundwater, particularly at the
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29 442 scales relevant to land-surface modelling; (ii) the storage of water in snow – in a manner that is both
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31 443 physically realistic and which maintains the energy balance at the surface; (iii) the representation of
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33 444 human interventions such as land cover changes, dams and irrigation in the hydrological system; (iv)
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35 445 the quantification and communication of uncertainty in a way that is accessible to stakeholders and
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37 446 which uses metrics defined by and of importance to end-users and decision makers; (v) the
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39 447 recognition and quantification of a wide range of ecosystem services provided by the river corridor
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41 448 and the linkage to environmental flow provision; and (vi) definition and quantification of multiple
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43 449 use as this is important for quantifying the true supply of the resource.
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48 450 Feedbacks can be extremely important, particularly where water fluxes are limited by soil moisture.
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50 451 However, given the diversity and complexities of both the physical feedbacks and interactions
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52 452 between water management and the hydrological cycle it is impossible at present to identify hard and
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54 453 fast rules to determine when and how coupled models should be used. It is suggested that the
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56 454 continued collection of individual case studies, such as those presented here, should ultimately
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1
2
3 455 provide guidance on coupled modelling and the incentive to improve the realism of Earth System
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5 456 Models.

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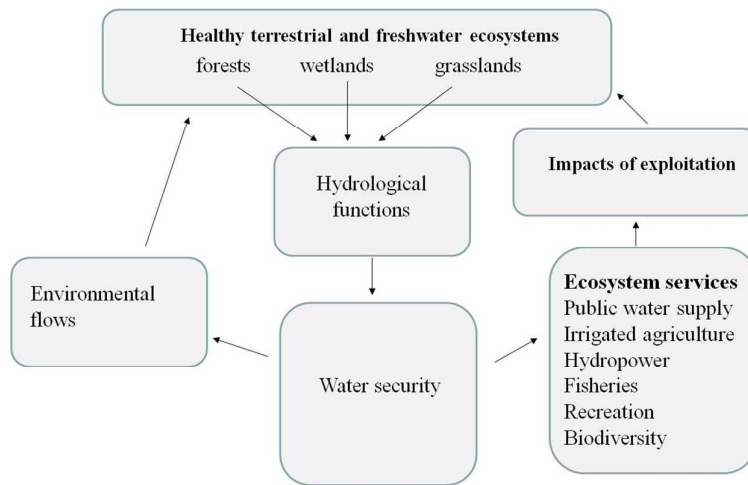
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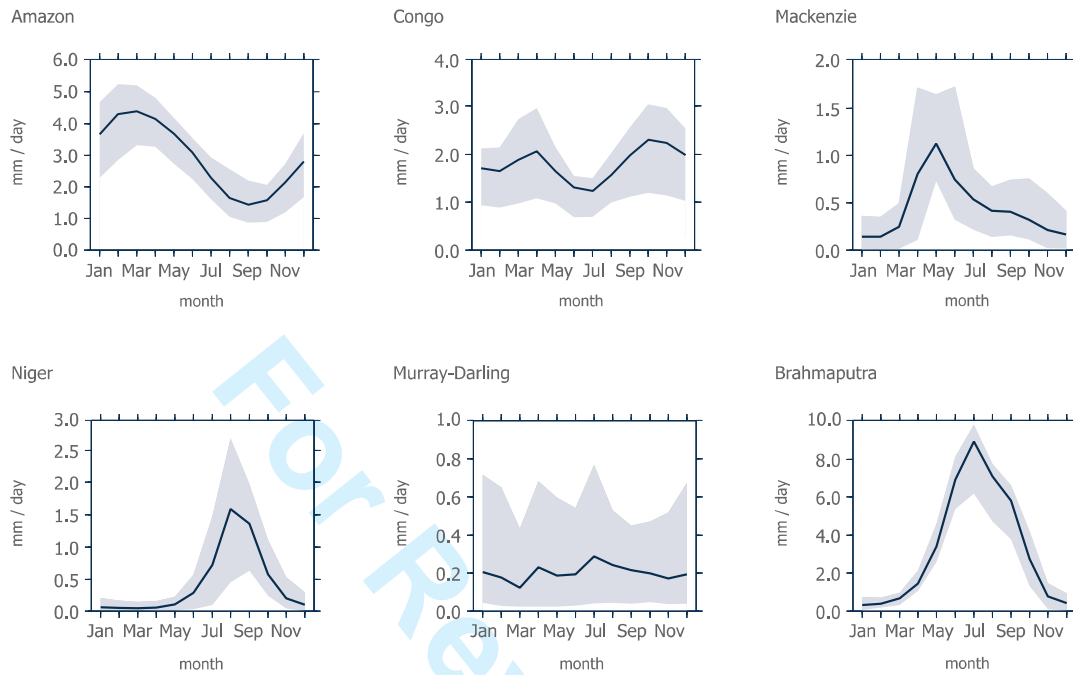
715 **Figure 1 Feedback between ecosystems and water security**

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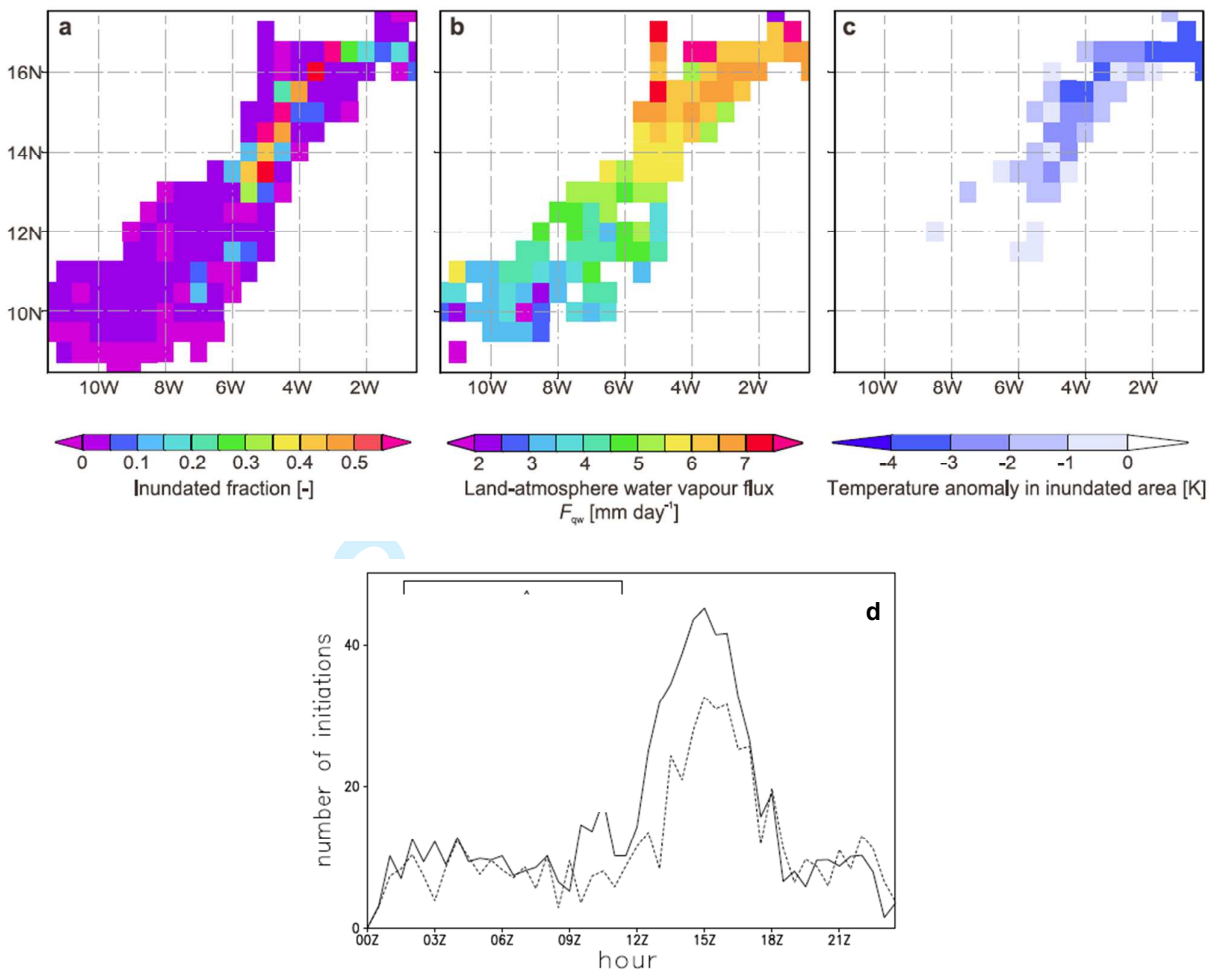
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719 **Figure 2 Multi-model total runoff for six of the world's major river basins for the period 1985-**
 720 **1999. Ensemble mean (black line) and range (shaded) of 13 hydrological and land surface**
 721 **models, from the WaterMIP inter-comparison (28, 53).**

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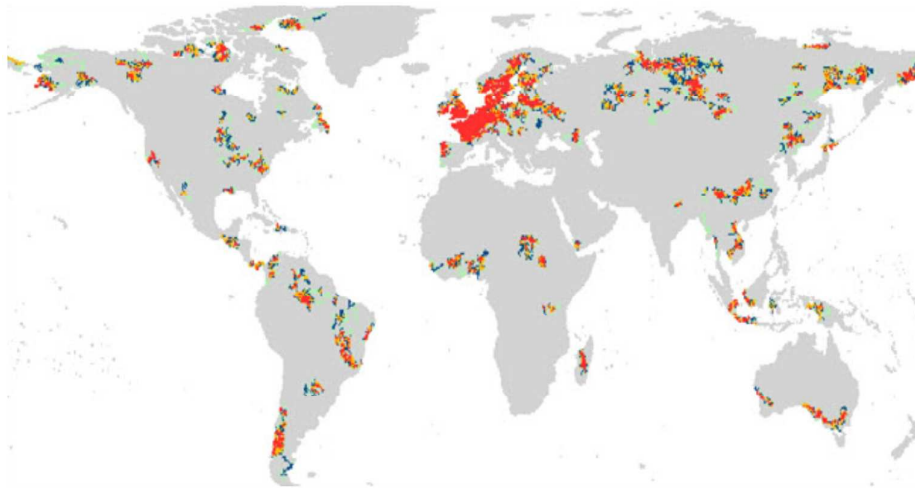
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725 **Figure 3 Role of seasonal inundation in land-surface evaporation and associated heat flux in**
 726 **the Inland delta of the Niger River, Mali Spatial pattern of model predictions. (a) Inundated**
 727 **fraction. (b) Land-atmosphere water vapour flux. (c) Temperature anomaly in inundated**
 728 **regions, measured as difference between inundated open-water tile and grid box mean over all**
 729 **tiles. (d) Diurnal cycle of storm initiations over the region 3–6.5 °W, 14–15.5 °N for wet (solid)**
 730 **and dry (dashed) periods. (After refs. 66, 67)**

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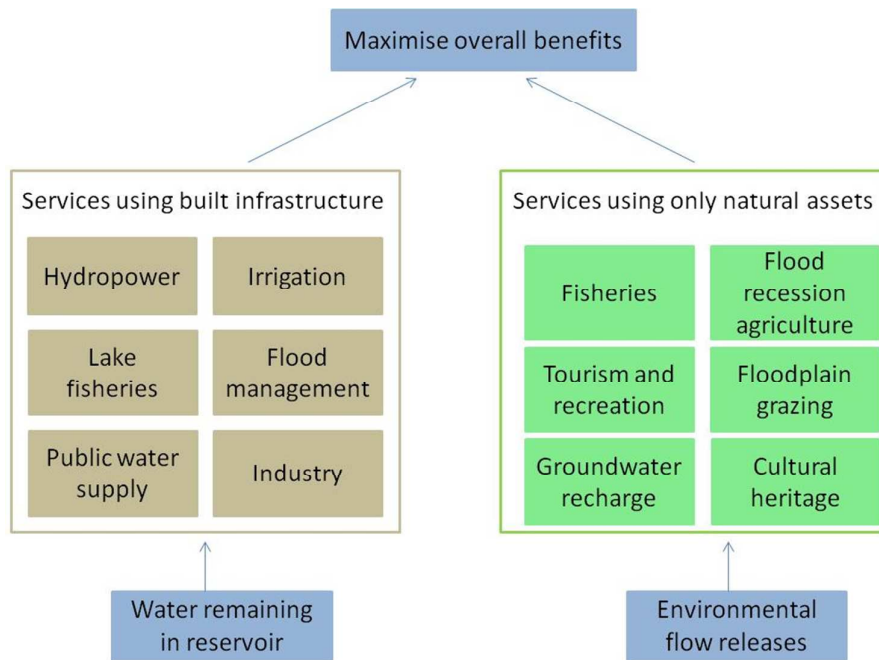


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734 **Figure 4 Synchronicity of global drought for August 1976. Red areas indicate where the**
735 **simulated runoff is lower than 5 out of 100 yr runoff (95%), orange: runoff lower than 10 out**
736 **of 100 yr runoff (90%), blue: runoff lower than 15 out of 100 yr runoff (85%) and light blue:**
737 **runoff lower than 20 out of 100 yr runoff (80%) (28)**

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741742 **Figure 5 Developing world trade-off (after ref. 97)**