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Water security for a planet under pressure: interconnected challenges of a changing world call for sustainable solutions

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Sustainability, equitable allocation and protection of water resources must occur within the framework of integrated management and water governance, but its implementation is problematic. Ongoing global climate change, increasing population, urbanization, and aspirations for better living standards present a challenge to the planetary sustainability. While water use at global scale currently seems to be within its planetary boundary, shortages prevail in several water-scarce and overpopulated regions, and are projected to increase. Furthermore large-scale impoverishment of aquatic biodiversity, ecosystem degradation and reductions in water quality are unaddressed 'side effects' in areas where water can be secured for human and economic uses. As the world prepares for Rio+20, challenges to the sustainability of global water security should be scrutinized. Of particular concern is the likelihood that the water-related Millennium Development Goals (MDGs) targets may not be achievable due to lack of funding commitments, and a failure of delivery mechanisms including water governance. Constraints on water availability and reductions in water quality jeopardize secure access to this resource for all legitimate stakeholders, including aquatic and terrestrial ecosystems. Water connects several socio-ecological, economic and geophysical systems at multiple scales and hence constitutes a 'global water system'. This should be considered both in technical interventions and in governance frameworks. Humans have been changing the global water system in globally significant ways since the industrial revolution, yet without adequate knowledge of the system and its response to change; and without sufficient understanding of how to govern the system at local and global scales. Water security in the 21st century will require better linkage of science and policy, as well as innovative and cross-sectoral initiatives, adaptive management and polycentric governance models that involve all stakeholders. Consensus solutions will need to be achieved by evidence-based mediation, rather than following untested 'panaceas', so as to ensure equitable and sustainable global water use.

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Introduction: towards Rio+20

The threefold increase of the global population during the 20th century has triggered a simultaneous sixfold increase in water use [1]. Widespread pollution has made good-quality freshwater scarce, posing threats to human health and biodiversity [2••]. The magnitudes of ongoing environmental transformations, including climate change, are signs of unsustainable socio-economic practice at global scale, raising the question how the planet will accommodate an additional three billion people by 2050.

This paper focuses on water security and its close links with physical, biological, chemical processes at multiple scales within the socio-economic and political contexts of a human-dominated Earth system. Given such complexity, water sustainability will require innovative and multisectoral initiatives, extending far beyond any management solutions proposed thus far.

The Ministerial Declaration of the 2nd World Water Forum [3] called for water security by:

'... ensuring that freshwater, coastal and related ecosystems are protected and improved; that sustainable development and political stability are promoted, that every person has access to enough safe water at an affordable cost to lead a healthy and productive life and that the vulnerable are protected from the risks of water-related hazards.'

To achieve these goals, seven challenges were formulated [3]:

- Meeting basic (human) needs;
- Securing the food supply;
- Protecting ecosystems;
- Sharing water resources;
- Managing risks;
- Valuing water; and
- Governing water wisely.

While pioneering on its own right, this list does not identify water as the key factor binding nature and society. The connections between nature and engineered water infrastructure, the water–energy–food security nexus, the high rates of freshwater biodiversity loss, and linkages between water and land use must all be addressed in the quest for sustainability [4•].

Human water security is a major political issue: The Millennium Development Goals (MDGs) [5] call for halving by 2015 the proportion of people without sustainable access to safe drinking water, and have been extended by adding the same requirement for sanitation. In addition, freshwater issues are embedded, at least implicitly in nearly all other MDGs. Hence the critical role of good water stewardship is essential for their achievement. It is essential that the forthcoming United Nations Conference on Sustainable Development — Rio+20 — acknowledges these complexities and reflects them in its results and declaration.

A fundamental, yet fragile resource

Water is irreplaceable

Water is irreplaceable and nonsubstitutable. It is a universal solvent and, hence, is a vector of compounds and transport medium, a climate regulator, a carrier of energy, and cooling and heating agent. Where and when it is in short supply (droughts) or in excess (floods), it is a major source of risk, strife and insecurity. Even where water is in abundant supply, its quality may compromise its use by humans and its ability to sustain aquatic biodiversity. This is evident from the presence of nutrients, agrichemicals, industrial wastes and persistent organic pollutants in many water bodies, high nitrate levels in groundwaters, heavy metals in river and lake sediments, and algal blooms and depleted oxygen that causes fish kills.

Rapid industrial development — without adequate water treatment or recycling — lead to pollution that endangers ecosystems and human health, ultimately compromising water security. In addition, residues of hundreds of pharmaceutical and cosmetic products enter freshwaters through municipal sewage, despite treatment by state-of-the-art technology, giving rise to unique 'chemical cocktails' with long-term environmental consequences that are little understood [6–8].

The global water system

The water cycle (Figure 1) [9•] represents the circulation of water through its atmospheric, terrestrial (surface and subsurface) and marine domains and its different phases (liquid, vapor and ice). Figure 1 shows the stores of water and fluxes between these stores as prevailed within 1979 and 2000. Carbon dioxide increases and its associated temperature increases and land use change over the next few decades will directly or indirectly lead to changes of these fluxes and storages [10]. Raising temperatures are expected to exacerbate increases of water use, and future water demands will need to be satisfied from a resource with an increasingly uncertain and variable distribution in space and time [11].

We have already experienced changing precipitation patterns, such as increasing rainfall intensity and longer dry spells, as well as higher evapotranspiration, and an increased frequency of extreme events such as floods and droughts. At high latitudes and altitudes more precipitation is falling as rain rather than snow and the seasonality of runoff is changing. In some areas new dams may be needed to increase the water storage capacity to alleviate droughts, and control floods.

Matters are complicated by the discovery of new pathways and thresholds within the water cycle that show that a local focus on water issues presents a serious risk of failing to understand important larger-scale dynamics with potentially major and possibly irreversible impacts on society and nature [4•]. They include the effects of deteriorating water quality on aquatic ecosystems and freshwater fisheries, and the potential exhaustion of over-exploited groundwater resources.

Water connects several interlinked, geophysical, socio-ecological and economic systems and, in this sense, constitutes a 'global water system' [12•]. Since the industrial revolution, when the Earth entered the Anthropocene epoch [13] in which humans have been changing the global water system in globally significant ways without adequate knowledge of the system and its response to change [4•].

There are also important uncertainties over the state of global water resources as well as the dynamics and interconnections of water, nutrient and material cycles. As far as the terrestrial part of the water cycle is concerned Figure 1 indicates water and vapor fluxes which may be distinguished as 'blue' water (the flux of surface and saturated groundwater flows governed predominantly by gravitational forces) and as 'green' water (taken up by plants or stored in the unsaturated soil matrix and returned to the atmosphere through evapotranspiration). Almost two-thirds of the terrestrial component of the global water system, about 73,000 km^3/year is 'green' water, ultimately a molecular forces driven feedback to

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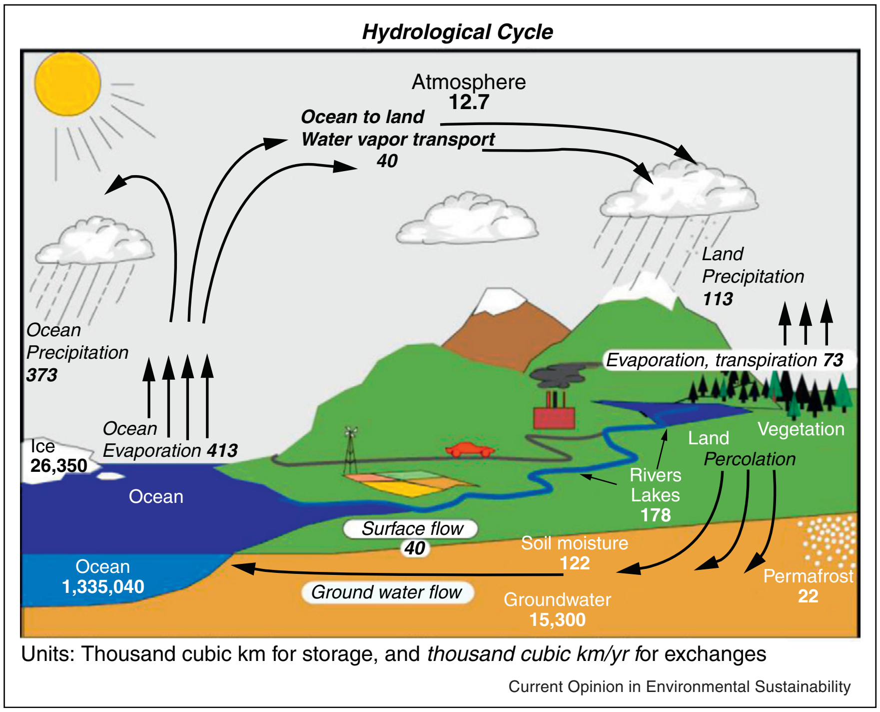
Figure 1



The water cycle with estimated water flux and storage compartments valid for the period 1979–2000
Printed with kind permission of the American Meteorological Society. (from Trenberth *et al.* [9•]).

the atmosphere, while the remaining, approximately 40,000 km^3/year 'blue' water is the primary subject of traditional water resources management. However, 'blue' and 'green' water fluxes are not independent, and integrated water resources management must account for both. 'Green' water fluxes are overwhelmingly influenced by agricultural and forestry practices and, hence, land use change, facts which underline the necessity of integrated land and water resources governance and management [14,15]. This is problematic, as the state of the world's freshwaters (both 'blue' and 'green') is not adequately monitored, creating significant obstacles to management and mitigation or prevention of water scarcity and water quality degradation. Impacts of changes on biodiversity and ecosystems will also be hard to predict, given that, for example, inventories for freshwater animals are very incomplete globally, particularly in the tropics [16].

Challenges of today and tomorrow

The Millennium Development Goals and beyond: a water governance perspective

Water problems in the public perception and discourse are first and foremost related to direct human needs and use. Despite this, over one billion people lack access to safe drinking water and about two billion people live without basic sanitation [17].

Nevertheless, improvement of access to water and sanitation is one of the more successful examples of global water governance. MDG 7 defines direct water-related targets to halve by 2015 the number of people without access to safe water and sanitation services. Significant progress has been made during the last decade. However, the proclamation of access to water and sanitation as a human right by the UN General Assembly in 2010 underscores the point that targets such as stipulated in MDG 7 which leave many people without water services are not ethically justifiable, even if they represent commendable milestones. Similar success of water governance cannot be reported for another global water target, the institutionalization of integrated water resource management (IWRM), irrespective that the Plan of Implementation of the Johannesburg Summit in 2002 called for IWRM and water efficiency plans by 2005 in all countries. Sectoral fragmentation still impedes effective implementation of integrated water governance and sustainable management practices at global, regional and national levels.

The MDGs will be reviewed in 2015. Efforts must be made now to ensure that focusing on the access goals will not cause deterioration of the environment. As pressures on the world's water resources increase, the achievement

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of the water-related MDGs by 2015 will need to be implemented within an IWRM framework. Even if, by 2015, all water-related MDGs were achieved, major water challenges would remain:

- How can access levels be made sustainable?
- How can water services be provided for an ever-growing human population?
- How can we ensure that provision of drinking water and sanitation does not endanger freshwater biodiversity and threaten the ecosystem goods and services that underpin human livelihoods?

Ensuring that no one remains without access to adequate water and sanitation should be a core aim of global water governance. Securing water for other vital human needs such as food and energy production, as well as safeguarding the quality and quantity of water for nature, should not be neglected in pursuance of water supply and sanitation goals. The scope and magnitude of institutional challenges are formidable. If governance structures are not adequate to address water problems in an integrated way what kind of new institutions are required? Will greater efficiency arise from a worldwide, uniform approach to water governance, or from a diversity of regional and local approaches? How far could polycentric governance models be successfully adopted? In short, the global 'water crisis' is ultimately a 'governance crisis' extending from the local to the planetary scale [18].

Planet on the edge

A recent assessment of whether our planet is on a sustainable trajectory has indicated that three consensus-based 'planetary boundaries' (see Table 1) have already been significantly transgressed [19••,20••].

Table 1

State of indicators and proposed planetary boundaries.

PLANETARY BOUNDARIES

Earth-system process	Parameters	Proposed boundary	Current status	Pre-industrial value
Climate change	(i) Atmospheric carbon dioxide concentration (parts per million by volume)	350	387	280
	(ii) Change in radiative forcing (watts per metre squared)	1	1.5	0
Rate of biodiversity loss	Extinction rate (number of species per million species per year)	10	>100	0.1–1
Nitrogen cycle (part of a boundary with the phosphorus cycle)	Amount of N_2 removed from the atmosphere for human use (millions of tonnes per year)	35	121	0
Phosphorus cycle (part of a boundary with the nitrogen cycle)	Quantity of P flowing into the oceans (millions of tonnes per year)	11	8.5–9.5	~1
Stratospheric ozone depletion	Concentration of ozone (Dobson unit)	276	283	290
Ocean acidification	Global mean saturation state of aragonite in surface sea water	2.75	2.90	3.44
Global freshwater use	Consumption of freshwater by humans (km^3 per year)	4,000	2,600	415
Change in land use	Percentage of global land cover converted to cropland	15	11.7	Low
Atmospheric aerosol loading	Overall particulate concentration in the atmosphere, on a regional basis	To be determined		
Chemical pollution	For example, amount emitted to, or concentration of persistent organic pollutants, plastics, endocrine disrupters, heavy metals and nuclear waste in, the global environment, or the effects on ecosystem and functioning of Earth system thereof	To be determined		

Boundaries for processes in red have been crossed.
(modified after Rockström *et al.* [19••]).

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This is clear evidence that human activities in the Anthropocene world are on an unsustainable trajectory. Freshwater use, at least at global scale, is not yet among the most critical threats for global sustainability (Table 1). The present global water withdrawal is approximately 4000 km^3 annually (or about 10% of the annual freshwater flows to the oceans; see Figure 1) of which an estimated 2600 km^3 is consumed. The difference of 1400 km^3 annually accounts for conveyance and application losses. The need to improve water use efficiency is thus evident. While present water consumption is below the critical threshold proposed in Table 1, this does not imply that withdrawals could increase indefinitely. Global values do not account for local conditions. Many watersheds and aquifers are significantly overstressed with water withdrawal for agricultural use alone close to or exceeding locally available renewable water resources [21].

Through its interconnecting functions, water has a role to play in many planetary boundaries. For instance, the unsustainable loss of global biodiversity in Table 1 appears to be far higher from freshwater ecosystems than from the marine or terrestrial realms [22]. Furthermore, changes in land use and water availability are intricately intertwined, and water vapor plays a crucial role in all atmospheric processes and is a potent green house gas affecting climate change. Transgression of the planetary boundary for water can be anticipated within this century as human population growth continues. Clearly a critical evaluation of how much water we use is needed, together with where, how and what we use it for.

We need to improve our scientific knowledge on the interdependency of planetary boundaries, and better understand how many, how much and for how long planetary boundaries have been (or will be) transgressed. An additional aspect needs consideration: how far could local and regional overuse of water resources scale up to global scale effects?

Where freshwater and marine problems meet: the coastal zone

The number and size of emerging coastal settlements, especially in developing countries are 'hot spots' for water security challenges. Estuaries and river deltas are coveted economic spaces and valuable ecosystems. They are being threatened by careless management of water upstream. In addition, to climate-change induced sea-level rise, many river deltas are subsiding due to upstream dams and reservoirs trapping sediments which would otherwise be deposited in deltas or/and by overexploitation of coastal aquifers [23]. Upstream modifications of river flows and dam construction obstruct migratory routes, affecting many commercial fish species and limit the transfer of nutrients that enhance flood-plain agricultural productivity. Environmental flow allocations and other mitigation actions can be planned to protect ecosystems including sensitive deltas, but implementation and stakeholder agreement remain challenging [24].

Achieving a sustainable 'water world'

Threats to water security for humans and nature

Human water security implies the provision of quality drinking and domestic water, water for energy generation, industry, and transport, maintenance of ecosystems and biodiversity and water for food security. Tradeoffs and potential for considerable conflict exist. Over 70% of 'blue' water withdrawal is used for food production [25], and the links between water security and food security will become increasingly evident as the demand for food grows in parallel with increased water requirements for industry and energy generation [26]. In addition, biodiversity in freshwater and terrestrial ecosystems depend upon provision of adequate quantities and quality of water. Meeting the future needs of growing human populations will have major implications for the supply of water to ecosystems. A recent global analysis addressing 23 threat factors or stressors for human water security and freshwater biodiversity [2••] shows that, threat to human water security and biodiversity frequently coincide (red shaded areas in Figure 2) but, in many places — especially in the developed world — human water security is achieved at the expense of freshwater biodiversity (yellow shaded areas). There are virtually no places where a high degree of water security for humans has been achieved without threatening biodiversity. This result reflects the 'traditional' management strategy of tolerating degradation of ecosystems and then applying costly remediation strategies (if at all) after the damage has been done. Competition for water between humans and nature will intensify in the future. New approaches, aiming to satisfy human demands while, at the same time, securing biodiversity and ecosystem services are urgently needed. Unavoidable compromises should be mediated by science in a transparent process.

The water–energy–food nexus

One billion people suffer hunger; two billion people exist on inadequate diets while the global population is still rapidly increasing. To meet the nutritional needs of all food production will have to double in the next 25 years [27]. Consequently agricultural water use will increase, unless potentially offset by improvements in water and land use efficiency.

There is much scope for such improvement: globally, at least half of the water withdrawn for irrigation does not reach the crops for which it is intended [28]. The recent increase in growing energy crops may supplement rural incomes, but it creates competition for water and land with food crops, and thus between food and energy security.

Hydropower is an important source of energy globally, and its share of the energy sector will increase at the

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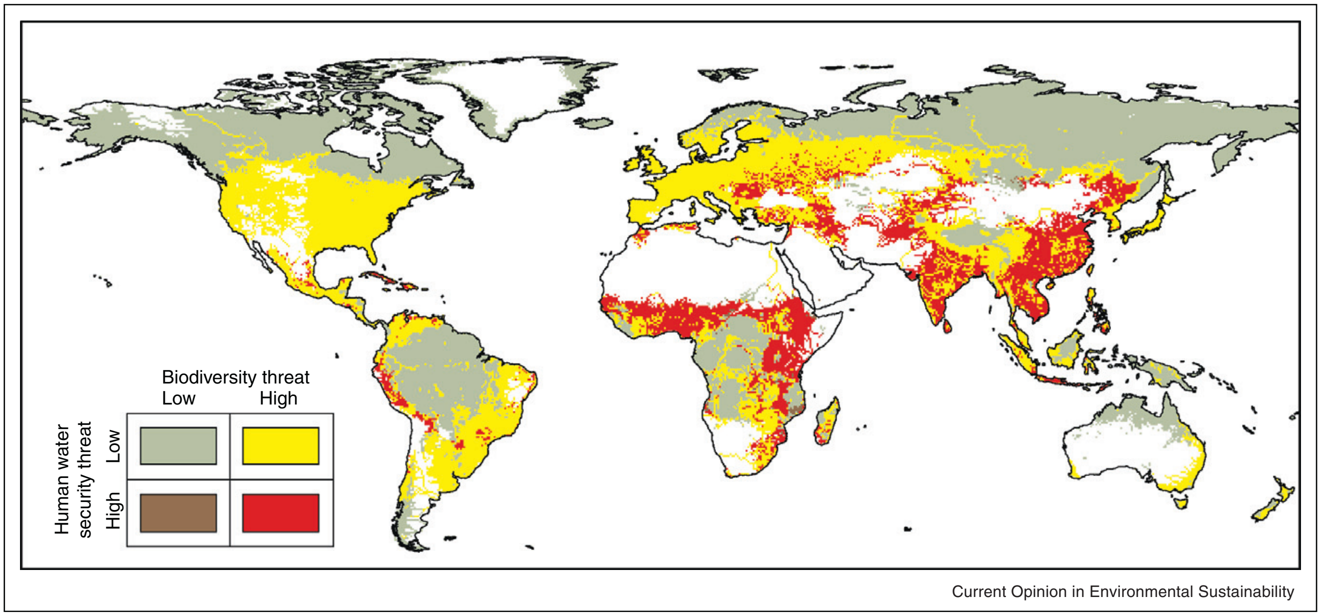
Figure 2



Prevailing patterns of threat to human water security and biodiversity from Vörösmarty *et al.* [2••]. Printed with kind permission of Nature Publishing Group, a division of Macmillan Publishers.

expense of fossil fuels. The benefits accruing need to be compared with the loss of biodiversity and vital ecosystem functions that accompany dam construction and modification of flow regimes to generate electricity [29]. Hydropower is certain to remain part of the global energy mix. Thus policies and practices need to be put in place to mitigate impacts on freshwater ecosystems. Science-based compromises will have to be found and hydropower generation managed adaptively to account for environmental flow requirements [24,30].

Even water resources management itself consumes energy. Water purification and desalination are very energy intensive, and energy is needed to pump and distribute water from rivers and aquifers. Saline groundwater or seawater has to be desalinized to meet water demands in arid areas, and this consumes substantial energy. Microfiltration and membrane technologies used in sewage treatment also have high-energy consumption [31].

Urbanization is opportunity rather than risk

By 2050 the world population is projected to reach about ten billion people with nearly seventy per cent of the population living in cities [32]. Most of these people will be born in developing countries where drinking water and adequate sanitation are still to be provided. Burgeoning cities also present challenges because of their demand for water and pollution of rivers, lakes and aquifers. Losses from municipal water-supply systems and seepage from sewers can reach alarming proportions as maintenance is often neglected [33]. In spite of these challenges, cities also provide opportunities for improvements in water supply and sanitation because concentrations of people and wealth in cities enable the deployment of efficient technical solutions that are unaffordable elsewhere.

Water interconnectivities at multiple scales

Economy and trade create spatial interconnectivities for water. Water circulates in the global economic system as an embedded ingredient ('virtual water') of food and other internationally traded products [34]. Arid countries may compensate for national water scarcity by importing water-intensive commodities. These water fluxes, which are entirely mediated by societal needs, expose important international or inter-regional water dependencies that should be considered in governance discussions [34].

The physical transfer of water between basins is a direct interconnectivity that sometimes triggers conflicts due to its high economic and ecological costs, and competition among potential users [35]. Despite these controversies, large-scale transfers are ongoing or planned. Moreover, as climate zones may start to shift, interbasin water transfers might be considered as adaptive measures.

Changes in land cover and use have a major influence on water movement and consumption, and through changing land-atmosphere feedbacks, affect precipitation patterns. Deforestation of the tropical rain forest, and the expansion of commercial and energy crops, depletes terrestrial biodiversity, and the resulting monocultures are vulnerable to

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pests and climate vagaries [36]. As noted earlier, the unique role of water as connecting medium among ecological and social systems mandates that water must be managed in a multisector environment. Conversely no socio-ecological system can be sustainably managed without adequate consideration given to water. Joint development strategies, especially for land and water management, are needed.

Towards better water governance

Constraints slowing the achievement of water security can arise from a lack of local knowledge, and institutional, professional and vocational capacities, shortage of funding and delivery capacity, including a lack of legislation or limited implementation of rules and regulations at all levels [37]. During periods of water scarcity, these constraints can accentuate the potential for conflicts among water users at local, basin and international scales. Thus far, however, sharing water from transboundary rivers and lakes has been relatively successful [38]. Although wars triggered by water conflicts between sovereign states are unlikely to occur in the 21st century, the potential for violence in water disputes increases with the extent of dependence of livelihoods on water [38] and the increasing human demand for a finite resource. Emerging tensions in shared river basins could be reduced or deferred by use of more water efficient irrigation techniques, alternative land management, and new water technologies. Adopting common governance principles and sharing benefits derived from water at all levels and implementing efficient water management practices will help facilitate cooperation on water issues.

Research on water governance is a relatively new interdisciplinary field. As mentioned above, IWRM is an internationally accepted framework to deal with water security issues [39,40]. However, IWRM practices must be adapted to changing conditions and needs instead of being treated as panaceas and applied to water issues without testing and long-term monitoring of their performance [41•]. An adaptive management approach which reviews IWRM would avoid conflicts and failures. IWRM cannot deliver the promised results unless it is embedded in an adequate governance framework and guided by political will.

Comparative analyses of water governance systems around the globe reveal that their performance is context sensitive but not context specific. Good water governance is achievable in most countries although financial resources help. Funding is a necessary but by no means sufficient condition for efficient and effective improvement. Improved water governance can be realized through polycentric governance, effective legal frameworks, reduced inequalities, open access to information, and meaningful stakeholder participation [42]. Simple 'panaceas' for governance reform and pathways towards improvement should no longer be promoted. The water sector needs institutional reforms towards effective and adaptive governance and management systems. This will require multi stakeholder debates at national and international levels placing water at the center of social and economic development including energy, food, climate change and biodiversity issues. Neither markets, nor governments nor civil-society movements can provide water security on their own [43].

Joint response to the water challenge

Given its global scope and interconnectedness water must be a priority on all political agendas. In spite of the importance of water to climate change, it has been forgotten in the climate debate. Water tends to be considered as a 'sectoral adaptation' which ignores its central role in the interlinked socio-ecological system, and the ethical imperative espoused by the UN General Assembly's resolution [44,45].

Although accurate forecasts are elusive, trends that will carry into the future are clear: human populations and the demand for water are increasing, and this is occurring in the context of anthropogenic climate change [10]. Climate change should be seen as a catalyzer for long-overdue water governance reforms, and improved integration in water resources management. Proposals in this context should be 'no-regret' measures, so that uncertainties in climate-change projections cannot be used as excuses for postponing action.

We are facing the possibility of pushing the planet beyond its carrying capacity unless development and resource use paradigms are revised fundamentally to encompass the principles of precaution, equity and sustainability. We need good interdisciplinary science, but also water governance and management practice based on 'water ethics' and compassion to secure water for humans and ecosystems.

Aspirations for 'water security' involve protecting and living with the water cycle by relying on responsible engineering schemes, developing risk awareness and preparedness, in combination with a coordinated legal framework, implementing policies and effective governance directed better water management. An additional challenge is that provision of water and its management and governance must be applied in conjunction with other processes shaping societies, economies and the environment [46]. This implies the societal endorsement of new water use concepts, valuation, and readiness to change and to share.

Political stability, economic equity and social solidarity are much easier to maintain with good water management and governance. The future should therefore be viewed through a 'water-lens' and implications of the complexities, role and intricate feedbacks of the global water system fully considered at all levels of the interlinked socio-ecological system. Oversimplification may

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yield one-sided, unsustainable solutions; overcomplicating could lead to inaction. A sustainable 'water world' must reflect social and political dynamics, aspirations, beliefs, values and their impact on our own behavior, along with physical, chemical and biological components of the global water system at a range of spatial and temporal scales. One thing is certain: development of a sustainable 'water world' requires innovative, interdisciplinary science and will need the engagement of all stakeholders.

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