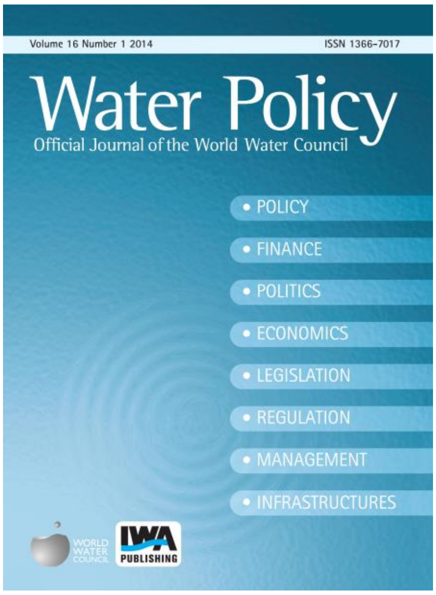
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Overcoming water challenges through nature-based solutions

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Abstract

Freshwater is a key resource and medium for various economic sectors and domestic purposes but its use is often at the expense of natural ecosystems. Water management must change to deal with urgent issues and protect aquatic ecosystems and their services, while addressing the demand for water from the competing claims for cities, agriculture, industry, energy and transport. In this paper key water challenges (shortage, pollution, aquatic ecosystems threatened) have been identified via global modelling. By the IMAGE-GLOBIO model chain a Trend scenario up to 2050 was modelled, as well as the potential of three 'pathways' aimed at halving average global biodiversity loss while also meeting the sustainable development goals. Biodiversity is then used as a guiding principle to address these challenges because water services depend on healthy and biodiverse ecosystems. Subsequently the potential of nature-based solutions is reviewed for four sub-sectors: cities, food production, hydropower, and flood protection, grouped under the three alternative pathways to meet key water challenges. Mainstreaming biodiversity into water policy requires integrated planning. Integrated Water Resource Management (IWRM) could provide an opportune starting point as a well recognised integrating framework for planning, to guide the actual implementation of nature-based solutions in sub-sectors.

Keywords: Aquatic biodiversity; Ecosystems approach; Global model; IWRM; Mainstreaming biodiversity; Nature-based solutions; Pollution; Water challenges; Water management; Water shortage

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Introduction

Freshwater is a key resource and medium for various economic sectors and domestic purposes but its use is often at the expense of natural ecosystems. The combined impacts of land-use changes, high water abstractions, flow modification, flood protection measures, increased nutrient loads and pollution have altered many rivers to such an extent that aquatic ecology is threatened, possibly irreversibly, worldwide (Millennium Ecosystem Assessment (MEA), 2005; Janse *et al.*, 2015). About 70% of the world's rivers are heavily impacted (Vörösmarty *et al.*, 2010). Aquatic ecosystems are exploited to the maximum extent in many areas of the world, and water scarcity and pollution now seriously hamper development (World Water Assessment Programme (WWAP), 2015).

Well-functioning freshwater ecosystems – rivers, lakes, streams, wetlands, aquifers and estuaries – provide biodiversity and ecosystem services such as water storage, water flow, natural water purification and flood protection. Natural water systems have been affected ever since people have tried to benefit from water services. But the current intensive water management with its related water infrastructure, for cities, food production, hydropower or flood protection, drastically changes hydrology and hampers environmental flows in many rivers (Grafton *et al.*, 2012). Wetlands provide important water services but are among the most affected aquatic ecosystems, threatened by dams, poor water quality and land-use practices upstream, conversion and encroachment (Bullock & Acreman, 2003; Rebelo *et al.*, 2010).

Water management must change to deal with these urgent issues and protect aquatic ecosystems and their services, while addressing the demand for water from the competing claims for cities, agriculture, industry, energy and transport. Nature-based solutions, such as the use of natural wetlands for water storage, have the potential to help balance biodiversity and a wide range of ecosystem services on the one side, with water management goals on the other (WWAP, 2012). Such solutions are at the heart of the ecosystem approach, a 'strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way' (www.cbd.int/ecosystem). This approach can be especially powerful when mainstreamed in dominant water policy mechanisms. Mainstreaming biodiversity is then defined as 'the process of embedding biodiversity considerations into policies, strategies and practices of key public and private actors that impact or rely on biodiversity, so that biodiversity is conserved and sustainably used both locally and globally' (Huntley & Redford, 2014).

This article uses future projections to analyse the main relationships between biodiversity and agricultural, river and urban water management, with an emphasis on surface water. By modelling various scenarios towards realisation of biodiversity targets, the potential of the ecosystems approach has been quantified. Based on a review of literature, we identified nature-based solutions in water management. Various barriers restrict their implementation, and we discuss these alongside levers and directions for policy making, providing concrete examples of win-win solutions that combine societal, business and ecological interests.

Methodology

Our analysis starts with an identification of the challenges to water management in terms of shortages, water pollution, and environmental and biodiversity impacts. These were derived from a model analysis by the IMAGE-GLOBIO model chain (Stehfest *et al.*, 2014). This is a chain of models for global integrated assessment that together make projections on climate change, land-use, nutrients and biodiversity at a 0.5 degree resolution, based on broad-scale developments of population, economy, energy and food demand. The aim of the modelling exercise was to give a broad general picture rather than detailed predictions.

First, the biodiversity impacts by 2050 of the so-called *Trend scenario* ('business-as-usual') were modelled, using demographic and economic projections from the Environmental Outlook to 2050 made by the Organisation for Economic Co-operation and Development (OECD, 2012) and the Roads from Rio + 20 study by the Netherlands Environmental Assessment Agency (PBL, 2012). The Trend scenario assumes a continuation of modernisation, with world development continuing to focus on economic development and globalisation. There is a gradual introduction of new technologies, a continued increase in per capita consumption of food, production of material, goods and services and use of energy, with a tendency towards saturation at higher income levels, while economic inequalities remain. No environmental or biodiversity measures are foreseen other than measures that contribute directly to human health, such as reducing air and water pollution. The outcomes clearly show the challenges for the water sector, such as a continued decline of aquatic biodiversity and diminished provision of freshwater ecosystem services (Kok *et al.*, 2014).

Subsequently, three alternative pathway scenarios have been designed to meet the Biodiversity 2050 Vision, in which by 2050 biodiversity is valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people. This Vision has been elaborated in the 'Aichi biodiversity targets', aimed at, among others, halving the rate of biodiversity loss in 2020 or 2030 (depending on the region) and realising a global network of protected areas that covers at least 17% of the earth's land area (www.cbd.int/sp/targets). The pathways also target the sustainable development goals (SDGs) by eradicating hunger, providing universal access to modern energy, mitigating climate change, conserving biodiversity and controlling air pollution (van Vuuren *et al.*, 2015). Using a model-based, back-casting approach, each development pathway includes a set of technical measures, policy interventions and behavioural changes that together limit biodiversity loss according to the Aichi targets. This translates into the conservation of a global-averaged 65% biodiversity intactness, referred to as 'mean species abundance' or terrestrial MSA[1], an indicator of ecosystem health (PBL, 2012).

The three pathways differ in their relative emphasis on interventions in each step from primary production to consumption (see van Vuuren *et al.* (2015) for a further elaboration of the assumptions in these pathways):

- The *global technology (GT) pathway* focuses on large-scale technologically optimal solutions, such as intensive agriculture, and on a high level of international coordination, for instance through trade liberalisation.
- The *decentralised solutions (DS) pathway* has a focus on regional priorities and ecology-friendly technologies. National policies regulate equitable access to food. Energy, food and wood are produced locally or regionally and agriculture is interwoven with natural corridors.

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[1] MSA ('Mean Species Abundance of original species') is an index, scaled 0–1, denoting the degree of intactness of the species composition in an (aquatic or terrestrial) ecosystem with respect to the undisturbed situation.

- The *consumption change (CC) pathway* mainly envisages changes in human consumption patterns, most notably by limiting meat intake per capita, by ambitious efforts to reduce waste in the agricultural production chain and through the choice of a less energy- and material-intensive lifestyle.

The total impact on biodiversity intactness may be underestimated as the assumptions underlying these factors were conservative. Some of the smaller-scale factors were omitted, but may have significant cumulative impacts.

Originally, the three pathways were designed to benefit terrestrial biodiversity without specifically addressing aquatic objectives (van Vuuren *et al.*, 2015). However, in this paper we use the pathways to analyse the main pressures on freshwater quality and biodiversity, such as agricultural land use, including irrigation, wetland conversion, pollution from urban sources and construction of dams for hydropower.

Within this scope, we assess synergies and trade-offs in the water sector, and review nature-based solutions to address these in various ways. In the sections below we first analyse the challenges in water management, as derived from the Trend scenario, assessing synergies and trade-offs. Subsequently, the three global pathways help to identify additional interventions that simultaneously address water challenges and biodiversity targets. Based on a review of scientific and grey literature, we selected the most promising nature-based solutions, using the three pathways as an entry point, for four major sub-sectors in water management: cities, water for food, hydropower and flood protection. As much as possible, real-life examples of the application of these interventions have been included.

Key challenges

The Trend scenario forecasts further deterioration of aquatic ecosystems and their services (Janse *et al.*, 2015). The main causes of freshwater biodiversity loss under the Trend scenario are expansion of agricultural land and intensification of land use, fragmentation and infrastructure, climate change, water flow alteration, exploitation of natural ecosystems – including fisheries and forestry – and tourism. Various water users each have their own demands and effects on the quantity and quality of the water as well as on the shape (morphology, level of canalisation, disruptions) of both surface water bodies and groundwater (Table 1). Of these, agriculture has the highest consumption globally, using at present about two thirds of the water that is mobilised from surface and groundwater (Rockström *et al.*,

Table 1. Groups of water users with an indication of their specific water demands and selected impacts.

	Relative requirements		Impacts on		
Users	Quantity	Quality	Quantity	Quality	Morphology
Irrigation and livestock	*High*	Moderate	*High*	Moderate/high	*High*
Domestic (drinking water)	Low	*High*	Low	Low	Low
Cities (wastewater)	Low	Low	Low	*High*	Low
Manufacturing	Moderate	Moderate	Low	*High*	Low
Electricity	*High*	Low	Low	Low	*High*
Transport/navigation	Moderate	Low	Moderate	Low	*High*
Nature	Moderate/high	*High*	Low	Low	Low
Flood protection	Moderate	Low	Moderate	Low	*High*

2009). Its impacts are also highest (Table 1), on both terrestrial and aquatic ecosystems and their biodiversity.

Challenges in water shortage and water for food

According to the Trend scenario, global freshwater extraction is expected to increase by 55% globally in 2050 compared to 2000, mainly due to increased use in industry, electricity generation and households, with important regional variations (OECD, 2012; PBL, 2012; Stehfest *et al.*, 2014). Although global food production is expected to increase by 70%, only a modest 9% increase in the water use for irrigated agriculture (currently about 70% of the total water demand) is foreseen in this Trend scenario. This is due to an expected limited potential for expansion of irrigated areas, competition with other water users, and especially a general increase in water use efficiency. There is however much uncertainty on this topic, the expected change ranging from −15% to +40% in different studies (see review in OECD, 2012). Despite these uncertainties, the challenges to keep up with this water demand will be high, and surface and groundwater resources will be increasingly threatened.

Due to changes in precipitation patterns and increased evaporation, water shortage is expected to be aggravated due to climate change, especially in those regions that already suffer most (WWAP, 2015). As in many areas in the world, rivers are turning dry and water is becoming polluted, the proportion of the world's population facing water stress is increasing, from 30% in 2010 to over 40% in 2050 (Molle *et al.*, 2010). According to the Trend scenario, by 2050 some $4.3 * 10^9$ people will live in areas of severe water stress, mainly in South Asia, the Middle East and North Africa, as well as large parts of China (OECD, 2012). Water stress problems are further aggravated due to land-use changes in catchments. Deforestation, erosion and conversion or drainage of wetlands have decreased water retention and storage capacity, decreasing the resilience of the hydrological system.

In agriculture and aquaculture, higher inputs of capital and agrochemicals under the Trend scenario can have negative impacts on biodiversity through water pollution, such as a 20–30% increase in eutrophication in lakes globally (Kok *et al.*, 2014; Janse *et al.*, 2015). At present, over 80% of the global nutrient load to freshwater that causes eutrophication is from diffuse sources, mainly agriculture (Bouwman *et al.*, 2011). This may change in relative terms because of rapid urbanisation and increased pollution from cities, but will remain very high in absolute quantities. These impacts are strongest in areas with intensive, especially irrigated, agriculture.

While freshwater aquaculture strongly depends on the availability of clean water, it also poses a threat to aquatic ecosystems through stocking commercial fish species at the expense of native species, overfishing, eutrophication and other pollution, as well as the spread of diseases and genetic pollution in wild populations.

Another important function of aquatic ecosystems is the provision of wild-caught fish, an important source of protein, particularly for the world's poor. Inland capture fisheries are affected by water scarcity and pollution but tend to be neglected in water management policies. On the other hand, overexploitation is observed as a problem in some freshwater lakes (Welcomme *et al.*, 2010).

Challenges in cities and urban water management

According to the Trend scenario, by 2050 nearly 70% of the world's population will live in cities, which implies an urban population increase of $2.8 * 10^9$ compared to today, with 670 cities of at least 500,000 inhabitants, including 88 with more than 5 million inhabitants, by 2050. Cities require clean drinking water and combine the high impacts on water quality of both domestic and manufacturing sectors, releasing daily flows of (in most countries) only partly treated wastewater into the environment, affecting aquatic biodiversity as well as downstream terrestrial ecosystems.

Pollution from point and diffuse sources has led to eutrophication, hypoxia and general degradation of many lakes, rivers, wetlands and coastal waters. Under the Trend scenario, nutrient effluents from urban wastewater are projected to increase 2.5-fold between 2000 and 2050 globally, and their contribution to total emissions to water bodies will increase from 10–20% to 25–35% in this period (Bouwman *et al.*, 2011; OECD, 2012). Most of this increase will take place in developing countries, due to population growth and rapid urbanisation. In 2010 about 60% of the world's population were connected to a sewerage system, while in lower income countries this was only 8% (Sato *et al.*, 2013). Increasing numbers of households will have improved sanitation and a connection to sewage systems, with nutrient removal in wastewater treatment systems lagging behind. The efficiency of wastewater treatment systems is expected to improve rapidly, but not fast enough to keep up with wastewater generation and nutrient inflows. Hence, under the Trend scenario, measures improving health in cities produces a trade-off in deteriorating water quality in rivers.

Challenges in hydropower

Hydropower generation requires an adequate discharge volume and river gradient, as well as a low concentration of suspended matter, as too much silt reduces the lifespan of the reservoir. Thermal power plants, regardless of the energy source, need sufficient discharge as cooling water to stay within the temperature standards, and the released water is usually very warm and sterile (Teixeira *et al.*, 2009). After a temporary levelling-off of new dam building during the past 20 years (Lehner *et al.*, 2011), developments have been increasing in recent years, mainly in Asia and South America, followed by Africa, increasingly through foreign investments. Hydropower is also stimulated because it is considered a renewable energy source that may fit in low-carbon emission scenarios. The remaining potential for growth is estimated at about 70% worldwide (Fekete *et al.*, 2010; Zarfl *et al.*, 2015).

River dams alter and obstruct flows, thus fragmenting rivers and creating serious barriers for migrating species, such as fish (see e.g. Dugan *et al.*, 2010). Nearly 60% of the world's large river systems are strongly or moderately fragmented (Nilsson *et al.*, 2005). The disturbance of the natural flow pattern has major consequences for the biodiversity in rivers and floodplain wetlands (Kuiper *et al.*, 2014). Dams also have negative impacts on water quality and on sediment transport in the river systems. In the filling phase of reservoirs, they can be net emitters of greenhouse gases such as methane. The resulting dam reservoirs, currently covering 0.3 million km^2 globally, affect large areas of terrestrial ecosystems, including agricultural and natural land (Lehner *et al.*, 2011). According to the Trend scenario, large dams are responsible for an average 19% reduction in biodiversity intactness (MSA) in rivers and 15% in floodplain wetlands (Janse *et al.*, 2015). In 2050, these figures may grow to 23% and 20% due to the projected increase in hydropower capacity in the Trend scenario.

Flood protection challenges

It is estimated that the population living in flood-prone areas will be $1.3 * 10^9$ by 2050, or 15% of the global population; an increase of $0.3 * 10^9$ compared with the present situation, due to a combination of urbanisation, land-use changes and increasing climate variability (Ligtvoet *et al*., 2014). The Trend scenario showed that 50% of the 88 cities with more than 5 million inhabitants by 2050, will rank highest with respect to vulnerability to coastal and river flooding, based on the size of the population exposed and gross domestic product per capita (Visser *et al*., 2012). In these same densely-populated areas, 'squeezing' rivers into narrow channels to facilitate navigation increases the risk of rivers overflowing during peak flows. Levees and embankments for flood protection have eliminated many biodiversity-rich floodplains, and connectivity between river, side-channels and wetlands has been lost. Likewise, the channelisation of smaller streams and the construction of embankments around lakes lead to loss of habitat diversity, riparian vegetation and fish spawning grounds.

Potential of the pathways

For a number of interventions or pressure factors in the Trend scenario, the impacts on the biodiversity intactness in aquatic ecosystems have been estimated: wetland conversion, impacts of land use in river catchments including pollution by nutrients (eutrophication) and major hydrological changes (Janse *et al*., 2015). According to the model, this will result in a considerable further decrease of (world-averaged) aquatic biodiversity intactness (Figure 1), the major decreases to be expected in Africa, Latin-America and parts of Asia. Subsequently, the three development pathways show different reductions in biodiversity intactness (Figure 1). The pathways have different impacts across regions and none of these are beneficial for all aspects of biodiversity in all regions of the world. The options incorporated in each of the three pathways are denoted with an asterisk (*) in Table 2. These are mainly related to land use, water use and pollution reduction. Other nature-based solutions for water management can be envisaged that reduce the pressures on aquatic ecosystems, such as catchment management and different hydropower options,

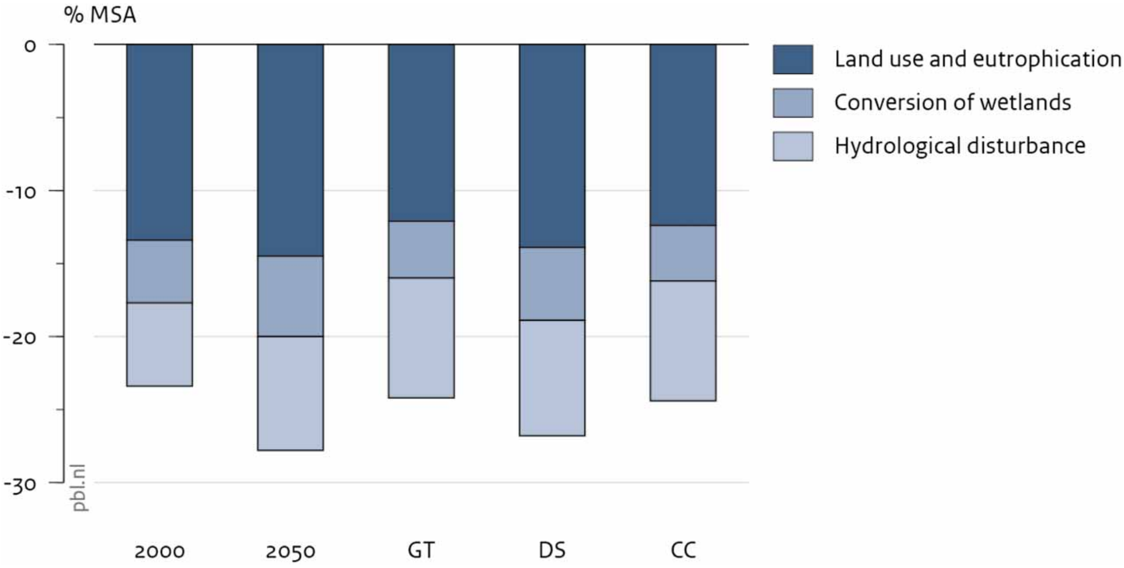

Fig. 1. Pressures driving global-averaged freshwater biodiversity loss under the Trend scenario (2050) and three development pathways (GT: global technology, DS: decentralised solutions, CC: consumption change). *Source:* PBL (Kok *et al*., 2014).

Table 2. Overview of challenges and options per sub-sector.

	Cities	Water for food	Hydropower	Flood protection
Main challenge	Clean water supply Waste disposal	Water shortage	Reliable low-silt flows	Vulnerable cities
Main impact	Pollution through wastewater	High water abstraction Pollution through nutrients and agrochemicals	Disruption of rivers	Disruption of rivers
Nature-based options				
GT	Improved water and waste treatment (*)	Improved resource efficiency(*) Genetic engineering	Regulatory installations	–
DS	Catchment protection Wastewater reuse	Multipurpose agroecosystems (*)	Alternative locations Watershed management	Natural infrastructure
CC	Waste prevention (*)	Reduced demand for animal products (*)	Alternative energy sources	–

(*) These options are included in the modelling of the pathways as shown in Figure 1.

but these were not yet included in the current model analysis (which was restricted to broad-scale developments, as explained before). Their potential, however, is discussed in the sections below.

Under the GT pathway, less agricultural land is required due to enhanced crop and animal productivity, thus reducing the need to convert wetlands. Productivity increase is enhanced by applying advanced technologies to reduce external impacts and create improved varieties and crops, aiming at closed cycles. As food production is intensified and concentrated in high-intensity agricultural areas, local negative impacts on biodiversity, e.g. by eutrophication or water abstraction, may be high in this pathway. Protected areas are realised at a highly aggregated level of realms, with new protected areas being assigned where they are least in conflict with agricultural expansion. Better technologies enable great improvements in urban wastewater treatment.

In contrast, under the DS pathway there is more conservation of biodiversity within agricultural regions and in managed forests, associated with mosaic landscapes with patches and strips of natural land interspersed with agroecosystems. Improved agricultural productivity is achieved through ecological intensification methods, using a variety of techniques including mixed cropping, natural water buffers, erosion prevention, and optimised natural pest control such as Integrated Pest Management. Protected areas are assigned at the detailed level of 779 different eco-regions (Olson *et al.*, 2001) and are more often placed close to existing agriculture, making them more vulnerable. With more dispersed negative impacts, water pollution reduction may be harder to manage. The benefits of lower nutrient losses from less intensively used cropland are apparently counteracted, on average, by the larger cropland area. This pathway shows the smallest benefits on average with respect to the Trend scenario, but that could be an underestimation. Actually, the DS pathway might offer the best opportunities for localised nature-based solutions, which have not yet been incorporated into the models.

In the CC pathway, consumer preferences are assumed to change in favour of less resource-intensive choices, such as less motorised traffic, more end-use water and energy savings, more re-use and recycling, and reduced waste along the food chains. Particularly because of the dietary shift to fewer animal products, less agricultural land is required. Water consumption for food and fibre production is reduced as consumers strive to reduce their water footprints.

Realising pathways and applying nature-based solutions

The potential of the three pathways can be expanded by developing nature-based solutions and water management practices, best implemented at sub-sector level. Such ecological practices of water management will particularly help realise the DS pathway, though the technologically more complicated ones especially fit within GT. Increased demand for ecologically produced food typically fits the CC pathway. Together, these interventions aim to prevent and mitigate the extensive environmental impacts of water abstraction, regulation and pollution on aquatic and terrestrial ecosystems. In the sections below, the different types of nature-based solutions are discussed by sub-sector, how they fit in the three pathways, what potential they have in different contexts and how they may complement each other.

Ecological water management for cities

Modelling the GT pathway included improved treatment of drinking water supply as well as wastewater. Many novel water treatment technologies are available that could be deployed on a larger scale by the municipalities, which benefits aquatic life downstream. This may not be viable in poor countries, where alternative solutions could include collection of urine or central co-composting, as well as more decentralised options.

DS in poor countries could be realised through cheaper alternatives for wastewater treatment, such as reuse. Urban and peri-urban agriculture can turn the nutrients from sewage into fruit, vegetables and fish, thus contributing to more diversified diets in cities, while diminishing the downstream nutrient load. This is already happening in more than 20 million hectares of urban cropland (Thebo *et al.*, 2014). Precautions are needed to avoid environmental or health risks (e.g. Karanja *et al.*, 2010). Combinations of treatment and aquifer recharge are also applied, where after initial treatment the soil acts as a natural secondary filter and the groundwater can be used for various purposes (Qadir *et al.*, 2015). Subsequently, using wastewater for greening of the city itself, in parks, forests, wetlands and urban agriculture, can enhance urban biodiversity as well as serve multiple ecosystem services, such as flood and temperature regulation. Likewise, the DS pathway offers options for protection of biodiversity and natural vegetation in catchment areas. Water boards and drinking water companies can help protect watersheds by actively stimulating land-use practices that cause less pollution, or preserve natural elements in the landscape. Such measures deliver cleaner water to cities more reliably and help reduce erosion and prevent floods (see also the discussion on payment for environmental services (PES) below).

CC could play a role in diminishing spillage of high quality drinking water and help reduce pollution in cities through waste prevention. Similarly, pollution prevention and reduction, by improving the quality of water resources upstream, reduces urban treatment costs and helps secure the supply and meet the demands of multiple users.

Ecological practices in water for food

Under the GT pathway, most potential improvement has been modelled to be achieved through technology and farming practices that increase resource efficiency (of water and other resources). Agrochemical companies are under pressure to produce pesticides that break down much quicker than currently applied formulas so that groundwater pollution is reduced, and soil stabilisers are being developed to combat erosion and land degradation. Evolving remote sensing technology is used to determine the timing of crop watering or drainage, but also to monitor pests (allowing for more environment-friendly control measures). Intensive closed-basin aquaculture, in which water is recycled and treated with filters and disinfection technologies, has a very high water use efficiency (Bunting, 2013). This complies with certification schemes in aquaculture, such as the ASC[2] ecolabel. Animal breeding could lead to the development of animals that are more food-efficient, while modern livestock management practices have the potential to reduce local water pollution and eutrophication.

As part of DS at the landscape level, efforts aim at combinations of nature-based water storage and agroecosystems serving multiple purposes, interspersed with nature. For instance, integrating crops with trees to preserve soil water, cultivating fish in rice fields, or using water harvesting for livestock as well as to prevent floods (Bossio *et al.*, 2010; Boelee, 2013). Diversity in fields and landscapes also helps increase ecosystem health and biodiversity, thus contributing to increased resilience (Jarvis *et al.*, 2007). For example, canals and hedgerows can also serve as corridors for fish and other wildlife, respectively; buffer zones around lakes and streams may reduce water pollution, while providing a habitat for predators of crop pests (Vohland & Boubacar, 2009; Boelee, 2013). Conservation of aquatic ecosystems would also enhance their function as a habitat for fish and benefit the inland fisheries sector.

Similarly, CC, driven by opposite lifestyle trends, would change the face of agriculture, its ecological and water footprints, as well as productivity. A shift towards more vegetable and less animal-based food, as well as reduced waste of food will have important impacts (included in the scenario modelling), like water savings, a reduced water footprint and reduced pressures from land-use and pollution. Consumer awareness of the ecological footprint and water consumption of food products will be an important lever to achieve this.

Sustainable hydropower

With the construction of many new hydropower stations in Asia, Africa and South America underway, sustainability concerns could be included from the onset and help realise the modelled pathways. There are opportunities in the phases of planning (location), construction/filling and operational management of the power plants, though the actual application is currently limited (International Energy Agency (IEA), 2006).

The GT pathway offers opportunities in the construction stage to include hi-tech infrastructure, such as multiple spillway valves that allow precise flow regulation (e.g. at the Hume dam in Australia) or fish elevators (e.g. at the Winooski Falls dam in the USA). Modelling can support optimisation of water releases for multiple purposes (Richter & Thomas, 2007; Smokorowski *et al.*, 2009; Kim *et al.*, 2012). Once the technology is in place, ‘sustainable dam management’ in the operation phase offers the possibility to release environmental flows to downstream ecosystems, to the benefit of biodiversity, fish migration and other services (Pittock, 2010). Ensuring water flows of the right quality at the right time is particularly crucial in river basins where upstream water abstractions have reduced the natural dry season water flows (Arthington *et al.*, 2009).

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[2] Aquaculture Stewardship Council; see www.asc-aqua.org.

DS at the planning and design stage could support the selection of dam locations with the least impact, for example in selected side branches instead of spread over the whole river, and using nature-based solutions at the landscape level, such as natural floodplain areas. These can be identified through the Hydropower Sustainability Assessment Protocol, which supplies useful guidance promoting ecological design (International Hydropower Association (IHA), 2014). In this protocol, the natural flow is controlled as far as possible in the reservoir filling phase and during operational management, using infrastructure that allows the passage of migratory fish and other aquatic species, as well as sediments. Hydropower plants benefit from intact vegetation in the upper catchments, as this prevents erosion and reduces the sediment load to the reservoirs (Wunder *et al.*, 2008), thereby reducing costs for dredging and increasing the life span of dams. Water quality in the reservoir itself could be managed, for instance by the restoration of habitats in riparian areas, together with effective monitoring and barriers against invasive species. Other measures that would fit within the DS pathway include retrofitting existing dams to make them serve multiple purposes and protect multiple ecosystem functions, for instance by adding fish passages (Calles & Greenberg, 2007; Williams, 2008). More drastic restoration options may involve the removal of an existing dam and its placement at another location where it causes fewer disturbances to the river system. In the Penobscot River (Maine, USA) two dams in the lower river were replaced with new dams in side branches. This reduced the disturbance to river flow and fish migration while the same hydropower capacity was maintained (Opperman *et al.*, 2011).

As part of the CC pathway, energy savings could reduce the demand for hydropower, though being more difficult to achieve in growing economies. Moreover, various alternatives to hydropower from large dams are currently available that are both more sustainable and more cost-effective than conventional dams (Totten *et al.*, 2010; Ansar *et al.*, 2014). These may be driven by the public as people become more aware of the environmental impacts of hydropower.

Nature-based flood protection

As the limits of conventional solutions to water regulation have become apparent, nature-based solutions increasingly play a role in flood control (Cohen-Shacham *et al.*, 2016). These are generally not high-tech, rarely influenced by consumers and largely effective at the basin level, so would contribute to the DS pathway. Natural infrastructure such as wide river floodplains with connected biodiversity-rich wetlands can be a cost-effective alternative to artificial embankments for flood protection (Department of Conservation, 2007; Pittock & Xu, 2010; United Nations Environment Programme (UNEP) *et al.*, 2014). For coastal protection too, intact coastal ecosystems such as estuaries, mangroves and salt marshes can help protect shorelines and coastal communities from the effects of disasters such as flooding and high waves. However, in places where almost all land is allocated and rivers are regulated (for instance in and near cities), nature-based solutions may be less feasible or be more expensive simply because such infrastructure takes up more space than conventional measures.

Towards implementation

The various interventions discussed above can contribute to the biodiversity targets for 2050 and address the multiple challenges in water management. While the modelled scenarios each have their emphasis, in reality different pathways will be followed to various extents across the world. Current investment mechanisms exist at city level, in agriculture, for hydropower and flood protection, so implementation of nature-based solutions needs effectively to be carried out by (sub)sectors, such as municipalities, waterboards and hydropower companies. Mainstreaming biodiversity into policy requires coordinated planning through, for example, Integrated Water Resource Management (IWRM) guided by the ecosystems approach, followed by implementation of nature-based solutions.

Integrated water management

Several of the nature-based solutions applied in sub-sectors serve multiple objectives and would benefit from integrated planning and coordination across sectors, for instance by district- or province-level authorities or by river basin organisations. Examples of multifunctional interventions include the use of natural infrastructure, safeguarding environmental flows, PES schemes and river and lake restoration. Wetlands or other nature-based solutions can be used for water storage but also improve water quality. Environmental flows, particularly preserving river flow in the dry season, often also serve the needs of recreation and tourism, now among the world's dominant economic sectors. PES schemes can be run by basin organisations or as direct contracts, e.g. between hydropower companies and groups of farmers or fishers and serve upstream and downstream interests alike. Well-designed restoration projects at natural streams or lakes reverse current degradation of aquatic ecosystems, restore biodiversity and safeguard their ecosystem services.

Theoretically, integrated planning can direct and strengthen sectoral implementation of multipurpose nature-based solutions. This is in line with the principles of IWRM, as are environmental flows. Globally, interest in water management for a broader range of ecosystem services is increasing. Strengthening and expanding the capacity for nature-based solutions in IWRM would offer excellent opportunities for mainstreaming biodiversity in water management (WWAP, 2015), as would the inverse: addressing water management challenges as part of an ecosystem approach (Cohen-Shacham *et al.*, 2016). However, in practice the designated river basin organisations do not always succeed in implementing even the basic principles of IWRM, due to various barriers (Medema *et al.*, 2008; Chéné, 2009).

Barriers and levers for a transition to nature-based solutions in water management

Nature-based solutions that serve dual purposes of improved water management and biodiversity conservation are already applied by actors worldwide, but not at a large enough scale to have sufficient impact. There are barriers to their implementation, as well as levers.

Four strong *barriers* prevent upscaling of these interventions into policy and biodiversity mainstreaming with global impact. First, while there is increasing political will at various scales (local, national, regional, and global), there may not be sufficient commitment to implementation. The various actors may sustain unequal relations, and conflicting interests between countries about water issues may hinder an integrated vision. Second, governance of water is dispersed and complex, with many competing interests. Although IWRM is a well-known approach that theoretically involves every important actor, only 10% of countries have actually adopted it (Global Water Partnership (GWP), 2014) and practical implementation is at best partial. Third, measures for reducing biodiversity loss, such as nature-based solutions, can be complicated and appear as win-win solutions mainly in the long term whereas immediate economic gains are less clear. Besides, costs and benefits are often unequally divided between various private and public sectors. Heavy modifications to rivers or other water bodies are often difficult to reverse, with present land use and land ownership limiting restoration possibilities. Moreover, mainstreaming biodiversity requires more knowledge of the basin and water system (van der Zaag, 2010). Fourth, innovative organisational arrangements are needed to support the integrated planning of ecological approaches and the implementation of nature-based solutions in the various (sub) sectors. This is because the success of measures often will depend on the actions of sectors other than water management only.

Conversely, specific *levers* can help the implementation of an ecosystems approach, such as the increasing public desire in many countries for landscape interventions and the availability of alternative technologies and nature-based solutions. The insight that nature-based solutions can yield multiple ecosystem services (not just energy generation, food production or nature conservation, for example) helps to broaden this support and provides policy space to experiment and learn (Ozment *et al.*, 2015). An interesting example is the current international dialogue on the 'water – energy – food nexus' that is used by some organisations to involve more stakeholders across levels and promote multifunctional ecosystem-friendly approaches (Krchnak *et al.*, 2011). At the global level, initiatives such as the Global Environmental Facility and its various programmes, such as the Transboundary Water Assessment Programme (www.geftwap.org), have contributed to better insights into the integrated management of international water systems and their associated risks. The more widespread use of cost-benefit analyses that consider the full valuation of ecosystem services could serve as a lever to demonstrate in what circumstances and under what conditions nature-based solutions, traditional architecture or a combination of the two are the most cost-effective. New eco-engineering decision support models are available that guide the selection of the best infrastructure options that tackle both water management problems and sustainable ecosystem services (UNEP *et al.*, 2014; Poff *et al.*, 2016). Mainstreaming of biodiversity in water management may also serve as a lever in itself, by involving a wider range of stakeholders. As ecosystems approaches like this are generally more knowledge-intensive than traditional ones (van der Zaag, 2010), they offer numerous business opportunities for organisations, SMEs (small and medium enterprises) and individuals that have more freedom to operate outside traditional disciplinary boundaries, supported by scientific approaches that can help identify trade-offs and synergies.

Conclusion

Future projections have shown challenges in water management, such as water shortages, pollution and deterioration of aquatic ecosystems, further aggravated by urbanisation, climate change and increasing demands for food production and hydropower. Scenario analysis of three alternative pathways targeted at the reduction of biodiversity loss while achieving SDGs helped to identify nature-based solutions that address water management challenges. Our review showed that many promising examples of such interventions exist and have potential for simultaneously addressing water and biodiversity concerns.

The successful mainstreaming of biodiversity in water management is a multi-faceted, long-term and often decentralised process, requiring new engagements between the biodiversity community, water managers and the various sub-sectors analysed in this paper. Mainstreaming biodiversity will require more awareness and knowledge, experimentation and experience sharing but has high potential for upscaling and implementation across scales. The required innovation, nature-based infrastructure and novel applications of high and low technologies, will offer great opportunities for business and development of new solutions by engineering and consulting companies alongside public authorities. Support of public authorities in the long term will be an important lever, as is the inclusion of major stakeholders.

Challenges in the water sector and biodiversity conservation goals can best be jointly addressed at the problem identification and planning stage via integrated adaptive approaches such as IWRM, while implementation is best carried out at (sub) sector level. Issues of water scarcity, pollution and infrastructure need specific local solutions that take into account the specific needs and constraints of cities, water for food, hydropower and flood protection. If biodiversity and healthy ecosystems are systematically integrated in water, energy, agriculture and other sectors and supported by policy, strong institutions and funding, ecological practices can be more widely implemented and promote the SDGs on water and biodiversity.

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