Hidden treasures: Human-made aquatic ecosystems harbour unexplored opportunities

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Abstract Artificial water bodies like ditches, fish ponds, weirs, reservoirs, fish ladders, and irrigation channels are usually constructed and managed to optimize their intended purposes. However, human-made aquatic systems also have unintended consequences on ecosystem services and biogeochemical cycles. Knowledge about their functioning and possible additional ecosystem services is poor, especially compared to natural ecosystems. A GIS analysis indicates that currently only ~ 10% of European surface waters are covered by the European Water Framework directive, and that a considerable fraction of the excluded systems are likely human-made aquatic systems. There is a clear mismatch between the high possible significance of human-made water bodies and their low representation in scientific research and policy. We propose a research agenda to build an inventory of human-made aquatic ecosystems, support and advance research to further our understanding of the role of these systems in local and global biogeochemical cycles as well as to identify other benefits for society. We stress the need for studies that aim to optimize management of human-made aquatic systems considering all their functions and to support programs designed to overcome barriers of the adoption of optimized management strategies.

Keywords Artificial waterbodies · Biogeochemistry · Ecosystem services · Water management

INTRODUCTION

Aquatic ecosystems are archetypal society–biosphere interfaces: civilizations not only settled near surface waters but shaped them according to their needs (Naiman 1995). On a local level, aquatic ecosystems provide resources and supporting services as well as absorb, cycle, and transport nutrients and waste (Grizzetti et al. 2016). At a global level, aquatic ecosystems play an important role in most of the Planetary Boundaries processes—freshwater use, land-system change, biosphere integrity, biogeochemical flows, ocean acidification, and climate change (Rockström et al. 2009; Steffen et al. 2015).

As water underlies most of Agenda 2030’s sustainable development goals (United Nations 2015) the management of water systems is key to sustainable development. However, even though social, ecological, local, and global functions of aquatic ecosystems are deeply intertwined, especially in human-made systems, connections between such functions are seldom considered in the monitoring of these systems (Jaramillo and Destouni 2015). Research on human uses and needs of water systems is often disconnected from research focusing on biogeochemical processes, element cycling, and ecological functioning (Vlachopoulou et al. 2014). Nonetheless, it is at the intersection of societal uses, needs, and biogeochemical functioning that effective management strategies can be found (Linton and Budds 2014; Olden et al. 2014).

The EU Water Framework Directive (WFD) implements an integrated river basin management for Europe with one objective to all of the member states—good status for all waters by a set deadline (EU 2000). The WFD as well as similar regulations in other countries as the Water Quality Standards by the US Environmental Protection Agency or the Water Quality Guidelines of the Canadian Council of

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Resource and Environment Ministers, principally focus on assessing whether a water body has a good ecological status or not (Birk et al. 2012). Such an inter-governmental, and integrated basin-wide approach to monitoring of water bodies is one of the most efficient (Teodosiu et al. 2003) and most ambitious instruments for water protection (Moss 2008; Voulvoulis et al. 2017), and calls for inclusive and participatory management strategies (Kaika 2003; Boyer et al. 2018). Adaptive management strategies are demonstrably effective in managing complex aquatic social-ecological systems (Folke et al. 2002), such as dams (Berkley 2013; Olden et al. 2014) or larger landscapes such as the Everglades (Gunderson 2001). Adaptive management strategies are key to managing surprises and incorporate learning (Gunderson 2001; Folke et al. 2002), to address diverse needs and perceptions of ecosystem status and dynamics (Boyer et al. 2018). They are in this way the appropriate toolbox to address the diversity of aquatic systems that contribute to and are shaped by biogeophysical processes from the local to global scales. A first step to implementing adaptive management strategies lies in recognizing the diversity of aquatic ecosystems from their biogeophysical and social perspectives.

Taking Europe as an example, the WFD only covers a fraction of existing surface waters (SW) (Fig. 1). A first estimate using public databases reveals that roughly 90% of European freshwater bodies (lakes, rivers, streams) fall outside the WFD (Table 1 and [Supplementary material](#)), pointing to a large information gap in terms of numbers, area, volumes, hydrology, biogeochemistry, ecology, and ecosystems services of freshwater systems. Our analysis shows that the WFD reporting covers about 70% of Europe's surface water area, and it specifically fails to address small water bodies which are known to have a disproportionately high impact on biogeochemical cycles (Holgersson and Raymond 2016). Importantly, though it aims to include ecological and societal ecosystem functions and requirements, the WFD fails to address certain aspects, such as the water-based processes that contribute to greenhouse gas (GHG) emissions (Moss et al. 2011). The fact that artificial waterbodies are mostly excluded from the proposed U.S. Clean Water Rule (EPA 2015) shows that our conclusions are not restricted to Europe.

In this paper, we put the spotlight on a group of SW that receives little attention in the WFD: human-made aquatic systems. They are typically created and managed for very proximal goals of economic or industrial functionality, with little consideration of their broader environmental or social impacts and benefits. Human-made water bodies are omni-present and can be crucial functional, aesthetic, economic, and logistical components of a landscape. In the Netherlands, for example the $\sim 300 \times 10^3$ km of ditches in a country of just 41×10^3 km² serve important roles in

agriculture and significantly shape the landscape. However, there are often poor estimates of the quantitative and qualitative importance of human-made waters. A notable exception are reservoirs, which are incorporated in the Global Lakes and Wetlands Database (Lehner et al. 2011b) and which have also already been included in the IPCC Guidelines on wetlands (IPCC 2006), though these guidelines highlight the paucity of data on reservoirs and that monitoring methods are not particularly specific to these types of waterbodies. Nonetheless, reservoirs are probably the best studied human-made SWs (Table 2), probably because they are very similar to lakes and in the case of drinking water reservoirs and reservoirs with recreational function their water quality is of direct importance for the intended function. In the case of hydropower dams, their greenhouse gas emission is important to enable comparison with other energy generating practices. An illustrative example how improved management options may create win-win situations are variable water withdrawal depth systems in reservoirs which not only can be used to optimise water quality in the reservoir but also to regulate downstream water temperature (Weber et al. 2019). We expect that like reservoirs (Lehner et al. 2011a), other human-made systems are likely to be patchily distributed over the globe and regionally highly abundant. We recognized a number of different aquatic systems: ditches, fish ponds, fish ladders, and small weirs, irrigation channels, and pump storage plants.

Here we show that there is a mismatch between the potential importance of human-made aquatic ecosystems and existing research. Our hypothesis is that human-made aquatic systems have diverse and significant effects on biogeochemical cycles and provide a range of different ecosystem services across scales (Fig. 2). Better knowledge and monitoring of these systems would enable us to manage them effectively for sustainable use. We focus our analysis on Europe but are convinced that our conclusions are also valid for other parts of the world, especially in the under-studied southern hemisphere. In the following sections, we present some examples of under-studied human-made aquatic systems. Based on that we develop a research agenda setting human-made water bodies at the nexus of social-ecological systems to uncover their roles in societal and biogeochemical processes and address their multifaceted management challenges.

DITCHES

Lowland ditch networks have primarily been constructed for drainage purposes (Dollinger et al. 2015). The proximal goal of most ditches is to maintain water levels such that agricultural revenues are optimized. Ditches, however,

Fig. 1 100 km² details of exemplary landscapes in different European regions. Colouring denominates surface water body differentiated by type. Maps were drawn by combining spatial datasets of surface waters covered by the WFD (EC 2017) and a total inventory of European surface waters (EC 2016) as explained in the Supplemental Information Fig. S1. Ditches, drainages, or other SW which were only recorded as 2-D linear structures are not present in the dataset (c.f. Supplemental Information Figs. S1 and S3). Different shades of grey are used for the map background, e.g. forests or urban areas. The maps are centred around Amersfoort, the Netherlands (a), Leipzig, Germany (b), Tábor, the Czech Republic (c) and Lleida, Catalonia (d) (Fig. S2). EU-Hydro dataset © European Union, Copernicus Land Monitoring Service 2018, European Environment Agency (EEA)

fulfil many other ecosystem services such as flood attenuation, water storage, water purification, and biodiversity conservation (Dollinger et al. 2015). Additionally, they play a vital role in how the landscape is appreciated, thereby influencing the recreational value of an area (Hahn et al. 2018). The contribution of ditches to these different

ecosystem functions can vary substantially as a function of ditch characteristics such as morphology, flow velocity, and trophic state as well as their connection to other surface waters (including other ditches) and to urban infrastructure (Herzon and Helenius 2008).

Table 1 Surface waters (SW) in Europe and their coverage by the water framework directive (WFD), i.e. reported in the Water information System for Europe (WISE). Numbers were calculated by combining spatial datasets of surface waters covered by the WFD (EC 2017) and a total inventory of European surface waters (EC 2016) as explained in the Supplemental Information

	Number		Area		Area (km ²)	
	<i>n</i>	(%)	(km ²)	(%)	Avg	Median
Total SW	253 099	100	407 820	100	0.4	0.04
Natural water body (in WISE WFD database)	14 946	5.9	62 992	55.9	4.2	0.92
Heavily modified water body (in WISE WFD database)	2438	1.0	14 739	13.1	6.0	0.91
Artificial water body (in WISE WFD database)	918	0.4	2084	1.9	2.3	0.42
Detected SW with missing information in WISE WFD database	234 797	92.8	32 804	29.1	0.1	0.03

Table 2 Literature survey using Google scholar done on 21.6.2018

Search term	Hits
Lake	3 720 000
Stream	4 710 000
Reservoir	3 640 000
Weir	1 010 000
“Drainage ditch”	26 000
“Fish pond”	31 700
“Fish ladder” or “fish pass” or “fish passage” or “fishway”	22 600
“Pump storage reservoir”	147
“Irrigation channel”	13 700

Ditches were recently identified as hotspots of GHG emissions to the atmosphere (Vermaat et al. 2011; Hyvonen et al. 2013; Luan and Wu 2015). A limited number of measurements in Dutch ditches, for instance, indicate average diffusive CH₄ emissions of 800 mg CH₄ m⁻² day⁻¹ (Schrier-Uijl et al. 2011). A simple extrapolation based on the total length of ditches in the Netherlands (Higler 1979), with a very modest estimated average width of 1 m, results in total ditch emissions of 2.4×10^5 kg CH₄ day⁻¹ ($\sim 8.2 \times 10^6$ kg CO₂-eq day⁻¹). Given total CH₄ emission of the Netherlands (Coenen et al. 2017), our extrapolation suggests that ditches may be responsible for 16% of national emissions. We need more research to understand the importance of ditches with respect to GHG emissions and to identify the main drivers of the variability in emissions. This information is necessary to upscale emission estimates from individual ditches to national or international scales.

The maintenance of ditches strongly influences their performance with respect to the services they provide. Trade-offs between these services often exist. Dredging and weeding improve waterlogging and decrease the release of nutrients from the sediments but may negatively impact biodiversity (Dollinger et al. 2015). Other measures may benefit multiple services: by reducing nutrient loads to ditches, for example, submerged plants can outcompete

floating plants. This contributes to achieving a Good Ecological Status and may potentially also decrease N₂O and CH₄ emissions, increase denitrification (Veraart et al. 2011), and increase phosphorus retention. Ditch management is clearly multifaceted, and we need to better understand how we can optimize ditch management to serve different ecosystem services simultaneously in a cost-effective way. Indeed, given the important contribution of ditches to agricultural services on the one hand, and to GHG emissions on the other hand, well-informed management can have substantial effect on sustainable agricultural processes and climate change mitigation.

FISH PONDS

Aquaculture ponds are human-made aquatic ecosystems whose main function is the production of fish or other aquatic organisms. They are distributed all over the world, from temperate to tropical regions. According to statistical data of the Food and Agriculture Organization of the United Nations, the total global surface area of freshwater aquaculture ponds is estimated to be 87.5×10^3 km² (Verdegem and Bosma 2009) which is a substantial area given that the total area of small (0.002 and 0.01 km²) natural lakes and ponds is estimated to be 50.7×10^4 km² (Verpoorter et al. 2014). Fish ponds are widespread—especially in countries where natural lakes are sparse—and are used predominantly for fish production. For instance, fishponds cover 1200, 460, 420, 410 and 270 km² in France, Poland, Germany, the Czech Republic and Hungary, respectively, covering 0.1–0.5% of the countries’ area (IUCN 1997). In some regions like the Czech Republic most of the surface waters not covered by the WFD are human-made ponds (Fig. 1c). In the Czech Republic only the 24 largest fishponds (representing $\sim 13\%$ of total fishpond area) have been included in the national evaluations and management focus of the WFD.

While the primary purpose of aquaculture ponds is production, they also provide various other ecosystem

Fig. 2 Scheme visualising the mismatch between significance and scientific knowledge of human-made aquatic ecosystems

functions such as flood regulation, climate regulation, maintaining structural complexity, and biodiversity within the landscape, and/or retention of sediments, organic matter, nutrients, and micro-pollutants and can be used for recreation (Boyd et al. 2010; Gaillard et al. 2016; Four et al. 2017). Individual pond purposes may conflict with each other, with the most common trade-off between needs to maximize fish production and needs for good water quality, water manipulations, and ecosystem services (Pechar 2000; Verdegem and Bosma 2009).

Productivity of fishponds is generally maintained through direct feeding of cultured fish or by adding manure to increase trophic conditions and augment food webs, which leads to increased availability of fish forage (Pechar 2000; Boyd et al. 2010; Chen et al. 2016). However, usually only a small part of feed and manure inputs are converted into fish biomass, because of low utilization efficiency [4–27%; (Hu et al. 2012; Chen et al. 2016)]. A large fraction of the added organic materials and nutrients ends up accumulating within aquaculture systems or is discharged into river networks (Chen et al. 2016; Yang et al. 2018). Organic remains (e.g. uneaten feeds, feces) originating from aquaculture production promote eutrophication, high phytoplankton biomass and provide supply of labile nutrients (C, N and P) to microbes which can stimulate microbial decomposition and subsequently GHG emissions (Yang et al. 2018) as well as nitrogen removal by denitrification (Chen et al. 2017). Recent studies suggest that aquaculture ponds in tropical and subtropical regions

might play a significant role in global GHG emissions (Boyd et al. 2010; Hu et al. 2012; Yang et al. 2018). For aquaculture ponds in temperate regions, however, representative data relating GHG emissions to the intensity of production are still rare and have been omitted in GHG inventories even in countries with a prominent aquaculture sector like the Czech Republic (CHMI 2017).

WEIRS, IRRIGATION CHANNELS, AND FISH LADDERS

Mankind has been damming rivers and streams and diverting water for millennia. In addition to their intended purpose, dams provide many ecosystem services like flood protection, water provisioning, fisheries, recreation, navigation, and energy. They also alter local hydrology, landscapes, downstream flow regimes, sediment transport, fish migration, and the whole biogeochemical ecosystem functioning, jeopardizing the services provided by the ecosystems that damming destroys locally or impacts downstream (Nilsson et al. 2005).

Dams are divers and the discrimination between dams and weirs is not always clear (Poff and Hart 2002). Large dams have attracted most research on ecological impacts of river regulation and on ecosystem services related to the presence of dams (Thornton et al. 1990; Straskraba et al. 1993). However, many river networks in developed countries are populated by a myriad of small retention structures (e.g.

weirs) that frequently escape attention of researchers and the general public, because their impacts and associated ecosystem services are not as conspicuous and obvious as those related to large dams (Couto and Olden 2018). Nonetheless, small artificial water bodies like weirs are extremely active in terms of biogeochemical processes, profoundly modifying the structure and functioning of river ecosystems far downstream from their location (Fencl et al. 2015). They harbour a number of ecosystem services providing benefits for society like power generation, irrigation infrastructures, or recreation (Winemiller et al. 2016). This is particularly true in arid and semiarid countries, where natural lowland lakes are scarce, and human-made ecosystems such as weirs are often the only lake-like features in the landscape.

Trade-offs between societal benefits and costs of dams are a classical topic in ecosystem services assessment (Dugan et al. 2010). Because different groups (e.g. environmentalists, freshwater ecologists, resource users) often see weirs and retention structures in general as an intrinsic negative impact on river networks (Boyer et al. 2018), decisions on how to manage those artificial water bodies (including their removal from the landscape) must be based on a balanced assessment of the relations between ecosystem services, the societal benefits they produce, the distributions of benefits, and the permanent co-evolution of these relations (Linton and Budds 2014). There are examples where stakeholder perceptions of different ecosystem services have been considered [e.g. Reilly and Adamowski (2017)]. However, holistic and adaptive approaches are not mainstreamed into the monitoring and management of smaller yet pervasive human-made aquatic systems.

Such a holistic assessment would be far from complete without consideration of all infrastructures associated to weirs. Many weirs are built to keep the water level constant to divert water for power generation or irrigation through a diversion channel network of varying complexity. Water withdrawal through these micro-topographic human-made features heavily alters natural flow regimes. The resulting decreased stream flows impact the whole biogeochemical functioning of downstream ecosystems (Richter et al. 2003). Moreover, studies performed in similar systems like roadside ditches suggest that diversion channels may also constitute biogeochemical cycling (Buchanan et al. 2013), potentially affecting ecosystem services related to nutrient abatement or GHG emissions. However, the contribution of irrigation channels to biogeochemical cycles and ecosystem services of the overall river network are overlooked. Nonetheless, diversion channels, particularly those devoted to irrigation, may also be a piece of the cultural landscape and constitute both tangible and intangible heritage assets (Martínez-Sanchis and Viñals 2015).

Weirs and dams have no or only very limited fish passage, in this way blocking or hindering fish migrations in

those systems (Katopodis and Williams 2012). Because fishes play an important role in ecosystem biodiversity and are crucial as food, installing fishways on weirs or dams was a logical step. Over the past century, water engineers, politicians, and the general public have increasingly called for the construction of fish passages, especially fish ladders. Implementation of the WFD enhanced the construction of different types of fish passages in the dammed rivers where presence of fishways was sufficient to achieving a good ecological status. As a result, many river dams are nowadays equipped with ladders and other facilities, to manage fish populations in riverine systems.

Fish ladders (also “fish pass”, “fish passage” or “fish-way”) have been studied globally with different methods. A search in Google scholar yielded 22 600 hits containing at least one of these 4 keywords (Table 2). Most of these hits (around 80%) address the role of fish ladders in fish migration. About 10% of the works on fish ladder systems also mention water chemistry or ecosystem services. Screening of the papers reveals a general lack of knowledge on how the fish ladders could affect the local water chemistry of the river, for example, the level of oxygenation, decomposition of organic matter, or GHG emissions. Though there is much knowledge on how fish ladders help salmonid fishes to reach the upstream spawning grounds, little is known about the effects of fish ladders on other fish populations, other biological communities and food web structures in the water body as a whole, nor on benefits to the surrounding environment and its users.

PUMP STORAGE RESERVOIRS

Pump storage reservoirs are the most established technology for short-term storage of electrical energy [globally 130 GW (Barbour et al. 2016)]. They consist of two reservoirs connected by a pump-power plant (the lower reservoir can also be a river, lake, or sea). During periods of excess electricity water is pumped uphill from the lower reservoir into an upper storage reservoir. The systems are used to buffer mismatches between production and consumption of electricity. Their importance will likely increase in the future with the increase in wind and solar energy production (Steffen 2012), energy sources with less regular intensity than conventional power plants. Currently the management of pump-storage plants is almost exclusively dictated by the electricity market (Perez-Diaz et al. 2015) with few restrictions due to tourism and/or fishing interests (Patocka 2014).

Pump storage plant operation creates rapid water level changes and modifies stratification in the reservoirs (Ibarra et al. 2015). It has been suggested that this has a number of environmental impacts, including bank erosion, water temperature variations, instable ice cover, spreading of

species, extension of the littoral, increased turbidity, killing of larger animals as well as problems related to aesthetics, tourism, and fishing (Patocka 2014; Hirsch et al. 2017). However, to our knowledge, these effects have never been systematically investigated. In Google scholar, there are only 147 hits for “pump storage reservoir” (Table 2) of which most are about technical issues. We suspect that high-frequency water level fluctuation should also affect biogeochemical cycling in the reservoirs. Some of these effects could be beneficial. Indeed, Potter et al. (1982) found that pump storage operation oxygenated the lower reservoir which resulted in precipitation of iron bound phosphorus and thus, lower nutrient concentrations. Water level fluctuations probably temporarily oxidize littoral sediments, which is likely to in turn increase the binding of phosphorus to ferric iron (hydr)oxides, increases nitrogen removal by coupled nitrification–denitrification, and might also shift GHG emissions from CH₄ to the less radiative active but longer dwelling CO₂ (Marcé et al. 2019).

SYNTHESIS

Biogeochemical cycling takes place in all human-made aquatic ecosystems. However, the functioning and roles of these systems are poorly understood and clearly understudied given their environmental and societal importance. Though many characteristics (such as GHG emissions, nutrient turnover, biodiversity) are common to all aquatic systems, their dynamics (e.g. water level fluctuation rates) and combinations of environmental and societal services are often specific to the type of human-made aquatic ecosystem and to the social-ecological environment in which they are embedded. In this way, social-ecological analyses of human-made waterbodies are clearly essential to (a) understand and monitor the full spectrum and magnitude of roles and impacts of aquatic systems in local and global biogeochemical processes and to (b) identify management strategies optimal to addressing multiple services. Importantly, as human-made systems, these water bodies can provide useful and usable systems to test and monitor processes that take place in less manipulable natural systems and thus serve as experimental setups on which to design and test innovative management options and monitoring frameworks.

Considering the potential impact of human-made surface waters on biogeochemical cycles, our knowledge about these systems is surprisingly poor. IPCC’s guidelines for National Greenhouse Gas Inventories have only recently expanded from only including reservoirs (IPCC 2006) to include drainage ditches in a wide range of soils and land-uses (IPCC 2014) and will likely further expand in the upcoming 2019 revision. This will likely trigger

further studies in these systems. In comparison with natural waters, these systems appear to be vastly under-studied (Table 2). We have here identified a number of important knowledge gaps:

- Information about the abundance and areal coverage of these systems is still poor. This information is the basis for upscaling of effects.
- Information about biogeochemical cycling in these systems is poor. It is not clear to what extent biogeochemical functioning of these artificial water bodies systems is comparable to or deviates from natural systems.
- The multiple social-ecological services provided by different human-made water bodies have to be identified.
- Management options and their interaction with and effect on biogeochemistry are not sufficiently explored.

From an anthropocentric point of view, the net outcome of the biogeochemical functioning can be either positive (e.g. nitrogen removal by denitrification) or negative (e.g. CH₄ emission). It is necessary to close all these research gaps in order to optimize the benefits and minimize the negative impacts of human-made water bodies. We argue that large advances in aligning the management of human-made aquatic systems for their multiple benefits still need to be made.

Based on this analysis we propose a research agenda:

- Support the construction of an inventory of different systems. Promising approaches are the use of public databases integrating remote sensing data and workflows, and distributed in situ sensor networks.
- Support and advance research to further our understanding of biogeochemistry of human-made water systems. Especially relevant are studies about GHG emissions and nutrient dynamics.
- Support research into identification of the benefits for society, including fishermen, farmers, industry, governmental agencies, recreational users and visitors that lie outside the immediate functionality of these systems.
- Secure support for studies aiming at the optimization of management of human-made water systems considering the immediate functionality of these systems as well as their other services.
- Support and advance programs designed to overcome barriers to the adoption of optimized management strategies.

Such research will help us to uncover the hidden treasures of human-made aquatic surface waters and manage them for the well-being of future generations.

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