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Water and health: From environmental pressures to integrated responses

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ABSTRACT

The water-related exposome is a significant determinant of human health. The disease burden through water results from water-associated communicable and non-communicable diseases and is influenced by water pollution with chemicals, solid waste (mainly plastics), pathogens, insects and other disease vectors. This paper analyses a range of water practitioner-driven health issues, including infectious diseases and chemical intoxication, using the conceptual framework of *Drivers, Pressures, State, Impacts*, and *Responses* (DPSIR), complemented with a selective literature review. *Pressures* in the environment result in changes in the *State* of the water body: chemical pollution, microbiological contamination and the presence of vectors. These and other health hazards affect the *State* of human health. The resulting *Impacts* in an exposed population or affected ecosystem, in turn incite *Responses*. Pathways from *Drivers* to *Impacts* are quite divergent for chemical pollution, microbiological contamination and the spread of antimicrobial resistance, in vectors of disease and for the combined effects of plastics. Potential *Responses* from the water sector, however, show remarkable similarities. Integrated water management interventions have the potential to address *Drivers, Pressures, Impacts,* and *State* of several health issues at the same time. Systematic and integrated planning and management of water resources, with an eye for human health, could contribute to reducing or preventing negative health impacts and enhancing the health benefits.

1. Introduction

The total of external pressures from the water-related exposome is a significant determinant of human health (Wild, 2012). Water practitioners are faced with unfamiliar challenges as their work not only benefits well-being, but may affect community health negatively. The disease burden related to water consists of communicable diseases (waterborne, water-washed, water-based, and water-related vector-borne diseases) and non-communicable diseases triggered by exposure to chemically polluted water (Johnson and Paull, 2011; Landrigan et al., 2017). Waterborne and water-related infectious diseases account for 3.4 million annual deaths worldwide (estimated for 2004 by Prüss-Üstün et al. (2008)). The Lancet Commission on Pollution and Health estimates 1.8 million deaths worldwide related to 'water' (mainly microbiological contamination) and 0.5 million deaths related to 'soil pollution, heavy metals and chemicals' (chemical pollution) (Landrigan et al., 2017). The Lancet Commission also highlights a group called 'pollution sources not currently quantified', in which for example plastics and pesticides are grouped. Plastic debris, particularly in the form of small particles (microplastics), in oceans, seas, rivers and lakes, has become an important environmental problem because of its ubiquitous prevalence, persistence, accumulation in aquatic food chains and adverse effects on aquatic organisms and potentially to human health (Hermabessiere et al., 2017; Li et al., 2016; Verma et al., 2016; Vethaak and Leslie, 2016; Wright et al., 2013). Many of the pollution sources in the environment include substances or materials for which water can be the main transport or transmission route.

Myers et al. (2013) indicated that more research is needed on the impact of ecosystem alteration or environmental interventions on the ecology of multiple diseases. Water is fundamental to human existence, but in a polluted or contaminated ecological state it may pose a health hazard. Water resources have been extensively managed, or environmentally altered, used and reused, for all kinds of economic reasons, such as drinking, food production, flood control, energy, industry, nature, and recreation, with subsequent effects on water quantity and quality. The many different water uses tend to be managed by various (sub-)sectors in a fragmented way, with varying degrees of attention to water quality. In addition to the obvious links between infectious diseases and water management (Myers and Patz, 2009), this also includes the role of water as a habitat for insects and other vectors and carrier

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for dispersion of pollutants. The latter comprise an increasingly important cause of non-communicable diseases in the global environmental disease load (Prüss-Üstün et al., 2016).

Hydraulic infrastructure and water management practices can influence human health in many ways. Safe water supply and sanitation help prevent faecal-orally transmitted diseases and reduce the pathogen load in the environment. Dikes prevent floods, water storage and irrigation systems provide water for people, animals and crops during droughts, and dams can generate electricity. On the negative side, such infrastructure can promote the growth of toxic algae and create habitats for the propagation of vectors, intermediate hosts and carriers of water-related diseases (mosquitoes, other insects, snails and rodents) (Erlanger et al., 2005; Keiser et al., 2005a, 2005b; Steinmann et al., 2006). Wastewater provides nutrient-rich reliable water for food production, but poses health risks to farmers and consumers (Drechsel et al., 2010); poorly managed waste from industry, agriculture, livestock and urban areas can contaminate and pollute downstream areas (Dufour et al., 2012; Evans et al., 2018; Landrigan et al., 2017; Mateo-Sagasta et al., 2018); and floods can spread faecal and chemical pollution in delta cities and agricultural land (Alderman et al., 2012). There are also numerous complex interactions and indirect effects as, for instance, deteriorated water quality reduces the availability of sufficient quantities of water and reduced water availability leads to more intensive water use and reuse. In turn, intensive farming typically increases the use of agro-chemicals and subsequent emissions of nutrients, pesticides, veterinary drugs and other compounds (Evans et al., 2018; Mateo-Sagasta et al., 2018). Despite these strong links between water management and human health, water management practitioners hardly cooperate, or integrate their research and management approaches, with the public health sector. Moreover, despite various calls for cross-sector collaboration (e.g. Freeman et al., 2013; Ministers of Foreign Affairs, 2007), implementation in practice is limited by institutional, political and financial barriers (see e.g. Barrett et al., 2002; McDonald et al., 2011).

The objective of this paper is to assess, from an environmental and water science perspective, the potential of integral water management to improve human health. To this end we identify components of the water-related exposome that could be managed by water practitioners, link these to negative and positive impacts on human health and show the nature and magnitude of water management as a *Response*, influencing public health outcomes. We apply the *Drivers, Pressures, Impact, State* and *Response* (DPSIR) framework and consider a wide range of health issues related to highly managed surface (freshwater and marine) and groundwater ecosystems together with options to address these. We introduce the DPSIR framework used to understand how health impacts are influenced by the *State* of aquatic ecosystems in Section 2. The results of our inventory are presented by type of *State* in Sections 3–6. Section 3 focuses on the *State* of chemically polluted water. Section 4 discusses the microbiological *State* of water bodies, resulting from domestic and agricultural pressures. Section 5 considers the *State* of water bodies as suitable breeding sites for vectors of disease. Section 6 considers potential cumulative effects of the example of plastic debris on the chemical, microbiological and habitat *State*. In Section 7 the potential contribution of the water sector to reducing water-related health risks is summarized pointing to opportunities for cross-sectoral collaboration.

2. Material and methods

Our analysis focuses on those water-related health issues that the authors as practitioners encounter in the water sector, grouped according to their effect on the water body (*State*). Insights from the authors' work are complemented with a brief selective literature review (Grant and Booth, 2009) to provide more general context, give additional examples and address knowledge gaps. For this review, typical combinations of key words from the selected health issues and the related water body were combined, for instance cyanobacteria + reservoirs, or plastic debris + rivers. Subsequently only those references were included that specifically addressed impacts on human health.

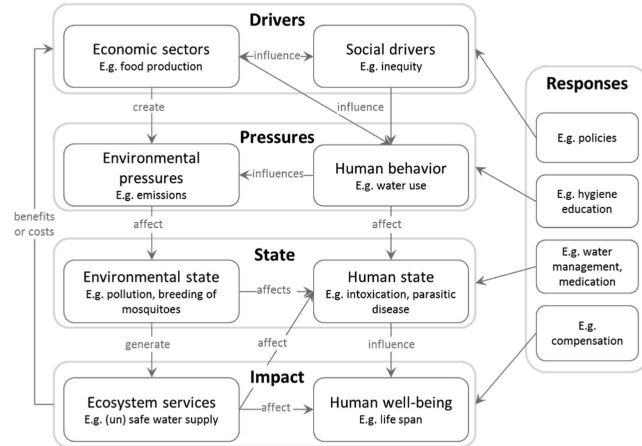

Fig. 1. Conceptual framework, based on Yee et al. (2012), for *Drivers, Pressures, State, Impacts*, and *Responses* in water and health, with parallel tracks for environmental (left) and human (right) health.

Water-related health issues can be analysed by applying the instrumental framework of DPSIR (*Drivers, Pressures, State, Impacts* and *Response*; Borja et al., 2006; WHO, 1997), adapted to environmental and human health by Yee et al. (2012). This tool structures several levels of cause-effect relations: Generic overall *Drivers* include global level autonomous population growth and climate change, steering economic activities in different sectors, e.g. food production, and social drivers, e.g. inequity in access to health services (Fig. 1). These *Drivers* lead to ecosystem alteration, through many interacting determinants such as changed land use, urbanisation and agricultural intensification. This creates environmental *Pressures*, e.g. emissions from agriculture or cities that people are exposed to throughout their lives-together constituting the water-related exposome. The *Drivers* also influence human behaviour and the way people interact with the environment, which in turn affects the environmental *Pressures*. The *Pressures* affect the *State* of both aquatic environmental health and human health, e.g. by pollution, contamination or breeding of mosquitoes and humans, causing e.g. intoxication or parasitic diseases (Prüss-Üstün et al., 2016; Landrigan et al., 2017). When the environmental *State* is deteriorating, ecosystem services will be negatively *Impacted*; or even disservices such as transmission of diseases can be delivered.

The environmental *Impact*, e.g. unsafe water supply, affects human well-being, as infections and intoxications in people will create a disease burden, influence well-being and eventually reduce life span. Whether or not an environmental *State* affects the human health *State* is determined by the impact pathways, their virulence (for pathogens) or their toxicity (for chemical compounds and plastic waste), exposure levels, and people's susceptibility or compound thresholds (Fewtrell and Kay, 2008). Human behaviour, influenced by socio-economic circumstances and individual choices, co-determine the extent of exposure, i.e. the *Pressures*, and whether or not the total of *Pressures* over time, the exposome, ultimately results in ill health.

Finally, responses can address *Drivers, Pressures, States*, as well as *Impacts* (Fig. 1). While the health sector recognizes the importance of environmental determinants, most efforts are directed towards curative services, e.g. medication as *Response* to the human *State*. Health services and prevention efforts are typically aimed at *Drivers* and *Pressures,* respectively. These could benefit from complementary environmental *Responses*. A good example of this is malaria. Global control efforts are targeted at case detection and treatment, coupled with prevention via insecticide-treated mosquito nets (ITNs). With increasing resistance to

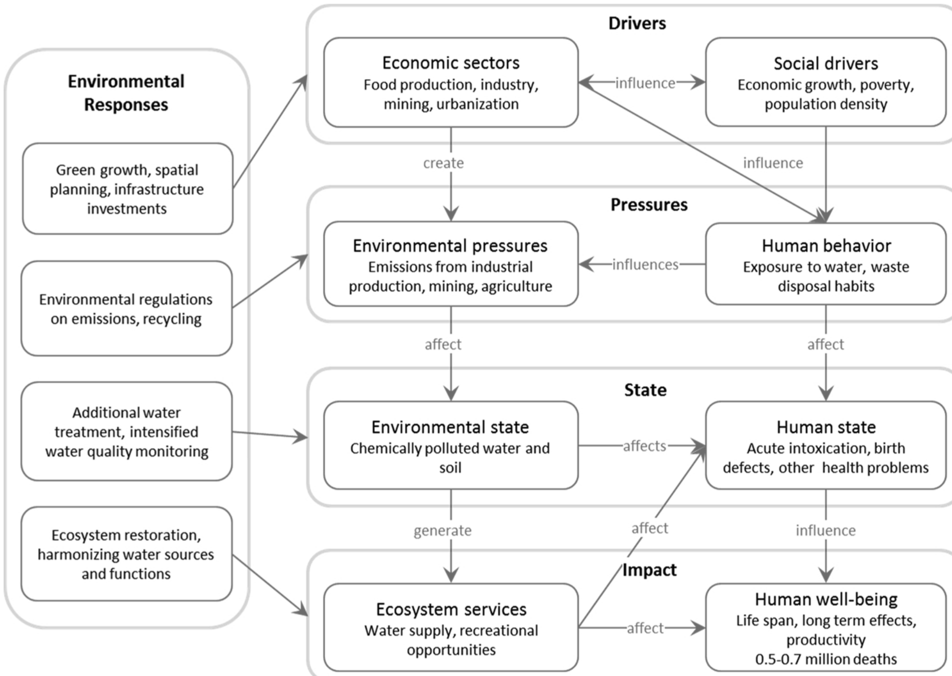

Fig. 2. *Drivers, Pressures, Impacts* and *Responses* for the *State* of chemical water pollution, with parallel tracks for environmental (left) and human (right) health (concept based on Yee et al. (2012); estimated annual deaths based on Landrigan et al. (2017) for 'soil pollution, heavy metals and chemicals').

drugs and insecticides, action from other sectors is needed to achieve long term control of malaria (UNDP and RBM, 2013). Planning and management of the environment are typical *Responses* in the realm of other sectors, such as agriculture, urban planning and water management, which have the potential to influence *Drivers, Pressures, States* and *Impacts* of various water-related health issues.

3. Chemical pollution

Population growth, rapid urbanization, economic growth and efforts to reduce poverty lead to intensified food production, mining of resources and industrial development (*Drivers* in Fig. 2). The rising population density in urbanised areas intensifies environmental *Pressures* from the domestic, agricultural and industrial emissions that are influenced by agricultural and industrial practices as well as waste disposal habits. Industrial activities that pollute the water system are manifold, including (small-scale) mining and raw resource manufacturing, the leather and textile industry, electronics industry, chemical industry, pharmaceutical industry, energy production, and transport. Water is used in these industries in processes, as a cooling agent, or to remove waste loads, sometimes directly emitted to surface waters. Mining can be highly polluting; for instance, small-scale gold mining in low-income countries exposes 15 million people to mercury that ends up in the aquatic environment and the local food chain (Gibb and O'Leary, 2014).

Domestic, industrial, and agricultural emissions in water lead to a polluted *State* with thousands of substances and their residues including nutrients, heavy metals, pesticides (insecticides, herbicides, fungicides), and pharmaceuticals (Evans et al., 2018; Oldenkamp et al., 2013). Substances from urban areas and industry usually pollute the environment as point sources, while agricultural chemicals may create diffuse pollution-these require very different risk management approaches. In many countries effluent treatment is insufficient. The resulting environmental *State* of chemical water pollution then depends on the development stage of the country or region, where rapidly urbanising and industrialising lower- and middle-income countries generally have poor water quality, reflected in high organic loads leading to high nutrient levels and low dissolved oxygen levels that can upset ecological systems (Fig. 2). This generates a reduction in ecosystem services, such as safe water supply and recreational opportunities.

The health *Impacts* are both direct, by exposure to polluted water via drinking, bathing, swimming or inhaling, and indirect, via the ecosystem (Corvalan, et al., 2005; Schwarzenbach et al., 2010). Sometimes exposure is triggered by flood events (Kintziger et al., 2017). Occasionally, acute intoxication occurs, but more often the effects take years to manifest, affecting life span, causing birth defects and incurring other long term health effects. The accumulation of confounding factors over time hampers specific attribution. Persistent and bioaccumulative chemicals will build up in the food chain (especially in water-related food such as fish and shellfish) and might pose health effects through food consumption (Schwarzenbach et al., 2010). In addition, there is evidence that polluted water fosters more pathogens (van der Zaan et al., 2010v; van Elsas et al., [van Elsas et al., 2012v]van Elsas et al., 2012). The health *Impact* of chemical water pollution remains largely unknown (Whitmee et al., 2015), but 0.7 million deaths worldwide are estimated to be related to the combination of 'soil pollution, heavy metals and chemicals' (Landrigan et al., 2017). In a deteriorating environment the health burden is not equally distributed, but the heaviest burden lies with the lower incomes (Myers et al., 2013).

Environmental *Responses* include restoration of ecosystems, whereby water sources are harmonized with their functions. Where feasible, intensive water quality monitoring can support the identification of areas for wastewater treatment, e.g. at industrial sites or communal level. Environmental regulations and recycling initiatives can reduce *Pressures* from emissions. Measures directed at the *Drivers* include green growth initiatives to reduce environmental impacts, better spatial planning and infrastructure investments to increase efficiency.

4. Microbiological contamination

Only 39% of the global population currently use safe sanitation services and worldwide 2.3 billion people still lack even basic sanitation (WHO/UNICEF, 2017). This absence of facilities is an important *Driver*

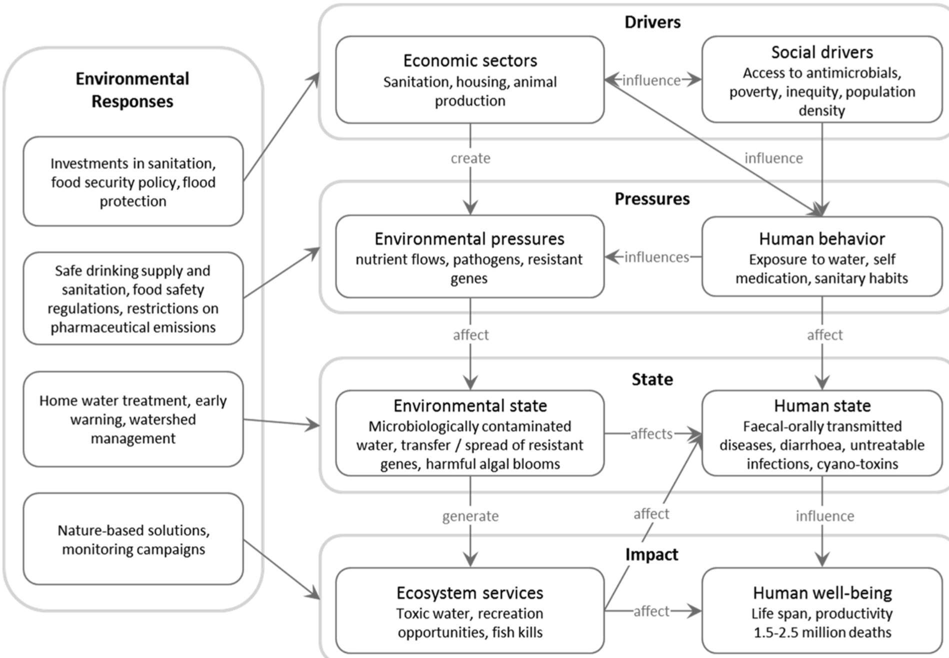

Fig. 3. *Drivers, Pressures, Impacts* and *Responses* for a *State* of microbiologically contaminated water, with parallel tracks for environmental (left) and human (right) health (concept based on Yee et al. (2012); estimated annual deaths based on Landrigan et al. (2017) for (microbiologically contaminated) 'water' and O'Neill (2016) for antimicrobial resistance).

for faecal-orally transmitted waterborne diseases (Fig. 3). As a result of poverty, inequalities and poor housing conditions, people may have no alternative but to resort to open defecation - these sanitary habits may aggravate *Pressure*. Nutrients and pathogens from open defecation, dysfunctional latrines or overflows of septic tanks or sewers, bring groundwater and surface water into a *State* of microbiological contamination. Manure from livestock, aquaculture and other animals add to the microbiological load (Dufour et al., 2012). People run a health risk by getting exposed to the pathogens in drinking water, via food, fingers and flies, through recreational activities in contaminated water (Harder Lauridsen et al., 2013) or in relation to floods (Alderman et al., 2012). The resulting human health *State* includes many faecal-orally transmitted diseases, often leading to diarrhoea, but also skin diseases, breathing difficulties or fever. *Impact* from gastrointestinal diseases leading to stomach aches and diarrhoea globally amounts to some 57 million DALYs (Prüss-Üstün et al., 2016). Proven effective environmental *Responses* are based on reduction of exposure by providing safe water supply, hygiene education and household water treatment (Fewtrell et al., 2005), and on reduction of contamination through sanitation, adaptations to sewerage systems and flood protection measures, including nature-based solutions.

Sector-based *Responses* can become new *Pressures*, as in the example of antimicrobial resistance. Antibiotic resistance is an increasing and urgent problem (Andersson and Hughes, 2014; Nordmann and Poirel, 2014) and the environment is an important factor in its spread (Fletcher, 2015). Antimicrobials (including antibiotics) are applied worldwide to control infections with parasites, bacteria, and fungi in human healthcare, in veterinary medicine, crops and aquaculture (Fig. 3). Some bacteria react by producing extended-spectrum beta-lactamases (ESBLs), enzymes that protect them against the antimicrobial activity of certain antibiotics. ESBL improves the survival rate of these bacteria in the presence of beta-lactams, which (in positive feedback mechanisms) stimulates the relative abundance of ESBL within the environment microbial communities. Hospitals, households, and manure from livestock are major sources of antibiotic resistance, especially in countries where the sale of such drugs is less regulated and self-medication is common (Dufour et al., 2012; Laxminarayan and Chaudhury, 2016). In urban areas, wastewater from households and hospitals is combined in downstream water bodies or at wastewater treatment plants. Such wastewater treatment systems, like storage systems for manure, bring together human faeces, animal manure, and their various antibiotic resistance compounds and nutrients in a *Pressure* cocktail that stimulates the transfer of antibiotic resistance genes to other microorganisms (Sabri et al., 2018; Karkman et al., 2019). Together this creates a new *State* of widespread prevalence of antibiotic-resistance bacteria, such as *E. coli* producing ESBL, and other antibiotic-resistance genes in the environment (Pruden et al., 2012; Wellington et al., 2013; Bengtsson-Palme et al., 2018).

As with chemical pollution, microbiological contamination can enter the environment from point source pollution, such as sewer outlets, or more diffusely, such as from grazing cattle or household latrines. Diffuse contamination requires area-specific solutions. The obvious environmental *Responses* for point pollution sources, wastewater treatment plants, are designed to reduce nutrient concentrations and hardly remove microorganisms. Like manure storage systems, these treatment plants become hotspots for the spread of microbial resistance, where pathogens take up the antibiotic resistance genes (Rizzo et al., 2013). In the Netherlands, 9–19% of *E. coli* in untreated wastewater from nursing homes produced ESBL (Franz et al., 2015). Dilution in the sewerage system reduced this by 2 log-factors to a level of 0.1–1% in the influent of local wastewater treatment plants, resulting in an effluent in which no more than 0.3– 0.8% of *E. coli* produce ESBL, to a level of 700–5400 kve/l. However, for the Netherlands as a whole, this means that up to 10^9 *E. coli* bacteria produce unknown quantities of EBSL per day that all end up in the surface water (Franz et al., 2015). Elsewhere in Europe, constructed wetlands and water catchments were identified as potential reservoirs of antibiotic resistance as well (Czekalski et al., 2015). Understanding the role of water in the transport and spread of antimicrobial resistance will support new *Responses*, such as structural monitoring and the development of environmental mitigating measures (Berendonk et al., 2015; Shallcross and Davies, 2014; Wellington et al., 2013). Regulations on discharge of pharmaceuticals into the environment and food safety standards on admissible levels of antibiotic residues in meat and poultry would be a good start to address various *Pressures* (Laxminarayan and Chaudhury, 2016; Fig. 3), while monitoring campaigns in water bodies would help to increase understanding of the role of the environment.

Chemical pollution can lead to microbiological pressures; an example is the *State* of cyanobacterial blooms due to the high levels of nutrients in an increasing number of stagnant water bodies (Fig. 3).

These blooms are widespread around the world, in natural lakes, human-made reservoirs (Ndlela et al., 2016), seas and oceans. They are aggravated by global warming (Paerl and Huisman, 2008). The toxins released by the cyanobacteria often lead to fish kills and can cause serious liver, digestive system, neurological, and skin diseases to people who swim or bathe in affected water bodies. During such blooms, the excreted toxins render water unfit for drinking or bathing by people or animals. Specific measures have to be taken as treatment is not always possible and water and fish may remain toxic. Environmental *Responses* include watershed management to regulate the inflow of nutrients into open water, flushing of water bodies to reduce residence times, enhancing vertical mixing and early warning systems.

5. Habitat for vector-borne diseases

The demand for increased food production has been a main *Driver* for intensification of agriculture, much of which requires water. Dams, reservoirs, and canals for irrigation, livestock, aquaculture, drinking, or power generation have created *Pressures*, in turn affecting the environmental *State* with suitable habitats for the propagation of (insect) vectors, intermediate hosts, and other carriers, creating optimal conditions for transmission of water-related diseases in previously unsuitable environments (Boelee et al., 2013; Erlanger et al., 2005; Keiser et al., 2005a, 2005b; Kibret et al., 2010, 2015; Steinmann et al., 2006). Water-based diseases (e.g. guinea worm, schistosomiasis, and leptospirosis) and water-related insect-borne diseases (e.g., malaria, dengue fever, chikungunya, Zika, river blindness, yellow fever, and filariasis) are transmitted through either insect vectors or intermediate hosts that spend some or all of their lives in water (Cairncross and Feachem, 1993). Many open water storage facilities, including reservoirs, ponds, and tanks, provide an ideal habitat for mosquitoes, flies, snails, or rodents, bringing both the vectors and the diseases closer to people (Myers et al., 2013; Patz et al., 2004). Water depth, soil, temperature, the presence of aquatic vegetation and predators, the chemical composition of the water, but also human activities determine the suitable *State* of water bodies as habitats for mosquitoes, snails, rodents and other vectors, intermediate hosts, or carriers (Fig. 4). Irrigated agriculture often is accompanied with higher use of pesticides that can induce insecticide-resistance in for instance malaria mosquitoes, thus adding *Pressures*.

The resulting health *Impact* can be high, with, for instance, malaria causing some 23 million DALYs annually worldwide (Prüss-Üstün et al., 2016). Water-related diseases disproportionately affect the poor, people with low access to health services or preventive measures such as ITNs. *Responses* in preventive and curative health care can be complemented with environmental measures: environmental modification through adapted design and engineering, environmental manipulation (recurrent actions, such as alternative operation and maintenance) and reduction of human-vector contact (Keiser et al., 2005c; WHO, 1980). In the case of water infrastructure, these options must be combined as changes in design necessitate adapted water management, especially when allowing for multiple use of water (Boelee et al., 2013). An example of this is the adapted siphon box on irrigation canals in Morocco that eliminated the snail host of schistosomiasis, while keeping the water cleaner and accessible for domestic uses (Laamrani et al., 2000).

6. Potential cumulative effects of plastic debris

Some types of pollution and contamination contribute to chemical, microbiological and habitat effects, for instance plastic debris that can act as a potential carrier for dispersing toxic chemicals, harmful algae and pathogens (GESAMP, 2016). UN Environment has identified plastic pollution, alongside climate change, as a growing global threat that might affect ecosystems, biodiversity and human systems through their potential impact on food resources and the consumption of aquatic food items contaminated with microplastics (Barboza et al., 2018; GESAMP, 2016; UNEP, 2014). Globally, between 1.15 and 2.41 million tonnes of mismanaged plastic waste are estimated to be carried to the ocean every year from rivers, be it directly, or via industrial and urban waste effluents, or from landfill leachates (Lebreton et al., 2017). River systems potentially act as major transporters for all sizes of plastic debris (Leslie et al., 2017). The majority of this *Pressure* (88–95% of the global load into the sea) flows through the 10 most contaminated rivers, though this analysis is based on limited and incomplete data (Schmidt et al., 2017). Two of these rivers are in Africa (the Nile and the Niger), while the remaining eight are in Asia. The rivers with the highest

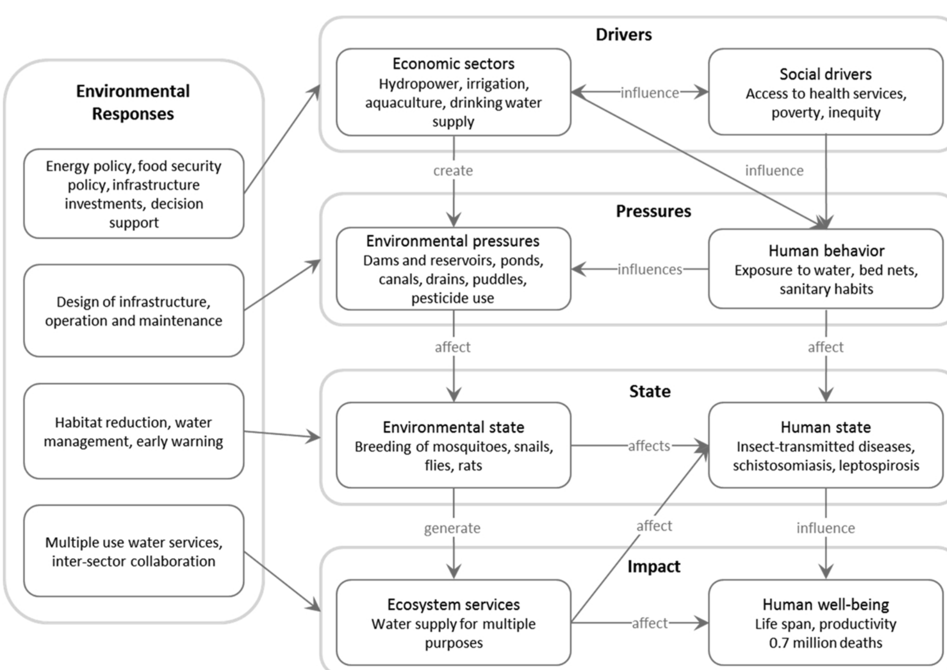

Fig. 4. *Drivers, Pressures, Impacts* and *Responses* for the *State* of water bodies as suitable breeding sites for vectors of disease, with parallel tracks for environmental (left) and human (right) health (concept based on Yee et al. (2012); estimated annual deaths based on WHO (2017)).

estimated plastic concentrations are in countries with low rates of waste management and comprise some of the world's longest rivers. They are often situated in tropical regions with large populations living in their catchment. Seas and oceans (Wagner et al., 2014) as well as freshwater environments (Blettler et al., 2017; Eerkes-Medrano et al., 2015) increasingly reach a *State* of high burdens of plastic pollution. Moreover, there might be large amounts of plastic waste present in river sediments and floodplains that could contribute to ecological and potential human health effects (Corcoran, 2015; Eerkes-Medrano et al., 2015; Vethaak and Leslie, 2016; Wright and Kelly, 2017).

The environmental *State* of plastic waste in water may affect human health, possibly in a cumulative way, through particle toxicity, chemical toxicity, as a substrate for microbial activity (Vethaak and Leslie, 2016) and via the creation of vector breeding habitats. The human health *State* is thus affected by i) effects of ingestion of plastics or plastic-derived chemicals; ii) effects of plastic-associated pathogens; and iii) the contribution of plastic in the creation of habitats for disease vectors.

i) *Chemical (and particle) pollution from plastic.* Upon ingestion, internalisation and potential translocation, very fine micro- or nano-sized plastic particles may cause particle toxicity and associated oxidative stress and inflammation (GESAMP, 2016; Wright and Kelly, 2017). Whether these internalised plastic particles may bring associated toxic chemicals into the human body, resulting in bioaccumulation in certain organs with consequent chemical risks, remains to be studied. Plastics can leach toxic additives into the water, or adsorb waterborne contaminants (Oberbeckmann et al., 2016), which aggravates the total chemical water pollution. These additives include hazardous chemicals such as bisphenol-A, brominated flame retardant, phthalates, UV stabilisers, residual monomers and colourants, leached by plastics into rivers and oceans, and taken up by aquatic organisms into the food web. These might expose people living in these catchment areas, with potential risks to both human health and the environment. Plastic-derived chemicals include a range of toxic substances often with endocrine disrupting, immunotoxic, or another toxic potency that could be hazardous to wildlife and humans (Gauquie et al., 2015; Lithner et al., 2011; Rochman et al., 2013). For example, experimental animal models and wildlife studies have provided evidence that several of the common plastic additives leaching from solid was, such as bisphenol A, phthalates and brominated flame retardants can cause immunosuppression and endocrine disruption and may contribute to both infectious and non-infectious diseases (Thompson et al., 2009; Teuten et al., 2009; Rogers et al., 2013; Schwarzenbach et al., 2006; Vos et al., 1989).

ii) *Microbiological contamination* via *plastic.* While drifting, plastic can act as a potential carrier for dispersing non-indigenous species, harmful algal bloom species, and pathogens (De Tender et al., 2015; Gauquie et al., 2015; Kirstein et al., 2016; Rochman et al., 2013), thus for example increasing infection rate and risk for infectious diseases (GESAMP, 2016; Keswani et al., 2016; McCormick et al., 2014). People are exposed to plastics as vehicles or vectors for pathogens via dermal contact or ingestion of microbial contaminated plastic particles. The implication of plastic waste as a carrier of disease on a global scale was recently suggested by Lamb et al. (2018). The authors provided correlative evidence between plastic trapped in coral reefs around the world and coral health, indicating that the plastic debris might result into a greater prevalence of coral disease, for example, by active transport of pathogens into coral reefs (Lamb et al., 2018). Identification of microbial pollutants on environmental plastic waste will help to investigate the potential risks better.

iii) Plastic as (habitat for) vectors of disease. Discarded plastic items, such as car tyres and Styrofoam fast food boxes, that can hold water near rivers, or after flooding or rainfall, may create excellent habitats with opportunities for mosquitos and other disease-bearing invertebrates (Epstein, 2015; Vethaak and Leslie, 2016). Similarly, floating plastic can create pockets where mosquito larvae or snails find shelter from predators.

Waterborne plastic waste may affect the human health *State* in various and cumulative ways, especially in tropical river regions. In many of these regions, large numbers of people have no access to safe water and still use rivers for drinking water, bathing, and washing and food resources. *Responses* include legislation and agreements to reduce waste and include recycling.

7. Discussion: Responses from the water sector

7.1. Water-related exposome: integrated research

The impact pathways are different for the various types of biological and chemical water pollution, which all have their own health effects. Interactions between chemical water quality, microbiology, and vectors further complicate the total *Impact*, as the example of plastic debris has shown. Various tools are available to disentangle and quantify these Impacts. Qualitative environmental and health impact assessments could be complemented with Quantitative Microbial Risk Assessment (QMRA) (e.g. Fuhrimann et al., 2016; WHO, 2016), and other methods to calculate the water-related disease burden (e.g. Devleesschauwer et al., 2014; Prüss-Üstün et al., 2016). New tools are being developed to assess the whole pathway of sources of chemical compounds to their health impacts, which will guide the selection of optimal abatement options (Brack et al., 2015). A comprehensive analysis could thus link the total water-related exposome, rather than separate *States*, to water management interventions. This has the potential to support decision making and facilitate the implementation of environment-based *Responses*, but does require different tools.

The need for integrated tools was confirmed at the *Impact of Environmental Changes on Infectious Diseases (IECID) conference* in Trieste, May 2017. When asked how they would spend a voucher for water research, almost half of the audience (49%, n = 53 out of 108 votes from 55 respondents) voted modelling to predict the impact of environmental factors, water flows and water quality, but also joint modelling. This can be as simple as layers in a GIS that show water infrastructure but could include modelling of environmental factors that determine the suitability of habitat for mosquitoes and other vectors of disease (Kistemann et al., 2011). Likewise, predictive models combining water flows and water quality that are used to improve water quality monitoring efforts could be extended to incorporate health risks and show probable impacts (Brack et al., 2015). For instance, hydrological forecasting models based on system characteristics take into account (expected) rainfall and other weather conditions, and combine this with upstream emissions of chemicals, nutrients, and pathogens (Hofstra and Vermeulen, 2016; Kroeze et al., 2016). In that way, health risks can be calculated in advance, for downstream water users. In addition to models, field tools such as mobile DNA detection can help to detect pathogens faster, usually within an hour and a half, without having to go to a laboratory. DNA sequencing can be complemented with the application of metagenomics to increase resolution and identify individual pathogens, or the presence of antibiotic-resistance genes.

7.2. Water management

The various *Responses* in the water sector, as discussed in Sections 3–6, show remarkable similarities. Many interventions have the potential to address several health issues at the same time. This makes it very attractive for health professionals to collaborate with the water sector. Investments in safe water supply and sanitation are important *Drivers* that have the potential to reduce in particular the *State* of microbiological contamination. For example, sanitation systems and improved wastewater treatment lead to reduced contamination, supporting the realisation of several sustainable development goals. In addition to improving human health (SDG 3) and access to clean water and sanitation (SDG 6), sanitation contributes to the alleviation of poverty (SDG 1), to sustainable cities and communities (SDG 11), and protects land and water (SDG 14, SDG 15; Landrigan et al., 2017). With reduction of plastic and other solid waste more prominently on the agenda of water managers, the amounts of plastic debris in river systems can be reduced eventually, resulting in lower abundances of plastic in rivers and oceans. Increased recycling efforts, extensive river clean-ups, and cost-effective and appropriate remediation and water-treatment technologies are environmental *Responses* that complement education campaigns and measures to reduce or ban the use of plastic packaging.

Increased availability of water for bathing and washing clothes, can lower infestations of lice and fleas, and help reduce skin and eye infections. Particularly in areas with limited domestic water supply, access to other water bodies, such as irrigation canals and reservoirs, can contribute to improved hygiene, thus reducing health risks (Boelee et al., 2007), provided this water does not carry heavy contamination or pollution from upstream areas.

Wastewater treatment, solid waste management, and adapted design of other infrastructures like dams and roads are additional *Responses* that reduce pressure on the environment. Alternative design and operation of water management infrastructure offer less obvious but potentially highly effective *Responses*. For instance, open reservoirs may be breeding sites for mosquitoes, snails and other vectors of disease but could be designed and operated in such a way that they receive less upstream contamination and pollution and offer less suitable habitats, for instance by fluctuating water levels, building free-draining hydraulic structures or by changing the vegetation on the shores (Boelee et al., 2013).

Measures to increase water safety and prevent flooding provide health benefits beyond the direct effects of reducing drowning and damage. The health impacts of floods are poorly quantified, particularly in the longer term, though mortality may be substantial (Alderman et al., 2012). Dikes, levees and dams offer protection from floods, thus preventing drowning, damage and infectious diseases such as leptospirosis, cholera and other gastrointestinal diseases.

7.3. Integration and collaboration

With the mounting *Pressure* on water resources and growing understanding of the connectivity between water systems, water is increasingly managed integrally. Integrated water management considers all water sources and uses in a water system, linking the many uses of groundwater to surface water and upstream to downstream. Integrated water management is implemented in various approaches, such as Integrated Water Resources Management (IWRM), Integrated River Basin planning and Management (IRBM) and Integrated Coastal Zone Management (ICZM). These can be powerful planning tools to address several, sometimes competing, societal needs. Integrated water management influences land use planning in river basins and deltas, and by steering wastewater management, has an impact on water quality from upstream to oceans. Integrated water management also has the ability to reduce exposure to pathogens, for instance by tackling sewage streams from cities, or offering safe bathing sites, thus reducing *Pressures,* changing human behaviour and lowering the negative health *Impact* of water resources management and actually increasing its benefits.

As part of integrated water management approaches, multi-purpose infrastructure can have manifold health benefits. For instance, smartly designed, well-managed multipurpose reservoirs can provide water for crops and livestock, thus supporting food security, and indirectly supply drinking water, without creating habitat for mosquitoes, snails or algae (Boelee et al., 2013; Carvalho et al., 2013). Such reservoirs can provide areas for safe bathing and swimming, while reducing instead of enhancing the risk of waterborne diseases (Brookes et al., 2006). Clean and healthy water systems can actually promote human health, when people can relax, exercise and recreate by the water (European Marine Board, 2013).

Water management decisions have a huge potential to incur health benefits on communities, especially on vulnerable groups. Public health and water resources are governed separately, so a focus is needed on multi-sector approaches supported by evidence from multidisciplinary research (Patz et al., 2004). Such cross-sectoral approaches have the potential to influence investments in, for instance, (plastic) waste management and other *Drivers*.

Governments and development banks invest heavily in water management planning (often river basin-oriented) to clean-up and rehabilitate the aquatic environment. Large-scale projects with considerable levels of investment are usually preceded by formal environmental impact assessments (EIA), with or without additional or incorporated health impact assessments (HIA; Birley, 2011; Fewtrell and Kay, 2008; Winkler et al., 2013, 2017). As the planning processes influence land use and have impacts on wastewater generation and treatment, it offers new opportunities to enhance human health outside the curative and preventive domains of the health sector.

When the health sector would get involved in IWRM or IRBM, *Responses* could be incorporated that target *Drivers, Pressures, State*, and *Impact* of both environmental and human health. More systematic planning, with wider availability of dedicated health impact tools, and interdisciplinary collaboration between public health and water managers all help to prevent the negative health impacts of water resources management and enhance the benefits. In addition to the management of wastewater and water quality, these could include water management *Responses* aimed at vectors and agents of disease such as mosquitoes, crustaceans and snails, as well as bacteria, viruses and parasites, and extend to improved solid waste management, in particular plastic, and green chemistry. Water management can increase health risks but could also prevent these or even enhance human health. When designed with health concerns in mind, water management measures have the potential to address a multitude of infectious diseases and other health issues.

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