# WORLD WATER QUALITY ASSESSMENT

First Global Display of a Water Quality Baseline

# Contributors

**Résumé**
Ilona Bärlund[6], Martina Flörke[13], Nynke Hofstra[20]

**Chapter 1**
Ilona Bärlund[6], Dietrich Borchardt[6], Christian Schmidt[6], Hartwig Kremer[16]

**Chapter 2**
Ting Tang[8], Seifeddine Jomaa[6], Claudia Faerber[7], Karin Schenk[3], Nynke Hofstra[20], Martina Flörke[13], Maryna Strokal[20], Michelle van Vliet[19], Joel Podgorski[14,18]

**Chapter 3.1**
Joost van den Roovaart[2], Lex Bouwman[19,9,10], Arthur Beusen[19,9], Jos van Gils[2], Tineke Troost[2], Daniel Odermatt[14], Stefan Simis[12], Kerstin Stelzer[1], Nynke Hofstra[20], Annette Janssen[20], Maryna Strokal[20], Ting Tang[8], Michelle van Vliet[19], Bruna Grizetti[4]

**Chapter 3.2**
Nynke Hofstra[20], Mirjam Bak[20], Gertjan Geerling[2], Andrew Gemmell[16,15], Alessio Ippolito[5], Issoufou Ouedraogo[17], Joel Podgorski[14,18], Eirini Politi[1], Jaime Rivera[13], Philipp Saile[7], Christian Schmidt[6], Stefan Simis[12], Kerstin Stelzer[1], Maryna Strokal[20], Michelle van Vliet[19], Mengru Wang[20], Jikke van Wijnen[11]

**Chapter 3.3**
Martina Flörke[13], Jaime Rivera[13], Arthur Beusen[19,9], Lex Bouwman[19,9,10], Hans H. Dürr[13], Thomas Heege[3], Joel Podgorski[14,18], Karin Schenk[3], Maryna Strokal[20], Ting Tang[8], Michelle van Vliet[19]

**Chapter 4**
Andrew Gemmell[16,15], Kornelius Riemann[16,15], Rowena Hay[15]

**Chapter 5**
Christian Schmidt[6], Nynke Hofstra[20], Joost van den Roovaart[2]

**Chapter 6**
Ilona Bärlund[6], Martina Flörke[13], Nynke Hofstra[20], Ting Tang[8]

[1] Brockmann Consult, Germany
[2] Deltares, The Netherlands
[3] EOMAP GmbH & Co.KG, Germany
[4] European Commission, DG Joint Research Centre, Italy
[5] European Food Safety Authority (EFSA), Italy (A. Ippolito is employed by the European Food Safety Authority. The positions and opinions presented in this document are those of the authors alone and do not necessarily represent the views or scientific works of the European Food Safety Authority)
[6] Helmholtz Centre for Environmental Research (UFZ), Germany
[7] International Centre for Water Resources and Global Change (ICWRGC), Germany
[8] International Institute for Applied Systems Analysis (IIASA), Austria
[9] Netherlands Environmental Assessment Agency (PBL), The Netherlands
[10] Ocean University of China, PR China
[11] Open University, The Netherlands
[12] Plymouth Marine Laboratory, United Kingdom
[13] Ruhr-University Bochum, Germany
[14] Swiss Federal Institute of Aquatic Science and Technology (EAWAG), Switzerland
[15] Umvoto Africa (Pty) Ltd, South Africa
[16] United Nations Environment Programme (UNEP), Kenya
[17] University of Fada N'Gourma, Burkina Faso
[18] University of Manchester, United Kingdom
[19] Utrecht University, The Netherlands
[20] Wageningen University, the Netherlands

Suggested citation:

World Water Quality Alliance (2021). *World Water Quality Assessment: First Global Display of a Water Quality Baseline*. A consortium effort by the World Water Quality Alliance - towards a full global assessment. Information Document Annex for display at the 5th Session of the United Nations Environment Assembly, Nairobi 2021.

The designations employed and the presentation of material on the maps do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

# Résumé


## Rationale

Increasing pollution of freshwater as a result of rapid economic growth and urbanization in developing countries, and sustained, chronic pollution including long-term legacies in developed countries poses a growing risk to public health, food security, biodiversity and other ecosystem services. The goal of the World Water Quality Assessment is to review the state of freshwater quality and its potential impacts on ecosystems health, human health and food security, in conjunction with pressures and key drivers to overcome the global water crisis in a targeted way.

The UN Environment Assembly Resolution from 2017, UNEP/EA.3/RES.10, 'Addressing water pollution to protect and restore water-related ecosystems' called for an assessment of global water quality. This current document provides a first global display of a water quality baseline as the pilot draft Assessment report to be delivered for UNEA-5 (2021/2022). It results from a networking activity mirroring the competences, interests and resources of the contributors, and does not claim completeness. This Assessment of global water quality will be continued to address the current challenges in terms of gaps in data and to arrive at a comprehensive baseline that can be updated in a more continuous way. It will further require more time to thoroughly address methodological issues facing a global water quality assessment. The innovative pathway chosen builds on experiences made in the Snapshot report (UNEP 2016) and the resulting Analytical Brief (UN-Water 2016) setting out key requirements towards a global assessment. The working groups involved and principal investigators representing several World Water Quality Alliance (WWQA) working groups will continue to achieve best possible alignment of available in-situ, modelling and remote sensing data date to provide a best possible global baseline and scenarios in early 2023 for presentation to UNEA 6 and to feed into the comprehensive mid-term review of the International Decade for Action on Water for Sustainable Development 2018-2028.

## Key findings

This first global display of water quality gives a versatile picture of the baseline state of global water quality and its impacts on ecosystems health, human health and food security. The results can be used to identify water quality hotspots and help to identify some of the key drivers. The outcome of the Assessment already at this initial demonstration state can provide context in support of the evaluation of reaching the Sustainable Development Goal SDG 6 target 6.3 by focusing on the specific indicator on ambient water quality 6.3.2 and its interlinkages with other targets and goals.

The key findings from the analysis presented include:

Chapter 2 'Methods'

- The Assessment core of innovation, the triangulation approach, aiming to combine in-situ, modelling and remote sensing data can help to overcome the implicit limitations of each data source alone. So far, however, the implementation has been successful on case-by-case only;
- The DPSIR (Drivers-Pressures-States-Impacts-Responses) causal chain conceptual framework connecting the drivers to pressures and responses opens new horizons of data collection from the three data sources, namely, in-situ monitoring, remote sensing and modelling.

Chapter 3.1 'Water quality impacts on ecosystem health'

- In 2020, anthropogenic nutrient sources contribute more than 70% to river nutrient loading;
- Most of the increase of river nutrient loading has been in Asia;
- Harmful algae blooms are now spreading in many river basins;
- Curbing global nutrient cycles requires paradigm shifts in food and waste systems;

- Two large scale European assessments on ca. 2,000 chemicals report chronic effects of (a mixture of) chemicals on aquatic species to be expected at 42%-85% of the studied sites, while 14%-43% of the sites are likely to experience some degree of species loss;
- Assessments as for Europe cannot be made on a global scale. Neither the measured data nor the information to generate predicted concentrations are available yet;
- The Human Impact and Water Availability Indicator (HIWAI) can be used to extrapolate results obtained for Europe. This proxy was found to correlate well with the expected loss of aquatic species in European surface waters.

Chapter 3.2 'Water quality impacts on human health'

- Modelling has been a prominent approach to derive estimates on human health impacts from contaminated water, the water quality state and the contamination sources;
- First estimates of human health impacts originating from the pathogen Cryptosporidium (single cell parasite) shows hotspots in areas where surface water is still regularly used for drinking directly and for arsenic hotspots are located in Asia. For most other contaminants to-date still no impact studies are available at the large scale;
- Concentration hotspots are, for most contaminants, densely populated areas, in particular where wastewater treatment is limited. For groundwater arsenic and surface water salinity concentrations, hotspot areas include India, China and Mongolia.

Chapter 3.3 'Water quality impacts on food security'

- First estimates of water quality impacts on food security show hotspots in north-eastern China, India, the Middle East, parts of South America, Africa, Mexico, United States and the Mediterranean;
- Estimates of water quality impacts on food security reveal that over 200,000 $km^2$ of agricultural land in South Asia may be irrigated with saline water exceeding the FAO guideline of 450 mg/l and over 154,000 $km^2$ show a high probability of groundwater having arsenic concentrations that exceed the WHO guideline value of 10 µg/l, respectively;
- Aquaculture and mariculture production are important to produce high-quality protein, but both can be at risk because of water pollution such as increased nutrient concentrations;
- Wastewater reuse in irrigation is an option to overcome water shortages and to close the nutrient cycle, however, the food may become contaminated by pathogens (and faecal coliform bacteria), Antimicrobial Resistant (AMR) microorganisms and chemicals in wastewater that has not been sufficiently treated.

Chapter 4 'World Water Quality Alliance - Africa Use Cases' (case studies contributing to the Assessment and stakeholder engagement)

- Cape Town's groundwater is vulnerable to water quality impacts from urban development in an area with various land-use activities, posing a risk to the planned potable water supply; hence aquifer protection zones were co-designed;
- Implications of water quality and its disturbance at Lake Victoria provide data to the Assessment and led to co-design of information products for the water food nexus with local fisheries stakeholders including a coastal eutrophication assessment, water temperature and stratification dynamics, and sediment chemistry;
- Water quality related information product options for the Volta basin are initially being explored with local partners including tools to determine the percentage of population vulnerable to poor water quality, and a remote sensing-based groundwater quality assessment.

Chapter 5 ‘Digital water quality platforms’

- A gap exists between the general availability of data, their level of coherent aggregation and synthesis which is required to provide useful information for different policy or management purposes. Appropriately designed platforms can help to overcome this gap;
- The key to engage platform users is their involvement already early on in the development phases of the platform in a co-design process;
- Multiple water quality platforms co-exist and target various water quality issues such as arsenic in groundwater or pathogens in African rivers. They should ideally reinforce each other by providing standardized data products to enable cross-platform sharing.

Water quality hotspots frequently overlap for many of the pollutants under consideration (namely, when natural sources of contamination are far less important than anthropogenic pollution) and located in densely populated areas. For a fully comprehensive global view, however, this Assessment is still in a preliminary stage, facing considerable lack of input data, on state and on impacts for all relevant water types, especially on contaminants/pollutants. Also for many contaminants relevant for human health, estimates of their current state are still unavailable at the large scale. Response options most often focus on reduction of sources. But, their impact has not yet been widely assessed. Also, data that quantitatively link water quality impacts to food security is often lacking at the large spatial scale, leaving efforts towards quantification of impacts at this large dimension difficult.

It is also evident that the emphasis of this Assessment, that is to encompass large- to global-scale water quality studies, still is on surface waters and data retrieved from modelling. The prospects of the Assessment triangulation approach, speaking to the joint use of data from in-situ monitoring, remote sensing and modelling have been shown exemplarily in Chapter 3 for each of the water quality impact themes. While this is opening promising perspectives to address data scarcity there are still technical, practical and conceptual challenges to be addressed concerning for example inconsistencies in spatial and temporal delineation and variables covered by each method.

## Major Challenges

To assess water quality in the environment globally data is required with scientifically rigorous coverage across time and space and reflecting a meaningful share of all waterbodies under consideration. As in the past in this requirement still reside the most significant challenges the Assessment aims to address over time.

Major data and knowledge gaps identified to-date include:

- still an urgent need for regularly monitored up-to-date and readily available data to do a thorough evaluation;
- the further development of methods for integrating different data sources (including in-situ monitoring, water quality models and remote sensing) for a comprehensive water quality evaluation is required;
- knowledge gaps on the importance of the environmental fate and transport pathways and which need to be closed, also to test model assumptions on these;
- that reporting should encompass the state, impacts (also indirect impacts), main sources and response options for all contaminants causing environmental and health risks;
- that the assessment of water quality impacts in quantitative terms remains difficult as in-situ data and modelling data are lacking (for example to capture the impacts of harmful algal blooms, HABs and hypoxia on fisheries, aquaculture and mariculture as well as pathogen contamination impacts on leafy crops and food safety or on diarrhoeal diseases);
- a continued and urgent requirement for innovative regulatory solutions, which include awareness raising among policy makers and all societal actors worldwide;

- an intrinsic need for better translation of response options to various target audiences by means of strong institutional collaboration across key water quality nexus dimensions and including the integration across water and health/food/ecosystem disciplines to implement effective measures.

In the next Assessment phase, the baseline water quality state and impact will be further elaborated. What especially requires improving is better integration of all sources of information: in-situ data, models and remote sensing, across the DPSIR framework. For this, the Assessment team needs strengthening in particular concerning competences in the fields of in-situ monitoring and remote sensing but also regarding the water bodies less visible in this report, i.e. groundwater and estuaries. Concerning modelling, the versatile contribution so far lacks especially large-scale results for many pollutants but also the basis required for scenario runs needs attention, as modelling is the only means to perform scenario studies.

Selected case studies will be carried on to develop in-country partnerships and collaboration, especially with water resource decision-makers in order to continue the co-design of water quality products and services using the World Water Quality Assessment triangulation approach needed e.g. to address mitigation options. Here attention will be paid to groups at risk like women because of their frequent usage of water from rivers and lakes for cleaning clothes and collecting water for cooking and drinking in the household, and children because of their play activities in local surface waters and also because they often have the task of collecting water for the household.

The triangulation approach will trigger new thinking in the scientific community and provide eventually new results to be included in the Assessment. To provide resilient and future-proof response options to decision-makers, the basis must be established for conducting scenario analysis of future development pathways of water quality in the freshwater system in response to future climate change, socio-economic development and response options. For complex new products beyond a pure community effort, such as a comprehensive scenario assessment across all modelling teams, different linked impacts models, or multi-pollutant approaches, additional resources would be required.

# Table of contents

# 1 Introduction

## 1.1 Background

Increasing pollution of freshwater as a result of rapid economic growth and urbanization in developing countries, and sustained, chronic pollution including long-term legacies in developed countries poses a growing risk to public health, food security, biodiversity and other ecosystem services.

A prerequisite for the implementation of measures to improve water quality – e.g. to monitor progress reaching the Sustainable Development Goal 6 target 6.3. on water quality and wastewater – is the availability of information on the current state of water quality as well as the key drivers of water quality changes. A preliminary *Snapshot of the World's Water Quality: Towards a Global Assessment* (UNEP 2016) revealed the lack of in-situ monitoring data which refer to measurements taken on the ground in the water directly particularly in developing countries, rendering the sole reliance on measured data impossible, both on continental and global and frequently also on national scales. The challenge to generate this information and transform it to actionable knowledge not only consists of a pure lack of data but also of making data accessible and providing them in a format that creates usable and understandable information for the various actors involved.

## 1.2 Objectives and approach of the World Water Quality Assessment

The goal of the global Assessment is to review the state of freshwater quality and its potential impacts on ecosystem health, human health and food security, in conjunction with its pressures and key drivers to overcome the global water crisis in a targeted way. Embedded in the World Water Quality Alliance, WWQA, a global community of practice comprising UN and external members world-wide and representing a wealth of expertise in the field of water quality, the Assessment also aims at raising awareness of the importance of water quality degradation for sustainable development and enabling countries to better assess the state of the water resources and aquatic environment as a prerequisite to effectively protect, maintain or restore water quality at sustainable levels. The Assessment is a key element in UNEP's long-term objective to foster a rolling global water quality appraisal including Services and Innovation concepts and to be supported by an advanced global environment monitoring system for freshwater (Figure 1.1).

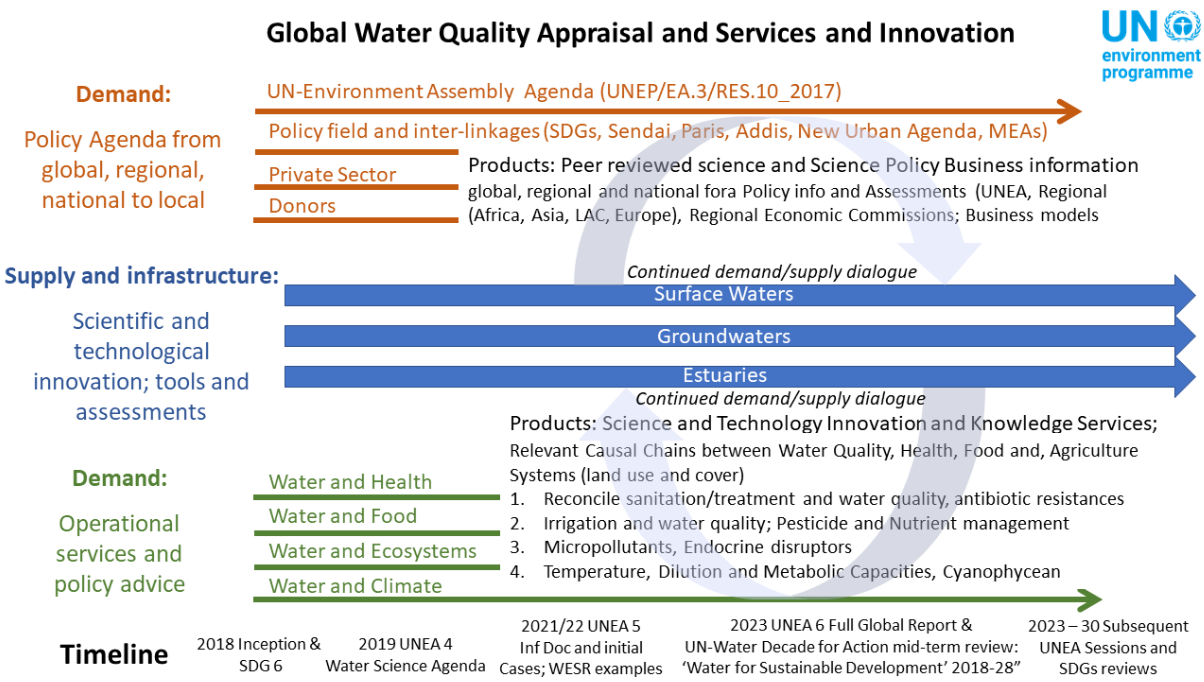


***Figure 1.1*** *A global water quality appraisal, services and innovation concept matching demand and supply of information towards reaching good environmental quality and achieving SDG 6 and its interlinked goals at large.*

The major components of the Assessment as identified in the Analytical Brief ***Towards a Worldwide Assessment of Freshwater Quality*** (UN-Water 2016) are: 1) Baseline Assessment of global water quality in surface and groundwater bodies, 2) Scenario Analysis of future pathways of water quality in the freshwater system and its compartments, and 3) Mitigation Options, reflecting information on pathways towards effectively protecting or restoring water quality at different scales.

Due to the inherent limitation of in-situ monitoring data which have been generated by direct measurements at source (see Chapter 2.1.2), it is not possible to undertake a comprehensive assessment of the state of global freshwater quality and related impacts from such sampling data alone. Therefore, the central methodological challenge in the World Water Quality Assessment is to innovatively consolidate the information basis by synthesizing data from in-situ monitoring, water quality modelling and remote sensing-based Earth Observation (the so-called triangulation approach, Figure 2.1B). Resulting data products and derived assessment information will provide consistent images of the current state of freshwater quality (baseline) and illustrate causal chains from drivers to impacts and response options using the DPSIR framework.

The ambition of the Assessment is to work at different scales: 1) the global scale to provide a consistent context on the state of water quality regarding key pollutants and to identify the impaired water bodies posing risks to human health, food security and ecosystem health; 2) the water body to river basin scale with the engagement of stakeholders where possible in respective case studies to synthesize information collectively and  to achieve their management needs relevant in their respective water system context including the implementation of the 2030 Agenda for Sustainable Development at relevant scales (the concept of a localized 2030 Agenda).

As said above, embedding is provided by the World Water Quality Alliance, WWQA – currently comprising more than 50 organizations globally – which represents a voluntary and flexible global UN and external expert, practitioner and policy network, advocating the central role of freshwater quality in achieving prosperity and sustainability. It brings together diverse disciplines and actors (including science, private sector and civil society) and forms the expert community of practice behind the author team of this document. As a product of this networking activity the present document mirrors the competences and interests of the participants and does not claim completeness.

## 1.3 This document

The mandate is reflected in Resolution UNEP/EA.3/RES.10, adopted by the United Nations Environment Assembly 3rd session end of 2017 on 'Addressing water pollution to protect and restore water-related ecosystems', which called for an assessment of global water quality and draw on and establish the necessary partnerships. This document is a first step towards the full World Water Quality Assessment requested. It demonstrates the achievable interim results to-date in acknowledging the complexity of meeting data scarcity and methodological challenges in combining data from various sources in a scientifically rigorous reliable and reproducible way. It provides already today a first global display of a water quality baseline as the pilot draft Assessment report to be delivered for UNEA-5 (2021/2022).

The core of the document is Chapter 3 'Water quality impacts' that is structured along the three crucial water quality impacts on ecosystem health, human health and food security. This chapter is based on readily available, published materials on the three themes that have been compiled as a state-of-the-art. The approaches applied (Assessment data-source triangle and the DPSIR framework) and the tools behind the results are introduced in Chapter 2 'Methods'. The full World Water Quality Assessment aims at stakeholder engagement and making data and actionable information accessible. These two aspects are introduced and illustrated in Chapter 4 which displays first efforts made to this effect by the World Water Quality Alliance ('WWQA Use Cases – Stakeholder engagement and product/service co-design') in three pilot locations across Africa and which feed into and supplement the Assessment and in Chapter 5 'Digital water quality platforms'.

# 2 Methods

*The integrated use of the triangulation approach combined with the DPSIR framework is an innovative approach to fill the data and knowledge gaps to better assess water quality at the global scale:*

- *The triangulation approach combines in-situ, modelling and remote sensing data through novel links, which can help to overcome the implicit limitations of each data source.*
- *A combination of data from the cornerstones of the triangle contributes to a better understanding of uncertainties in simulated water quality variables and helps consolidate the water quality assessment, especially in data-scarce regions with limited in-situ water quality monitoring data.*
- *The triangulation approach has the potential to maximise the information gained from in-situ data, modelling knowledge and remote sensing products, and identify focal regions to improve water quality monitoring and modelling and develop strategies towards sustainable water quality management.*
- *The DPSIR framework as a causal chain connecting the drivers to pressures and responses opens new horizons of data collection from in-situ monitoring, remote sensing and water quality modelling.*

## 2.1 Approach

### 2.1.1 The DPSIR framework

The DPSIR (Drivers-Pressures-States-Impacts-Responses, Figure 2.1A) framework was developed in the early 1990s. It was adopted by the European Environmental Agency (EEA) in 1995 as a conceptual framework illustrating the cause-effect relationships for environmental problems (Smeets and Weterings 1999). Since its development, the use of the DPSIR framework, alongside with indicator development in a meaningful manner for decision-makers (OECD 2003), has been further extended, for structuring information (Kristensen 2003). It allows the integration of knowledge from multiple disciplines, and explains and visualizes the interactions between the environmental and socio-economic dynamics (Lundberg 2005). Therefore, the DPSIR framework was used by multidisciplinary studies (Tscherning *et al.* 2012), such as dealing with air quality (Relvas and Miranda 2018), and nature-based tourism development (Mandić 2020). The framework was also used in water quality studies and land-coast assessments, such as linking water pollution with human health (e.g., Boelee *et al.* 2019) and nutrient load management in hinterland catchments and in coastal and marine environments and their interactions (Salomons *et al.* 2005; Dolbeth *et al.* 2016). Hence, the DPSIR framework has shown capability across different spatial scales, ranging from case study (Carr *et al.* 2007), and regional (Hamidov *et al.* 2018), to the global scale (Odermatt 2004). Besides, a large body of research on sustainable development has broadened the use of the DPSIR framework as a beneficial assessment tool connecting the drivers to impacts and intervention priorities as well as a communication tool between multidisciplinary researchers, policymakers, and key stakeholders for problem understanding, participatory scenario analysis and for supporting decision making. In the current report, the DPSIR framework is used as an overarching structure for the water quality assessment at regional and global scales (see e.g., Table 3.1 on human health).

### 2.1.2 The triangulation approach

Water quality monitoring, evaluation, and prediction are increasingly recognised as priority research topics to improve the science base for water quality management. The most common water quality evaluation methods are i) in-situ data analysis based on data generated from direct measurements in the water systems and laboratory analysis, ii) water quality modelling, and iii) remote sensing. Generally, these methods are used separately and bilaterally, but rarely integrative. In-situ data is of fundamental importance because it provides the ground truth as the basis for water quality assessment and management on its own, especially at the local and regional scales. Moreover, it is irreplaceable when it comes to the validation and testing of modelling and remote sensing results. The in-situ data analysis is well recognised as a data-dependent approach and in-situ data collection is often costly, labour-intensive, and time-consuming. Its applicability mainly depends on in-situ data availability in terms of parameters, temporal and spatial coverage. For the model-driven analysis, often mathematical models and methods are developed and/or validated using in-situ data in specific regional or local case studies. The transferability and spatial validation of these approaches to other regions - characterised by different physiographical features - are usually uncertain, in part due to lack of publicly available data for model evaluation and inconsistent monitoring standards and units. Modelling is the only method, out of the three, that can assess future projections and alternative mitigation options. The remote sensing analysis has more capabilities regarding its consistent spatiotemporal coverage compared to in-situ data and modelling analyses. Additionally, the satellite-based remote sensing can reconstruct measurements into the past based on historical satellite images up to 40 years back in time. The competence of remote sensing to reconstruct the past environmental status together with its spatiotemporal scanning capability makes it an innovative tool for water quality assessment across different spatiotemporal scales. Also, remote sensing analysis is subject to natural limits such as the presence of clouds and only limited water quality properties that can be directly obtained or inferred by optical-spectral imaging.

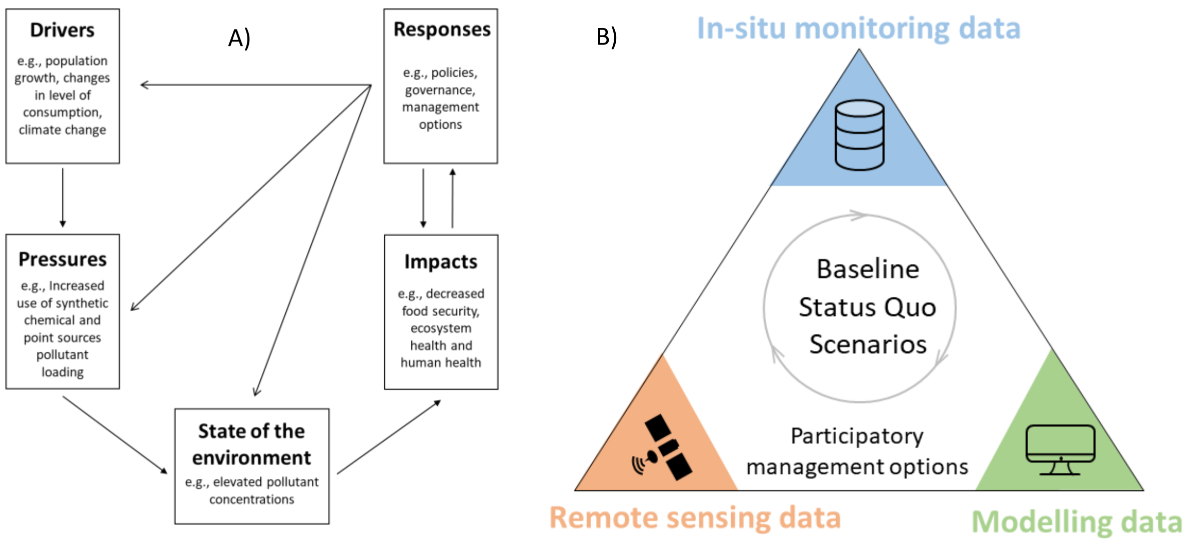


***Figure 2.1 A)*** *The DPSIR assessment framework, illustrating the flow of cause-effect relationships for a given environmental problem (modified from Tscherning 2012; Carr et al. 2007).* ***B)*** *The World Water Quality Assessment triangle suggested as an innovative approach combining the in-situ data, modelling data and remote sensing data for better water quality assessment across different scales (Source: GlobeWQ project).*

To overcome the limitations of each data source, an appropriate combination of in-situ, modelling and remote sensing data is proposed as innovative triangulation approach to better assess water quality at local, regional and global scales (Figure 2.1B). The triangulation approach strengthens the available information and data from in-situ, modelling and remote sensing (see for example Chapter 3.1 on nutrient pollution) and overcomes their implicit limitations through novel links. The three data sources can be integrated to give a robust assessment of the baseline or status quo conditions through adequate validation of models and remote sensing products. A robust baseline assessment including the identification of hotspots over time and location (geospatial) is a prerequisite for making reliable projections using future scenarios considering participatory management options co-designed with stakeholders. The World Water Quality Assessment triangle in principle is able to address the whole causal chain reflected in the DPSIR framework including feedback loops (Figure 2.1.A). Data from in-situ and remote sensing sources provide information on the status and in some cases impact aspects of the DPSIR framework. Combining the two with models, the Assessment triangle can reliably link to the underlying drivers, pressures and impact, and enable assessing the effects of different response options. This report focuses on exploring the availability of the three types of data and the potentials to integrate them for a global comprehensive water quality assessment, in order to facilitate a full implementation of the triangulation approach in the next stage.

## 2.2 Tools

As indicated in the World Water Quality Assessment triangle, mainly three types of tools and products are used in this report, namely in-situ data, water quality modelling and remote sensing products.

### 2.2.1 In-situ data

In-situ monitoring remains the most frequently used way for water quality data collection at the national and local scales. Various regional in-situ datasets are available, such as Water Information System for Europe (WISE) and U.S. National Water Quality Portal. However, accessing and compiling such data at the global scale has been challenging due to inconsistencies in technical aspects (e.g. sampling, chemical analysis, reporting methods) and politic barriers, among others. An open-access global surface and groundwater salinity dataset has been recently published (Thorslund and van Vliet 2020). It is a synthesized dataset comprising electrical conductivity in-situ monitoring data of global, regional and local resources for 1980-2019. UNEP's Global Environment Monitoring System for Freshwater (GEMS/Water) Programme, established in 1978, collects worldwide freshwater quality data for assessments of state and trends in global inland water quality. Surface and groundwater quality monitoring data gathered from the global GEMS/Water monitoring network of member states and organisations is shared through the GEMStat information system. GEMStat is hosted by the GEMS/Water Data Centre (GWDC) within the International Centre for Water Resources and Global Change (ICWRGC) at the Federal Institute of Hydrology, in Koblenz, Germany.

As of October 2020, the growing GEMStat database contained more than 14 million entries for rivers, lakes, reservoirs, wetlands and groundwater systems from 88 countries and approximately 11,000 stations (Figure 2.2). Overall, data is available between the time period from 1906 to 2020 for about 500 parameters. The largest proportion is contributed by inorganic and organic compounds and nutrients (Figure 2.3). Currently, the largest number of the data comes from river stations, followed by data from groundwater, lakes, reservoirs and wetlands. The greatest coverage of stations is currently available from Latin America and the Caribbean (7596). Most values are contributed by Latin America and the Caribbean (4.4 million), Europe (4.3 million) and North America (3.6 million).

The water quality data available in GEMStat can be used for status quo evaluation, policymaking, research purposes or within the scope of education and training initiatives. Since March 2019, the available water quality data can be directly downloaded from the GEMStat portal. The data are mostly used for research purposes, but also used as input into international assessments, such as the 'Snapshot of the World's Water Quality: Towards a Global Assessment' (UNEP 2016) and the World Bank report 'Quality Unknown: The invisible water crisis' (Damania *et al.* 2019). In this report, GEMStat was used for the validation and testing of several water quality models (e.g., WorldQual and MARINA models, see Table 2.2).

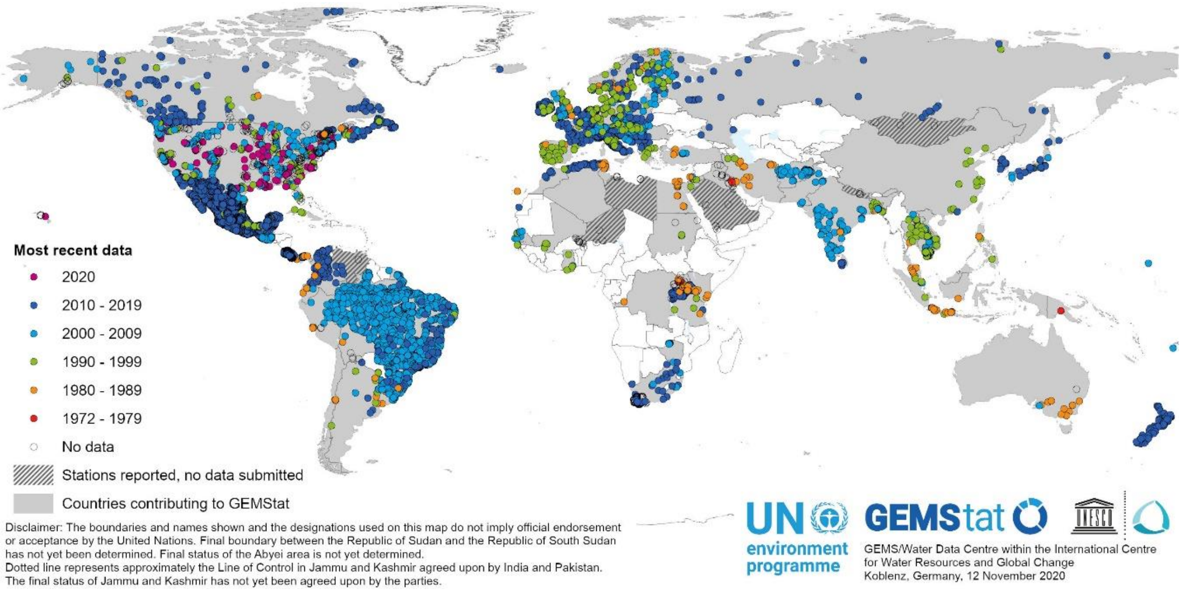


***Figure 2.2*** *Spatiotemporal availability of GEMStat data worldwide indicated by most recent sampling data.*

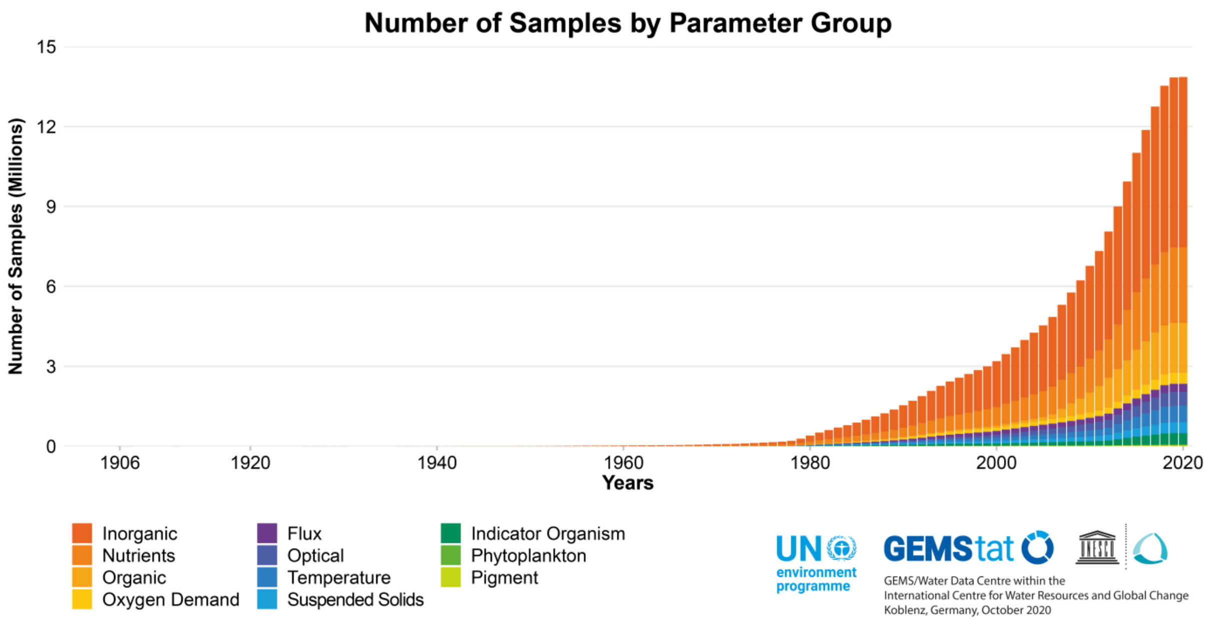


***Figure 2.3*** *Temporal availability of water quality samples in GEMStat by parameter group since first data record from 1906.*

## 2.2.2 Remote sensing products

Remote sensing products have huge potential to provide additional water quality information with large spatial coverage for inland and coastal water bodies. This is particularly beneficial in places where in-situ monitoring is missing or lacking due to practical or financial constraints (e.g., Africa, Asia). Since the start of Landsat missions in the 1970s, experts have developed algorithms to extract water quality information from remote sensing satellite images (Klemas *et al.* 1971, Maul and Gordon 1975). In the past decade, several efforts were initiated to provide inland water quality dataset at large (global and continental) scales (Table 2.1), such as Diversity II (Odermatt *et al.* 2018), the UNESCO world water quality portal (Heege *et al.* 2019), Copernicus Global Land Service (CGLS) and AquaSat (Ross *et al.* 2019) using remote sensing products from different satellites and sensors. However, it is still poorly integrated with other sources of water quality information (Ross *et al.* 2019), especially modelling results. On the positive side, the recent evolvement towards higher resolution (e.g., Sentinel-2, Landsat 8/9) and higher overpass frequency (e.g., Sentinel-3, Planet Doves) of satellites together provide unprecedented opportunities to utilize remote sensing technology and apply the triangulation approach for inland and coastal water quality monitoring and assessment and are available from commercial providers at various levels. However, product quality assurance standards to ensure inter-comparability and improving quality are not yet available on a common base, but under development.

Remote sensing can estimate optically-active water quality parameters, most commonly turbidity, total suspended solids (TSS), Secchi disk depth (SDD), coloured dissolved organic matter (cDOM), surface water temperature ($T_{sw}$), chlorophyll a (Chl-a), and trophic state index (TSI). Other parameters that can be estimated include total organic carbon, dissolved organic carbon, ammonia nitrogen, orthophosphate and total phosphorus (Gholizadeh *et al.* 2016). Table 2.1 provides an overview of remote sensing products and datasets with a global coverage that are used in the current report.

### 2.2.3 Water quality modelling

While in-situ monitoring and remote sensing products provide information on water quality state and to some extent impact on aquatic ecosystems (e.g., eutrophication), most water quality models can go beyond state assessment and link the state with the drivers and pressures, and assess the impacts of alternative management options and – as the only tool in the triangulation approach – assess and predict future changes. Modelling is therefore of critical importance in the Assessment triangle to fully address each element in the DPSIR framework, such as scenario analyses towards assessing the impact of and response to climate change and socio-economic developments on water quality.

Large-scale (global and continental) water quality modelling started in the 1990s with nutrient export modelling (Caraco and Cole 1999; Kroeze and Seitzinger 1998; van Vliet *et al.* 2019). In the past decade, large-scale water quality models have emerged quickly for nutrients (Beusen *et al.* 2015; Mayorga *et al.* 2010; Ouedraogo *et al.* 2016) and other water quality parameters, including water temperature (Punzet *et al.* 2012; van Beek *et al.* 2012; Wanders *et al.* 2019; van Vliet *et al*. 2020), salinity (Voß *et al.* 2012; UNEP 2016; van Vliet *et al.* 2020), organics (Wen *et al.* 2018; Voß *et al.* 2012; UNEP 2016), arsenic (Amini *et al.* 2008a; Podgorski and Berg 2020), fluoride (Amini *et al.* 2008b), microorganisms (Kiulia *et al.* 2015; Vermeulen *et al.* 2019; Reder *et al.* 2015), plastics (Siegfried *et al.* 2017; Lebreton *et al.* 2017; van Wijnen *et al.* 2019), pharmaceuticals (Oldenkamp *et al.* 2019), pesticides (Ippolito *et al.* 2015) and other chemicals (van Wijnen *et al.* 2017; Wannaz *et al.* 2018) and toxins (Janssen *et al.* 2019; van Gils *et al.* 2020). Efforts are also made to model the impact of water pollution at large scales, such as on ecotoxicological risks (De Baat *et al.* 2019), biodiversity (Dumont *et al.* 2012), human health (Limaheluw *et al.* 2019), and water scarcity (van Vliet *et al.* 2017, van Vliet *et al.* 2020). Furthermore, multi-pollutant models are being developed that integrate modelling approaches of multiple groups of pollutants (e.g. WaterGAP-WorldQual, MARINA-Global, QUAL, WFLOW-DWAQ, see Table 2.2). Such multi-pollutant models allow to assess multi-pollutant problems of water systems in a holistic matter, and enable us to better understand synergies and trade-offs associated with interactions between pollutants and their drivers (Strokal *et al.* 2019). This allows to explore effective response options where reducing one pollutant may reduce another. However, it remains challenging to compare or integrate modelling results from different models (van Vliet *et al.* 2019) due to inconsistencies in model inputs, spatial and temporal resolution and coverage as well as simulated water quality parameters. Such inconsistencies can be easily seen in Table 2.2, which provides a summary of the models that are used in Chapter 3.

***Table 2.1*** *Water quality products and datasets derived from Remote Sensing.*

| **Remote sensing products/datasets** | | **Water quality parameters**[1] | **Spatial resolution**[2] **& coverage** | **Temporal resolution & coverage** | **Key Documentation** |
|---|---|---|---|---|---|
| Diversity II | | TSS, turbidity, cDOM, $T_{sw}$, Chl-a, cyanobacteria and floating vegetation | 300 m<br>350 lakes worldwide | monthly<br>04/2002–03/2012 | Odermatt *et al.* (2018)<br>http://www.diversity2.info/products/documents/ |
| CGLS (Copernicus Global Land Service) | Optical | Turbidity, trophic state index, Spectral reflectance | 300 m<br>4265 lakes worldwide | 10-day<br>2005-2011 and 2016-present | https://land.copernicus.eu/global/products/lwq |
| | Thermal | $T_{sw}$ | 1000 m<br>1000 lakes worldwide | 10-day<br>04/2002-03/2012 and 2016- present | https://land.copernicus.eu/global/products/lswt |
| UNESCO-IHP IIWQ World Water Quality Portal and ESA Hydrology-TEP SD6 Reporting Portal | | Turbidity, SDD, $T_{sw}$, TSS, Chl-a, trophic state index, harmful algae bloom (HAB) indicator | 90 m for global inland and coastal waters<br>10-500 m (mostly 30 m) for use cases | Single snapshot between 2013-2017 for global inland and coastal waters<br>Daily to seasonal for 2010 onwards for use cases | http://sdg6-hydrology-tep.eu/<br>www.worldwaterquality.org |

1 TSS: total suspended solids, cDOM: coloured dissolved organic matter, $T_{sw}$: surface water temperature, Chl-a: chlorophyll a, and SDD: Secchi disk depth

2 Resolution of raw data. Final products might be of lower resolution due to aggregation

***Table 2.2*** *Brief summary of the large-scale water quality models used in the current report.*

| **Models** | **Simulated water quality parameters** | | **Water body type[2]** | **Spatial aggregation of model outputs** | | **Temporal aggregation of model outputs** | | **Key references** |
|---|---|---|---|---|---|---|---|---|
| | **Parameter group** | **Parameters[1]** | | **Resolution[3]** | **Coverage** | **Resolution[3]** | **Baseline year** | |
| DRASTIC | Nutrients | $NO_3^-$ | a | 15 km | Africa | 10-year | 1990-2010 | Ouedraogo *et al.* (2016) |
| GlobalAsGW | Geogenic contaminants | Arsenic | a | 30 arcseconds | Global | NA (static)[4] | Pre-2019 | Podgorski and Berg (2020) |
| GloWPa | Microorganisms | Cryptosporidium | b | 0.5 degree | Global | Monthly | Around 2010 | Vermeulen *et al.* (2019) |
| GREMiS | Others | Microplastics | b, d | Basin | Global | Annual | 2000 | van Wijnen *et al.* (2019) |
| IMAGE-GNM | Nutrients | TN, TP, Si | a, b, c | 0.5 degree | Global and (sub-)national | Annual | 1970-2015 | Beusen *et al.* (2015), van Puijenbroek *et al.* (2019) |
| Insecticide model | Pesticides | Insecticides[5] | b | 5 arcminutes | Global | NA (static)[4] | 2000-2010 | Ippolito *et al.* (2015) |
| MARINA-Global (multi-pollutant) | Nutrients | DIN, DON, DIP, DOP | b, d | Sub-basin | Global | Annual | 2010 | Strokal *et al.* (n.d., 2016, 2019), van Wijnen *et al.* (2017) |
| | Microorganisms | Cryptosporidium | | | | | | |
| | Others | Microplastics, Triclosan | | | | | | |
| MARINA (version 2.0) | Nutrients | DIN, DON, DIP, DOP | b, d | Sub-basin | China | Annual | 2012 | Wang *et al.* (2020a) |
| | Others | ICEP | | | | | | |
| QUAL | Physical | Water temperature | b, c | 0.5 degree | Global | Monthly | 1980-2010 | van Vliet *et al.* (2020) |
| | Organics | BOD | | | | | | |
| | Salinity | TDS | | | | | | |
| WaterGAP-WorldQual | Physical | Water temperature | b, c | 5 arcminutes | Global | Monthly | 1971-2010 | Punzet *et al.* (2012) |
| | Nutrients | TP | | | Africa, Asia, Europe and Latin America | | 1990-2010 | Voß *et al.* (2012), Reder *et al.* (2015), Fink *et al.* (2018) |
| | Organics | BOD | | | | | | |
| | Salinity | TDS | | | | | | |
| | Microorganisms | Faecal Coliform | | | | | | |
| WFLOW-DWAQ | Others | Contaminants[6] | b, c | 1 km | Europe | Annual | 2017-2018 | van Gils *et al.* (2020) |

1. $NO_3^-$: nitrate, TN: total nitrogen, TP: total phosphorus, Si: Silica, BOD: biological oxygen demand, TDS: total dissolved solids, DIN: dissolved inorganic nitrogen, DON: dissolved organic nitrogen, DIP: dissolved inorganic phosphorus, DOP: dissolved organic phosphorus, ICEP: Indicator for coastal eutrophication potential.
2. Water body types: a: groundwater, b: rivers, c: lakes and reservoirs d: coastal waters.
3. Typical reporting resolution used in the current document, which could be lower than the simulation resolution due to aggregation or averaging.
4. The model is time dependent but can account for climate inputs of different time periods.
5. Vulnerability, hazard and risk potential for insecticide runoff, non-substance specific.
6. The model simulates the cumulative impact on ecology for 1785 chemical of emerging concern, including pharmaceuticals and pesticides.

# 3 Water quality impacts on ecosystem health, human health and food security

## 3.1 Ecosystem health

*Main messages:*

*Nutrient pollution*

- *In 2020 anthropogenic nutrient sources contribute more than 70% to river nutrient loading.*
- *Curbing the global nutrient cycles requires paradigm shifts in food and waste systems.*
- *N:P ratios in global rivers have increased primarily due to selective retention filters.*
- *Agricultural sources contribute more than half of the total river nutrient loading. Sewage contributes 17% of the total river nutrient loading.*
- *Most of the increase of river nutrient loading in the past 50 years has been in Asia.*
- *Harmful algae blooms are now spreading in many river basins.*

*Toxic stress*

- *The chronic and acute lethal effects of (mixtures of) chemicals on aquatic species are significant. Two large scale European assessments report chronic effects on aquatic species to be expected at 42%-85% of the studied sites, while 14%-43% of the sites are expected to experience some degree of species loss.*
- *Assessments, as mentioned above for Europe, cannot be made on a global scale. Neither the measured data nor the information to generate predicted concentrations are available yet.*
- *The Human Impact and Water Availability Indicator (HIWAI) can be used to extrapolate the results obtained for Europe. This proxy was found to correlate well with the expected loss of aquatic species in European surface waters. Tentative results are available for Africa.*
- *At present no ready-to-use solution can deal with the many substances and degradation products, protection targets and modes-of-action for chemicals to affect humans and the environment.*
- *Yet, hopeful local steps can and are being taken like research on innovative regulatory solutions, awareness raising, investments in sanitation and initiating substances authorization procedures world-wide.*

### 3.1.1 Introduction

In this chapter, two water quality issues with major impact on ecosystem health are described: i) nutrient pollution and ii) toxic stress by chemicals.

Fertilizers, primarily nitrogen (N) and phosphorus (P) that have played a major role in the increased food production, enter soils, groundwater and surface water and are transported towards coastal seas. This has resulted in a wide range of environmental problems, ranging from groundwater pollution, loss of habitat and biodiversity, the creation of coastal dead zones, occurrence of harmful algal blooms, and fish kills as well as human health impacts (Damania *et al.* 2019, Diaz and Rosenberg 2008; Howarth *et al.* 2011; Michalak *et al.* 2013; Rabalais *et al.* 2001; Turner *et al.* 2003; Vollenweider 1992).

Currently, over 350,000 chemicals and mixtures of chemicals have been registered for production and use (Wang *et al.* 2020b). And, as a result of their use, many of these chemicals find their way to freshwater systems (Stroomberg *et al.* 2018, Liška *et al.* 2015, Schulze *et al.* 2019) and coastal waters (UNESCO and HELCOM 2017). There they may accumulate and negatively affect the aquatic ecosystem.

### 3.1.2 Nutrient pollution

#### 3.1.2.1 Impact/State

In freshwaters, algal blooms are often dominated by cyanobacteria that may generate toxins, rendering the water unsuitable for drinking, irrigation, bathing or swimming. Also, increased growth of algae may result in oxygen depletion and even hypoxia in the water body after the decay of the algal biomass. This, in turn, may lead to bad smells affecting local tourism, as well as to massive fish kills affecting local fisheries (Janssen *et al.* 2020).

Globally, lakes constitute an important source of water, food, and recreation. However, increasing water pollution threatens the ability of lakes to provide these and other ecosystem services (Fink *et al.* 2018). Lake eutrophication specifically, is a global environmental issue that poses a survival risk to aquatic organisms affecting fisheries and aquaculture. Alarmingly, eutrophication already is a worldwide phenomenon, with rapidly declining aquatic biodiversity (Janse *et al.* 2015). One of the symptoms of eutrophication and biodiversity loss is illustrated in Figure 3.1 showing remote sensing observations for 450 lakes with high cyanobacteria dominance, now occurring across all continents. Trend analyses indicate increases over time, and in several cases even regime shifts, in many lakes.

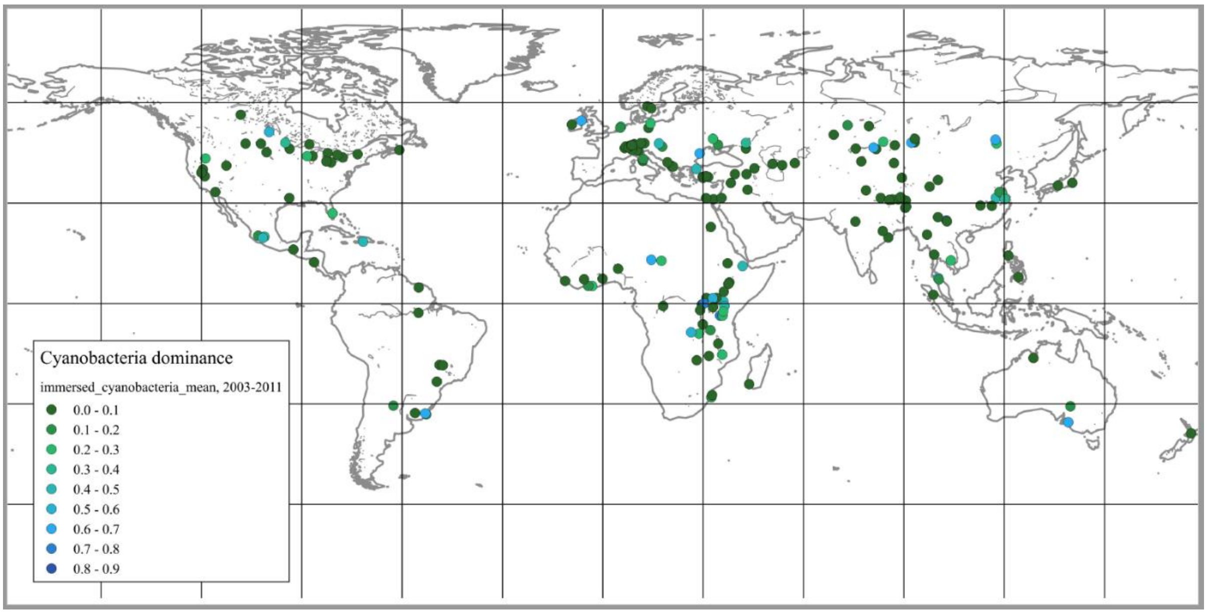


***Figure 3.1*** *Mean cyanobacteria dominance in the years 2003-2011 for 300 of the world's largest lakes (source: Diversity II water quality dataset (Odermatt et al. 2018). Each lake pixel can be classified as cyanobacteria or green algae dominated. The map shows the two classes' relative frequency for the whole nine years of data acquired by ENVISAT-MERIS (Matthews and Odermatt 2015).*

The global map of the trophic state index (Figure 3.2, top) shows that satellites are able to identify freshwater systems in different stages of eutrophication. Such information can be used in combination with data on P accumulation in lake and reservoir sediments (Figure 3.2, middle), as an indicator for the potential occurrence of cyanobacteria blooms, and the level of original freshwater biodiversity (Figure 3.2, bottom), i.e. the species loss due to human interferences in aquatic ecosystems, including nutrient loading differentiated by sources and dam construction in rivers.

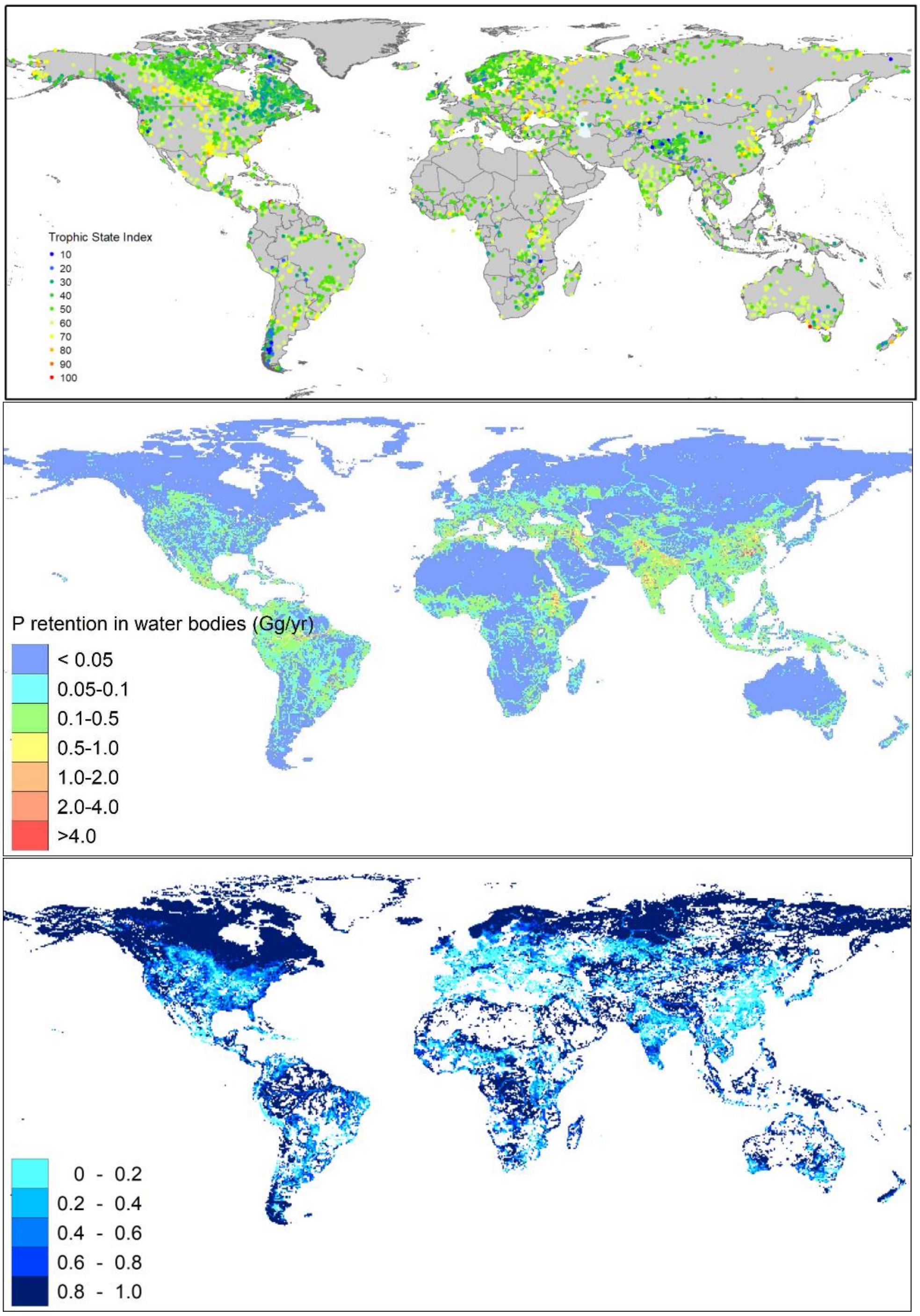


***Figure 3.2 Top****: Averaged Trophic State Index (TSI) derived from chlorophyll concentration for 4264 globally distributed lakes (example September 2020) (source: Copernicus Global Land Service Lake Water Products). TSI is derived from Sentinel-3 OLCI 300 m resolution satellite observations to serve as a proxy of ecosystem eutrophication. TSI (Carlson, 1977) relates algal biomass to the concentration of surface chlorophyll-a. The index is used globally in inland water quality monitoring programmes where integration of multiple observation methods is required. TSI < 40 marks oligotrophic waters, 40-50 mesotrophic, 50-70 eutrophic and 70-100+ hypereutrophic. Source: Copernicus Land Monitoring Service (CLMS).* ***Middle:*** *simulated P retention in global water bodies in 2015, reflecting the uptake of P by aquatic plants as an indicator of trophic state. Source: IMAGE-GNM. (Beusen et al. 2016).* ***Bottom:*** *Level of original freshwater biodiversity in 2010, whereby 100% indicates the situation without human disturbance. Source: GLOBIO model (Janse et al. 2015).*

### 3.1.2.2 Drivers/pressures

Eutrophication is partially a natural driven process, but it is severely enhanced by anthropogenic nutrient input from agriculture activities or untreated discharge of wastewaters.

In the Earth system, the nutrient cycles have intensified dramatically during the past 50 years. The global N (from 255 to 446 Tg $yr^{-1}$, +75%) and P cycles (24 to 46 Tg $yr^{-1}$, +92%) increased rapidly between 1970 and 2020 (Figure 3.3 a, b). The world population increased by 3 billion inhabitants between 1970 and 2020 (Figure 3.4). As a result, the protein and P consumption and excretion also increased significantly (Figures 3.3 and 3.4), which reflects population growth and a shift towards more consumption of meat and dairy along with growing incomes. However, nutrient flows related to food consumption are a minor term compared to those in agriculture, the economic sector that produces the food (Figure 3.3 a, b). It is also clear that the inputs of nutrients in natural ecosystems is relatively stable or slowly declining, and that anthropogenic inputs into the earth system are now dominating (Figure 3.3 a, b).

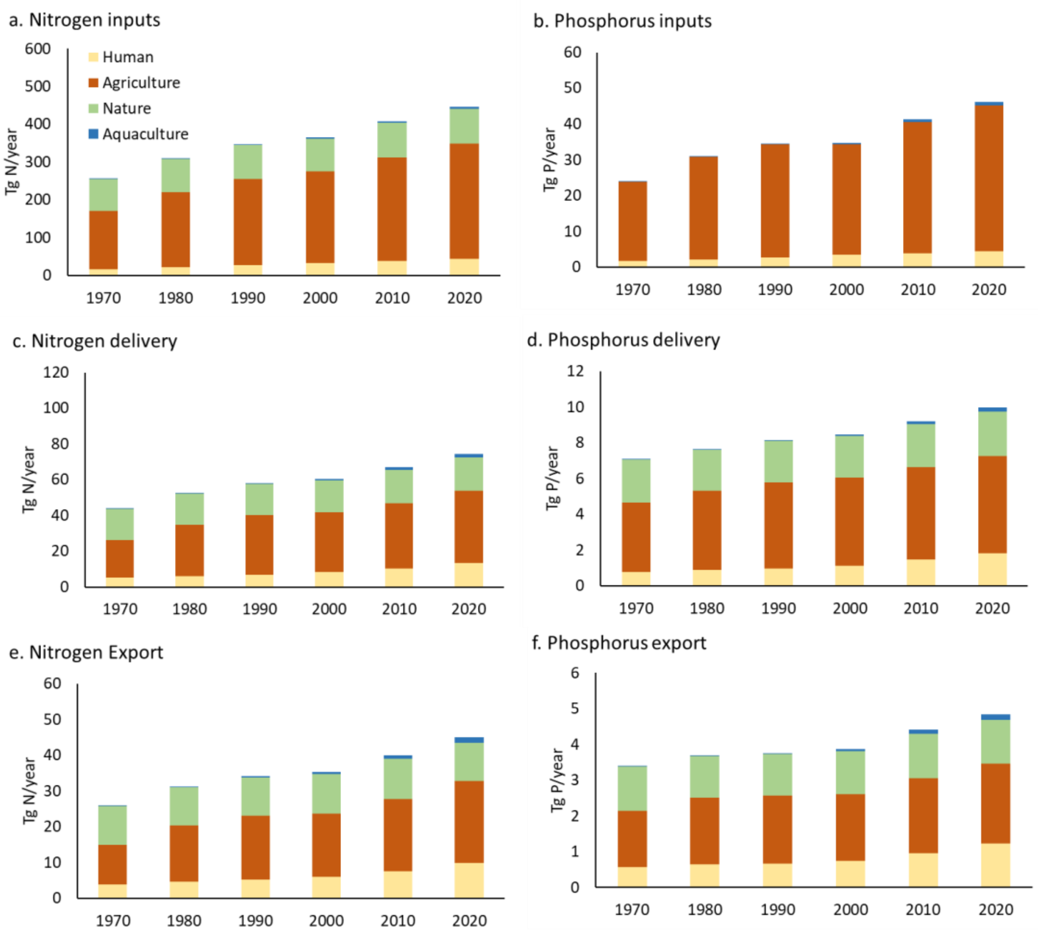


***Figure 3.3*** *N **(a)** and P **(b)** inputs, delivery to surface water **(c and d)**, and river export to the coastal waters **(e and f)** for the human, agriculture, aquaculture and natural systems for the world for 1970-2020. The inputs include: human system – N and P in food consumption; agriculture system – N and P from fertilizer, animal manure, biological N fixation and atmospheric N deposition; aquaculture system – feed N and P intake; natural system – biological N fixation, atmospheric N deposition. Delivery is the direct discharge to surface water from aquaculture and from sewage in the human system, for agriculture and natural systems nutrients are delivered through groundwater discharge and surface runoff, and for natural systems N and P in litter from vegetation in flooded areas and P from rock weathering. Data from IMAGE-GNM (Beusen et al. 2016).*

Globally, the delivery to inland water bodies of total N (from 49 to 81 Tg $yr^{-1}$) and P (7.5 to 10.5 Tg $yr^{-1}$) increased rapidly between 1970 and 2020 (Figure 3.3 c, d). Natural sources declined slightly, while anthropogenic sources increased from 58% in 1970 to 74% of the total delivery in 2020 at the global scale (Figure 3.3 c, d), implying that with the rapid increase in the total N and P delivery, there has been an immense intensification of the societal nutrient usage and discharge. It is clear agriculture is now the most important source, contributing 52% in 2020, which is primarily due to increasing food production (Figures 3.3 c, d).

Globally around 40% of the total population is connected to a sewage system at present, and wastewater treatment installations remove 26% of the emissions from connected households. The remaining N and P in the untreated wastewater plus effluents after wastewater treatment currently contribute 15-17% to total nutrient delivery.

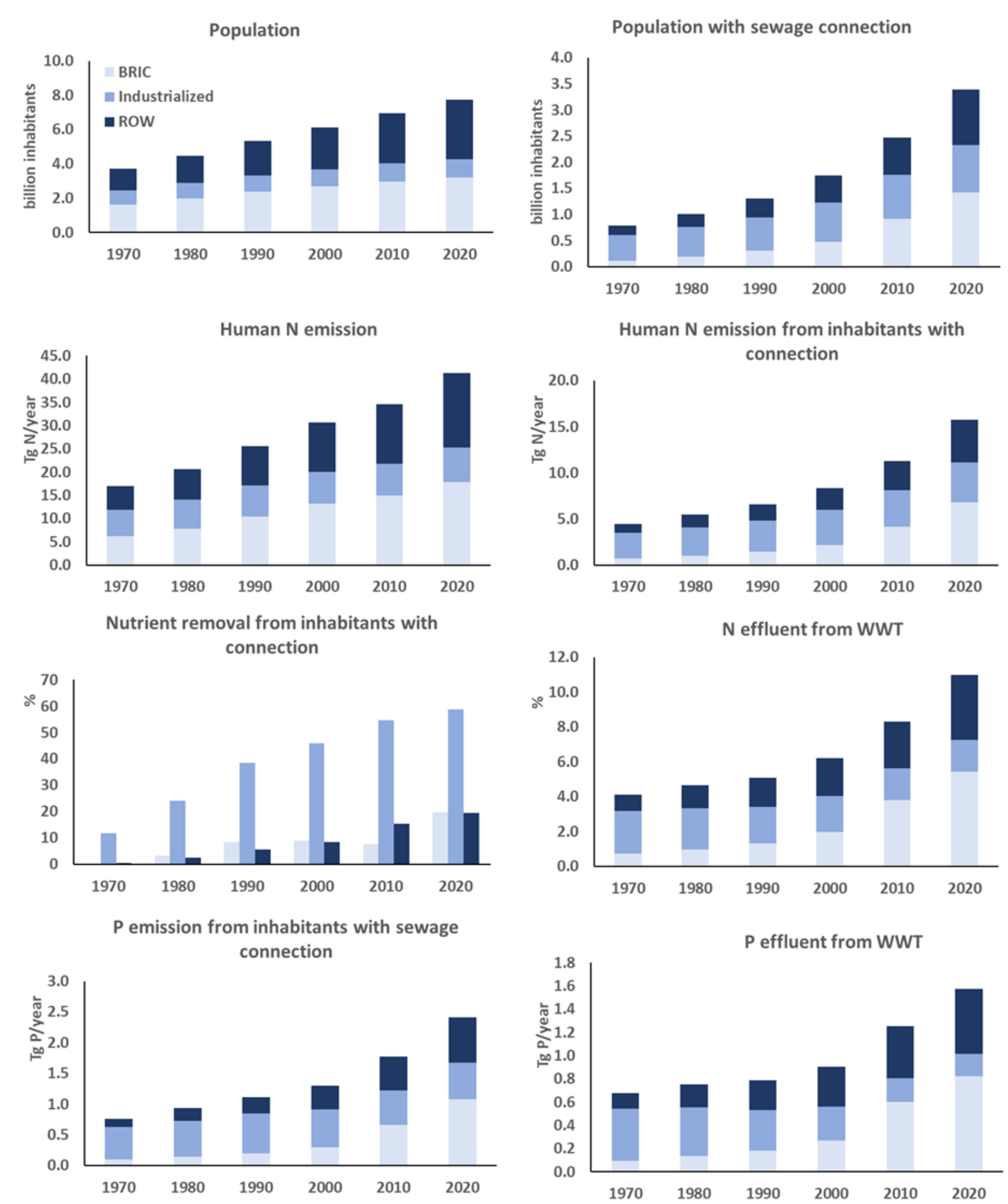


***Figure 3.4*** *Total population, population with sewage connection, total human N emission, human N emission from connected households, nutrient removal, N effluent from wastewater treatment plants, human P emission from connected households, and P effluent from wastewater treatment plants for 1970-2020 for BRIC (Brazil, Russian Federation, India and China), IND (industrialized countries of North America, Europe, and Japan and Australia), ROW (Rest of the world) countries and the world (van Puijenbroek et al. 2019).*

Aquaculture is a minor source at the global scale (Figures 3.3 a-d), but particularly in Southeast Asia it is becoming a locally significant source of nutrients (Wang *et al.* 2020c). With the rapid increase of anthropogenic sources, the relative contribution of natural sources has been decreasing. Natural sources contributed to 37% (for P) and 42% (for N) to total nutrient delivery in 1970, and in 2020 this contribution shrank to 27-28%.

Currently global river export to coastal waters amounts to 49 Tg $yr^{-1}$ of N and 5 Tg $yr^{-1}$ of P (Figure 3.3 e, f). Global N export has increased by 60% since 1970, and global P export by 31%. The contributions of the various sources to river export differ from that for the delivery, since the retention processes in the river systems depend on the location and distance of the point of delivery, the travel time in relation to the surface water volume, temperatures, etc. Natural sources contributed 40-44% in 1970 and 27-30% in 2020 to river export. Sewage contributed 10% to total P delivery in 1970, and 17% in 2020, while the global contribution of sewage to river export was 15% and 23%, respectively for 1970 and 2020. This means that while there has been a rapid increase in total N and P export, the mix of sources also changes with anthropogenic sources gradually becoming dominant and point sources increasingly important in the river export. This is related to the increasing number of world inhabitants living in cities at short distance to coasts, with short travel distances and limited retention.

In addition to nutrient loading per se, the coastal research community has become increasingly aware that the N:P ratio is essential. Disruption of the N:P ratio away from the Redfield molar ratio of 16:1 is one of the major causes of harmful algal bloom (HAB) proliferation, even in a situation of declining nutrient loads. On the global scale there is a gradually increasing molar N:P ratio in the water drained by rivers to the oceans between 1970 and 2020, from values of around 18 to close to 22. The N:P ratio of nutrient delivery to surface waters also shows an increase but at a lower level of 14 to 17. The difference between the nutrient composition in the water flowing into the oceans and the delivery to surface water bodies is caused by the more efficient retention of P versus N in water bodies and sediments during the transport from land to sea. Under such conditions harmful algal blooms (HABs) often increase in frequency, area and toxicity (Glibert 2017).

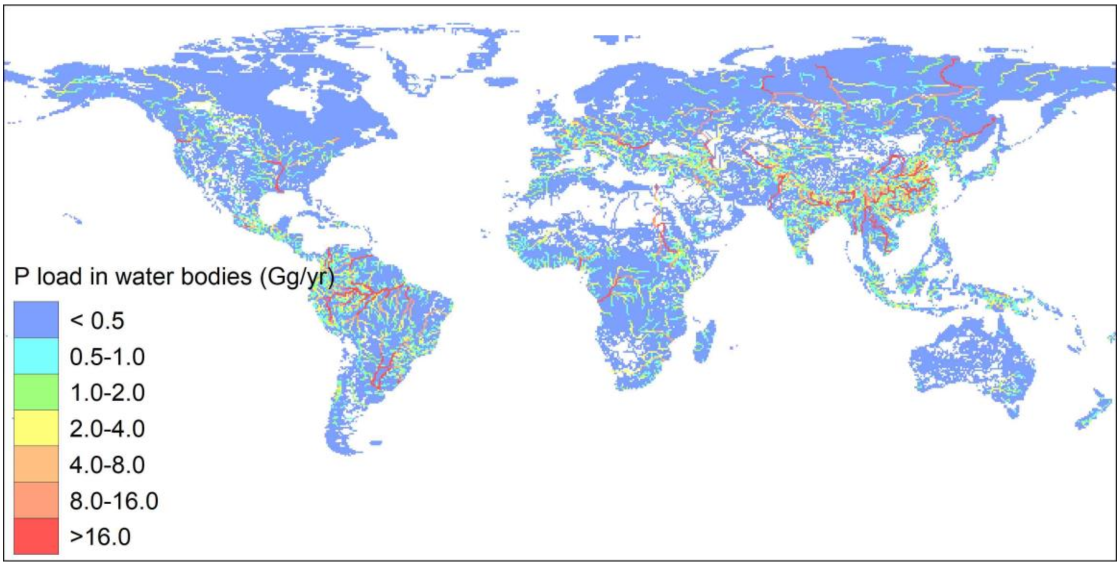


***Figure 3.5*** *Simulated annual P load of world-wide surface water bodies in 2015. Source: IMAGE-GNM (Beusen et al. 2016).*

Data collected in China's coastal waters (Liang 2012) combined with the river P loading data shown in Figure 3.5 indicate that in Chinese coastal waters there is a threshold for HAB proliferation of 25. Since the N:P ratio exceeds this value (from around the year 1980 onwards), HAB started to increase in both frequency and area. This problem is rapidly expanding. Global rivers with anthropogenic sources >50%

that discharge water with N:P ratio>25 (see Figure 3.24), exported 6 Tg N $yr^{-1}$ in 1970, and 18 Tg $yr^{-1}$ in 2020 (an increase by more than a factor of 3) (Figure 3.6). This suggests that the changes in the nutrient cocktail in the global river nutrient export may have been one of the major causes of the increased HAB proliferations in coastal waters as observed in recent decades (Glibert 2017; Glibert 2019).

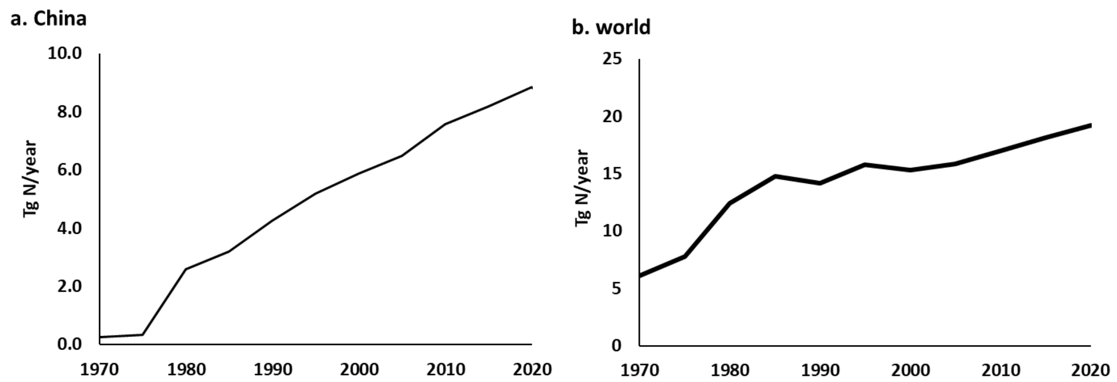


***Figure 3.6*** *N export for China* ***(a)*** *and the world* ***(b)*** *for all river basins with dominant (>50%) anthropogenic N sources and N:P molar ratio >25. Source: IMAGE-GNM (Beusen et al. 2016).*

The effect of HABs on mariculture production losses is discussed in the Food security Chapter 3.3.4.

#### 3.1.2.3 *Response*

Eutrophication can be mitigated by controlling the nutrient cycles or by measures to improve the resilience or reduce the perturbations of aquatic ecosystem. Since agriculture is globally the main source of nutrients in water bodies (Figure 3.3), controlling nutrient cycles can start in the human system by reducing the internal N and P cycles in the food production system, i.e. by reducing the inefficient feed – livestock production process and by reducing food wastage (Kummu *et al.* 2012). Although this is one of the most effective ways to reduce eutrophication, it depends on human behaviour as it is directly related to our diets (Westhoek *et al.* 2014). Furthermore, the food production system can be more efficient in the use of nutrients. Nutrient use efficiency can be enhanced by changing management, tuning inputs to the needs of plants and animals (Wang *et al.* 2020d; Zhang *et al.* 2015). For example, several directives by the European Commission (European Commission 1991a,b) have reduced diffuse nutrient emissions from agriculture and nutrient discharge from sewage. As a result, water quality of the Rhine River improved. Annual average total nitrogen (TN) concentration in the German-Dutch border declined from >7 mg/L in the 1970s to 2.3 – 2.6 mg/L during 2010 – 2013[1], which is close to the EU standard (2.5 mg/L) (Liska *et al.* 2015). Total P concentrations declined from >0.9 mg/L in the 1970s to values around 0.1 mg/L now. However, large parts of European rivers still have "less than good quality" with respect to P concentrations, clearly affected by diverse sources and the P legacy effect (McCrackin *et al.* 2018), see Figure 3.7.

Unwanted effects of measures such as in the European Union is the increasing N:P ratio, as observed in the Rhine and many European rivers (Romero *et al.* 2013), and rivers and lakes in China (Tong *et al.* 2020; Finlay *et al.* 2013). This calls for a balanced management of both N and P from the diverse nutrient sources in river basins, including agriculture, sewage and industry.

Several on-site solutions are available, targeted on lowering the local nutrient availability or increasing the resilience of rivers, lakes and coastal waters. For example this is illustrated by restoring the nutrient buffering capacity of the natural embankment and wetlands around lakes as demonstrated for Lake

[1] Ministry of Infrastructure and Environment (Rijkswaterstaat) 2019, The Netherlands, retrieved from http://live.waterbase.nl/waterbase_wns.cfm?taal=nl (in Dutch)

Taihu in China (Sun *et al.* 2015). Re-oligotrophication may be a costly strategy, and even where vast reductions in nutrient loading were achieved, lakes do not respond as expected. Reducing nutrient loads may lead to less algal production, organic matter sedimentation, less oxygen depletion and therefore less denitrification. This may lead to increasing nitrate concentrations and rising N:P ratios, as observed in a series of large global lakes (Finlay *et al.* 2013).

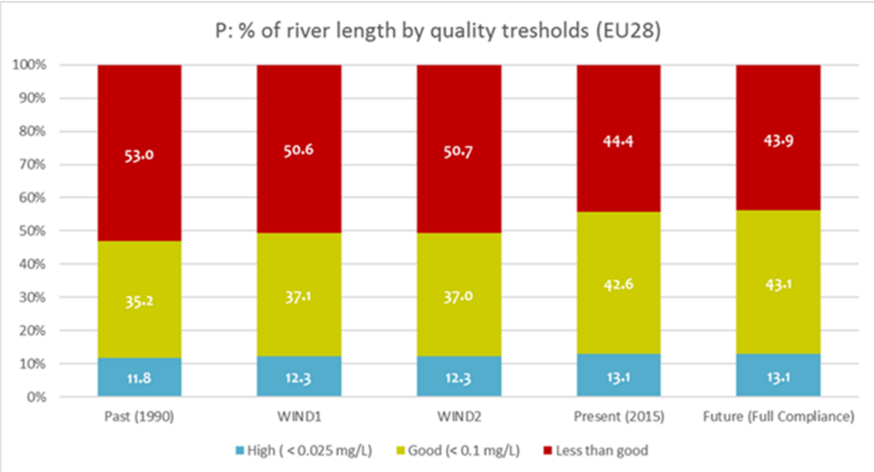


***Figure 3.7*** *Fraction of EU28 river length with mean annual phosphorus concentration < 0.0025 mg/L (high quality), < 0.1 mg/L (good quality), or higher (less than good quality). WIND refers to the scenario "What If No Directive". Implementation of UWWTD (Urban Wastewater Treatment Directive) reduced the fraction of rivers in less than good quality from 53% (past, 1990) to about 44.4% (present, 2015). Full compliance of UWWTD may accomplish further reduction, however other sources of pollution should be considered.*(*Pistocchi et al. 2019*)

In order to develop properly balanced response strategies to reduce nutrient pollution of inland and coastal waters, that account for the diversity of nutrient sources and transport pathways, the triangulation approach (see Chapter 2.1.2) needs to be further explored to integrate in-situ monitoring of water quality (Figure 3.7), monitoring of the impacts using remote sensing and modelling (see e.g. Figures 3.1 and 3.2). Scenarios can be used to drive these models to assess the level of mitigation that is needed to achieve improvement of water quality in a given timeframe, such as outlined in Figure 3.7. Analysis of future scenarios can help us to compare the effectiveness of the various actions and strategies in future situations, accounting for land use change, population growth, climate change and human interferences in the earth system.

### 3.1.3 Toxic stress

#### 3.1.3.1 Impact/State

Effects from chemicals on aquatic species are commonly estimated by comparing the concentrations of chemicals in surface waters to thresholds derived from indicator organisms in laboratory tests on algae, macro-invertebrates and fish species. Projections for acute effects in the field are made on the basis of short-term laboratory tests for lethal endpoints (e.g. mortality). Projections for chronic effects in the field are made on the basis of longer-term laboratory tests for non-lethal endpoints like reproduction or growth. It is furthermore assumed that effects on individual species are likely to cause effects on aquatic ecosystems, such as losses of biodiversity or species shifts.

An assessment based on measured environmental concentrations in more than 10,000 European water bodies (Malaj *et al.* 2014), concluded that chronic effects on aquatic species were expected at 42% of the studied sites and acute lethal effects at 14% of those sites. The authors noted that, although these are already serious numbers, they are likely to underestimate the actual risks, due to the limited number of chemicals that are being measured.

Posthuma *et al.* (2019) reported a similar assessment based on predicted environmental concentrations (PECs), generated by state-of-the-art Europe-wide mathematical modelling (van Gils *et al.* 2020). The expected chronic and acute effects on aquatic species were estimated for a mixture of 1,785 chemicals in 10,658 water bodies across Europe. Results indicated that 79% to 85% of European waterbodies are expected to experience chronic effects (Figure 3.8) while 16% to 43% are expected to experience some degree of species loss (Figure 3.9).

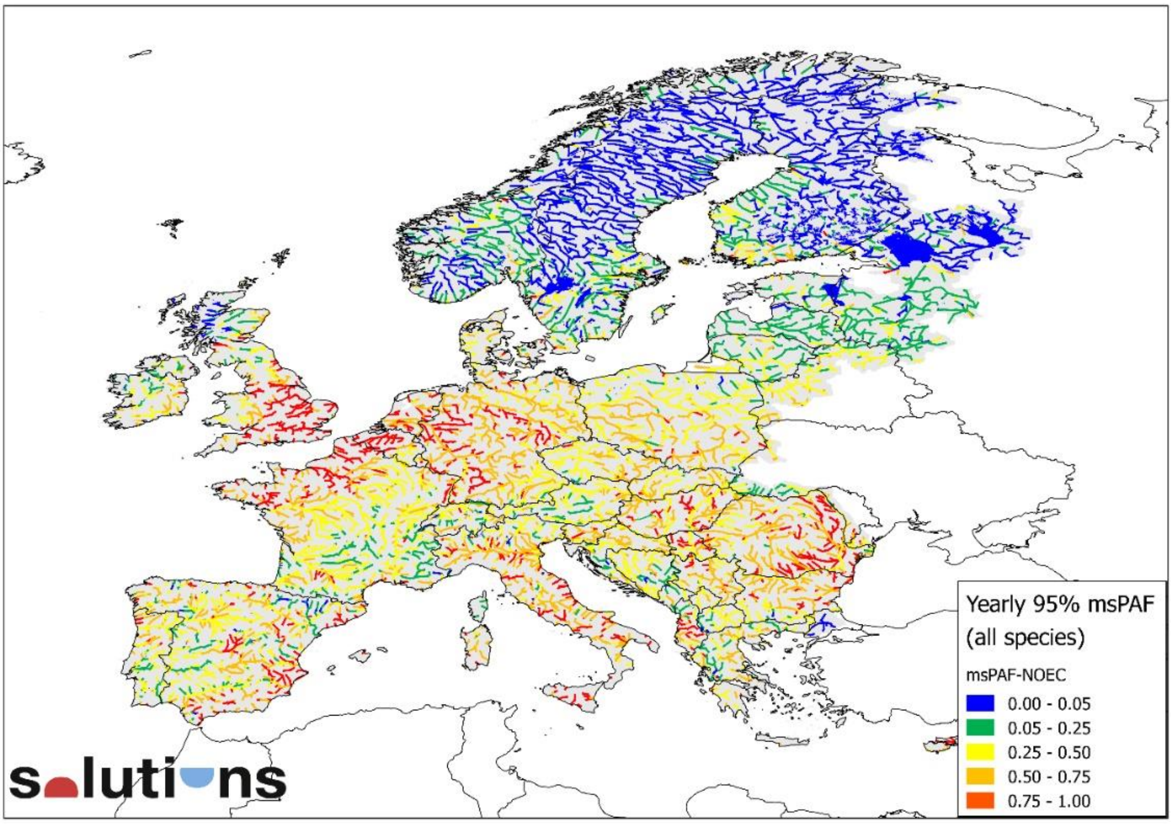


***Figure 3.8*** *Chronic effects on aquatic ecosystems in Europe, estimated from Predicted Environmental Concentrations of 1,785 chemicals. Effects are expressed in terms of msPAF, the 'multi-substance potentially affected fraction of species', ranging from 0 (no species affected) to 1 (all species affected). The msPAF-NOEC expresses toxic stress in relation to the regulatory concept of "sufficient protection" of aquatic ecosystems (initial effects, distress), used in European legislative frameworks (REACH, WFD). The blue-green class boundary distinguishes between sufficient and insufficient protection, with other colours represent increasing distress (exposure higher than the no-effect level).* (*Posthuma et al. 2019*)

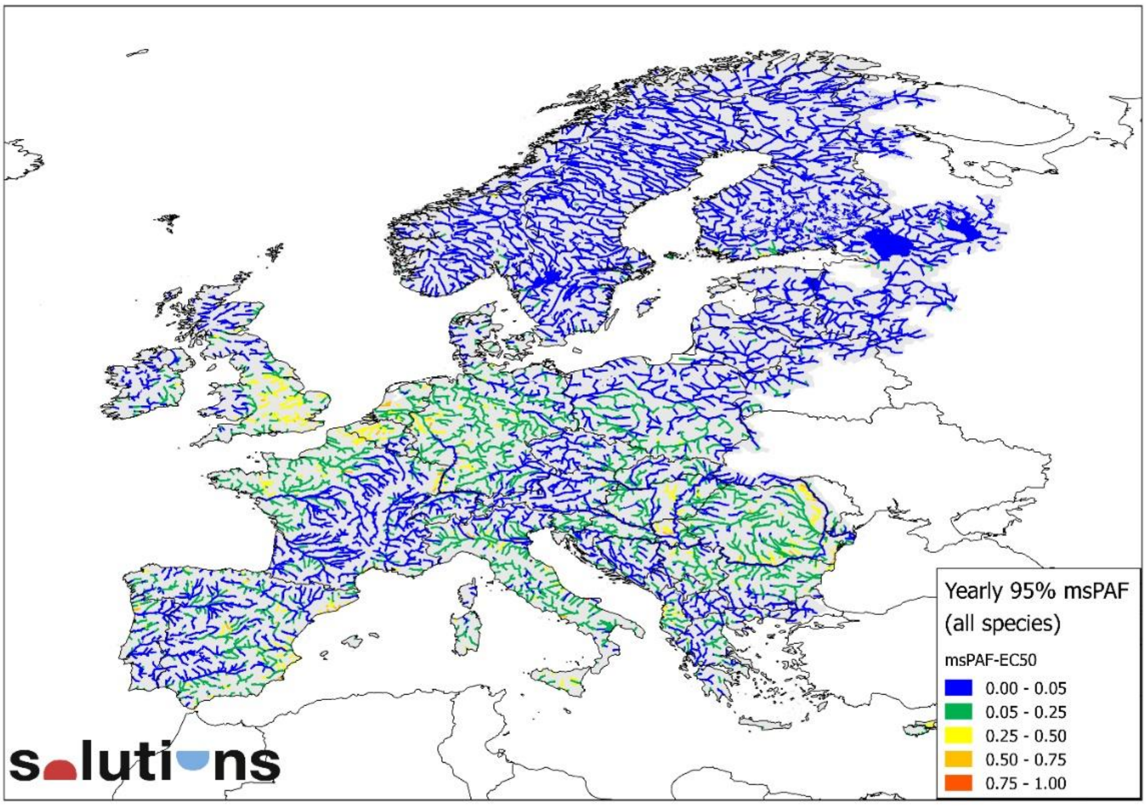


***Figure 3.9*** *Acute effects on aquatic ecosystems in Europe, estimated from Predicted Environmental Concentrations of 1,785 chemicals. Effects are expressed in terms of msPAF, the 'multi-substance potentially affected fraction of species', ranging from 0 (no species affected) to 1 (all species affected). The msPAF-EC50 expresses toxic stress in relation to the regulatory concept of ecological impact magnitudes (species loss). The color scale relates to increased biodiversity effects, found in empirical studies, which can be aligned with the ecological impact classification used in the European Water Framework Directive to define excellent, good, moderate, poor, and bad water quality.* (*Posthuma et al. 2019*)

Assessments as presented above for Europe cannot be made on a global scale. Neither the measured concentration data nor the information to generate predicted concentrations are so far available on a global scale. A tentative assessment for other continents has been proposed that extrapolates the above results obtained for Europe on the basis of a simple proxy called *Human Impact and Water Availability Indicator (HIWAI).*

This proxy combines information about population density, economic activity, river dilution capacity and downstream transport and can be easily calculated using a hydrological model. The HIWAI was found to correlate well with the expected loss of aquatic species in European surface waters as shown in Figure 3.9. For illustration, the extrapolation of these results to the African continent is shown in Figure 3.10. Currently this work is being extended to the global scale.

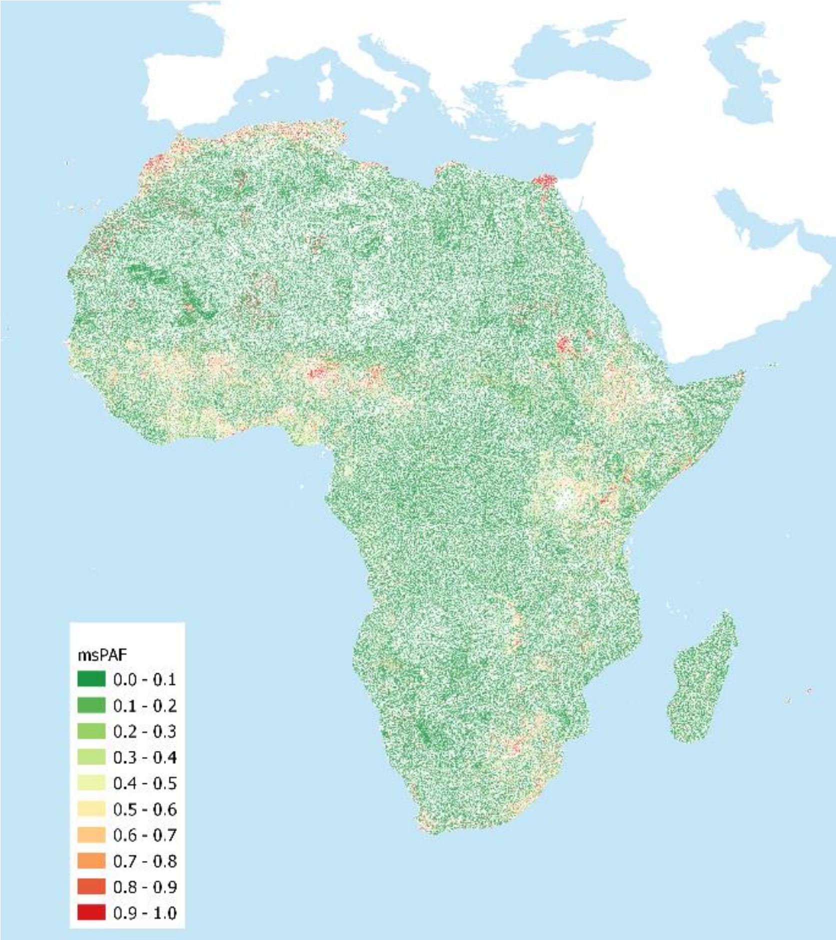


***Figure 3.10*** *Approximate worst case acute toxic pressure by chemicals, expressed in terms of msPAF, the 'multi-substance potentially affected fraction of species' expressing expected species loss.*

### 3.1.3.2 Drivers/pressures

Chemicals are used for a reason. Obvious drivers are the increasing food demand leading to increased use of pesticides and veterinary drugs, as well as the demand for improved health and public wellbeing leading to increased use of pharmaceuticals. More in general, increasing economic development leads to an increasing use of a very wide range of chemicals in industry, in buildings and constructions, in the outdoor environment and the indoor environment. Different types of uses in combination with the properties of the chemicals in question lead to variable fractions of the volume of chemicals used leaking to the environment (air, wastewater, surface waters, soils). On average, this leakage fraction may well amount to 10-20% (van Gils *et al.* 2020).

In 1965, the CAS Chemical Registry System was introduced, which issued unique CAS Registry Number® to identify chemical substances without ambiguity. In 2009, this system made its 50 millionth substance registration, while that number had doubled to 100 million in 2015[2].

Global chemical sales (excluding pharmaceuticals) are projected to grow from EUR 3.47 trillion in 2017 to EUR 6.6 trillion by 2030 (Figure 3.11, UNEP 2019). Asia is expected to account for almost 70 per cent of sales by then.

---

[2] https://www.cas.org/about/cas-history

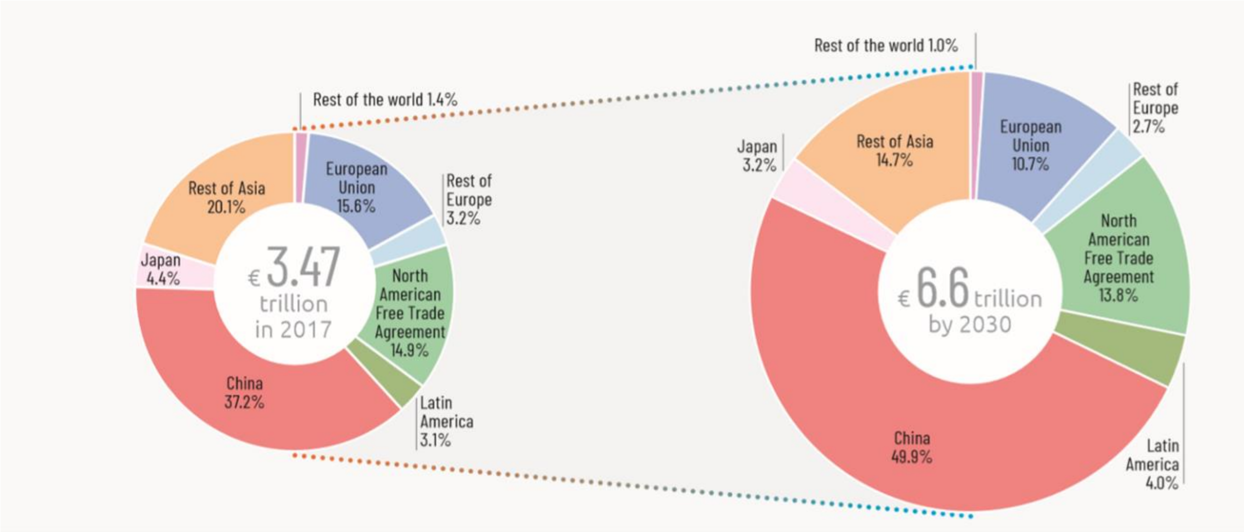


***Figure 3.11*** *Projected growth in world chemical sales (excluding pharmaceuticals), 2017-2030 (adapted from UNEP 2019).*

It is challenging to obtain a quantitative and complete overview of the resulting local pressures. Model-based approaches may partly help out (Brack *et al.* 2017). The quantification of contaminant emissions (as also used in the above described models) may be provided by various methods, e.g. by Wastewater Treatment Plant, WWTP, pathway modelling, by modelling of the terrestrial run-off and erosion pathway or by inverse modelling. However, none of these approaches can easily address hundreds or thousands of chemicals on a continental or even global scale. This limits the possibilities to effectively manage chemicals in aquatic ecosystems.

#### 3.1.3.3 Response

Responses to the presence of hazardous chemicals can be arranged at two levels. The most effective is prevention of the use of chemicals presenting unacceptable risks to humans and the environment. This is particularly relevant for persistent and mobile toxic chemicals (PMT) as these are not removed by natural processes and may spread over large distances. This requires an effective chemicals "admission to market" legislative system to be in place and to be enforced. A challenge is to determine if a chemical is presenting unacceptable risks to humans and the environment, in a way that can withstand the economic pressure of bringing new chemicals to the market. Reactive responses by mitigation or remediation measures are also possible, but not always effective. Relatively cheap is the (additional) treatment of already intercepted wastewater flows in treatment plants. Chemical leakages that reach the environment in a more diffuse way are much harder to abate. In such cases, only good application practices (e.g. for pesticides, paints) may offer some degree of reduction of leakages to the environment.

### 3.1.4 Data and knowledge gaps

This assessment shows that there still is a strong need for better and more regularly monitored data on nutrient pollution:

- Long-term monitoring data on nutrient concentrations at various locations within river basins is scant and sparse and is limiting our ability to validate models at different scales. Data for some of the largest rivers in the world is even not available at all.
- The contributions of sewage, agriculture, aquaculture and natural sources to nutrient loading of global river basins is uncertain. This is related to data limitations but also knowledge gaps on the importance of the various transport pathways, the biogeochemical processing in groundwater systems, riparian zones and in streams, lakes and reservoirs.

- Nutrient legacies from past management has been shown to have an important contribution to current river nitrate and phosphate loading; however, the magnitude of these nutrient fluxes is uncertain. Reducing this uncertainty requires specialized experiments in combination with models.

Concerning toxic stress, effective management of chemical pollution is currently hampered by both knowledge gaps and data gaps:

- Data to quantify chemicals use volumes and use types are sparse at best (e.g. Europe, US) and often non-existent.
- The knowledge to set up effective legislative frameworks to deal with chemicals is lacking. In some parts of the world, substance authorization procedures are in place that aim at eliminating non-desirable chemicals even before they are used. Such procedures have proven extremely useful. It is however difficult to incorporate chemical mixtures in such procedures.
- Regulations to protect the environment and human health also have difficulties with mixtures, i.e. cumulative effects. As there are simply too many substances and degradation products, too many protection targets and too many modes-of-action for chemicals to affect humans and the environment, approaches that single out any of the above will never provide holistic solutions. There is at present no ready-to-use solution.
- In Europe, a recent “Green Deal” call for research projects aims at providing a sound knowledge base for innovative regulatory solutions. Elsewhere, there are definitely no-regret actions to be taken. This includes awareness raising among policy makers worldwide, investments in sanitation while making sure that collected wastewater is treated and not discharged untreated, and initiating substances authorization procedures world-wide in order to avoid a situation that hazardous substances banned in one place find their way to other parts of the world.

## 3.2 Human health

*Main messages:*

- *Human health is directly and indirectly affected by contaminants in water ranging from pathogens, Antimicrobial Resistant (AMR) microorganisms, toxin-producing phytoplankton, organic micropollutants, arsenic and heavy metals, to elevated concentrations of inorganic nutrients, salinity and microplastics.*
- *Data to quantitatively link water quality to human health is often lacking at the large spatial scale, making quantification of impacts difficult. Large-scale water quality monitoring databases such as GEMStat provide data on a limited number of contaminants from in-situ sampling and with sparse spatial coverage and sampling frequency. Remote sensing can provide spatially-explicit information on, among others, the risk posed by phytoplankton blooms and sources, such as irrigation water jeopardizing food safety.*
- *Modelling efforts have been a prominent source of information on human health impacts from contaminated water, the water quality state and the sources.*
- *First estimates of human health impacts for the pathogen Cryptosporidium and arsenic show hotspots in areas where surface water is still regularly used for drinking directly and in Asia, respectively. For most other contaminants no impact studies are available at the large scale.*
- *For a limited number of contaminants, concentrations in surface and/or groundwater are available from model simulations. However, for many contaminants relevant for human health and water type estimates of their state are still unavailable at the large scale.*
- *Concentration hotspots are, for most contaminants, densely populated areas, in particular where waste water treatment is limited. For groundwater arsenic and surface water salinity impacts, hotspot areas include India, China and Mongolia.*
- *Sources of contamination are most often related to human activity, such as domestic water use, agriculture (use of manure, irrigation) and manufacturing.*
- *Response options most often focus on reduction of exposure by reducing contamination sources and treating or avoiding the water source, and can be evaluated using epidemiology and scenarios. The impact of the response options has not yet been widely assessed.*

### 3.2.1 Introduction

Water quality is closely related to human health (Boelee *et al.* 2019). This relationship has been studied ever since John Snow linked a cholera outbreak in London to contaminated water in 1855 (Snow 1855). *Vibrio cholerae* in water still plays a large role in the annual 1.4 – 4.3 million cholera cases that continue to occur globally (Momba and Azab El-Liethy 2017; Ali *et al.* 2012). The SARS-CoV-2 virus, which causes the COVID-19 pandemic, is the pathogen that is currently in the spotlight. This virus also enters the water cycle, as a significant percentage of COVID-19 cases sheds the virus with their stool (Wölfel *et al.* 2020). Although SARS-CoV-2 has been detected in wastewater and in surface water that received untreated wastewater (Guerrero-Latorre *et al.* 2020), thus far there has been no evidence for presence of viable or infectious virus particles in wastewater, or for wastewater, surface or drinking water as transmission source (La Rosa *et al.* 2020; Bilal *et al.* 2020; WHO 2020). Instead, the EU launched a comprehensive umbrella study coordinated by the JRC and linked to the World Water Quality Alliance to explore the potential of a wastewater – based sentinel RNA residual monitoring of viral fractions as a future advanced monitoring concept. Water-borne pathogens include viruses, bacteria, protozoa and helminths. In addition to pathogens, a number of other water contamination risks threaten human health.

The toxic compound arsenic is widely present in groundwater and can lead to skin, vascular and nervous system disorders and cancer (Hughes 2002). Recent estimates show that 94 – 220 million people are exposed to high arsenic concentrations in groundwater (Podgorski and Berg 2020). Similarly, fluoride, nitrate, heavy metals, and salinity in (ground)water pose human health risks.

Biotoxins are formed by some cyanobacteria and these are a particular nuisance due to a common trait of bloom-forming species to accumulate at the water surface, requiring closure of bathing sites and drinking water intakes (Backer *et al.* 2015). Furthermore, a large number of different organic micropollutants that originate in manufacturing and agriculture are present in waters and pose a health risk to the population (Landrigan *et al.* 2018). These organic micropollutants can have a variety of impacts, such as disruption of the endocrine, reproductive and immune systems and are able to cause behavioural problems, cancer, diabetes and thyroid problems (Schwarzenbach *et al.* 2010). More recently recognised contaminants that influence human health are emerging contaminants, such as antimicrobial resistant microorganisms (AMR) and microplastics (Boelee *et al.* 2019) or nanomaterials. AMR are a major concern worldwide (WHO 2015), because infections with AMR microorganisms are often much more difficult to treat than infections with microorganisms that are not resistant. Although the role of water in the spread of AMR is not yet quantified, its importance has been strongly recognised (Larsson *et al.* 2018). Similarly, for microplastics potential health risks are obvious, but knowledge on the extent to which they affect human health is limited (Prata *et al.* 2020; Rist *et al.* 2018) just like the role that water plays in human health risk assessments (Koelmans *et al.* 2019). And, while focus in terms of plastics has largely been on the marine realm UNEP will soon publish guidance on monitoring and addressing plastics in freshwater (UNEP in prep).) In general, the large number of direct human health impacts shows that the relation between water quality and human health is multi-faceted.

In addition, human health can also indirectly be threatened by contaminated water. For example, nutrient concentrations in surface waters likely influence the habitats of vectors that could cause diseases, such as malaria (Myers and Patz 2009), whilst soil erosion favours increased suspended matter to harbour pathogens. Plastic debris could also create ideal habitats for disease vectors and act as reservoirs for pathogens (Vethaak and Leslie 2016). Water temperature influences the persistence of pathogens in water (Vermeulen *et al.* 2019). Moreover, several water pollutants influence food quality and safety by irrigation (see Chapter 3.3.5) and both are indirectly linked to human health. While we recognise the importance of these indirect effects, data on these effects are very limited; this assessment will therefore only focus on the most obvious indirect effects.

Water quality is related to human health through exposure. People are exposed to water in many different ways, depending on their location, livelihood, culture, wealth, gender etcetera. The most common exposure pathways can be summarised as drinking, bathing, ingestion during domestic use, eating irrigated vegetables, rice (or rice products) or aquatic plants (such as water spinach), eating contaminated fish and shellfish, and skin contact. These exposure pathways highlight that the quality of ground, surface and coastal waters is relevant to human health.

This chapter builds on the earlier 'Snapshot of the World's Water Quality' (UNEP 2016). In this earlier assessment, faecal coliforms were the contaminant included to represent human health impacts. The assessment concluded that the rural population at risk of health problems, which is defined as the population in contact with water contaminated with high concentrations of faecal coliforms, could be up to hundreds of millions of people in Latin America, Africa and Asia (UNEP 2016). Whilst this was an important realisation, faecal coliform concentrations do not usually correlate very well with pathogen concentrations, as they can grow in the water body (Devane *et al.* 2020; Byappanahalli and Fujioka 1998), and many more contaminants can have human health impacts. The current chapter incorporates more water quality variables and exposure routes. The objective of this chapter is to assess the impact of water quality on human health. To this aim, we provide a wide overview of the relation between water quality variables and direct and indirect human health impacts. Additionally, based on available data from in-situ observations, remote sensing and large-scale models, we evaluate human health hotspots related to impaired water quality.

### 3.2.2 Results

To evaluate the direct and indirect impacts of water quality on human health, we developed a non-exhaustive overview of the human health impacts (Table 3.1). This Table shows that there are a large number of direct and indirect links between water quality and human health. Also interrelations exist between water quality variables, their sources, state, impacts and response. For example, pathogens and nitrate have to some extent the same sources and therefore also potentially similar relevant response options. The overview makes it clear that quantitative evidence for the links between water quality and human health is still largely lacking at continental or larger scales. Nevertheless, the World Water Quality Assessment encompasses a wide range of focus areas that will be highlighted here.

GEMStat has data available for a number of the contaminants in Table 3.1. These data vary in space and time. For example, faecal coliform data are available for 6451 stations across the world, while *Escherichia coli* data are available from 3790 stations in North America, South America, Japan and New Zealand. Unfortunately, these data are not the best indicators for human health impacts from pathogens. Data for Salmonella are available for 62 stations along rivers in Europe, but only for a few years in the early 1990s. Also, for arsenic, many heavy metals, nutrients and organic micropollutants some data are available in GEMStat (see Chapter 2.2.1). In this chapter we do not evaluate the GEMStat data, because they are scattered and recent data relevant for health are scarce as most contaminants relevant for health are not included in the indicators for SDG 6.3.2. We therefore only report on potential data analyses that have been performed. Several of the large-scale water quality models use or have used GEMStat data for their calibration. In those cases, the use of models and data are highlighted in Table 3.1.

***Table 3.1*** *The influence of water quality on human health. This list is non-exhaustive, as no detailed literature has been performed. The colour coding is as follows: blue: GEMStat or other large-scale databases, red: remote sensing, yellow: modelling, and green refers to a combination of GEMStat and modelling. Dark colours are for surface water, light colours are for groundwater.*

| **Water quality variable** | **Impact** | | **State***  | **Sources** | **Response options** |
|---|---|---|---|---|---|
| | **Direct** | **Indirect** | | | |
| Pathogens (viruses, bacteria, protozoa and helminths) | Acute and chronic gastroenteritis, fever, mortality, hepatitis, pneumonia, cancer, among others[1] | Stunting, learning deficits, food safety threatened | Cryptosporidium concentrations[2]<br>Rotavirus loads[3] | Human faeces, livestock manure, wildlife | Improved water, sanitation and hygiene (WASH), wastewater treatment, manure management, reduce exposure e.g. by boiling drinking water or stopping recreational use, vaccines |
| AMR | Reduced ability to treat infections[4] | Former diseases become problem once again[4] | | Human faeces, livestock manure, presence of antimicrobials in the environment | Reduced use of antimicrobials |
| Toxic algae / cyanobacteria | Producing toxins that cause gastroenteritis[5], respiratory failure[29] | Stunting, bioaccumulation risk | Cyanobacteria concentrations | Develop in the water in situations with high nutrient concentrations | Reduced inputs of nutrients into the surface waters by wastewater treatment, manure management |
| Organic micropollutants (eg. pesticides, pharmaceuticals, and many others) | Disruption of the endocrine, reproductive and immune systems, behavioural problems, cancer, diabetes and thyroid problems[6,7]. Direct effects due to pharmaceuticals in drinking water are very unlikely[8,9]. | Use of anti-microbials can cause AMR, bioaccumulation risk | Insecticide runoff[10]<br>Pharmaceuticals occurance[11] | Pesticides: Agricultural use, home/garden use Pharmaceuticals: medical use, home medical use, Other: specialised chemicals in manufacturing | Pesticides: stricter use management and registration of use to better estimate local impacts, improve management and control, better inform and update policies. Pharmaceuticals: stricter use policies at home, hospitals and (large scale) farms, better registration of use to improve impact assessment and policy formulation. |

| | | | | | |
|---|---|---|---|---|---|
| Arsenic | Skin, vascular and nervous system disorders and cancer[12] | Food quality and safety threatened | Arsenic concentrations | Primarily natural sources, also from mining activities and pesticides | Switch to low-arsenic sources, if available, or filter |
| Fluoride | Dental and skeletal diseases[13] | | Fluoride concentrations[14] | Primarily natural sources, also from pesticides | Switch to low-fluoride sources, if available, or filter |
| Nitrite/nitrate | Blue baby syndrome[15] | | Nitrate concentrations[16]<br>Dissolved inorganic nitrogen loads | Land application of nitrogen from manure, sewage or industrial sludge, septic systems, geologic nitrogen mobilised by irrigation water[15]. For surface water also human waste and discharge of animal manure from livestock production (only in China), use of synthetic fertilizers, atmospheric N deposition.[17] | Reduced inputs of nutrients into the ground and surface waters by wastewater treatment, manure management, switch to low-nitrate sources, filter drinking water |
| Heavy metals | Cancer, other toxic effects, diarrhoea and vomiting[18] | Food quality and safety threatened | Heavy metal concentrations[19] | Manufacturing, agriculture, domestic wastewater, atmospheric deposition, leakage from pipes[18] | Reduce heavy metal use in manufacturing and agriculture, replace pipe network, switch to low-heavy-metal sources, if available |
| Salts/salinity | Hypertension, increased risk of (pre)eclampsia infant mortality[20] | Food quality and safety threatened | Salinity (TDS)[20]<br>Salinity (TDS)[21] | Irrigation return flows, domestic waste water, manufacturing[21] | Reduced TDS inputs, improved irrigation management and desalination |
| Plastics, incl. microplastics | Particle toxicity leading to oxidative stress, cell damage, inflammation, and impairment of energy allocation functions, toxicity of substances leaching out of plastic[22], but unquantified | Habitat for pathogens and vectors that can spread infectious diseases | Microplastics concentrations[23]<br>Microplastics concentrations[24] | Personal care products, clothing fibres, car tire wear, macroplastics in mismanaged solid waste[23] | Mitigation measures for car tire wear, improved solid waste management[23] |

*The state variable here is the state of the water quality variable for which data are available from GEMStat (https://gemstat.org) or other large-scale databases, or from remote sensing or models from the WWQA consortium for large spatial scales from continents to global.

[1] Aw (2018); [2] Vermeulen *et al.* (2019); [3] Kiulia *et al.* (2015); [4] WHO (2015); [5] Codd *et al.* (1999); [6] Landrigan *et al.* (2018); [7] Schwarzenbach *et al.* (2010); [8] de Jesus Gaffney *et al.* (2015); [9] WHO (2012); [10] Ippolito *et al.* (2015); [11] aus der Beek *et al.* (2016); [12] Hughes (2002); [13] Internat. Progr. Chem. Safety (2002); [14] Amini *et al.* (2008); [15] Canter (1996); [16] Ouedraogo *et al.* (2016); [17] Strokal *et al.* (2016); [18] Chowdhury *et al.* (2016); [19] Kumar *et al.* (2019); [20] Shammi *et al.* (2019); [21] van Vliet *et al.* (2020); [22] Vethaak and Leslie (2016); [23] van Wijnen *et al.* (2019); [24] Li *et al.* (2020).

### 3.2.2.1 Impacts

Human health and the change in human health due to impaired water quality can be quantified through the mortality rate, which is one of the indicators of Sustainable Development Goals (SDG) 3 "Ensure healthy lives and promote well-being for all at all ages". For example, Indicator 3.9.2 is the "Mortality rate attributed to unsafe water, unsafe sanitation and lack of hygiene" (Wölfel *et al.* 2020). The 2015 global burden of disease study (GBD) attributed 1.8 million deaths in 2015 to contaminated water from unsafe or untreated sources (Landrigan *et al.* 2018). However, many diseases do not lead to death. Another common metric is the Disability Adjusted Life Year (DALY), which sums the years of life lost and the years of healthy life lost to quantify the disease burden (Murray and Lopez 1996). DALYs can be added up across regions and diseases. Whilst DALYs are not yet commonly used to evidence health impacts, another way of quantification is to estimate exposure (e.g. population in contact with contaminant (UNEP 2016)). Additionally, the exceedance of safe water guidelines can be evaluated, such as the exceedance of drinking or bathing water guidelines. As this chapter will show, evaluations of human health impacts due to impaired water quality are not yet widely available.

Water quality human health impact evaluation was available at the large scale from the literature for pathogens, arsenic and salinity only. Models helped evaluate these health impacts. For Cryptosporidium, Quantitative Microbial Risk Assessment (Haas et al. 1999) was used to evaluate the disease burden. Preliminary results for the population drinking surface water directly (Figure 3.12a) and for the sub-Saharan population drinking surface water directly and tap water made from surface water (Figure 3.12b) show that in particular in Africa and Papua New Guinea people still drink surface water directly and that the countries with a large share of the population consuming surface water directly have the highest disease burden. The rural population drinking surface water contaminated with faecal coliforms directly has decreased between 2008 and 2017, but at different rates across Latin America, Africa and Asia (Wölfel et al. 2020). To make the evaluation complete, other exposure pathways should be included and the analysis should be repeated for other pathogens.

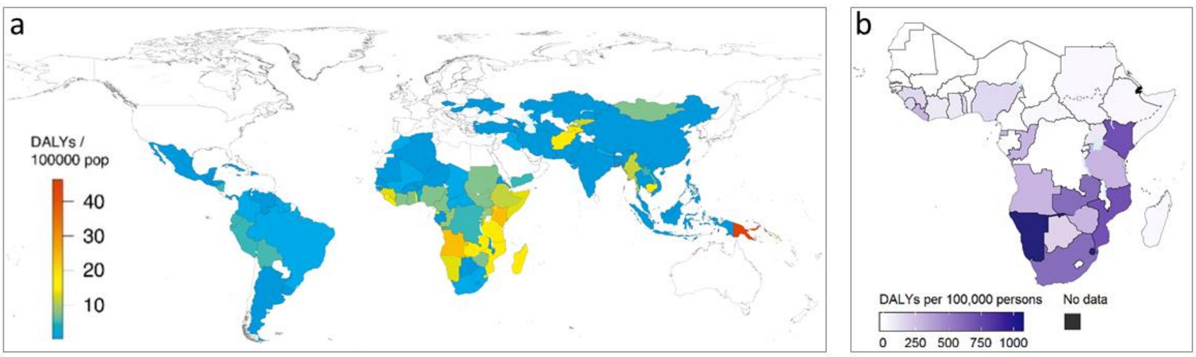


***Figure 3.12*** *Disease burden (expressed in DALYs per 100 000 population per year) for cryptosporidiosis contracted from* ***a)*** *drinking raw surface water (2 l/day all year - Countries that appear white on the map have no population depending on raw surface water for their drinking water according to data from the Joint Monitoring Programme (JMP) of WHO and UNICEF, Hofstra et al. 2019) and* ***b)*** *drinking raw surface water and tap water made from surface water (Limaheluw et al. 2019) for approximately the year 2010. Figure a does not take potential higher DALYs for the immunocompromised population that has HIV-AIDS into account, while Figure b does.*

While the preliminary analyses for pathogens showed that Africa was a main hotspot, Asia is the main hotspot for arsenic in groundwater, both in terms of the most affected area as well as the proportion of the affected population (Figure 3.13). An estimated 94 million to 220 million people are potentially consuming high arsenic concentrations in groundwater. This estimate of impact accounts for the proportion of households utilizing untreated groundwater in both urban and nonurban areas of each country.

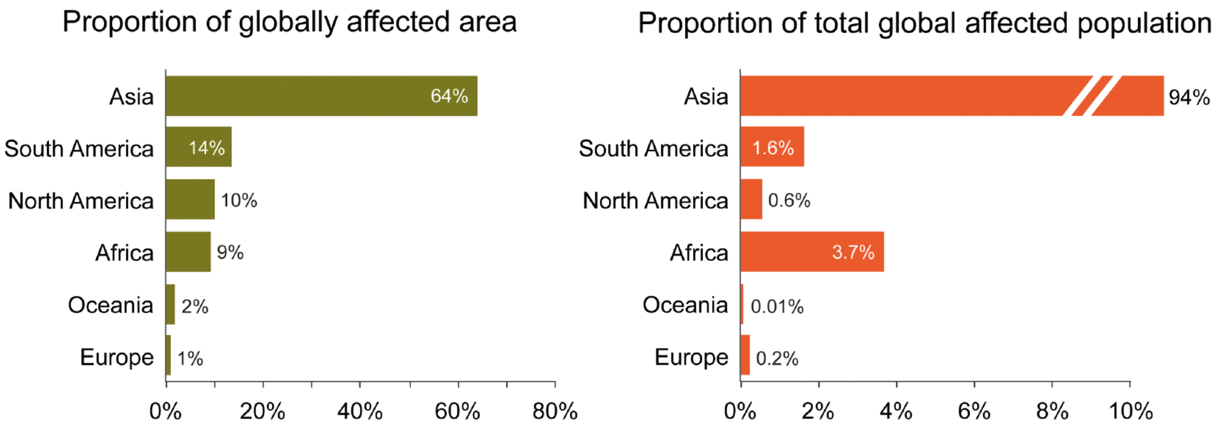


***Figure 3.13*** *Proportions of land area and population potentially affected by arsenic concentrations in groundwater exceeding 10 mg/l by continent (Podgorski and Berg 2020).*

For salinity, the drinking water quality is classified as good when the concentration of Total Dissolved Solids (TDS) is below 600mg/l (WHO 2017). Figure 3.14D shows that in many parts of the world strong reductions are required when surface water would be used for drinking directly, in particular in northeast China, northern India and countries east of the Caspian Sea. Also for heavy metals these drinking water guidelines are frequently violated across the world and surface water needs to be treated before consumption (Kumar et al. 2019).

#### 3.2.2.2 State

The water quality state is increasingly being reported on under SDGs 6 and 14. This section summarises a number of large-scale water quality state analyses, mostly from the World Water Quality Alliance community. For many contaminants, no large-scale analyses of loads, concentrations or other indicators are available from the literature. A complete assessment of all contaminants in all water types cannot yet be made, which implies that significant global health impacts remain unknown.

Figure 3.14 provides an overview of the contaminants for which the state is available at a large scale. (Darker) red values show hotspots, areas with high concentrations, for each of these contaminants. These hotspots are similar for many of the contaminants, including Cryptosporidium, faecal coliforms (from the previous UNEP report (UNEP 2016)), insecticides, dissolved inorganic nitrogen (which includes nitrite and nitrate), salinity (TDS) concentrations and microplastics. These hotspots often closely link to the population density, the sanitation situation and wastewater treatment efficiency in these areas, for example in China, India, Nigeria, Middle East and some basins in Central and Latin America. For arsenic, the hotspots are slightly different, as these are closely linked to irrigation (Figure 3.21 in chapter on Food security) and/or geogenic background. Some areas overlap for these contaminants, such as areas in northeast China and Mongolia and areas in northwest India. The probability of having arsenic concentrations in groundwater larger than 10 mg/l is also particularly high along the Indus, Ganges and Brahmaputra rivers in South Asia and in north-eastern Argentina, while salinity has hotspots in the Middle East, North Africa and western parts of Argentina. For pathogens, concentrations vary throughout the year, but hotspots remain mostly the same.

The results in Figure 3.14 are mostly modelling results whilst Figure 3.15 demonstrates how remote sensing can be used as a proxy for exposure risk for potentially harmful phytoplankton blooms, including cyanobacteria. While mitigation of risk can already be effectively aided by remote sensing of larger surface waters (in the order of several $km^2$), in-situ sampling will always be required to confirm the production of toxins at dangerous concentrations.

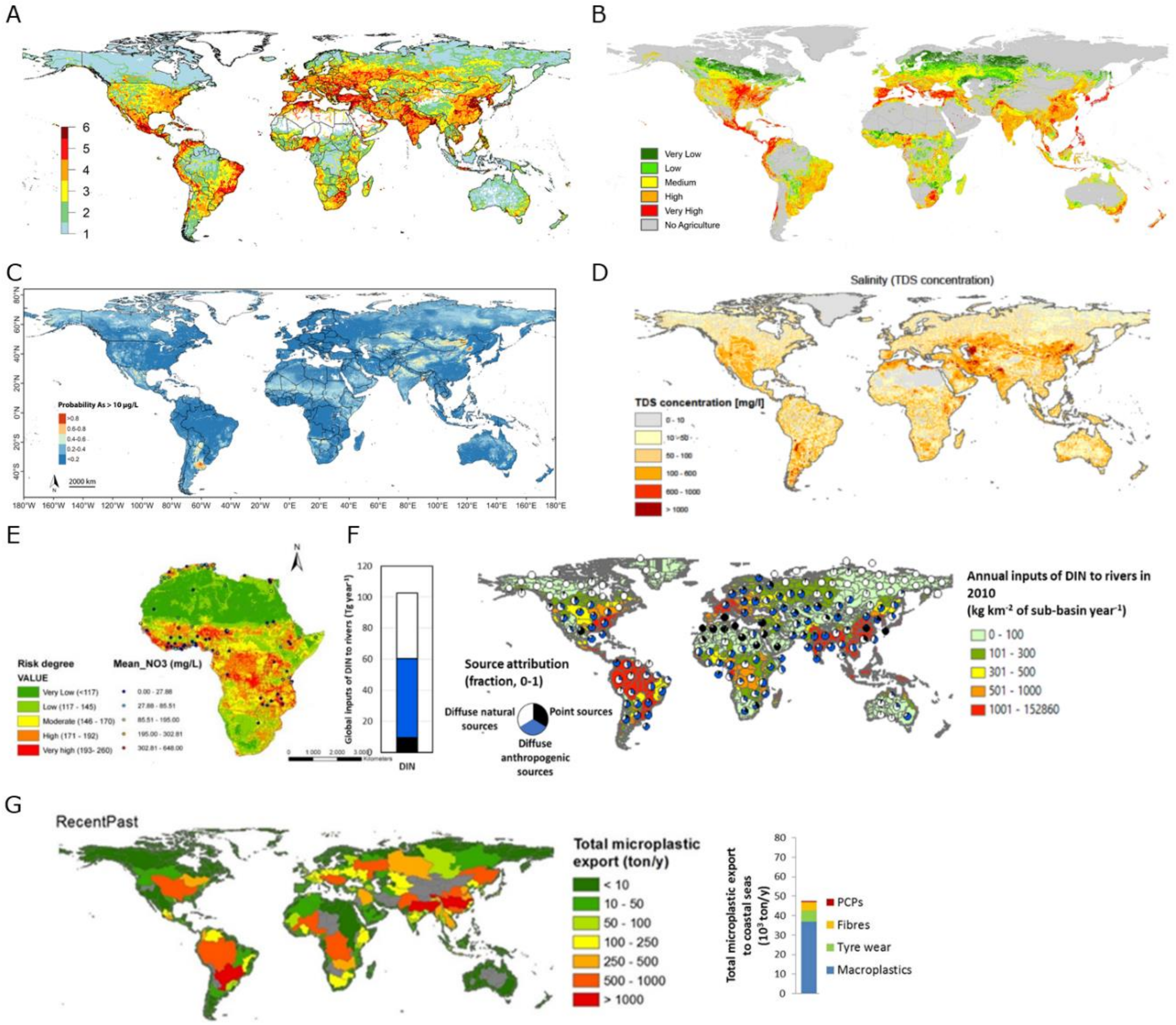


***Figure 2.14*** *Water quality state.* ***A.*** *Annual mean oocyst concentration categorised to WHO pollution categories (1 very pristine (~0.001 oocyst/l) to 6 grossly polluted (~100 oocyst/l)) (Medema et al. 2009). Each category represents one log10 unit change in concentrations (Vermeulen et al. 2019).* ***B.*** *Spatial distribution of potential insecticide runoff to stream ecosystems. The class boundaries (−3;−2;−1; 0) are the same as those used by Kattwinkel et al. (2011). Grey areas indicate the absence of any relevant agricultural activity (Ippolito et al. 2015).* ***C.*** *Modelled probability of geogenic arsenic concentration in groundwater exceeding the WHO guideline for arsenic in drinking water of 10 µg/l for the entire globe (Podgorski and Berg 2020).* ***D.*** *Salinity concentration (van Vliet et al. 2020), values above 600mg/l violate the drinking water standards.* ***E.*** *Spatial distribution of mean nitrate concentration in groundwater (Ouedraogo et al. 2016).* ***F.*** *Total annual inputs of dissolved inorganic nitrogen (DIN) to rivers in sub-basins from point and diffuse sources worldwide. Annual inputs of dissolved inorganic nitrogen (DIN) to rivers worldwide (bar graphs, Tg year$^{-1}$) and to rivers in sub-basins (maps, kg km-2 of sub-basin area year$^{-1}$) in 2010. Pies show the shares of the sources in the DIN inputs to rivers. The pies on the maps are for rivers in the largest sub-basins only (176 sub-basins covering more than 50 grids of 0.5˚). Results are from the MARINA-Global model (Strokal et al. 2016), aggregated to 10,226 sub-basins for the year 2010 using model inputs of Strokal et al. (2019) for point sources and of Bodirsky et al. (2012) for diffuse sources.* ***G.*** *Total river export of microplastics to coastal areas for the recent. Endorheic basins (except those of the Caspian See and Lake Aral) are excluded (grey) and the source contribution (Van Wijnen et al. 2019).*

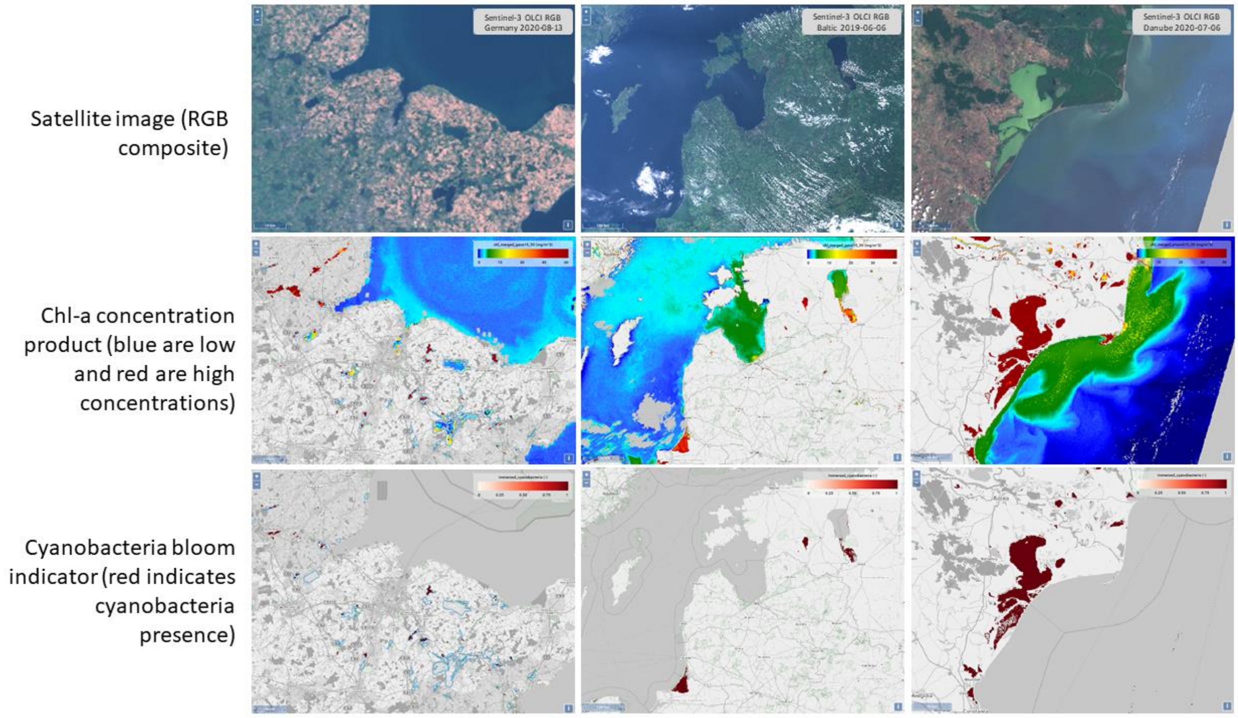


***Figure 3.15*** *Remote sensing of potentially toxic cyanobacteria blooms. Sentinel-3 OLCI RGB images (top panel) on various dates can be used across the world in inland, transitional and coastal bodies to estimate chl-a concentrations that indicate blooms (middle panel), and an OLCI-based cyanobacteria presence indicator (bottom panel) indicates cyanobacteria dominance in the water, i.e. cyanoblooms. Examples shown for northern Germany-southwest Baltic* ***(left)****, southeast Baltic-north-western Europe* ***(middle)****, and Danube Delta-Romania* ***(right)****. Images credit: https://www.cyanoalert.com/.*

### 3.2.2.3 Sources

Main sources for most contaminants are anthropogenic emissions from domestic use, agriculture and manufacturing industries (see Table 3.1 and Figure 3.14). In some cases, such as arsenic, fluoride, several heavy metals, nitrate and salinity in groundwater, and geogenic sources can also play a role. For pathogens, point sources, which represent human faeces that reach the rivers directly after open defecation in urban areas or when hanging toilets are used, and indirectly through the sewer network and after treatment (if available), are often the dominant sources (Wölfel *et al.* 2020). Diffuse sources, comprising livestock manure and faeces from people practicing open defecation in rural areas are only the dominant source in areas with sparse population (Vermeulen *et al.* 2019). For dissolved inorganic nitrogen (including nitrate and nitrite) in surface waters, point sources, including sewers and open defecation (direct inputs of human waste to rivers without treatment) from human waste and direct discharges of animal manure from livestock production (only in China), are the main sources in northern Africa and South Korea, while in many other parts diffuse anthropogenic sources, including the use of synthetic fertilizers and animal manure on land, atmospheric N deposition on agricultural land and biological $N_2$ fixation by crops and recycling of residues, are the main contributors (see Figure 3.14E). Main sources of salinity are irrigation return flows in Africa and Asia and manufacturing in Europe and North America and a combination of domestic waste and manufacturing in Latin America (van Vliet *et al.* 2020) (see Food security chapter, Figure 3.19) Finally, for plastics the main source of microplastics in rivers is macroplastics from mismanaged solid waste (see Figure 3.14F).

The models that are used regularly to simulate water quality usually require input data on the sources and their emissions. These include data from observations (e.g. the Joint Monitoring Programme, JMP (WHO/UNICEF) collects country reports on sanitation facilities), literature, other models (such as population simulations, climate data, hydrology) and could also include data from remote sensing (e.g. land use data used to evaluate lake water quality (Damania *et al.* 2019)).

#### 3.2.2.4 Response options

Response options to reduce the health risk related to impaired water quality can include a reduction in exposure, such as a reduction in the source emissions, treatment of the water before use or using a different water source, and prevention of the health problem, for example by vaccines or treatment. A number of response options have been summarised in Table 3.1, and as this study is focussed on the relation between water quality and human health, these options are mostly geared towards reduction in exposure. The response options mentioned include, among many others, improved water, sanitation and hygiene (WASH), manure management, reduced industrial emissions, using drinking water filters or using water from other sources.

The influence of response options can be evaluated using epidemiology studies in which the health effects before and after an intervention are evaluated. Additionally, scenarios can be used with the large-scale water quality and health impact models to evaluate the change in impact. These scenarios could be management scenarios that evaluate the effect of the different interventions. One such example at the large scale evaluated the difference in pathogen emissions from humans to the surface water under different socio-economic development scenarios. The main conclusion was that improved wastewater treatment and eradication of open defecation are expected to reduce the human emissions to surface waters in the future, despite population growth (Hofstra and Vermeulen 2016; Wölfel *et al.* 2020). Such scenario analyses have potential for evaluation of emissions to surface and groundwater, water quality and health risk for all contaminants mentioned in Table 3.1. Lastly, to increase the effectiveness of proposed response options, the actors and institutions managing water quality and public health need more collaboration and integration.

### 3.2.3 Data and knowledge gaps

The assessment on the links between water quality and human health has highlighted that a large amount of observational, remote sensing and, in particular, modelling work relevant to quantify this link has been developed. However, the assessment also shows that there is still a strong need for better, more regularly monitored and up-to-date data to do a thorough evaluation.

Required research and action includes:

- Reporting on the state, impacts (also indirect impacts), main sources and response options for all contaminants causing health risks.
- Quantification of the impacts using DALYs, in order to sum up over the different contaminants.
- Evaluation of response options for multiple contaminants and using consistent and comprehensive scenarios, including consistent exposure estimates, throughout the assessment. These response options should maximise synergies and minimise trade-offs in reduction of multiple contaminants.
- Translation of response options to policy; institutional collaboration and integration across water and health disciplines is needed to effectively implement responses.
- More data on a wider range of contaminants and risks for validation as well as data-driven modelling. Only the salinity indicator for SDG 6.3.2 (Wölfel *et al.* 2020) is directly related to human health and this chapter shows that many more indicators are important to consider in sampling schemes. In addition to country sampling schemes and despite its limitations, citizen science could also provide a relevant data source and create health impact awareness.
- Aggregation of the large number of project results at spatial scales smaller than continents. These publications will together be able to provide understanding of contamination levels and health impacts across the world.
- Improving the integration of all sources of information: in-situ data, models and remote sensing, across the DPSIR table.

## 3.3 Food security

*Main messages:*

- *Food security and food safety are already affected by reduced water quality in many regions of the world and trends of further deterioration are widespread.*
- *High levels of salinity, arsenic, chemicals, emerging pollutants, pathogens and microplastics in irrigation water are components of major concern.*
- *First estimates of water quality impacts on food security show hotspots in north-eastern China, India, the Middle East, parts of South America, Africa, Mexico, United States and the Mediterranean.*
- *Estimates of water quality impacts on food security reveal that over 200,000 $km^2$ of agricultural land in South Asia may be irrigated with saline water exceeding the FAO guideline for irrigation water of 450 mg/l and over 154,000 $km^2$ with a high probability of groundwater having arsenic concentrations that exceeds the WHO guideline for drinking water of 10 µg/l, respectively.*
- *Kashmir Valley, parts of Punjab, and the states of Haryana and Uttar Pradesh in India are vulnerable to poor water quality due to high salinity and arsenic levels in irrigation waters.*
- *Freshwater aquaculture production is strongly concentrated in southern and eastern Asia and seriously affected by phosphorus loading, which, in freshwaters is the major driver of eutrophication.*
- *Aquaculture and mariculture production are important to produce high-quality protein, but both can be at risk because of water pollution such as increased nutrient concentrations.*
- *Large-scale water quality monitoring databases (GEMStat) provide data on a limited number of pollutants in some regions and remote sensing data is useful to validate model outcomes, particularly for chlorophyll-a.*
- *Data that quantitatively link water quality impacts to food security is often lacking at the large spatial scale, making quantification of impacts difficult.*
- *Wastewater reuse in irrigation is an option to overcome water shortages and to close the nutrient cycle, however, the food may become contaminated by pathogens (and faecal coliform bacteria), Antimicrobial Resistant (AMR) microorganisms and chemicals in wastewater that has not been sufficiently treated.*

### 3.3.1 Introduction

Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life (FAO 1996). Close to 750 million people were exposed to severe levels of food insecurity and an estimated 2 billion people face some form of food insecurity – i.e. without regular access to safe, nutritious and sufficient food (FAO 2020). Achieving the Zero Hunger target (SDG 2) in the world by 2030 remains a huge challenge.

Water plays an important role for food production (crops, fisheries, livestock), food processing and preparation, and thus ensures food security and food safety. Water quality and its impact on food products and various operations in food industries are often underestimated. Most of the water is used in primary food production, i.e., it is used for crop irrigation, compared to food processing and preparation. Irrigated agriculture accounts for 20% of the total cultivated land but about 40% of the crop production worldwide is harvested on irrigated land (FAO 2014; Siebert *et al.* 2015). Crop yields are higher on irrigated land: the same area can be cultivated more than once a year under favourable climate and water conditions. Salinity is the most important threat for irrigation water quality. Irrigation with saline water results in salt accumulation in the soil profile. This increases soil osmotic pressure and thus reduces water uptake by crops and inhibits photosynthesis by decreasing $CO_2$ availability to the plant cells leading to reduction in crop yield and plant nutrition (Machado and Serralheiro 2017). Globally, about 70% of the abstracted water is used by agriculture, mainly for irrigation purposes, and including livestock and aquaculture (FAO 2016). Based on FAO AQUASTAT country statistics, globally 34 million ha (ca. 11%) of irrigated land is salinized by irrigation to some degree and an additional 60–80 million ha are affected to some extent by waterlogging and related salinity. This compromises food productivity, especially in large irrigation schemes in India, Pakistan, China and the United States. Arsenic in groundwater is another major problem in many countries worldwide but most severe in Southeast Asian countries (Farooq *et al.* 2019; Podgorski and Berg 2020). Arsenic in groundwater used for irrigation serves as an important source of arsenic accumulation in the top soil horizon depending on the crops grown (Farooq *et al.* 2019). However, arsenic accumulates not only in the top soil but also bioaccumulates in vegetables, rice and other crops posing a risk of food chain contamination and hence to human health (Moyano *et al.* 2009; Mondal *et al.* 2010; Ruíz-Huerta *et al.* 2017).

Aquaculture is an important source of proteins in large parts of the world. Global aquaculture production has increased from less than 1 million tonnes (Mt) in 1950 to 110 Mt in 2016, while the growth of capture fisheries production has peaked (FAO 2020; Yu *et al.* 2018). Although aquaculture contributes to local water quality deterioration, it is at the same time vulnerable to eutrophication and hypoxia in rivers and coastal waters from anthropogenic nutrient loading (Diaz *et al.* 2012). Climate effects such as increasing temperature can foster Cyanobacteria and harmful algal blooms (HABs) in aquaculture ponds.

Food safety is affected by quality of water not only used in irrigation, but the entire supply chain from food production to consumption. Water used in each step of the food supply chain can be an important route of exposure for various contaminants, such as pathogens, heavy metals, persistent organic pollutants (POPs), emerging pollutants (e.g., Triclosan) and microplastics. Microbial contamination of irrigation water is of particular concern for leafy crops (Allende and Monaghan 2015; Pachepsky *et al.* 2011), while heavy metals, POPs and microplastics tend to bioaccumulate in aquaculture (Rashed 2001), livestock (Giri *et al.* 2020) and soils (Boots *et al.* 2019). Food security and food safety cannot be achieved without tackling water issues since lack of safe water worsens food insecurity. Water pollution in both agricultural and non-agricultural sectors damages health and nutrition and reduces food production, constraining agricultural and economic development, especially in densely populated regions where water is already scarce and wastewater treatment is poor. Quantitative data that are required to link the impact of water quality to food security are often lacking, making it difficult to quantify the impact. Data derived from water quality modelling in combination with remote sensing can close data gaps and therefore help to identify hotspots and map the pathways of pollutant intakes.

## 3.3.2 Salinity pollution

### 3.3.2.1 Impact and State

Around 34 million hectares of irrigated land worldwide (equalling 340,000 km²) are affected by salinization (i.e. ca. 11% of the global irrigated area), 77% of which is in Asia, particularly in Pakistan, China and India. Using saline water for irrigating crops can result in severe yield losses and decreased quality (Zörb *et al.* 2018). In South Asia, the total irrigated area has increased by around 8% in the period 2008-2017. The non-rice irrigated area exhibits a stronger increase of 12% in the same period. These areas are mainly located in India and Pakistan, constituting around 70% and 12% of the total irrigated area in the region, respectively. Severe salinity concentrations (exceeding 450 mg/l according to FAO guidelines) in surface waters likely impair the use of river water for irrigation. Likewise, the threatened irrigated area has steadily increased driven by the growing trend in surface water irrigated area. Model outcomes reveal that more than 200,000 km² (22% of the irrigated area) of agricultural land may be irrigated with saline water exceeding 450 mg/l. Estimates of the irrigated area at risk indicate that the countries at higher risk are Afghanistan, Pakistan, Sri Lanka, and India (Figure 3.16).

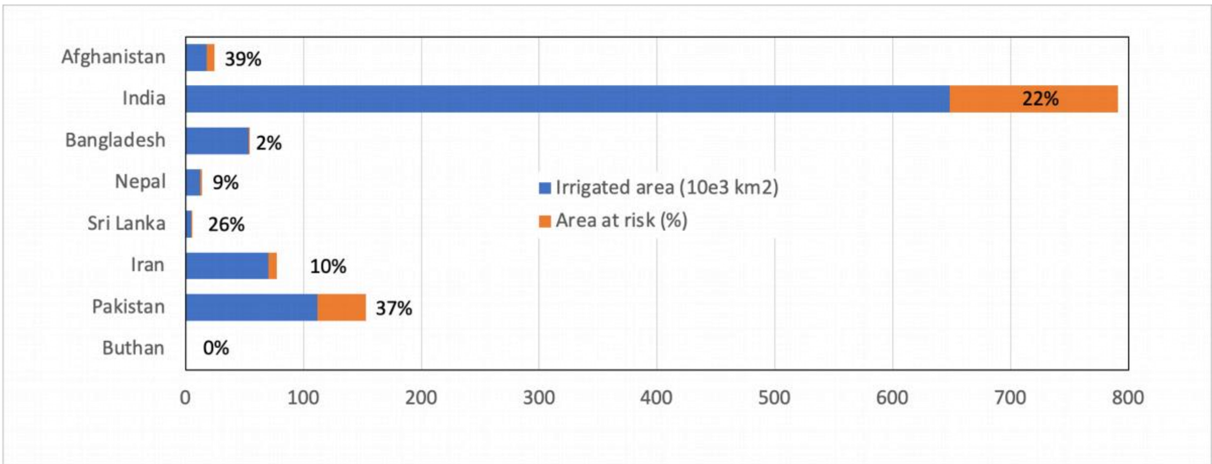


***Figure 3.16*** *Average percentage of irrigated areas at risk due to salinity pollution in the period 2008-2017 in Southern Asia. Data based on Klein Goldewijk et al. (2017), Siebert et al. (2013), UNEP (2016), Flörke et al. (2013) and Voß et al. (2012).*

A common metric of salinity pollution in rivers is the total dissolved solids concentration (TDS). Global spatial patterns of simulated salinity in terms of TDS in-stream concentrations, show distinct high-saline hotspot regions in north-eastern China, India, the Middle East, parts of South America, Africa, Mexico, United States and the Mediterranean (Figure 3.17). These simulated hotspots correspond well with salinity hotspots derived from global monitoring data (Thorslund and van Vliet 2019). Salinity pollution especially threatens areas where surface waters with relatively low dilution capacity are of high demand for irrigation. This poses a considerable risk for food security in semi-arid regions.

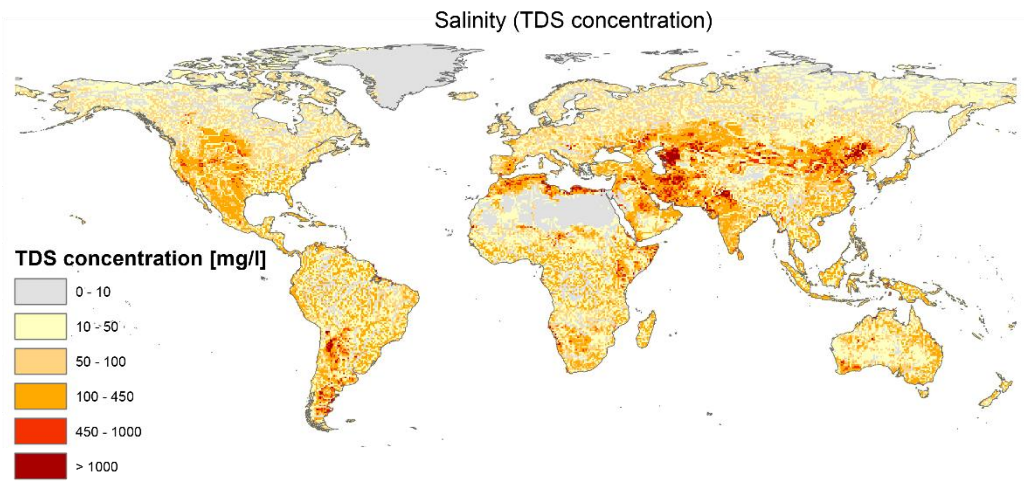


***Figure 3.17*** *Global surface water salinity hotspots (average simulated in-stream TDS concentrations). Regions with water availability less than 1 $m^3s^{-1}$ are masked (white). Details are provided in the supplementary information of van Vliet et al. (2020).*

Upstream land use affects the quality of water entering the irrigated area downstream and reduces water availability and quality for irrigation purposes (Figure 3.18). South Asia is one of the hotspot regions where water quality degradation due to high salinity impacts agricultural food production.

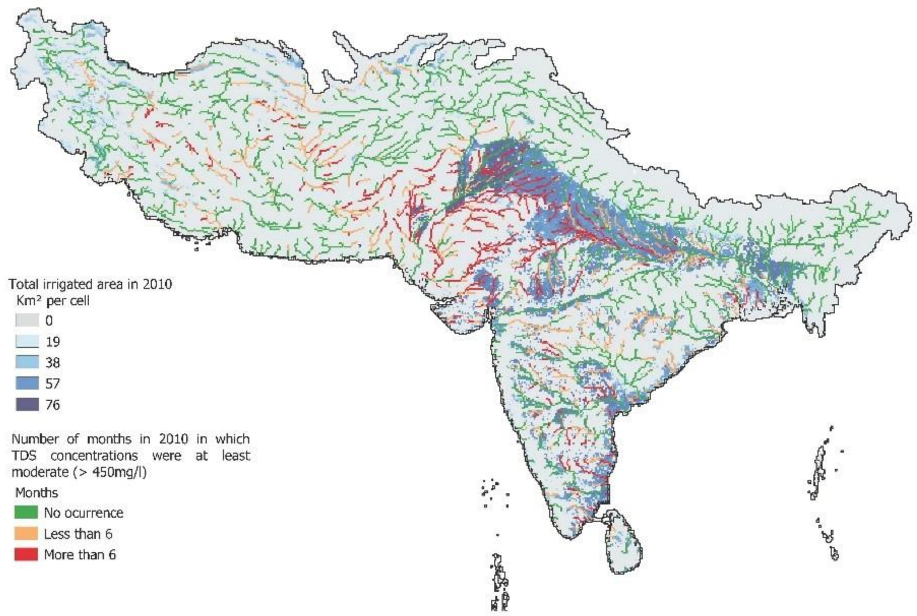


***Figure 3.18*** *Spatial distribution of the total irrigated area in South Asia in 2010 and river stretches showing their frequency (months per year) where TDS concentrations are moderate to severe (severe = threshold of 450 mg/litre exceeded, WorldQual simulations, UNEP 2016; irrigated area according to HYDE 3.2.1, Klein-Goldeweijk et al., 2017).*

### 3.3.2.2 Drivers and Pressures

Two main causes of salinization influence food production: natural (primary) salinization where soluble salts accumulate in soils through natural processes and anthropogenic (secondary) salinization as a result of anthropogenic interventions such as return flow from irrigation, wastewater treatment and industrial and mining operations as well as road-deicing and overextraction of groundwater aquifers (sea-water intrusion, saltwater upconing). Irrigation water use plays a key role in hotspot regions (Figures 3.17, 3.18) and relations are found with sectoral return flows and aridity levels. Strong interactions exist between salinity and different sectoral water uses (Flörke *et al.* 2019). A strong diversity in contributing sources exists between regions, with a high contribution of irrigation return flow particularly in Asia and Africa, manufacturing in North America and Europe, and combination of manufacturing and domestic use in South America (Figure 3.19).

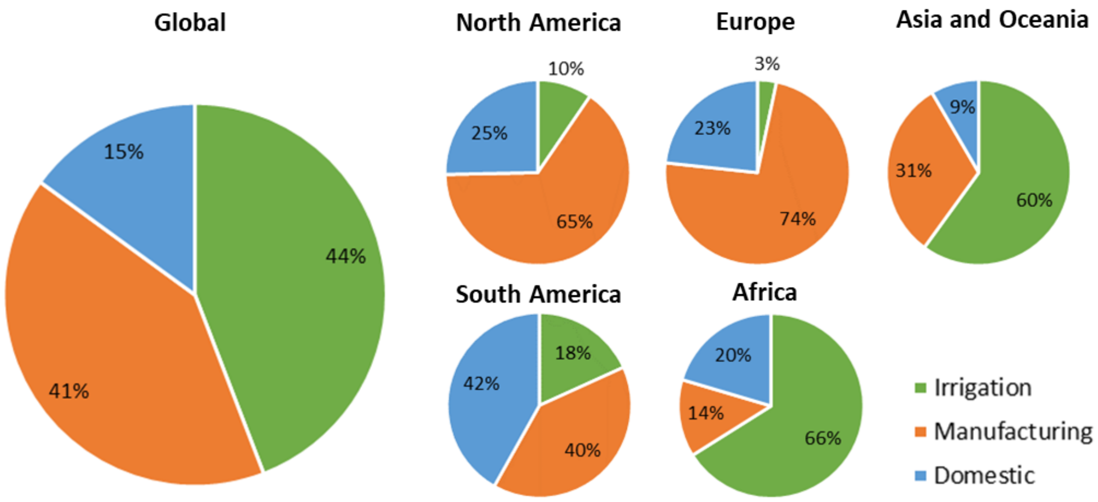


*Figure 3.19* *Share of anthropogenic TDS loadings by main sources (in percentage) derived based on simulated data of van Vliet et al. (2020).*

Population growth, wealth and dietary changes have increased food production from irrigated land. This drives the expansion of irrigated area and intensification of land-use and management practices and hence contributes to an increase in salt affected area (Figure 3.20). In addition, climate change accelerates both primary and secondary salinization through higher temperatures, less rain and reverse evaporation rates which in turn affect irrigation requirements (Daliakopoulos *et al.* 2016).

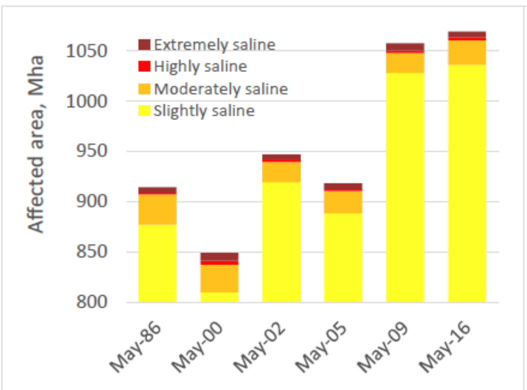


*Figure 3.20* *Salt affected land area for different years Ivushkin et al. 2019).*

## 3.3.3 Arsenic pollution

### 3.3.3.1 Impact and State

Next to salinity impacts, high levels of arsenic pose a risk to groundwater resources used for irrigation in South Asia, too. Groundwater irrigated areas where there is a high probability of arsenic pollution in aquifers (concentrations higher than 10 µg/l) can be highlighted (Figure 3.21). Health impacts of consuming arsenic in such crops (or in drinking water) are varied and are generally experienced through the long-term ingestion of arsenic, resulting in arsenicosis (see Chapter 3.2.2.1 on Human health).

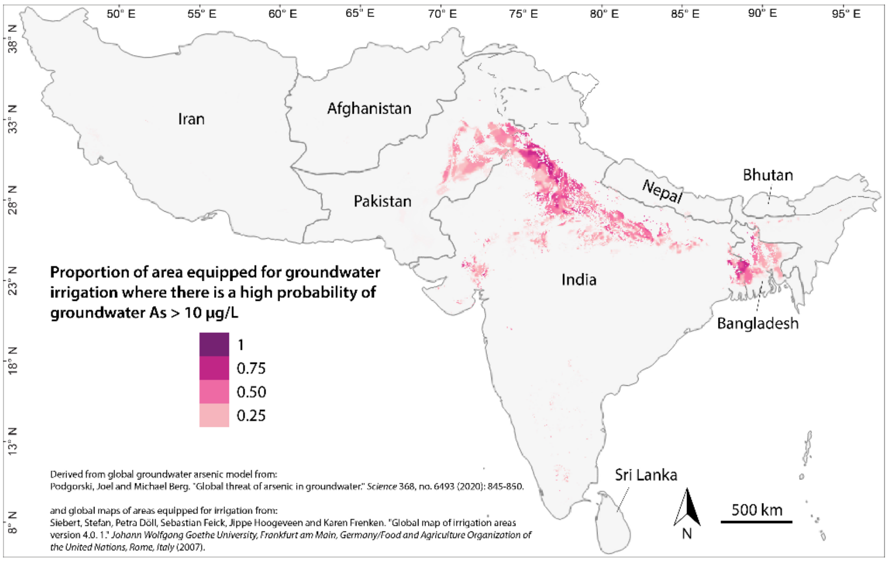


***Figure 3.21*** *Proportion of area equipped for groundwater irrigation where there is a high probability of groundwater having arsenic concentrations higher than 10 µg/l (Podgorski and Berg 2020).*

It is estimated that over 154,000 km² of agricultural land in South Asia may be irrigated with groundwater that exceeds the WHO guideline value of 10 µg/l. This estimate is based on a global prediction model of the occurrence of naturally occurring arsenic in groundwater (Figure 3.22) as well as maps of areas equipped for irrigation (Siebert *et al.* 2007). Areas such as the Kashmir Valley, parts of Punjab, and the states of Haryana and Uttar Pradesh in India are vulnerable to irrigation water supply because both groundwater and surface water resources are highly affected by poor water quality. These are generally areas characterized by very high irrigation intensity (above 60%) and overexploited groundwater resources that, nonetheless, contribute to more than 35% of the total production of food grain in India (Dhawan 2017). Irrigation with high arsenic water is the pressure that results in a state of heightened arsenic concentrations in both the water and soil at the surface, which can ultimately result in hazardous concentrations of arsenic in crops.

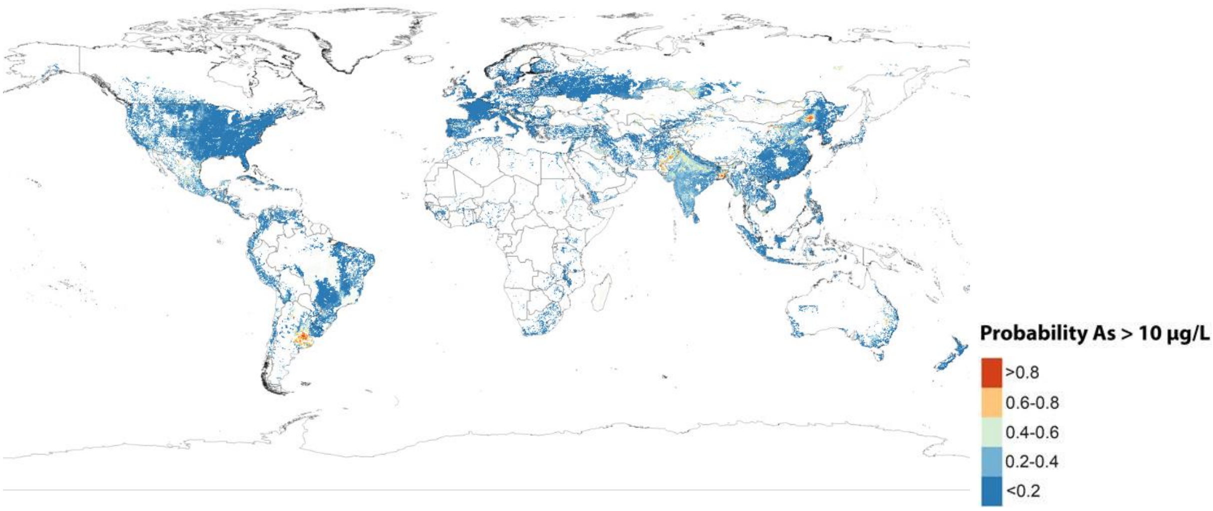


***Figure 3.22*** *Modelled probability of arsenic concentration in groundwater exceeding 10 mg/litre in areas equipped for irrigation for the entire globe (Podgorski and Berg 2020).*

### 3.3.3.2 *Drivers and Pressures*

Arsenic is present in trace amounts throughout Earth's crust and, as such, often leaches from rocks and sediments into groundwater. In the case of South Asia, anoxic conditions in aquifers often lead to the release of arsenic that is frequently present in geologically recent sediments, particularly along the Indus and Ganges rivers (Figure 3.22). Arsenic release in aquifers is controlled by climate, particularly precipitation and evapotranspiration processes are of importance due to creating conducive conditions for arsenic release under reducing conditions (e.g., waterlogged soils) as well as high aridity associated with oxidizing, high-pH conditions.

## 3.3.4 Nutrient pollution

### 3.3.4.1 *Impact and State*

A large part of all freshwater fish, mostly lower value from an economic point of view, and shrimp, are cultured in ponds (Bureau of Fisheries Ministry of Agriculture 2003; Tacon and De Silva 1997). In particular, aquaculture systems in cages, as well as shellfish (oyster, mussel, abalone) production are sensitive to water pollution and algal blooms. Aquaculture production is located in water bodies seriously affected by phosphorus (P) loading, which, in freshwater is the major driver of eutrophication. There is a strong overlap between aquaculture production regions and P loading (Figure 3.5 in Chapter 3.1.1.2 on Ecosystems health). For example, freshwater aquaculture production may be at risk in southern and eastern Asia (Figure 3.23). One of the major HAB species in freshwater systems are cyanobacteria (Merel *et al.* 2013) that bloom under conditions of low N and high P availability. There is a marked difference in ecological functioning between freshwater systems and coastal waters. This difference is due to multiple factors including $N_2$ fixation in freshwater systems and the lack thereof in coastal systems, and differences in N and P recycling between lakes and coastal systems. Common metrics of eutrophication (e.g., chlorophyll-a), total nitrogen (TN) and total phosphorus (TP) alone are not adequate for understanding biodiversity changes, especially those associated with HAB proliferations. Harmful algae can increase disproportionately with increasing nutrient loading, depending on the proportion in which nutrients are available. As mentioned in Chapter 3.1.2.2, HABs proliferate under conditions of high N:P ratios. Intensive aquaculture production in Eastern and Southern Asia is in sea regions where the river inputs are dominated by anthropogenic N sources and have high N:P ratios. (Figure 3.24). Many reports show that Chinese mariculture frequently experiences production loss due to HABs (Yu *et al.* 2018).

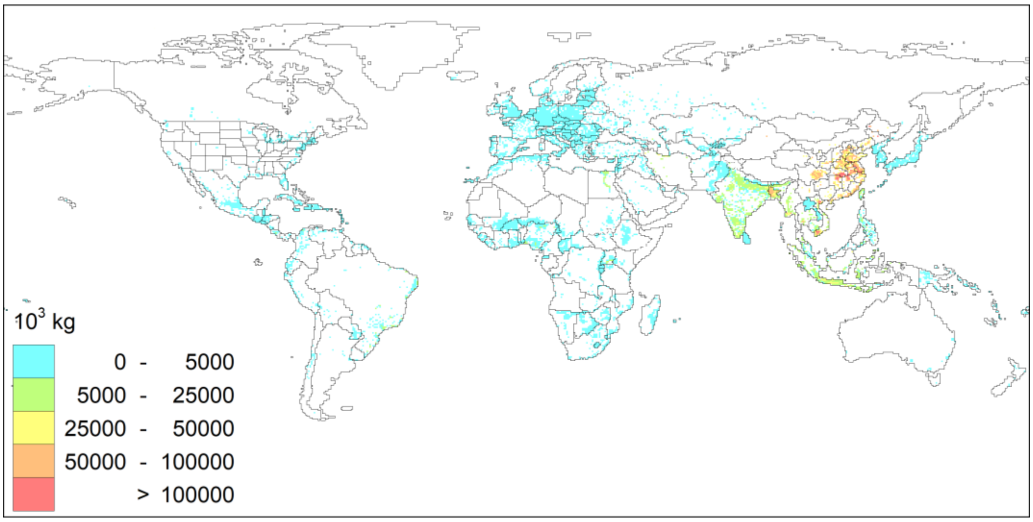


***Figure 3.23*** *Freshwater aquaculture production in 2015. Numbers are in $10^3$ kg fresh weight per year (Beusen et al. 2015).*

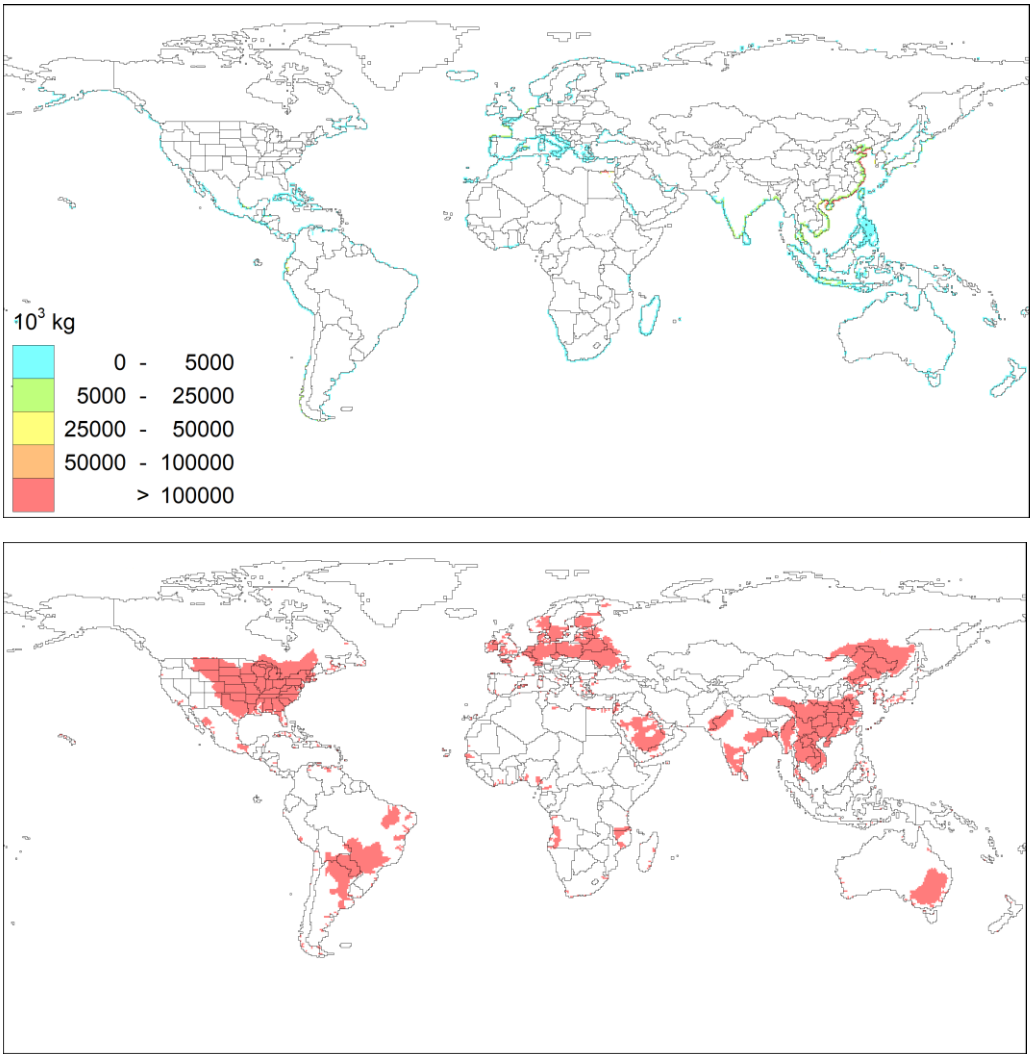


***Figure 3.24*** *Mariculture production (top) food production (numbers are in $10^3$ kg fresh weight per year) and rivers where nutrients are primarily (>50%) from anthropogenic sources and with high molar N:P ratio in the discharge to coastal waters for the year 2015 (Beusen et al., 2016). When N:P ratio exceeds 25:1, the frequency and areas of HABs may increase rapidly (Liang 2012).*

Satellite data help to identify areas affected by cyanobacteria, HABs, and growth of phytoplankton biomass by, e.g. using retrieved chlorophyll-a concentration (Figure 3.25). This study can be extended globally as well as underlined with larger time series data of high-resolution satellite images. Harmful Bloom Indicators calculated from satellite data can further support the monitoring of aquaculture; datasets are also available in the SDG6 portal (see Table 2.1). In order to identify aquaculture fields that could be at risk to unfavourable water quality conditions, all inland water bodies larger than 0.05 km² have been assessed using satellite data and a classification scheme after Carlson (1977) into 4 main trophic state classes ranging from oligotrophic to hypereutrophic, an expression of the level of ecological water quality. In the given Chinese example, the majority, 55%, are mesotrophic, which equals a range of 2.6 to 20 µg/l chlorophyll-a.


***Figure 3.25*** *Chlorophyll-a one-time snapshot map of China with zoom to aquaculture fields south of Wuhan. Assessment of trophic state according to Carlson of all inland water bodies in China larger 0.05 km² for one time step using satellite data from Landsat 8 (processing © EOMAP, satellite data © USGS). The worldwide dataset can be accessed through the SDG6 portal (http://sdg6-hydrology-tep.eu/).*

### 3.3.4.2 Drivers and Pressures

The anthropogenic impact on river nutrient loading has been increasing rapidly, from around 6 Tg N $yr^{-1}$ (equals 6 Mio tonnes) in 1970 to 24 Tg $yr^{-1}$ (equals 24 Mio tonnes) in 2015, which is 43% (equals 56 Mio tonnes) of the total global river N export (see Figure 3.3 in Chapter 3.1.1.2 on Ecosystem health). In this period the dramatic increase in nutrient loading has not been compensated by increased retention in river basins (Beusen *et al.* 2016). At present, the river basins that are dominated by anthropogenic sources correspond to most densely populated regions of the world, with intensive food and energy production, and population centres that are drained by sewers to dispose of the waste streams from households and industries (see Chapter 3.1, Figure 3.5).

For dissolved inorganic nitrogen, agricultural activities from the use of synthetic fertilizers, animal manure, atmospheric N deposition and fixation are dominant sources of nitrogen in rivers. This is different for dissolved organic nitrogen and dissolved inorganic and organic phosphorus as direct manure discharges to rivers are dominant sources of nutrients in rivers in many parts of China (Figure 3.26). Inadequate sewage systems are major sources of increased nutrient concentrations in urbanized areas and contribute to harmful algae blooms, eutrophication and low dissolved oxygen and formation of hypoxic or dead zones. Both capture fisheries and aquaculture are vulnerable to external factors that lead to a reduction in water quality (Diaz *et al.* 2012; Smith *et al.* 2010).

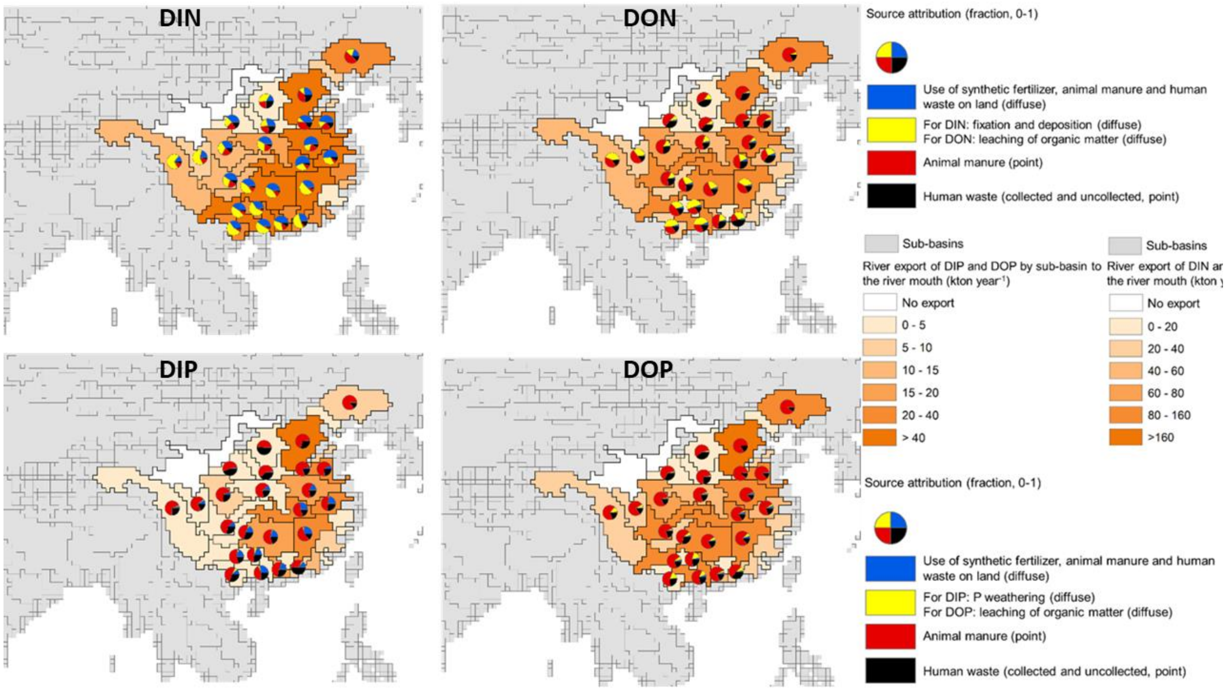


***Figure 3.26*** *Coastal water pollution with nitrogen and phosphorus in China in 2012. Results are from the MARINA model for China (Wang et al. 2020).*

### 3.3.5 Food safety

Water quality is of concern for food security but also food safety, as it might impact ecosystems health (Chapter 3.1) and human health (Chapter 3.2) through the food chain. The fate of chemicals used for agricultural purposes, such as pesticides, is determined by substance properties and by processes such as degradation, sorption and sedimentation in the soil and the aquatic environment. These chemicals could accumulate in different environmental compartments and enter the food chain, thus causing concern for the environment (see Chapter 3.1.2) and human health (see Chapter 3.2.1). Wastewater reuse in irrigation is an option to overcome water shortages and to close the nutrient cycle, however, the food may become contaminated by pathogens (and faecal coliform bacteria), antimicrobial resistant microorganisms (AMR) and chemicals in wastewater that has not been sufficiently treated (see Chapter 3.2). In addition, wastewater reuse might bring other negative effects to agricultural production and food safety like soil salinization and bioaccumulation.

Emerging pollutants such as Triclosan, which is an antibacterial and antifungal chemical used in hygiene products globally (van Wijnen *et al.* 2017) and microplastics are discharged into rivers through sewage systems that also transport nutrients and microbial contaminants from households. In the aquatic environment, Triclosan could pose a risk to various aquatic organisms, for example by acting as an endocrine disruptor (Fang *et al.* 2010) whereas marine and riverine fish are affected by microplastic contamination (McNeish *et al.* 2018). River basins with high Triclosan and microplastics inputs are characterized by high urbanization and mainly located in Europe, India, China and some individual sub-basins in South and North America (Figure 3.27). These hotspot areas largely match areas of high nutrient and pathogen loads (see Figures 3.5 and 3.14 on ecosystems health and human health, respectively). Main sources of Triclosan in sewers is the use of personal care products while of microplastics are laundry, household dust, the use of personal care products and car tyre wears on roads (Figure 3.27).

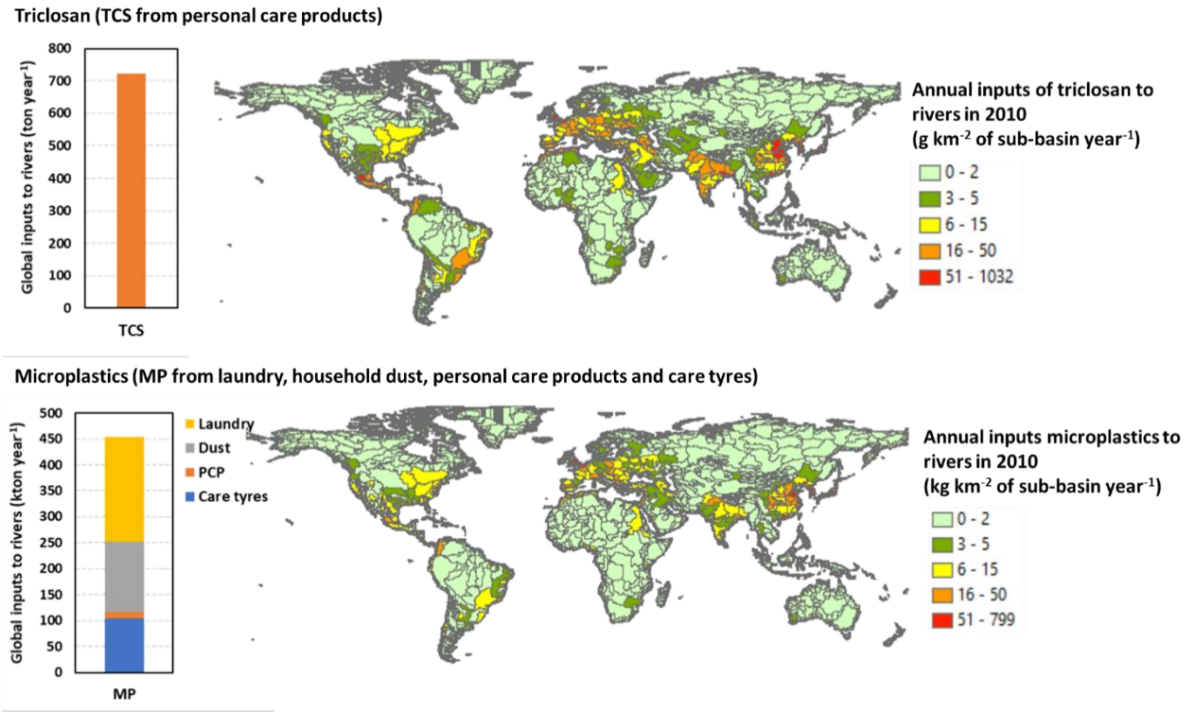


***Figure 3.27*** *Urban-related inputs of Triclosan and microplastics to rivers in sub-basins worldwide. Results based on the MARINA-Global model (Strokal et al. 2019; van Wijnen et al. 2017; Siegfried et al. 2017), aggregated to sub-basins for the year 2010.*

### 3.3.6 Response options

- Although different arsenic filtration technologies exist, they are generally not capable of handling the large quantities of water used in irrigation.
- Proper irrigation management measures can help to restore the salt balance in the soil profile, which mitigate the negative impacts from irrigation with saline water.
- Mismanaged waste is one of the most important sources of plastic pollution. Responses should be directed to policies to better collect and manage solid waste (e.g., circular economy).
- Reduction of pollution discharge by improved wastewater treatment to decrease pollution intake into freshwater systems and support safe use of wastewater reuse.
- High nutrient use efficiencies and improved manure management (i.e., recycling of manure on land instead of dumping to rivers).
- Stricter and upfront regulatory assessment and restrictions are needed on the use of emerging pollutants (e.g. Triclosan) and microplastics as the most fundamental source control measure to limit contaminants entering the environment and subsequently the food system.

### 3.3.7 Missing data / more research required

- Models cover some but not all of the important water quality parameters. More research is needed to better understand natural and human-driven processes, environmental behaviour and interaction with food production and food safety.
- The assessment of water quality impacts on food security is difficult in quantitative terms as in-situ data and modelling data are lacking. For example, the impacts of HABs and hypoxia on capture and aquacultural fisheries and pathogen (or faecal coliforms as a proxy) contamination impacts on leafy crops and food safety.
- More research is needed to understand the effects of response strategies and to demonstrate their efficiencies.

- The application of remote sensing data and information in regard to water quality is (so far) limited to address water quality challenges. Further exploitation of data and improvements in model accuracy and data resolution are required as well as the development of methods for integrating different data sources (e.g. in-situ, models) for a comprehensive water quality monitoring and evaluation.
- Future research may use more sophisticated methods such as machine learning and artificial neural networks instead of (linear) regression analysis.

# 4 World Water Quality Alliance Africa Use Cases – Stakeholder engagement and product/service co-design

*Key messages:*

- *Cape Town's groundwater is vulnerable to water quality impacts from urban development in an area with various land-use activities, posing a risk to the planned potable water supply. As a results, aquifer protection zones we co-designed.*
- *Key water quality challenges at Lake Victoria were identified as eutrophication; algal blooms (incl. cyanobacteria); hypoxia, and siltation/turbidity affecting fish breeding. Water quality data and information products and services being co-developed are a coastal eutrophication assessment, water temperature and stratification dynamics, and sediment chemistry.*
- *The Volta Basin water quality impacts were identified as domestic and industrial effluent, mining impacts, agricultural runoff, and aquaculture; expected to be exacerbated in the future by climate change, population increase, urbanization, and land use change. Water quality product options being explored are a tool to determine the percentage of populations vulnerable to poor water quality, and a remote sensing-based groundwater quality assessment.*

## 4.1 Introduction

The Africa Use Cases provide an initial testbed that puts the quality of surface water and groundwater into the context of the local 2030 Agenda and its multiple linkages across the Sustainable Development Goals. The United Nations Environment Programme is cooperating with relevant organisations and convenes the UN-Water Expert Group on Water Quality and Wastewater in the World Water Quality Alliance. The objective is to provide an evidence base that links water quality hotspots to solutions and investment priorities. Crucial is a multi-stakeholder in-country driven process defining demand for water quality services (using experience in global problems to support local solutions). The "Use Cases" are integral to the World Water Quality Alliance and a contribution to the Assessment as explained hereunder.

The aim of the Africa Use Cases is twofold: first, to evaluate availability and accessibility of data in selected locations/systems and to test the integration of those available in-situ, remote sensing-based earth observation and modelling data to derive the best possible current state of water quality (baseline). To this end there is an explicit and intentional overlap with the case studies foreseen in the World Water Quality Assessment and this work feeds into and co-benefits the work of the Assessment; both teams collaborate closely.

Second, the Use Cases practically explore how to carry local engagement of water stakeholders with external experts – here represented by members of the World Water Quality Alliance - beyond the assessment of state and causal chains of water quality. The goal is to identify priority water quality issues and hotspots and to co-design, pilot and demonstrate innovative information services and their application for water quality improvement with the potential to upscaling and operational use.

For this initial effort three locations in Africa have been selected focused on urban groundwater (Cape Town); a lake of ecological and economic importance (Lake Victoria and associated basin); and a watercourse with pathogen risks (Volta River). In the mid- to long-term the Alliance shall build on experiences made here to provide further services at scale to shift the water quality needle, engage with UN Country Teams and to enable upscaling to locations in similar driver-pressure-state and impact contexts for adequate response. Hence, fostering South-South learning and collaboration is a central characteristic of this Alliance approach.

## 4.2 Cape Town Groundwater

Three aquifers are being targeted by the City of Cape Town for potable water supply: The Atlantis Aquifer, Cape Flats Aquifer (CFA), and Table Mountain Group (TMG) Aquifer.

The CFA is a sedimentary primary aquifer underlying most parts of the city that is highly vulnerable to pollution from land use activities, including small scale agriculture, landfill sites, cemeteries, various industrial areas, sand mining and informal settlements without proper sanitation. The urban setting of the CFA (and to an extent the Atlantis Aquifer) results in salinization and anthropogenic contamination with nutrients, microbiological and industrial contaminants, hydrocarbons and contaminants of emerging concern (see Figure 4.1a indicating the exceedances of water quality guideline limits). The TMG Aquifer on the other hand occurs in relatively pristine areas with very good water quality, except naturally occurring elevated concentrations of iron and manganese.

The extensive in-situ monitoring data collected over the last three years for the city's groundwater development projects was supplemented with RS/EO data, to provide a detailed land-use map identifying potential pollution sources, and a range of modelling from GIS-based vulnerability mapping to numerical flow and transport modelling to assist with the assessment (i.e. through the use of the World Water Quality Assessment triangulation approach, Chapter 2.1, Figure 2.1).

The Cape Town Aquifer Use Case built on the existing stakeholder network and structures that were established as part of the groundwater development projects by the City of Cape Town. At the committee meetings the Department of Water and Sanitation (DWS) as regulatory authority suggested the development of a groundwater management plan for each aquifer. Based on the presented water quality data, Scientific Services (a department of the City of Cape Town) and the agricultural users of the Cape Flats Aquifer suggested that an aquifer protection plan is developed to address water quality concerns in the area.

As a result, a groundwater protection scheme was developed for the CFA (Figure 4.1b) to ensure the protection of groundwater quality to abstraction boreholes. The Groundwater Protection Scheme is composed of several components, namely Groundwater Protection Zones (GPZs), vulnerability mapping and ranking (using DRASTIC-model Specified Vulnerability Index - DSVI), potentially contaminating activities (PCAs), and a remediation plan (to be developed separately for each identified pollution). The vulnerability mapping indicated a very high (orange) to extreme high (red) vulnerability of the aquifer to pollution sources on surface. To reduce the risk of pollution entering the proposed abstraction boreholes for water supply, protection zones limiting certain land use activities were proposed, depending on the expected residence time of pollutants entering the aquifer (modelled as lifetime expectancy). Zone II (purple) and Zone III (dark green) require strict restrictions to land use activities that can potentially pollute the aquifer.

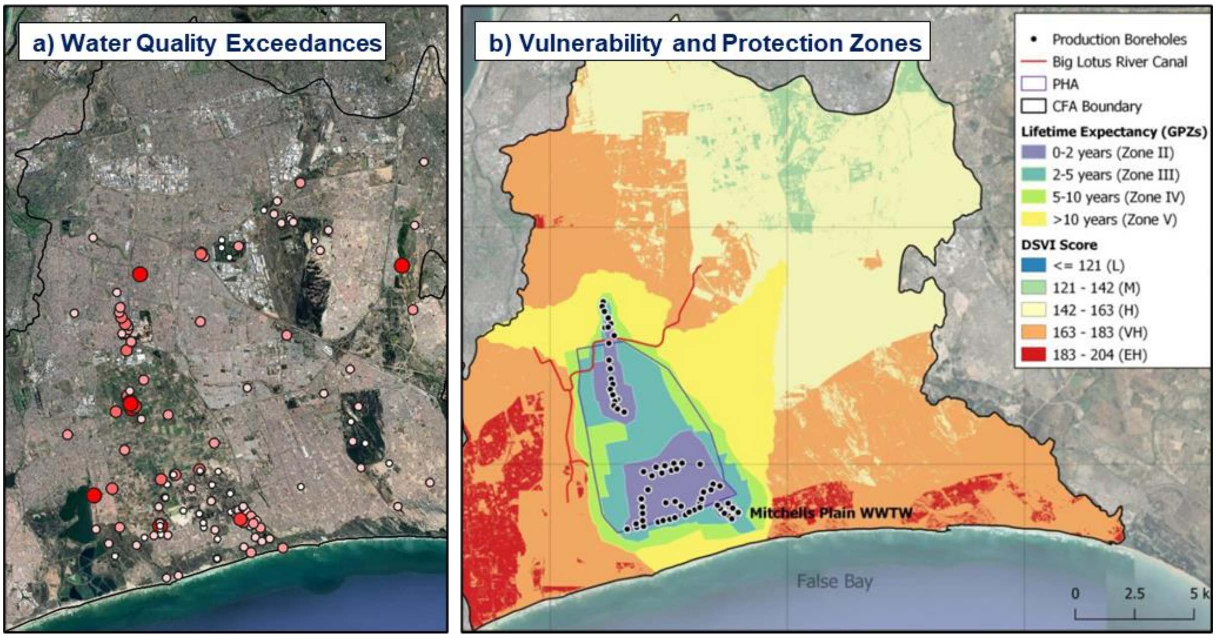


***Figure 4.1*** *Mapping of the Cape Flats Aquifer, with* ***a)*** *an example of a map format used to represent monitored borehole chemical results; larger icons representing higher relative concentrations and,* ***b)*** *Cape Flats Aquifer Vulnerability and Protections Zones relative to production boreholes.*

## 4.3 Lake Victoria Basin

The stakeholder engagement concept and data acquisition context for the Lake Victoria Use Case was introduced to and shared with local actors at a symposium and workshop in Kenya and Uganda. Central was the to establish the aims to collectively assess water quality challenges and associated impacts at Lake Victoria and it's catchment; develop a stakeholder network, and assess data sources and types associated with Lake Victoria and any limitations to the sharing of such data. Subsequent virtual workshops were organised by the Alliance team with riparian fisheries organisations (KMFRI, NaFIRRI and TAFIRI[3]). The aim of these meetings was to discuss water quality data and information products and services to be co-developed to target hotspots. In-country direct engagement was not pursued due to pandemic travel restrictions.

The potential water quality products and services agreed upon to co-design by the riparian fisheries organisations and in-country partners (KMFRI, NaFIRRI and TAFIRI) and World Water Quality Alliance representatives were:

- Coastal Eutrophication:
    - Available data sources are being assessed to indicate the potential of coastal eutrophication, including the identification of hot spots and potential seasonal patterns. This demand driven tool is being developed to characterise the potential of algal blooms to impact fisheries or to identify potential links between aquaculture and coastal eutrophication. This includes the joint use of:
        - Remote sensed earth observation (provided by EOMAP), incl. turbidity and chlorophyll-a values for the Lake.
        - Water quality modelling to determine total phosphorus inputs into the lake from identified sources such as the domestic sector, agriculture, background loadings etc. (provided by Ruhr-University Bochum, Germany).

[3] KMFRI: Kenya Marine & Fisheries Research Institute; NaFIRRI: National Fisheries Research Institute (Uganda); TAFIRI: Tanzanian Fisheries Research Institute

- In-situ measurements provided to date (river/lake measurements of nutrients such as nitrate, phosphate etc.) via GEMStat and in-country partners. This information is being used to validate the model and RS/EO data.

➢ Outcomes envisioned include the identification of nutrient hotspots, their drivers, and their temporal and spatial dynamics (Figure 4.2) so that priorities can be defined and potential management strategies can be efficiently directed. Further, scenario modelling can be used to evaluate the effectiveness of a wide range of management alternatives.

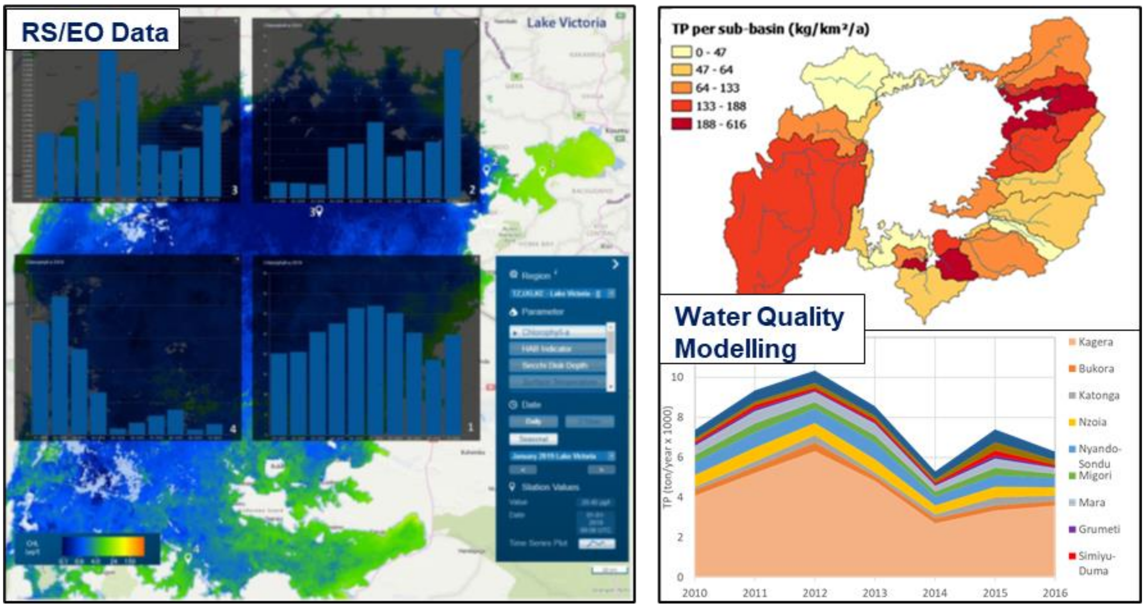


***Figure 4.2*** *Examples of available data sources to complement in-situ data, showing time-series of chlorophyll-a (used with permission of Heege 2020, Lake Victoria time series (http://sdg6-hydrology-tep.eu, data available up to daily from September 2020 onwards) and total phosphorus loadings modelled from main sources (industrial fertilizers, manure, geogenic background, and the domestic sewered sector) per lake sub-basin (used with permission of the Chair of Engineering Hydrology and Water Resources Management at Ruhr University Bochum).*

- Water temperature and stratification dynamics:
  - Monitoring activities by different research institutions of the adjacent countries generated a valuable record of water temperatures in Lake Victoria over the past years; including data jointly collected by TAFIRI, NaFIRRI and KMFRI under the coordination of the Lake Victoria Fisheries Organisation (LVFO) which has been shared with the Alliance. The aim is to use a freely available lake model (GLM 3.1, General Lake Model) to simulate temperature dynamics in Lake Victoria to inform the extent of stratification and vertical mixing in the water column. At the same time, this initiative brings together monitoring results from different countries and institutions and generates not only the required data for the modelling but also provides data for many other applications in research and development. Directly interfacing with the Assessment, the following research topics are being targeted by the Helmholtz Centre for Environmental Research (UFZ) and LVFO:
    - Model-based reconstruction of water temperatures of Lake Victoria over the past 30-years at daily resolution
    - Water temperature projections for Lake Victoria until 2100 based on different climate scenarios (Representative Concentration Pathways) RCP 2.6, RCP 6.0, RCP 8.5)
    - Potential effects of water temperature dynamics and mixing events on phytoplankton dynamics (derived from satellite-based remote sensing provided by EOMAP)

- Sediment chemistry:
    - UFZ has offered to collaborate with KMFRI on collected sediment chemistry, water profile physico-chemical quality parameters in the Nyanza Gulf (Kenya) and sediment and water samples near Kampala, Uganda. There is a potential for the joint assessment of sediment release of nutrients, turnover, and indication through algae blooms obtained from remote sensing (EOMAP).

## 4.4 Volta Basin

To assess the Volta water quality challenges and associated impacts, and to assess data sources and types and any limitations to the sharing of such data there was attendance by Alliance members at various conferences in Ghana. In addition, a Stakeholder Engagement Workshop was held in Accra, Ghana to assess the key water quality hotspots and water quality data and information products and services that may be of interest; and the to initiate a bottom-up social engagement process.

The key water quality challenges identified by the Stakeholder Engagement Workshop participants were: poor sanitation resulting in elevated bacterial contamination, mining activities and heavy metal and turbidity impacts, industrial effluent (including plastics and micro-plastics), agricultural runoff of fertilizers and pesticides, leading to increased aquatic alien plants, and water quality impacts to and from aquaculture. A further challenge is there is not a consolidated Ghana government department mandated to water quality monitoring, with this role currently split.

Discussions towards potential water quality product and services are ongoing, in part due to ongoing development of in-country partnerships and collaboration. The initial products and services being investigated to take forward include:

- The Ghana National Disaster Management Organization (NADMO) proposed an innovative tool that translates poor water quality severity (measured through a water quality index) into poor water quality impact (expressed in terms of vulnerability of affected populations). The water quality index would be derived in collaboration with World Water Quality Alliance partners. The vulnerability profiling would include the Volta Basin baseline household survey (which includes data on households' water sources and poverty status, as well as population data and administrative boundaries).
- University of Fada N'Gourma, Burkina Faso proposed a groundwater quality assessment based on the DRASTIC vulnerability mapping method and remote sensed data. The DRASTIC acronym is based on the major hydrogeologic factors which affect and control groundwater movement (Depth to groundwater, Recharge, Aquifer type, Soil media, Topography, Impact of vadose zone, and hydraulic Conductivity). The University of Fada N'Gourma methodology incorporates land use data with the DRASTIC parameters to assess groundwater pollution risk (GPR) at a pan-African scale, including the Volta River basin (Figure 4.3, Ouedraogo *et al.* 2016).

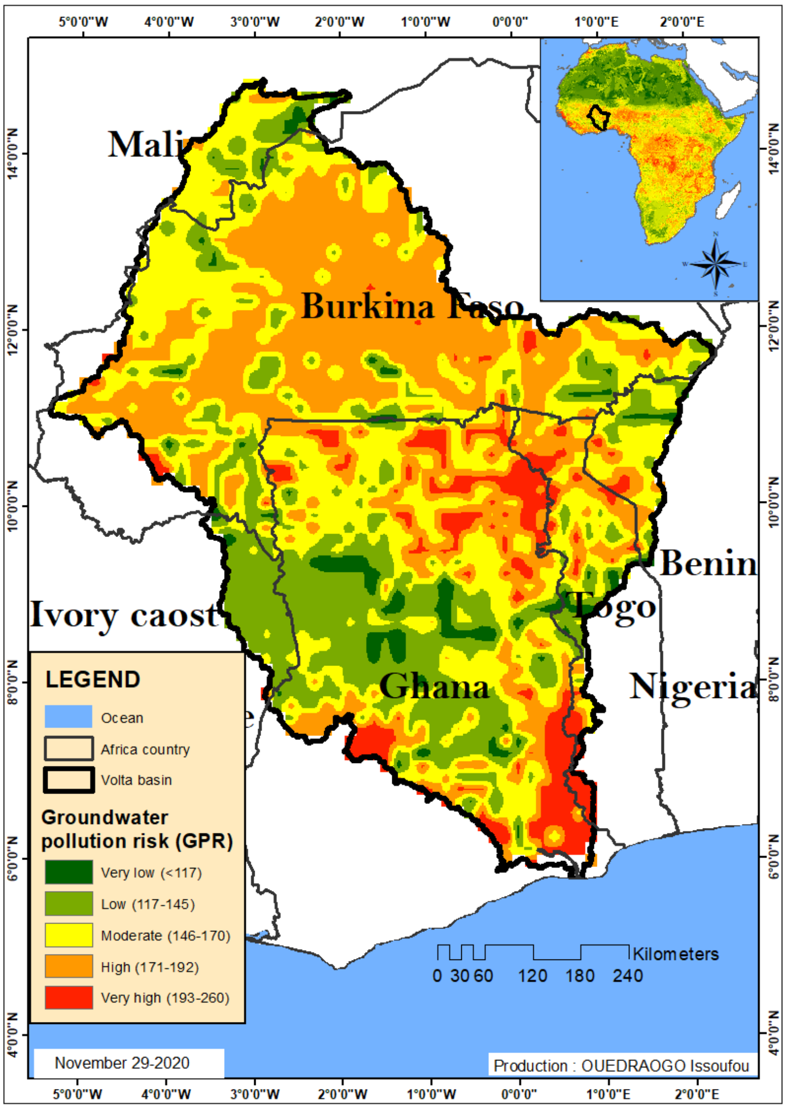


***Figure 4.3*** *Mapping the groundwater pollution risk (GPR) for the Volta River basin using the composite DRASTIC groundwater vulnerability index which included land use. The higher the GPR, the greater the groundwater pollution risk (Ouedraogo et al. 2016).*

## 4.5 Way forward

Below we summarize key findings and next steps that result from findings and lessons learned in the Use Case approach so far and which underpin the relevance of bringing interdisciplinary expert competence as reflected in the World Water Quality Alliance into dialogue and co-design on country and system level to advocate for stepping from data to solutions:

- Ongoing development of in-country partnerships and collaboration, especially with water resource decision-makers to solve real-world problems for real impact, thereby benefiting in-country stakeholders and data providers to break the north-south divide. This needs sustainable funding and long-term investment. Initial exchange with UN Resident Coordinators are encouraging and suggest, in future, to regularly engage UN Country Teams in this process if possible.
- There is a need to investigate options for integrating data derived from the Assessment triangle approach into a single dataset that can be used for water quality decision-making. The Cape Town Use Case successfully combined these three data types to develop aquifer protection zones and a risk analysis that are practically implementable by the in-country stakeholders. This was

achieved through an integration team with overlapping experience in the data types.

- A need to improve the impact of research through more effective science-policy interface, as well as better communication of the science via impact stories.
- A standard protocol for data sharing to ensure data providers retain data ownership and recognition. An example to use is the GEMS/Water Data Policy which allows data providers to select from three different levels of data sharing.
- Development of a common data-management system, with agreed data types and formats that allows for better collaboration between organisations/ institutions/ countries. This database option should have ownership by the data providers to ensure maintenance and longevity.
- In-country capacity building in the collection and assessment of data (in-situ data, citizen science, modelling and RS/EO).
- Further development of the Africa Use Case concept to cover various water resource types and scales. This may include linking headwater protection to recharge (Cape Town Use Case); transboundary aquifers, the surface water/groundwater interface (e.g. wetlands).

# 5 Digital water quality platforms

*Main messages:*

- *A gap exists between the general availability of data, their level of coherent aggregation and synthesis which is required to provide useful information for different policy or management purposes. Appropriately designed platforms can help to overcome this gap.*
- *The key to engage platform users is their involvement already in the early development phases of the platform in a co-design process. This ensures that the data and information provided as well as the functionalities for analysis and visualization match the user needs.*
- *Ideally, co-design is a continuous process where the platform evolves with the user needs improving the user experience.*
- *Multiple water quality platforms co-exist and should ideally reinforce each other by providing standardized data products to enable cross-platform sharing*

## 5.1 What are digital, geospatial platforms?

Nowadays, we constantly interact with digital platforms in various areas of life. Examples are social media platforms like Twitter, media platforms like Youtube and service platforms like Uber and knowledge platforms like StackOverflow. Geospatial platforms support the collection and processing of environmental data, enable access to aggregated data products and visualize data in a way that knowledge can be disseminated to the target audience. As an example in UNEP the World Environment Situation Room, features such a service and utility (Chapter 5.4.5).

There are many digital tools for water quality which provide platform functionalities but are termed something else - database, app, information system or portal for example. One such example, which is also discussed in this report, is the Global Freshwater Quality Database (GEMStat) which is the operational part of the GEMS/Water Programme of the United Nations Environment Programme (UNEP). GEMStat collects and aggregates global water quality self-reported by countries. GEMStat provides visualization data in interactive maps as well as download functions and accessible programming interfaces (APIs) which enables the easy integration of GEMStat data into other platforms. Another one is the SDG 6.6.1 app, which visualizes information on water related ecosystems drawing on products from the Copernicus Land Service.

## 5.2 What are they good for?

Generally, we live in a data rich world - not everywhere and every time - but today we have access to more environmental monitoring data than ever before in history. This general data richness does not guarantee for information richness. Already pointed out by Ward *et al.* (1986) there exists a "Data-rich but Information-poor Syndrome" in water quality monitoring. Since the mid-1980s this problem has likely been sharpened as more data requires more elaborate methods to extract the desired information.

The increasing amount of openly available data as such does not automatically mean that these data are considered in the decision-making process. A gap exists between data availability and accessibility on the one hand and the level of aggregation and synthesis of data required by users on the other. For example, the launch of high-resolution earth observation satellites such as Landsat 8 and Sentinel 2a and 2b opened up avenues towards a globally harmonized picture of optically detectable water quality parameters such as turbidity and chlorophyll. If data of Landsat-8, Sentinel-2A, and Sentinel-2B are combined they will provide a global median revisit interval (time elapsing between observations of the same point on earth) of less than 3 days (Li and Roy 2017). Thus, water quality changes could be monitored with high resolution both in space and time. This information source so far remains largely untapped as the processing of the raw images requires expertise and infrastructure to handle the enormous amounts of data. And, the limited range of parameters that can be sensed from satellites requires to be complemented with the wide range of water quality parameters coming with in-situ observations as well as with water quality models which are the only tools that can also be used to make projections of future water quality.

With an appropriate platform, data and information can be processed in a way that the complexity is reduced and actionable information is created, e.g. by identifying hotspots of poor water quality, main sources and by recognizing water quality trends in target water bodies which can then be used to guide priorities for investments.

## 5.3 Co-design is the key

Digital water quality data vary in terms of content, spatial and temporal coverage and functionality. The key to engage users is their involvement in the development of the platform in a co-design process. This ensures that the data and information provided as well as the functionalities for analysis and visualization match the user needs. Ideally, co-design is a continuous process where the platform evolves with the user needs improving the user experience.

For example, the knowledge to practice (K2P) project aims on improving the accessibility to the existing body of evidence on pathogens in excreta and sewage through a platform that Water, Sanitation and Hygiene (WASH) practitioners can use. Through a stakeholder engagement workshop held in Kampala, Uganda in 2018, WASH practitioner recommended that newly developed platforms and tools should build on existing approaches as well as incorporating the cost of measures and technologies to improve sanitation (Tumwebaze *et al*. 2019). Many other recommendations from numerous stakeholders were taken into account in the project, resulting in six iterations of the tool before it became available in its current form.

Platform infrastructures combined with relevant training on options, utility and limitations involving the user community across society can help to furnish water actors with the competence to optimally derive and apply the information provided. This will increase the likelihood that the essential step between access to information and uptake into the decision-making process is made.

## 5.4 Platforms supporting the World Water Quality Assessment

This section provides a brief overview on the platforms discussed and applied in this report (Table 5.1). It is worth noting that a lot more platforms are operational at the time of writing serving their users with water quality information across different spatial scales from local to global.

### 5.4.1 GlobeWQ

The GlobeWQ project develops a web-based platform for hosting, visualizing and analysing data from in-situ and remotely sensed observations and modelling. The platform implements the triangulation concept of the World Water Quality Assessment (see Chapter 2.1.2) in data products and analysis tools. In particular, the platform enables the visualization of the state, trends and impacts of selected water quality variables and their underlying drivers. For example, information on global salinity hotspots (measured and modelled) will be provided on the platform (see Chapter 3.3.2).

The content and the functionality of the GlobeWQ platform is tailored towards user needs, which are mapped during workshops with local stakeholders. For example, at Lake Victoria (Africa) eutrophication has been identified as a major threat to water quality and to fish farming (see Chapter 4.3 and Figure 5.1). Therefore, through links with the World Water Quality Alliance a matching between demand and supply can be pursued in GlobeWQ and link to the Assessment work and its causal chain cases: to inform fish farming organisations about hotspots and seasonal patterns of algal blooms, remotely sensed turbidity and chlorophyll-a concentrations are combined with available in-situ measurements of nutrients such as nitrate and phosphate. Water quality modelling is used to determine nutrient inputs into the lake from lake tributaries and their terrestrial sources such as agriculture or domestic wastewater.

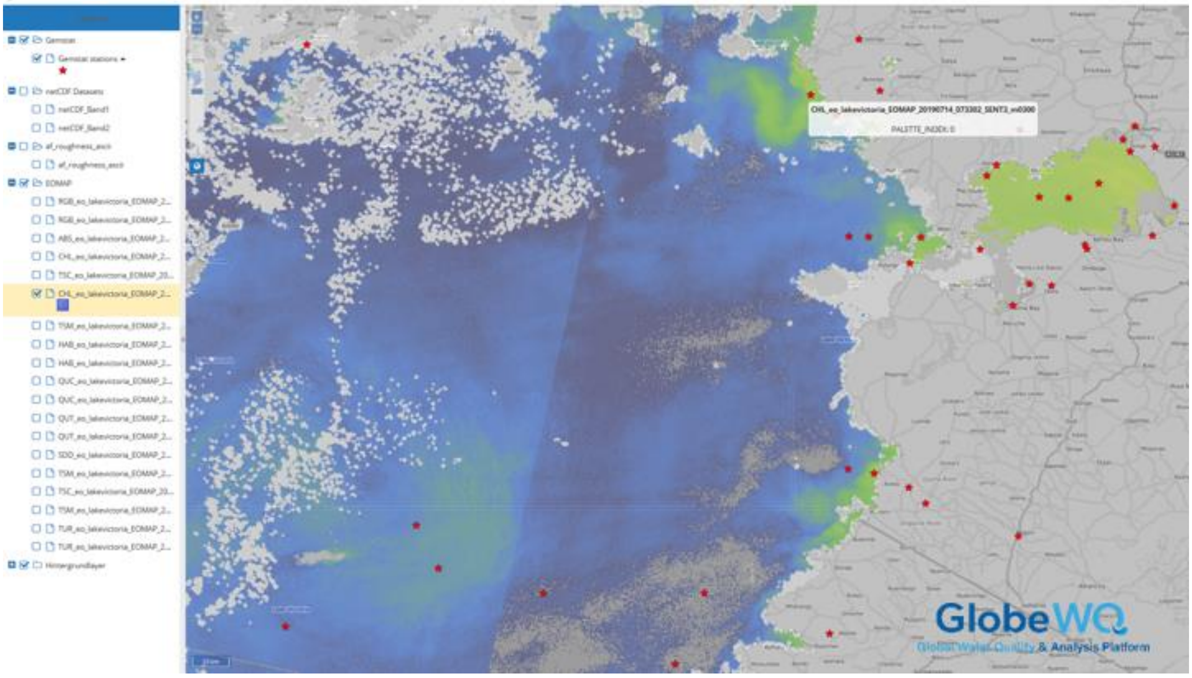


***Figure 5.1*** *Chlorophyll-a concentration in the north-eastern part of Lake Victoria, derived from satellite images. Clearly visible are the elevated concentrations in Kisumu bay on the eastern part of the map. Depicted are also the available stations of in-situ data from the GEMstat data base.*

### 5.4.2 Project and platform: Water Pathogen Knowledge to Practice (Water-K2P)

The mission of the Water Pathogen Knowledge to Practice (Water-K2P) project is to provide tools that allow access to pathogen data on viruses, protozoa and bacteria to support sanitation safety planning.

The key water quality tool is the 'Pathogen Flows and Mapping (PFM) Tool' which allows prediction of areas with high emissions of pathogens to surface waters and evaluate the impact of scenarios of changes in population growth and changes in access to improved sanitation facilities and increased conveyance and treatment of wastewater and faecal sludge.

The Water-K2P project, funded by the Bill and Melinda Gates Foundation, is part of the Global Water Pathogen Project, which comprises a recent online book entitled "Sanitation and Disease in the 21st Century: Health and Microbiological Aspects of Excreta and Wastewater Management", the PFM tool and also a Treatment Plant Sketcher Tool, which predicts the effectiveness of a wastewater or faecal sludge treatment system at removing and reducing pathogens.

The PFM tool is available for the world at the resolution of 0.5 x 0.5 degree latitude x longitude grids and was also employed for a case study in Kampala City, Uganda to support prioritizing decisions for improved sanitation in the city. The outputs of Pathogen Flow and Mapping Tool provided a visual representation of the level of pathogens released into the environment based on sanitation coverage in order to guide action to decrease the amount of disease-causing organisms in the environment (Figure 5.2). The tool is flexible to include other case studies. The tool will be integrated into World Environment Situation Room (WESR), see Chapter 5.4.5.

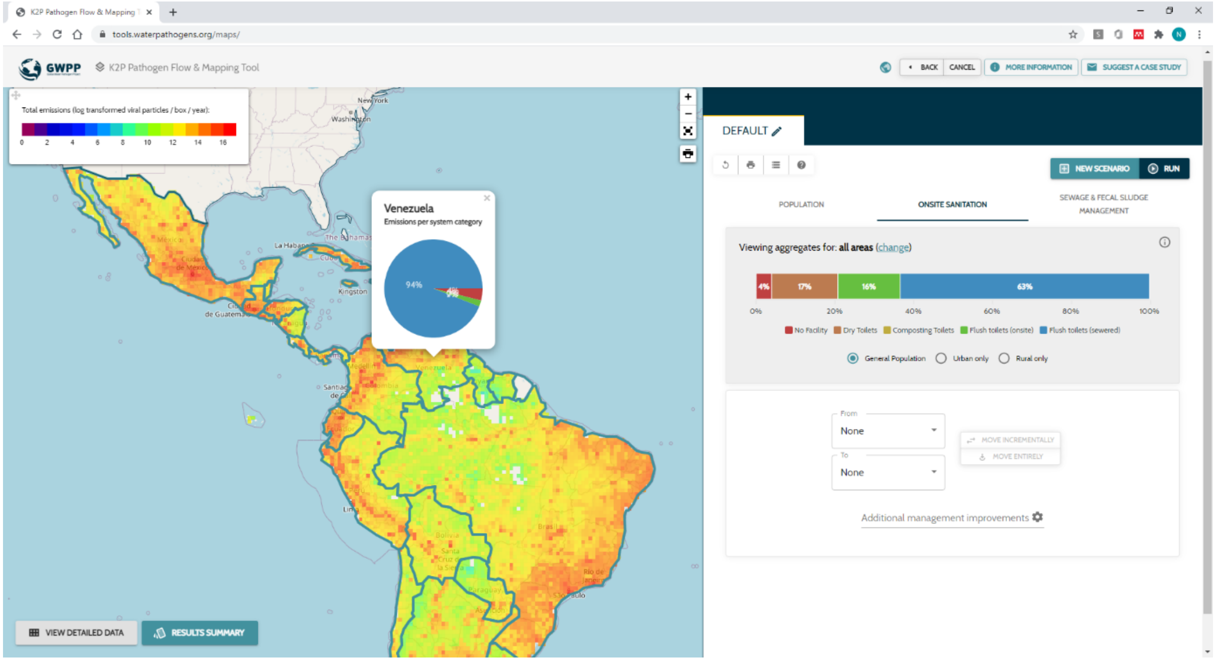


***Figure 5.2*** *Water-K2P screenshot.*

### 5.4.3 The Groundwater Assessment Platform (GAP)

The Groundwater Assessment Platform (GAP) provides an online GIS-based data and information portal for groundwater quality, with a special focus on the geogenic contaminants arsenic and fluoride. These naturally occurring groundwater contaminants impact the health of hundreds of millions of people worldwide

The platform provides global arsenic and fluoride contamination risk maps and also enables users to upload data and create maps and customized groundwater quality models. The platform also hosts the GAP Wiki where users can share documents and discuss relevant issues in an open setting.

### 5.4.4 BlueEarth Data

BlueEarth Data is a platform developed by Deltares that shares operational and historic water-related data for oceans, coasts and rivers at a global scale for professional specialists, researchers, and water managers. BlueEarth Data is part of a larger initiative called BlueEarth, which is an integrated open platform with information and tools to support water-related planning processes. To explain the past and explore the future.

The global data is presently grouped under the Flooding, Coastal Management and Offshore themes. These themes incorporate global datasets that include river discharge and storm surge forecasts, shoreline changes, bathymetry, and metocean conditions. Also, third party data services are incorporated to fortify the integration of the various data services and interactivity with the community of users. The users can visualise and interact with the data, the data can be acquired by downloading the data or by using one of the available APIs for integration with third party applications.

By adding new datasets the number of themes will be extended towards among others: Climate, Water Quality & Sub-Soil.

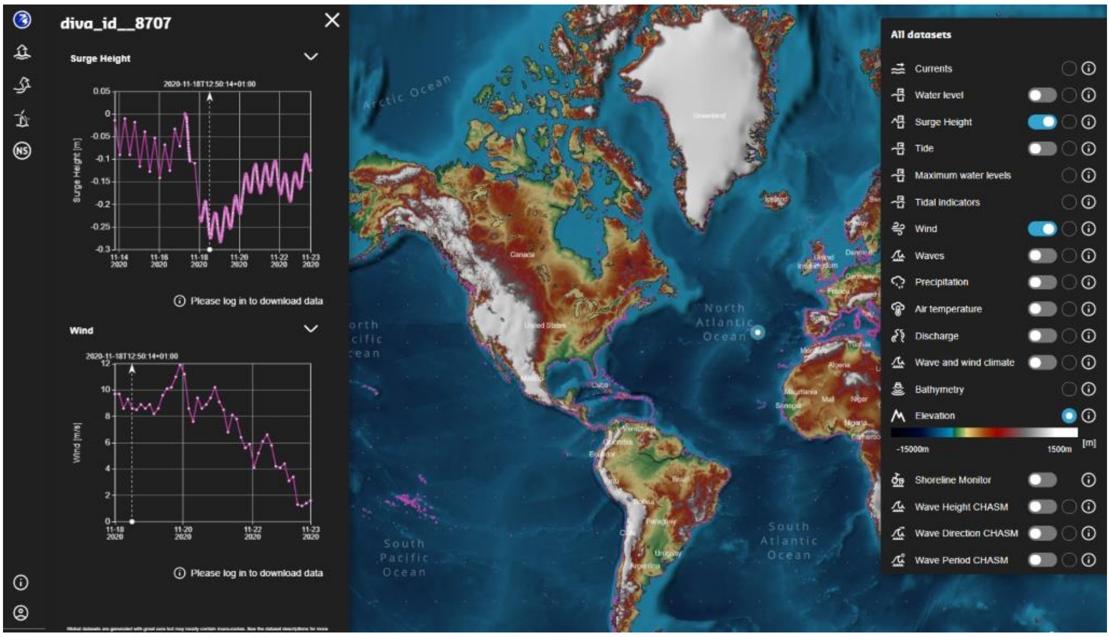


***Figure 5.3*** *BlueEarth Data platform screenshot.*

### 5.4.5 SDG6 world water quality portal

The SDG6 world water quality portal, a free online visualizer for global satellite-based water quality products. Currently available datasets include a merged global set of water quality parameters in 90m resolution for all inland water bodies and coastal areas. Time series products are available in 30m sampling resolution for selected regions. For three use cases in Africa temporal aggregates, i.e. monthly and seasonal averages as well as spatially aggregated water body averages are available. The portal is co-funded by the Thematic Exploitation Platform for Hydrology by European Space Agency (ESA).

### 5.4.6 World Environment Situation Room (WESR)

The World Environment Situation Room is a demonstration platform in UNEP that will continue to evolve as development progresses. The project is global with overarching environmental policy relevance and impact. It includes geo-referenced, remote-sensing and earth observation information integrated with statistics and data on the environmental dimension of sustainable development. It targets country policy makers, top environmental policy makers, the environmental scientific community, business and interested citizens. The platform is essential as a knowledge instrument to support progress on delivering the environmental dimension of Agenda 2030 for Sustainable Development. The platform facilitates in transforming data into information products and services which can be used by non-data experts.

***Table 5.1*** *Overview on the platforms supporting the World Water Quality Assessment.*

| *Platform* | *Audience* | *Method/Data* | *Scale/Coverage* | *Notes* | *Parameters* |
|---|---|---|---|---|---|
| World Environment Situation Room(WESR) Mapping app | Stakeholder; non data experts | General purpose; displays the environmental dimension of Agenda 2030 for Sustainable Development | global | Continuously evolving platform; not exclusively for water quality | Not predefined |
| GlobeWQ | Local stakeholders for use cases, global data (countries) | In-situ and remote sensing data combined with water quality model | global; surface water | Currently under development | Water quality parameters with focus on eutrophication human health and ecosystem quality, to be specified |
| SDG Reporting Portal | Stakeholder; non data experts | Satellite-based water quality | global, selected focus regions | Part of the ESA Hydrology-TEP project | Biological (Chl-a, HAB, cDOM) and physical (Secchi depth, Temperature) |
| Groundwater Assessment Platform (GAP) | Drinking water supply planners | In-situ measurements combined with geostatistical models | global groundwater | | Focus on the geogenic contaminants arsenic and fluoride |
| Water-K2P | Water and sanitation safety planners | Model driven by country level or higher resolution data on population, urbanization, disease incidence and pathogen shedding rates, sanitation technologies, and the treatment of wastewater and faecal sludge to estimate pathogen loadings | global, surface water | Co-designed with local stakeholders, Geoprocessing capabilities for calculating scenarios of pathogens loadings | Pathogens |
| BlueEarth Data | Professional specialists, researchers, water managers | Shares operational and historic water-related data | global, oceans, coasts and rivers | BlueEarth Data is part of a larger initiative called BlueEarth, which is an integrated open platform with information and tools to support water-related planning processes. To explain the past and explore the future. | Global datasets that include river discharge and storm surge forecasts, shoreline changes, bathymetry, and metocean conditions, which will be extended towards among others: climate, water quality & sub-soil |

# 6 Summary and outlook

The Assessment outcome so far is a product of a networking activity mirroring the competences, expertise and action focus as well as resources of the contributing WWQA working groups and principle investigators in consultation with UNEP. It gives a versatile picture of the baseline, close to the present state of global water quality and its impacts on ecosystems health, human health and food security (Chapter 3). Here, we have included a variety of substances and demonstrate using the DPSIR framework exemplary links to impacts and drivers as well as sketch out possible responses. The results can be used to identify water quality hotspots and help to identify some of the key drivers. The outcome of the Assessment already at this initial demonstration state can provide context in support of the evaluation of reaching the Sustainable Development Goal SDG 6 target 6.3 by focusing on the specific indicator on ambient water quality 6.3.2 and its interlinkages with other targets and goals. For this objective the Assessment can draw on regional co-design processes or digital water quality platforms as described in Chapters 4 and 5, respectively.

It is however evident, as also shown by the methodological portfolio summarized in Chapter 2, that the emphasis of this Assessment, i.e. of large- to global-scale water quality studies still is on surface waters and data retrieved from modelling. The prospects of the triangulation approach, i.e. joint use of data from in-situ monitoring, remote sensing and modelling have been shown exemplarily in Chapter 3 for each of the water quality impact themes, however, there are technical, practical and conceptual challenges to be addressed e.g. inconsistencies in spatial and temporal delineation and variables covered by each method.

Several data and knowledge gaps were distinguished in this Assessment phase and summarized in the previous Chapters. The general data and knowledge gaps are:

- still an urgent need for regularly monitored, up-to-date and readily available data to do a thorough evaluation;
- the application of remote sensing data and information in regards to water quality is (so far) limited to address water quality challenges. Further exploitation of data and improvements in model accuracy and data resolution are required as well as the development of methods for integrating different data sources (including in-situ monitoring, water quality models and remote sensing) for a comprehensive water quality evaluation;
- knowledge gaps on the importance of the environmental fate and transport pathways and which need to be closed, also to test model assumptions on these;
- for reliable trend analysis e.g. of nutrient loading and eutrophication, long-term monitoring data is still sparse;
- reporting should encompass the state, impacts (also indirect impacts), main sources and response options for all contaminants causing environmental and health risks; the assessment of water quality impacts in quantitative terms remains difficult as in-situ data and modelling data are lacking (for example to capture the impacts of harmful algal blooms, HABs and hypoxia on fisheries, aquaculture and mariculture as well as pathogen contamination impacts on leafy crops and food safety or on diarrhoeal diseases);
- only the salinity indicator in the SDG 6.3.2 index is directly related to human health but many more indicators could be considered in sampling schemes;
- the knowledge to set up effective legislative frameworks to deal with chemicals, especially chemical mixtures is lacking;
- a continued and urgent requirement for innovative regulatory solutions, which include awareness raising among policy makers and all societal actors worldwide;
- an intrinsic need for better translation of response options to various target audiences by means of strong institutional collaboration across key water quality nexus dimensions and including the integration across water and health/food/ecosystem disciplines to implement effective measures.

In the next Assessment phase, the baseline water quality state and impact will be further elaborated. What especially requires improving is better integration of all sources of information: in-situ data, models and remote sensing, across the DPSIR framework. For this the Assessment team needs strengthening in particular concerning competences in the fields of in-situ monitoring and remote sensing but also regarding the water bodies less visible in this report, i.e. groundwater and estuaries. Concerning modelling, the versatile contribution so far lacks especially large-scale results for many pollutants but also the basis required for scenario runs needs attention, as modelling is the only means to perform scenario studies.

Selected case studies will be carried on to develop in-country partnerships and collaboration, especially with water resource decision-makers in order to continue the co-design of water quality products and services using the World Water Quality Assessment triangulation approach needed e.g. to address mitigation options. Here attention will be paid to groups at risk like women because of their frequent usage of water from rivers and lakes for cleaning clothes and collecting water for cooking and drinking in the household, and children because of their play activities in local surface waters and also because they often have the task of collecting water for the household.

The triangulation approach introduced in this report will trigger new thinking in the scientific community and provide eventually new results to be included in the Assessment. To provide resilient and future-proof response options to decision-makers, the basis must be established for conducting scenario analysis of future development pathways of water quality in the freshwater system in response to future climate change, socio-economic development and response options. For complex new products beyond a pure community effort, such as a comprehensive scenario assessment across all modelling teams, different linked impacts models, or multi-pollutant approaches, additional resources would be required.

# References


Ali, M., Lopez, A.L., You, A.Y., Kim, Y.E., Sah, B., Maskery, B. and Clemens, J. (2012). The Global Burden of Cholera. *Bulletin of the World Health Organization* 90, 209–218.

Allende, A. and Monaghan, J. (2015). Irrigation Water Quality for Leafy Crops: A Perspective of Risks and Potential Solutions, *Int. J. Environ. Res. Public Health* 12(7), 7457-7477. https://doi.org/10.3390/ijerph120707457

Amini, M., Mueller, K., Abbaspour, K.C., Rosenberg, T., Afyuni, M., Møller, K.N., et al. (2008). Statistical Modeling of Global Geogenic Fluoride Contamination in Groundwaters. *Environmental Science & Technology* 42(10), 3662–3668. https://doi.org/10.1021/es071958y

Aw, T. (2018). Environmental Aspects and Features of Critical Pathogen Groups. In: J.B. Rose and B. Jiménez-Cisneros, (eds) Global Water Pathogen Project. http://www.waterpathogens.org (J.B. Rose and B. Jiménez-Cisneros) (eds) Part 1 The Health Hazards of Excreta: Theory and Control) http://www.waterpathogens.org/book/environmental-aspects-and-features-of-critical-pathogen-groups. Michigan State University, E. Lansing, MI, UNESCO. https://doi.org/10.14321/waterpathogens.2

Ayers, R.S. and Westcot, D.W. (1985). Water quality for agriculture. FAO irrigation and drainage paper 29, rev. 1, p. 186. Food and Agriculture Organization of the United Nations, Rome, 186. Available at: http://www.fao.org/docrep/003/T0234E/T0234E00.htm

Backer, L.C., Manassaram-Baptiste, D., LePrell, R. and Bolton, B. (2015). Cyanobacteria and algae blooms: Review of health and environmental data from the harmful algal bloom-related illness surveillance system (HABISS) 2007–2011. Toxins (Basel, 7, 1048–1064.

van Beek, L.P.H., Eikelboom, T., van Vliet, M.T.H. and Bierkens, M.F.P. (2012). A physically based model of global freshwater surface temperature. *Water Resources Research* 48(9), W09530. https://doi.org/10.1029/2012WR011819

aus der Beek, T., Weber, F.-A., Bergmann, A., Hickmann, S., Ebert, I., Hein, A. and Küster, A. (2016). Pharmaceuticals in the environment—Global occurrences and perspectives. *Environ. Toxicol. Chem* 35, 823–835.

Beusen, A.H.W., van Beek, L.P.H., Bouwman, A.F., Mogollón, J.M. and Middelburg, J.J. (2015). Coupling global models for hydrology and nutrient loading to simulate nitrogen and phosphorus retention in surface water - Description of IMAGE-GNM and analysis of performance. *Geoscientific Model Development* 8(12), 4045–4067. https://doi.org/10.5194/gmd-8-4045-2015

Beusen, A.H.W., Bouwman, A.F., Beek, L.P.H.V., Mogollón, J.M. and Middelburg, J.J. (2016). Global riverine N and P transport to ocean increased during the 20th century despite increased retention along the aquatic continuum. *Biogeosciences* 13(8), 2441–2451. https://doi.org/10.5194/bg-13-2441-2016

Bilal, M., Nazir, M.S., Rasheed, T., Parra-Saldivar, R. and Iqbal, H.M.N. (2020). Water matrices as potential source of SARS-CoV-2 transmission – An overview from environmental perspective. *Case Stud. Chem. Environ. Eng* 100023. https://doi.org/10.1016/j.cscee.2020.100023

Bodirsky, B.L., Popp, A., Weindl, I., Dietrich, J.P., Rolinski, S., Scheiffele, L., Schmitz, C. and Lotze-Campen, H. (2012). N2O emissions from the global agricultural nitrogen cycle-current state and future scenarios. *Biogeosciences* 9, 4169–4197.

Boelee, E., Geerling, G., Zaan, B., Blauw, A. and Vethaak, A.D. (2019). Water and health: From environmental pressures to integrated responses. *Acta Tropica* 193, 217–226. https://doi.org/10.1016/j.actatropica.2019.03.011

Boots, B., Russell, C.W. and Green, D.S. (2019). Effects of microplastics in soil ecosystems: above and below ground. *Environ. Sci. Technol.* 53, 19, 11496–11506. https://doi.org/10.1021/acs.est.9b03304

Brack, W., Dulio, V., Ågerstrand, M., Allan, I., Altenburger, R., Brinkmann, M., et al. (2017). Towards the review of the European Union Water Framework Directive: Recommendations for more efficient assessment and management of chemical contamination in European surface water resources. *Science of The Total Environment* 576, 720–737. https://doi.org/10.1016/j.scitotenv.2016.10.104.

Bureau of Fisheries Ministry of Agriculture (2003), China fisheries yearbook, 2003 Rep., China Agriculture Press, Beijing, China.

Byappanahalli, M.N. and Fujioka, R.S. (1998). Evidence that tropical soil environment can support the growth of Escherichia coli. *Water Science and Technology* 38, 171–174.

Canter, L. W. (1996). Nitrates in Groundwater. Lewis publishers.

Caraco, N.F., & Cole, J.J. (1999). Human impact on nitrate export: An analysis using major world rivers. *Ambio* 28(2), 167–170. https://doi.org/10.2307/4314870

Carlson, R.E. (1977). A trophic state index for lakes. *Limnology and Oceanography* 22(2), 361–369.

Carr, E.R., Wingard, P.M., Yorty, S.C., Thompson, M.C., Jensen, N.K. and Roberson, J. (2007). Applying DPSIR to sustainable development. *Int. J. Sust. Dev. World* 14, 543–555.

Chowdhury, S., Mazumder, M.A.J., Al-Attas, O. and Husain, T. (2016). Heavy metals in drinking water: Occurrences, implications, and future needs in developing countries. *Science of the Total Environment* 569–570, 476–488.

Codd, G. (1999). Cyanobacterial toxins, exposure routes and human health. *Eur. J. Phycol* 34, 405–415.

Daliakopoulos, I.N., Tsanis, I.K., Koutroulis, A., Kourgialas, N.N., Varouchakis, A.E., Karatzas, G.P. and Ritsema, C.J. (2016). The threat of soil salinity: a European scale review. *Sci Total Environ* 573, 727-739. http://dx.doi.org/10.1016/j.scitotenv.2016.08.177

Damania, R., Desbureaux, S., Rodella, A.-S., Russ, J. and Zaveri, E. (2019). Quality Unknown: The Invisible Water Crisis. The World Bank. https://doi.org/10.1596/978-1-4648-1459-4

De Baat, M.L., Kraak, M.H.S., van der Oost, R., De Voogt, P. and Verdonschot, P.F.M. (2019). Effect-based nationwide surface water quality assessment to identify ecotoxicological risks. *Water Research* 159, 434–443. https://doi.org/10.1016/j.watres.2019.05.040

Devane, M.L., Moriarty, E., Weaver, L., Cookson, A. and Gilpin, B. (2020). Fecal indicator bacteria from environmental sources; strategies for identification to improve water quality monitoring. *Water Research* 185, 116204.

Dhawan, V. (2017): Water and Agriculture in India. Background paper for the South Asia expert panel during the Global Forum for Food and Agriculture.

Diaz, R.J. and Rosenberg, R. (2008). Spreading dead zones and consequences for marine ecosystems. *Science* 321, 926–929.

Díaz, J., Rabalais, N.N. and Breitburg, D.L. (2012). Agriculture's Impact on Aquaculture: Hypoxia and Eutrophication in Marine Waters. Background reports supporting the OECD study "Water Quality and Agriculture: Meeting the Policy Challenge", available online http://www.oecd.org/agriculture/water (last access 4 November 2020).

Döll, P., Hoffmann-Dobrev, H., Portmann, F.T., Siebert, S., Eicker, A., Rodell, M., Strassberg, G. and Scanlon, B.R. (2012). Impact of water withdrawals from groundwater and surface water on continental water storage variations. *Journal of Geodynamics* 59-60, 143-156, doi:10.1016/j.jog.2011.05.001

Dolbeth, M., Stålnacke, P., Alves, F.L., Sousa, L.P., Gooch, G.D., Khokhlov, V. et al. (2016). An integrated Pan-European perspective on coastal Lagoons management through a mosaic-DPSIR approach. *Scientific Reports* 6(1).

Dumont, E., Williams, R., Keller, V., Voß, A. and Tattari, S. (2012). Modelling indicators of water security, water pollution and aquatic biodiversity in Europe. *Hydrological Sciences Journal* 57(7), 1378–1403. https://doi.org/10.1080/02626667.2012.715747

European Commission (1991a). Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources Rep. Brussels.

European Commission (1991b). Directive 1991/271/EEC concerning urban waste water treatment Rep. Brussels: European Economic Community.

FAO - Food and Agriculture Organization of the United Nations (1992). The use of saline waters for crop production - FAO irrigation and drainage paper 48. Chapter 6 Management principles and practices for safe use of saline water, http://www.fao.org/3/t0667e/t0667e0b.htm#chapter%206%20%20%20management%20principles%20and%20practices%20for%20safe%20use%20of%20saline%20water (last access 4 November 2020)

FAO - Food and Agriculture Organization of the United Nations (1996). Rome declaration on world food security and world food summit plan of action. World Food Summit, November 13–17, 1996, Rome. http://www.fao.org/3/w3613e/w3613e00.htm (last access: 26 October 2020)

FAO - Food and Agriculture Organization of the United Nations (2014). Did you know …? Facts and figures about, http://www.fao.org/nr/water/aquastat/didyouknow/index3.stm (last access: 27 October 2020)

FAO - Food and Agriculture Organization of the United Nations (2016). Total Withdrawal by Sector, http://www.fao.org/nr/water/aquastat/tables/WorldData-Withdrawal_eng.pdf (last access: 22 October 2020).

FAO - Food and Agriculture Organization of the United Nations (2020), FishStatJ - Software for Fishery and Aquaculture Statistical Time Series. http://www.fao.org/fishery/statistics/software/fishstatj/enRep., Fisheries and Aquaculture Information and Statistics Service, Food and Agriculture Organization of the United Nations, retrieved 30 October 2020, Rome.

FAO, IFAD, UNICEF, WFP and WHO (2020). The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets. Rome, FAO. https://doi.org/10.4060/ca9692en (last access: 27 October 2020)

Farooq, S.H., Chandrasekharam, D., Dhanachandra, W. and Ram, K. (2019). Relationship of arsenic accumulation with irrigation practices and crop type in agriculture soils of Bengal Delta, India. *Appl Water Sci* 9, 119. https://doi.org/10.1007/s13201-019-0904-1

Fink, G., Alcamo, J., Flörke, M. and Reder, K. (2018). Phosphorus Loadings to the World's Largest Lakes: Sources and Trends. *Global Biochemical Cycle*s 32(4), 617-634. https://doi.org/10.1002/2017GB005858

Finlay, J.C., Small, G.E. and Sterner, R.W. (2013). Human Influences on Nitrogen Removal in Lakes. *Science* 342(6155), 247–250.

Flörke, M., Kynast, E., Bärlund, I., Eisner, S., Wimmer, F. and Alcamo, J. (2013). Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. *Global Environmental Change* 23 (1), pp. 144–156. 10.1016/j.gloenvcha.2012.10.018.

Flörke, M., Bärlund, I., van Vliet, M.T.H., Bouwman, A.F. and Wada, Y. (2019). Analysing trade-offs between SDGs related to water quality using salinity as a marker. *Current Opinion in Environmental Sustainability* 36, 96-104. doi:https://doi.org/10.1016/j.cosust.2018.10.005.

Gholizadeh, M., Melesse, A. and Reddi, L. (2016). A Comprehensive Review on Water Quality Parameters Estimation Using Remote Sensing Techniques. *Sensors* 16(8), 1298. https://doi.org/10.3390/s16081298

van Gils, J., Posthuma, L., Cousins, I.T., Brack, W., Altenburger, R., Baveco, H., et al. (2020). Computational material flow analysis for thousands of chemicals of emerging concern in European waters. Journal of Hazardous Materials, 397, 122655. https://doi.org/10.1016/j.jhazmat.2020.122655

Giri, A., Bharti, V.K., Kalia, S., Arora, A., Balaje, S.S. and Chaurasia, O.P. (2020). A review on water quality and dairy cattle health: a special emphasis on high-altitude region. *Appl Water Sci* 10, 79. https://doi.org/10.1007/s13201-020-1160-0

Glibert, P.M. (2017). Eutrophication, harmful algae and biodiversity — Challenging paradigms in a world of complex nutrient changes. *Marine Pollution Bulletin* 124(2), 591–606. https://doi.org/10.1016/j.marpolbul.2017.04.027

Glibert, P.M. (2019). Harmful algae at the complex nexus of eutrophication and climate change. *Harmful Algae* 101583. https://doi.org/10.1016/j.hal.2019.03.001

Guerrero-Latorre, L., Ballestros, I., Villacrés-Granda, I., Granda, M.G., Freire-Paspuel, B. and Rios-Touma, B. (2020). SARS-CoV-2 in river water: Implications in low sanitation countries. *Sci. Total Environ* 743, 140832.

Haas, C.N., Rose, J.B. and Gerba, C.P. (1999). Quantitative microbial risk assessment. John Wiley & Sons, Inc.

Hamidov, A., Helming, K., Bellocchi, G., Bojar, W., Dalgaard, T., Ghaley, B.B, et al. (2018). Impacts of climate change adaptation options on soil functions: A review of European case-studies. *Land Degradation & Development* 29(8), 2378–2389.

Heege, T., Schenk, K. and Wilhelm, M.-L. (2019). Water Quality Information for Africa from Global Satellite Based Measurements: The Concept Behind the UNESCO World Water Quality Portal (pp. 81–92). https://doi.org/10.1007/978-3-030-06040-4_5

Heikens, A. (2006). Arsenic contamination of irrigation water, soil and crops in Bangladesh: Risk implications for sustainable agriculture and food safety in Asia. RAP Publication 2006/20, FAO Regional Office for Asia and the Pacific, Bangkok, 38 pp., http://www.fao.org/a-ag105e.pdf (last access 5 November 2020).

Hofstra, N., Vermeulen, L.C., Derx, J., Flörke, M., Mateo-Sagasta, J., Rose, J. et al. (2019). Priorities for developing a modelling and scenario analysis framework for waterborne pathogen concentrations in rivers worldwide and consequent burden of disease. *Curr. Opin. Environ. Sustain*, 36.

Hofstra, N. and Vermeulen, L.C. (2016). Impacts of population growth, urbanisation and sanitation changes on global human Cryptosporidium emissions to surface water. *Int. J. Hyg. Environ. Health* 219.

Howarth, R., Chan, F., Conley, D.J., Garnier, J., Doney, S.C., Marino, R. and Billen, G. (2011). Coupled biogeochemical cycles: Eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems. *Frontiers in Ecology and the Environment* 9(1), 18–26. https://doi.org/10.1890/100008

Hughes, M.F. (2002). Arsenic toxicity and potential mechanisms of action. *Toxicol. Lett* 133, 1–16.

International Programme on Chemical Safety. (2002). International Programme on Chemical Safety. *Fluorides* 268.

Ippolito, A., Kattwinkel, M., Rasmussen, J.J., Schäfer, R.B., Fornaroli, R. and Liess, M. (2015). Modeling global distribution of agricultural insecticides in surface waters. *Environmental Pollution* 198, 54–60. https://doi.org/10.1016/J.ENVPOL.2014.12.016

Ivushkin, K., Bartholomeus, H., Bregt, A., Pulatov, A., Kempen, B. and de Sousa, L. (2019). Global mapping of soil salinity change. *Remote Sensing of Environment* 231:111260, doi: 10.1016/j.rse.2019.111260

Janse, J.H., Kuiper, J.J., Weijters, M.J., Westerbeek, E.P., Jeuken, M.H.J.L., Bakkenes, M., et al. (2015). GLOBIO-Aquatic, a global model of human impact on the biodiversity of inland aquatic ecosystems. *Environmental Science & Policy* 48, 99–114. https://doi.org/10.1016/j.envsci.2014.12.007

Janssen, A.B.G., Hilt, S., Kosten, S., Klein, J.J.M., Paerl, H.W. and Waal, D.B.V. (2020). Shifting states, shifting services: Linking regime shifts to changes in ecosystem services of shallow lakes. *Freshwater Biology,* Article in press. https://doi.org/10.1111/fwb.13582

Janssen, Annette B.G., Teurlincx, S., Beusen, A. H. W., Huijbregts, M. A. J., Rost, J., Schipper, A. M., et al. (2019). PCLake+: A process-based ecological model to assess the trophic state of stratified and non-stratified freshwater lakes worldwide. Ecological Modelling, 396, 23–32. https://doi.org/10.1016/j.ecolmodel.2019.01.006

de Jesus Gaffney, V., Almeida, C.M.M., Rodrigues, A., Ferreira, E., Benoliel, M.J. and Cardoso, V.V. (2015). Occurrence of pharmaceuticals in a water supply system and related human health risk assessment. *Water Res* 72, 199–208.

Jones, E. and van Vliet, M.T.H. (2018). Drought impacts on river salinity in the southern US: Implications for water scarcity. *Science of The Total Environment* 644, 844-853, https://doi.org/10.1016/j.scitotenv.2018.06.373.

Jones, E., Qadir, M., van Vliet, M.T.H., Smakhtin, V. and Kang, S.M. (2019). The state of desalination and brine production: A global outlook. *Science of the Total Environment* 657:1343-1356.

Kattwinkel, M., Kühne, J.-V., Foit, K. and Liess, M. (2011). Climate change, agricultural insecticide exposure, and risk for freshwater communities. *Ecol. Appl* 21, 2068–2081.

Kiulia, N., Hofstra, N., Vermeulen, L., Obara, M., Medema, G., Rose, J., et al. (2015). Global Occurrence and Emission of Rotaviruses to Surface Waters. *Pathogens* 4(2), 229–255. https://doi.org/10.3390/pathogens4020229

Klein Goldewijk, K., Beusen, A., Doelman, J. and Stehfest, E. (2017). New anthropogenic land use estimates for the Holocene; HYDE 3.2. *Earth System Science Data* (9), 927–953. DOI: 10.5194/essd-2016-58.

Klemas, V., Borchardt, J.F. and Treasure, W.M. (1971). Suspended sediment observations from ERTS-1. *Remote Sensing of Environment* 2(C), 205–221. https://doi.org/10.1016/0034-4257(71)90094-0

Koelmans, A.A., Nor, N.H.M., Hermsen, E., Kooi, M., Mintenig, S.M. and De France, J. (2019). Microplastics in freshwaters and drinking water: Critical review and assessment of data quality. *Water Research* 155, 410–422.

Kristensen, P. (2003). EEA core set of indicators. Revised version April 2003. Adopted version for ECCAA countries, May 2003, Technical Report, pp. 1–79.

Kroeze, C. and Seitzinger, S.P. (1998). Nitrogen inputs to rivers, estuaries and continental shelves and related nitrous oxide emissions in 1990 and 2050: A global model. *Nutrient Cycling in Agroecosystems* 52, 195–212. https://doi.org/10.1023/a:1009780608708

Kumar, V., Prihar, R.D., Sharma, A., Bakshi, P., Sidhu, G.P.S, Bali, A.S. et al. (2019). Global evaluation of heavy metal content in surface water bodies: A meta-analysis using heavy metal pollution indices and multivariate statistical analyses. *Chemosphere* 236, 124364.

Kummu, M., Moel, H., Porkka, M., Siebert, S., Varis, O. and Ward, P.J. (2012). Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. *Science of The Total Environment* 438, 477–489. https://doi.org/10.1016/j.scitotenv.2012.08.092

La Rosa, G., Bonadonna, L., Lucentini, L., Kenmoe, S. and Suffredini, E. (2020). Coronavirus in water environments: Occurrence, persistence and concentration methods - A scoping review. *Water Research* 179, 115899.

Landrigan, P.J., Fuller, R., Acosta, N.J.R., Adeyi, O., Arnold, R., Basu, N.N. et al. (2018). The Lancet Commission on pollution and health. *The Lancet* 391, 462–512.

Larsson, D.G.J., Andremont, A., Bengtsson-Palme, J., Koefoed Brandt, K., de Roda Husman, A.M., Fagerstedt, P. et al. (2018). Critical knowledge gaps and research needs related to the environmental dimensions of antibiotic resistance. *Environment International* 117, 132–138.

Lebreton, L.C.M., van der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A. and Reisser, J. (2017). River plastic emissions to the world's oceans. *Nature Communications* 8(1), 15611. https://doi.org/10.1038/ncomms15611

Li, C., Busquets, R. and Campos, L.C. (2020). Assessment of microplastics in freshwater systems: A review. *Sci. Total Environ* 707, 135578.

Li, J. and Roy, D.P. (2017). A Global Analysis of Sentinel-2A, Sentinel-2B and Landsat-8 Data Revisit Intervals and Implications for Terrestrial Monitoring. *Remote Sensing* 9(9). https://doi.org/10.3390/rs9090902

Liang, Y. (2012). Investigation and evaluation of red tide disasters in China (1933-2009). Ocean Press (in Chinese).

Limaheluw, J., Medema, G. and Hofstra, N. (2019). An exploration of the disease burden due to Cryptosporidium in consumed surface water for sub-Saharan Africa. *Int. J. Hyg. Environ. Health* 222, 856–863. https://doi.org/10.1016/j.ijheh.2019.04.004

Liska, I., Wagner, F., Sengl, M., Deutsch, K. and Slobodnik, J. (2015). Joint Danube Survey 3 A Comprehensive Analysis of Danube Water Quality. ICPDR – International Commission for the Protection of the Danube River. Vienna/Austria. Retrieved from http://www.danubesurvey.org/sites/danubesurvey.org/files/nodes/documents/jds3_final_scientific_report_1.pdf.

Lundberg, C. (2005). Conceptualizing the Baltic Sea ecosystem: an interdisciplinary tool for environmental decision making. *Ambio* 34, 433–439.

Machado, R.M.A. and Serralheiro, R.P. (2017). Soil Salinity: Effect on Vegetable Crop Growth. Management Practices to Prevent and Mitigate Soil Salinization. *Horticulturae* 3(2), 30, https://doi.org/10.3390/horticulturae3020030

Malaj, E., Ohe, P., Grote, M., Kühne, R., Mondy, C. and Usseglio-Polatera, P. (2014). Organic chemicals jeopardise freshwater ecosystems health on the continental scale. *Proc. Natl. Acad. Sci* 111, 9549–9554. https://doi.org/10.1073/pnas.1321082111.

Mandić, A. (2020). Structuring challenges of sustainable tourism development in protected natural areas with driving force–pressure–state–impact–response (DPSIR) framework. *Environment Systems and Decisions*. DOI: 10.1007/s10669-020-09759-y

Matthews, M.W. and Odermatt, D. (2015). Improved algorithm for routine monitoring of cyanobacteria and eutrophication in inland and near-coastal waters. *Remote Sensing of Environment* 156. https://doi.org/10.1016/j.rse.2014.10.010

Maul, G.A. and Gordon, H.R. (1975). On the Use of the Earth Resources Technology Satellite (LANDSAT-1) in Optical Oceanography. *Remote Sensing of Environment* 4(C), 95–128. https://doi.org/10.1016/0034-4257(75)90008-5

Mayorga, E., Seitzinger, S.P., Harrison, J.A., Dumont, E., Beusen, A.H.W., Bouwman, A.F., et al. (2010). Global Nutrient Export from WaterSheds 2 (NEWS 2): Model development and implementation. *Environmental Modelling and Software* 25(7), 837–853. https://doi.org/10.1016/j.envsoft.2010.01.007

McCrackin, M.L., Muller-Karulis, B., Gustafsson, B.G., Howarth, R.W., Humborg, C., Svanbäck, A. and Swaney, D.P. (2018). A Century of Legacy Phosphorus Dynamics in a Large Drainage Basin. *Global Biochemical Cycles* 32(ue 7), 1107–1122.

McNeish, R.E., Kim, L.H., Barrett, H.A., Mason, S.A., Kelly, J.J. and Hoellein T.J. (2018). Microplastic in riverine fish is connected to species traits. *Sci Rep* 8, 11639. https://doi.org/10.1038/s41598-018-29980-9

Medema, G.J., Teunis, P., Blokker, M., Deere, D., Davison, A. Charles, P. and Loret, J.F. (2009). Risk Assessment of Cryptosporidium in Drinking Water. WHO World Health Organization, Geneva.

Merel, S., Walker, D., Chicana, R., Snyder, S., Baurès, E. and Thomas, O. (2013). State of knowledge and concerns on cyanobacterial blooms and cyanotoxins. *Environment International* 59, 303-327, doi: https://doi.org/10.1016/j.envint.2013.06.013

Michalak, A.M., Anderson, E.J., Beletsky, D., Boland, S., Bosch, N.S.m Bridgeman, T.B. et al. (2013). Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. *Proceedings of the National Academy of Sciences* 110(16), 6448–6452. https://doi.org/10.1073/pnas.1216006110

Momba, M. and Azab El-Liethy, M. (2017). Vibrio cholerae and Cholera biotypes. In: Global Water Pathogen Project. (J.B. Rose & B. Jiménez-Cisneros, Eds.). UNESCO. https://doi.org/10.14321/waterpathogens.28

Mondal, D., Banerjee, M., Kundu, M., Banerjee, N., Bhattacharya, U., Giri, A.K. et al. (2010). Comparison of drinking water, raw rice and cooking of rice as arsenic exposure routes in three contrasting areas of West Bengal, India. *Environ. Geochem. Health* 32, 463–477, DOI 10.1007/s10653-010-9319-5

Moyano, A., Garcia-Sanchez, A., Mayorga, P., Anawar, H.M. and Alvarez-Ayuso, E. (2009). Impact of irrigation with arsenic-rich groundwater on soils and crops. *J. Environ. Monit.* 11, 498–502, DOI: 10.1039/b817634e

Murray, C.J. and Lopez, A.D. (1996). The Global burden of disease: a comprehensive assessment of mortality and disability from diseases, injuries, and risk factors in 1990 and projected to 2020. Harvard School of Public Health, 1–46.

Myers, S. S. and Patz, J. A. (2009). Emerging threats to human health from global environmental change. *Annu. Rev. Environ. Resour* 34, 223–252.

Odermatt, S. (2004). Evaluation of mountain case studies by means of sustainability variables. *Mt. Res. Dev* 24, 336–341.

Odermatt, D., Danne, O., Philipson, P. and Brockmann, C. (2018). Diversity II water quality parameters from ENVISAT (2002–2012): a new global information source for lakes. *Earth Syst. Sci. Data* 10(3), 1527–1549. https://doi.org/10.5194/essd-10-1527-2018

OECD. (2003). Environmental Indicators – Development, Measurement and Use. Report. Organisation of Economic Co-operation and Development.

Oldenkamp, R., Beusen, A.H.W. and Huijbregts, M.A.J. (2019). Aquatic risks from human pharmaceuticals - Modelling temporal trends of carbamazepine and ciprofloxacin at the global scale. *Environmental Research Letters* 14(3). https://doi.org/10.1088/1748-9326/ab0071

Ouedraogo, I., Defourny, P. and Vanclooster, M. (2016). Mapping the groundwater vulnerability for pollution at the pan African scale. *Sci. Total Environ* 544, 939–953. https://doi.org/10.1016/j.scitotenv.2015.11.135

Pachepsky, Y., Shelton, D.R., McLain, J.E.T., Patel, J., Mandrell, R.E., (2011). Chapter Two - Irrigation Waters as a Source of Pathogenic Microorganisms in Produce: A Review, Editor(s): Donald L. Sparks, Advances in Agronomy, Academic Press, Volume 113, Pages 75-141, ISBN 9780123864734, https://doi.org/10.1016/B978-0-12-386473-4.00002-6

Parkinson, S., Krey, V., Huppmann, D., Kahil, T., McCollum, D., Fricko, O., Byers, E., Gidden, M.J., Mayor, B., Khan, Z., Raptis, C., Rao, N.D., Johnson, N., Wada, Y., Djilali, N., Riahi, K. (2019) Balancing clean water-climate change mitigation trade-offs. Environmental Research Letters 14, 014009.

Pistocchi, A., Dorati, C., Grizzetti, B., Udias, A., Vigiak, O. and Zanni, M. (2019). Water quality in Europe: effects of the Urban Wastewater Treatment Directive. A retrospective and scenario analysis of Dir. 91/271/EEC Rep., EUR 30003. Luxembourg: EN Publications Office of the European Union. https://doi.org/10.2760/303163

Podgorski, J. and Berg, M. (2020). Global threat of arsenic in groundwater. *Science* 368(6493), 845–850. https://doi.org/10.1126/science.aba1510

Posthuma, L., Gils, J., Zijp, M.C., Meent, D. and Zwart, D. (2019). Species sensitivity distributions for use in environmental protection, assessment, and management of aquatic ecosystems for 12 386 chemicals. *Environmental Toxicology and Chemistry* 38(4), 703–711. https://doi.org/10.1002/etc.4373.

Prata, J.C., Costa, J.P., Lopes, I., Duarte, A.C. and Rocha-Santos, T. (2020). Environmental exposure to microplastics: An overview on possible human health effects. *Science of the Total Environment* 702, 134455.

Punzet, M., Voß, F., Voß, A., Teichert, E. and Bärlund I. (2012). A Global Approach to Assess the Potential Impact of Climate Change on Stream Water Temperatures and Related In-Stream First-Order Decay Rates. *Journal of Hydrometeorology* 13(3),1052-1065. DOI: 10.1175/JHM-D-11-0138.1

Rabalais, N.N., Turner, R.E. and Wiseman, W.J. (2001). Hypoxia in the Gulf of Mexico. *Journal of Environmental Quality* 30(2), 320–329.

Rashed, M.N. (2001). Monitoring of environmental heavy metals in fish from Nasser Lake. *Environment International* 27, 27-33.

Reder, K., Flörke, M. and Alcamo, J. (2015). Modeling historical fecal coliform loadings to large European rivers and resulting in-stream concentrations. *Environmental Modelling & Software* 63, 251–263. https://doi.org/10.1016/J.ENVSOFT.2014.10.001

Relvas, H. and Miranda, A.I. (2018). Application of the DPSIR framework to air quality approaches. *Air Quality, Atmosphere & Health* 11(9), 1069–1079.

Rist, S., Carney Almroth, B., Hartmann, N.B., & Karlsson, T.M. (2018). A critical perspective on early communications concerning human health aspects of microplastics. *Science of the Total Environment* 626, 720–726.

Romero, E., Garnier, J., Lassaletta, L., Billen, G., Gendre, R. L., Riou, P. and Cugier, P. (2013). Large-scale patterns of river inputs in southwestern Europe: Seasonal and interannual variations and potential eutrophication effects at the coastal zone. *Biogeochemistry* 113(1–3), 481–505. https://doi.org/10.1007/s10533-012-9778-0

Ross, M. R. V., Topp, S. N., Appling, A. P., Yang, X., Kuhn, C., Butman, D., et al. (2019). AquaSat: A Data Set to Enable Remote Sensing of Water Quality for Inland Waters. *Water Resources Research* 55(11), 10012–10025. https://doi.org/10.1029/2019WR024883

Ruíz-Huerta, E.A., de la Garza Varela, A., Gómez-Bernal, J.M., Castillo, F., Avalos-Borja, M., SenGupta, B. and Martínez-Villegas, N. (2017). Arsenic contamination in irrigation water, agricultural soil and maizecrop from an abandoned smelter site in Matehuala, Mexico. *Journal of Hazardous Materials* 339, 330–339.

Salomons, W., Kremer, H.H., and Turner, R. K. (2005). The Catchment to Coast Continuum. In Crossland, C.J., Kremer, H.H., Lindeboom, H., Marshall Crossland, J.I. and Le Tissier, M.D.A. (Eds.) (2005). Coastal Fluxes in the Anthropocene, The Land-Ocean Interactions in the Coastal Zone Project of the International Geosphere-Biosphere Programme , *Springer,* 145-200; ISBN 978-3-540-27851-1

Schulze, S., Zahn, D., Montes, R., Rodil, R., Benito Quintana, J., Knepper, T., et al. (2019). Occurrence of emerging persistent and mobile organic contaminants in European water samples. *Water Res* 153, 80–90. https://doi.org/10.1016/j.watres.2019.01.008.

Schwarzenbach, R.P., Egli, T., Hofstetter, T.B., von Gunten, U. and Wehrli, B. (2010). Global water pollution and human health. *Annu. Rev. Environ. Resour* 35, 109–136.

Shammi, M., Rahman, M., Bondad, S. and Bodrud-Doza, M. (2019). Impacts of Salinity Intrusion in Community Health: A Review of Experiences on Drinking Water Sodium from Coastal Areas of Bangladesh. *Healthcare* 7, 50.

Siebert, S., Döll, P., Feick, S., Hoogeveen, J. and Frenken, K. (2007). "Global map of irrigation areas version 4.0. 1." Johann Wolfgang Goethe University, Frankfurt am Main, Germany/Food and Agriculture Organization of the United Nations, Rome, Italy.

Siebert, S., Henrich, V., Frenken, K. and Burke, J. (2013). Update of the digital global map of irrigation areas to version 5.

Siebert, S., Kummu, M., Porkka, M., Döll, P., Ramankutty, N. and Scanlon, B.R. (2015). A global data set of the extent of irrigated land from 1900 to 2005. *Hydrol. Earth Syst. Sci.* 19, 1521–1545. doi:10.5194/hess-19-1521-2015

Siegfried, M., Koelmans, A. A., Besseling, E. and Kroeze, C. (2017). Export of microplastics from land to sea. A modelling approach. *Water Research* 127, 249–257. https://doi.org/10.1016/J.WATRES.2017.10.011

Smeets, E. and Weterings, R. (1999). Environmental indicators: typology and overview. Technical Report, pp. 1–20.

Smith, M.D., C.A. Roheim, L.B. Crowder, B.S. Halpern, M. Turnipseed, J.L. Anderson, F. Asche, L. Bourillón, A.G. Guttormsen, A. Khan, L.A. Liguori, A. McNevin, M.I. O'Connor, D. Squires, P. Tyedmers, C. Brownstein, K. Carden, D.H. Klinger, R. Sagarin, and K.A. Selkoe (2010). Sustainability and Global Seafood. *Science* 327, 784-786.

Snow, J. (1855). On the Mode of Communication of Cholera. Churchill.

Strokal, M., Kroeze, C., Wang, M., Bai, Z., & Ma, L. (2016). The MARINA model (Model to Assess River Inputs of Nutrients to seAs): Model description and results for China. Sci. Total Environ, 562, 869–888. https://doi.org/10.1016/j.scitotenv.2016.04.071

Strokal, M., Spanier, J.E.E., Kroeze, C., Koelmans, A.A., Flörke, M., Franssen, W., et al. (2019). Global multi-pollutant modelling of water quality: scientific challenges and future directions. *Current Opinion in Environmental Sustainability* 36, 116–125. https://doi.org/10.1016/j.cosust.2018.11.004

Strokal, M., Bai, Z., Franssen, W., Nynke, H., A.A., K., Ludwig, F. and Al., E. (n.d.). Urbanization: an increasing source of multiple pollutants to rivers in the 21st century. *Urban Sustainability*, accepted.

Stroomberg, G., Neefjes, R., Jonge, J., Bannink, A., Haar, G. and Zwamborn, C. (2018). Jaarrapport 2017, De Rijn. RIWA-Rijn. Nieuwegein, The Netherlands. Retrieved from https://www.riwa-rijn.org/publicatie/jaarrapport-2017-de-rijn/.

Sun, X., Xiong, S., Zhu, X., Zhu, X., Li, Y. and Li, B. L. (2015). A new indices system for evaluating ecological-economic-social performances of wetland restorations and its application to Taihu Lake Basin, China. *Ecological Modelling* 295, 216–226. https://doi.org/10.1016/j.ecolmodel.2014.10.008

Tacon, A.G.J. and De Silva, S.S. (1997). Feed preparation and feed management strategies within semi-intensive fish farming systems in the tropics. *Aquaculture* 151(1-4), 379-404.

Tacon, A.G.J. and Halwart, M. (2007). Cage aquaculture: a global overview, in Cage aquaculture - Regional reviews and global overview, edited by M. Halwart, D. Soto and J. R. Arthur, pp. 1-16, Food and Agriculture Organization of the United Nations, Rome.

Thorslund, J. and van Vliet, M.T.H. (2019): Freshwater salinisation and its drivers: A critical water quality challenge with implications for agricultural development, conference paper of Saline futures, Leeuwarden, the Netherlands.

Thorslund, J. and Vliet, M.T.H. (2020). A global dataset of surface water and groundwater salinity measurements from 1980–2019. *Sci. Data* 7, 231. https://doi.org/10.1038/s41597-020-0562-z

Tong, Y., Wang, M., Penuelas, J., Liu, X., Paerl, H.W., Elser, J.J., et al. (2020). Improvement in municipal wastewater treatment alters lake nitrogen to phosphorus ratios in populated regions. *Proceedings of the National Academy of Sciences*, 201920759. https://doi.org/10.1073/pnas.1920759117

Tscherning, K., Helming, K., Krippner, B., Sieber, S. and Gomez y Paloma, S. (2012). Does research applying the DPSIR framework support decision making? *Land Use Policy* 29(1), 102–110.

Tumwebaze, I.K., Rose, J.B., Hofstra, N., Verbyla, M.E., Musaazi, I., Okaali, D.A., et al. (2019). Translating pathogen knowledge to practice for sanitation decision-making. *Journal of Water and Health* 17(6), 896–909. https://doi.org/10.2166/wh.2019.151

Turner, R.E., Rabalais, N.N., Justic, D. and Dortch, Q. (2003). Global patterns of dissolved N, P and Si in large rivers. *Biogeochemistry*, 64, 297–317.

UNEP (2016). A Snapshot of the World's Water Quality: Towards a Global Assessment. United Nations Environment Programme, Nairobi, Kenya. 162pp.

UNEP (2019). Global Chemicals Outlook II From Legacies to Innovative Solutions: Implementing the 2030 Agenda for Sustainable Development – Synthesis Report.

UNESCO and HELCOM (2017). Pharmaceuticals in the Aquatic Environment of the Baltic Sea Region — A Status Report. Paris: UNESCO Publishing.

UN-Water (2016). Towards a Worldwide Assessment of Freshwater Quality. A UN-Water Analytical Brief. UN-Water, Genève, Switzerland. 36pp.

Vermeulen, L.C., van Hengel, M., Kroeze, C., Medema, G., Spanier, J.E., van Vliet, M.T.H. and Hofstra, N. (2019). Cryptosporidium concentrations in rivers worldwide. *Water Res* 149, 202–214. https://doi.org/10.1016/J.WATRES.2018.10.069

Vethaak, A.D. and Leslie, H.A. (2016). Plastic Debris is a Human Health Issue. *Environmental Science and Technology* 50, 6825–6826.

van Puijenbroek, P.J.T.M., Beusen, A.H.W., Bouwman, A.F. (2019) *Global nitrogen and phosphorus in urban wastewater based on the Shared Socio-economic pathways*, Journal of Environmental Management, 231, 446-456, doi: 10.1016/j.jenvman.2018.10.048.

van Vliet, M.T.H., Flörke, M. and Wada, Y. (2017). Quality matters for water scarcity. *Nature Geoscience* 10(10), 800–802. https://doi.org/10.1038/ngeo3047

van Vliet, M.T.H., Flörke, M., Harrison, J.A., Hofstra, N., Keller, V., Ludwig, F., et al. (2019). Model inter-comparison design for large-scale water quality models. *Current Opinion in Environmental Sustainability* 36, 59–67. https://doi.org/10.1016/j.cosust.2018.10.013

van Vliet, M.T.H., Jones, E.R., Flörke, M., Franssen, W.H.P., Hanasaki, N., Wada, Y. and Yearsley, J.R. (2020). Global water scarcity including surface water quality and expansions of clean water technologies. *Environmental Research Letters*, in press. https://doi.org/10.1088/1748-9326/abbfc3

Vollenweider, R.A. (1992). Coastal marine eutrophication: principles and control. *Science of the Total Environment* (Vol. Supplement, 1-20). https://doi.org/10.1016/B978-0-444-89990-3.50011-0

Voß, A., Alcamo, J., Bärlund, I., Voß, F., Kynast, E., Williams, R. and Malve, O. (2012). Continental scale modelling of in-stream river water quality: A report on methodology, test runs, and scenario application. *Hydrological Processes* 26(16), 2370–2384. https://doi.org/10.1002/hyp.9445

Wallender, W.W. and Tanji, K.K. (2012). Agricultural salinity assessment and management, 2nd ed. ed. ASCE manual and reports on engineering practice no. 71. American Society of Civil Engineers, Reston.

Wanders, N., Vliet, M.T.H., Wada, Y., Bierkens, M.F.P. and Beek, L.P.H. (Rens). (2019). High-Resolution Global Water Temperature Modeling. *Water Resources Research* 55(4), 2760–2778. https://doi.org/10.1029/2018WR023250

Wang, M., Kroeze, C., Strokal, M., Vliet, M.T.H. and Ma, L. (2020a). Global Change Can Make Coastal Eutrophication Control in China More Difficult. *Earth's Future* 8(4). https://doi.org/10.1029/2019EF001280

Wang, Z., Walker, G.W., Muir, D.C.G. and Nagatani-Yoshida, K. (2020b). Toward a global understanding of chemical pollution: a first comprehensive analysis of national and regional chemical inventories. *Environ. Sci. Technol.* 54, 5, 2575-2584. https://doi.org/10.1021/acs.est.9b06379

Wang, J., Beusen, A.H.W., Liu, X. and Bouwman, A.F. (2020c). Aquaculture Production is a Large, Spatially Concentrated Source of Nutrients in Chinese Freshwater and Coastal Seas. *Environmental Science & Technology* 54(3), 1464–1474. https://doi.org/10.1021/acs.est.9b03340

Wang, H., Long, W., Chadwick, D., Velthof, G. L., Oenema, O., Ma, W., et al. (2020d). Can dietary manipulations improve the productivity of pigs with lower environmental and economic cost? A global meta-analysis. *Agriculture, Ecosystems & Environment* 289, 106748. 10.1016/j.agee.2019.106748

Wannaz, C., Franco, A., Kilgallon, J., Hodges, J. and Jolliet, O. (2018). A global framework to model spatial ecosystems exposure to home and personal care chemicals in Asia. *Science of the Total Environment* 622–623, 410–420. https://doi.org/10.1016/j.scitotenv.2017.11.315

Ward, R.C., Loftis, J.C. and McBride, G.B. (1986). The "data-rich but information-poor" syndrome in water quality monitoring. *Environmental Management* 10(3), 291–297. https://doi.org/10.1007/BF01867251

Wen, Y., Schoups, G. and van de Giesen, N. (2018). Global impacts of the meat trade on in-stream organic river pollution: the importance of spatially distributed hydrological conditions. *Environmental Research Letters* 13(1), 014013. https://doi.org/10.1088/1748-9326/aa94f6

Westhoek, H., Lesschen, J. P., Rood, T., Wagner, S., Marco, A. D., Murphy-Bokern, D., et al. (2014). Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. *Global Environmental Change* 26, 196–205. https://doi.org/10.1016/j.gloenvcha.2014.02.004

WHO (2012). Pharmaceuticals in drinking water.

WHO (2015). Global Action Plan on Antimicrobial Resistance.

WHO (2017). Guidelines for drinking-water quality (4th edition, incorporating the 1st addendum).

WHO (2020). Water, sanitation, hygiene, and waste management for SARS-CoV-2, the virus that causes COVID-19.

van Wijnen, J., Ragas, A.M.J. and Kroeze, C. (2017). River export of triclosan from land to sea: A global modelling approach. *Science of the Total Environment* 621, 1280–1288. https://doi.org/10.1016/j.scitotenv.2017.10.100

van Wijnen, J., Ragas, A.M.J. and Kroeze, C. (2019). Modelling global river export of microplastics to the marine environment: Sources and future trends. *Science of the Total Environment* 673, 392–401. https://doi.org/10.1016/j.scitotenv.2019.04.078

Wölfel, R., Corman, V.M., Guggemos, W., Seilmaier, M., Zange, S., Müller, M.A., et al. (2020). Virological assessment of hospitalized patients with COVID-2019. *Nature* 581, 465–469.

Yu, R.-C., Lu, S.-H. and Liang, Y.-B. (2018), Harmful Algal Blooms in the Coastal Waters of China, in Global Ecology and Oceanography of Harmful Algal Blooms. Ecological Studies (Analysis and Synthesis), vol 232., edited by P. M. Glibert, B. E., B. M., P. G. and Z. M., Springer, Cham.

Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P. and Shen, Y. (2015). Managing nitrogen for sustainable development. *Nature* 528(7580), 51–59. https://doi.org/10.1038/nature15743

Zörb, C., Geilfus, C.-M. and Dietz, K.-J. (2018). Salinity and crop yield. *Plant Biology* 21 (Suppl. 1), 31–38, doi:10.1111/plb.12884