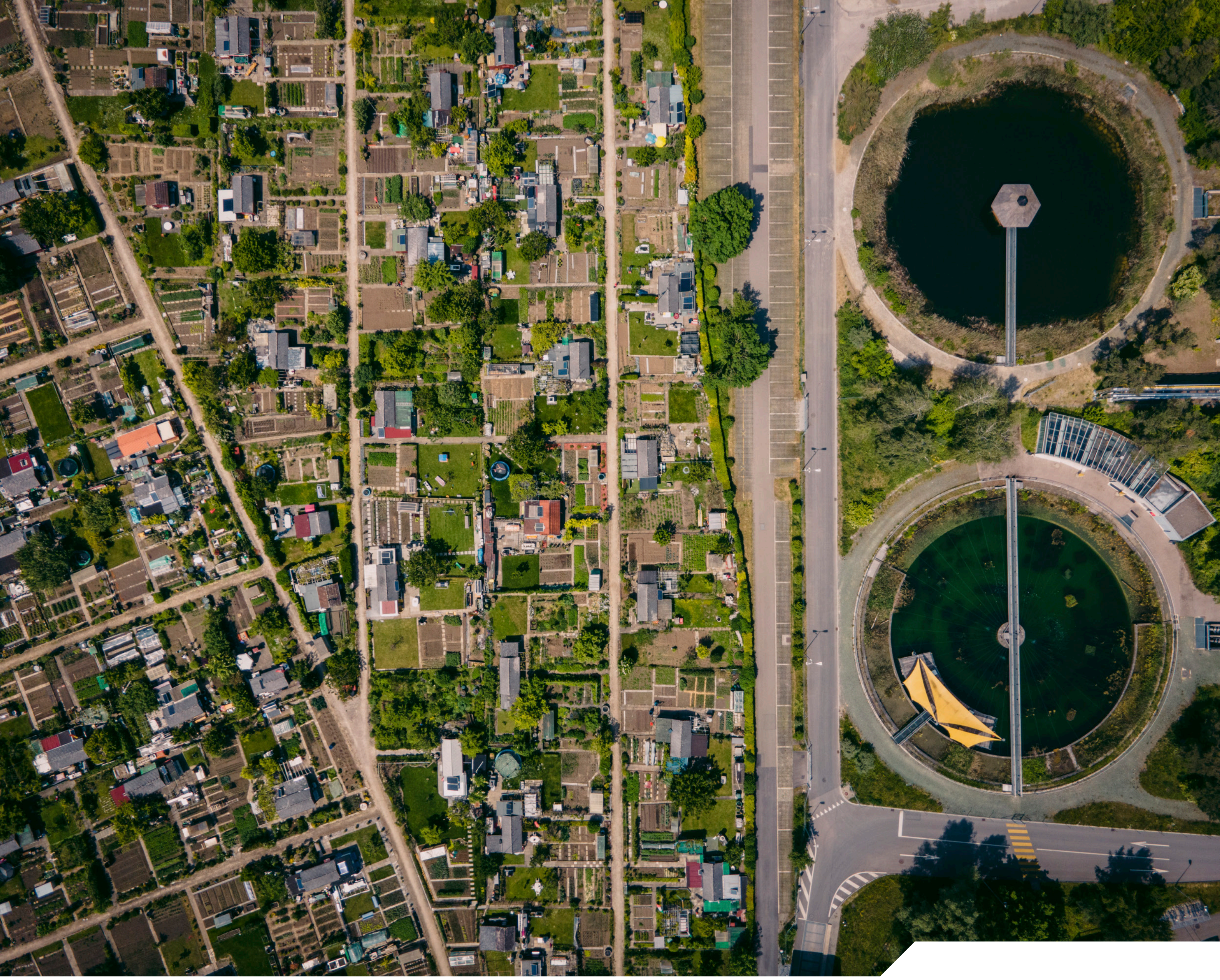

GlobeWQ

FINAL REPORT

Quality Known

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FONA Research for Sustainability

An Initiative of the Federal Ministry of Education and Research GRoW WATER AS A GLOBAL RESOURCE

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Suggested citation: GlobeWQ (2023). Quality Known-GlobeWQ Final Report. Leipzig

ISBN: 978-3-944280-72-1

Funding: The GlobeWQ project was funded by the Ministry for Education and Research, Germany under the funding code FKZ 02WGR1527.

Disclaimer: All responsibilities for the content remain with the authors.

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Summary

Water quality is an essential component of the Sustainable Development Goals (SDGs), specifically highlighted in SDG 6, which focuses on „Ensuring availability and sustainable management of water and sanitation for all.“ While the title may suggest a primary emphasis on drinking water and sanitation, SDG 6 encompasses a much broader scope, including the preservation of aquatic ecosystems and the maintenance of ambient water quality.

Maintaining and restoring good ambient water quality is essential for the integrity of aquatic ecosystems on the one hand, while on the other hand aquatic ecosystems provide services to society such as natural purification of water and the storage of freshwater in the landscape. But water quality hazards are present all over the world: 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.

In 2019 a report entitled „Quality unknown“ by the Worldbank concluded that the water quality status is largely invisible and unknown because of the lack of information on water quality. In the 2021 progress update on SDG 6.3.2, water quality could not be assessed for about three billion people due the lack of water quality data. It is obvious that there is a need to improve water quality information.

The GlobeWQ project was designed to address the global challenge of improving water quality information. It was conducted from October 1st, 2019 to December 31st, 2022 funded by the German Federal Ministry of Education and Research (BMBF).

At a global scale, GlobeWQ has further developed and applied the WorldQual water quality model, providing information on concentration of fecal coliform bacteria, biological oxygen demand and total dissolved solids for rivers worldwide. A data-driven approach was applied to estimate global nitrate concentrations.

In addition to global information products, GlobeWQ has also developed regional platforms in collaboration with local users through a co-design process. Currently, there are operational demonstration cases for the Elbe basin in central Europe, Lake Sevan in Armenia, and Lake Victoria, which is Africa‘s largest lake. The GlobeWQ platform, which is web-based, provides access to global and regional water quality information by integrating data from satellite imagery, in situ observations, and model results. It employs free and open software, established standards, and interfaces to ensure interoperability with other platforms.

Clean water is essential for human and ecosystem health, but pressures on water quality will continue into the future. Numerous studies have examined the future of water resources from a quantitative perspective, but little attention has been paid to the future of water quality. This is reflected by the fact that there were no scenarios on water quality, i.e. projections on sanitation and treatment levels and other specific information are missing in the Shared Socioeconomic Pathways (SSPs). A workstream ‘Scenario Analysis for World Water Quality Assessment’ was initiated under the umbrella of the World Water Quality Alliance and members of the GlobeWQ project team participated in and contributed to the development of a set of “light” world water quality scenarios. First model results show an increase in BOD and FC concentrations in many regions of the World in the SSP2-RCP6.0 scenario in 2050 although sanitation and treatment improved globally. The efforts made in this scenario are not sufficient to achieve SDG6.3. Further measures are required to reduce water pollution and protect human health and the environment from possible risks associated with water quality.

1. Introduction

1.1. The background: Sustainable Development Goals, the World Water Quality Alliance and the funding measure Global Resource Water – GRoW

1.1.1. Sustainable Development Goals

Water quality is anchored in the Sustainable Development Goals (SDGs). Water resources are specifically addressed in SDG 6 „Ensure availability and sustainable management of water and sanitation for all." Although the title implies a focus on drinking water and sanitation, this SDG aims at a much broader scope including aquatic ecosystems and ambient water quality. Maintaining and restoring good ambient water quality is essential for the integrity of aquatic ecosystems on the one hand, while on the other hand aquatic ecosystems provide services to society such as natural purification of water and the retention of freshwater in the landscape.

Consequently, SDG Target 6.3 aims to improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally by 2030.

Indicator 6.3.2 monitors the proportion of water bodies with good ambient water quality, as per national and/or subnational water quality standards and based on measurements of five water quality parameters that inform on the most common pressures on water quality at the global level.

Tracking the progress on SDG Target 6.3. is hampered by the lack of data that is observed (or that is reported). In the 2021 progress update on SDG 6 (UNEP GEMS/Water 2021) it has been stated that over 3 billion people are at risk because of lacking information on water quality which is particularly prevalent in the poorest countries where in turn many people still rely on unimproved drinking water sources. This highlights the need for timely, credible water quality information.

1.1.2. The World Water Quality Alliance

In December 2017 the United Nations Environment Assembly (UNEA) adopted the Resolution 3/10 "Addressing water pollution to protect and restore water-related ecosystems" (UNEP/EA.3/Res.10) calling for an assessment on global water quality. One trigger for the UNEA Resolution was the United Nations Environment Programme (UNEP) report *Snapshot of the World's Water Quality: Towards a Global Assessment* (UNEP 2016) revealing the lack of monitoring data particularly in developing countries, rendering the sole reliance on measured data impossible. The snapshot report was complemented by a UN-Water Analytical Brief *Towards a Worldwide Assessment of Freshwater Quality* (UN-Water 2016) laying out a roadmap for a worldwide assessment.

In November 2018 a workshop was held where UNEP with support from the World Meteorological Organization (WMO) initiated the process towards a World Water Quality Assessment. The goal of the World Water Quality Assessment is to review the state of freshwater quality and its potential impacts on human health, food security and ecosystem services, in conjunction with its drivers to raise awareness of the importance of water quality degradation on sustainable development and to enable countries to better assess the situation and effectively protect, maintain or restore water quality at sustainable levels. A first global display (WWQA 2021) of the water quality was delivered as a pilot for UNEA-5 in 2021.

To further engage beyond an assessment of the state of water quality but to implement information services, agendas and actions to tame water quality issues the World Water Quality Alliance (WWQA) was founded. The WWQA represents a voluntary, flexible and global, multistakeholder network that advocates the central role of freshwater quality in achieving prosperity and sustainability. It explores, monitors, analyzes and communicates water quality risks at global, regional, national and local levels with the aim of identifying solutions for the maintenance and restoration of the health and well-being of both ecosystems and humans. The WWQA serves countries throughout the lifetime of the 2030 Agenda for Sustainable Development and beyond. The GlobeWQ project is embedded as a workstream in WWQA contributing to the World Water Quality Assessment of current and future water quality. *World Water Quality Alliance (WWQA)*

1.1.3. The BMBF Funding Measure Global Resource Water – GRoW

As a contribution to the Sustainable Development Goals of the United Nations (especially SDG 6 - Water and Sanitation), the German Federal Ministry of Education and Research (BMBF) initiated the funding measure “Global Resource Water” (GRoW). In the main phase, 12 research consortia and one networking and transfer project with a total of more than 300 people from science, industry and practice conducted research and collaborated in case study areas around the world. The guiding principle of the funding measure is to link global analyzes with local approaches to solutions. An integrated perspective was chosen to look at the complex reality of sustainable water management with its cross-connections to the thematic complexes of energy, food security, ecosystems and climate change *(Global resource water – GRoW)*. The GlobeWQ project is associated with the funding measure GRoW. It directly takes up the vision of linking global and local scales.

1.2. The GlobeWQ project

The GlobeWQ Project, with its full title “GlobeWQ – Pilotprojekt Analyze- und Service-Plattform Globale Wasserqualität” (Global Water Quality Analysis and Service Platform), started on October 1st 2019 and ended on December 31st 2022 *(GlobeWQ)*. Improving water quality is one of the major societal challenges worldwide and consequently a key issue in the UN 2030 Agenda for Sustainable Development. Strategies and measures to reach this goal require coherent determination, analysis and visualisation of water quality from regional to global scales. The GlobeWQ project has delivered a prototype for such an analysis and service platform. The conceptual core of GlobeWQ lies within the complementary use of data from in situ monitoring, modeling and remote sensing (the so-called Triangulation Approach) to assess the water quality status. The GlobeWQ platform is operational within the scope of the prototype and maintained beyond the duration of the project. The ultimate goal is to continue pursuing the GlobeWQ concepts and to further develop the GlobeWQ platform to a hub for water quality information services - globally and locally.

The GlobeWQ prototype is a web-based platform that provides access to global and selected regional water quality information. This includes global and selected regional water quality information, linking water quality data from satellite imagery, in situ observations, and model results. The GlobeWQ platform is based on free and open software, established standards and interfaces. GlobeWQ data products can be made available as a WebMapService and WebFeatureService, if needed. This ensures interoperability with other platforms.

The consortium of the GlobeWQ project consists of the Helmholtz Centre for Environmental Research – UFZ, the Ruhr University Bochum (RUB) and the two SMEs EOMAP and Terrestris. Associated with the GlobeWQ project are strategic partners: the German Environment Agency (UBA), the European Environment Agency (EEA), the UN Environment Programme (UNEP) and the International Centre for Water Resources and Global Change (ICWRGC).

1.3. Is water quality really unknown?

In 2019 the World Bank published a report entitled Quality unknown: The invisible water crisis (Damania et al. 2019) suggesting that water quantity - either too much during floods or too little during droughts receives great attention because of its immediate impacts and visibility but the consequences of poor water quality remain largely unnoticed. This perception still holds but there is increasing momentum to advocate the importance of both water quantity and water quality - including the World Water Quality Alliance with its Assessment of global water quality. The GlobeWQ project has taken important steps away from “quality unknown” to “quality known”. Despite data gaps in in situ monitoring data, the GlobeWQ tackles the challenge not only by integrating additional water quality information but also by making data accessible and providing them in a format that creates usable and understandable information for various users.

1.4. Purpose of the report

This report presents the results of the GlobeWQ project. These results contribute to the World Water Quality Assessment by providing water quality information at global scale and for selected case studies.

The report demonstrates the opportunities to improve water quality information by combining data from in situ observations (sensor data and water samples that are subsequently analyzed in a laboratory), remote sensing and water quality modeling. Each of the methods has its merits; while in situ observations cover a wide range of parameters and are often perceived as most reliable, satellite imagery is available virtually everywhere, but only a limited range of water quality parameters can be derived. Models for waterflow and water quality are the only tools that can be used for future predictions and the analysis of scenarios. In the GlobeWQ project we combine information from different sources by applying the Triangulation Approach.

2. When and where is which water quality information needed

2.1.Water quality variables in the SDG context

It is simple to define what sufficient water quantity is but defining good water quality is much harder. For example, the Global Database of Freshwater Quality (GEMStat, ICWRGC 2023) hosts water quality data comprising about 500 different parameters. The GEMStat database contains data from both monitoring programmes which are typically long-term, regular, standardized measurements and surveys which are typically designed for a shorter period and may focus on specific substances or substance groups. It is hardly possible to monitor such a large number of parameters, let alone on a global scale. Thus, a parsimonious approach is needed to obtain robust insight into water quality.

At global scale, the SDG 6.3.2 indicator is implemented for tracking progress on ambient freshwater quality (SDG 6.3.). The SDG 6.3.2. indicator parameters for Level 1 (basic) monitoring only include basic physical and chemical parameters in order to ensure the feasibility of monitoring and to lower the barriers to measure the required parameters (UN Water 2018) **(Tab. 1).**

Parameter group	Parameter	River	Lake	Groundwater
Oxygen	Dissolved oxygen	x	x	
	Biological oxygen demand, chemical oxygen demand	x		
Salinity	Electrical conductivity/Total dissolved solids (TDS)	x	x	x
Nitrogen	Total oxidized nitrogen Total nitrogen, nitrite, ammoniacal			
	Nitrate			x
Phosphorus	Orthophosphate Total phosphorus	x	x	
Acidification	pH	x	x	x

Table 1: Parameter groups and parameters for the global water quality indicator SDG 6.3.2. at Level 1 (basic monitoring)

The SDG 6.3.2 Level 1 monitoring parameters are typical in situ parameters which are measured either by a probe (e.g. dissolved oxygen concentration) or by sampling and subsequent laboratory analysis. Countries can include other water quality parameters in the SDG 6.3.2. indicator reporting, the so-called Level 2 monitoring. It provides the flexibility to include information which is of national concern or relevance. Method-wise Level 2 monitoring can include remote sensing, water quality modeling and data collected by citizen science initiatives e.g. for biological indicators.

2.2. Water Quality variables covered by the GlobeWQ project

The water quality variables covered in the GlobeWQ project relate to Level 1 and Level 2 SDG 6.3.2 monitoring. As the GlobeWQ project contributes to the World Water Quality Alliance and here to the World Water Quality Assessment in particular, the water quality variables covered relate to the ambition to provide insight into water quality related risks namely to human health, food security and ecosystem health.

Biological oxygen demand

Biological oxygen demand (BOD) is a measure of how much oxygen is consumed by bacteria and other microorganisms as they break down organic matter present in the water. BOD is often used as an indicator of the degree of organic pollution in surface waters. The higher the BOD concentration the more oxygen is consumed. When more oxygen is consumed than produced, the dissolved oxygen level decreases. Wastewater from wastewater treatment plants (WWTPs) often contains organic substances that are decomposed by bacteria and other microorganisms using oxygen. BOD is therefore one of the main parameters used in the Urban Wastewater Treatment Directive for controlling wastewater discharges. High BOD values imply that dissolved oxygen concentrations decrease with impacts on aquatic life. Therefore, organic pollution is of particular concern because it threatens the functioning of inland fisheries and aquatic ecosystems in general (UNEP, 2016). As inland fisheries substantially contribute to food supply for hundreds of millions of people in poor, rural communities around the world (FAO 2003, UNEP 2016), BOD pollution has consequences for aquatic ecosystems and ambient water quality but also for food security. Improving wastewater treatment could effectively tame BOD pollution in rivers.

Dissolved oxygen

Dissolved oxygen (DO) and biological oxygen demand (BOD) are related parameters. Sufficient DO concentrations are essential for the survival of aquatic organisms. High BOD levels implying that DO is consumed can lead to a decrease in DO concentrations. Monitoring both helps assess the level of organic pollution and its potential impacts on aquatic life. Unlike BOD, DO can be automatically measured at relatively low cost with in situ sensors.

Nutrients

Life depends on nitrogen and phosphorus as essential nutrients. But too much in one place is not good either. We have far exceeded the planetary boundary for both nutrient flows (Steffen et al. 2015). This is causing changes to ecosystems and biodiversity. Overall, the excessive input of nitrogen and phosphorus into rivers accelerates eutrophication. Controlling and reducing the release of these nutrients into water bodies is crucial for mitigating eutrophication and maintaining healthy river ecosystems. This can be achieved through improved agricultural practices, wastewater treatment, and better land management strategies that aim to minimize nutrient runoff and promote sustainable nutrient cycling.

In GlobeWQ nutrient concentrations are covered globally with nitrate (NO_3^-) and total phosphorus (TP) concentrations. At Lake Victoria TP loadings are provided. Time series of concentrations and loadings provide information on the past and current state of nutrient pollution. Additional information is needed to simulate future scenarios of nutrient pollution and to understand the relationship between past inputs and the current state. Therefore, initially for Europe, the GlobeWQ project has reconstructed the Nitrogen surplus starting at the beginning of industrialization in 1860.

Salinity

All freshwaters have a geogenic background of dissolved ions as a result of weathering. Mixing with tidal waters in coastal areas introduces salt water into the rivers and increases salinity. Anthropogenic sources of salinity are typically irrigation return flows and domestic, industrial as well as mining wastewater.

Salinity pollution has multiple impacts particularly on food security and ecosystem health. High salinity limits the use of water for irrigation as the majority of food crops are not salt tolerant. Salinity pollution has wide-ranging negative impacts on aquatic ecosystems at the individual, population, community, and ecosystem levels (Cañedo-Argüelles et al. 2017). Freshwater organisms have a limited tolerance to salinity and usually cannot adapt to salinity concentrations significantly higher than natural background levels. Persistent, elevated salinity in rivers has also facilitated the spread of toxic brackish algae species in rivers in the southern USA (Roelke et al. 2010) and in the Oder River in Europe (Chapter 6.4) causing harmful algal blooms. Salinity pollution is a global problem but tends to be more severe in arid and semi-arid regions where the dilution capacity of rivers and lakes is lower and the use of irrigation higher (UNEP 2016).

Fecal coliform bacteria

The presence of fecal coliform bacteria (FC) indicates the contamination by feces from humans or animals. The presence of fecal bacteria in surface water is also an initial indication that the water may be polluted by other pathogens that can also be found in feces causing illness, including typhoid fever, viral and bacterial gastroenteritis, and hepatitis A. Hence, FC pollution poses a health risk to people getting in contact with this water by bathing or drinking. A study by Reder (2017) estimated that between 79 and 314 million people in rural areas in Latin America, Africa, and Asia come into contact with highly polluted surface water. According to WHO and other literature, it appears that the most vulnerable groups of these people are likely to be women and children because they fetch or play in water (Reder 2017). Further, about 4 billion cases of diarrhoea are caused worldwide each year by the ingestion of water contaminated with fecal matter caused by inadequate sanitation and hygiene (WHO 2014).

Optical water quality parameters

Optical water quality parameters are those that can be measured using multispectral satellites, which detect the light reflected from the earth's surface and its water bodies. Most relevant optical parameters are directly and quantitatively related to in-vivo absorption and scattering spectra of the different optical-active components. These measurements were utilized in the GlobeWQ project to provide information related to ecosystem health for lakes and rivers and include the following parameters:

Chlorophyll-a concentration: Chlorophyll-a is a major pigment of phytoplankton which occurs in almost all surface water bodies. Chlorophyll is the most common proxy to quantify the eutrophic status of water bodies, and accordingly a relevant parameter used in directives to monitor and compare the ecological status.

Harmful algal bloom indicator (HAB): This parameter is used to identify or indicate the occurrence of Cyanobacteria, which in high concentrations can have negative impacts on aquatic ecosystems, human and animal health. The parameter is based on the specific absorption of pigments such as Phytocyanin, and provided either as indicator, or quantitatively related to in-vivo-absorption of the relevant pigments, and can statistically be correlated o the various in situ measures of Cyanobacteria. Turbidity: Turbidity is a measure of water clarity, quantitatively linked to scattering of particles and accordingly related to the presence of suspended particles in the water. High turbidity levels can indicate sediment runoff, erosion, or pollution, affecting light penetration and aquatic ecosystems.

Colored Dissolved Organic Matter CDOM, also called Yellow Substance/Gelbstoff, is quantified through its specific light absorption behaviour and accordingly quantified in terms of absorption. It related to organic molecules such as humic and fulvic acids. CDOM influences water color, light availability, and can interact with other pollutants, affecting water quality and ecosystem processes.

Secchi Depth SD is one of the most established measures of water transparency, accordingly strongly related to both turbidity and absorption. It is easy to determine in situ and therefore used in water quality assessments since more than 150 years.

Urban Discharge Fraction

Aquatic ecosystems are often subject to multiple stressors that negatively impact the ecosystem health. These stressors can arise from various factors such as altered habitat conditions (e.g., changes in flow regimes and temperatures) and chemical pollution. In rivers and lakes worldwide, there is a wide range of chemicals present though often at low concentrations. Emerging evidence suggests that even these low-concentration chemical mixtures can pose risks to the ecological status of rivers and lakes. Many chemicals originate from waste water-also treated waste water. Monitoring this large range of chemicals is hardly possible in a consistent way. In GlobeWQ we used the urban discharge fraction - defined as the local fraction of treated waste (Büttner et al. 2022) as a proxy indicator for water quality driven by the inputs of treated waste water. It has been shown that an urban discharge fraction of 6.5% is a critical ecological threshold that explains why many rivers in Europe fail to reach good ecological status. This indicator has been applied to Europe.

3. State of information on water quality and the triangulation concept

3.1. In situ data

The key information source for water quality is data from in situ observations which comprise measurements from sensors such as temperature or electrical conductivity (EC) sensors and data generated from water samples and subsequent laboratory analysis.

Most accessible in situ-data stems from regional and national monitoring programmes which have been established based on environmental laws and pollution control programmes. Because water quality is critical for many domains of society there are multiple partially redundant regulations and monitoring obligations (e.g. EU WFD 2000, EU BWD 2006). Water quality monitoring programmes are driven by the legal framework and by the specific purpose they address which results in heterogeneous data with regard to parameters, methods, spatial and temporal density and consistency.

Environmental laws have been established in 176 countries and 164 countries have created cabinet-level bodies responsible for environmental protection (UNEP 2019).

Implementation and enforcement of environmental laws including those on water quality often fall short in low gross domestic product (GDP) countries because of underfunded institutions. As a consequence a large data gap exists between high and low GDP countries. Despite many data gaps there is an increasing amount of in situ data available globally.

The GEMStat database

The Global Database of Freshwater Quality GEMStat is organised by the International Centre for Water Resources and Global Change (ICWRGC) in Koblenz, Germany, and it offers inland water quality data as part of the United Nations Environment Programme's GEMS/Water program (UNEP). GEMS/Water was founded as a global network for water quality monitoring in 1978. The database collects water quality data from monitoring networks around the world, with voluntary submissions from countries and organizations. The database contains over 15 million entries from approximately 130,000 stations in over 80 countries, with 500 different parameters (Fig. 1 and Fig. 2).

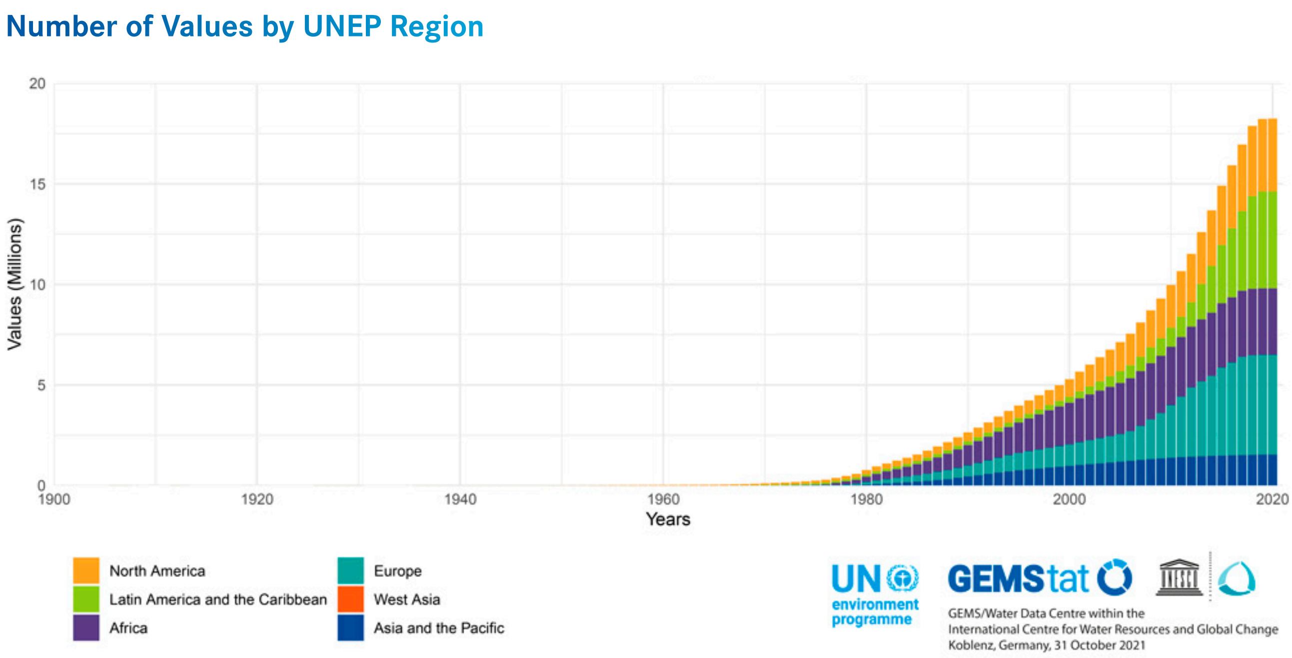


Figure 3.1: Temporal patterns of the amount of values stored in the GEMstat database.
Source (https://gemstat.org/about/data-availability)

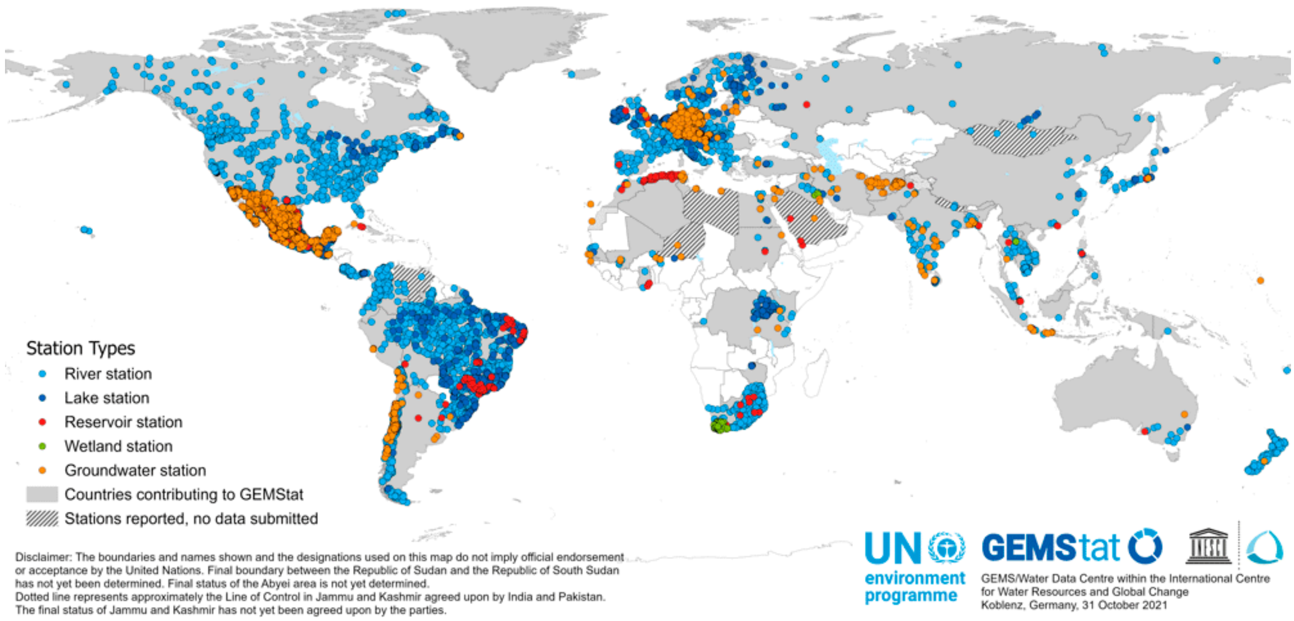


Figure 3.2: Spatial coverage of the GEMStat database. Source (*https://gemstat.org/about/data-availability*)

Further global data sets on water quality

The GEMStat database is an extremely valuable resource for in situ data on water quality. However, not all countries contribute data or contribute only a small fraction of available data. Thus, for achieving an improved spatial coverage, researchers compiled data sets on water quality which integrate different data sources. These data can then be used to calibrate models. Examples of such integrated data sets are the GRQA: Global River Water Quality Archive (Virro et al. 2021) or the global salinity dataset of Thorslund and van Vliet (2020). These data sets have the disadvantage that they are typically compiled only once and thus lose their topicality over time but they provide probably the best available spatial coverage for the time period they cover.

The GLObal RIver CHemistry (GLORICH) database contains hydrochemical data from over 1.27 million observations and over 18,000 sampling locations around the world. The samples come from a variety of environmental monitoring programs as well as scientific literature (Hartmann et al. 2014). However, after sorting the data and extracting the longest time series, the data selected ranged from 1972 to 2010, and was distributed in Germany, the UK, the USA, Norway, Brazil, and France.

National and regional databases and data sets

In addition to global databases and data sets, there exist numerous national and regional datasets and databases. For example, the Water Quality Portal (WQP) *(Water quality portal 2023)* in the US, is one of the world‘s largest standardized water quality databases. It is created by the US Geological Survey (USGS), the US Environmental Protection Agency (EPA), and the National Water Quality Monitoring Council, (Water Quality Data Home). In Europe the WISE data base *(European Environment Agency 2023)* provides data relevant for the European Water Framework Directive. Data from water quality sensors becomes increasingly available and if made available online allows near-real time insight into water quality. Examples are the UNDINE in Germany *(BAFG 2023)* which provides online water data for both discharge and water quality. The examples are far from being complete. Many countries increasingly provide water quality information. For example, from China current water quality information is provided in near-real time for a large amount of river stations for the last 4 hours. *(CNEMC2023)*

Opportunities and limitations

In situ data is the “gold standard” for water quality data and water sampling the most trusted method. Chemical analysis of water samples provides insight in a wide range of water quality variables. In situ data also serves as “ground truthing “ for remote sensing and for calibration, validation or training of models.

Often there is a time lag of at least several months between the sampling and the availability of data in databases. In databases such as GEMstat where data of various providers are aggregated the time lags can be even longer. To raise awareness and to enable informed decisions there is a need for timely data which can be achieved for example if data providers would make data available not only for manual download but also via web services so that updates can be more or less automatically taken up by data aggregators and users.

In situ water quality sensors also provide the opportunity for timely water quality information as they measure water quality variables directly without the need for laboratory analysis. When these sensors are coupled to a web service they allow for instantaneous access to water quality data. However, water quality sensors can cover only a limited range of water quality parameters.

Currently, the greatest limitation of in situ data from a global perspective is limited spatial coverage. In addition, available data are often discontinuous or outdated. While limitations for a World Water Quality Assessment often relate to the spatial gaps in in situ data, the timeliness and temporal continuity of data are equally important

3.2. Remote sensing data

Satellite remote sensing has opened unprecedented opportunities for environmental observation for weather, air pollution, land use change or data on topography or bathymetry. With the launch of the Landsat missions in the 1970s, algorithms have been developed to extract water quality information (Klemas et al. 1971, Maul and Gordon 1975). Since available satellites have evolved towards higher spatial resolution (e.g., Sentinel-2, Landsat 8/9) and higher overpass frequencies (e.g., Sentinel-3, Planet Doves) and provide opportunities for water quality observation with high spatial and temporal resolution accompanied with a large spatial coverage.

With remote sensing of optically-active water quality parameters, most commonly turbidity (TUR), total suspended solids (TSS), Secchi disk depth (SDD), coloured dissolved organic matter (cDOM), Chlorophyll a (Chl-a), Cyanobacteria indicators (HAB) and trophic state index (TSI) can be observed. Surface water temperature can also be measured. The range of water quality parameters is restricted to those that modify the optical properties of water such as turbidity and chlorophyll content. Other water quality parameters can be estimated by using optically active water constituents as proxy parameters for the parameters of interest.

Compared to water sampling and laboratory analysis, the range of water quality parameters which can be detected is relatively limited. At the same time, the measurement via satellite is more cost-efficient compared to traditional sampling methods which usually require personnel effort in the field and may also include extensive analysis work in a laboratory.

The spatial extent of a water body has been one of the limiting factors of the observation via remote sensing methods. With increasing spatial resolution, smaller water bodies and rivers can increasingly be observed. The following table shows an overview of the most common satellite systems which are used in the remote sensing of water bodies.

Satellite system	Temporal resolution	Spatial resolution	Notes
Planet SuperDoves	Up to daily	3 meter	Commercially available
Sentinel-3	Up to daily	300 meters	Freely available
Sentinel-2	5 days	10 meters	Freely available
Landsat 8/9	8 days	30 meters	Freely available
Landsat 5/7	16 days	30 meters	Finished satellite missions, but data can be used from archive since 1984
Modis Aqua / Terra	Up tp daily	1000 meters	Can be used for large scale, high temporal coverage observations

Satellite system	Temporal resolution	Spatial resolution	Notes
WorldView-2 WorldView-3	Upon request	2 meters	Commercially available, can be tasked over area of interest in a certain time window
SkySat	Up to daily	0.5 meters	Commercially available, can be tasked over area of interest in a certain time window. Mainly used for visual/ true colour observations due to low number of spectral bands (4)
VIIRS (aboard NOAA-20/21 SUOMI-NPP))	Up daily	750 meters	Can be used for large scale, high temporal scale observations
EnMap	27 days	30 meters	Hyperspectral satellite (228 spectral bands), high potential for specialized vegetation/algae mapping on water bodies
PRISMA	29 days	30 meters	Hyperspectral satellite (237 spectral bands), high potential for specialized vegetation/algae mapping on water bodies

Table 3.1: Overview on the available satellite systems.

Data from the SuperDove satellites was employed in the scope of the observation and analysis of the Oder incident in 2022 in combination with data from the Sentinel-2 satellites, and proved to be useful due to the high temporal coverage, as well as the additional spectral channels in the visible spectrum.

Currently, there are a few water quality data products and information services based on satellite data available at global scale.

- UNESCO world water quality portal – Archive; Rivers, Lakes Coastal, Global. *http://sdg6-hydrology-tep.eu*

- Copernicus Global Land Service (CGLS) – Lake Surface Water Temperature – Operational, Lakes, Global. *https://land.copernicus.eu/global/products/lwq*

For Europe and Africa there is the
- Copernicus Global Land Service (CGLS) – Lake Water Quality – Operatitional, Lakes, Global. *https://land.copernicus.eu/global/products/lwq*

The GlobeWQ Platform provides operational (regularly updated) remote sensing- based water quality information for Lake Victoria (see Chapter 6.3) and parts of the Elbe River in Germany. For Lake Victoria, there is water quality data from Landsat 8 and Sentinel-2 available (archive), in the scope of the operational monitoring, the most recent data from Sentinel-3 is processed and uploaded to the GlobeWQ Platform. Additionally, a monthly median is generated and uploaded to the platform, which shows the trends on the lake on both the spatial as well as temporal scale. For the Elbe River monitoring, data from the Sentinel-2 satellites is processed and uploaded to the Platform.

Limitations and Opportunities

Satellite remote sensing provides ample opportunities for improving global water quality information availability. Remote sensing data is practically available globally. The raw data of major satellites is freely available such as those from Copernicus and NASA missions (Sentinel-2, Sentinel-3, Landsat 8, Landsat 9). Satellite derived water quality data is independent from local infrastructure and resources. When uniform methods are used to evaluate the raw data, the results are free from uncertainties that can arise from the use of different methods, as is the case with in situ data. As the processing of raw data (from the raw image to water quality data products) is fast, satellite water quality estimates can be made available in near real time. Processing of raw image data is easily scalable if the derivation of water quality properties is executed automatically. In the scope of the GlobeWQ project, the water quality processing and upload is conducted automatically.

Cloud cover usually prevents the use of optical satellite data which makes observation frequencies less predictable than those from sampling or in situ sensors. The range of water quality parameters is restricted to those that modify the optical properties of water such as turbidity and chlorophyll content. Other water quality parameters can be estimated by using optically active water constituents as proxy parameters for the parameters of interest. Correlations between these parameters have been analyzed in previous studies (Karakaya et al. 2011; Guo et al. 2021; Shang et al. 2021). Among those parameters are Dissolved oxygen, Biochemical oxygen demand, Chemical oxygen demand, Total phosphorus, pH, Total nitrogen, Ammonia, Nitrate and Dissolved phosphorus.

The spatial resolution of the satellite data determines the minimum size of the water body which can be covered. The best practice recommendation for the minimum extent of a water body is three times the spatial resolution of the satellite system. Trust into satellite derived water quality products has been seen to be lower than the trust into in situ data. However, deriving water quality from satellite imagery must be treated as its own methodology, which can and should be compared to in situ sampling, the different methodological backgrounds must be considered nonetheless.

This calls for a product quality assurance standard which ensures inter comparability and improving quality. Despite its potential global availability, remote sensing data has not been integrated into models at larger spatial scales. Locally predominantly chlorophyll data is used for algal bloom early warning in lakes and reservoirs (Bresciani et al. 2019).

3.3. Water quality modeling

Data from in situ monitoring and remote sensing provides information on the state of water quality and if done consistently of its trajectory over time. Water quality models are the only tools that can provide predictions of future states of water quality. Beyond prediction, models can be applied in scenario analyzes and results in turn can be used to assess the effects of actions and management decisions. Models, either mechanistic, conceptual or data driven, integrate different kinds of data from point measurements to area-based remote sensing observations and national statistical data on drivers of water quality such as, land use, population density or sanitation practices and waste water treatment infrastructure to derive spatially and temporally explicit and consistent estimates of the selected water quality parameters over time. Models can be a useful contribution for understanding how the drivers of water quality and the catchment characteristics interact that control the transport of pollutants including time lags and legacy effects.

There are a variety of water quality models and modeling approaches, ranging from data driven regression and artificial intelligence to conceptual models and process based mechanistic models. The water quality models cover a wide spatio-temporal spectrum, ranging from river section to catchment to global scale in temporal resolution of daily, monthly and annual values.The application of a particular model and the scale to be considered depend on the complexity of the problem as well as the spatial and temporal perspective. The number of large-scale and global water quality models has increased in recent years. Due to limited data availability and different interests, these models focus so far on the simulation of water temperature and selected substances, such as nutrients, salinity, bacteria, BOD, microplastics and chemicals (Strokal et al. 2019, van Vliet et al. 2019)

WorldQual

In GlobeWQ, the focus for global water quality models was to further develop WorldQual, a large-scale water quality sub-model of the WaterGAP3 modeling framework. The global integrated water model WaterGAP3 consists of two main components: (i) a water balance model to simulate the characteristic macro-scale behaviour of the terrestrial water cycle in order to estimate water availability (Schneider et al. 2011, Verzano 2012); and (ii) a water use model to estimate water withdrawals and consumptive water uses for agriculture, industry and domestic purposes (aus der Beek et al. 2010, Flörke et al. 2013, Flörke et al. 2018).

Limitations and Opportunities

Water quality models are the only tools that allow for predictions of future states of water quality and the analysis of scenarios. Scenarios important to assess the potential impacts of environmental changes such as land. Models are integrators of different types of data and generate spatially and temporally explicit and consistent estimates of the selected water quality parameters over time.

As model results can only be as good as the input data, the accuracy of modelled water quality deteriorates if input data is missing. Additionally if timely input data is not available model results will be equally dated or the recent state of water quality will already be a modelled prediction. Currently, water quality models rely on in situ data for parameterization and calibration. The use of remote sensing data to inform water quality models has great potential but has not been exploited to date.

During the co-design process of the GlobeWQ case studies it turned out that model results have lower acceptance than in situ data. In the future this can be addressed by providing and communicating the model results in combination with the model uncertainty. Additionally trust can be built by generating ensemble model runs and combining their results for robustness and uncertainty quantification.

Unlike weather models and hydrological models for flood forecasting, water quality models are currently rarely operational, meaning that new data is not directly included on a regular basis and model outputs are updated accordingly. However, particularly for short-term water quality issues such as accidental spills and algal blooms, operational water quality models provide opportunities for taming negative impacts by providing early warning.

3.4. The triangulation approach

Each of the three elements - in situ data, data from remote sensing and results from water quality modeling has its merits but also its limitations. Most limitations arise from spatial and temporal coverage which are key challenges of all three elements. Sampling depends on adequate spatial coverage by monitoring networks and a sampling frequency that reflects the variability of the hydrological system (Jordan & Cassidy 2011). On the other hand, the results derived from remote sensing images and modeling also depend on good in situ measurement data. The transfer of knowledge from data-rich regions supports the application of remote sensing and modeling in regions where measured data are lacking. Therefore, and to overcome the limitations and to improve water quality information in terms of spatial coverage, a combination of all three elements, i.e. timely information and spatial and temporal coherence, is a promising approach for generating water quality information.

In the GlobeWQ project and the Word Water Quality Alliance, the concept of combining in situ data, data from remote sensing and results from water quality modeling to improve water quality information and to tame data gaps in space and time has been termed the triangulation approach (Figure 3.3 (the triangle). Figure 3.4 provides an overview on the opportunities and limitations of each of the three corners of the water quality triangle in situ data.

The GlobeWQ project applies the water quality triangulation for several use cases, for example Lake Victoria (Chapter 6.3), where satellite remote sensing is applied to provide timely water quality information for the lake surface, particularly on Chlorophyll-a to detect algal blooms which are harmful to aquatic life. Results from WorldQual provide information on the nutrient loadings which are a key driver of harmful algal blooms. In situ data, from both the lake and its tributaries is integrated from the GEMStat database.

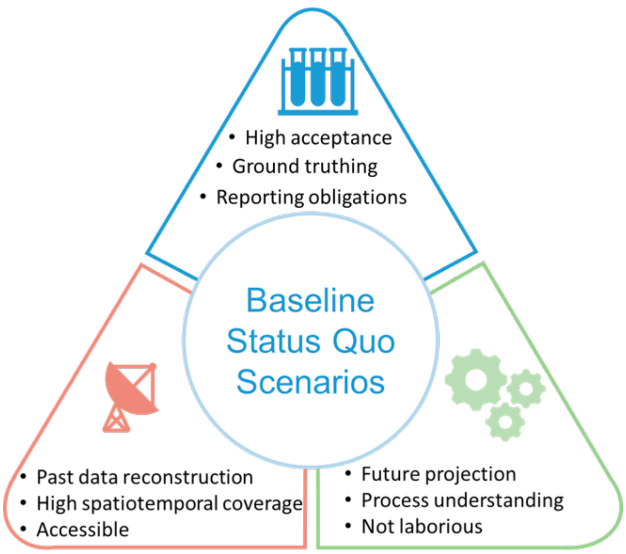


Figure 3.3: Concept of the Triangulation Approach.

Figure 3.4: Spatial and temporal characteristics of in situ, remote sensing and modeling tools (red=low, yellow=medium, green=good).

4. The big picture – global scale trends, hotspots and future scenarios of water quality

Although water quality is mostly monitored and assessed locally or regionally, it is a problem of global concern. Surface and groundwater resources of good water quality are fundamental to human and ecosystem health but are being challenged as economic growth, demographics and climate change lead to widespread and severe degradation in many regions of the World. Thus, water quality must ultimately be incorporated into large- and global-scale water resources assessments and SDGs research, e.g. to identify remote impacts or support countries where no monitoring infrastructure is in place. To gain a broad understanding of water quality trends, comprehensive global assessments are required to identify areas of concern (i.e., hotspots), provide a basis for impact studies, and enable future projections under global change scenarios to develop solution strategies and support decision making. Results from global-scale water quality modeling provide insights into in-stream pollution and the contribution of loads from different sectors along various pathways, i.e. providing the big picture of both the current and future status and trends.

4.1. Drivers of water quality

The state of ambient water quality is always linked to human activity. Insufficient ambient water quality is caused by inputs such as untreated municipal wastewater (i.e., point sources). In addition to point sources, diffuse sources such as inputs originating from the use of fertilizers and pesticides on agricultural land have impacts on water quality. Drivers that impact water quality are connected and the presence of humans is central to all of them (Vörösmarty et al. 2010). Population development and sanitation as well as agricultural land use determine to great extent the intensity of anthropogenic-driven pollution of surface waters.

4.1.1. Sanitation and waste water treatment

One of the main reasons for poor ambient water quality is the discharge of untreated wastewater into surface waters. Consequently, to track the progress towards achieving good ambient water quality, the SDG indicator 6.3.1 monitors the proportion of total, industrial and domestic wastewater flows safely treated. The fraction of waste water safely treated highly depends on the countries' income level. In high-income countries about 70% of the municipal and industrial wastewater is treated. In contrast, in low-income countries only 8% of wastewater is treated (WWAP 2017).

Figure 4.1 exemplarily shows this development for sanitation in Africa by comparing the percentage of population served by sewered and non-sewered facilities in the years 2010 and 2017. In general, sewerage coverage in sub-Saharan Africa remains very low without significant improvements in the 8-year time period with the exception of Nigeria and Somalia. The levels of primary, secondary, and tertiary treatment indicated by the pie diagrams in the left column of Figure 4.1 do not show a positive development. Even South Africa experienced a deterioration in wastewater treatment. Northern Africa keeps the highest sewer connections and treatment rates which have been slightly improved in Morocco and Egypt.

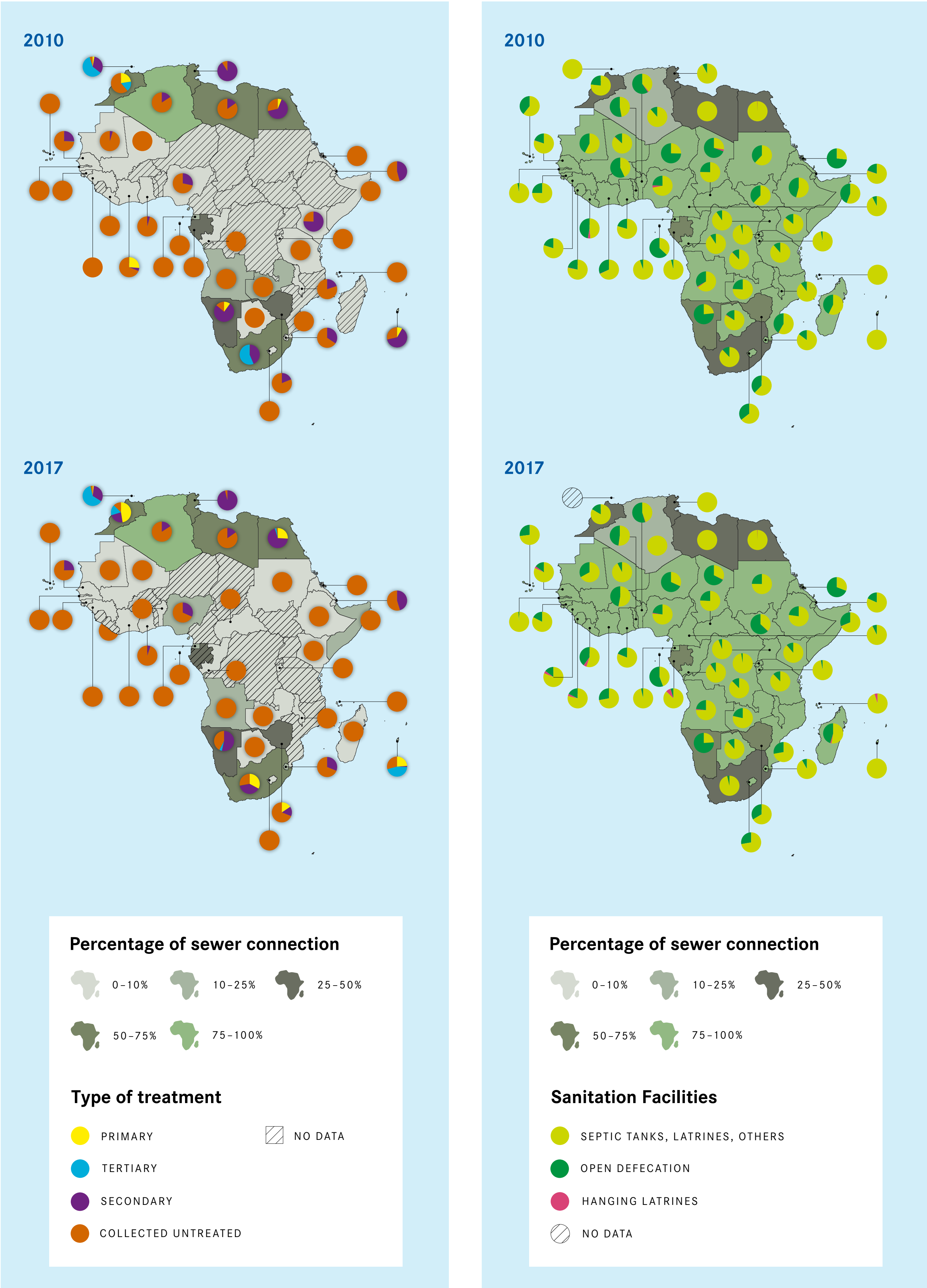


Figure 4.1: Percentage of population served with sewered (left) and non-sewered (right) sanitation practices in Africa.

For other continents, Table 4.1, shows the general trends. It indicates that sewer coverage has been expanding together with secondary and tertiary treatment levels. This trend in turn also explains the shrinking of the first level of treatment. In Asia, onsite sanitation is still relevant but it's becoming less widespread while open defecation has experienced a considerable decline.

Continent (comparison 2010-2017)	Sewerage connections				Onsite/No sanitation	
	Connection rate	Prim. treat.	Sec. treat.	Ter. treat.	Connection rate	Open. Def
Asia	Y	N	Y	Y	N	N
Africa	S	S	S	S	S	N
North America	Y	N	Y	Y	–	–
Latin America	S			Y	–	–
Europe	Y			Y	–	–
Oceania	S	N	N	Y	–	–

Table 4.1: General trends in sanitation infrastructure per continent. Y indicates improvement, N deterioration, S no change. Onsite/No sanitation infrastructure is only shown for Asia where it's still relevant.

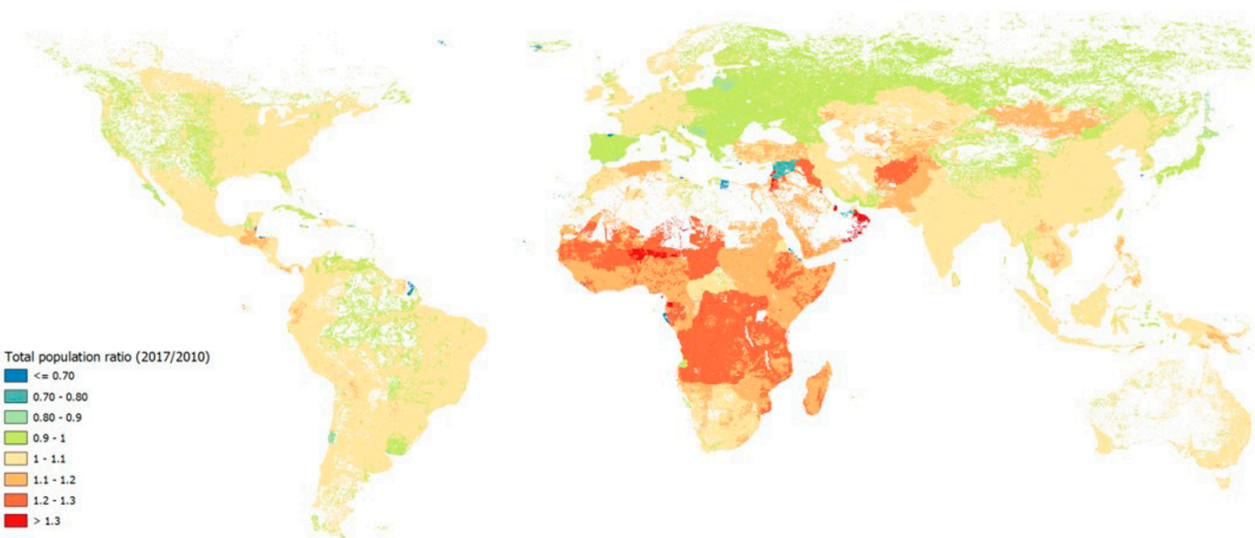


Figure 4.2: Total population ratio between 2017 and 2010. Red-coloured areas indicate a relative increase in the period 2010-2017. (Source: HYDE 3.2.1 and UN population statistics)

Figure 4.2 depicts the ratio between the total population in 2017 compared to 2010. The strongest increase can be seen in Sub-Saharan Africa and in the Middle East especially around Syria which features a significant decline in population. Also noteworthy is the population growth in Southern- and -East Asia and the Americas.

Trend in cropland

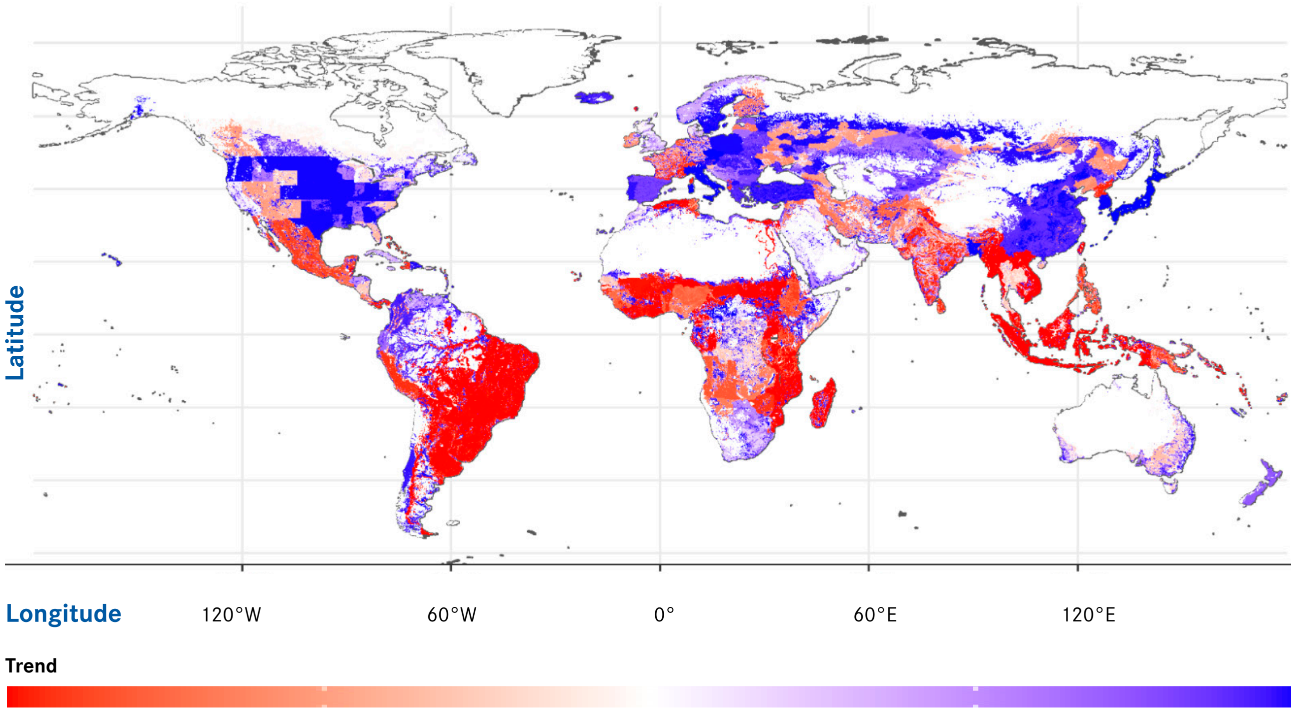


Figure 4.3: Trend in cropland area between 1990 and 2015 (Data source Source: HYDE 3.2.1).

4.1.2 Agriculture

Agriculture which includes crop farming and livestock is a major source of global water pollution by nutrients (Mateo-Sagasta et al. 2017). Nutrient pollution mainly originates from the use of inorganic fertilizers and from manure resulting from livestock production. The global inorganic fertilizer use which includes nitrogen, phosphorus and potassium increased by 46% between 1990 and 2019, from 137.8 to 200.6 million tonnes (Mt). (FAO 2022). Agricultural use of nitrogen was 77.1 Mt in 1990, rising to 113.3 Mt in 2020, or 56% of total inorganic fertilizers use For phosphorus, there was an increase from 36.0 Mt in 1990 to 48.1 Mt in 2020 , and for potassium from 24.7 Mt in 1990 to 39.2 Mt in 2020. It is important to note that the global per capita use of fertilizers remained practically constant with 25.9 kg per capita in 1990 and 25.7 kg per capita in 2020. Use per capita is the highest in Oceania (83 kg/capita), followed by the Americas (54 kg/capita), Europe (33 kg/capita), Asia (24 kg/capita) and Africa (5 kg/capita) (FAO. 2022).

The total mass of nitrogen generated by livestock manure increased between 1990 and 2018 by 23% to 125 Mt/year (FAO 2020). In 2018 the total amount of livestock manure deposited on agricultural land was 116 Mt. Between 1990-2018 the N inputs from manure applied to soils did not increase substantially (4%). In 2018, Asia had the largest share of livestock manure, followed by the Americas, while Africa had the fastest growth since 1990, nearly doubling manure production (FAO 2020).

Intensive agriculture is the main cause of nutrient pollution, both in high-income countries and many emerging economies. In many regions of the world, cropland area has substantially expanded since 1990 (Fig. 4.3). The use of fertilizers has increased in tandem with population growth. Unless there are significant changes in agricultural practices and dietary habits, agriculture will continue to be a significant and potentially expanding source of pollution in the future.

4.2. Global trends and hotspots of water quality

4.2.1. Fecal coliform bacteria

One aspect of water pollution is the microbial contamination of surface waters. Here fecal coliform bacteria are a common indicator for microbial pollution (NRC 2004). Even though the presence of fecal coliform bacteria (FC) is a sign of fecal pollution, the absence of FC does not guarantee that the water is free of any pathogens because not all pathogens have the same characteristics as FC (NRC 2004, Wu 2011). Global fecal pollution is of major concern, for example the WHO and UNICEF Joint Monitoring Programme for Water Supply and Sanitation (JMP) state that 3.6 billion people still lack access to safely managed sanitation in their home (Global WASH Fast Facts). Globally, 44% of the wastewater from households is not safely treated, i.e. treated by secondary or higher processes (UN-Water 2021).

4.2.1.1. Health risks from fecal coliform bacteria pollution

FC pollution in rivers indicates the contamination by feces from humans or animals. FC pollution poses a health risk to people getting in contact with this water by bathing or drinking. A study by Reder (2017) estimated that between 79 and 314 million people in rural areas in Latin America, Africa, and Asia come into contact with highly polluted surface water. According to WHO and other literature, it appears that the most vulnerable groups of these people are likely to be women and children because they fetch or play in water (Reder 2017). Further, about 4 billion cases of diarrhoea are caused worldwide each year by the ingestion of water contaminated with fecal matter caused by inadequate sanitation and hygiene (WHO 2014). The presence of fecal bacteria in surface water is an initial indication that the water may be polluted by other pathogens that can also be found in feces causing illness, including typhoid fever, viral and bacterial gastroenteritis, and hepatitis A.

4.2.1.2. How is fecal coliform bacteria pollution assessed

FC concentrations are usually measured in cfu / 100 ml, where cfu stands for colony forming units and is an estimate of the number of bacteria in a sample. To assess health risks, concentrations of FC are divided into 3 classes: low, moderate, and severe (see Table 4.2). In this section, the focus is on the identification of FC pollution hotspots. Hotspots are river reaches characterized by prolonged severe pollution. More specifically, river reaches that have been showing at least 30 months of severe FC pollution during a five-year period are defined as hotspots. Two five-year periods (1990-1994 and 2011-2015) were considered. The analysis of global FC pollution is based on the results of the global water quality model WorldQual.

Water pollution class	FC concentration (cfu/100 ml)	Description
Low pollution	$x \leq 200$	Generally suitable for contact (including, e.g. swimming and bathing)
Moderate pollution	$200 < x \leq 1,000$	Only suitable for contact during irrigation and fishing activities, but not for other contact
Severe pollution	$x > 1,000$	Generally unsuitable for contact

Table 4.2: Overview of FC concentration classes considered in this study. (Source: UNEP 2016)

4.2.1.3 Global and continental trends in fecal coliform bacteria loadings

FC loadings are calculated by breaking down the contributions from different point and diffuse sources (Williams et al. 2012). Figure 4.4 shows the global aggregated FC loadings in 2017 estimated with WorldQual.

Global hotspots are Southern- and South-East Asia, some areas in the Middle East including Syria and Yemen; surroundings of Lake Victoria, Nigeria, Ethiopia, and the Nile's delta in Africa; the Andean region and the Brazilian coast in South America; and areas of Mexico and Guatemala in Central America. In North America and Europe loadings hotspots are scattered and localized in the largest metropolitan areas. Sources of FC are almost exclusively related to inputs of human feces which is related to a lack of sewage collection and an appropriate level of wastewater treatment. In particular the increase of sewer connections without adequate treatment, as a result of population growth in urban areas, but without adequate treatment, combined with population growth is a key driver of the occurrence of emerging hotspots.

Between 1990 and 2017 the global FC loading has increased by 77% . Despite improvements in sanitation the fractions of the different sectors contributing the loadings have remained broadly constant at global scale. Different regions of the world are not following the same trajectory, and the continents are progressing differently with regards to their FC loadings. Figure 4.4 provides an overview of the trends of total and sectorial FC loadings in the different continents. In Asia the main contributor is the domestic sector by the sewered (point source) and non-sewered (diffusive source) sanitation categories. These loadings are calculated based on per-capita emissions, the population and manufacturing industries connected to specific sanitation infrastructure, factors accounting for effective treatment levels, and the loadings washed-off from agricultural land and urban surfaces (Reder et al. 2015, UNEP 2016). In Asia, the loadings pressure is essentially driven by population and better sewerage coverage especially in urban areas. However, it seems that proper treatment is not growing on a par with population growth. The loadings' growing rate reached a maximum in the period 2005-2010 and it has experienced a slowdown in the rising trend afterwards. In Europe and Africa, FC loadings are one order of magnitude lower compared to Asia. In Africa, FC loadings have been increasing almost steadily for both the sewered and the non-sewered contributions. On the other hand, Europe exhibits a clear negative trend mostly driven by improved and more efficient wastewater treatment.

Results for North and South America also indicate that the domestic sewered sector is the dominant source of FC loadings. These loadings level off after 2010, reaching a value of around 105x10^{19} cfu in South America and 75x10^{19} cfu in North America. In Australia, most FC loadings come also from the domestic sewered sector but contributions from manure (livestock) and urban surface runoff are also considerable.

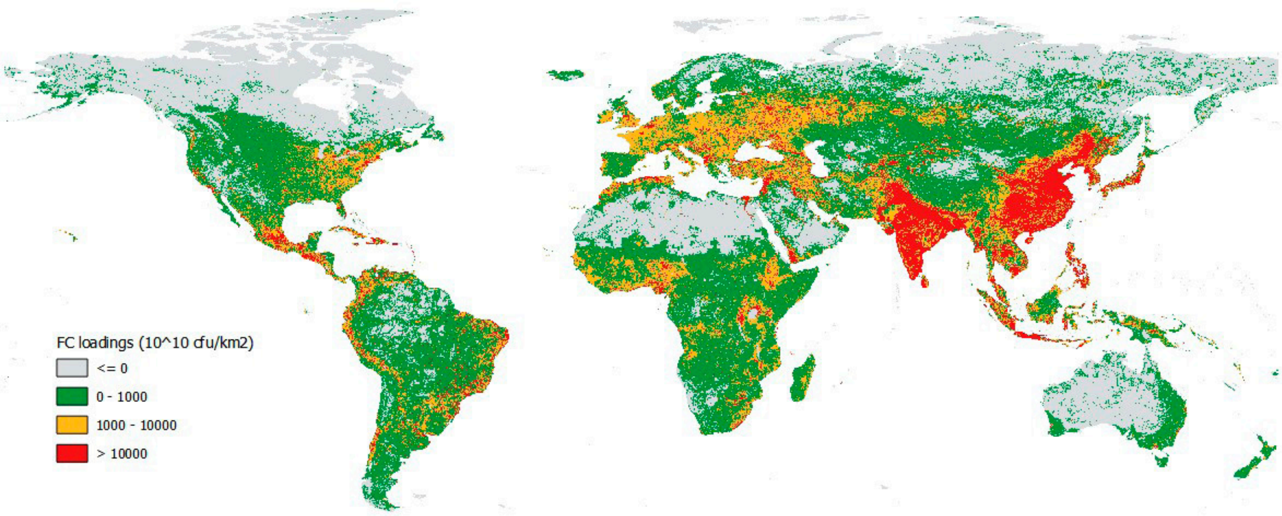
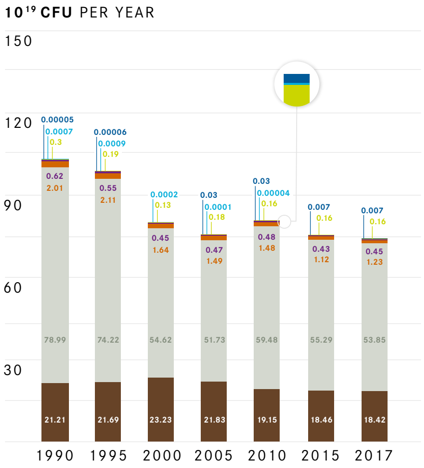


Figure 4.4: Total FC loadings on grid-scale level in 2017. Units: 10^{10} cfu/km².

Europe



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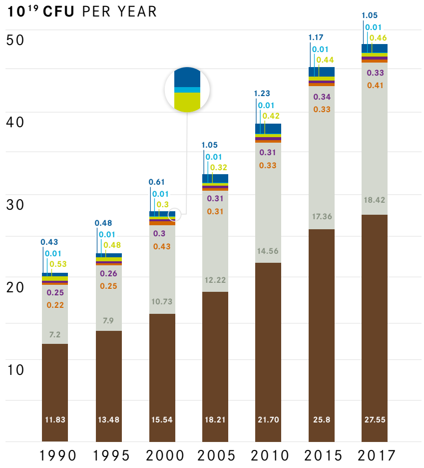
Africa



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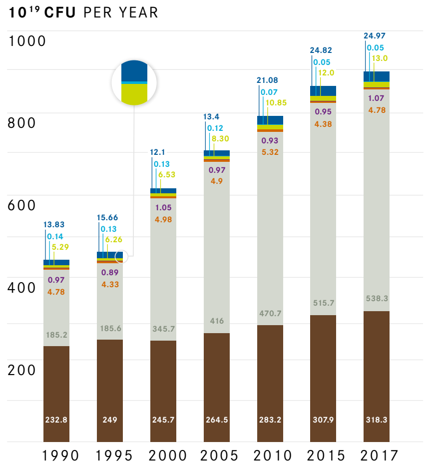
Asia



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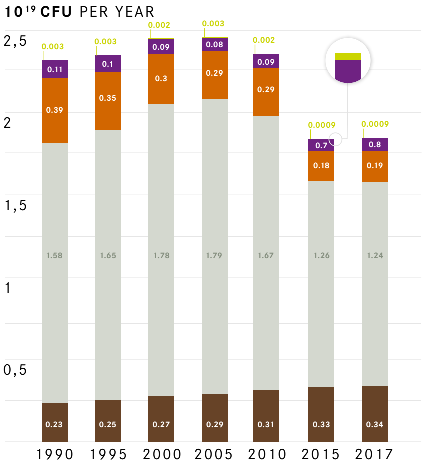
Australia



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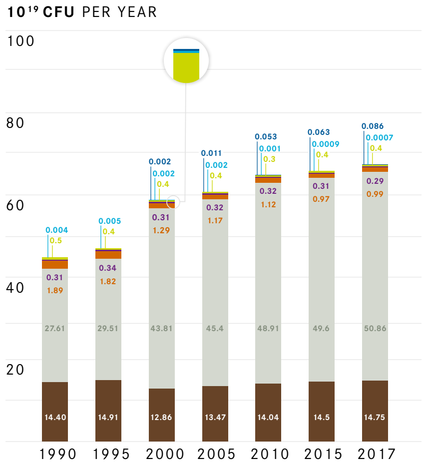
North America



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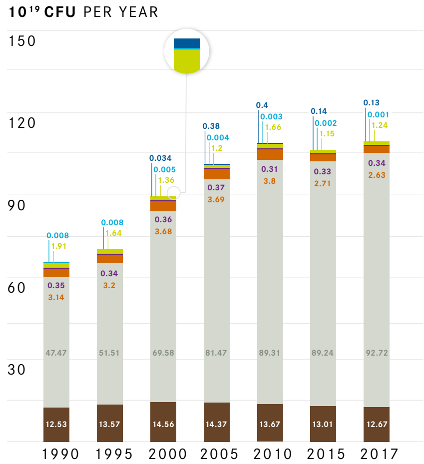
South America



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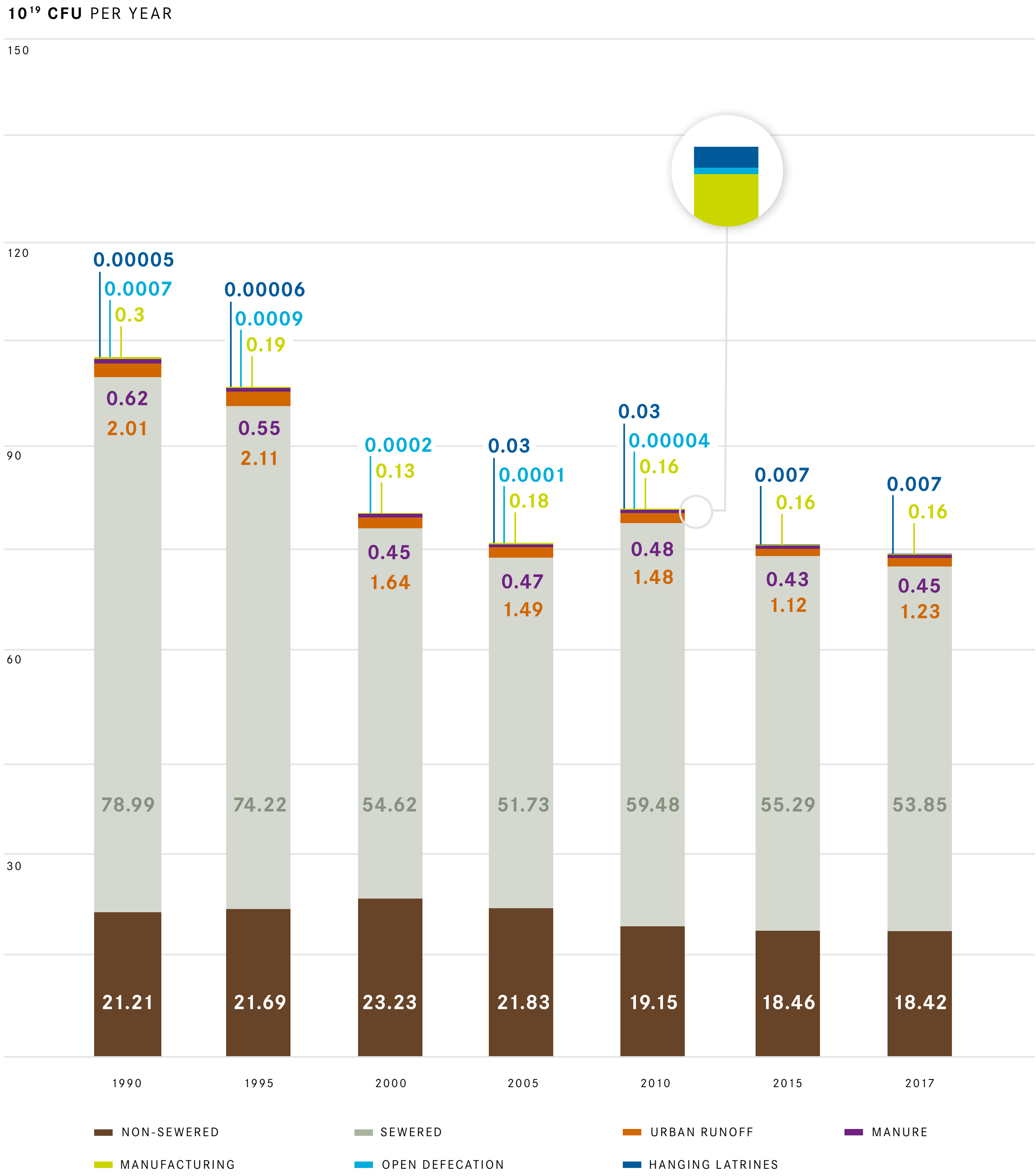
NON-SEWERED SEWERED URBAN RUNOFF MANURE
MANUFACTURING OPEN DEFECATION HANGING LATRINES

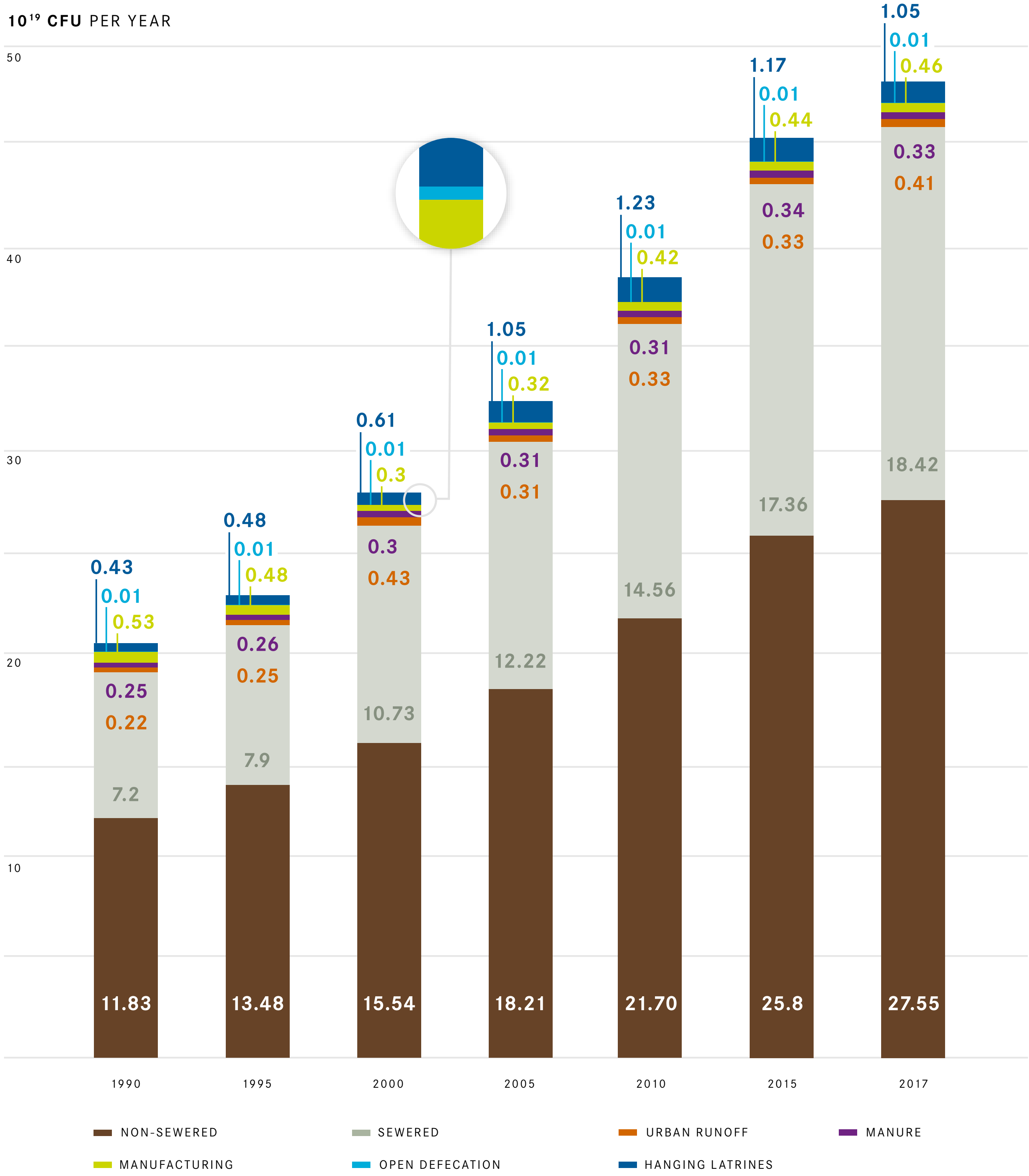
Figure 4.5: Trends of FC loadings according to different point and diffuse sources as estimated for different continents between 1990 and 2017.

Europe



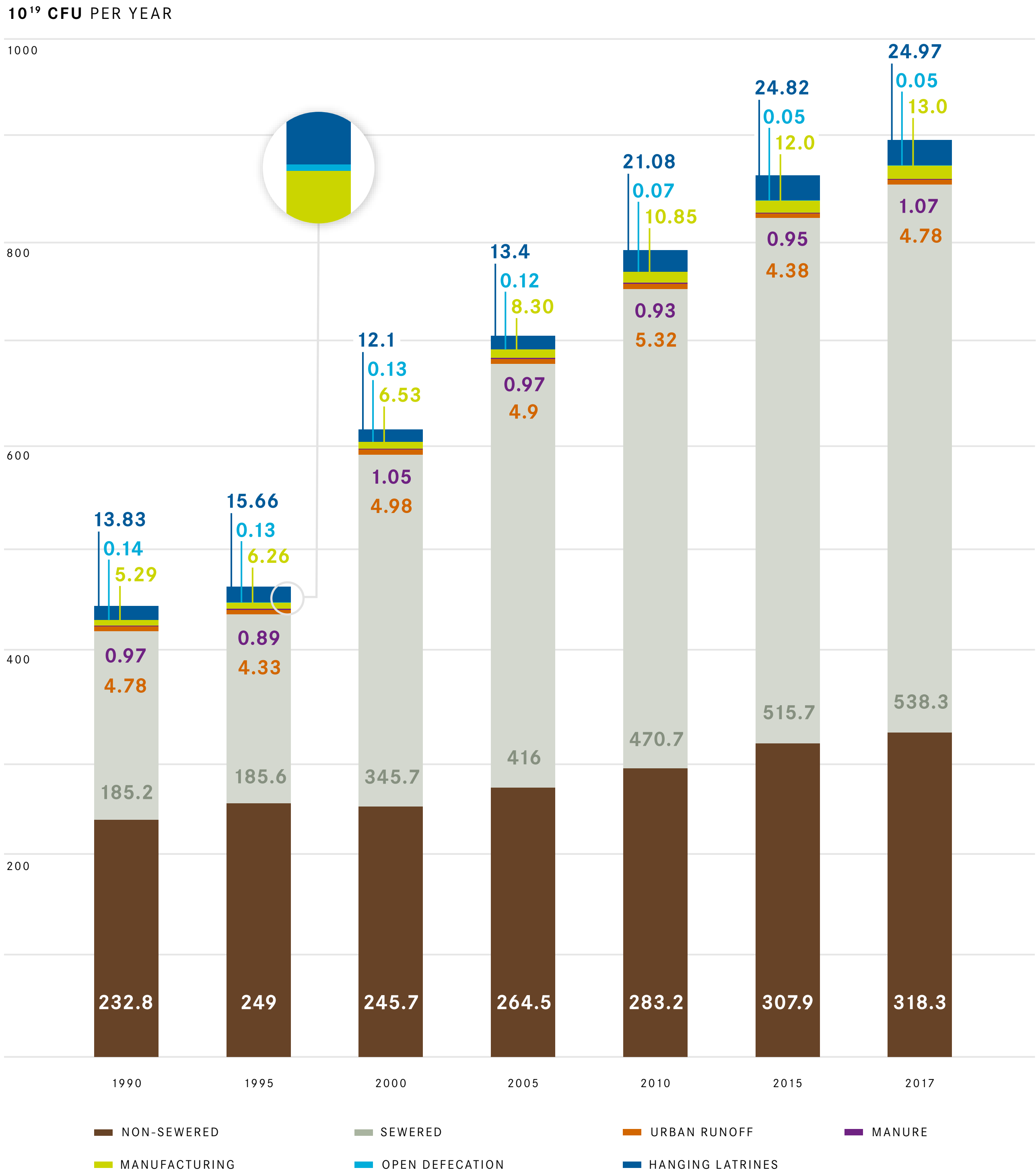
10^{19} CFU PER YEAR
150
120
90
60
30
0.00005
0.0007
0.3
0.62
2.01
78.99
21.21
0.00006
0.0009
0.19
0.55
2.11
74.22
21.69
0.0002
0.13
0.45
1.64
54.62
23.23
0.03
0.0001
0.18
0.47
1.49
51.73
21.83
0.03
0.00004
0.16
0.48
1.48
59.48
19.15
0.007
0.16
0.43
1.12
55.29
18.46
0.007
0.16
0.45
1.23
53.85
18.42
1990
1995
2000
2005
2010
2015
2017
NON-SEWERED
SEWERED
URBAN RUNOFF
MANURE
MANUFACTURING
OPEN DEFECATION
HANGING LATRINES

Africa



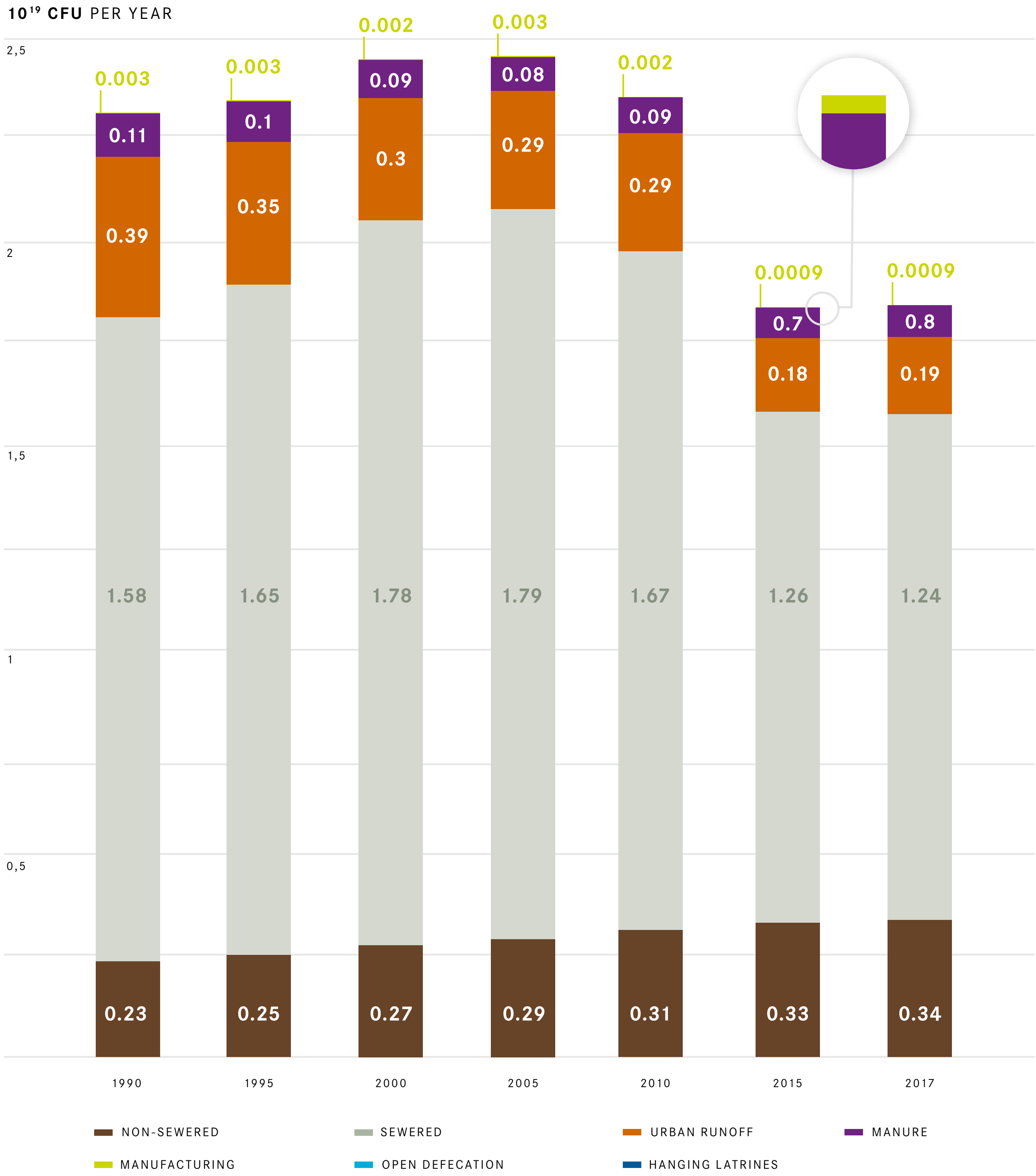
10¹⁹ CFU PER YEAR
50
40
30
20
10
1.05
0.01
0.46
0.33
0.41
18.42
27.55
1.17
0.01
0.44
0.34
0.33
17.36
25.8
1.23
0.01
0.42
0.31
0.33
14.56
21.70
1.05
0.01
0.32
0.31
0.31
12.22
18.21
0.61
0.01
0.3
0.3
0.43
10.73
15.54
0.48
0.01
0.48
0.26
0.25
7.9
13.48
0.43
0.01
0.53
0.25
0.22
7.2
11.83
1990
1995
2000
2005
2010
2015
2017
NON-SEWERED
SEWERED
URBAN RUNOFF
MANURE
MANUFACTURING
OPEN DEFECATION
HANGING LATRINES

Asia



10¹⁹ CFU PER YEAR
1000
800
600
400
200
13.83
0.14
5.29
0.97
4.78
185.2
232.8
15.66
0.13
6.26
0.89
4.33
185.6
249
12.1
0.13
6.53
1.05
4.98
345.7
245.7
13.4
0.12
8.30
0.97
4.9
416
264.5
21.08
0.07
10.85
0.93
5.32
470.7
283.2
24.82
0.05
12.0
0.95
4.38
515.7
307.9
24.97
0.05
13.0
1.07
4.78
538.3
318.3
1990
1995
2000
2005
2010
2015
2017
NON-SEWERED
SEWERED
URBAN RUNOFF
MANURE
MANUFACTURING
OPEN DEFECATION
HANGING LATRINES

Australia


10^19 CFU PER YEAR
2,5
2
1,5
1
0,5
0.003
0.11
0.39
1.58
0.23
0.003
0.1
0.35
1.65
0.25
0.002
0.09
0.3
1.78
0.27
0.003
0.08
0.29
1.79
0.29
0.002
0.09
0.29
1.67
0.31
0.0009
0.7
0.18
1.26
0.33
0.0009
0.8
0.19
1.24
0.34
1990
1995
2000
2005
2010
2015
2017
NON-SEWERED
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URBAN RUNOFF
MANURE
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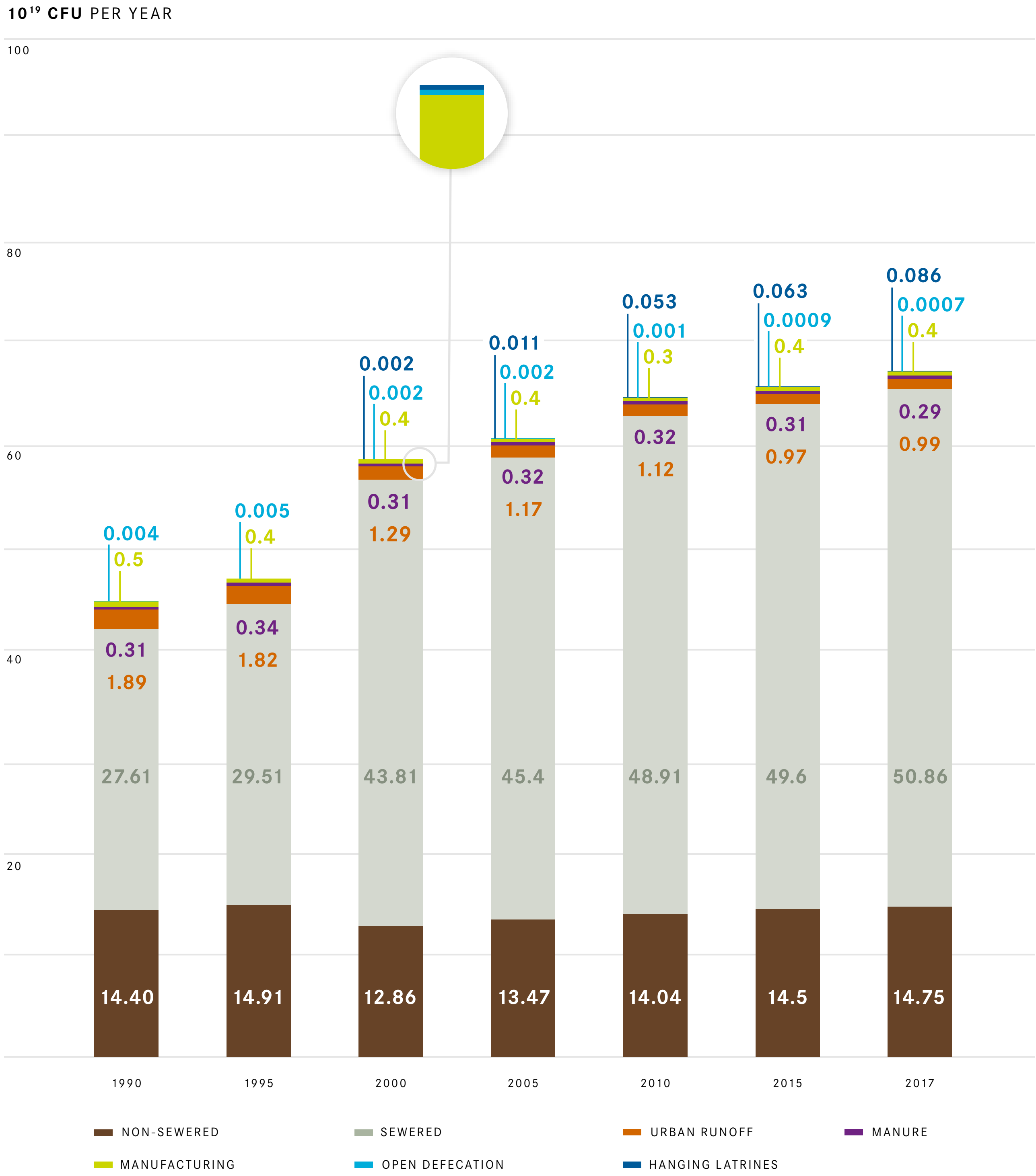
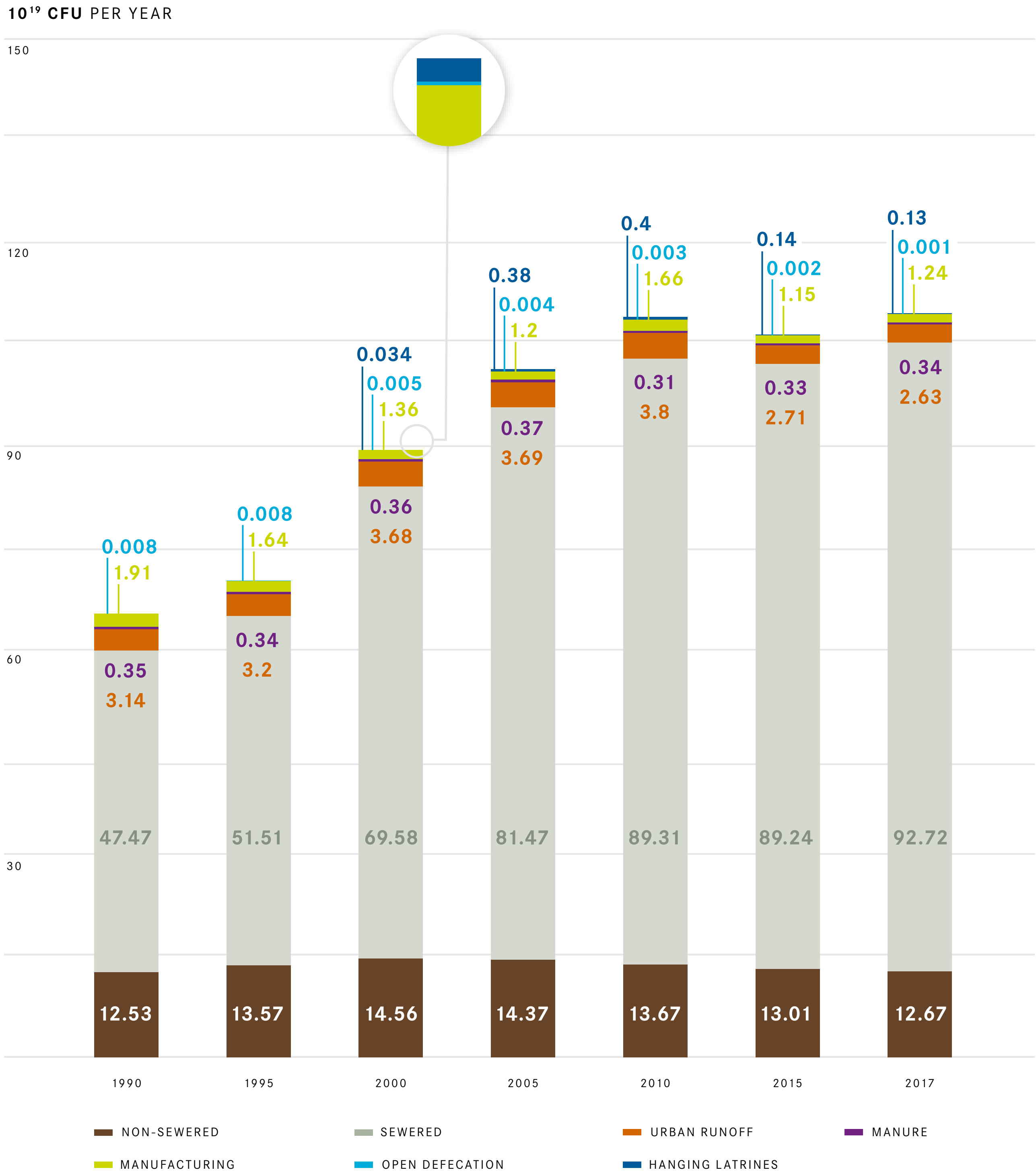
HANGING LATRINES

North America



South America



Hotspots of Fecal Coliform Bacteria Pollution in Rivers between 1990–1994 and 2011–2015

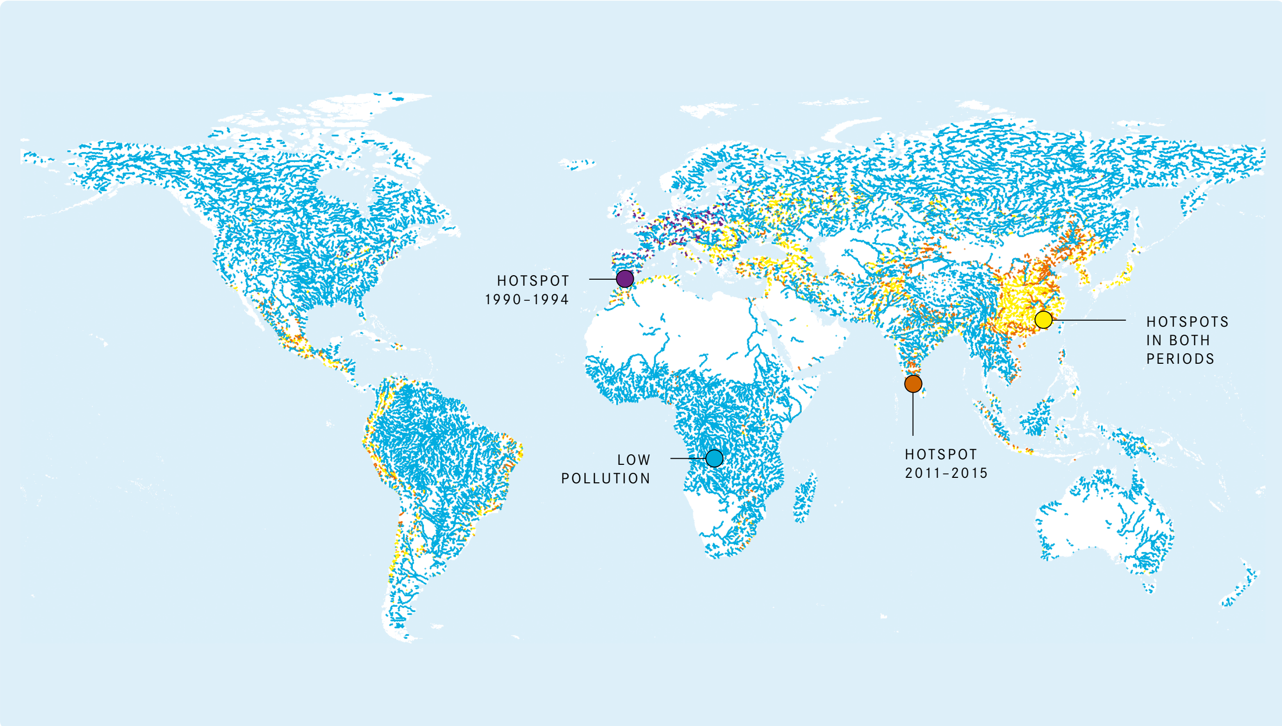


Figure 4.6: Global river network showing simulated hotspots of FC pollution for the periods 1990-1994 and 2011-2015.

4.2.1.4. Fecal coliform bacteria pollution in rivers worldwide

Figure 4.6 shows the global distribution patterns of FC pollution hotspots for two time periods: 1990-1994 and 2011-2015. River reaches are classified as FC pollution hotspots if they are in the severe pollution class for half of a five-year period. The map distinguishes between river reaches that were identified as hotspots only in 1990-1994 or in 2011-2015 and river reaches that were hotspots in both time periods.

Globally, the fraction of river reaches classified as hotspots is increasing. In the period between 1990 and 1994, 11% of river reaches analyzed were classified as hotspots, and 14% in the second period.

However, the extent and number of hotspots is not the same worldwide (Figure 4.7). Between 1990-1994 and 2011-2015, hotspot river reaches decreased in Europe, Australia and New Zealand, and North America.

The largest increase occurred in Sub-Saharan Africa and South-Eastern Asia, where the number of hotspot river reaches increased by more than 200%. Nonetheless, the absolute number of hotspot river reaches compared to the total number of river reaches captured by the model is still relatively small. The highest percentage of hotspots is found in Western Asia and Eastern Asia, where more than 50% of river reaches fall into the hotspot class (Figure 2).

Hotspots of Fecal Coliform Bacteria Pollution in Rivers between 1990-1994 and 2011 -2015

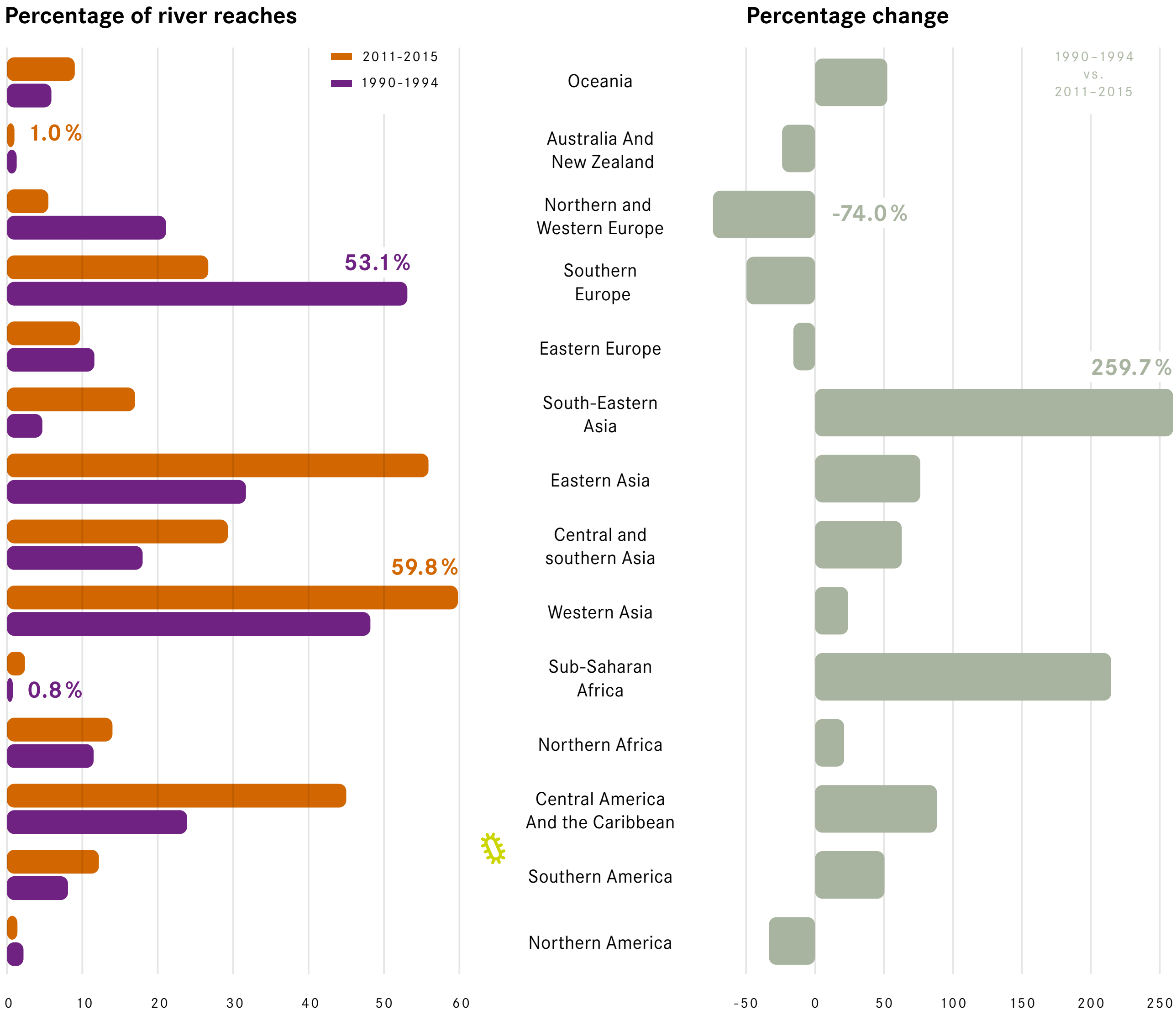


Figure 4.7: Fraction of river reaches classified FC pollution hotspots for the periods 1990-1994 and 2011-2015.

4.2.2. Organic pollution

Surface waters experience organic pollution when an excessive amount of readily biodegradable substances enters. Bacteria and other microorganisms decompose biodegradable matter which leads to the consumption of oxygen, and hence, depletion of dissolved oxygen in the water. The reduction in dissolved oxygen has detrimental consequences for aquatic fauna, particularly fish and benthic invertebrates, as they depend on this vital element for their survival and proper functioning. Biological oxygen demand (BOD) is often taken as the principal indicator of organic pollution (EEA 2022, UNEP 2016).

4.2.2.1. Risks from organic pollution

BOD is a measure of how much oxygen is consumed by bacteria and other microorganisms as they break down organic matter present in the water. BOD is often used as an indicator of the degree of organic pollution in surface waters. The higher the BOD concentration the more oxygen is consumed. When more oxygen is consumed than produced, the dissolved oxygen level decreases which has impacts on aquatic life. In general, high BOD levels are caused by high levels of organic pollution, usually caused by poorly treated wastewater. Therefore, organic pollution is of particular concern because it threatens the functioning of inland fisheries and aquatic ecosystems in general (UNEP 2016). As inland fisheries substantially contribute to food supply for hundreds of millions of people in poor, rural communities around the world (Kelleher et al. 2012, UNEP 2016), BOD pollution has consequences for aquatic ecosystems and ambient water quality but also for food security.

4.2.2.2. How is BOD pollution assessed

BOD concentrations as an indicator for organic pollution are measured in mg/l. To assess ecosystems at risk, BOD concentrations are classified into 3 classes: low, moderate and severe (Tab. 4. 3). In this section the focus is on the occurrence of severely polluted rivers and particularly on hotspots. Hotpots are rivers that are characterized by prolonged severe pollution. More specifically, river reaches that have been showing at least 30 months of severe BOD pollution during a five-year period are defined as hotspots. Two five-year periods (1990-1994 and 2011-2015) were considered.

The analysis of global BOD pollution is based on results from the global water quality model WorldQual. The model calculates monthly BOD concentration in rivers for the period between 1990 and 2017.

Water pollution class	BOD concentration (mg/l)	Description
Low pollution	$x \leq 4$	Indicates river reaches with low organic load and usually sufficient oxygen supply and high species diversity.
Moderate pollution	$4 < x \leq 8$	River reaches with moderate organic load but possibly critical oxygen conditions; suspended discharges occur but have no major effect on biota.
Severe pollution	$x > 8$	River reaches where depletion of dissolved oxygen can be extreme, potentially resulting in fish kills.

Table 4.3: Classes of organic water pollution according to river concentrations of BOD used in this report. Concentration is expressed in mg/l and based on water quality standards as of UNEP (2016).

4.2.2.3 Global and continental trends in BOD loadings

The total gridded BOD loadings are mapped in Figure 4.8. As for FC, the calculation of BOD loadings depends on the waste loadings per person, the type of sanitation, the degree to which sanitation systems are connected to sewers and wastewater is treated, and the loadings washed-off from agricultural land and urban surfaces. Overall, loading hotspots mostly coincide with those found for FC (see Figure 4.4). With the help of modeling it is not only possible to analyze the change in loadings over time, but also to analyze the different pathways and key sectors contributing to high concentrations in rivers.

Figure 4.9. provides an overview of the trends of total and sectorial BOD loadings in the different continents. In Asia the manufacturing sector contributes a substantial fraction of the total BOD loading. Manufacturing loads are estimated as a function of the return flows calculated with the manufacturing water use model and industry-specific average raw effluent concentrations. National numbers are downscaled to the grid scale based on urban population (Flörke et al. 2013). In Asia, contrary to the trend shown by FC loadings, the BOD loadings are still increasing mainly induced by the manufacturing sector (Fig. 4.9).

A different tendency can be seen in both South America and North America. Firstly, it should be noted that the total loadings are one order of magnitude lower than in Asia. The lower fraction of manufacturing loadings in the Americas compared to Asia may be due to lower intensity of water withdrawals, and hence in return flows, in countries such as the USA, Mexico, and Brazil compared to China and India. Also, the lower loadings estimated for North America compared with South America can be explained by the improved wastewater treatment in countries such as the USA and Mexico. On both continents, the growth rate of BOD loadings is at least stagnating or decreasing during the last decade.

A similar trend like for North America can be seen for Europe where total BOD loadings are consistently declining from 6.2×10^6 tons per year in 1990 to 4.6×10^6 tons per year in 2017. The main contribution can be related to the sewered domestic sector, indicating that wastewater is collected and properly treated. In Africa, on the other hand, the BOD loadings rose steadily after the year 2000, with an estimated total load of 2.8×10^6 tons per year rising to 4.6×10^6 tons per year in 2017. Here the dominant sources are the domestic sewered and non-sewered sectors with wastewater either not or not properly treated.

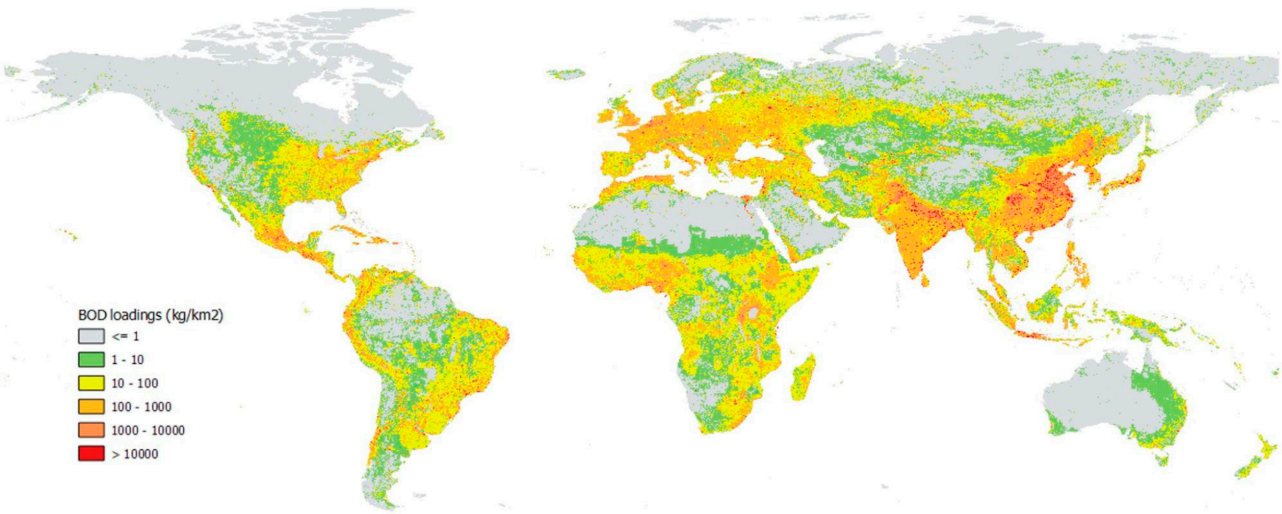


Figure 4.8: Total BOD loadings on grid-scale level in 2017. Units: kg/km².

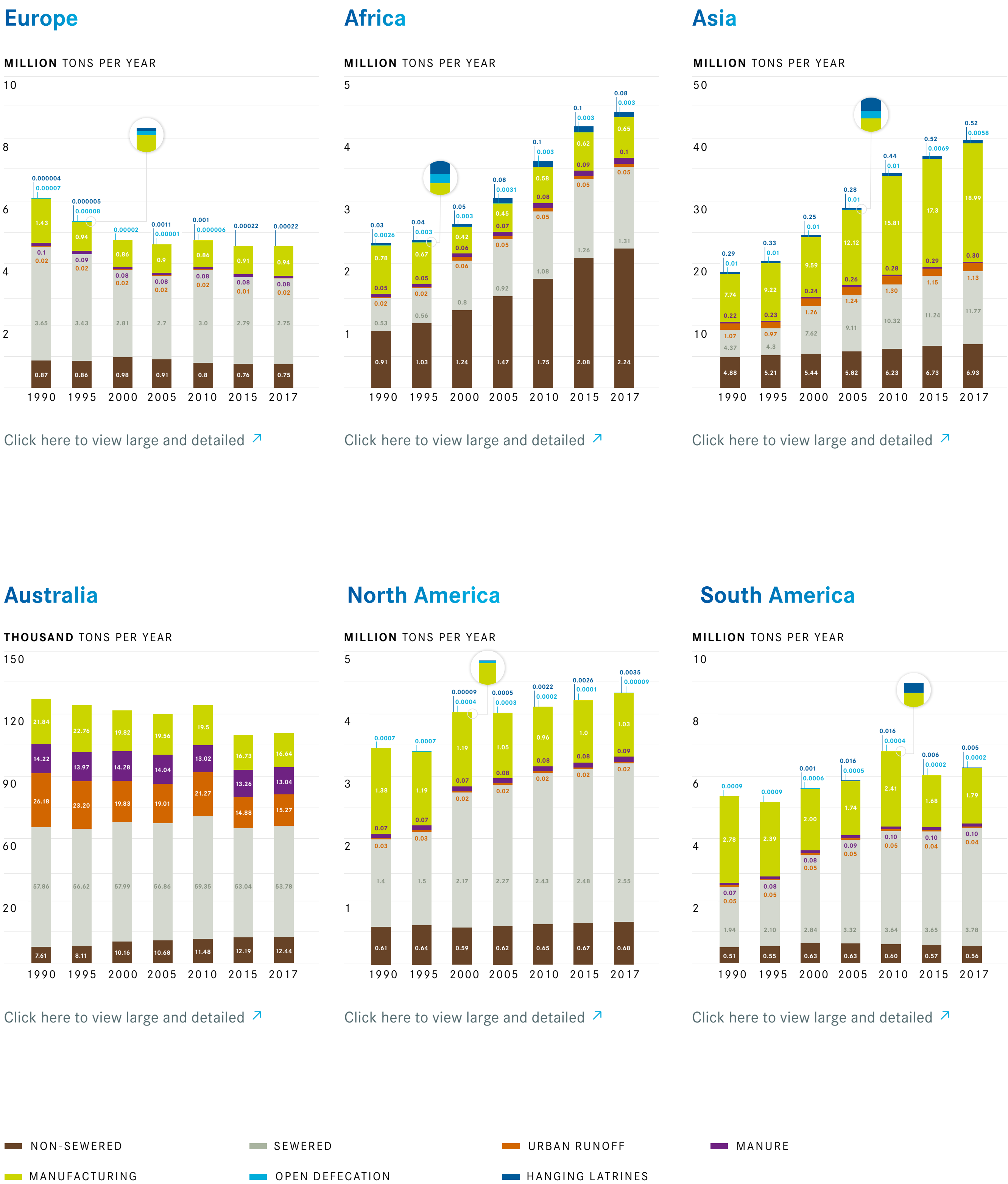
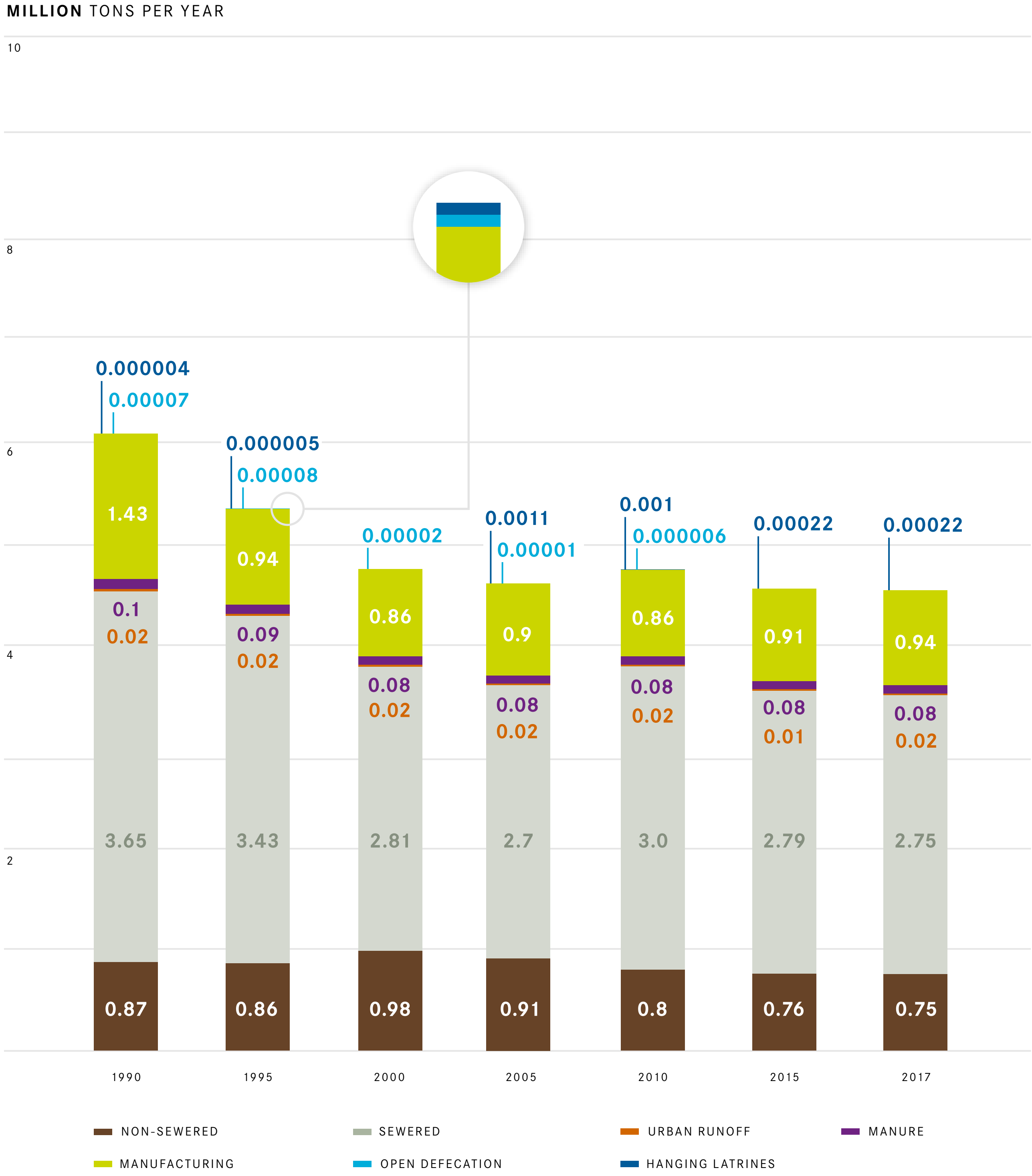
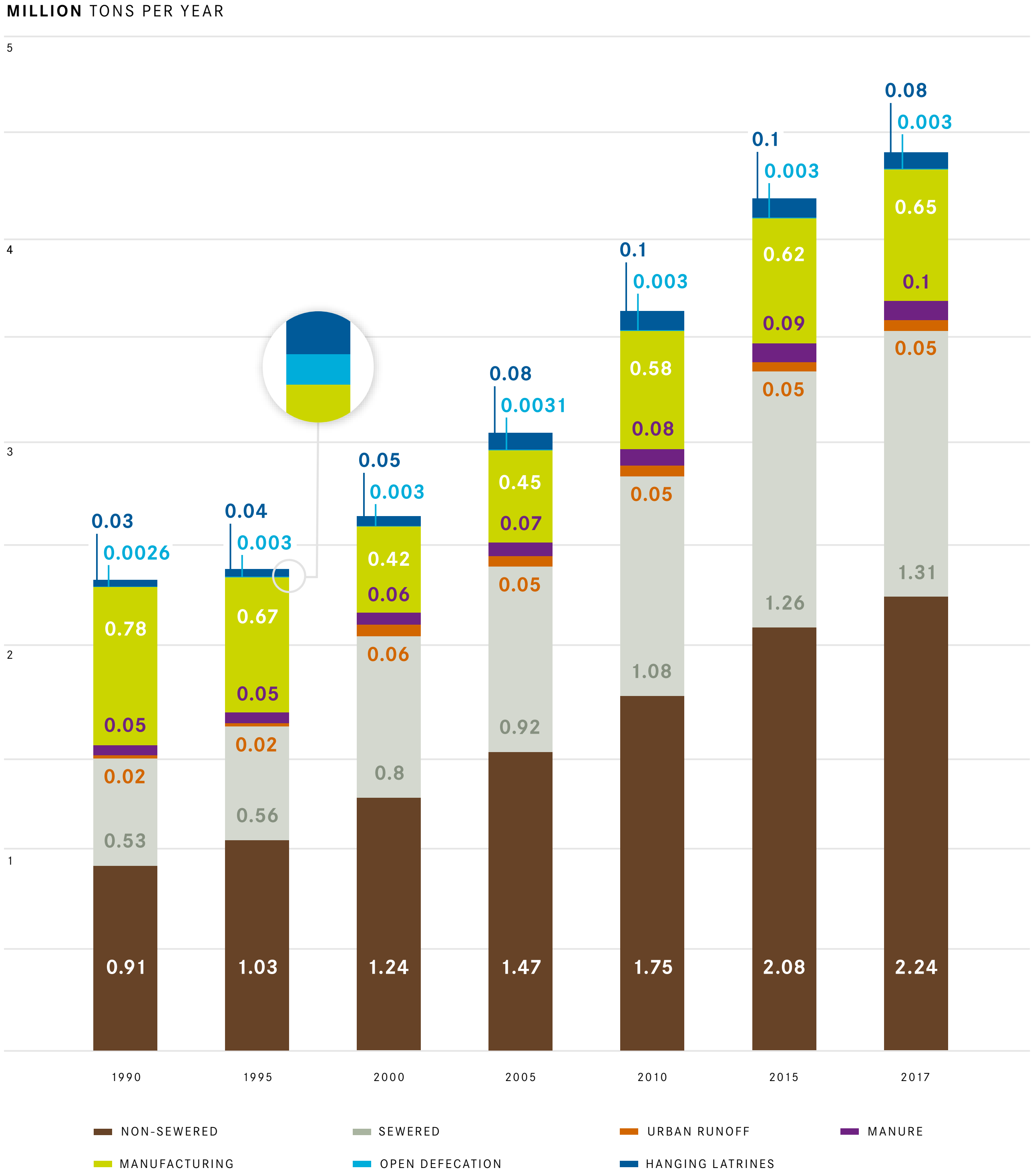


Figure 4.9: Trends of FC loadings according to different point and diffuse sources as estimated for different continents between 1990 and 2017.

Europe

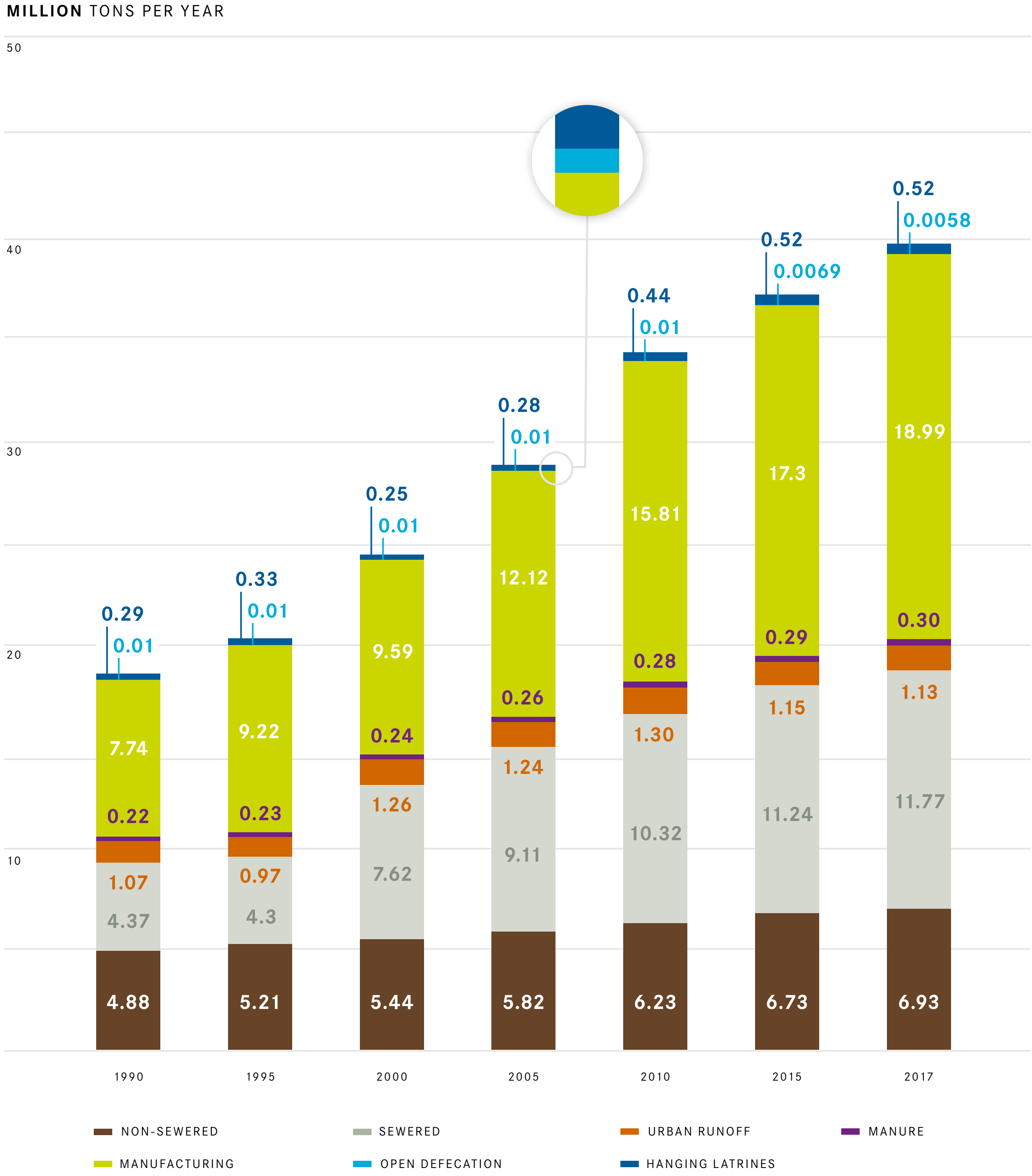

MILLION TONS PER YEAR
10
8
6
4
2
0.000004
0.00007
1.43
0.1
0.02
3.65
0.87
0.000005
0.00008
0.94
0.09
0.02
3.43
0.86
0.00002
0.86
0.08
0.02
2.81
0.98
0.0011
0.00001
0.9
0.08
0.02
2.7
0.91
0.001
0.000006
0.86
0.08
0.02
3.0
0.8
0.00022
0.91
0.08
0.01
2.79
0.76
0.00022
0.94
0.08
0.02
2.75
0.75
1990
1995
2000
2005
2010
2015
2017
NON-SEWERED
SEWERED
URBAN RUNOFF
MANURE
MANUFACTURING
OPEN DEFECATION
HANGING LATRINES

Africa

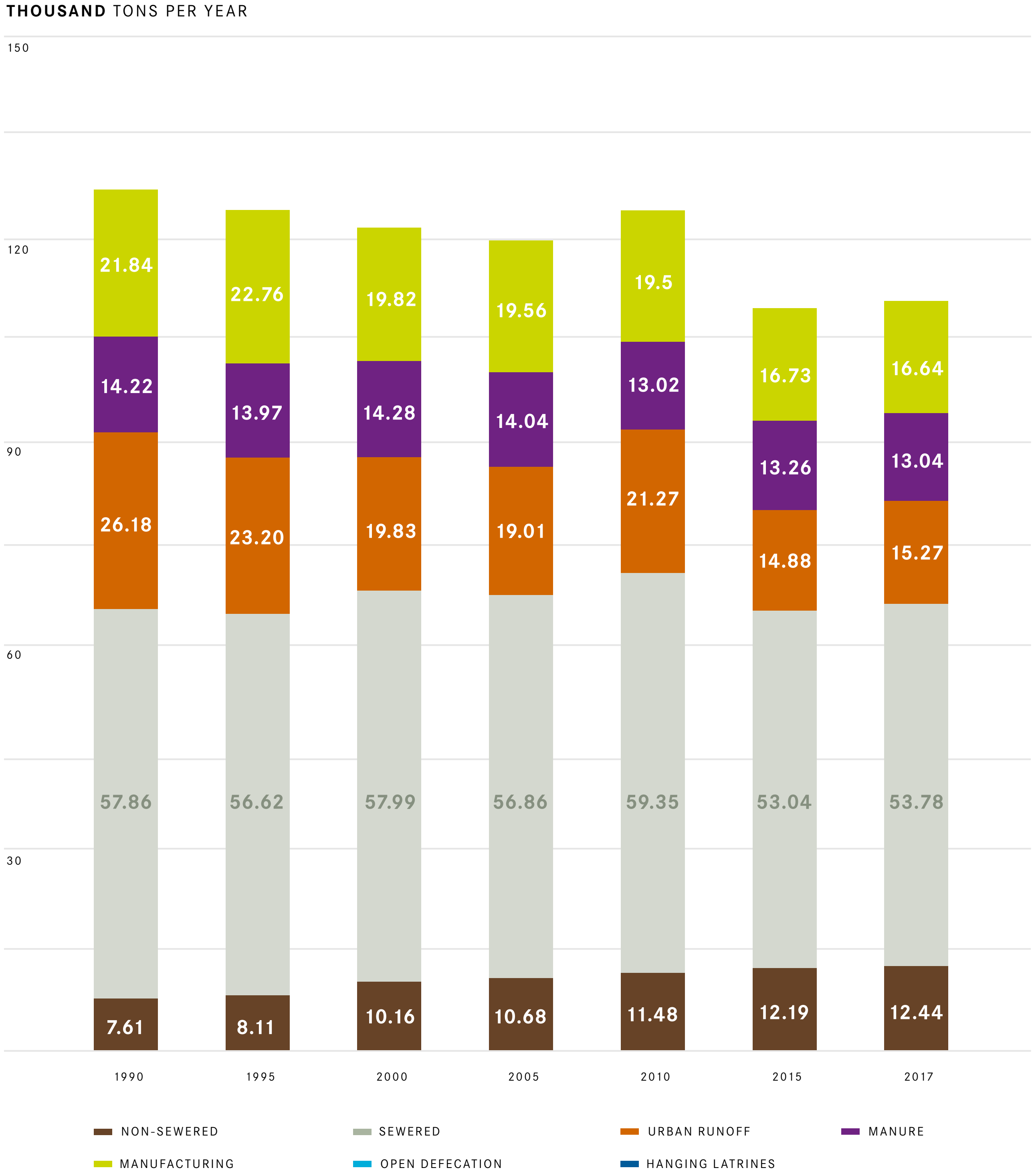


MILLION TONS PER YEAR
5
4
3
2
1
0.03
0.0026
0.78
0.05
0.02
0.53
0.91
0.04
0.003
0.67
0.05
0.02
0.56
1.03
0.05
0.003
0.42
0.06
0.06
0.8
1.24
0.08
0.0031
0.45
0.07
0.05
0.92
1.47
0.1
0.003
0.58
0.08
0.05
1.08
1.75
0.1
0.003
0.62
0.09
0.05
1.26
2.08
0.08
0.003
0.65
0.1
0.05
1.31
2.24
1990
1995
2000
2005
2010
2015
2017
NON-SEWERED
SEWERED
URBAN RUNOFF
MANURE
MANUFACTURING
OPEN DEFECATION
HANGING LATRINES

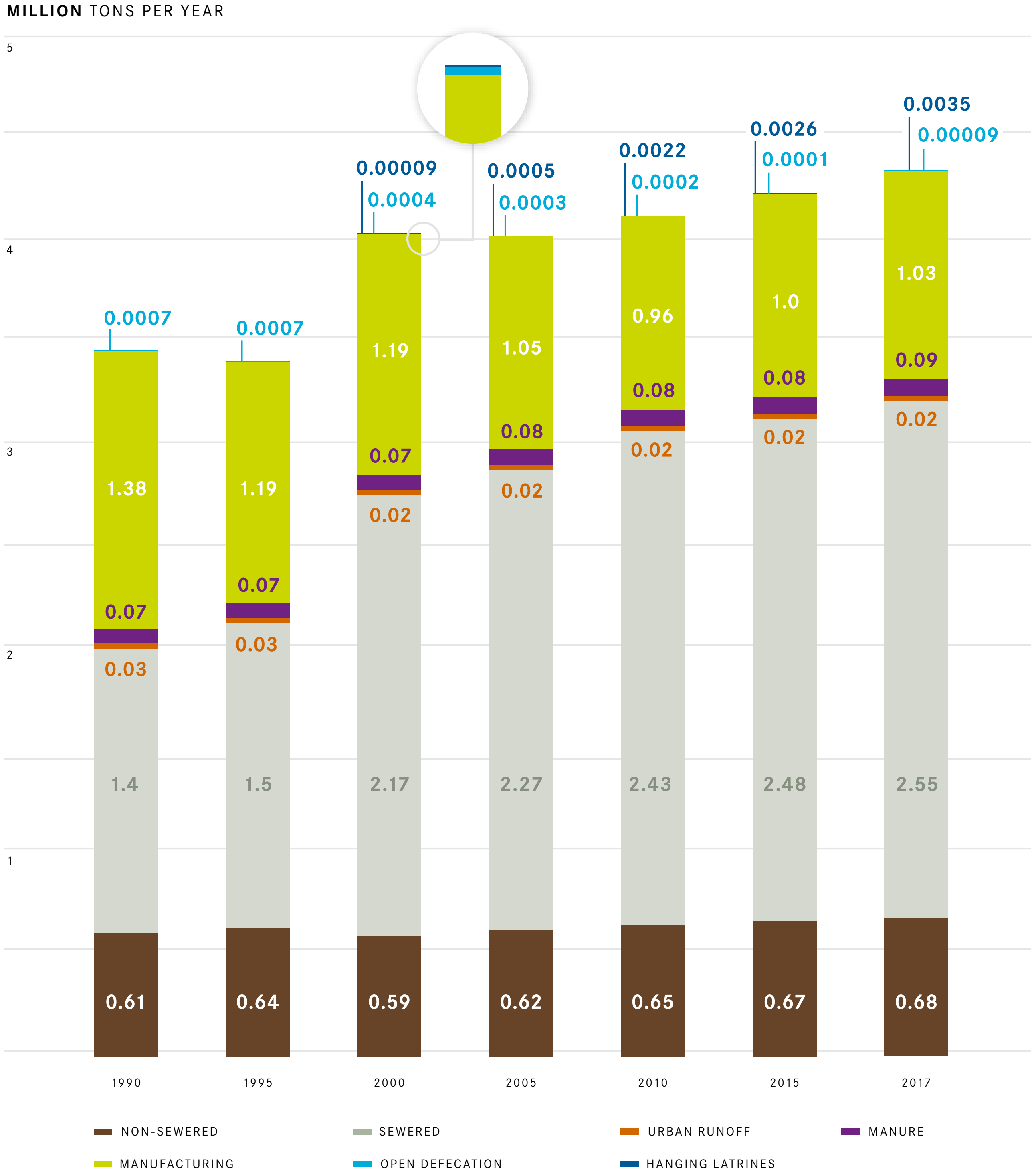
Asia


MILLION TONS PER YEAR
50
40
30
20
10
0.29
0.01
7.74
0.22
1.07
4.37
4.88
0.33
0.01
9.22
0.23
0.97
4.3
5.21
0.25
0.01
9.59
0.24
1.26
7.62
5.44
0.28
0.01
12.12
0.26
1.24
9.11
5.82
0.44
0.01
15.81
0.28
1.30
10.32
6.23
0.52
0.0069
17.3
0.29
1.15
11.24
6.73
0.52
0.0058
18.99
0.30
1.13
11.77
6.93
1990
1995
2000
2005
2010
2015
2017
NON-SEWERED
SEWERED
URBAN RUNOFF
MANURE
MANUFACTURING
OPEN DEFECATION
HANGING LATRINES

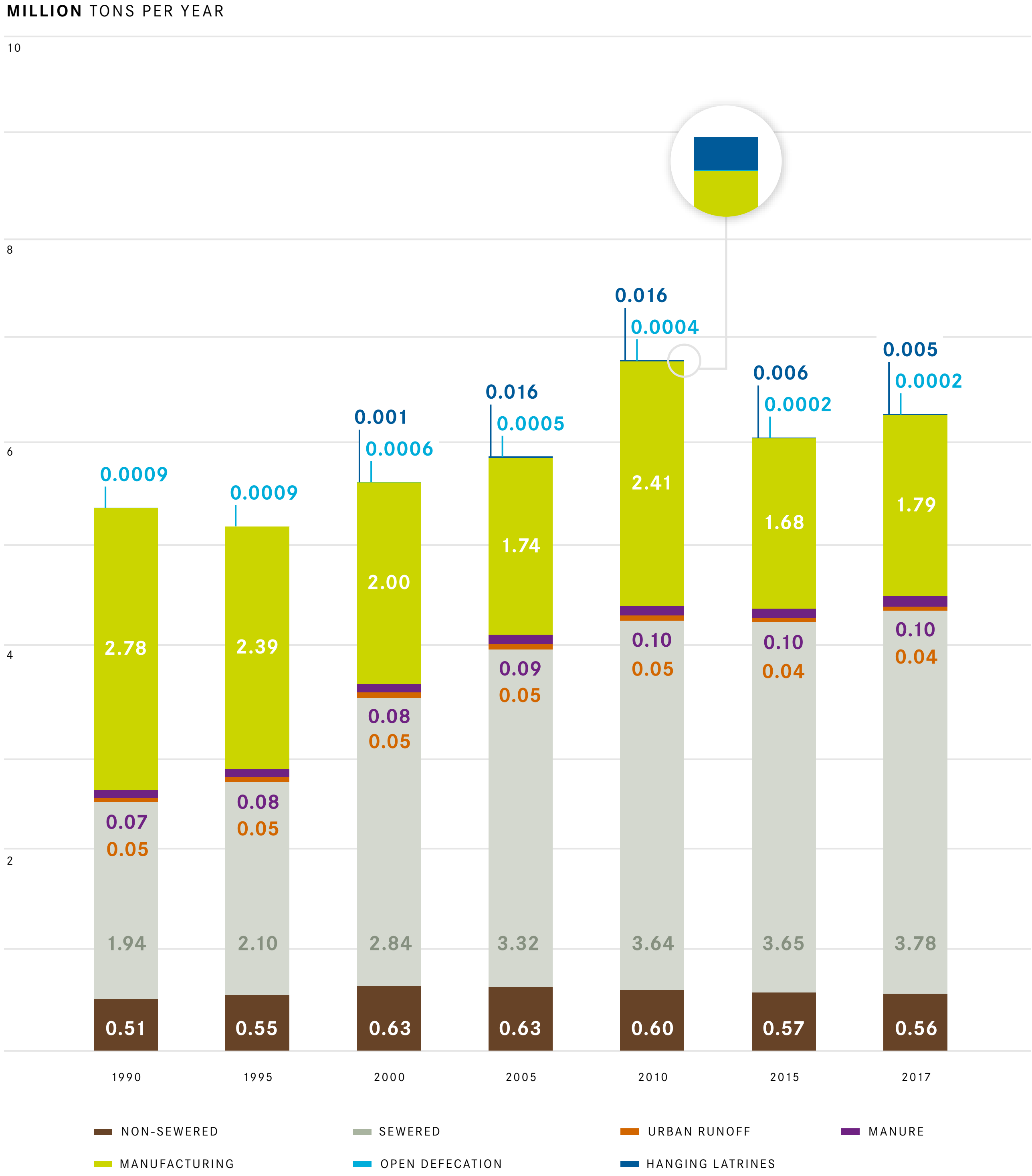
Australia


THOUSAND TONS PER YEAR
150
120
90
60
30
21.84
14.22
26.18
57.86
7.61
22.76
13.97
23.20
56.62
8.11
19.82
14.28
19.83
57.99
10.16
19.56
14.04
19.01
56.86
10.68
19.5
13.02
21.27
59.35
11.48
16.73
13.26
14.88
53.04
12.19
16.64
13.04
15.27
53.78
12.44
1990
1995
2000
2005
2010
2015
2017
NON-SEWERED
SEWERED
URBAN RUNOFF
MANURE
MANUFACTURING
OPEN DEFECATION
HANGING LATRINES

North America



South America



Hotspots of Organic Pollution in Rivers between 1990-1994 and 2011-2015

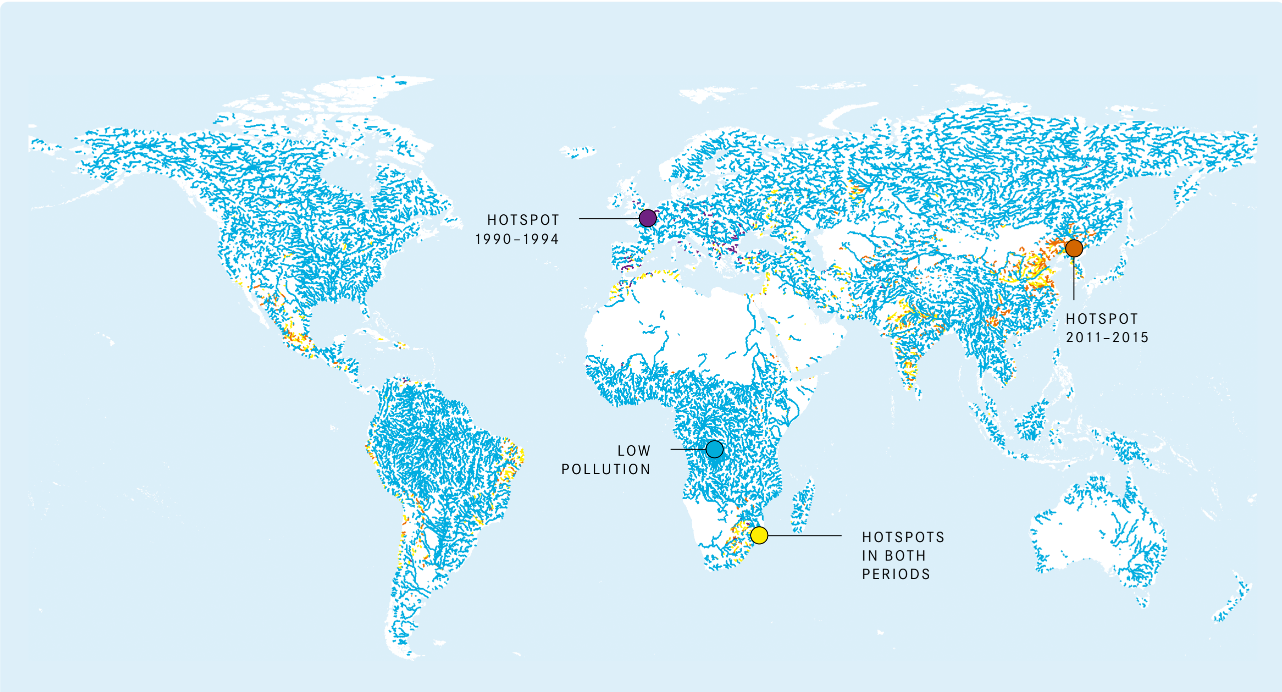


Figure 4.10: Global river network showing hotspots of organic pollution for the periods 1990-1994 and 2011-2015.

4.2.2.4. Organic pollution in rivers worldwide

About 30% of the river reaches considered within the modeling are characterized by low pollution throughout the simulation period between 1990 and 2017. Nevertheless, about 23% of the river reaches are classified as severely polluted for at least one month per year. In addition, the analysis shows that the number of river reaches that are heavily polluted in any given year is increasing slightly. While in 1990 about 11% of river reaches were classified as severely polluted for at least one month per year, in 2017 the figure increased to 13%. At this point, it should be emphasized that not only the number of river reaches has increased between the two time periods, but also the time period in which a heavily polluted river section falls into the class of heavy pollution. This time period has increased from four months in 1990 to five months in 2017.

Rivers are classified as BOD pollution hotspots if they are in the severe pollution class of BOD concentrations for half of a five-year period. Figure 4.10 shows the global distribution patterns of BOD pollution hotspots for two time periods: 1990-1994 and 2011-2015. The map distinguishes between rivers that were identified as hotspots only in 1990-1994 and 2011-2015 and rivers that were hotspots in both time periods. Obviously, most hotspot rivers are present in both time periods

Globally, the fraction of river reaches classified as hotspots is increasing, similar to the trend shown for rivers with severe pollution. In the period 1990-1994, 11% of river reaches were classified as hotspots, and 14% in the second period.

Hotspots of Organic Pollution in Rivers between 1990-1994 and 2011-2015

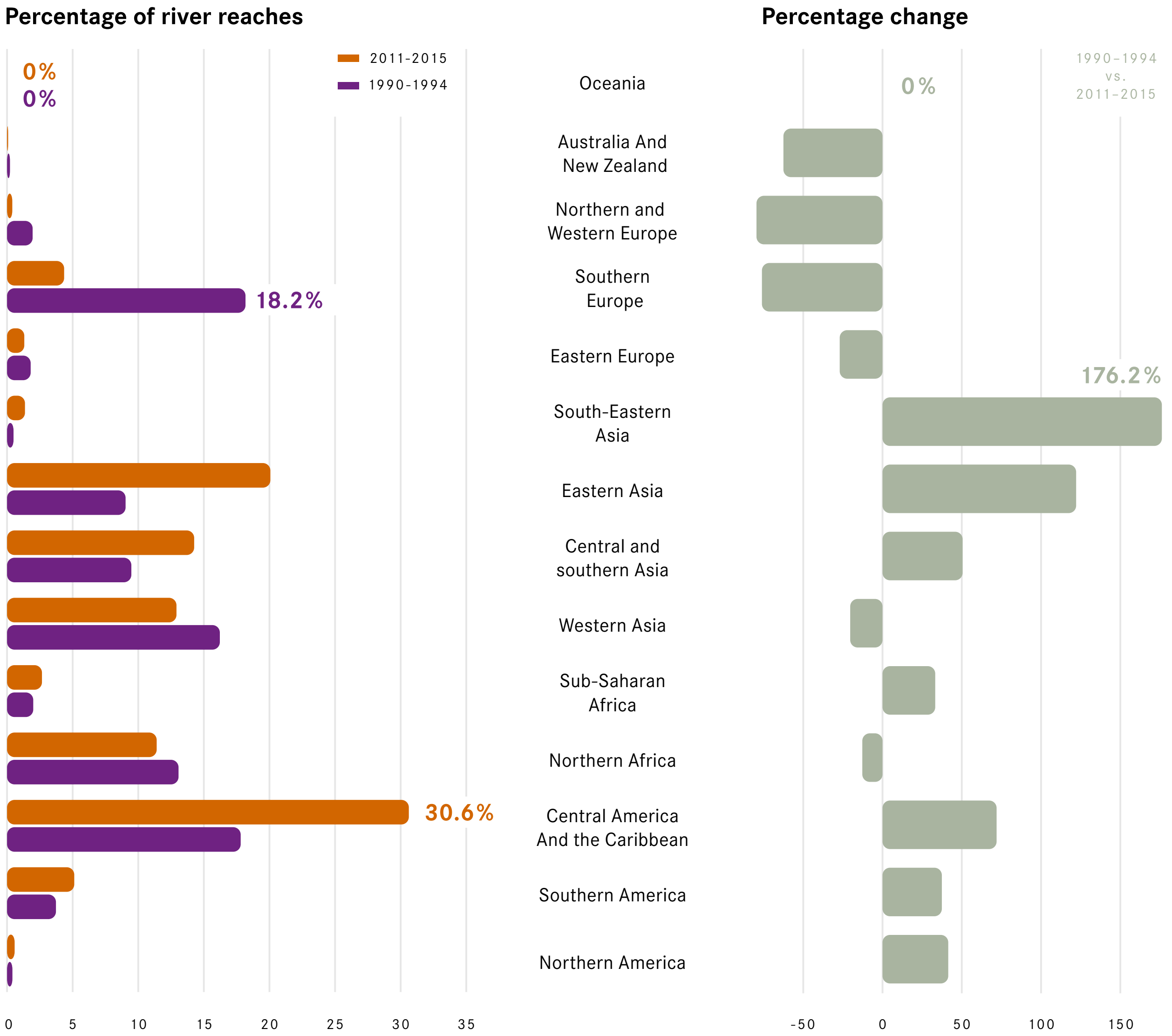


Figure 4.11: Fraction of rivers classified as hotspots of organic pollution for the periods 1990-1994 and 2011-2015.

The extent of hotspots varies in space and time (Figure 4.11). Between the two time periods, 1990-1994 and 2011-2015, hotspot river reaches decreased in Europe, Australia and New Zealand, and North America. The largest increase occurred in Eastern Asia and South-Eastern Asia, where the number of hotspot rivers increased by more than 200%. However, the absolute number of hotspot rivers is still relatively low. The highest proportion of hotspots is in Central America and the Caribbean, where more than 30% of rivers fall into the hotspot class (Figure 4.11).

4.2.3. Salinity

In the past, water salinisation was primarily considered a significant issue in arid and semi-arid regions and areas with inadequate irrigation management. However, it is now increasingly recognized as a global environmental problem affecting not only dry regions but also humid areas due to human influences (Flörke et al. 2019, Kaushal et al. 2015). There are two primary causes of salinisation that lead to the release of salt into river systems: natural or 'primary' salinisation and anthropogenic or 'secondary' salinisation. Natural salinisation occurs when soluble salts accumulate in soils through natural processes such as physical or chemical weathering of parent rock materials and the transportation of these materials through groundwater (e.g. Daliakopoulos et al. 2016). Dryland salinity is mainly observed in arid and semi-arid regions where evapotranspiration exceeds precipitation (Butcher et al. 2016) and is an example of natural salinisation. On the other hand, secondary salinisation is a result of human activities, particularly the use of saline groundwater for irrigation (Custodio 2002) , or inadequate drainage of naturally saline soils in (semi) arid zones (Smedema and Shiati 2002). However, not only inefficient irrigation practices contribute to the salinisation of streams and rivers, but also salt pollution from road de-icers, urban runoff, domestic and industrial wastewater, and mining operations (e.g. Cañedo-Argüelles et al. 2017, Hintz and Relyea 2019, Kaushal et al. 2015). In freshwaters, salinity is commonly defined and measured as the mass of 'total dissolved solids' (TDS); this approach is also used in this report.

4.2.3.1. Risks from salinity pollution

High salinity levels in freshwater systems pose risks to the safety of drinking water and infrastructure as well as food security. Elevated salt levels in drinking water can have implications for individuals on sodium-restricted diets, potentially contributing to hypertension (Nahian et al. 2018). They also impact water corrosivity, which can lead to the leaching of metals from pipes used in delivering drinking water (Stets et al. 2018). Salinity concentrations exceeding a threshold of 450 mg/l make freshwater resources unusable for irrigation and hence affects food security. Around 34 million hectares of irrigated land worldwide are affected by salinisation (i.e. >10% of the global irrigated area), 77% of which is in Asia, particularly in Pakistan, China and India (Mateo-Sagasta and Burke 2010). The fish kill in the Oder river in August 2022 was very likely a resalinity, which, together with other factors, led to a mass proliferation of a brackish water algae that is toxic to fish. Overall, salinity pollution originating from weathering of soils and rocks and/or human activities threatens ecosystems and human well-being, and has become a prevalent water quality concern that needs proactive management today and in the future.

4.2.3.2. How is salinity pollution assessed

Salinisation refers to an increase in the concentration of total dissolved solids (TDS) in water and can often be determined by an increase in chloride (Kaushal et al. 2015). The salt content of water can be easily detected either by the measure of total dissolved solids (TDS) or electrical conductivity (EC) of the solution (Pillsbury 1981). TDS and EC are generic measures of the salt concentrations in freshwater systems in a liter of water, with units of milligrams per liter (mg/l) for TDS and microsiemens per centimeter (uS/cm).10 This is also the approach used in this report and in contrast to FC and BOD also moderate pollution to be in line with the approach in UNEP (2016) (TDS concentration >450 mg/l, Table 4.4). A river is defined as hotspots if it has been showing at least 30 months of severe or moderate salinity pollution in a five year period. To compare the change of hotspots over time two five year periods (1990-1994 and 2011-2015) were selected. The analysis of global salinity pollution is based on results from the global water quality model WorldQual. The model calculates monthly TDS concentration in rivers for the period between 1990 and 2017.

Water pollution class	TDS concentration (mg/l)	Description
Low pollution	$x \leq 450$	No restrictions for use in irrigation (FAO 1985)
Moderate pollution	$450 < x \leq 2000$	Increasingly problematic for use in irrigation (FAO 1985)
Severe pollution	$x > 2000$	Severely problematic for use in irrigation (FAO 1985)

Table 4.4: Classes of salinity pollution according to river concentrations of TDS used in this report. Concentration is expressed in mg/l and based on water quality standards as defined in UNEP (2016).

TDS loadings 2017, t/km²

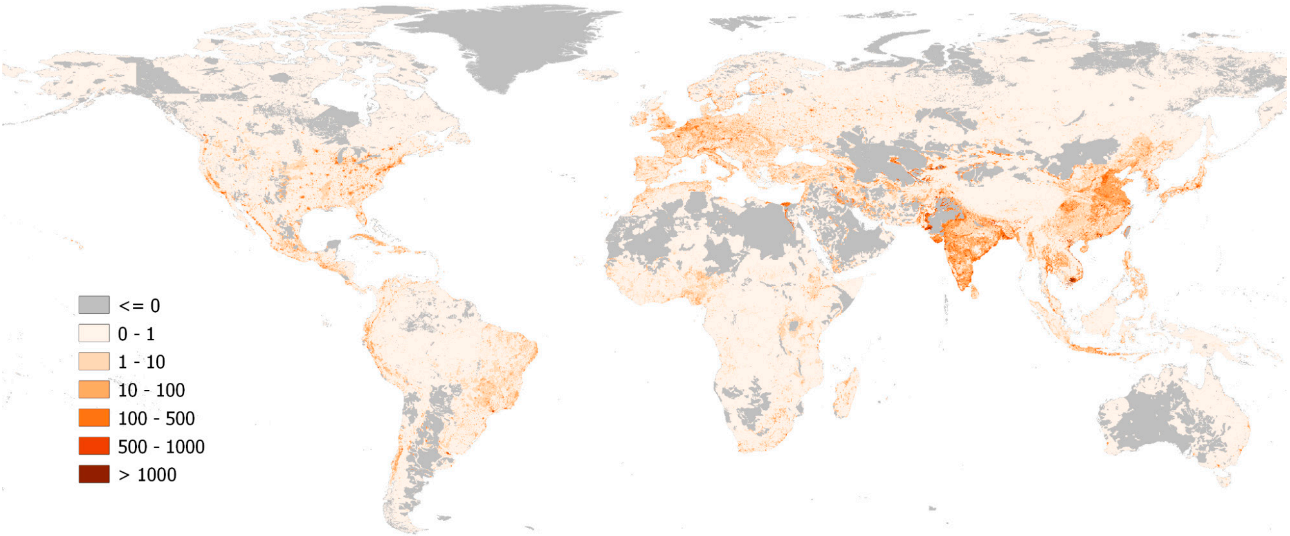


Figure 4.12: TDS loadings originating from anthropogenic sources for the year 2017. Units: tons/km².

4.2.3.3. Global and continental trends in salinity loadings

TDS loadings originate from geogenic (e.g., weathering) and anthropogenic (e.g., manufacturing, irrigation) sources. The anthropogenic TDS loadings are displayed on a grid-cell level in Figure 4.12. Hotspots of salinity loadings can be found on every continent worldwide, however, bigger patterns are located particularly in India and China, but the lower Nile and Aral Sea basins are visible, too.

The sources contributing to salinization vary widely from region to region. In Asia, most of the salinity loading to rivers results from return flows from irrigated areas (see Figure 4.13), while in North America and Europe, the processing industry has a greater impact. Although salinity pollution mainly threatens areas where rivers and streams with relatively low dilution capacity are in high demand for further use.

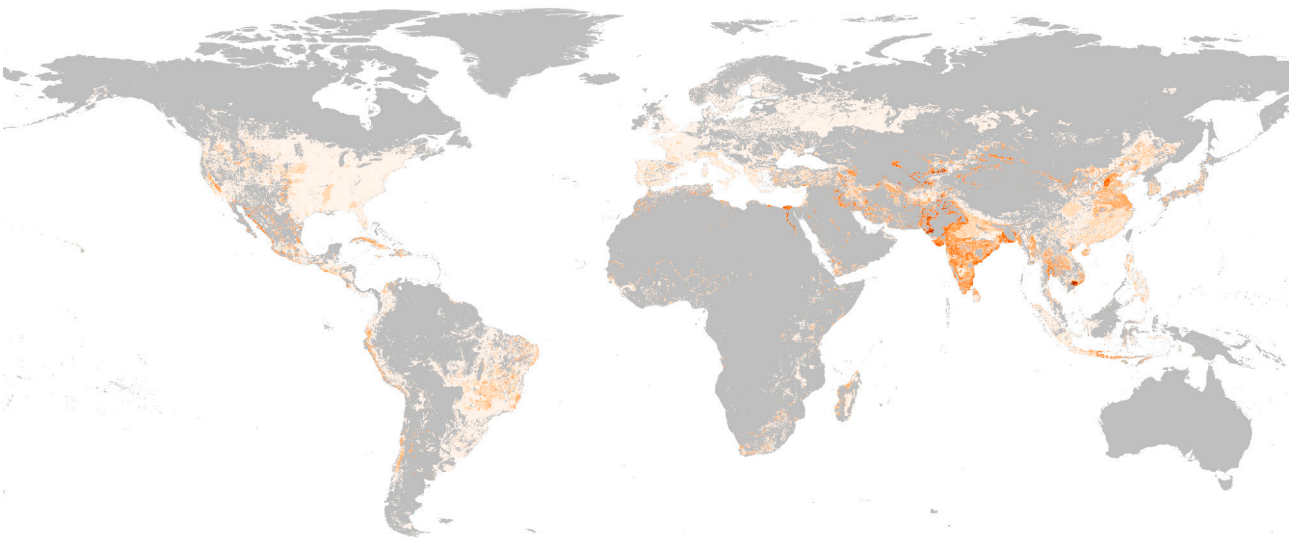


Figure 4.13: TDS loadings originating from irrigation return flows for the year 2017. Units: tons/km².

As displayed in Figure 4.14, anthropogenic salinity pollution has steadily increased since 1990. While TDS loads from the domestic sector play a rather minor role, the largest contributions are from irrigation return flows. The return flows from irrigated areas potentially transfer large amounts of salts from cropping areas to surface waters, but vary with changing climatic conditions, areas used for irrigation, and water use efficiencies. The second most important contributing sector is the manufacturing industry, where wastewater polluted with salts is discharged into rivers. Runoff from mining activities as well as road salts are important sources of salinity in some rivers, but not considered in this study. Therefore, in some regions, the loadings of total dissolved solids are likely to be underestimated.

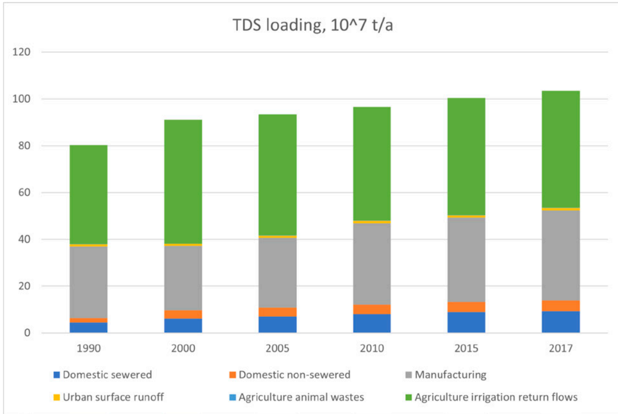


Figure 4.14: Trends of global TDS loadings according to different point and diffuse sources between 1990 and 2017. Units: 10^7 tons/year.

4.2.3.4. Salinity pollution in rivers worldwide

The vast majority, about 87% of the river reaches considered, is characterized by low salinity pollution throughout the simulation period between 1990 and 2017.

Rivers are classified as salinity pollution hotspots if they are in the severe or moderate pollution class of salinity concentrations for half of a five-year period. Figure 4.15 shows the global patterns distribution of salinity pollution hotspots for two time periods: 1990-1994 and 2011-2015. The map distinguishes between rivers that were identified as hotspots only in 1990-1994 and 2011-2015 and rivers that were hotspots in both time periods. Globally, the fraction of river reaches classified as hotspots is approximately constant at 1.3 and 1.5 % respectively for the first and the second period. The extent of hotspots varies in space and time (Figure 4.16). Salinity pollution is typically low in humid and moderate climates such as Northern Europe and Northern America. Salinity pollution is highest in Asia and tends to increase. The largest increase between the two assessment periods occurred in South- Eastern and Eastern Asia, where the number of hotspot rivers increased by more than 50%.

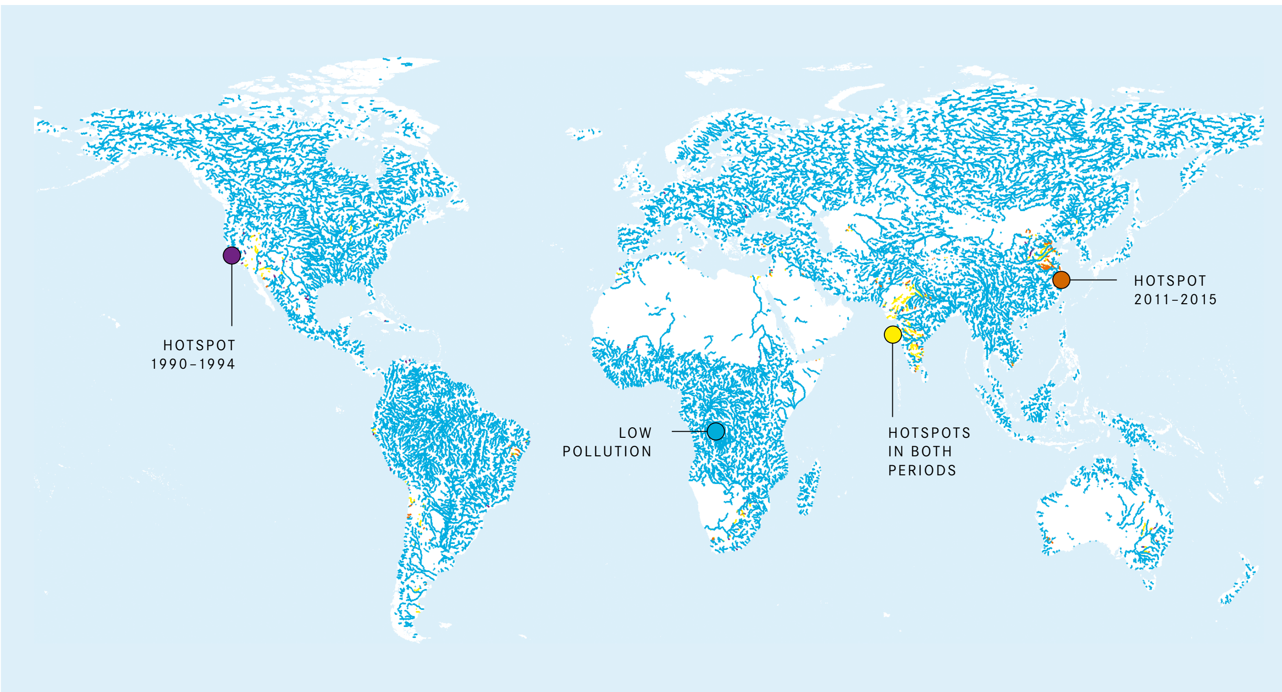


Figure 4.15: Global river network showing hotspots of salinity pollution for the periods 1990-1994 and 2011-2015.

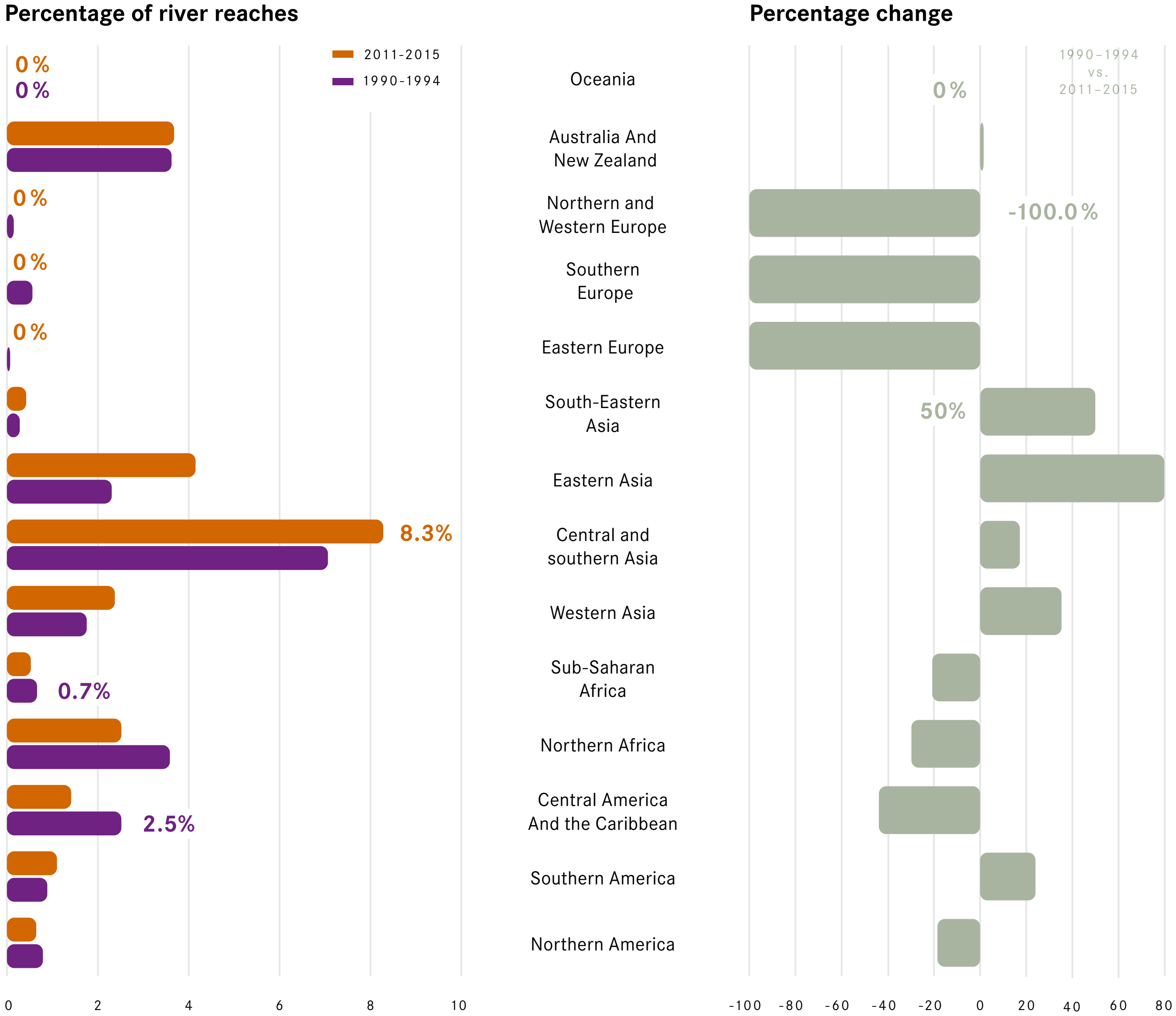


Figure 4.16: Fraction of rivers classified as hotspots of salinity for the periods 1990-1994 and 2011-2015.

4.2.4. Nitrate

4.2.4.1. Risks from nitrate pollution

Nitrogen is an essential nutrient without which life cannot exist. But the production of artificial fertilizers substantially distorted the natural nitrogen cycle to an extent that nitrate is considered a global problem that exceeds planetary boundaries (Steffen et al. 2015). High nitrate concentrations in surface waters can lead to eutrophication, i.e., excessive plant and algal growth. As a result, microbial decomposition of plant and algal material depletes oxygen, which can lead to the death of aquatic life. Nitrate in drinking water can impair the body's ability to carry oxygen, which can lead to the so-called "blue baby syndrome".

Water pollution class	Nitrate concentration (mg/l)	Description
Low pollution	x ≤ 1	Conditions close to natural background
Moderate pollution	1 < x ≤ 5	Moderately polluted
Severe pollution	x > 5	Chronically elevated nitrate concentrations

Table 4.5: Classes of nitrate pollution according to river nitrate concentrations used in this report.

4.2.4.2. How is nitrate pollution assessed

For water intended for human consumption, the World Health Organization (WHO) has set a guideline that nitrate concentrations should exceed 50 mg/l to protect against the “blue baby syndrome”. Increased risk of colorectal cancer has been observed when drinking water has nitrate concentrations above 3.87 mg/L (Schullehner et al. 2018) Ecological thresholds to protect aquatic ecosystems are not as clearly defined. Many countries and regions have their own regulations with a wide range of nutrient criteria (Poikane et al. 2019). In this report we selected a pragmatic approach, yet with rather low thresholds where monthly average concentrations above 5 mg/l nitrate are classified as severe pollution (Tab 4.5) Unlike for FC, BOD and TDS the global assessment of nitrate concentration in rivers is based on a data driven analysis that estimates monthly nitrate concentration for a period between 1990 and 2015 (see Section A.2).

4.2.4.3. Nitrate pollution in rivers worldwide

About 21% of the global river reaches considered are characterized by low nitrate pollution throughout the analyzed period between 1990 and 2015. Rivers are classified as nitrate pollution hotspots if they are in the severe pollution class of nitrate concentrations for half of a five-year period. Figure 4.17 shows the global patterns of nitrate pollution hotspots for two time periods: 1990-1994 and 2011-2015. The map distinguishes between rivers that were identified as hotspots only in 1990-1994 and 2011-2015 and rivers that were hotspots in both time periods. Unlike waste water related pollution such as FC and BOD, nitrate pollution hotspots are also occuring in high income countries.

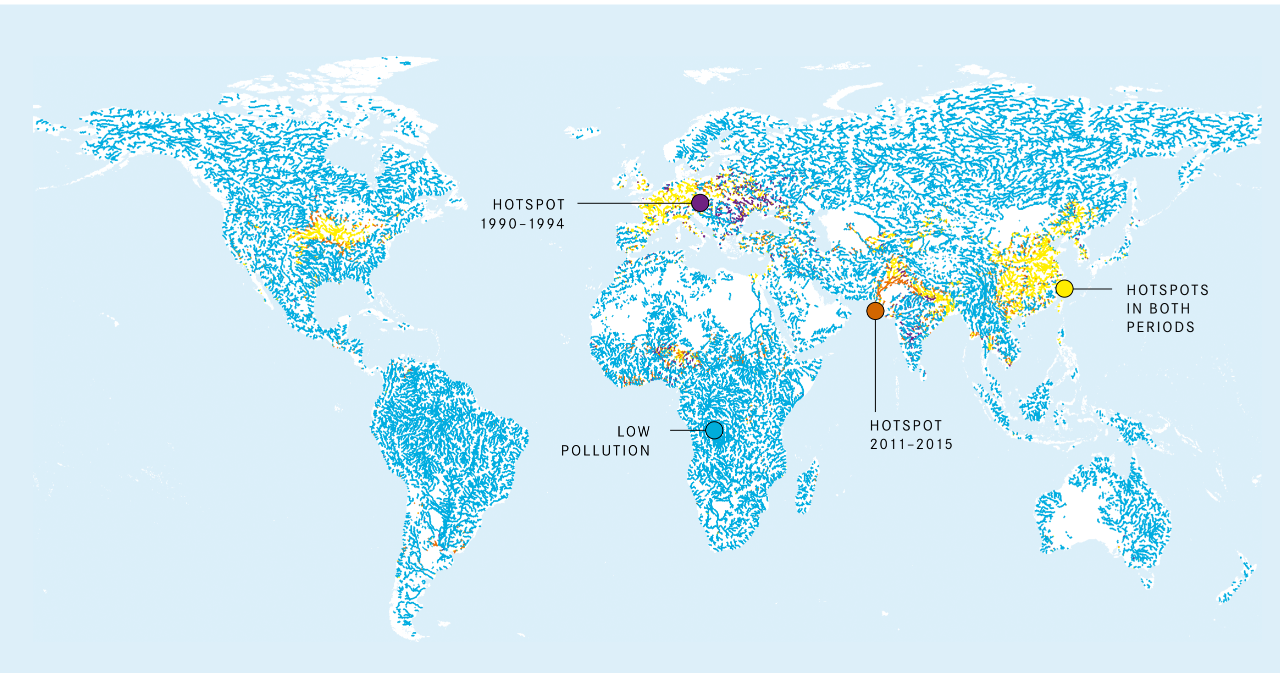


Figure 4.17: Global river network showing hotspots of salinity pollution for the periods 1990-1994 and 2011-2015.

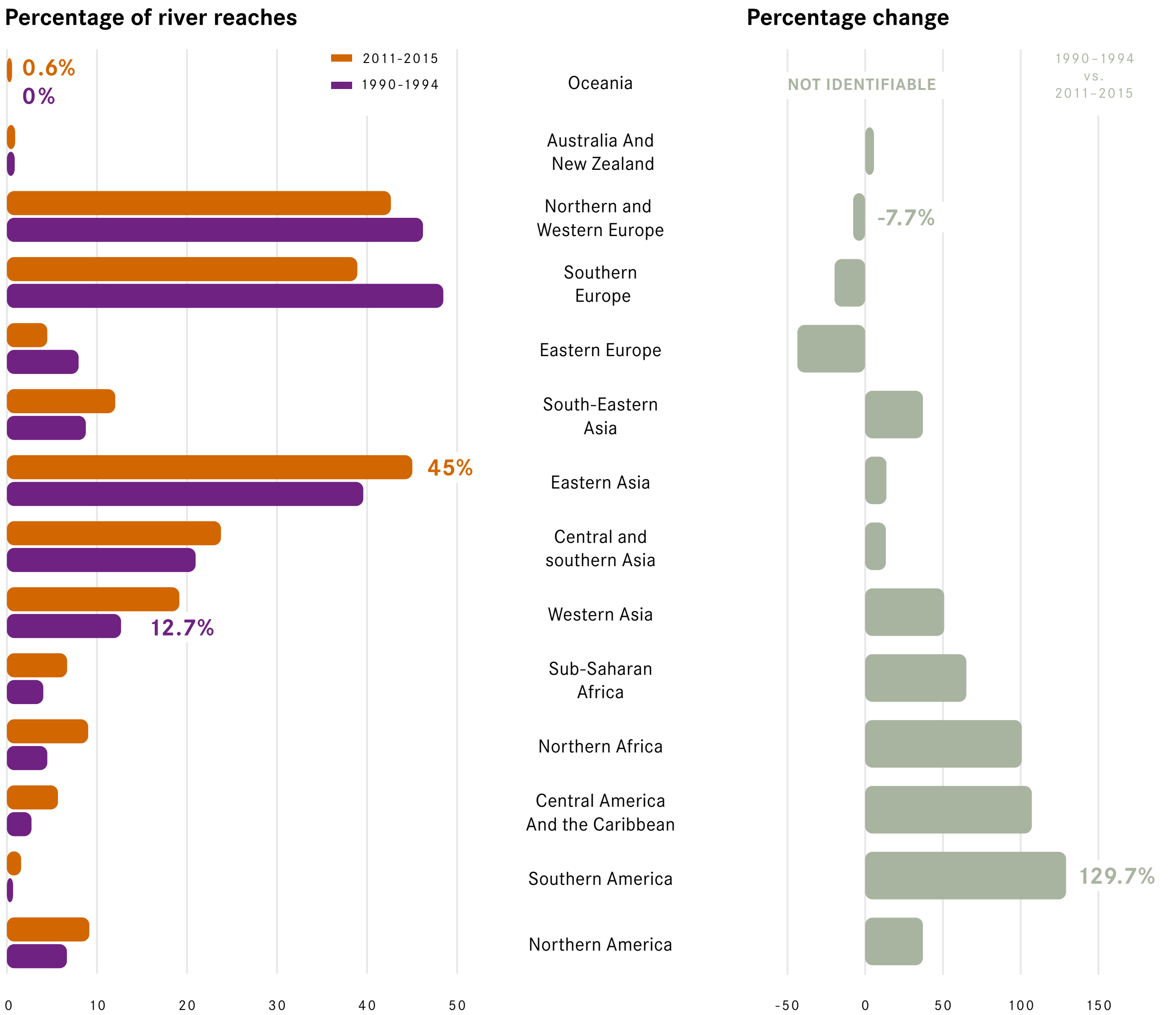


Figure 4.18: Fraction of rivers classified as hotspots of nitrate pollution for the periods 1990-1994 and 2011-2015.

Globally, the fraction of river reaches classified as hotspots is relatively constant. In the period 1990-1994, 11% of river reaches were classified as hotspots, and 12% in the second period. While in Europe the number of hotspot rivers is decreasing, most regions of the world are characterized by an increasing number of hotspots(Figure 4.18). The largest increase between the two assessment periods occurred in South America , where the number of hotspot rivers increased by more than 100%. This is alarming as the example of Europe shows that legacy pollution of nitrate poses risk for water quality for decades and even beyond.

4.3. Future scenarios of water quality

Clean water is essential for nature and society, but humans pollute the water during its use and alter the quality of water resources in several ways. Increasing water use in the domestic and industrial sectors and intensified agricultural activities as a result of socio-economic development leads to increased return flows that all potentially contribute to water pollution, which in turn enhances imbalances between demand and supply of good quality water. Problems differ and are large in many world regions, particularly in developing countries (UNEP 2016), and the problems are expected to increase in the future due to a growing population, food demand and climate change. Water of adequate quantity and good quality is a prerequisite to achieve the UN Sustainable Development Goals (SDGs). Water quality needs to be included in assessments providing an overview on the status of future water resources and in SDGs research.

Several global assessments were carried-out in the past (e.g., Millennium Ecosystem Assessment (Alcamo et al. 2005); UNEP's Global Environment Outlook (Rothman et al. 2007). In the last years, much effort is spent on impact studies related to the future of water resources in terms of quantity (e.g., the Inter-Sectoral Impact Model Intercomparison Project, ISIMIP), but the future of water quality is so far rarely addressed at large and global scales. The modeling of future water quality not only requires input data representing hydrological, water use and socio-economic conditions, moreover, data is required on the development of sanitation and future treatment of wastewater and agricultural practices (i.e., information on fertilizer input etc.). To close this gap, water quality scenarios need to be developed. A World Water Quality Alliance (WWQA) working group dedicated significant efforts to build storylines and derive quantitative scenarios. The community consensus followed the shared socioeconomic pathways (SSPs; O'Neill et al. 2014), ISIMIP phase 2 (Frieler et al. 2017), the International Nitrogen Management System project (INMS, De Vries et al. 2020), and work on future sanitation of van Puijenbroek et al. (2019). Finally, three storylines and scenarios were developed to analyze future climate change based on a wide spectrum of assumptions regarding demographic and economic growth and attitude towards environmental problems and resource depletion. The tree scenarios are as follows:

(1) SSP1-RCP2.6 combination. A sustainability scenario characterized by good progress toward sustainability, with ongoing efforts to achieve development goals while-reducing resource intensity and fossil fuel dependency.

(2) SSP2-RCP6.0 combination. A scenario describing a business-as-usual world.

(3) SSP5-RCP8.5 combination. A scenario following a traditional development with a focus on economic growth with continued high greenhouse gas emissions.

Results of the scenario development process and scenario analysis is expected to be published within this year.

4.3.1 Modeling framework and input data

For GlobeWQ, water quality scenario simulations were carried out with the global models WaterGAP3 (hydrology, water withdrawal and water consumption) and WorldQual (loadings and in-stream concentrations). Model runs were performed for FC and BOD based on the scenario inputs developed within WWQA. In this context, the model input and assumptions were set-up with input data representing the conditions of the SSP2-RCP6.0 scenario combination. The sources of specific input data are listed in Table 4.6.

Variable	Historical data	Future data (SSP2-RCP6.0)
Population	Until 2020: HYDE 3.1, HYDE 3.2, UN Statistics	NCAR
Sanitation	Until 2015: Reder 2014 (PhD Thesis), OECD, Eurostat, JMP, and several country-specific sources.	van Puijenbroek et al. (2019)
Livestock	Until 2015: FAO	IMAGE model (INMS project)
GDP	Until 2020: World Bank	IMAGE model (INMS project)
Industrial Value Added	UN Statistics economic statistics	IMAGE model (INMS project)
Manufacturing Gross Value Added	From national statics, Flörke et al. (2013)	IMAGE model (INMS project)

Variable	Historical data	Future data (SSP2-RCP6.0)
Hydrology	WaterGAP3 model. The hydrology model was forced with observational dataset EWEMBI (Frieler et al. 2017, Lange 2016, Lange 2018)	WaterGAP3 model. The hydrology model was forced with bias-corrected climate forcing from ISIMIP2b (Frieler et al. 2017, Lange 2018). Output from four different Global Circulation Models (GCM) was used: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5

Table 4.6: Sources of specific input data for the WaterGAP3 and WorldQual models.

4.3.2 Future FC loadings and in-stream concentrations

Figure 4.19 shows the global trend in FC loadings for the SSP2-RCP6.0, i.e. a business-as-usual scenario world, calculated as the average value across the four GCM-driven model outputs, for the time period 2010 to 2099, by pollution source (Fig. 4.19, left diagram) and per continent (Fig. 4.19, right diagram). Grid-based model results are aggregated to draw a global picture of the main sources (domestic, manufacturing, and agricultural sectors) and continental contributions. The estimates of the loadings are based on sanitation data from van Puijenbroek et al. (2019) and hydrological model outcomes were driven by four GCMs.

Considering that the domestic sector (sewered and non-sewered) is the most relevant source of FC pollution (left diagram in Figure 4.19), a continuous reduction in FC loadings starts after the year 2040 and is mainly driven by improvements in sanitation practices, i.e. increasing sewage connection rates and treatment levels. Asia is the most contributing continent to the global FC loadings but will reduce the contribution tremendously until the end of the 21st century. The FC loadings of the other continents will decrease after 2040, too, whereas FC loadings increase until 2060 in Africa and then start to decline (Fig. 4.19, right diagram)

An overview of the monthly median FC concentrations (across all GCMs in case of the scenario simulations) in the years 2015, 2030, and 2050 is shown in Figure 4.20.

In 2015, global hotspots, i.e. river stretches with concentrations above 1000 cfu/100ml are mainly located in eastern China, India, Pakistan, Central Asia, Eastern Europe, the Balkans, Turkey, and the Caucasus. In Africa, hotspot regions are in Nigeria, North-Western and Southern Africa, Ethiopia, and the surroundings of Lake Victoria. On the American Continent, the most populated areas become visible along the coastlines in Latin America.

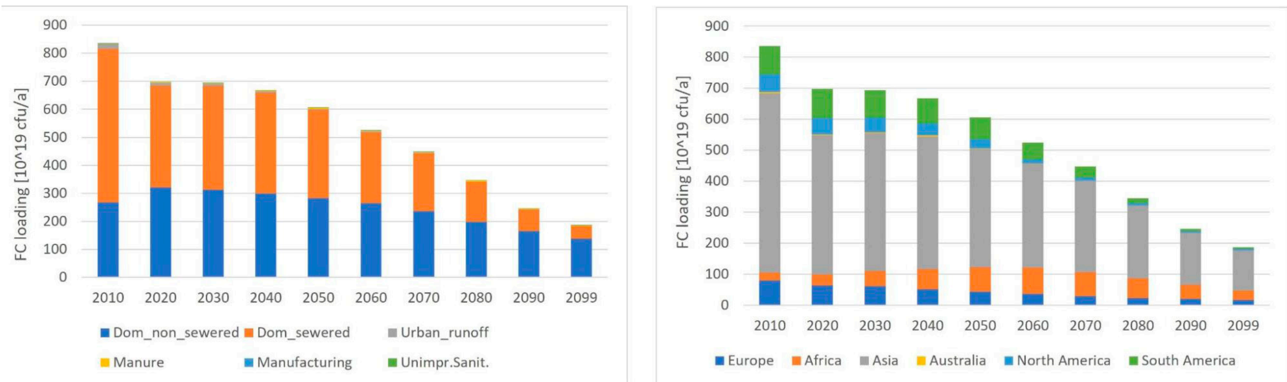


Figure 4.19: Future development of FC loadings globally until the end of the 21st century as simulated by the WorldQual model. The left diagram shows the development according to the different sources while the right diagram provides an overview of the continental contributions.

Looking ahead into the future reveals that in general the hotspot regions are expected to decrease over time except for Africa where hotspots are likely to increase. However, many hotspot regions correspond to the year 2015 but to a lesser extent and intensity. Although sanitation practices and wastewater management (i.e., increasing connections to treatment plants and improved treatment levels) further improve over time, most of the hotspots in the base year (2015) are still apparent in 2050. In these regions, high FC concentrations are either caused by high FC loadings due to population growth (e.g., China, India) or by the impact of climate change, which can be expected to play a role, too, since prolonged drier periods are very likely in some of the hotspot regions in the future (e.g., Mediterranean region). However, the impact of climate change compared to the future socio-economic development and sanitation practices has not yet been evaluated but needs to be analyzed in more detail.

High colony forming units of FC in rivers threatens human health as it indicates recent fecal contamination and greater likelihood of the presence of disease-causing pathogens, such as bacteria, viruses, and parasites. Still, with population growth and climate change many inhabitants are likely to be at risk of health problems associated with FC intakes in the river systems. According to the model results, additional FC concentration hotspots are expected to occur in Eastern Europe, Turkey, the MENA region, Western Africa, Mexico, the Andean region, and the Brazilian coast. A general positive trend due to further decrease in FC loadings is more likely for the second half of the century.

Global estimations of FC concentrations

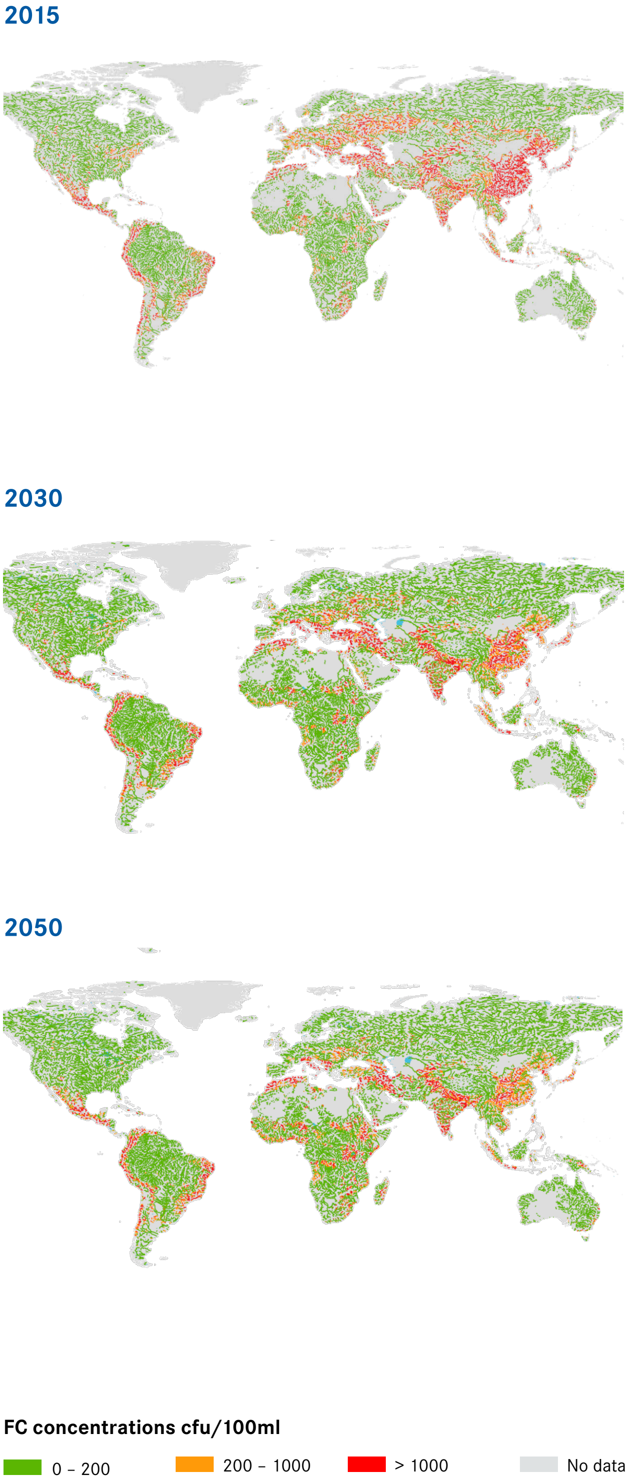


Figure 4.20: FC in-stream concentrations for the years 2015, 2030, and 2050 as represented by the monthly median of the given year. Future FC concentrations are based on simulations driven by the output of the four GCMs. Units: cfu/100 ml

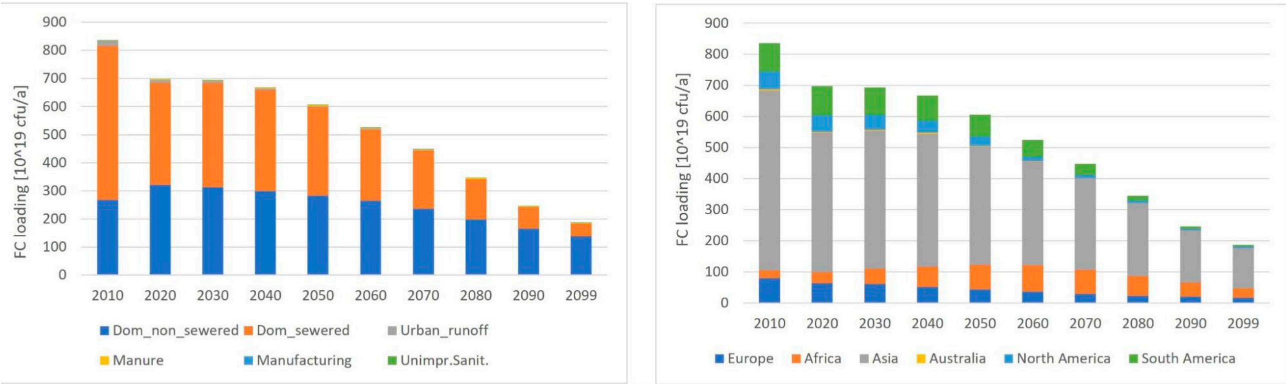


Figure 4.21: Future development of BOD loadings globally until the end of the 21st century as simulated by the WorldQual model. The left diagram shows the development according to the different sources while the right diagram provides an overview of the continental contributions.

4.3.3 Future BOD loadings and in-stream concentrations

Figure 4.21 shows the outcomes of the WaterGAP3-WorldQual model simulations for BOD according to the SSP2-RCP6.0 scenario, i.e. a business-as-usual scenario world. Grid-based model results of BOD loadings are differentiated into the various sources such as the domestic, manufacturing, and agricultural sectors, and then aggregated to continental and global numbers. Like for the FC scenario results (see Section 4.3.1), the model results are based on sanitation data from van Puijenbroek et al. (2019) and hydrological model outcomes were driven by four GCMs.

Overall, BOD loadings are expected to increase until 2060 and then decline afterwards (Fig. 4.19). The main contributing sector is the domestic sector, however, the contribution from the manufacturing sector is likely to rise until the end of the century. While the domestic sewered and non-sewered sources contribute to a positive development (i.e., reduction in BOD loading), the increasing manufacturing loadings counteract the same positive trend as compared to the FC loadings (Fig. 4.21). Like for the FC loadings, the largest contribution of BOD loadings is from Asia, here especially from the countries which are in economic transition. While the continental contributions of Asia, Australia, Europe, North and South America are expected to slowly decline over time, BOD loadings in Africa are likely to increase until 2100 (Fig. 4.21, right diagram).

The median of expected BOD in-stream concentrations is visualised for the years 2015, 2030, and 2050 (Figure 4.21). According to the maps, hotspots (i.e., where concentrations exceed the threshold of higher than 4 mg/l) are visible in North-East China, India, Pakistan, Mexico, Brazil, the MENA region, and particularly in Northern and Southern Africa. Overall, BOD concentrations are expected to decrease in most river stretches globally, but hotspots continue to exist as compared to the year 2015. While most hotspots decrease in extent over time, the hotspots in Africa are expected to increase. Here, the growth in BOD loadings lead to high BOD concentrations up to the year 2050. (Figure 4.21).

As one plausible future, the model calculations for SSP2-RCP6.0 shows that water quality problems associated with BOD will still exist on all continents of the world, including many industrialised, transition and developing regions (Figure 4.22). Globally, in most river stretches BOD concentrations will be below the threshold of 4 mg/l in the future as a result of treatment improvements.

First results have been gained for the SSP2-RCP6.0 scenario. As one of the future pathways, the model synthesis for SSP2-RCP6.0 shows that water quality problems associated with FC and BOD are expected to decrease in nearly all parts of the world. However, pollution hotspots are likely to exist on every continent including industrialised, transition and developing countries. The results for SSP2-RCP6.0 indicate that concentrations exceed the thresholds by 2050, i.e. two decades beyond the SDG 6.3.2 target year 2030, in several, and even large regions of the world. For FC, an improvement is expected in many industrialized countries, but a deterioration of rivers may occur in several developing countries. As a next step, the WorldQual model will be applied to simulate the other two scenarios. A scenario assessment will be conducted based on the model results as well as in comparison with the outcomes of other global-scale models as part of the Water Quality MIP which is now a new (sub)-sector of ISIMIP.

Global estimations of BOD concentrations

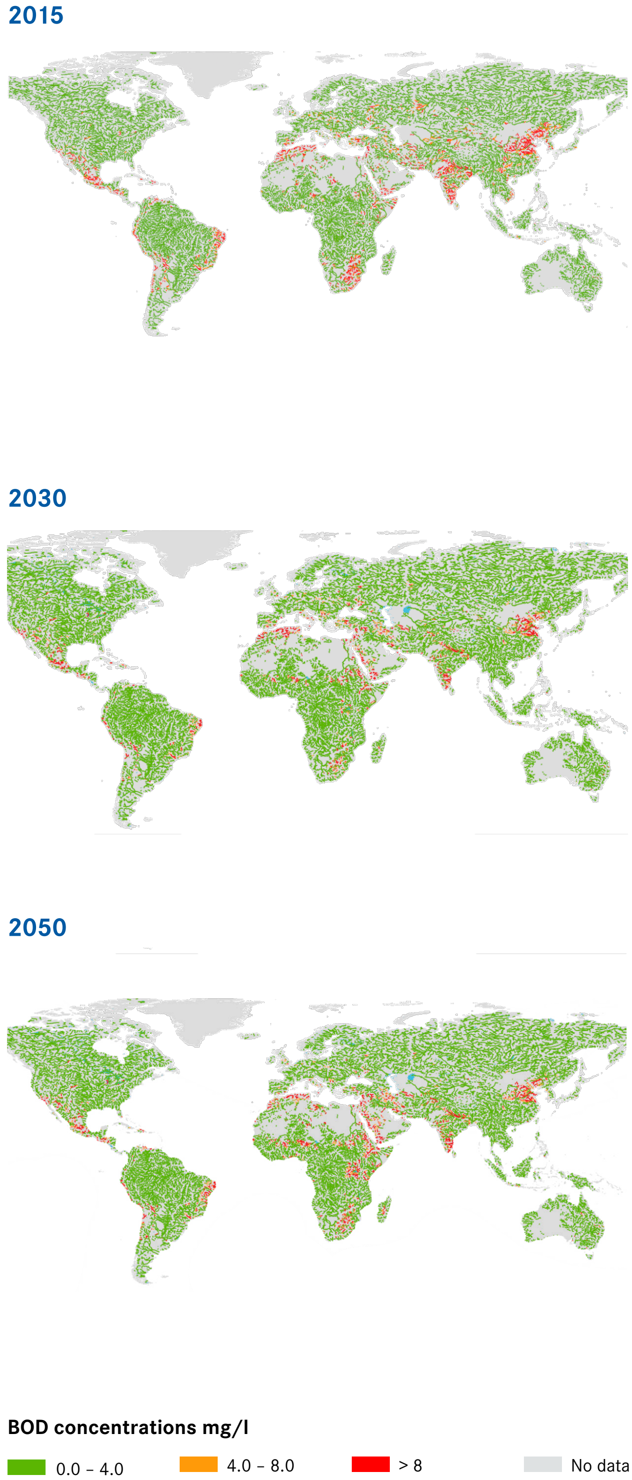


Figure 4.22: BOD in-stream concentrations for the years 2015, 2030, and 2050 as represented by the monthly median of the given year. Future BOD concentrations are based on simulations driven by the output of the four GCMs. Units: mg/l

5. Persistent pressures on water quality in Europe: Nitrogen legacies and urban discharge

5.1. Nitrogen legacies in Europe

5.1.1. Nitrogen-from a nutrient to a pollutant

Nitrogen is an essential nutrient without which life cannot exist. But since the early 20th century, the Haber-Bosch process has made it possible to produce artificial fertilizers by fixing atmospheric nitrogen. This has led to rising crop yields and improved food security. On the other hand, the natural nitrogen cycle has been substantially distorted as today humans generate much more reactive nitrogen than all natural processes combined. This distortion of the nitrogen cycle and the excess production of reactive nitrogen such as nitrate is considered a global problem that exceeds planetary boundaries (Steffen et al. 2015).High levels of reactive nitrogen (mostly nitrate) in surface waters can lead to eutrophication, i.e., excessive plant and algal growth. As a result, microbial decomposition of plant and algal material depletes oxygen, which can lead to the death of aquatic life. Nitrate in drinking water can impair the body's ability to carry oxygen, which is especially dangerous for infants and can lead to the so-called „blue baby syndrome".

The Haber-Bosch process allows the production of large quantities of mineral fertilizers, which have been applied in vast amounts in Europe since the 1930s. This has led to an imbalance of nitrogen in the landscape and a nitrogen surplus in soils (N surplus). The N surplus is calculated as the sum of total N-inputs, mainly from atmospheric deposition and mineral fertilizers, minus total N-outputs, mostly through crops. Nearly 70% of N-inputs originate from mineral and organic fertilizers, followed by atmospheric deposition, which accounts for about 15% of N-inputs. In response to the ecological impacts of high nitrogen levels, the European Union (EU) has implemented nitrogen legislation to reduce nitrogen pollution in the environment. This began in 1991 with the Nitrates Directive, which restricts the use of nitrogen-based fertilizers in agriculture to reduce groundwater pollution. Today, the Water Framework Directive aims to protect and restore the quality of European waters, with reducing nitrogen pollution remaining on the agenda. High nitrate concentrations are still a pressing issue for drinking water safety and aquatic ecosystem health in Europe.

High nitrate concentrations are still a pressing issue for drinking water safety and aquatic ecosystem health in Europe. Efforts to reduce nitrogen inputs often have limited or delayed effects on nitrogen in surface water which can be attributed to large legacy N-stores that have accumulated in groundwater and soils. An analysis of the time lags between nitrogen inputs into river catchments and outputs in more than 200 catchments in Germany and France revealed an average time lag of 5 years between a reduction in nitrogen inputs and an effect on surface water quality (Ehrhardt et al. 2021). While the average time lag is often less than 10 years, there can be significant long-term effects stemming from the fractions of nitrogen with decadal time delays.

5.1.2. Reconstruction of the Long term annual Nitrogen surplus across Europe (1850-2019)

Understanding current and future nitrate pollution in Europe requires a detailed understanding of the inputs and the residence time (i.e. time lags between nitrogen inputs and outputs) in the catchments to assess the current state of nitrogen pollution and to project its future trajectory (Basu et al. 2022). In the GlobeWQ project the efforts in this regard have been concentrated on the long-term (1850-2019) reconstruction of nitrogen surplus. This is an indispensable prerequisite for developing future nitrogen pollution scenarios.

The European N surplus data set (Batool et al. 2021) comprises N surplus from agricultural (cropland and pasture) and non-agricultural soils across Europe at a spatial resolution of 5 arcmins (≈10 km at the equator) over more than a century (1850 – 2019). The underlying method (Appendix A.3 for more details) explicitly accounts for uncertainties arising from the sources of input data and methodological choices for key components of N surplus (i.e., fertilizer, manure, and N removal rates).

Figure 5.1 summarizes the Nitrogen balance for soils in Europe since 1850. The N surplus in Europe tripled from about 20 kg/ha/year to about 60 kg/ha/year between the 1930s and until the late 1980s. Since the peak,

Nitrogen Balance for Soils throughout Europe

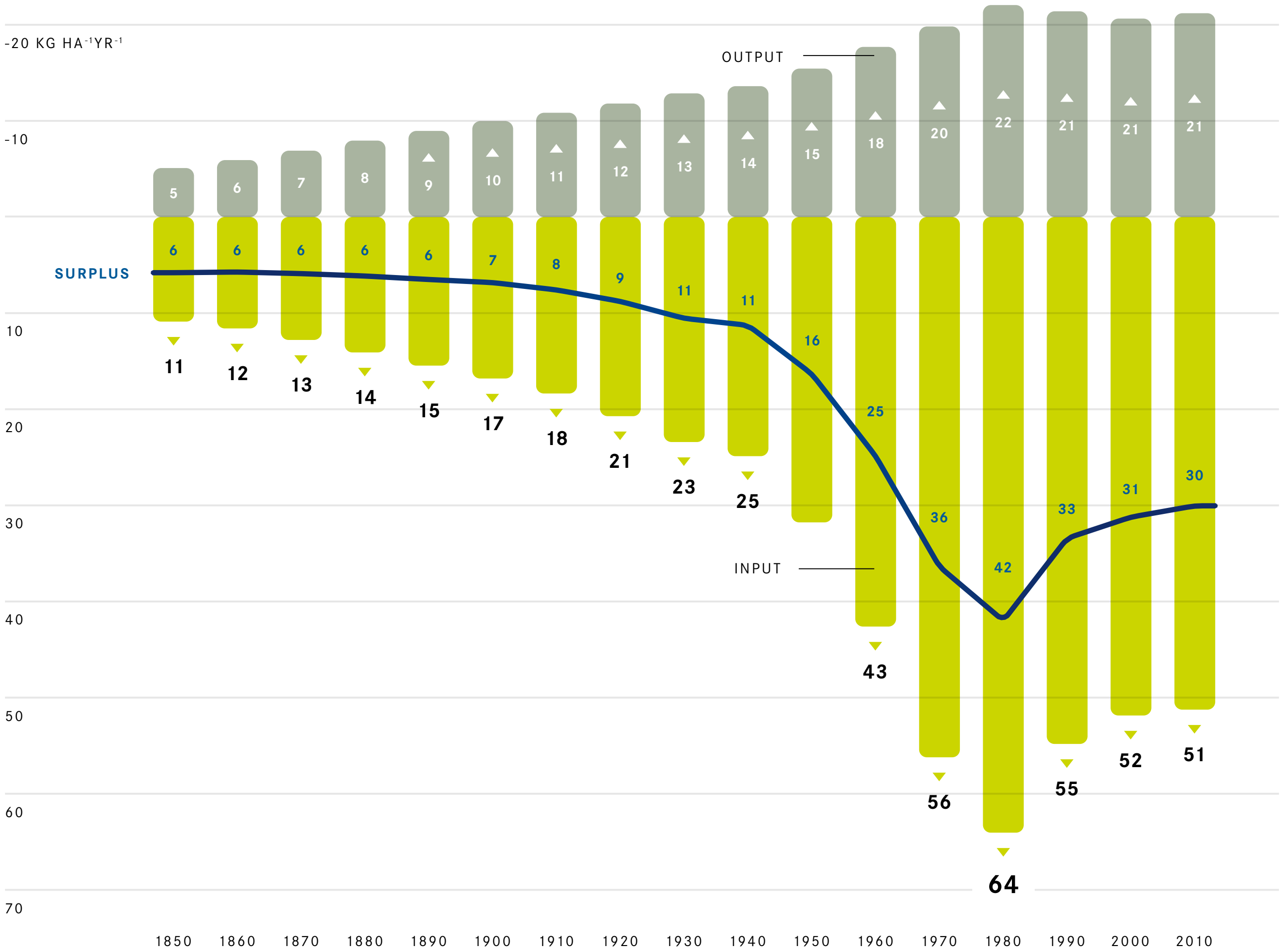


Figure 5.1: Reconstructed Nitrogen balance for soils in Europe since 1850 in kg N per hectare and year. N surplus tripled between the 1930s and till the end of the 1980s from about 20 kg/ha/year to about 60 kg/ha and year. N surplus reached its peak value around 1990 and has declined since then. N surplus is still about 5 times higher than in the preindustrial period.

N surplus has declined but is still about 5 times higher than in the pre-industrial period.

The spatiotemporal patterns of N surplus are shown in Figure 5.2, illustrating a snapshot for the years 1900, 1930, 1960, 1990, 2000, and 2015. A clear latitudinal pattern was observed, with lower N surplus values in northern Europe, higher values in mid-latitudes, especially

in western and central Europe, and moderate values in southern Europe. Additionally, N surplus showed substantial temporal changes in most areas during the period 1850-2019, except for northern Europe, which remained relatively stable at low values. These findings emphasize the significance of having a long-term dataset of N surplus to quantify temporal trends. In European industrialized countries, most grid cells had the highest N surplus values around 1990, which subsequently declined, particularly in countries such as Denmark, Germany, Latvia, Lithuania, Estonia, Belarus, Ukraine, among others. On the other hand, Spain displayed an upward trend in most grid cells during the period 1960-2000 and a gradual downward trend thereafter.

The gridded N surplus data allows to examine the N surplus at different spatial and temporal aggregation levels. Figure 5.3, for example, shows the agricultural and total N surplus estimates over time and across regions- EU-28, Germany and the Danube river basin. Figure 3 also depicts, the uncertainties of N surplus. An interactive visualization of the N surplus data set is available on the GlobeWQ platform.

The annual spatial variation in N surplus

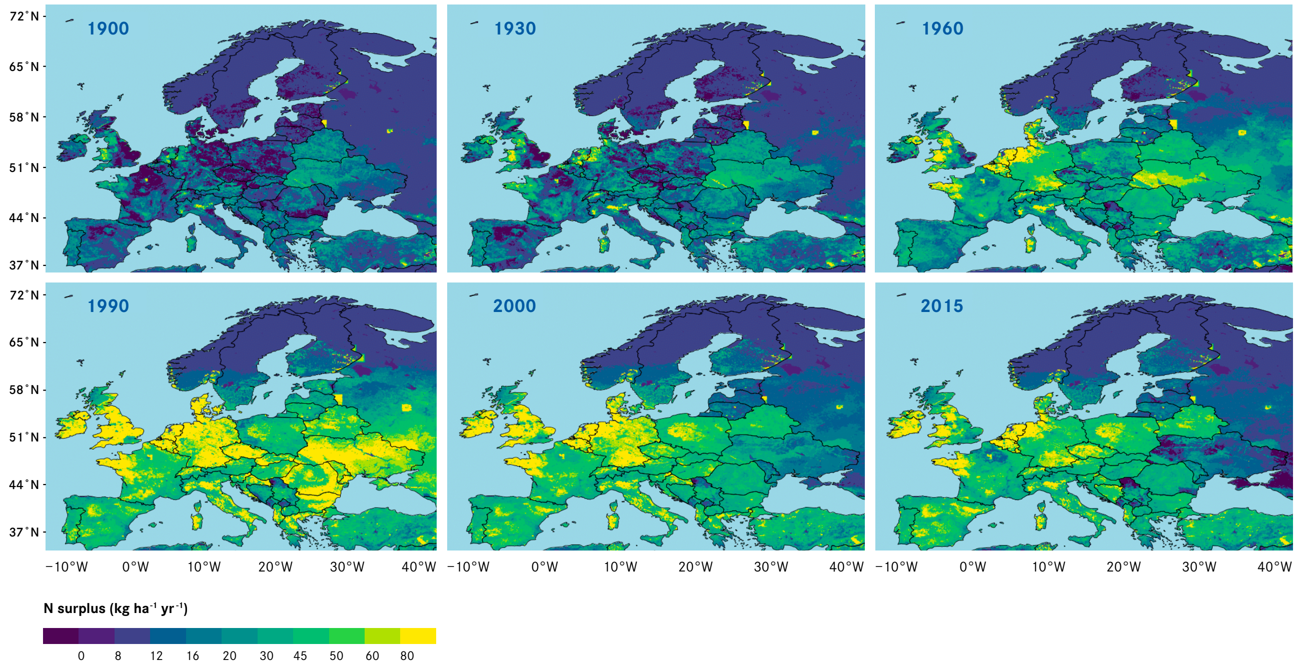


Figure 5.2: Snapshots of N surplus (kg/ha of grid area/yr) across Europe. The figure shows the annual spatial variation in N surplus given as the mean of our 16 N surplus estimates for the selected years.

Agricultural N surplus for Europe, Germany and the Danube river

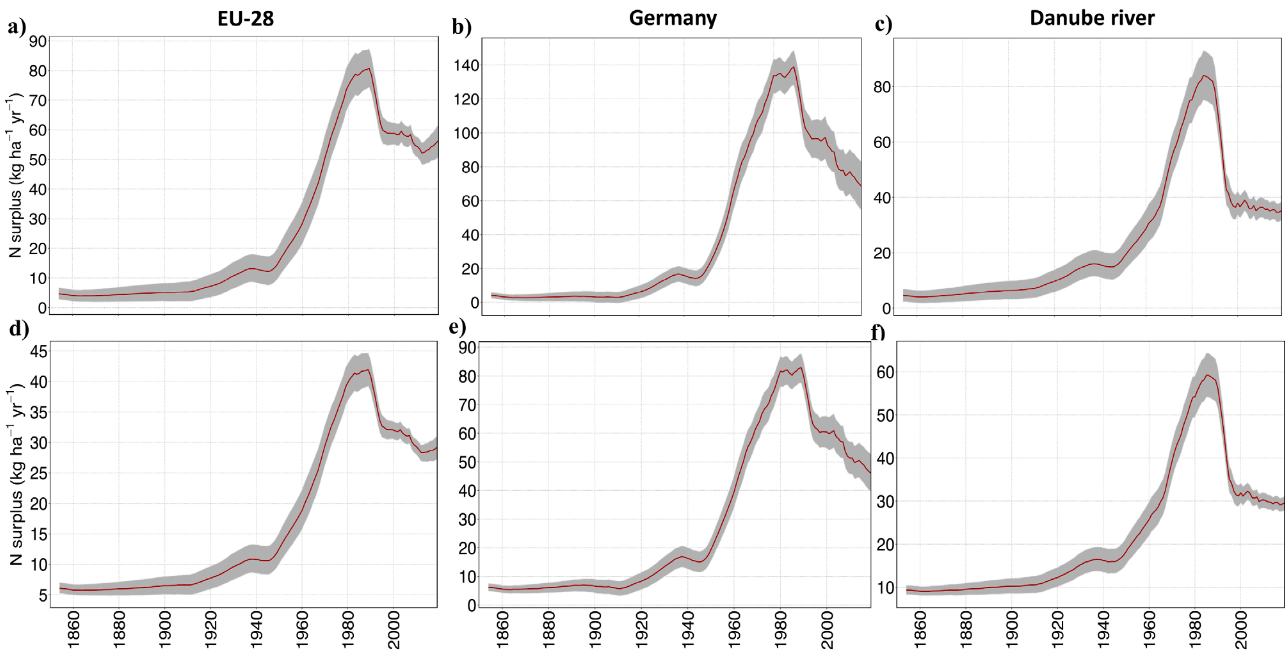


Figure 5.3: Agricultural N surplus (kg/ha of agricultural area/yr) and total N surplus (kg/ha of physical area/y) for EU-28, Germany and the Danube river basin (5 years moving average during 1850-,2019). The grey color ribbon in each panel shows the ranges (minimum and maximum values) of the 16 N surplus estimates reconstructed in this study, whereas the average value is presented by a red line. (a-c): Agricultural N surplus for EU-28, Germany and Danube river, (d-f): Total N surplus for EU-28, Germany and Danube river.

5.1.3. Implications from Europe for other regions of the world

Many European water bodies still suffer high nitrogen levels despite numerous measures to reduce inputs into the environment. A major part of this problem is the accumulation of past nitrogen inputs which are now legacy stores in soils and groundwater that impair an immediate effect of reducing nitrogen inputs. Understanding legacy pollution and time lags is important for evaluating the efficiency of implemented nitrogen mitigation measures in different river basins in Europe under the Water Framework Directive. Substantially cutting down the N surplus is one of the most important actions, but accumulated nitrogen in agricultural soils may also provide other opportunities to use and recycle stored nitrogen. Nitrogen concentrations and loads in groundwater can be reduced by restoring wetlands and thus fostering natural attenuation. The ultimately best way to safeguard water quality is to avoid nitrogen pollution and to keep the inputs and outputs in balance.

5.2. Urban discharge fraction as point source proxy for water quality and ecological status of river water bodies

The aim of this chapter is to introduce the urban discharge fraction (UDF) as a simple point source proxy for assessing the water quality and ecological status of water bodies. This proxy can be applied globally to identify potentially threatened water quality and ecological status of river water bodies. The main advantage of UDF is its ease of calculation and application to stream and river networks (Appendix A.4). Therefore, UDF could be easily incorporated into local monitoring systems wherever data on urban water discharge, river network topology, and river discharge are available simultaneously.
UDF could be used as a first indicator of water quality problems even before certain substances are measured.

Stream order, wastewater treatment plant (WWTP) effluents, and urban discharge fraction are important factors that can impact the ecological status of streams and rivers. Stream order refers to the hierarchical classification of streams based on their size and the number of tributaries they have (Fig. 5.4). WWTP effluents can have significant impacts on the ecological health of streams and rivers. These effluents can contain high levels of nutrients, such as nitrogen and phosphorus, which can lead to eutrophication and harmful algal blooms. They can also contain a range of other pollutants, including heavy metals, substances of emerging concern including pharmaceuticals, and microplastics, which can harm aquatic organisms and degrade water quality and ecological

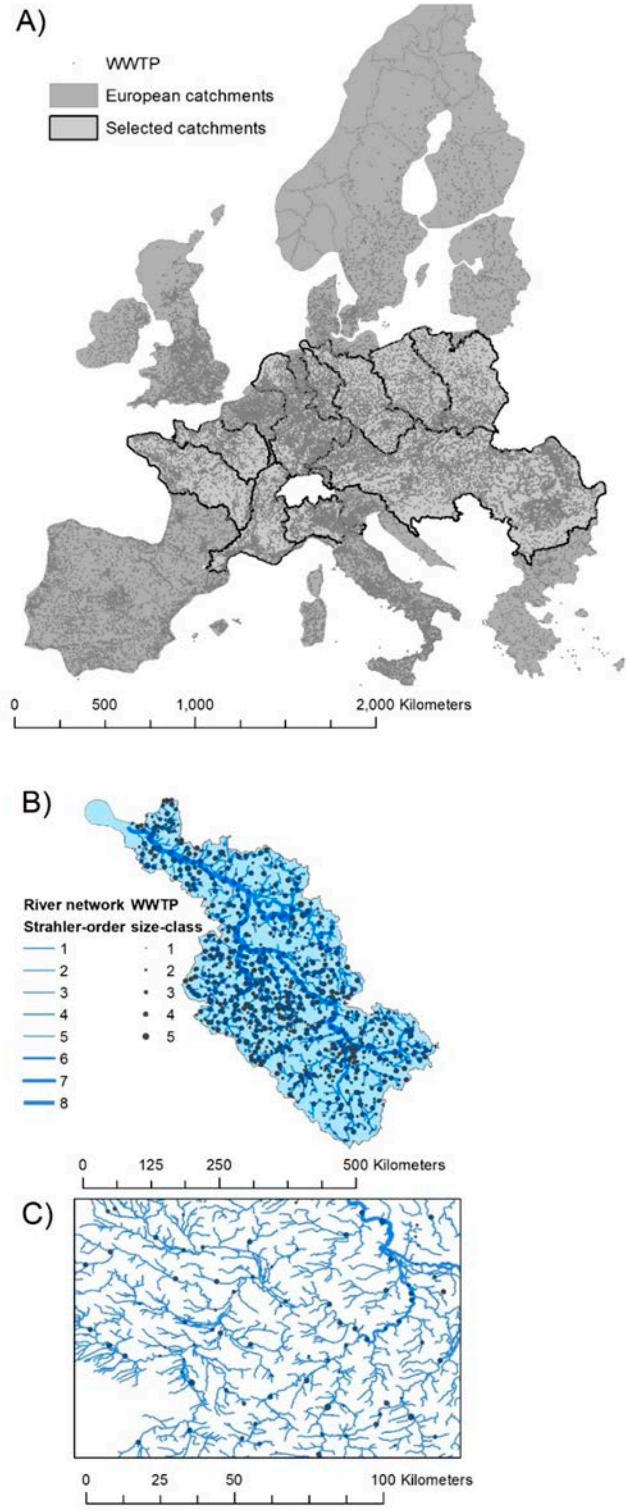


Figure 5.4: European wastewater treatment plants with population equivalents > 2000 reported under the umbrella of the European wastewater treatment directive. A) Data from the 10 selected catchments are used to validate the relation between UDF and stream order based on the total data on smaller data sets. B) Example of Elbe catchment showing the river network and the wastewater treatment plants indicating the size-class related to number of population equivalents. C) A more detailed view to the river-network (EU-Hydro) that built the base and provided the information of stream order and segment length.

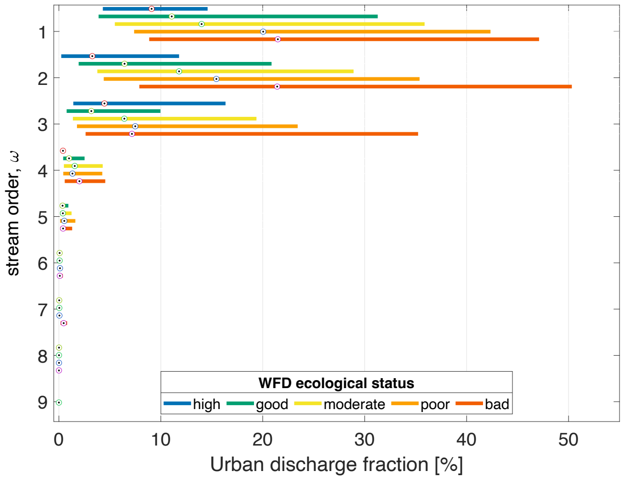


Figure 5.5: Ecological status differentiated by stream order across all river types in Europe shown with the corresponding UDF median and interquartile range (Büttner et al. 2022).

status. The urban discharge fraction (UDF), which refers to the proportion of urban runoff that enters streams and rivers via WWTP effluents or combined sewer overflows, can have a significant impact on the ecological status of these waterways.

Here, we summarise the results of a study using this concept based on European data (Büttner et al. 2022). The concept of UDF is applied in the Oder river case study (Chapter 6.4) during investigation of the Fish kill event in August 2022.

The results of the second reporting cycle of the European Water Framework directive (WFD) show that despite decades of regulatory efforts less than only half of the European rivers and streams are in good ecological status due to the multiple pressures including wastewar from households and small industries (EEA 2018). Using public data of the European Urban Wastewater treatment directive, UDF under low flow conditions from about 26500 WWTPs were connected with the ecological status of the related river segments. Selecting the small rivers and testing the hypothesis that stream ecological status degradation across Europe is related to the local intensity of wastewater discharge represented as UDF, with an expected stream-order (ω) dependence based on the scaling laws that govern receiving stream networks, revealed that ecological status in streams (ω≤3) declined consistently with increasing UDF across river types and basins (Fig. 5.5). In contrast, ecological status in larger rivers (ω≥4) was not related to UDF. From a continental-scale logistic regression model (accuracy 86%) an ecologically critical threshold UDF = 6.5% ± 0.5 was identified. This threshold is exceeded by more than one third of WWTPs in Europe, mostly discharging into smaller streams (Fig. 5.6).

There are two main reasons why wastewater treatment plants fails to protect stream ecosystems in Europe: first, the entry points of WWTPs into the stream networks are not always at the optimal position because the dilution capacity of receiving waters especially during low flow conditions is not enough considered and second, a system-oriented approach is missing taking into account the location in the river network, the quantity of generated wastewater, water reuse, and local discharge conditions in the whole river network. The estimated threshold could be considered as an upper limit for a safe operating space for UDF in streams. New strategies for wastewater management are necessary that combine an integrated view of wastewater generation, treatment, and wastewater reuse with direct consideration of the receiving water body in the context of a river network.

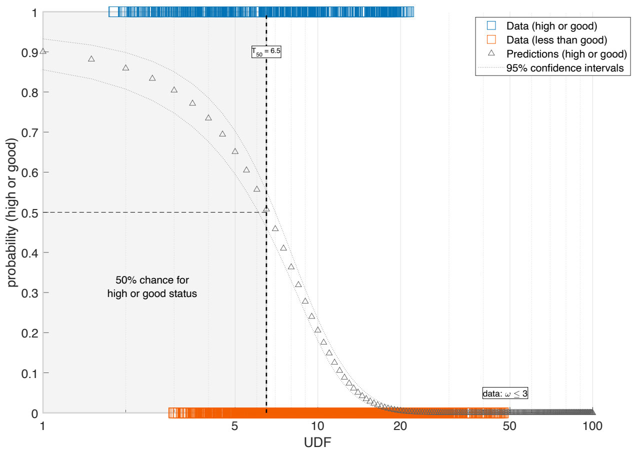


Figure 5.6: Deriving a UDF maximum threshold for improved ecological status of river networks. The binomial logistic regression model is based on data for the small streams (·≤3). The vertical dashed line indicates the T50 = 6.5% threshold of 50% probability of a local stream segment to have high or good ecological status (Büttner et al. 2022).

6. The GlobeWQ Case studies

The World Water Quality Assessment, mandated by the UN-ENVIRONMENT, relies on the GlobeWQ case studies to demonstrate the crucial role of water quality in sustainable development. The case studies are central pillars of the UN-ENVIRONMENT mandated World Water Quality Assessment (UNEP/EA3/RES10; 2017).

The case studies provide practical examples of the GlobeWQ platform prototype, methodologies, and tools, and in particular the demonstration of the triangulation approach. These groups are characterized by different starting and framework conditions in terms of preliminary works, data availability, and network partners, both experts and users. The case studies cover a wide range of socio-economic conditions and have a global geographical distribution.

Group A: Good Initial and Framework Conditions
The case studies with good initial and framework conditions are characterized by various features. Firstly, there are already preliminary works that can be built upon. Secondly, there are existing monitoring data that can be integrated into GlobeWQ. Thirdly, local partner networks and structures are established both on-site and within the GlobeWQ consortium. Fourthly, the potential users of the GlobeWQ platform are known and reachable.

Group B: Incomplete Initial and Framework Conditions
In the case studies of Group B, there are limited preliminary works, and monitoring data is either scarce or not freely available. Another aspect is the incompleteness and unreliability of existing partner networks and structures. These may need to be revived or even built from scratch to ensure effective collaboration. Potential users are generally known, but collaboration did not exist prior to the project.

Group C: Largely Unknown Initial and Framework Conditions
In Group C, no known preliminary works exist, and therefore, there is no existing data foundation to build upon. Partner networks and structures are incomplete and unreliable, similar to Group B, and they need to be identified and integrated initially. Potential users are often still unknown.

The case studies provide an opportunity to test the GlobeWQ concept through concrete, user-driven examples. In direct user dialogue, three case studies, one from each group A-C, were implemented on the GlobeWQ platform. The following sections will provide a closer explanation of the development and status of these use cases.

6.1. Elbe case study

6.1.1. Background

The Elbe river and its catchment is the group A case of the GlobeWQ project. Thus, there is already a substantial amount of information to draw on. This makes it more difficult to contribute further to the existing pool of data and knowledge. The case study has been mainly developed with the Flussgebietsgemeinschaft (FGG) Elbe which is a cooperative association for managing and protecting the water resources of the Elbe River Basin in Germany composed of representatives from the federal states of Germany through which the Elbe River flows.

The main goal of the FGG Elbe is to implement the European Union's Water Framework Directive, which aims to achieve a good ecological and chemical status for all surface waters within the EU, including rivers like the Elbe. The FGG Elbe works towards this goal by promoting sustainable water management practices and coordinating efforts to improve the water quality of the Elbe River Basin.

6.1.2. Water quality issues in the Elbe River

One major water quality challenge in central European river basins, including the Elbe is the long-term pollution of the entire system with nutrients in particular nitrogen (mostly in the form nitrate). Since the Haber-Bosch process allowed the production of large quantities of mineral fertilizers, the N surplus in Europe tripled from about 20 kg/ha/year to about 60 kg/ha/year between the 1930s and until the late 1980s (see Chapter 5.1). Despite efforts to reduce nutrient loadings particularly from diffuse sources remain a key threat to water quality and the ecological status of the Elbe river. As a result of high nutrient concentrations the Elbe river often faces phytoplankton growth in summer with chlorophyll-a concentrations often above 150 µg/l. Oxygen depletion in the region of the Hamburg Harbour is one of the negative consequences. In combination with low discharge conditions, this zone of low oxygen concentration can extend also upstream to the weir at Geesthacht, as in 2018 and 2022.

6.1.3. Objectives

In joint virtual workshops the possibilities of providing water quality information through the GlobeWQ project and how it can support the federal states, the FGG, and the IKSE in their tasks were discussed. The key thematic area that has been identified was the need for timely and spatially distributed information on water quality particularly on patterns of phytoplankton growths.

6.1.4. Implementation

The GlobeWQ *platform prototype* for the Elbe River is focused on the timely provision of water quality data for the main stem of the Elbe River. In situ data of water temperature and dissolved oxygen from automatic monitoring stations of the federal states are regularly updated and provided by the *UNDINE portal*. These data are aggregated on the GlobeWQ platform. Landsat, Sentinel-2 and Planet satellite data are processed automatically for the area from Schnackenburg downstream to the tidal part of the Elbe River. Thus, spatial and temporal gaps of the in situ monitoring are significantly reduced for parameters accessible from satellites, such as Chlorophyll, turbidity or Cyanobacteria. The GlobeWQ platform combines the different data and allows easy access to the integrated information. The combination of parameters allows a rapid examination of the chlorophyll-a dynamic and forms the basis for interpretation.

The GlobeWQ platform for the Elbe is operational and receives regular updates with new data from automated stations and processed satellite images. This does not only allow for an assessment of the current state but also provides insight into the spatio-temporal patterns of water quality , for example seasonal patterns of chlorophyll-a concentrations (Fig. 6.1).

The Elbe case study has demonstrated the capabilities of combining in situ and remote sensing information. The combination of parameters allows a rapid examination of the chlorophyll-a dynamic and forms the basis for further interpretation.

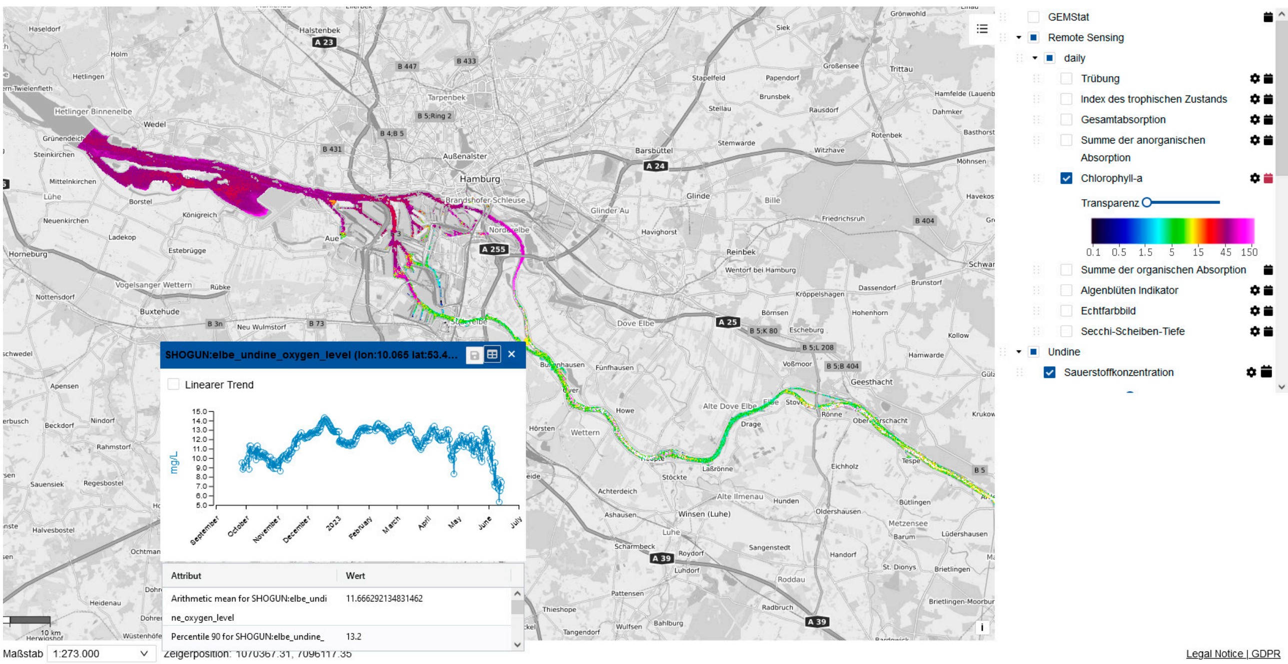


Figure 6.1: Snapshot of the GlobeWQ Elbe platform (13.6.2023) showcasing increased Chlorophyll-a concentration in the lower Elbe river and the Hamburg Harbour. Data from remote sensing and UNDINE stations are combined to provide a comprehensive overview. The time charting tool shows a sharp decline of dissolved oxygen concentrations starting in early June. The GlobeWQ Elbe platform is operational and regularly updated with new data from the automated stations and processed satellite images. The menu is in German as the Elbe use case primarily targets users in Germany.

6.2. Lake Sevan

6.2.1. Background

The lake Sevan use case is categorized as group B use case with some preliminary information and connection to regional stakeholders. The Lake Sevan case study is associated with two other projects. The SEVAMOD2 project aims to develop a nutrient management concept and a 1D eutrophication model for Lake Sevan, integrating physical and ecological factors such as nutrients, plankton, and oxygen. The project also involves the use of satellite-based remote sensing to estimate water quality and the evaluation of alternative management scenarios. In addition to these research activities, the project includes a capacity-building component to train Armenian researchers in satellite remote sensing and lake modeling. The GlobeWQ project also cooperates with the EU4Sevan project, an initiative funded by the European Union aimed at supporting the sustainable management of Lake Sevan in Armenia. The EU4Sevan project has several objectives, including the development of a comprehensive lake management plan, the implementation of measures to reduce pollution and protect biodiversity, and the establishment of a monitoring and early warning system for environmental threats.

6.2.2. Water quality issues in the Lake Sevan region

Lake Sevan is the largest freshwater lake in the Caucasus Region (Surface area 1,242 km^2) and one of the largest freshwater high-mountain lakes of Eurasia. It is located at an altitude of about 1,900 m above sea level. The area of the Lake Sevan Basin is about 5,000 km2 which is about one sixth of the territory of Armenia. For Armenia, Lake Sevan has significant economic, cultural, and recreational value. It is a source of drinking water, irrigation water, and production of hydropower. It also serves as a recreational area. However, because of the intensive and unsustainable use during the past decades (e.g., insufficient development of sanitation solutions, intensive use of pesticides and fertilizers, over abstraction of water for irrigation), the water quantity and quality have significantly deteriorated. The Lake faces numerous environmental challenges and has also suffered significant biodiversity loss. The restoration and preservation of the lake's ecological balance, as well as its protection and sustainable use are top priorities of the Armenian Government.

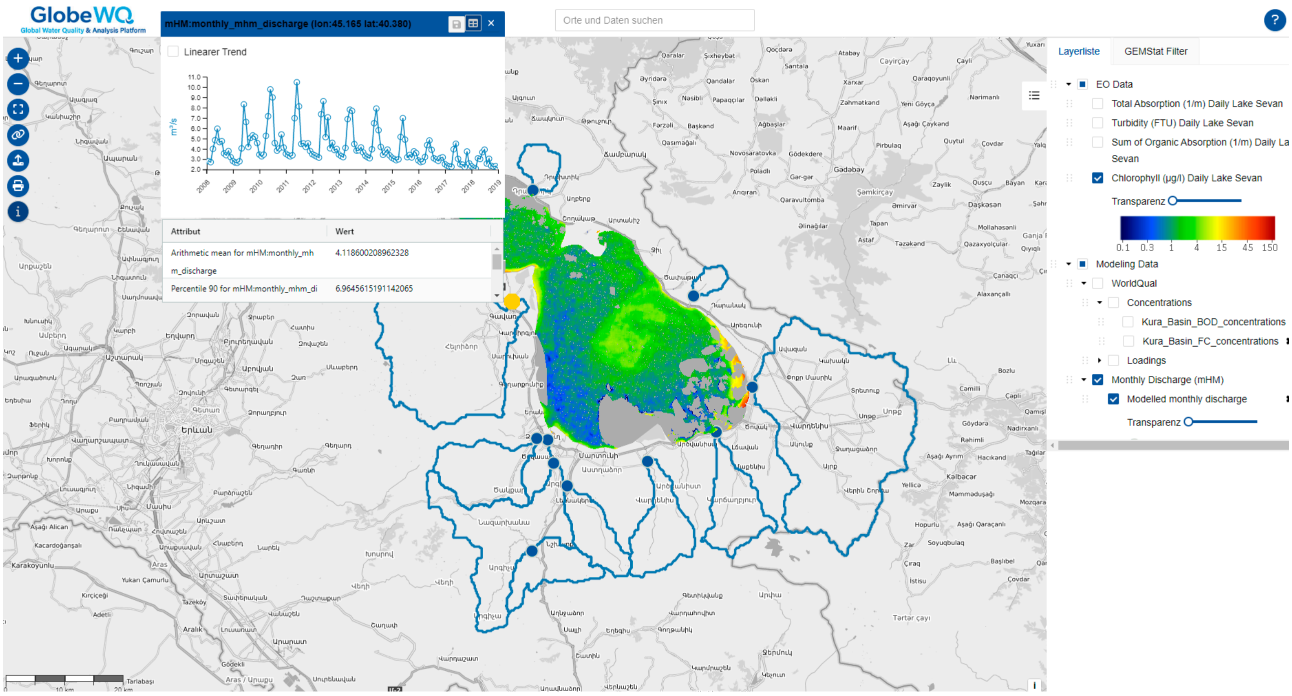


Figure 6.2: Example view of the GlobeWQ platform for Lake Sevan. Monthly modelled inflows into Lake Sevan at one tributary and chlorophyll concentrations at the lake surface from satellite remote sensing.

6.2.3. Objectives

What emerged from several meetings and working visits is the need to first improve the information available on water quantity. Water quantity is always the basis for water quality modeling so the initial focus on water quantity does not contradict with the ambition of GlobeWQ. The objective of the hydrologic modeling is to reconstruct the monthly inflow for Lake Sevan from 1979 to present on a catchment-specific basis, allowing for analysis of long-term and changing inflow patterns, including the seasonal distribution of inflows. The model resolution used for this analysis is 1 km^2. To further demonstrate the capabilities of the GlobeWQ platform, the Worldqual model was applied to provide Phosphorus loadings to the lake.

6.2.4. Implementation

Currently a prototype of the Lake Sevan platform is available for demonstration purposes that includes runs of the hydrological model mHM providing monthly discharge of 12 major tributaries to the lake for a period of 11 years between 2008 and 2018. The results on monthly Phosphorus loadings, as well as data from remote sensing for the lake surface (Figure 6.2, 6.3). The Lake Sevan case study will be continued. Data products of GlobeWQ will feed into the monitoring and management of the lake Sevan basin in the near future.

Phosphorus loadings into the Lake Sevan

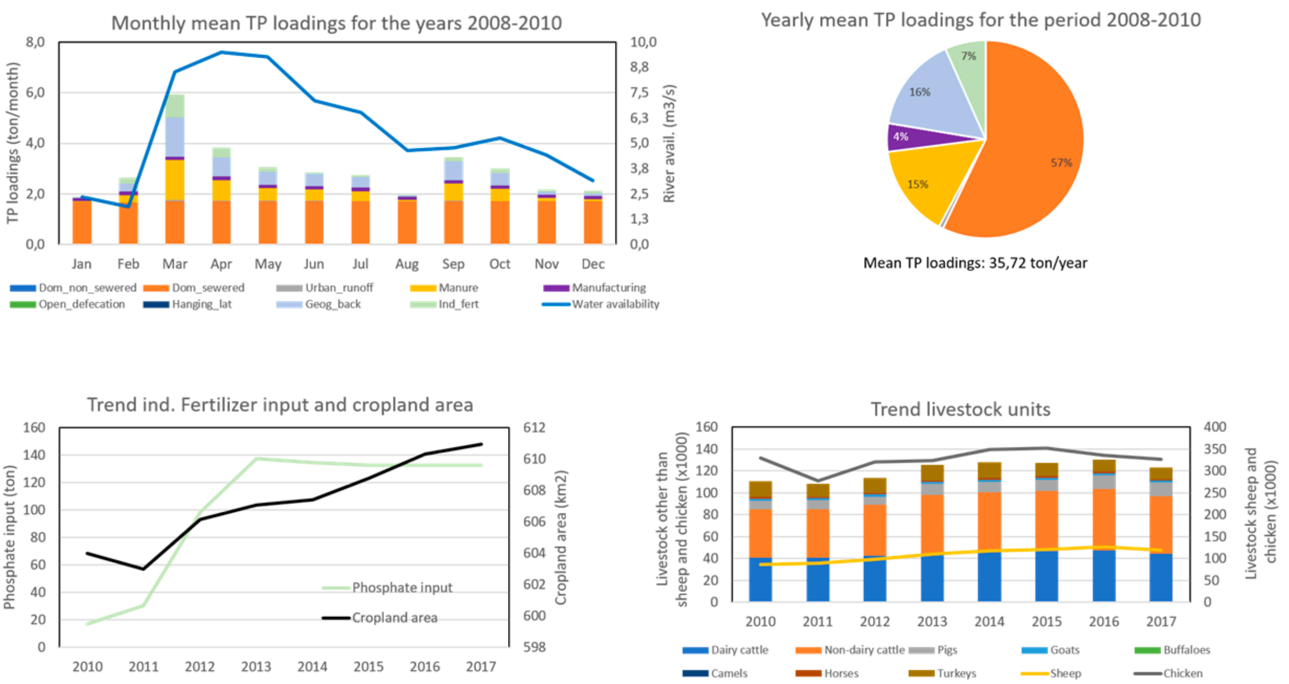


Figure 6.3: Trends of and sources of Phosphorus loadings into the Lake Sevan catchment.

6.3. Lake Victoria

6.3.1. Background

The Lake Victoria case study has been the first one which was established for the GlobeWQ platform. It is categorised into the “red category which implies that neither prior easily accessible data nor prior partner networks have been established at the beginning of the project. The Lake Victoria Use Case is one of the three African Use Cases that was piloted by the World Water Quality Alliance (WWQA). The WWQA Africa Use Cases aimed to bridge from data to solutions for three study areas: Lake Victoria transboundary basin, the transboundary Volta River basin and Cape Town Aquifers. In particular the focus has been on implementing the “triangulation approach” of in situ data. Remote sensing and water quality modeling which is also central to the GlobeWQ project. The process is driven from defining a demand for water quality services based on regional stakeholder involvement. For Lake Victoria virtual workshops have been organised with representatives from the fishery organisations of Kenya, Tanzania and Uganda. Potential Water quality data and information products were discussed.

6.3.2. Water quality issues in the Lake Victoria region

Lake Victoria is Africa’s largest lake and the second largest freshwater body in the world by surface area after Lake Superior. It contributes substantially to the economies and livelihoods of the Riparian States (Kenya, Tanzania, Uganda). Particularly, fishery is an important economic sector for the entire region (Njiru et al. 2018). Despite its importance, lake water quality is under pressure through oil spills, discharge of waste water, inputs of solid waste and diffuse nutrient inputs (Hecky et al. 2010; Njiru et al. 2014; Nyamweya et al. 2020). High nutrient loadings are one of the key factors causing harmful algal blooms (Stager et al. 2009; Hecky et al. 2010). Algal blooms threaten fish populations directly when resulting in low oxygen conditions (Ochumba 1990; Hecky et al. 1994; Njiru et al. 2019). Moreover, cyanobacteria-producing harmful algal blooms (cyanoHABs), can lead to the enrichment of microcystin in fish, which can in high concentration pose risks to human health (Mchau et al. 2019; Roegner et al. 2020).

6.3.3. Objectives

Through the WWQA stakeholder workshops for Lake Victoria it has been recognized that there is the need to better observe the occurrence of algal blooms and provide timely data. Monitoring algal blooms in Lake Victoria requires a multi-method approach due to the large size of the lake, its transboundary nature, and data collection challenges. Better information is needed to develop strategies to reduce point and diffuse nutrient inputs.

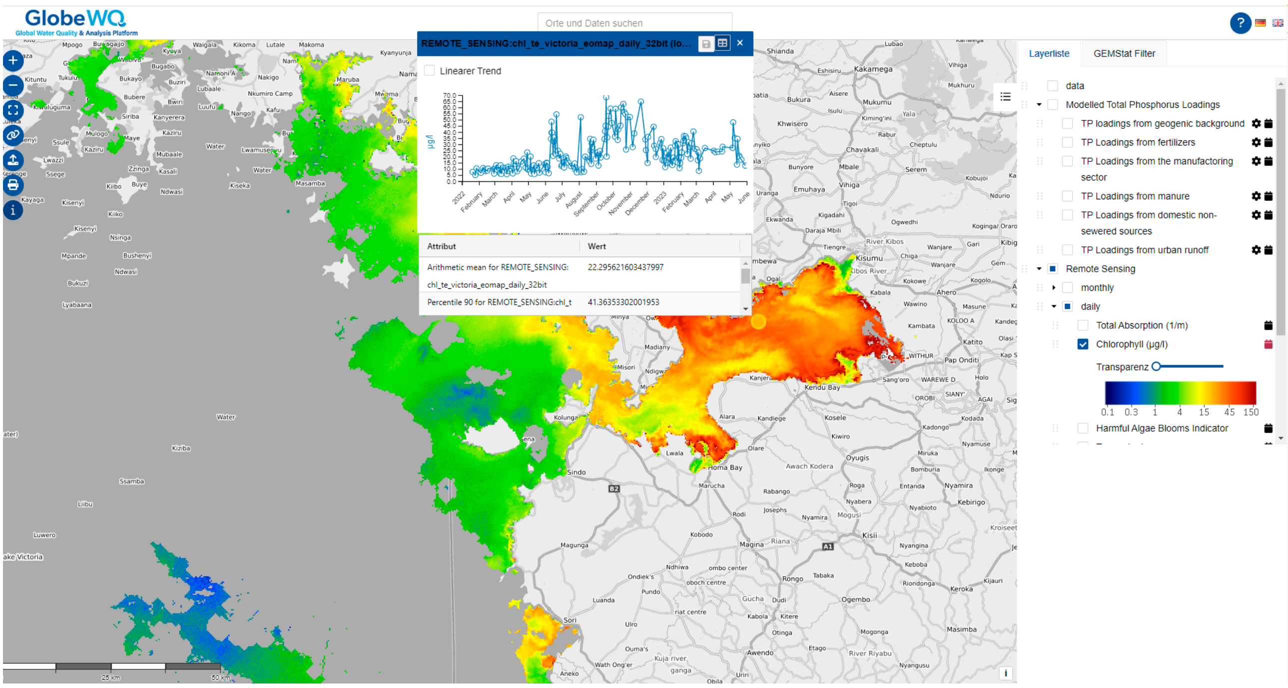


Figure 6.4: Chlorophyll-a concentrations from satellite remote sensing for the Winam Gulf in the North Eastern part of Lake Victoria which is a hotspots of algal blooms.

6.3.4. Implementation

In situ observations at Lake Victoria are available from the GEMStat database. While these observations partially provide insight into the long term history of water quality, the monitoring interval is often irregular and the information is rarely up to date. Harmful algal blooms can develop over hours or days and thus information is needed with short lead time and a lake-wide spatial coverage. To tackle this information gap we provide water quality information based on satellite remote sensing for optical lake water quality including Chlorophyll-a, Temperature and the Harmful algal bloom (HAB) indicator on the GlobeWQ platform (Fig. 6.4). The data is updated for each satellite overfly of the Copernicus Satellites Sentinel 2a and 2b. The water quality model WorldQual is applied to provide long-term information on the loadings of Phosphorus, Biological Oxygen demand, fecal coliform bacteria and Total suspended solids from the tributary catchments of Lake Victoria between 1990 and 2017.

Modelled loadings of Total Phosphorus reveal that five of the tributary catchments to Lake Victoria contribute to more than 70% of the annual loadings (Fig. 6.5). As revealed by remote sensing information, the Winam Gulf is susceptible to high Chlorophyll-a concentrations on the one hand because of its limited water exchange with the main lake and on the other hand because of the nutrient loadings received from the Nyando and Sondu catchments.

6.3.5. Reducing concerns regarding data sharing

As almost always, there is a lack of available, up-to-date, spatially distributed in situ data. While data for Lake Victoria is available in the GEMstat base, which is integrated into the GlobeWQ platform, there is much more data available from different national monitoring programmes. In the stakeholder workshops we learned that the willingness to share data is very low. This applies not only to the provision of data for the GlobeWQ project, but also to the exchange between the authorities of Kenya, Tanzania and Uganda. In order to make the GlobeWQ platform easily usable for the regional stakeholders, we have included the possibility of a temporary data upload for in situ point data. Users can compare the data products, e.g. from remote sensing, with their own measurements or download data from the GlobeWQ platform and use it together with their own data without having to share data themselves. Such a solution is not ideal, but it helps to provide added value for the users.

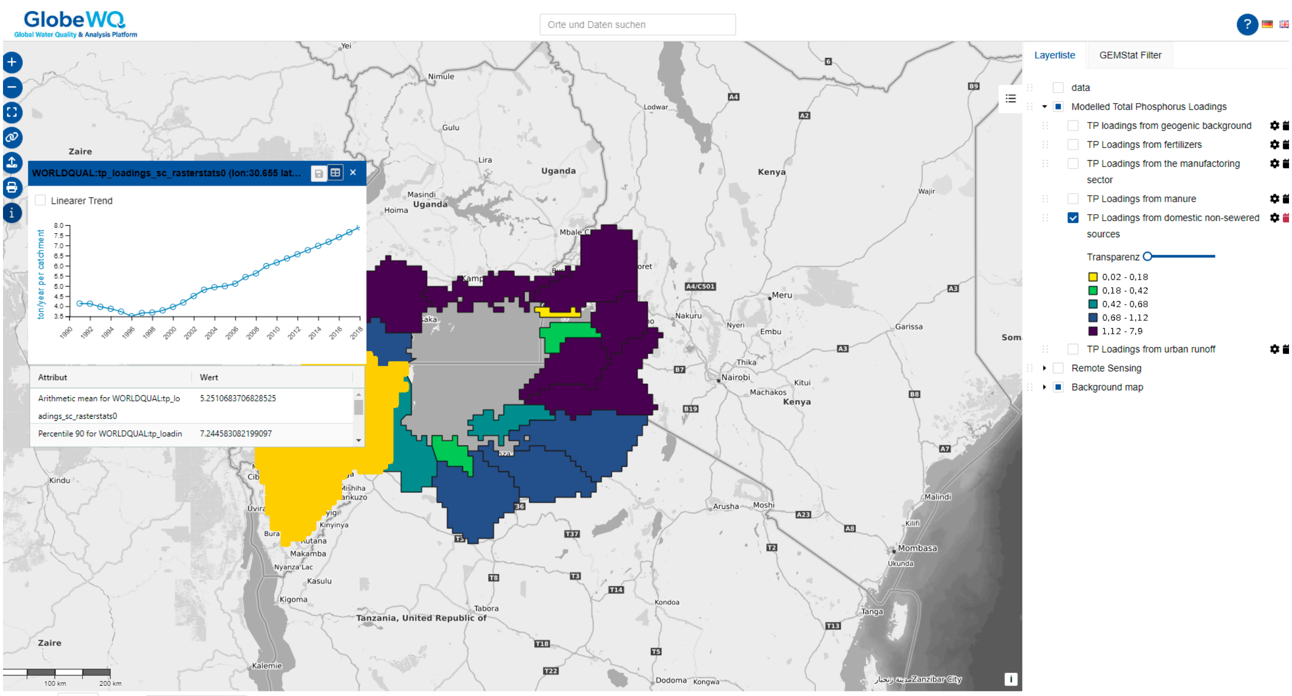


Figure 6.5: Modelled total phosphorus loading from domestic point sources. The time series chart shows the Kagera basin and the trajectory of loadings between 1990 and 2017.

Spatio-temporal patterns of the algal bloom and the fishkill

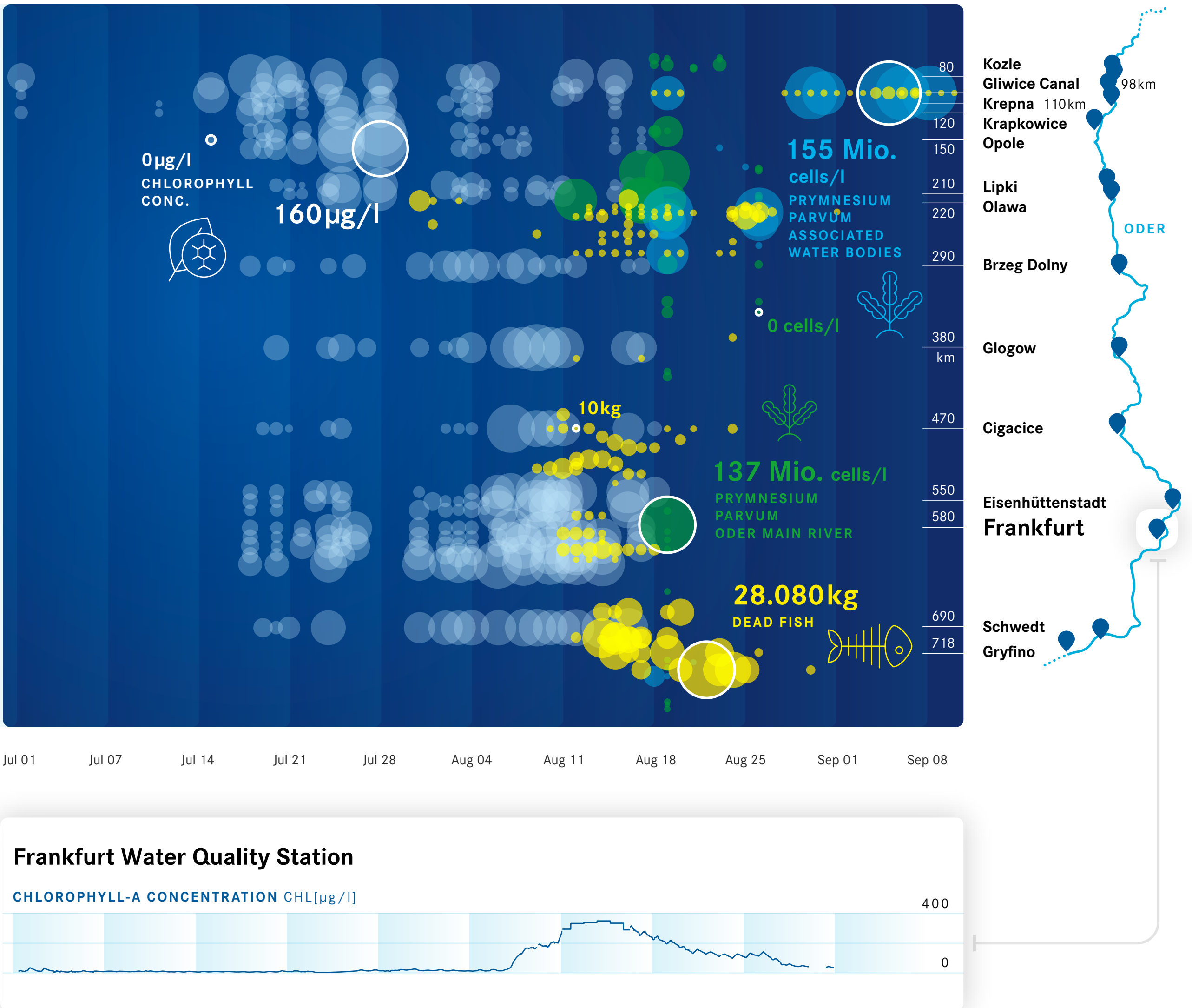


Figure 6.6: Graphical synthesis of the time and space patterns of the algal bloom in the Oder river in August 2022. Upper panel: Time space trajectory of the algal bloom and the fishkill in the Oder river. Lower panel: Time series of chlorophyll-a concentration measured at the Frankfurt water quality station (km 580).

6.4. The ad-hoc case study of the Oder River

6.4.1 Backround

The Oder River has become an ad hoc case study triggered by the large-scale fish and molluscs die - off in Summer 2022. It falls into a category A case. The Oder River case shows that there is a need for timely water quality information services.

Along a 500 km stretch of the Oder River in Poland and Germany. A total of ~250 (IOŚ-PIB 2022) - 360 tons (Free et al. 2023) of dead fish were reported. Several possible causes of the fish die-off have been investigated, including toxic substance spills (UBA 2022). The environmental authorities of both countries have investigated the possible causes of the event and have explored various possible explanations. They have independently concluded that the fish kill was caused by a bloom of Prymnesium parvum, which produces the toxin prymnesin (IOŚ-PIB 2022, UBA 2022). Prymnesium parvum is a species of algae normally found in brackish water, but has been able to establish itself in the Oder River, which is characterized by increased salinity caused by the discharge of highly saline mining water (UBA 2022). In the summer of 2022, several factors accumulated, which favor the bloom of algae in general and that of Prymnesium parvum in particular. First, extremely low discharge conditions resulted in enhanced salinity due to low dilution and longer residence time and thus time to form algae blooms. Algae growth potential was further enhanced by high water temperatures and intense sunlight, which together could potentially create conditions that favored mass growth of the brackish water algae Prymnesium parvum in the Oder River system.

The Oder River is a major transboundary river in central Europe. It has a basin area of ~120,000 km^2. The population in the basin is about 16 Mio inhabitants (JRC Oder Fact sheet, 2023). The kilometerization of the Oder river used here begins in the Czech Republic at the confluence with the Opava river. The total length of the Oder river from here to the in the Baltic Sea is 866 km. For about 500 km, it flows through Poland , and is a transboundary river between Poland and Germany before it flows into the Baltic Sea (Fig. 6.6).

6.4.2. Approach

In this case study the GlobeWQ approach is applied to synthesize available data and information from different sources, including reports from the German and Polish authorities (UBA 2022, IOŚ-PIB 2022) and the Joint Research Centre of the European Commission (JRC) (Free et al. 2023) on the Oder fish die-off.

In addition, high-resolution satellite data is used alongside ground-based data to gain insights into the spatio-temporal total chlorophyll concentration. The urban discharge fraction is used as an indicator for potential ecotoxicological stress. The analysis demonstrates the spatio-temporal patterns of the algal bloom and other factors related to water quality (Fig. 6.6). It is revealed that the ecosystem faces multiple stressors, not only from the algal bloom itself but also from other factors, which increase the susceptibility of the fish to the algal toxin.

6.4.3 Implementation

A prototype operational early warning system has been developed for the Oder River, utilizing satellite data and data from automated water quality stations in the river. The system incorporates a multi-factor risk indicator, which can be integrated into an alert system. This alert system provides information on critical chlorophyll concentrations based on satellite measurements across the river network. It also takes into account ecological risks by considering factors such as water temperatures, salinity, river discharge, and water residence times.

Figure 6.7 illustrates an example of the initial version of the system, displaying the varying levels of water risk along the upper Oder river in July 2022.

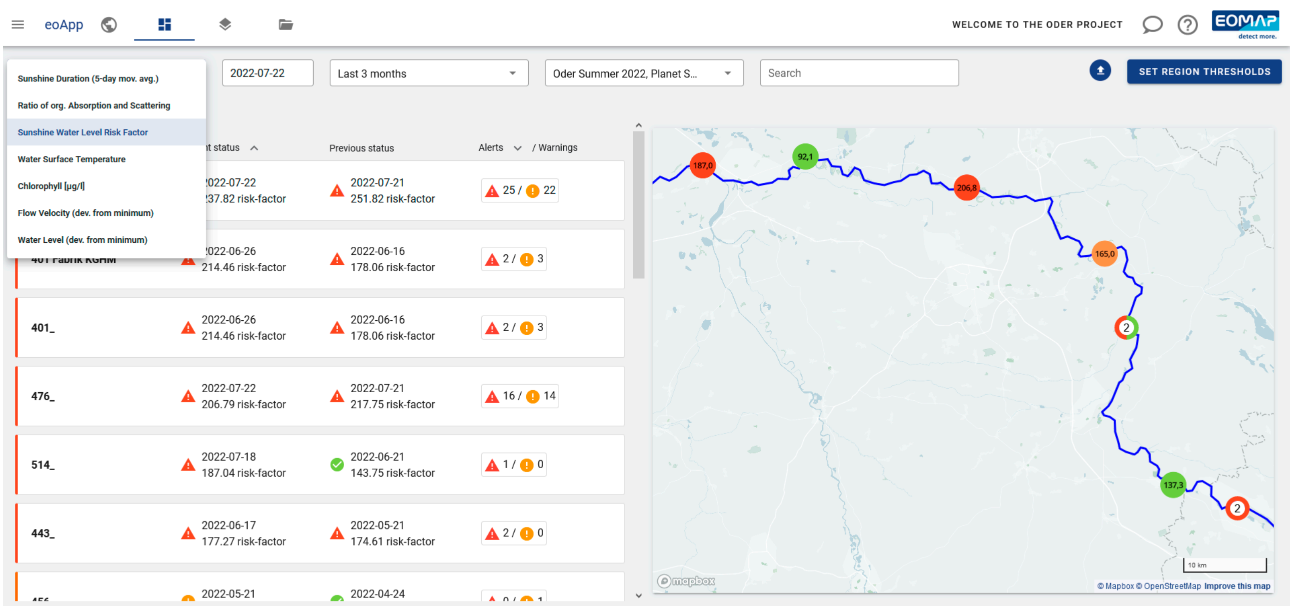


Figure 6.7: Early warning system implemented in the eoApp® by EOMAP for the Oder river visualizing combined risk factors.

7. The GlobeWQ platform and digital applications for water quality information

7.1 From data to information

A lack of water quality information typically results from a lack of data, as for example illustrated by the global spatial inequality of in situ data (CH 3). However, it's important to note that data alone does not equate to easily accessible information on water quality. Information is the results of analyzing, aggregation and interpreting data (Zins 2007). Data is a collection of facts and information sets those facts into context. As far back as 35 years ago, Ward et al. (1986) highlighted the "Data-rich but Information-poor Syndrome" in water quality, pointing out that despite the availability of (in situ) monitoring data, there was a lack of routine data analysis and derived information. The amount of environmental data has increased since the 19080s, and we live in a data-rich world with more data than ever before, including in the field of water quality. However, compared to weather and climate information or hydrological data on floods, information services for water quality are still in the early stages of development.However, reliable and timely water quality information would pay off Yet certainty and timeliness of water quality information pays off. Research by Venus and Sauer (2022) suggests that uncertainty about monitoring significantly reduced the public willingness to pay for environmental measures.

7.2 The GlobeWQ platform

Nowadays, we frequently interact with digital information services. With regard to environmental information, it is probably weather forecasts that we access most often. Weather information is provided through geospatial (or web-based GIS) platforms that enable access to information products in a way that knowledge can be delivered to audiences ranging from laymen to experts.

The goal of the GlobeWQ project was to improve water quality information by combining different data sources using the triangulation concept and providing an information platform that ensures easy access to water quality information tailored to the needs of users. In the GlobeWQ platform prototype, vector (e.g., point data from monitoring stations) and raster (e.g., satellite imagery) data and information products are provided for visualization and further analysis.

7.2.1 Co-design of the platform

Chapter 6 provides an overview on the case studies of GlobeWQ and how they have been implemented on the GlobeWQ platform. The diversity in terms location, scale, available data and background information shows that there is no single solution when it comes to the content and functionality of the platform. The development and implementation of the GlobeWQ platform for the use cases was approached through a co-design process that involved collaboration between developers and users.
In the GlobeWQ project virtual workshops helped to understand the user needs to ensure that the information provided as well as the functionalities for analysis and visualization matches the user requirements. The co-design process also includes consideration of technical factors, such as available data and data processing, and integration with other systems and platforms. These technical factors must be considered to ensure that the information platform is functional and efficient. Ideally, co-design is a continuous process in which the platform evolves with the user needs and improves the user experience.

7.2.2. Technical implementation of the GlobeWQ Platform

The implementation of web-based GIS can be divided into two broad categories: client-side and server-side. Client-side implementation is where the GIS application runs entirely in the web browser, while server-side implementation is where the GIS application is hosted on a remote server, and the user accesses it through a web browser. Implementing web-based GIS requires a suite of tools that can work together to provide a complete GIS solution. The major components of a web-based GIS include a web server, a map server, a database server, and a client-side user interface.

One of the most popular and versatile standards for implementing web-based GIS is the Open Geospatial Consortium's (OGC) Web Map Service (WMS) and Web Feature Service (WFS). These standards define how spatial data can be accessed and shared over the Internet. WMS provides a standard method for sharing maps, while WFS provides a standard method for sharing geospatial data features.

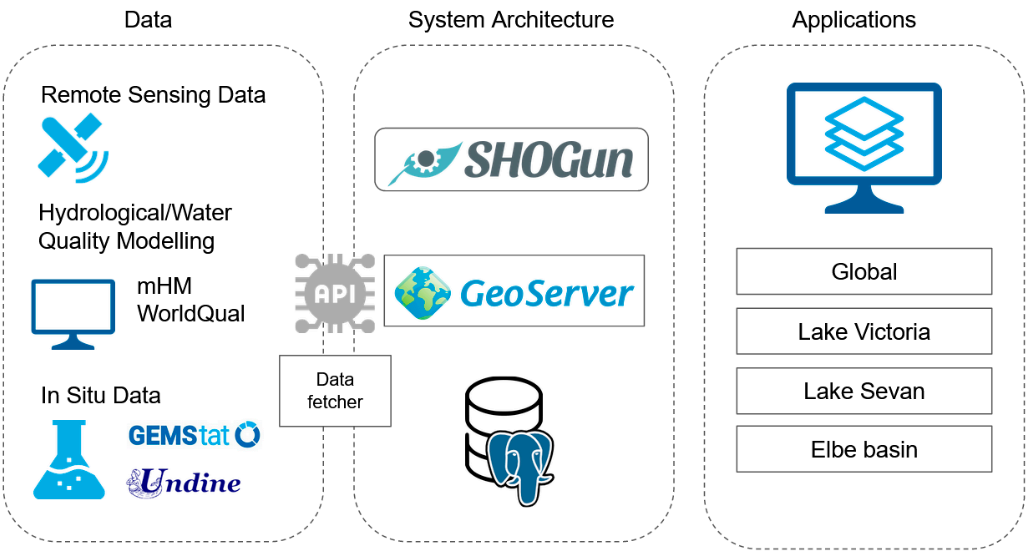


Figure 7.1: Dataflows and architecture of the GlobeWQ Platform.

Figure 7.1 illustrates the architecture and data flows of the GlobeWQ platform. The most widely used free and open-source GIS server is the Open Source Geospatial Foundation's (OSGeo) GeoServer, which is also used in the GlobeWQ project. It is a Java-based server that implements the WMS and WFS standards. GeoServer can work with a variety of data sources, including spatial databases such as PostGIS, shapefiles, and remote web services such as OpenStreetMap. GeoServer also provides styling features that allow users to customize the appearance of maps and features. Another important component of web-based GIS is the database server. PostGIS is an open-source extension to the PostgreSQL relational database that provides spatial data types and functions. It is widely used for storing and managing geospatial data in web-based GIS applications. PostGIS can be used in conjunction with GeoServer to provide fast and efficient spatial data management.

The client-side user interface is an essential component of web-based GIS. It provides the user with the ability to interact with the GIS application and visualize the spatial data. A popular open source client-side user interface for web-based GIS is OpenLayers. This is a JavaScript library that provides a variety of tools for displaying and interacting with maps and features. In the GlobeWQ context OpenLayers was integrated with GeoServer in the SHOGun software to provide a complete web-based GIS solution. The Global Freshwater Quality Database (GEMStat) was integrated into the GlobeWQ platform via a proprietary interface and incorporated into the use case portals.

A custom module was implemented in the GlobeWQ client that enables filtered data queries with the help of several combined requests against the GEMStat API. It is thus possible to filter the GEMStat stations spatially (by region, country, river basin) and by content (station type, parameter group, parameter type). Furthermore, this GEMStat module interacts with the Time Slider module, so that temporal filtering is also possible. In addition to the above components, the web-based GIS also requires a web server running to host the GIS application. Apache is a popular open-source web server that was used to host the web-based GIS application. The exchange of geospatial data between different stakeholders, such as data providers, data aggregators, and data users, can be challenging due to differences in data formats, data structures, and data semantics. To enable effective data exchange, standards and interfaces are essential.

Standards are a set of guidelines that define a common language, format, and structure for geospatial data. As already mentioned above some of the widely used standards in the geospatial context include the Open Geospatial Consortium (OGC) standards, which cover various aspects of geospatial data, including spatial reference systems, coordinate transformations, data encoding, and service interfaces. Other standards, such as the ISO 19100 series and INSPIRE, provide a more comprehensive framework for managing and sharing geospatial data across different domains and countries.

Interfaces, on the other hand, are software components that facilitate the interaction between different systems or applications. In the geospatial context, interfaces are essential to enable data exchange between data providers, data aggregators, and data users. The Web Map Service (WMS) and Web Feature Service (WFS) provide access to geospatial data over the internet, while other interfaces, such as the OGC Catalogue Service for the Web (CSW), enable users to search for geospatial data across multiple repositories and platforms using the metadata provided.

By adopting standards and interfaces, geospatial data providers, aggregators, and users can ensure that their data is interoperable, which means that it can be shared and used across different platforms and applications. Interoperability not only enables more efficient data exchange but also supports collaboration and innovation in the geospatial community. Furthermore, standards and interfaces can help ensure data quality, consistency, and reliability, which are essential for decision-making and policy development.

8. Conclusions

Global water quality

Water quality is rooted in the United Nations Sustainable Development Goal 6 "Ensure availability and sustainable management of water and sanitation for all". Water in sufficient quantity and quality is essential for all aspects of life and sustainable development.The SDG indicator 6.3.2. - “Good ambient water quality” is connected to safe drinking water and thus human health , food security and ecosystem health. A good ambient water quality supports the sustainability of water-related ecosystems, which, in turn, generate ecosystem services. By maintaining a good ambient water quality, efforts required for providing safe drinking water can be reduced. Achieving and maintaining a good ambient water quality is essential for promoting sustainable development, safeguarding human health, ensuring food security, and preserving ecosystems. In the 2021 progress update on SDG Indicator 6.3.2, it was reported that approximately 60% of the monitored waterbodies have good ambient water quality across regions worldwide (UN-Water 2021). However, this estimate is based on data from less than half of the world's countries. Only 49 countries reported data in 2017 and 2020, enabling to reveal trends in water quality. Out of these 49 countries, only 19 have shown improvements in ambient water quality. With its global data products GlobeWQ helps to close this information gap. The analysis confirms that the world is currently off track in achieving good ambient water quality by 2030.

For human health-related water quality variables FC (fecal coliforms) and BOD (biochemical oxygen demand) concentrations in river reaches identified as pollution hotspots, more new hotspots have emerged after 2010 than have disappeared. The WorldQual model provides information on spatial patterns and trends of loadings and concentrations with global coverage at the scale of catchments and river networks. Increasing FC and BOD pollution is mostly driven by population growth and urbanization in conjunction with insufficient wastewater treatment. Thus treatment of waste water would largely reduce impacts on human health and on ecosystems.

Europe’s pollution legacies

The release of excess nutrients is one of the major threats to water quality globally. Europe has a decades-long history of nitrogen inputs to soils and water bodies. This has resulted in the accumulation of large nitrogen stores in soils and groundwater, contributing to elevated nitrate concentrations in freshwater resources and hampering nitrogen mitigation efforts. High nitrate concentrations are still a pressing issue for drinking water safety and aquatic ecosystem health in Europe, even though the inputs have been reduced. The results from the global data-driven analysis for nitrate suggest that a large fraction of rivers is still in good quality with regard to nitrogen pollution. The reconstructed historical trajectory of Nitrogen surplus in Europe helps to understand how historical inputs interact with the current state of water quality. It clearly shows that once nitrogen accumulates in the landscape at continental scales, restoration is hardly possible and therefore the protection of water bodies and preventive measures should have a very high priority in order to prevent Europe's case from being repeated in other parts of the world.

Europe’s river ecosystems under stress

Less than half of Europe's rivers and streams are in good ecological status which is partially related to persistently high nutrient concentrations, but also the result of multiple other stressors like legacy pollutants such as heavy metals and persistent organic pollutants. Most rivers in Europe have been modified by channelization, straightening, and impoundment, which affects flow regimes and habitat structures and impairs the ecological functioning of rivers. Despite a high degree of wastewater treatment, not all substances are removed during the treatment process, for example, not all pharmaceuticals. High fractions of treated urban water pose ecological risks but cannot be measured as easily as for example BOD and require elaborate analytical techniques. One simple indicator that can be used is the fraction of treated urban wastewater in streamflow. The ecological status of streams and smaller rivers declines as the fraction of urban waste water in streamflow increases. The critical threshold for good ecological status is a UDF of 6.5%, which is exceeded by more than one third of the wastewater treatment plant discharges in Europe.

The need for speed and endurance in water quality monitoring, modeling and information provision

The 2021 progress update report on SDG 6.3. 2 (UNEP. 2021) highlights the need for and the benefit of credible and timely data on water as it enables evidence-based policymaking, regulations, planning and investments. Gaps in water quality data are often perceived as gaps in terms of measured parameters and even more so in the spatial gaps which still exist in many parts of the world.

Additionally to patchy spatial coverage of in situ data, there is often also a time lag between the time of the observation and the time that data becomes available in databases and is further taken up in reports and information products. The time lag in the provision of in situ data cascades into water quality modeling as they rely on the assimilation of observational data. Similar to observations of the water quality status, also data on drivers such as land use, population and sanitation is often available only with a multi year time lag which in turn hinders the update of water quality models.

Similar to weather and climate data, water quality information is mostly needed at two time scales. Weather services provide near real time information, forecasts and early warning on harmful weather events. Multidecadal weather data allows for the detection of long term climate trends.

The short time scale (days to weeks) of water quality information needs to address e.g. acute pollution from spills and high concentrations of wastewater during droughts and low flow periods which reduce the dilution capacity. As seen in the Oder river in summer 2022, timely water quality information is needed for the detection of algal blooms risk and critical states of the aquatic ecosystem.

The second essential time scale is the multi year to multidecadal time scale. Long, consistent records of water quality are extremely valuable as they contain information on the long term trajectory of water quality and also the connection to its drivers. The success of measures, for example, on point source control can be documented with long consistent time series. As current impacts on water quality also can be a result of past activities, long-term data is needed to develop measures and policies that acknowledge the potentially multidecadal time lag between the implementation of reduction measures and measurable success.

Both time scales, short-term, acute water quality impacts and long-term water quality trajectories are interlinked. One example is the large-scale fish die-off in the Oder river in summer 2022 where a long-term increase in salinity promoted the spread of a toxic, brackish algae species which is typically not native in freshwater.

The GlobeWQ platform use cases and the triangulation approach

A common thread among all use cases is the user demand for timely information on water quality. GlobeWQ addresses this need in particular by leveraging remote sensing capabilities for water quality observations and by integrating data from available in situ water quality sensors. The GlobeWQ platform has also implemented an interface to the global water quality database GEMStat so that updates there are also available on the GlobeWQ platform and can be combined with GlobeWQ information products. Beyond the improved availability of timely data, the use of a "triangulation approach" in GlobeWQ, combining in situ data, remote sensing, and water quality modeling, provides more comprehensive, complete information on water quality issues.

To ensure sustained adoption and usage of the GlobeWQ platform, a co-design approach has been employed, incorporating user feedback gained through workshops to improve the GlobeWQ platform. For example, a temporary data upload feature was implemented based on user requests enabling users to visualize their data on the platform without the need for permanent data sharing. The underlying motivation is to lower the barriers to platform usage as well as to data sharing in general.

The GlobeWQ platform employs a modular design to provide use case-specific and global data products. The use case specific applications are tailored to user needs in terms of functionality and data products.

Quality known

The GlobeWQ project has made significant contributions to improving global water quality information. By utilizing both model-based and data-driven approaches, it has enhanced our understanding of the global state of water quality. Under the umbrella of the World Water Quality Alliance, the GlobeWQ project also contributed to the development of future scenarios of water quality until 2050. In many regions, achieving good water quality remains a challenge, as past trends, current conditions, and future projections indicate increasing pressures and potential pollution risks. Despite regional data gaps there is sufficient knowledge on drivers and the state of water quality to guide actions to prevent or reduce water pollution.

GlobeWQ has demonstrated that across scales, methods such as water quality sensors, data from remote sensing and modeling tools are readily available to provide data and information. The world has the tools at hand to provide water quality information timely and at adequate spatial scales to inform about the state of water quality and also to keep this information up to date. They just need to be used.

Technical Appendix

A.1. The WorldQual Model

WorldQual is a global scale water quality sub-model of the WaterGAP3 modeling framework. The global integrated water model WaterGAP3 consists of two main components: (i) a water balance model to simulate the characteristic macro-scale behaviour of the terrestrial water cycle in order to estimate water availability (Schneider et al. 2011, Verzano 2012); and (ii) a water use model to estimate water withdrawals and consumptive water uses for agriculture, industry and domestic purposes (aus der Beek et al. 2010, Flörke et al. 2013, Flörke et al. 2018).

WaterGAP3 operates on a 5 x 5 arc minute spatial resolution (9x9 km at the equator) on a daily basis. Model results can then be further aggregated to larger regional scales or temporal units.

Based on the time series of climatic data, the hydrological model calculates the daily water balance for each grid cell, taking into account physiographic characteristics like soil type, vegetation, slope, and aquifer type. Runoff generated on the grid cells is routed to the catchment outlet on the basis of a global drainage direction map (Lehner et al. 2008), considering the extent and hydrological influence of lakes, reservoirs, dams, and wetlands. The climate input for the hydrology model consists of precipitation, air temperature and solar radiation data merged and bias-corrected for ISIMIP from EartH2Observe, WFDEI and ERA-Interim (Lange 2016) for the period 1979-2016. The hydrology model has been updated and calibrated accordingly to deliver the input required by WorldQual and the Water Use models (surface runoff, water availability, reservoir storage, flow velocity etc.).

WorldQual calculates loadings to rivers and the resulting in-stream concentrations using the hydrological information simulated by WaterGAP3 on a monthly temporal basis. WorldQual is designed to simulate biochemical oxygen demand (BOD5), fecal coliform bacteria (FC), total phosphorus (TP), and total dissolved solids (TDS) (Voß et al. 2012, Reder et al. 2015, UNEP 2016, Fink et al. 2018). Loadings are calculated in WorldQual for point sources and diffuse sources. Here, point sources include domestic sewage, wastewater from manufacturing industries and urban surface runoff while diffuse sources are agricultural inputs from manure application. Scattered settlements are classified as both point and diffuse sources and include the loads from the population not connected to wastewater treatment plants (WTPs) and the rural population connected to WTPs. To distinguish between different types of sanitary waste disposal in scattered settlements that are not connected to WTPs, three classes were built: i) Scattered settlements with private disposal facilities, such as septic tanks, pit toilets, bucket latrines etc. (point or diffuse source), ii) scattered settlements where people practise open defecation (diffuse sources), and iii) scattered settlements with hanging latrines (point sources). Industrial fertilizer and natural background emissions are not considered as sources for BOD5 and FC emissions but for total P and TDS.

In GlobeWQ, progress has been focused on the expansion of the input data required to provide global and updated estimations (close to current conditions) of pollution loads and in-stream concentrations. The current model's backbone was developed and implemented for the Snapshot Report (UNEP 2016) which geographically covered the continents of Africa, Asia, and Latin America providing estimations of loadings and concentrations for key water quality parameters until the year 2010. For the GlobeWQ project, all input data have been expanded in space and time to include the continents of North America, Europe and Oceania up to the year 2017.

A.2. Global data driven analysis

In the GlobeWQ project, we conducted a global-scale analysis of hotspots and trends in water quality using two main approaches: the WorldQual model and a data-driven approach. Data-driven approaches can encompass various analysis methods, ranging from simple statistical linear regression to advanced deep learning techniques. Due to the increasing availability of observational data, as well as data on drivers of water quality such as population density, land use or waste water treatment infrastructure, combined with today's computational capabilities, data-driven analysis models are becoming increasingly popular.

One commonly used machine learning algorithm is "Random Forests." This algorithm combines the predictive power of decision trees with randomness. The algorithm constructs multiple decision trees on randomly selected portions of the training data and feature sets, which combines their predictions to produce predictions with higher accuracy. The randomness in the process helps reduce overfitting and increases model diversity, leading to improved generalization performance. Random forests are used in many domains, including finance, healthcare, and natural language processing. They can be used to solve both classification and regression problems.

To set up the Random Forests model, data preparation included the collection and harmonization of explanatory variables (drivers) related to water quality. Table A.2.1 provides an overview of the collected explanatory variables, covering a the period from 1990 to 2015. These variables were aggregated to a consistent 5 arc minute spatial resolution grid, equivalent to approximately 9 by 9 km at the equator.

Project	Description	Periodical	Resolution (in degree)	Resolution (in arcmin)	Resolution (in km at the equador)	Data link
SoilGrids (2017 updated 2022)	producing soil information for the globe with quantified spatial uncertainty	single year (-)	0,0416°	2,5‘	~5 km	
Elevation Slope (2018)	A suite of global, cross-scale topographic variables for environmental and biodiversity modeling	Yearly (2010)	0,0833°	5‘	~10 km	
Natural Fertilizer (2018)	Global distribution data for cattle, buffaloes, horses, sheep, goats, pigs, chickens and ducks	Yearly (1961 – 2013)	0,0833°	5‘	~10 km	
Synthetic Fertilizer (2016)	gridded nitrogen and phosphorus fertilizer use for global agriculture production	Yearly (1990 – 2015)	0,5°	0,5‘	~55 km	
Social Grids (2018)	Gridded global datasets for Gross Domestic Product and Human Development Index	Yearly (1960 – 2015)	0,0833°	5‘	~10 km	
HYDE (2018)	Anthropogenic land use estimates for the Holocene	Yearly (1960 – 2015)	0,0833°	5‘	~10 km	

Project	Description	Periodical	Resolution (in degree)	Resolution (in arcmin)	Resolution (in km at the equador)	Data link
EDGAR (2020)	Emissions Database for Global Atmo-spheric Research	Yearly (1970 – 2018)	0,1°	6‘	~11 km	

Table A.2.1: Data products used as the basis for generating the explanatory variables for the Random forest model. All variables were harmonized to a regular 5 arc minute spatial resolution grid.

For training the the Random Forest model data were divided into 80% for training and 20% for testing of the algorithm. Using the Ranger package (R), a Grid Search was performed on the training data to determine the optimal values of hyperparameters (including the number of trees) in order to maximize model performance. As a result, the random forest algorithm using 700 trees was used to predict the water quality parameters at a global scale for the period 1990-2015.

Observed in situ water quality data w was taken from the Global River Water Quality Archive (Virro et al. 2021).

Multiple evaluation measures were utilized to assess the model's performance including R^2 and Root Mean Squared Error (RMSE). The R^2 indicates the proportion of the outcome's variance that can be covered by the explanatory variables. While the RMSE calculates the average squared difference between the original data and predicted data. The RMSE was used mainly as an objective function to produce the important features of explanatory variables.

The prediction function was then used to generate predictions on a new set of data after the preferred model had been determined. Maps of predicted, gridded where generated as raster images.

A.3. Reconstruction of long-term N surplus in Europe

Here, we provide details on our methodology for reconstructing the long-term annual time series of the land use and the individual components of the N surplus at gridded level (5 arcmin) over the time period 1850-2019.

To reconstruct the long-term N surplus various databases harmonized, considering different time periods (1850-1960 and 1961-2019) and frequencies (yearly, decadal, snapshots), as well as varying spatial resolutions (global trends, country-level values, gridded values). The harmonization methodologies used in previous studies (Byrnes et al. 2020, Lu et al. 2017, Potter et al. 2010) were employed to ensure consistency. It is important to note that uncertainties arising from discrepancies in data sources and methodological choices were taken into account when estimating the major components of N surplus. It is important to note that uncertainties arising from discrepancies in data sources and methodological choices were taken into account when estimating the major components of nitrogen surplus. For this purpose, 16 gridded time-series of nitrogen surplus estimates were constructed, combining two estimates for fertilizer, four estimates for animal manure, and two estimates for nitrogen removal from pastures.

In particular, the reconstruction method adopted country-level data from FAOSTAT (Food and Agriculture Organization Corporate Statistical Database). These data provide the longest records spanning from 1961 to 2019, encompassing variables such as mineral fertilizer, animal manure, crop production, and crop harvested area on a global scale. Furthermore, the country-level dataset of Einarsson et al. (2021) was employed, which provides data for the period between 1961 and 2019. This dataset contributed information on animal manure, the distribution of fertilizer and manure to cropland and pasture, specific harvested areas for fodder crops, and fodder crop production. FAOSTAT includes data for total agricultural areas based on national statistics, whereas, Einarsson et al. (2021) derives estimates for croplands by combining information from FAOSTAT, Eurostat and several national datasets for European countries. To ensure consistency and address spatial variations, the country-level estimates were downscaled using, for most variables, the spatial variability in land use areas (Ramankutty et al. (2008) dataset), and crop specific harvested areas and crop production (Monfreda et al. (2008) dataset) for the year 2000. The utilization of consistent grid-level datasets avoids the mismatch at grid level due to differences in spatial variation from different data sources. Additionally, information from the History Database of the Global Environment (HYDE version 3.2) by Klein et al. (2017) was incorporated to reconstruct the temporal trajectories of various land cover/uses, such as croplands, pastures, forests, and other natural vegetated areas, at an annual and decadal temporal resolution.

By implementing the described methodology, an ensemble of 16 estimates of N- surplus was reconstructed by including major uncertainties from the underlying datasets. Regarding spatial scale, it is recommended not to utilize our dataset at the gridded level because of the uncertainties in the spatial disaggregation schemes, but rather at higher aggregation levels, such as country level, the different European socio-economic regions/states/provinces (e.g. NUTS 0, NUTS 1, NUTS 2 levels), and river basin scale (see Section 5.1.4 and Figure 2) to support different land and water management activities. The methodology provides a consistent approach based on available information for the reconstruction of N surplus over a long time period. The methodology can be adapted to incorporate additional and updated datasets.

A.4. Estimation of the urban discharge fraction

Treated wastewater, despite undergoing treatment processes, still contains organic matter, nutrients, pharmaceutical residues and pesticides, and microplastics, all of which can cause stress to aquatic ecosystems. The urban discharge fraction (UDF), which refers to the proportion of treated wastewater that is present in river discharge, can serve as an indicator for the impact of point sources, specifically wastewater treatment plants (WWTPs), on the ecological status of rivers. UDF is calculated as:

$$UDF = QU/(QU + QR) \qquad (1)$$

where QU is wastewater treatment plant outflow, and QR is discharge of the river at the location of the WWTP effluent. QU was calculated as sum of wastewater from households and small industries (QH), storm water (QSW), and sewer infiltration water (QSIW):

$$QU = QH + QSW + QSIW \qquad (2)$$

where QH was estimated as population equivalents (PE) multiplied by the mean water usage per capita in Germany (126 L/day) (destatis 2019). The mean per capita drinking water usage across the European Union is 124 L/capita/day based on the annual billed drinking water (EurEau 2021). QSW and QIW was estimated as half of the amount of QH based on German data (destatis 2019):

$$QSW = 0.5 * QH \text{ and } QSIW = 0.5 * QH \qquad (3)$$

The UDF can be calculated as local UDF (UDF_local) and as accumulated UDF (UDF_accu). The local UDF describes local conditions neglecting all upstream located wastewater treatment plants (WWTP). The accumulated UDF takes into account also the upstream WWTPs. All QU from upstream WWTP is summed up for the UDF_accu calculation. It always applies:

$$UDF_{local} <= UDF_{accu} \qquad (4)$$

The river discharge (QR) was modelled by a mesoscale hydrological model (mHM) and provided on European scale in a 5km grid (Samaniego et al. 2010; Kumar et al. 2013; Samaniego et al. 2019). Daily discharge was modelled for a 30-year period (1981 - 2010). Q10 (low flow) or other meaningful statistics can be used according to the specific requirements of the assessment.

The concept of UDF was applied and published in different studies (Yang et al. 2019a; Yang et al. 2019b; Büttner et al. 2020; Büttner et al. 2022).

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