UNEP

A Snapshot of the World's Water Quality: Towards a global assessment

Chapter 1–5 Literature

ISBN Number: 978-92-807-3555-0

Job Number: DEW/1975/NA

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Suggested Citation

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

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Design & Layout

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Acknowledgements

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Funding

The Government of Norway and the Government Canada through its Environment Canada as well as UN Water are gratefully acknowledged for providing the necessary funding that made the production of this publication *"A Snapshot of the World's Water Quality: Towards a global assessment"* possible.

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1 Introduction

At the 1992 Earth Summit, freshwater was highlighted in Agenda 21 as a topic of worldwide concern (UN, 1992). Since then, the crucial role played by freshwater in global development, global health, and in sustainability, have been highlighted many times and action has been called for in several international summits. While a strong message emerged from these summits about freshwater in general, the same cannot be said about the worldwide challenge of poor water quality. For example, the Millennium Summit in 2000 produced the Millennium Development Goals (MDGs) (UN, 2000) which focused on urgently needed improvements to drinking water and sanitation but did not specifically call for improvements in water quality. Yet, adequate quantities of good quality freshwater are essential for human health, food security (particularly inland fisheries) and the aquatic environment itself. Twenty years after Agenda 21, the United Nations Conference on Sustainable Development, Rio +20, again placed water at the core of sustainable development. This time, the outcome document "The Future We Want" (UN, 2012) recognised water as being linked to several key global challenges and highlighted the need to reduce water pollution, improve water quality and reduce water loss.

At the United Nations Sustainable Development Summit in New York in September 2015, the General Assembly adopted 17 Sustainable Development Goals (SDGs), which aim to build on the MDGs and complete what they did not achieve (UN, 2015). Goal 6 "Ensure availability and sustainable management of water and sanitation for all" (UN, 2015) specifically calls for sustainable withdrawals, access to adequate quantity for all and an improvement in water quality by 2030. For the first time, there is an acknowledged need to protect aquatic ecosystems and to preserve ambient water quality. Progress towards this goal will need to be monitored and currently indicators for monitoring ambient water quality are still being developed and agreed upon. UN-Water, the inter-agency coordination mechanism for all freshwater and sanitation related matters, is co-ordinating various actions within the UN system that will contribute to the implementation of the SDGs, including monitoring of water quality (through GEMS/Water – see below), as well as providing advice and support on mechanisms for protecting water bodies and aquatic ecosystems through projects such as the production of the Compendium of Water Quality Regulatory Frameworks: Which Water for Which Use (UN-Water, 2015a) and the International Water Quality Guidelines for Ecosystems (UNEP, 2015c).

Sources of good quality water for drinking and domestic use, whether surface or groundwater, are fundamental to human health. In some world regions between 70 per cent and 85 per cent of the population rely on surface waters as their source of drinking water (Morris et al. 2003) although in some countries it can be 90 per cent or more. Consumption of water containing pathogens or elements that are potentially toxic can lead to health impacts ranging from discomfort to death (WHO, 2011). Pathogens in human sewage that contaminate surface and groundwaters used for drinking or food preparation, recreation or irrigation of food crops, are responsible for many diseases, especially diarrheal diseases such as cholera. Recent estimates suggest that 58 per cent of total deaths from diarrhoea (which is amongst the top ten causes of death worldwide) in low- and middle-income countries are due to poor quality drinking water, together with inadequate sanitation and hygiene (WHO, 2014b). Although this figure has improved from the estimate of 88 per cent in 2000, water bodies contaminated with human excreta and used for other human activities (such as drinking, cooking and cleaning, recreation and irrigation) pose a serious threat to the health of the water users, especially women and children as articulated in Chapter 3.

The essential services that aquatic ecosystems provide for human society, either directly or indirectly, were identified by the Millennium Ecosystem Assessment (2005a) and recently highlighted again in the World Water Assessment Programme (WWAP) report "Water for a Sustainable World" (WWAP, 2015). These essential services include water for drinking and irrigation, purification of wastewaters, fisheries for food, hydroelectricity, flood regulation, wetland plants for fuel and construction, and water and nutrient cycling. Up until relatively recently, interest in water quality was focused purely on direct human uses with little effort being directed towards monitoring or maintaining water quality for the benefit of the natural communities of aquatic organisms, i.e. ecosystems. But these ecosystems are important not only from the ethical standpoint of conserving biodiversity, but also because they are an important source of food and livelihood for many people in developing countries. As noted in Chapter 3, inland fisheries are a major source of animal protein in many parts of the developing world. Poor water quality disturbs the balance of aquatic ecosystems, often resulting in changes in fish species and declines in valuable fish stocks. Contamination with organic matter from domestic and food waste, and increases in nutrient levels from agricultural activities, are two of the major threats to inland fisheries, combined with reduced water levels and interruptions to migration routes by dams and weirs (Welcomme et al., 2010; FAO, 2014).

What is causing water pollution?

Water quality is naturally influenced by the climatological and geochemical location of the water body through temperature, rainfall, leaching, and run-off of elements from the Earth's crust. However, most surface water bodies around the world are also affected to some extent by impacts from human activities, particularly the discharge of waste products (including sewage) or addition of sediments, salts and minerals with run-off from agriculture and urban settlements. Chapter 3 articulates the extent of this impact for key water quality indicators. Even in remote locations, water in lakes contains traces of toxic compounds carried in the atmosphere from waste discharges in industrialised regions.

Domestic and municipal wastewater

Human sewage contains pathogens, organic matter, and chemicals used by people, such as pharmaceutical products. Human and animal excreta can potentially contain a variety of transmissible pathogens, such as viruses, bacteria, protozoa and worms. The occurrence of these pathogens depends on geographical location and the occurrence of the disease in the local population. Practically speaking, it is not possible to monitor water for the presence of all potential pathogens, whereas it is relatively simple to detect the presence of faecal matter by the presence of faecal coliform bacteria (see Chapter 3). Globally, such indicators are used to indicate contamination by faecal matter and the possibility of pathogens being present, and they are an essential indicator for risks arising from contact with surface waters and drinking water.

Organic matter in sewage or in manure and food waste is naturally degraded in water bodies by chemical and microbiological activity (see Chapter 3). These degradation processes use up the dissolved oxygen (DO) in the water, causing stress for many aquatic organisms including fish species that require oxygen for respiration. The demand for oxygen in a water body is used as an indicator of organic matter pollution through the biochemical oxygen demand (BOD) test. This test is widely used to determine the impact of sewage releases into rivers. Severe organic pollution, as it is sometimes called, can lead to complete deoxygenation (anoxia), in which very few organisms can survive. Low DO levels also lead to chemical reactions that result in the release or formation of other toxic compounds such as ammonia and hydrogen sulphide in sediments and bottom waters. Ammonia is also a common component of excretion products and can be found in high concentrations in sewage. It is therefore often measured in polluted water bodies because it is particularly toxic to fish (see Box 3.3).

Agriculture and other land-based activities

Intensification of agricultural production to meet growing food demands leads to pressure on water resources for irrigation and to degradation of surface water quality from run-off carrying fertilisers and pesticides from agricultural land. Groundwaters can also be contaminated with agricultural chemicals through infiltration. Sometimes the abstraction of water for irrigation substantially reduces available surface water volumes and contributes to declining water quality by returning water that is contaminated with salts, fertilisers and pesticides. The increased levels of minerals and salts damage the ecosystem (Cañedo-Argüelles et al., 2013) and make the water less suitable for other uses, particularly irrigation (see Chapter 3).

One of the most studied and best understood impacts on water bodies is the increase in nutrients arising from land-based activities resulting in eutrophication and the associated changes in aquatic ecosystems, both freshwater and coastal (Schindler, 2006; Smith et al., 2006). In most pristine water bodies, levels of the nutrients nitrogen and phosphorus are low, arising only from the leaching of minerals or from decomposition of living matter. Higher levels are typically an impact of human activity, particularly fertiliser run-off from agricultural activities and the discharge of sewage effluents (see Chapter 3). The resulting eutrophication enhances productivity, which can have negative consequences for water use, such as growth of nuisance plants and algal blooms, changes in ecosystem structure and fish species, and deoxygenation when algal blooms decompose (Box 3.4; Schindler, 2006). Rivers ultimately carry their burden of pollutants, including sediments and nutrients, to the coastal zone and, increasingly, eutrophication is being detected in coastal waters (e.g. Borysova et al. 2005). The first global assessment of water quality in 1988 highlighted that eutrophication was already a global problem then (UNEP/WHO, 1988; Meybeck et al., 1989) and, with increasing demand for food production and wastewater disposal over the last three decades, eutrophication is still a major water quality issue today (Millennium Ecosystem Assessment, 2005b).

Wastewater from many land-based sources including agriculture, industry and domestic sewage carry dissolved salts and minerals to surface waters. The concentration and nature of these dissolved salts, such as chlorides and sulphates, varies according to the source. However, in high concentrations they upset the natural chemical balance of the receiving water, leading to salinisation and making the water unfit for particular uses (especially industrial uses) and for sensitive aquatic organisms. This is sometimes called "salinity pollution". Salinisation of freshwater is occurring at the global scale and can be detected by the relatively simple measure of total dissolved solids (TDS) (see section 3.4).

Industrial activities and emerging pollutants

Social and economic development depends on access to adequate quantities of good quality water for manufacturing and production processes, and the treatment and assimilation of waste products. Some industrial processes, such as the production of pharmaceutical compounds, require very high quality water and others, such as paper production require large quantities. Meeting these needs in the future will be a major challenge if current levels of water use and degradation continue (WWAP, 2015).

As far back as the 1970s it was realised that the discharge of waste products containing metals and chemical compounds was impacting the aquatic environment, particularly the aquatic food chain and predatory animals and birds. Many metals (e.g. mercury, cadmium, arsenic) and most synthetic organic compounds (e.g. PCBs, pesticides) are toxic to living organisms, including people, at high enough concentrations. This issue has been partly addressed by the inclusion of guideline levels for metals and compounds in the WHO Guidelines for Drinking-Water Quality (WHO, 2011). Practically speaking, only the most toxic and persistent compounds are measured in water bodies on a regular basis, apart from in drinking water, because the range of possible compounds is huge, the concentrations are usually low, and the techniques for measurement expensive (Petrovic, 2014). The availability of such data at a global scale is therefore sparse, even though for some countries it is widely available (Hughes et al., 2012). Today, new forms of toxic compounds are being evaluated for their potential to reach the aquatic environment and to lead to potential damage to aquatic systems or even human health through consumption of contaminated water (Corcoran et al., 2010). These new and emerging compounds include excreted and metabolised pharmaceutical products, such as hormones and different classes of drugs. The range of potential compounds that could be monitored is huge and currently there are few monitoring programmes that routinely include them. The water quality situation with regards to these compounds should be dealt with in future assessments.

Need for data and monitoring to support assessment and to support the identification of solutions

Most nations are concerned primarily with the quality of their own waters, except in situations where water bodies cross national boundaries and international agreements or programmes have been put in place. Monitoring is often directed specifically towards the safety of drinking water or control of waste discharges, and is guided by national or local policy and legislation. With increasing environmental awareness in the 1970s it was realised that water quality at a global scale was inevitably likely to deteriorate and a means of monitoring this over time was needed in order to define and set global priorities for protection of water resources. The 1972 Stockholm Conference on the Human Environment called for the establishment of a global water monitoring programme and in 1978 GEMS/Water (Global Environment Monitoring System for Water) was set up as an inter-agency programme under the United Nations Environment Programme (UNEP), World Health Organization (WHO), World Meteorological Organization (WMO) and United Nations Environmental, Scientific and Cultural Organization (UNESCO). The intention was to collect global water quality data and to increase the capacity of developing countries to undertake the necessary monitoring. In the 1980s a first attempt was made to use the GEMS/Water database to carry out a global assessment of water quality. However, the inconsistent spatial and temporal coverage of the data, together with large variations in the range of water quality variables reported to the database meant that the first global water quality assessment (UNEP/WHO, 1988; Meybeck et al., 1989) had to rely on the use of other data sources, together with the results of special studies published in the scientific literature. Nevertheless, the assessment highlighted a number of water quality issues that were occurring on a global scale, e.g. eutrophication, organic matter pollution from sewage and elevated nitrate in groundwaters (Meybeck et al., 1989) and which have been further specified in later studies based on GEMS/Water data (e.g. UNEP 2008). Today the situation is unfortunately very similar. But this report combines the limited amount of data with modelling to successfully obtain a first picture of the water quality situation in rivers throughout Latin America, Africa, and Asia. Moreover, there are now monitoring programmes in some world regions that are intended to track the long-term changes in these issues at the river basin scale, to identify new issues and to provide the information that will assist in identifying solutions (e.g. Liska et al., 2015 for the Danube River basin). It has now been 27 years since the first and only global water quality assessment. The time is overdue to again assess where the world stands with regards to the quality of its freshwaters.

How to read the report

This report addresses the need to assess the current world water quality situation so as to identify the scope and scale of the "global water quality challenge". This is a pre-study of a full assessment. The first objective of this pre-study is to provide some of the building blocks for a full-scale world water quality assessment. The second objective is to present a preliminary estimate of the water quality situation of freshwater ecosystems in the world, with a focus on rivers and lakes on three continents.

Since it is a pre-study and not a full assessment the scope of the report is limited. It focuses on a small number of important water quality problems in surface freshwaters – pathogen pollution, organic pollution, salinity pollution and eutrophication, and their relevance to human health, food security, and livelihoods. Likewise it concentrates on a small, but important set of impacts of these water quality problems: i) the threat posed by pathogen pollution to people coming into contact with contaminated surface waters, ii) the impact of organic pollution on inland fisheries and their connection to food security, iii) the impact of salinity pollution on limiting water use for irrigation, and (iv) the impact of human activities on the loading of nutrients to lakes. Because it is only a pre-study it is not feasible to cover all parts of the world in the same detail. In particular, the analysis of water quality in rivers concentrates on the continents of Latin America, Africa and Asia because of the fewer assessments available about water quality on these continents as compared to North America, Europe or Australia.

As noted above, the report takes a combined data- and model-driven approach, which makes best use of available information and compensates for the limitations of both approaches (see Chapter 3). Observed data come from the UNEP Global Environment Monitoring System for Water (GEMS/Water), and modelling results from the global WaterGAP/WorldQual model.

To describe and analyse the world water quality situation, the "DPSIR" conceptual framework is used, which divides different aspects of a system into linked "drivers", "pressures", "states", impacts" and "responses". This framework is used to structure the material in the report, but is not referred to explicitly in the report.

The report is structured into five chapters, including this Introduction. Chapter 2 evaluates the availability of global data and gives an example of use of these data for in-stream water quality analysis; Chapter 3 gives first estimates of water quality problems on three continents using the combined data-model approach to determine the scale of the water quality challenge, to set priorities for action in hot spot areas, and for monitoring; Chapter 4 presents eight case studies of water quality issues at the basin level that illustrate the wide range of water quality challenges and how they are being met; and Chapter 5 outlines the wide range of options to meet the water quality challenge and raises critical issues that need to be considered to meet this challenge.

As a whole, the report addresses especially persons interested in the methodology proposed, the exemplary results presented and lessons learned – in organisations dealing with global water related issues, in water authorities worldwide or in academia – by providing a sweeping view of some important aspects of the global water quality challenge and pointing the way to a needed full assessment of the world water quality situation.

2 State of observational knowledge

Aim of this chapter

- To review the availability of water quality data at the international level and suggest how to make more data available.

Main messages

- Data are essential for developing, monitoring and evaluating water resources management strategies
- New technologies and monitoring strategies will simplify data acquisition and strongly expand data availability in the near future
- The Global Environment Monitoring System (GEMS) is a suitable platform to aggregate global water quality data
- At present, the GEMStat database is a critical source of data because it has sparse spatial and temporal coverage and its data holdings do not have a high level of coherence.
- Further developing and strengthening GEMS/Water, and giving it clear institutional objectives and mandates, will increase the global availability of water quality data and enable a reliable global assessment of water quality.
- The hot spot areas of pollution identified in this report can be used as input in deciding where to expand monitoring efforts

2.1 Why do we need global data?

Understanding the global and regional patterns of water quality, both in the past and present, is necessary if we are to come to grips with risks to water security and ways to minimize these risks. Furthermore, this knowledge is a basis for future projections of water quality under the influence of global change.

The observational data needed for this understanding must capture the temporal dynamics of water quality components and have to be coherent over local, catchment and global spatial scales. The selection of key water quality parameters is an equally important task. They should cover the major characteristics of the freshwater system including its physical characteristics, oxygen balance, nutrient status, mineral composition and presence of specific pollutants. They should also reflect the influence of anthropogenic pressures and impacts.

In order to retrieve reliable information from large data bases with data driven methodologies (such as analytical statistics, time series or spatial analysis) there is a need for complementary meta-information regarding hydrology, sampling location, analytical methodologies and quality assurance.

Currently, water quality monitoring programmes and available data bases are usually based on water quality samples collected at specific times and locations and their subsequent laboratory analysis. In the near future it is expected that these traditional techniques will be complemented by remote sensing data, which will become available at spatial resolutions covering whole river networks and lakes of various sizes. The next generation of hyperspectral sensors will provide information that can be linked to a wide set of water quality parameters and that will require ground truthing of the spectral signals.

Furthermore, autonomous water quality monitoring techniques are developing rapidly and will allow for new approaches for setting-up large scale monitoring networks. Photosensors have been miniaturised, and dropped in price, and are now widely available for popular electronic devices such as smartphones. Due to this development, water users and citizens could be much more closely involved in future monitoring efforts. Therefore, future data bases for water quality will build on the existing systems, but may expand significantly with regard to methodologies, sources of information and therefore spatial and temporal coverage.

2.2 What data are available from GEMS/Water?

2.2.1 GEMS/Water Programme and GEMStat

The GEMS/Water Programme, established in 1978, is the primary source for global water quality data. Today, GEMS/Water consists of several entities[1] and is oriented towards building knowledge on inland water quality issues worldwide. Key activities include data collection, research, assessment and capacity building. The twin goals of the programme are to improve water quality monitoring and assessment capacity in participating countries, and to determine the state and trends of regional and global water quality.[2]

The data from participating countries are made available within the GEMS/Water online database, GEMStat. Formerly located in Canada, the responsibility of GEMStat moved to the Federal Institute of Hydrology (BFG) in Germany in 2014. At present, GEMStat includes data from more than 100 countries, and contains approximately five million entries for lakes, reservoirs, wetlands and groundwater systems.

2.2.2 Review of data availability (status 2014)

The availability of data in GEMStat was assessed for a selection of parameters of particular importance to the status of water quality of inland freshwaters. In particular the spatial and temporal coverage of data was evaluated. A complete list of the data available for this study (river basins, stations per river basin, number of measurements, number of measured parameters, time frame) is given in Appendix A. The station densities and temporal coverage of data on the river basin scale are depicted in Figure 2.1. Overall, data is available for some 110 river basins worldwide for the time period of 1990 to 2010. Data from one third of these river basins are older than 10 years.

To judge the adequacy of the density of stations, other water quality monitoring programs in the world can be considered. For example, according to the European Water Framework Directive – WFD (European Commission, 2000), the legally binding instrument for water policy in Europe, "surveillance monitoring" aims to evaluate long-term changes in natural conditions and changes resulting from widespread anthropogenic activities. In general, the station density of surveillance monitoring has a minimum of one station per 2,500 km^2 within a river basin, equivalent to four stations per 10,000 km^2. At these stations, the monitoring frequency for physico-chemical parameters (e.g. temperature, pH, nutrients, salinity, and oxygen) is four times per year. The station density and frequency of measurements for "operational" monitoring (for assessing the current status and short term changes of waterbodies) could be much higher in order to achieve an acceptable level of confidence and precision.

In the United States, a monitoring programme in the State of South Carolina has a station density of 3.8 stations per 10,000 km^2 (U.S. EPA, 2003)[3] and another in the State of Wisconsin has an average density of 1.6 stations per 10,000 km^2 (Anon, 1998)[4].

Compared to the above examples which range from around 1.5 to 4 stations per 10,000 km^2, the densities of stations in the GEMStat data base (Figure 2.1) are very low. In GEMStat, 71 out of the 110 river basins with data have a density of 0.5 stations per 10,000 km^2 or less. Only 57 countries report data in the time period of 1990 to 2010. The average density for the Latin American continent is 0.3 stations per 10,000 km^2, for Africa 0.02 stations per 10,000 km^2, and for Asia 0.08 stations per 10,000 km^2 during the time period between 1990 and 2010. Against this background, it is of course difficult to obtain a representative and valid assessment of the water quality for an entire river basin. Furthermore, the selection of water quality parameters measured was not consistent, and the frequency of measuring water quality parameters is very variable. Depending on the parameter, the range is from 1 to 12 measurements per year, parameter and station. The average monitoring frequency for Latin America and Africa is 4, and for Asia 5.5 measurements per year, parameter and station. Because of the huge data gap and the high variability of data metrics, a valid comparison of water quality status or trends between catchments is not feasible with the current data base. A proposal on how to further develop and improve the utility of the GEMStat data is described in Box 2.1.

[1]The GEMS/Water Global Program Coordination Unit in Nairobi, Kenya, the GEMS/Water Capacity Development Centre at the University of Cork, Ireland and the GEMS/Water Data Centre at the Federal Institute of Hydrology, Koblenz, Germany.
[2]*http://www.gemstat.org*
[3]These sites target the most downstream access of each of the Natural Resource Conservation Service (NRCS) 11-digit watershed units in the state, as well as the major waterbody types that occur within these units. For example, if a watershed unit ends in estuarine areas at the coast, integrator sites are located in both the free-flowing freshwater portion and the saltwater area.
[4]One station with a disproportionally large drainage area was left out of the average of the 43 recommended stations.

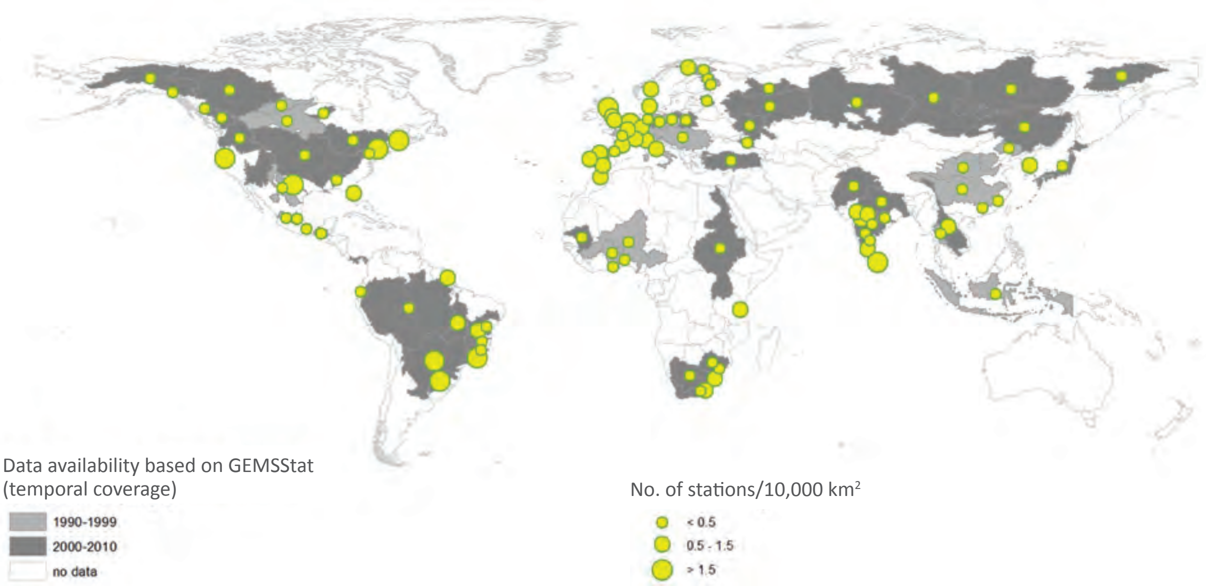


Figure 2.1: Temporal coverage (grey shading) and station density (size of circles) of GEMStat data (Data source: GEMStat, 2014; GIS data source: GRDC, 2007).

Box 2.1: Utility of GEMS data on the way towards a world water quality assessment

Water quality data of GEMStat should be used together with robust, valid, reliable and comparable methods to comprehensively assess global water quality. Using the concentration of a specific parameter in a river basin, water quality could be classified for given levels or ranges of concern. These data need to be clearly linked to the functionality of riverine ecosystems and food security issues with respect to water quality requirements for freshwater fish and invertebrates such as crayfish or mussels.

It is important to know baseline concentrations of water quality parameters so that temporal trends of water quality can be tracked. A trend analysis could indicate an improvement, deterioration or stagnation in the quality of water for a specific time period.

As a simple example, thresholds were selected to classify the water quality of river basins in two categories, above and below "levels of concern". While thresholds were mainly derived from established water quality requirements of a healthy fish fauna, compliance with the levels of concern could also be interpreted as lower risk for food security.

For the analyses of trends, and taking into account the sparse temporal coverage of data, median concentrations of the water quality parameters were calculated for the decades 1990 to 1999 and 2000 to 2010. Non-parametric statistical tests indicated whether the differences between the time periods were insignificantly or significantly changing (increasing or decreasing). The methods employed for the analysis took into account the heterogeneity of GEMStat data by focusing on robust metrics and are therefore widely applicable.

The following map (Figure 2.2) visualises an example of a risk classification for the parameter dissolved oxygen in river basins where data are available. The top map indicates whether the mean oxygen concentration of all measurements in a river basin under consideration are above or below an example threshold "level of concern" (7 mg/l)[5], and the bottom map shows the trend of data. Fewer river basins appear in the trend analysis in the lower map because several river basins were lacking data for either 1990–1999 or 2000–2010. Dissolved oxygen concentrations (1990-1999) were at or below the level of concern (7 mg/l) at various stations in Latin America, Asia and India. A decreasing trend of dissolved oxygen was observed in stations in Eastern Europe and India.

[5] "Level of concern" in this chapter is used to mean the pollutant concentration above (or below) which significant negative impacts occur. In this report these concentrations are derived from water quality standards from official sources such as government departments or UN agencies. This level of concern is derived from guidelines for temperate zones. The potential impacts have to be evaluated in the framework of regional climatic and other conditions.

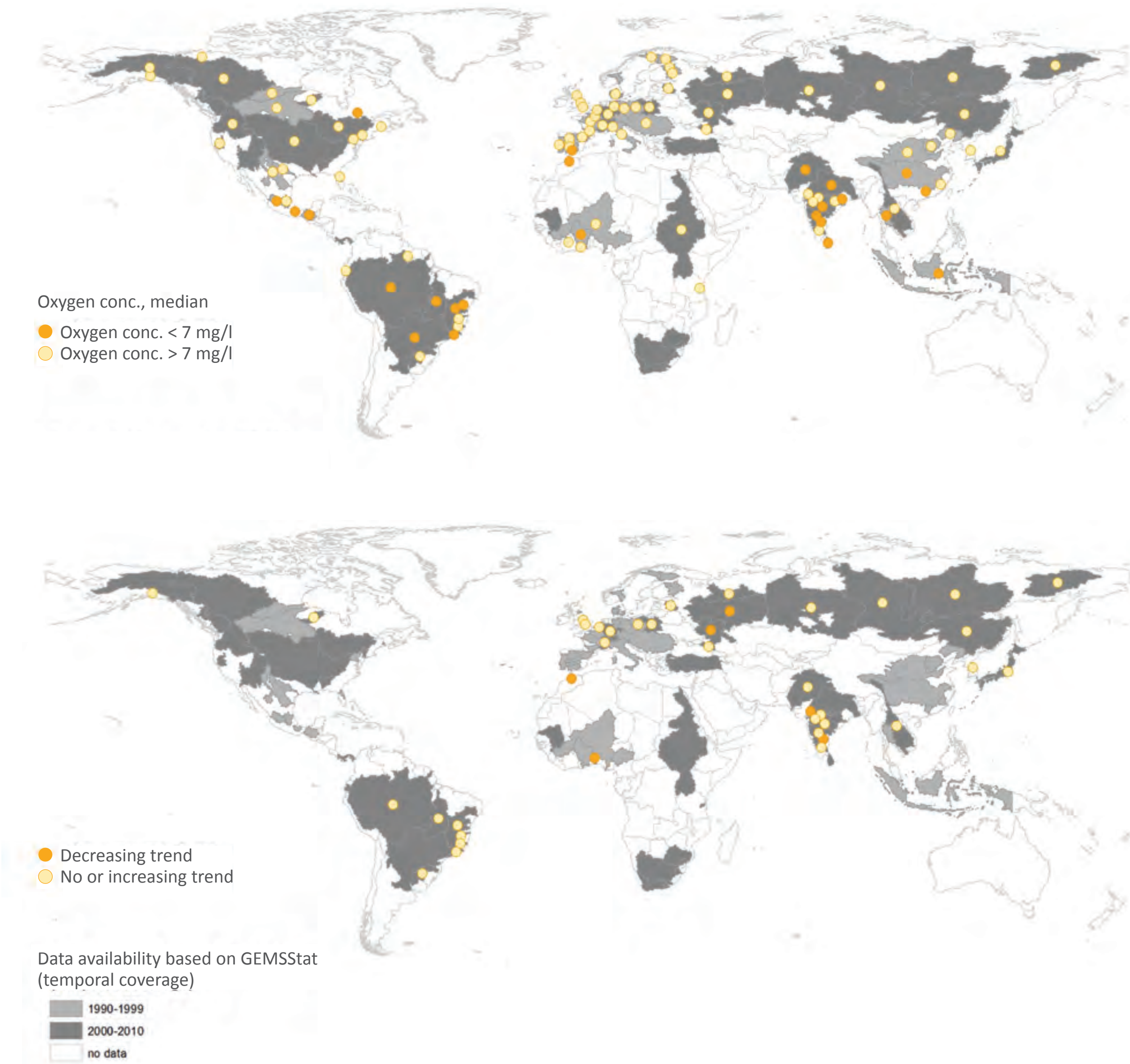


Figure 2.2: Example of risk classification for dissolved oxygen by comparing measured levels with a level of concern (above), and decadal trends (below) for major river basins. Data source: GEMStat, 2014. Light grey river basins: data available until 1999. Dark grey river basins: data available until 2010.

2.3 Can data from the scientific literature help fill the data gap?

One option to supplement the sparse data in GEMStat is to use data from the scientific literature. To assess the feasibility of this option 120 reports and publications on water quality in Africa were reviewed. To judge the suitability of data in these publications for assessments the following attributes were noted: availability of precise sampling location (GIS-data), temporal and spatial coverage of data, adequacy of information on analytical methods, and the number of water quality parameters. For this, only publications were studied that provided measured data.

The conclusion was that the data published for Africa are very dissimilar and disparate. Most published data are aggregated over long time periods and/or over several sampling stations. Furthermore, specific locations of sampling stations are usually not available and the selection of parameters was restricted. Overall, they were not comparable with GEMStat data which are based on monitoring results and raw data. On the other hand, data from scientific literature can be used to supplement GEMStat data for the purpose of model testing and preparing model inputs and they are used for this purpose in Chapter 3.

2.4 What is the potential of remote sensing?

Part of the solution to the urgent global data gap is to derive water quality information from remote sensing products. Satellite sensors potentially offer reproducible and globally consistent earth observation data with a high scientific standard (Bukata, 2005). Therefore, remote sensing can provide data where it is too expensive to monitor water quality or at locations that are remote.

Space-born remote sensing can provide data of selected water quality parameters at spatial scales and with temporal resolutions that exceed the density of ground based monitoring stations by several orders of magnitude. Examples for the next generation of satellite missions are: hyperspectral HyspIRI (Hyperspectral Precursor and Application Mission, launch in 2010, pixel resolution 60x60m, combination of hyperspectral and thermal sensors), the multispectral missions (Copernicus mission, Sentinel 2 & 3, launch in 2016) and the hyperspectral Environmental Mapping and Analysis Program (EnMAP) starting in 2018. The latter will have a pixel resolution of 30 m x 30 m and a scanning capacity of 30 km x 5,000 km per day following sun synchronous orbits (EnMAP, 2015). This would allow for the comparative analysis of a given location on the earth's surface within four days.

Because the optical sensors detect reflected sunlight, parameters which have an effect on the optical properties of water can be deciphered. For this purpose, the spectral signatures have to be analysed with optical models that depict the relationship between the reflectance and the concentration of relevant water quality constituents (ZhongPing, 2006). Remote sensing platforms can identify and quantify several key water quality indicators:

- sea surface temperature,
- chlorophyll a (an indicator of the concentration of algae),
- various ecologically important phytoplankton groups including potentially toxic algal blooms in eutrophic coastal and inland waters,
- secchi depth / transparency,
- coloured dissolved organic compounds,
- turbidity, different fractions of suspended mineral and organic particles, and
- sediment dynamics in estuaries, tidal flats, wetlands, and mangrove forests.

Most efforts at collecting water quality data from space-born remote sensing platforms have focused on the oceans and coastal areas rather than rivers and lakes. Collecting and interpreting data of inland waters is a big challenge because of the higher complexity of the optical signal from freshwaters and the relatively smaller dimensions of many inland surface water bodies and river networks. Rivers often exhibit turbidity levels of one or more orders of magnitudes higher than coastal or marine environments at a high temporal dynamics. Furthermore, humic and organic substances interfere spectrally with the measurement of parameters such as turbidity and transparency (Olmanson et al., 2014). Moreover, to acquire data for smaller rivers and streams, a much higher spatial resolution is needed than for oceans or coastal areas. However, few available sensor data with a sufficiently high spatial, spectral and radiometric resolutions became available recently, such as Sentinel-2 (10-20 m) and Worldview-2/3 (1–2 m) data, in combination with robust physics based retrieval algorithms reflecting the complex interplay of extreme concentration ranges and applicable for a wide range of previous and upcoming satellite sensors (Heege et al., 2014) .

For water quality assessments, the potential usability of remote sensing data of lakes is better than that of river networks. Because of larger surface areas and typically higher clarity of lakes, remote sensing data are available from a larger set of satellite missions, including Sentinel-2, Landsat, and MODIS, covering a wider range of spatial resolutions or spectral information. Currently, remote sensing platforms can provide diverse information about lake characteristics, especially clarity, transparency, coloured dissolved organic matter, chlorophyll and other algal pigments (e.g. Matthews et al., 2010, Chawira et al., 2013).

A great advantage of space-born remote sensing is that it can provide a long-term, simultaneous record of water quality in water bodies over large regions. For example, Landsat images show the "clarity" parameter of more than 10,000 lakes in Wisconsin (USA) for a time period of more than 20 years (Olmanson et al., 2014).

Despite the many advantages of remote sensing acquisition of water quality data, the following limitations should be kept in mind:

- The water quality parameters that can be measured by remote sensing are small in number and limited to those which influence the optical properties of the water.

- The application of remote sensing for water quality assessments of rivers is further limited by the spatial resolution and spectral information of the satellite missions in place and the complexity of the optical properties of running waters.
- The potential of remote sensing for water quality assessments of lakes is higher than that of rivers because of their larger size and the lower complexity of water properties and conditions.
- Water quality parameters such as chlorophyll-a and algae bloom indicators can be directly derived from remote sensing data. Other water quality information requires models that convert spectral signals from remote sensing platforms to water constituents. Empirical models require ground-truthing of remote sensing with ground-based measurements, while physical based models derive optical properties also harmonized and independent of in-situ measurements, as proven for lakes e.g. by the EU Glass (Global Lakes Sentinel Services) project (GLASS, 2016; EOMAP, 2016).
- A prerequisite for successful ground-truthing is the availability of good quality surface water quality measurements on high spatial and temporal resolution. Thus an aquatic sensor network is required providing systematically monitored water quality parameters that can be stored in global databases and made accessible for calibration and validation of remote sensing data.
- Future satellite-born remote sensing platforms will have higher spatial resolutions and hyperspectral optical signals and will therefore be much more applicable to the assessment of inland waters. However, it is important to combine this new generation of satellite data with ground-based measurements (Wireless Ad-hoc Sensor Networks for Environmental Monitoring; Mollenhauer et al., 2015) so that the greatest value can be derived from these data.

2.5 How can more data be made available?

1. Incorporating existing national and regional monitoring data

Following technological advancements and legal obligations, more and more countries are providing their monitoring data publicly and online. However, this is mostly limited to developed countries with a strong technical focus. Furthermore, most of these countries have developed their own data exchange formats and access methods that complicate transfer of data into GEMStat. In order to promote the interoperability of data on the international scale, members of the joint WMO/OGC Hydrology Domain Working Group are standardizing open data exchange formats and web services such as WaterML2 and Sensor Observation Services. These steps will lay the foundations for a globally distributed water resources information system. GEMS/Water is not only aiming to support the standardisation process, but also to implement these standardised formats and services at the national and sub-national scale to enhance data flows.

UNEP is currently developing the Indicator Reporting Information System (IRIS), a web-based platform that allows countries to share their environmental datasets, derive indicators and produce reports. Starting in 2015, GEMS/Water will support the rollout of the IRIS by working with countries to further improve the spatial and temporal coverage of their water quality data. Provided that the IRIS will be adopted by countries, it could become a key component in providing access to selected national water quality monitoring data.

2. Setting up national freshwater monitoring working groups

The current GEMS/Water networking and data collection strategy is based on the network of National Focal Points (NFPs), which have the responsibility to facilitate the data flow between GEMS and national states. However, frequent personnel changes at the NFPs hamper communication and data flows. One approach to overcome this barrier is to set up national freshwater monitoring working groups including governmental and scientific representatives who provide a link between national monitoring activities and regional and global assessment programs. On the regional level, newly established GEMS/Water regional hubs (as recently set up in Brazil) can support the maintenance and extension of the Global Monitoring Network and increase the exchange of data.

3. Raising awareness with political instruments

On the political level, UNEP and other UN-Water partner organisations can increase awareness of water quality issues and gaps in water quality monitoring coverage. Declarations such as Resolution 1/9 of the United Nations Environment Assembly on water quality data exchange help to further improve data availability.

4. Retrieving data from citizen science projects and remote sensing based water quality data

New data sources from citizen science and remote sensing are becoming increasingly available and could supplement governmental monitoring data (Box 2.2).

The recently established Water Quality Community of Practice uunder the "Integrated Global Water Cycle Observations" theme of the Group of Earth Observations has supported the development of algorithms to derive water quality data from optical satellite imagery. As noted above, physical constraints and the limited spatial resolution of the satellite sensors restrict their use to a subset of water quality parameters (turbidity, total suspended solids, chlorophyll a) in lakes and other large freshwater bodies. However, recent and future satellite missions such as Sentinel 2 with their improved spatial and temporal resolution will enable the development of new algorithms that cover rivers and smaller inland water bodies. GEMS/Water is supporting this work by coordinating the collection of calibration and validation data by the network partners with the aim of creating operational remote sensing water quality data services in collaboration with major space agencies.

Box 2.2: What is Citizen science?

Citizen science is the practice of public participation and collaboration in scientific research in order to further knowledge. Through citizen science, people share and contribute to data monitoring and develop and expand collection programmes. Collaboration in citizen science involves scientists and researchers who develop and coordinate the programme and unpaid volunteers such as students, amateur scientists, or teachers.

One example is Volunteer Water Quality Monitoring within the National Water Resource Project at the Universities of Wisconsin and Rhode Island in the United States.[6] The goal of this project is to expand and strengthen the capacity of existing extension volunteer monitoring programmes and support development of new groups. This project includes the training of volunteers in monitoring water quality and developing internet and web-based tools for data management. In 2005, this project engaged 8,600 trained volunteers in monitoring lakes, wells, rivers, estuaries and beaches. In total, the project involves 30 separate collaborative programmes in 30 different states. Local and regional programme coordinators are responsible for the expansion of the programme.

Another example is the development by the Delft University of Technology of new mobile sensing methods for water quality monitoring for use in citizen science projects. Delft is developing "indicator strips" as a convenient and practical way for volunteers to collect water quality data.[7]

A third example is the "World Water Monitoring Challenge" (WWMC) run by Earth Echo International, an environmental education organisation in collaboration with the Water Environment Federation and the International Water Association. As part of this program, volunteers are encouraged to test the quality of their local waterways and share their findings. To facilitate this, the WWMC sells individual and classroom water-testing kits for measuring temperature, acidity (pH), clarity (turbidity) and dissolved oxygen. Each kit contains an informative instruction book and enough reagents to repeat up to 50 tests. The location of stations, data and further information are made accessible to the public on an interactive web site.[8]

5. Setting priorities for monitoring

Considering the high costs of monitoring, it is important to set priorities for collecting field data. The hot spot areas identified in Chapter 3 for pathogen, organic and saline pollution can be used as input in deciding where to expand monitoring efforts.

[6] *http://www.usawaterquality.org/volunteer/*
[7] *http://www.citg.tudelft.nl/en/about-faculty/departments/watermanagement/sections/water-resources/leerstoelen/wrm/research/all-projects/msc-research/current-msc-research/application-of-citizen-science-and-mobile-sensing-in-water-quality-monitoring/*
[8] *http://www.monitorwater.org/default.aspx*

3 Water pollution on the global scale

Aim of this chapter

To gain a global overview of water quality problems in the surface waters of three continents.

Main messages

- A "combined data driven/model driven approach" is used to assess water quality on three continents and make the best use out of both measurement data (GEMStat) and modelling results (WorldQual).
- Severe pathogen pollution already affects around one-third of all river stretches in Latin America, Africa and Asia. The number of people at risk to health by coming into contact with polluted surface waters may range into the hundreds of millions on these continents. Among the most vulnerable groups are women and children.
- Severe organic pollution already affects around one-seventh of all river stretches in Latin America, Africa and Asia and is of concern to the state of the freshwater fishery and its importance to food security and livelihood. Countries reliant on inland fisheries as a food source should be vigilant about increasing organic pollution. Groups affected by organic pollution include local poor rural people that rely on freshwater fish as a main source of protein in their diet and poor fishers that rely on the inland fishery for their livelihood.
- Severe and moderate salinity pollution already affects around one-tenth of all rivers in Latin America, Africa and Asia and is of concern because high salinity levels impair the use of river water for irrigation, industry and other uses.
- Anthropogenic loads of phosphorus to the majority of major lakes are significant and may cause or accelerate eutrophication and disrupt the natural processes of these lakes. Most of the largest lakes in Latin America and Africa have increasing phosphorus loads.
- The immediate cause of increasing water pollution is the growth in wastewater loadings to rivers. Different pollutants have different predominant sources. The ultimate drivers of increasing water pollution are population growth, increased economic activity, intensification and expansion of agriculture, and increased sewerage with inadequate treatment.

3.1 Introduction: A combined data and modelling approach

The water quality of the world's rivers and lakes is undergoing important changes. As described in Chapter 1, water quality has markedly improved in many developed countries, although some problems persist such as eutrophication and water contamination by micropollutants and heavy metals. Meanwhile, in developing countries the tendency seems to be towards increasing water pollution as urban populations grow, material consumption increases and the volume of untreated wastewater volumes multiplies. This chapter examines the extent and trends in water pollution worldwide with a focus on Latin America, Africa and Asia. It also describes the combined data-driven and model-driven approach used to obtain these estimates. The methodology takes into account two major factors: First, that a considerable amount of measurement data is necessary for the assessment of three continents, but an adequate amount of data is not available from the GEMStat database (as noted in Chapter 2). Nevertheless, GEMStat is the most comprehensive data set available and should be exploited in any assessment. Secondly, great progress has been made over the last fifteen years in modelling global and continental water resources (e.g. Sood and Smakhtin, 2015) and advancing the assessment of water resources in ungauged or poorly-gauged river basins (Sivapalan et al., 2003). Therefore, modelling results are used to fill in the data gaps in the GEMStat data base. The combined data-driven and model-driven approach (Figure 3.1) makes the best use out of both measurement data and modelling results and is used throughout Chapter 3:

i. GEMStat data are used for a preliminary analysis of the water quality situation of each continent. Since there are large spatial and temporal gaps in these data they were used in aggregate form to compute the statistical occurrence of different levels of pollutants. Results from this statistical analysis are presented as frequency diagrams and "box-and-whisker plots" in this chapter (see Figure 3.2 for example).

ii. GEMStat data are used together with additional data from the scientific literature to test and calibrate the "WorldQual" model. WorldQual is a computational scheme for simulating water pollution loadings to rivers and key water quality parameters in rivers around the world (See Appendix B). WorldQual is part of the WaterGAP modelling framework which has been used for over a decade to estimate hydrological characteristics of rivers worldwide (Alcamo et al., 2003; Flörke et al., 2013; Müller Schmied et al., 2014; Schneider et al., 2011; Verzano et al., 2012).

iii. After testing and calibration, WorldQual is used to comprehensively compute water quality data. This includes data-sparse areas and during time periods not covered by GEMStat (See, for example, Figure 3.1). In this way, WorldQual acts as a tool to fill in the gaps of the GEMStat data. WorldQual calculations provide a detailed picture of the spatial and temporal distribution of water pollution on the three continents.

iv. Hot spot areas identified through this approach can then be used as input in deciding where to expand monitoring efforts.

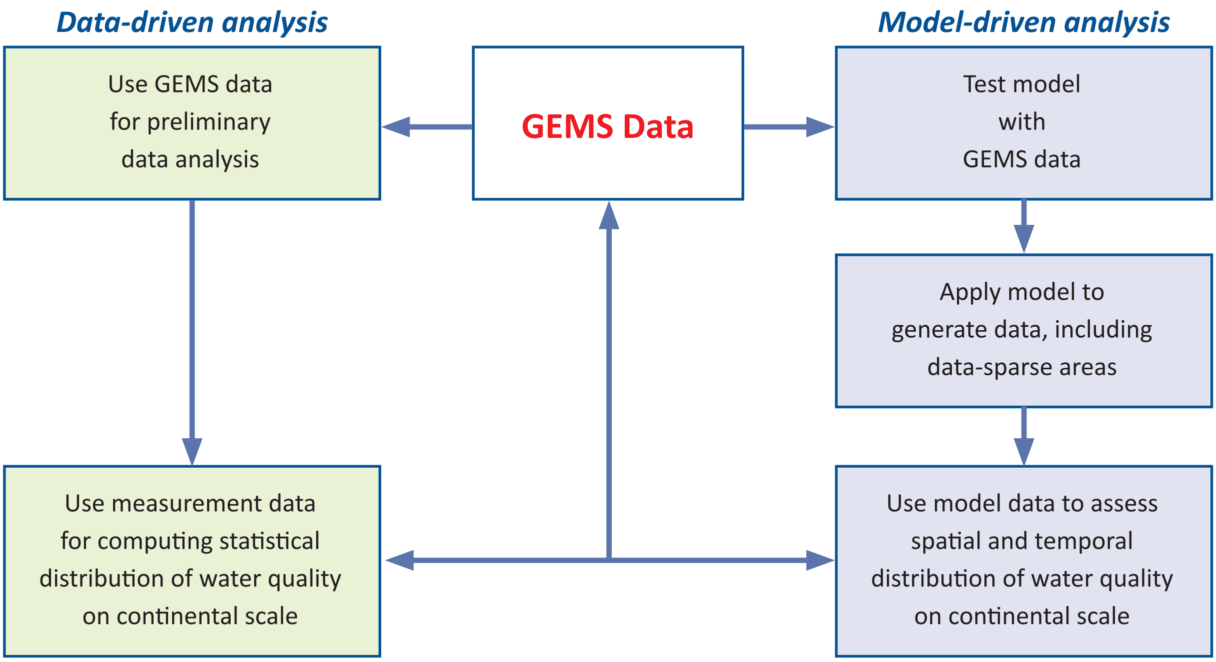


Figure 3.1: The "combined data-driven/model-driven" approach of this pre-study.

3.2 Pathogen pollution and the health risk

3.2.1 What health risks are related to polluted water?

Water is obviously crucial to human health. The WHO advises that at least 7.5 litres per day per person are necessary to meet "the requirements of most people under most conditions" and at least another 20 litres per day to cover basic hygienic needs (WHO, 2015a). Of course, the quality of this water must also be high to avoid diseases. UNICEF (2008) estimates that 3.4 million people die each year from diseases associated with pathogens in water, including cholera, typhoid, infectious hepatitis, polio, cryptosporidiosis, ascariasis and diarrhoeal diseases (Stanwell Smith, 2002; WHO, 2014b; WHO, 2008; WHO, 2006). Worldwide about 4 billion cases of diarrhoea are caused each year by the ingestion of water contaminated by faecal matter, as well as by inadequate sanitation and hygiene (WHO, 2014b), and of these cases 1.8 million are fatal. Worldwide more than 40 million people were treated for schistosomiasis in 2013 (WHO, 2015b) and as many as 1.5 billion people are infected with soil-transmitted helminth infections (WHO, 2015c). All of these diseases are largely excreta-related and many of them are due to the presence of human waste in water.

How do people get exposed to dangerous pathogens in water? An obviously important route is by drinking contaminated water. Recognizing the importance of the public health threat of drinking unclean water, the international community has been striving to reach the Millennium Development Goal of halving the number of people without access to a safe drinking water supply by 2015. As a result of these efforts, 2 billion people have gained access to safe water since 1990 (WHO/UNICEF, 2014a; WHO/UNICEF, 2015). A new set of international objectives, the "Sustainable Development Goals" include new ambitious objectives for clean water and health (UN, 2015b).

While the international community has goals for reducing the number of people exposed to unclean drinking water, less attention has been paid to another important route through which people are exposed to pathogens, namely through direct contact with polluted rivers, lakes and other surface waters (WHO, 2003). In this report, particular attention is paid to this route. The poor in rural areas of developing countries often use surface waters for bathing, for washing clothes, as a source of cooking water and sometimes for drinking water. In both developing and developed countries surface waters are used for recreational bathing, for fishing and as a water supply for irrigation.

Many different types of pathogens in water, including protozoan, parasites, bacteria and viruses, cause diseases. Since it is too costly to measure all types of pathogens everywhere, most monitoring studies of polluted water focus on one or a few types of indicator organisms that suggest the presence of pathogens. Here one of the most common indicators is used, "faecal coliform bacteria". Although most faecal coliform bacteria are in themselves not harmful, they are associated with faeces of humans and animals. Moreover, high levels of these bacteria are usually correlated with the presence of dangerous pathogens (WHO, 2001; Savichtcheva & Okabe, 2006). Several countries have acknowledged the connection between faecal coliform bacteria and health risks by setting limits for faecal coliform bacteria in their water bodies (Appendix B).

To assess the level of pathogen pollution, it is necessary to refer to a benchmark for safe and unsafe faecal coliform bacterial levels. Benchmarks used in this study are shown in Table 3.1. The boundaries of these classes are derived from the water quality standards of 17 countries (Appendix B).

Table 3.1: Classes of pathogen water pollution according to river concentrations of faecal coliform bacteria assigned in this report. Concentration is expressed in conventional units of "coliform-forming units per 100 millilitres" (cfu/100 ml). Based on water quality standards of 17 countries listed in Appendix B.

Water pollution class	Faecal coliform 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

3.2.2 What is the level of pathogen pollution?

GEMStat analysis

Since the data from GEMStat are too sparse to analyse pathogen pollution in spatial or temporal explicit details (see Section 2.2.2) they were consolidated into general statistical distributions on a continental basis for the period 2000 to 2010. (Table 3.2 and Figure 3.2). The median concentration of faecal coliform bacteria in African rivers based on a sparse number of measurements (N=215) is 1,500 cfu/100 ml. Therefore, it is considerably higher than the severe pollution level (Table 3.1) derived from the national water quality standards listed in Appendix B. The medians for Latin America (N = 1,725) and Asia (N = 4,131) are a factor of ten lower and, therefore, in the low pollution class. In Africa, about 50 per cent of all measurements exceed the severe pollution level of 1,000 cfu/100 ml, in Asia and Latin America about 25 per cent (Figure 3.2, right). Therefore this sparse data set indicates that a substantial fraction of river waters is polluted.

Modelling analysis

Building on the analysis of the GEMStat data, the results from the modelling analysis provide a more detailed picture of the spatial and temporal distribution of faecal coliform bacteria on the three continents.

Figure 3.3 shows an example of average monthly levels of faecal coliform bacteria from February 2008–2010[1] according to the water pollution classes in Table 3.1. Stretches of rivers in the "severe pollution" class are marked in red and occur on all continents, especially in Asia with many river stretches in southwest and eastern Asia. This is in agreement with Evans et al. (2012) and UNEP (2010) who emphasised that faecal coliform pollution of rivers from domestic sources is a major problem in Asia because of inadequate access to sanitation and connections to sewers.

However, it is not advisable to focus on results from a single month because it is well known that the level of water pollution varies from month to month due to the influence of different monthly river basin conditions on a river's capacity to dilute wastewater, on the die-off rate of bacteria in streams, and on the pollution washed-off from land surfaces. Therefore, it is also important to estimate the month-to-month variation of faecal coliform bacteria throughout the year. Table 3.3 provides estimates of the length of river stretches affected by pathogen pollution taking into account the month-to-month variation of river pollution. Around 261,000 to 327,000 km of Latin America's rivers, or about one-quarter of all river stretches, are in the severe pollution class. For Africa, the estimate is around 200,000 to 343,000 km, or around one-fifth to one-quarter of its river stretches, and for Asia around 493,000 to 793,000 km, amounting to about one-third to one-half of its entire river stretches.

Another way of judging the intensity of pollution is to estimate the number of months in a year in which severe pollution occurs. In general, the higher the frequency of high pollution levels, the greater the potential threat to people who come into contact with surface waters. Figure 3.4 shows the frequency of months per year in different river stretches in which severe pollution levels occurred from 2008 to 2010. Here, river stretches with severe pollution in six or more months each year are considered "hot spot areas". These include river stretches particularly along the western and eastern South American coastlines, in North Africa, the Middle East, and southern and eastern Asia.

Also of interest are the temporal trends in river pollution from 1990 to 2010[2]. As will be seen in Section 3.2.4, loadings of faecal coliform bacteria have increased over the last two decades on the average in Latin America, Africa and Asia. Apparently, although sanitation coverage has increased and treatment levels have improved in some countries (UNICEF, 2014), the efforts being made were not sufficient to reduce faecal coliform loadings reaching surface waters (see Box 3.2).

One consequence is that in-stream concentrations of faecal coliform bacteria have increased over this period throughout almost all of Latin America (59 per cent), Africa (63 per cent) and Asia (69 per cent) (Figure 3.5). In total, 64 per cent of the river stretches on these three continents have an increase in faecal coliform bacteria. A subset of these river stretches with an "increasing trend of particular concern" amount to 25 per cent of the total kilometres of rivers in Latin America, 18 per cent in Africa, and 51 per cent in Asia where faecal coliform levels increased to a severe level, or were at a severe level in 1990 and had worsened by 2010. These can be considered hot spot areas. Above, an alternative definition for "hot spot areas" was used, namely, river stretches having severe pathogen pollution for six months or more per year. It turned out that there is a considerable overlap in the river stretches that are hot spots according to both sets of criteria (Table 3.4). Particular attention should be paid to these areas in further efforts at monitoring and investigating pathogen river pollution.

[1]Results are presented for an average February over a three year period (2008–2010) to avoid presenting anomalous results caused by unusual weather conditions in a particular month and year.

[2]Here and elsewhere in the modelling analysis the water quality conditions during the three-year period 2008 to 2010 were examined rather than only those of 2010. A three year period is used to filter out unusual monthly water flow conditions that might lead to unusually high or low levels of in-stream concentrations of pollutants. The focus of this assessment was to determine the overall average state of water quality in rivers rather than the worst or best conditions.

Table 3.2: Overview of data availability and statistical values for faecal coliform bacteria in the time period 2000–2010. Data source: GEMStat. SD = Standard deviation. Units: [cfu/100 ml]

Continent	No. of stations/ 10,000 km²	No. of measurements	Median	10th percentile	90th percentile	SD
Latin America	0.027	1,725	135	0	17,410	367,514
Africa	0.001	215	1,500	93	46,000	112,006
Asia	0.036	4,131	140	3	4,000	135,742

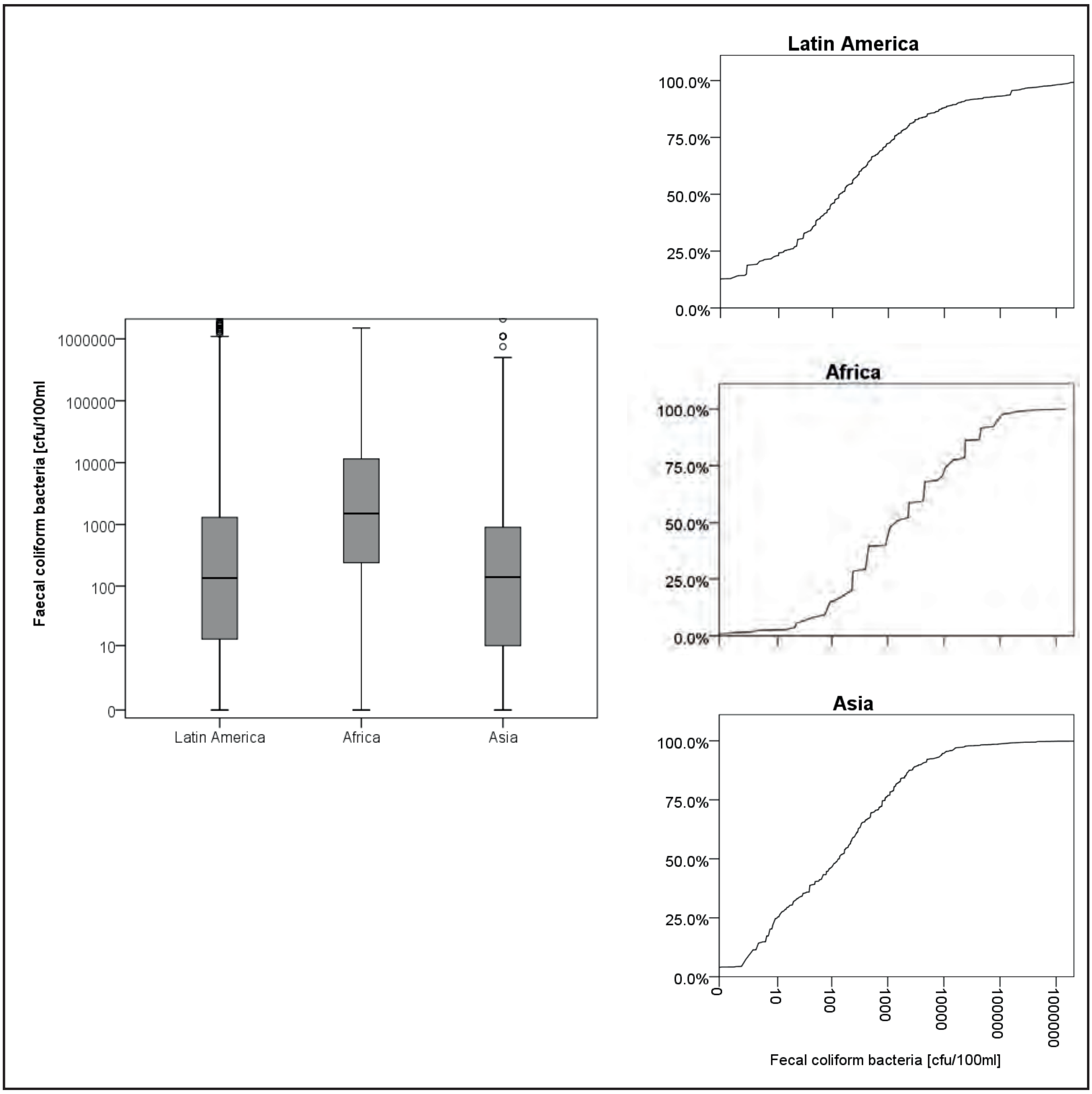


Figure 3.2: Statistical distributions of all GEMStat faecal coliform data in Latin America, Africa and Asia for the period 2000–2010. Box-and-whisker plots (left) and cumulative frequencies (right). The upper and lower boundaries of the boxes in the box-and-whisker plots indicate the 25th to 75th percentile and the line in between these boundaries the median (50th percentile).

Table 3.3: Length and percentage of river stretches (km) within various pathogen pollution classes. The minimum and maximum monthly stretches within the period of 2008 to 2010 are indicated.[a]

Water pollution class	Faecal coliform concentration (cfu/100 ml)	Latin America (min, max)	Africa (min, max)	Asia (min, max)
Low pollution	x ≤ 200	722,000–785,000 60–65%	965,000–1,122,000 63–74%	553,000–886,000 35–56%
Moderate pollution	200 < x ≤ 1,000	157,000–160,000 ~13%	203,000–216,000 13–14%	203,000–236,000 13–15%
Severe pollution	x > 1,000	261,000–327,000 22–27%	200,000–343,000 13–23%	493,000–793,000 31–50%

[a]Minimum and maximum estimates are the lowest and highest monthly estimates per continent in the 36-month period from 2008 to 2010. These are the ranges which correspond to the cases in which severe pollution is at a minimum or maximum on a continental basis.

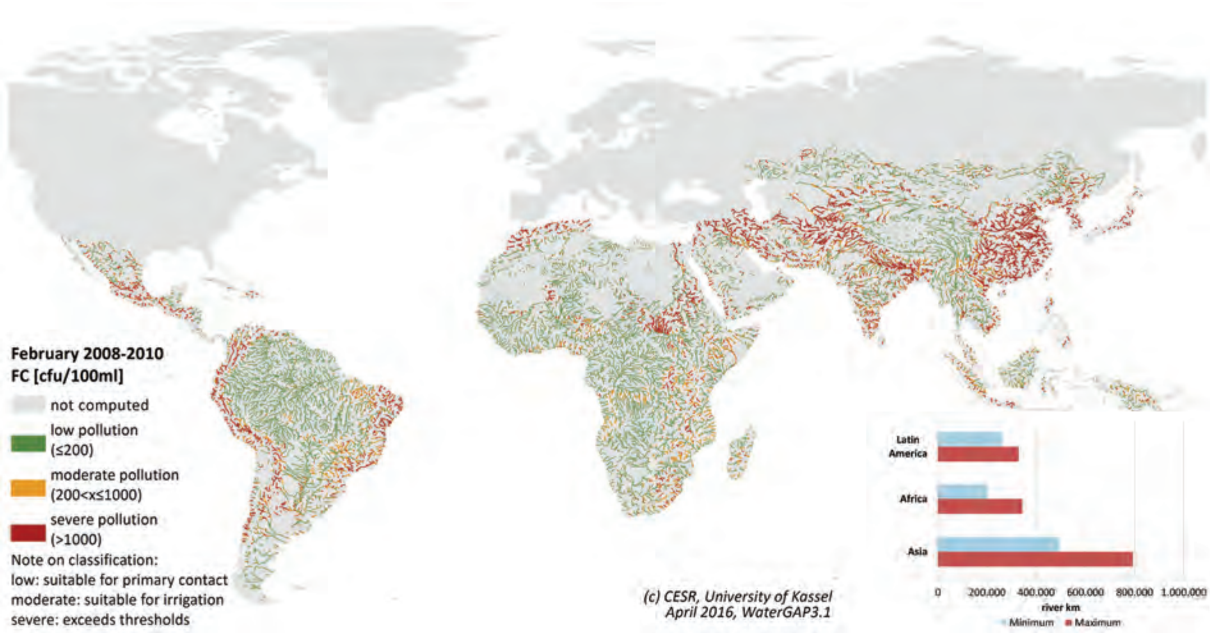


Figure 3.3: Estimated in-stream concentrations of faecal coliform bacteria (FC) for Latin America, Africa and Asia for February 2008–2010. Bar charts show minimum and maximum monthly estimates of river stretches in the severe pollution class per continent in the 36-month period from 2008–2010, corresponding to data in Table 3.3.

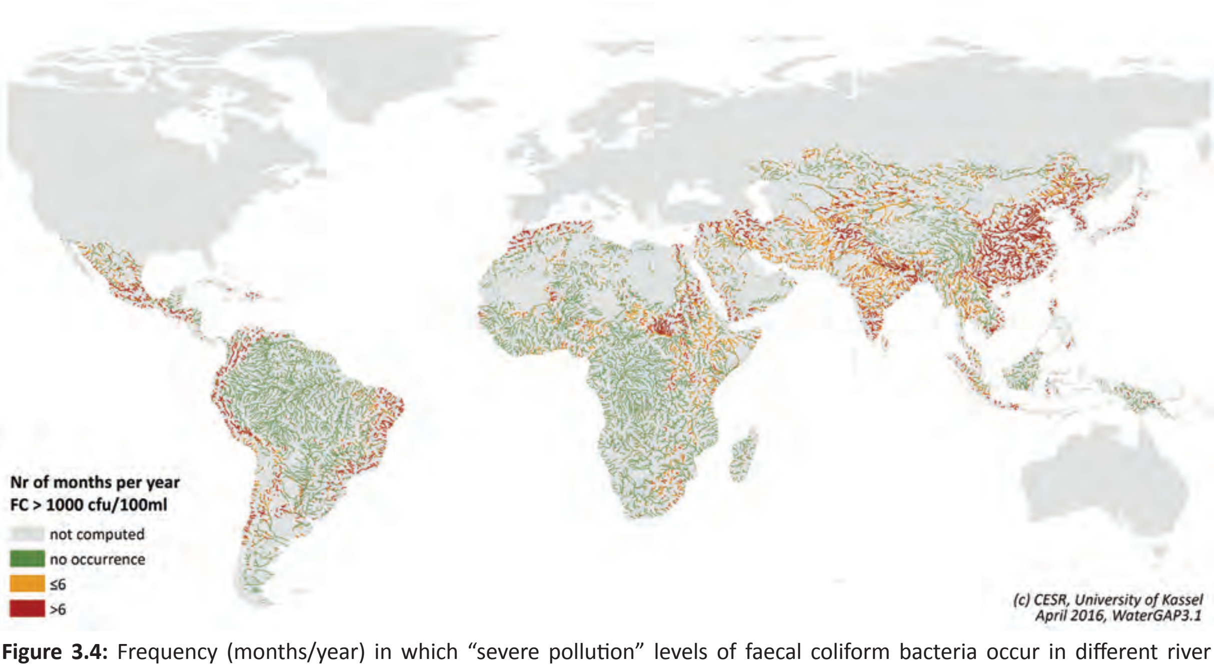


Figure 3.4: Frequency (months/year) in which "severe pollution" levels of faecal coliform bacteria occur in different river stretches over the period from 2008–2010.

[3]"Increasing trend of particular concern" in this report means a pollution level that increased into the severe pollution category in 2008-2010, or was already in the severe pollution category in 1990–1992 and further increased in concentration by 2008–2010.

Figure 3.5: Trend in faecal coliform bacteria levels in rivers between 1990–1992 and 2008–2010. River stretches marked with orange or red have increasing concentrations between these two periods. River stretches marked red have an "increasing trend of particular concern"[3].

Table 3.4: Hot spot areas of faecal coliform pollution appearing in both Figure 3.4 and Figure 3.5.

• Central America • West coast of Latin America • Upland river basin on Argentina border • East coast of Latin America • Northwest Africa • Nile river basin	• Some river stretches in Southern Africa • Middle East • Ganges river basin • Some river stretches in Southern India • Many river stretches in East Asia

Box 3.1: Estimating the rural population coming in contact with severe pathogen pollution

The following method was used to estimate the size of the rural population coming in contact with surface water severely polluted with faecal coliform bacteria (> 1000 cfu/100 ml). First, data on the percentage of rural population using surface waters for bathing, washing or as main water source were gathered from various case studies in developing countries (e.g. Brazil, China, Ghana, and Nigeria). Secondly, national data on the percentage of rural population using surface water as drinking water were compiled from the WHO/UNICEF Joint Monitoring Programme (JMP). The JMP data were used as a proxy of the percentage of rural people using surface water and as a lower limit of estimates for each country since the JMP data were found to be usually smaller than literature data from these countries. To make an upper limit for each country, the JMP estimate for a particular country was multiplied by a factor of 1.94. The factor 1.94 is the median ratio between literature values in various case studies from different countries and the JMP national value of the country where the case studies took place. In this way, lower and upper estimates were derived of the percentages of rural population in each country that regularly comes in contact with surface waters.

Next, the subset of rural people was estimated who not only use surface water but also may come into contact with polluted water. Using the gridded population data base from HYDE (version 3.1; Klein Goldewijk, 2005; Klein Goldewijk et al., 2010) and UNEP (2015a) the rural population living in proximity of river stretches in the "severe pollution" category of faecal coliform bacteria[a] (i.e. within one grid cell, or approximately 10 km, of the respective river stretches) was estimated. For each country, the number of rural people living in proximity of the severe pollution was multiplied by the upper and lower estimates of the percentage of rural people using surface waters. As a result the estimates in Table 3.5 were obtained.

This procedure may lead to an overestimate of the people exposed to pathogen pollution because people obviously avoid, if possible, surface waters that are grossly polluted. On the other hand, the number of people exposed may be underestimated because urban populations are not taken into account, and because the percentage of people using surface waters near rivers is likely to be proportionately higher than the national average percentage data coming from the JMP data base.

[a]For these estimates the river stretches in the severe pollution category for faecal coliform bacteria in the median month (on a continental basis) over the 36-month period during 2008-2010 were used.

3.2.3 People at risk of pathogen river pollution

A very important question in assessing the world water quality situation is the number of people at health risk through contact with surface waters. Unfortunately, no authoritative global estimates exist. Many published studies (See Appendix B) estimate that 5 per cent or more of rural inhabitants in many developing countries regularly come into contact with surface waters. It is expected that the exposure of the rural population to contaminated surface water through bathing, clothes washing, etc. will be much larger than the exposure of the urban population because urban populations tend to be more often serviced with public water supply and tend to have less access to surface waters.

The number of rural people coming in contact with polluted surface waters was estimated as described in Box 3.1. For Latin America, the number of people is estimated to be approximately 8 to 25 million people, for Africa around 32 to 164 million, and for Asia around 31 to 134 million people (Table 3.5). The ranges reflect the uncertainties of these first estimates, which are based on literature and the JMP database. Despite the uncertainties, the message of these estimates is that at least up to hundreds of millions of people may be at a health risk because of their contact with polluted surface waters.

While both men and women use surface waters for bathing, women are at particular risk because of their frequent usage of water from rivers and lakes for cleaning clothes and collecting water for cooking and drinking in the household (Adeoye et al., 2013; Barbir and Prats-Ferret, 2011; Gazzinelli et al., 1998; Kabonesa and Happy, 2003; Lindskog and Lundqvist, 1989; Manyanhaire and Kamuzungu, 2009; Sow et al., 2011; Thompson et al., 2003). Children are also at particular risk because of their play activities in local surface waters and also because they often have the task of collecting water for the household (Adeoye et al., 2013; Aiga et al., 2004; Choy et al., 2014; Engel et al., 2005; Gazzinelli et al., 1998; Kabonesa and Happy, 2003; Lindskog and Lundqvist, 1989; Sow et al., 2011; Thompson et al., 2003).

Using polluted water for irrigation also poses a health risk to both the farmers who come in direct contact with the water and the consumers of fruits and vegetables irrigated with polluted water (FAO, 1997).

Table 3.5: Estimated number of people (in millions) living in rural areas coming in contact with surface waters that were severely polluted. Estimates for period 2008 to 2010.

Latin America (min, max)	Africa (min, max)	Asia (min, max)
8.1–24.8	31.7–164.3	30.6–133.7

3.2.4 Sources of faecal coliform bacteria

Many factors influence the level of faecal coliform bacteria in rivers. One is the capacity of the river to dilute wastewater loadings of bacteria; another is the die-off rate of these bacteria as it is affected by temperature, sunlight and their settling rates. These factors are taken into account as described in Appendix B.

A very important factor, and one that society can influence considerably, are wastewater loadings into surface waters. Several sources of loadings are taken into account as shown in Table 3.6. These loadings depend on the waste produced per person, the type of sanitation, the degree to which sanitation systems are connected to sewers, and the level to which sewage is treated. Controlling levels of faecal coliform bacteria loadings at the source is the key to providing microbiologically safe drinking water and surface waters (see Chapter 5).

Most of the faecal coliform pollution in Latin America comes from sewered domestic wastes (81 per cent) followed by non-sewered domestic sources. Collection of domestic sewage and its untreated delivery to rivers has contributed to bacterial pollution in rivers. Rivers flowing through densely-populated urban and industrial areas are more likely to be contaminated by faecal coliform bacteria (see Figure 3.8) and tend to fall into the "severe pollution" category for faecal coliform bacteria. Other sources of faecal coliform loadings are urban surface runoff and wastewater discharges from the manufacturing sector.

For Africa, the majority of faecal coliform bacteria come from non-sewered domestic sources (56 per cent) followed by sewered domestic sources (41 per cent) from scattered settlements. Sub-Saharan countries have the lowest levels of sanitation coverage. In this region, 644 million people had no access to an improved sanitation facility in 2012 (WHO/UNICEF, 2014a).

In Asia, about half the faecal coliform bacteria comes from sewered domestic waste. The other half comes from non-sewered domestic waste sources from scattered settlements. Only about one-third of all wastewater in Asia is treated; the lowest treatment rates are in South Asia (about 7 per cent) and Southeast Asia (about 14 per cent). According to the Report of the WHO/UNICEF Joint Monitoring Programme on Progress on Drinking Water and Sanitation (WHO/UNICEF, 2014a), more than 1 billion people have no access to an improved sanitation facility in Southern Asia, including 792 million people in India. Due to the high population density together with a low-level coverage of improved sanitation and treatment, faecal coliform loadings are considerable and cause severe pollution in many rivers in Asia.

As noted earlier, the levels of faecal coliform bacteria in rivers have been estimated to increase over the last two decades because of increases in loading. On the continental average basis, from 1990 to 2010 loadings have increased by 64 per cent in Latin America, by 97 per cent in Africa and by 86 per cent in Asia (Figure 3.7). Faecal coliform loadings increased mainly because of the large increase of domestic wastes, both sewered and non-sewered. Main driving forces of these increases have been the growth of population and growing sewer connections without treatment of wastewater. It is likely that loadings of faecal coliform bacteria to rivers would have been lower if the new sewer systems had not been built (See Box 3.2).

Box 3.2: Faecal coliform loadings to rivers are higher because of the lack of wastewater treatment.

As noted in the text, pathogen pollution has increased over large stretches of rivers over the past decades. A large fraction of the increase is due to the expansion of sewer systems that discharge wastewater untreated into surface waters. If the sewer systems had not been built, it is likely that the loadings of faecal coliform bacteria to Africa's rivers would have been around 23 per cent lower than they are now (See Figure 3.6 below). This is because the new sewers deliver human wastes to rivers that would otherwise have remained (unsafely) on the land.

On one hand, by taking the wastewater away from populated areas, the sewers have reduced the health risk posed by unsafe sanitation practices on land. On the other hand, by dumping sewage untreated into surface waters, they have transferred the health risk from the land to surface waters.

The solution, however, is not to build fewer sewers, but to treat the wastewater they collect.

Figure 3.6 shows faecal coliform loadings for Latin America, Africa and Asia in 2010 according to two sets of assumptions. The left bar of each continent is the best estimate for 2010. This estimate takes into account increasing rates of connections to sewer systems (as described in Appendix B). The right bar is an estimate assuming that connection rates to sewers did not increase after 1990. The difference between this estimate and the best estimate shows the impact of expanding sewer systems on faecal coliform loadings.

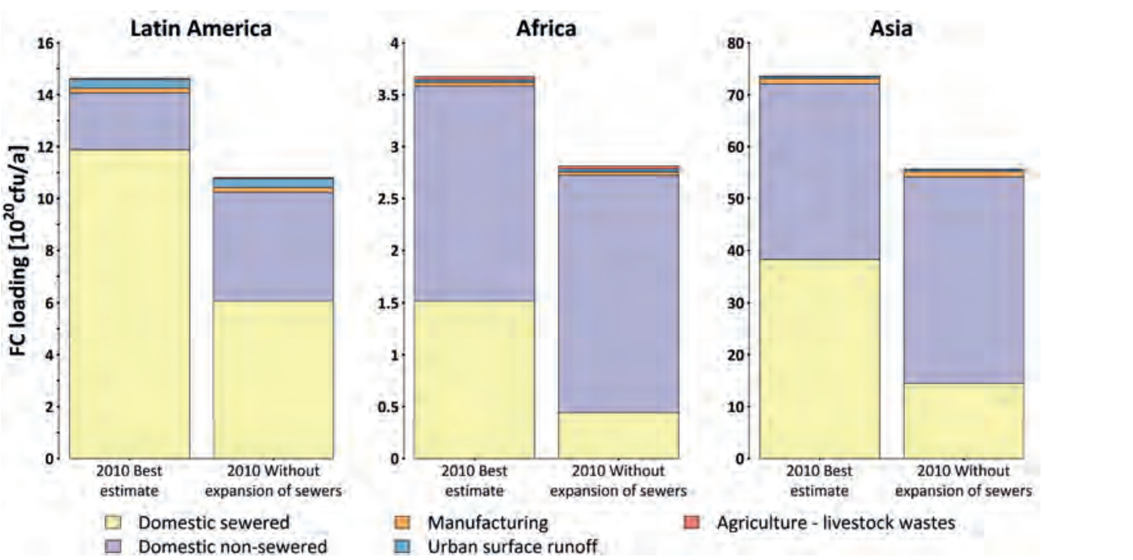


Figure 3.6: Faecal coliform bacteria loadings for Latin America, Africa and Asia for two sets of assumptions: the "best estimate 2010" and "without expansion of sewers".

Table 3.6: Categories of faecal coliform bacteria loadings accounted for in estimates of in-stream concentrations.

- Domestic sewered (point sources)
- Domestic non-sewered – hanging latrines (point sources); domestic septic tanks, pit toilets, open defecation (diffuse sources)
- Manufacturing (point sources)
- Urban surface runoff (diffuse sources)
- Agriculture – animal wastes (diffuse sources)

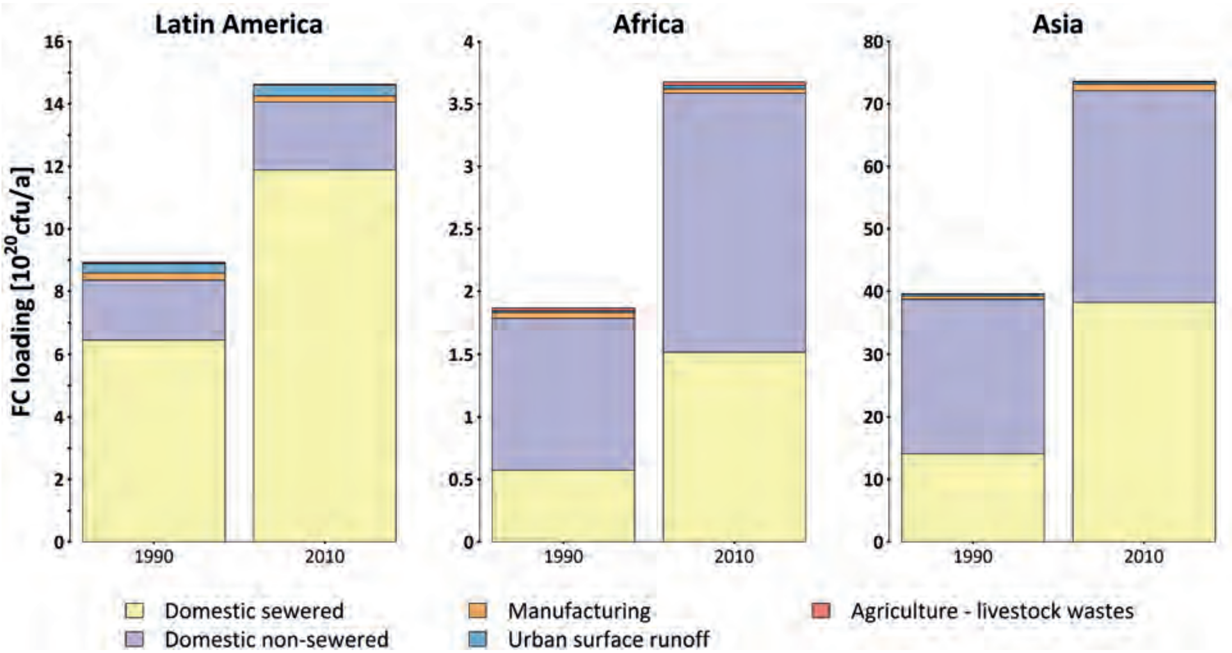


Figure 3.7: Faecal coliform bacteria loadings for Latin America, Africa and Asia for 1990 and 2010.

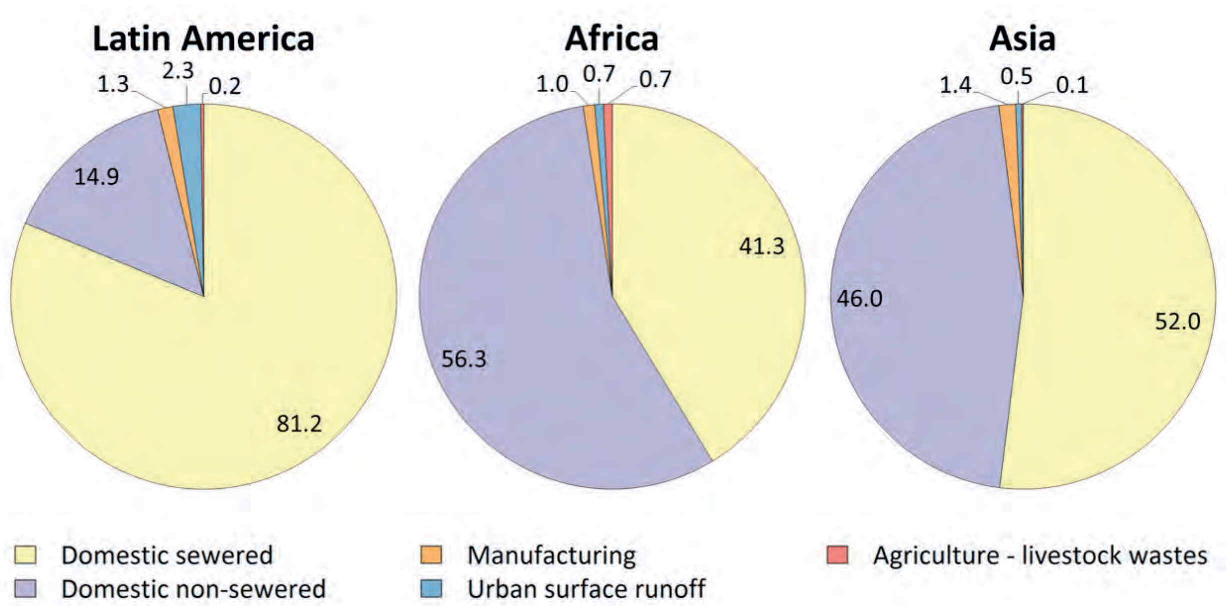


Figure 3.8: Distribution of faecal coliform loadings according to source for 2010. Units: percentage.

3.3 Organic pollution and the threat to the inland fishery and food security

3.3.1 What is organic pollution?

The health of fish and aquatic fauna is threatened by many changes to the natural state of water bodies, including the destruction of their habitat, contamination with trace toxic substances, and "organic pollution". Here the focus is on "organic pollution"[4], a common term used to describe the set of processes associated with depletion of dissolved oxygen in a water body (e.g. EEA, 2015; Lobo et al., 2015; Noel & Rajan, 2015; Gao et al., 2013; Vidal et al., 2013; Haury et al., 2006; FAO, 1996). Organic pollution occurs when an excess of easily biodegradable matter enters surface waters. The decomposition of this matter by bacteria and other microorganisms consumes oxygen and depletes dissolved oxygen from the water column. The depletion of dissolved oxygen has a very negative effect on aquatic fauna, especially fish and benthic invertebrates, which rely on this oxygen for their survival and functioning.

There are many different causes of organic pollution. The main causes in rivers near heavily populated and industrialised areas are discharges of domestic and industrial wastewater which typically contain large quantities of biodegradable or oxidisable substances.

Another cause, particularly where rivers are impounded, is eutrophication. In this case, large loads of nutrients into the river from domestic and agricultural sources stimulate the growth of algae in the slow moving reaches of rivers behind dams. When the algae die off they are decomposed by bacteria and other microorganisms which deplete the oxygen resources of the river. Organic pollution is also caused by the wash off of animal wastes into rivers, urban runoff, and other sources.

We begin this subchapter with a discussion of inland fisheries because they are particularly threatened by organic pollution.

3.3.2 The importance of inland fisheries to food security

Inland fisheries represent an invaluable and often irreplaceable contribution to food security for hundreds of millions of people in poor, rural communities around the world (FAO, 2003; World Bank et al., 2010). The reported global inland fisheries harvest in 2012 was 11.6 million tonnes (FAO, 2014), although these harvest figures are widely acknowledged to be grossly underestimated in many countries (FAO, 2012).

Globally, fish from inland waters is the sixth most important supplier of animal protein (Welcomme, 2010). Locally, the inland fish catch can be a much more significant source, especially for populations living near rivers and lakes and in land-locked countries (Welcomme, 2010). For example, the catch of inland fish accounts for 44 per cent of the animal protein produced in Malawi, 64 per cent in Bangladesh and Cambodia, and 66 per cent in Uganda (2007 figures from Welcomme, 2010).

China, Bangladesh, India, and Myanmar recorded the highest inland catch both in Asia and the world with over 1 million tonnes each in 2010, while Cambodia, Myanmar and Uganda had the highest consumption per person with 27, 20, and 12 kg/capita for 2010, respectively (Welcomme, 2011).

These fisheries harvest hundreds of aquatic species from almost all freshwater ecosystems (Welcomme, 2011). They are characteristically informal in nature, require no or low entrance fees, minimal start-up costs and equipment, and need only basic skill levels to participate. Thus, inland capture fisheries are an important source of livelihoods and employment in developing countries. For the period of 2010 to 2012, FAO (2014) estimated that inland fisheries provided employment for 21 million fishers. Inland fisheries also provided 38.5 million jobs in post-catch processing and other related activities (World Bank et al 2010). Almost all of these jobs were in small scale fisheries, occupied by mostly low-income people, with over half of the total workforce being women (World Bank et al., 2010).

[4]Should not be confused with problem of "persistent organic pollutants" (POP) which are "chemical substances that persist in the environment, bioaccumulate through the food web, and pose a risk of causing adverse effects to human health and the environment"(UNEP, 2015b).

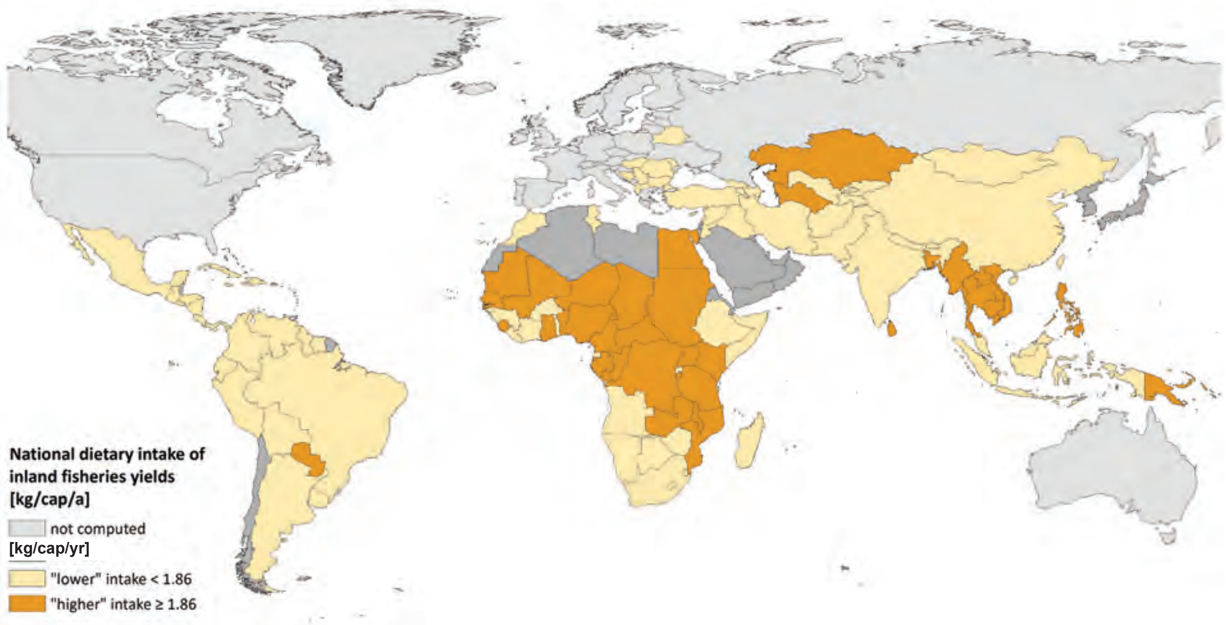


Figure 3.9: National dietary intake of inland fisheries yields (kg/capita/2010).
Data Source: FishstatJ (FAO, 2014), country population data (World Bank)

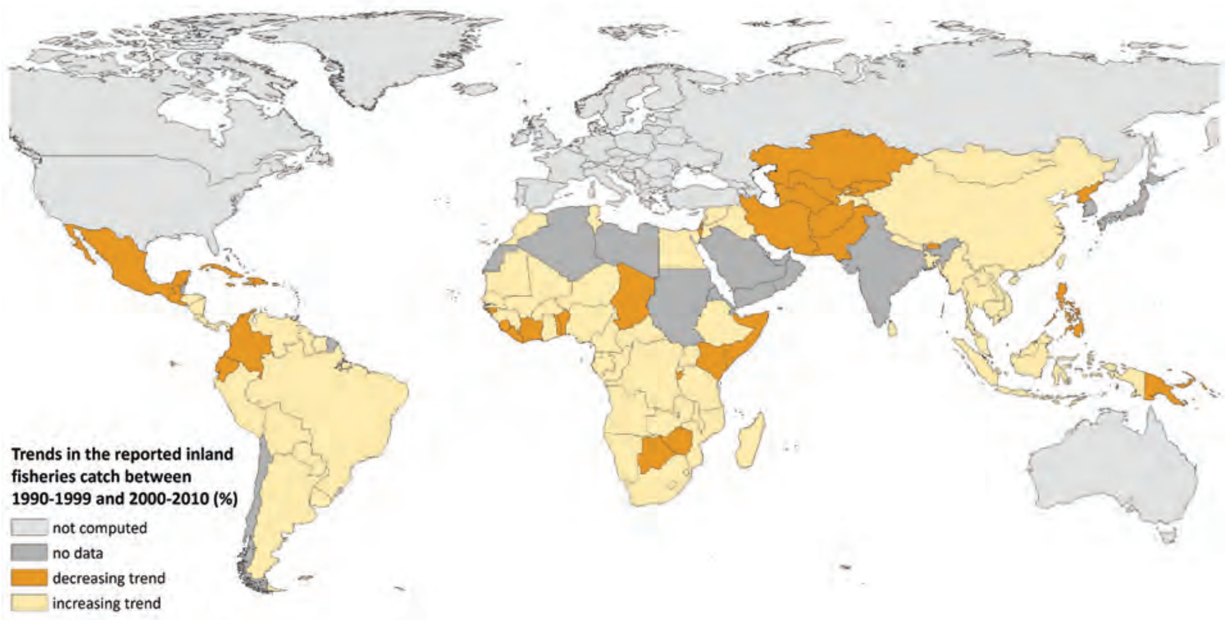


Figure 3.10: National inland fisheries catch trend between the time periods 1990–1999 and 2000–2010.
Data Source: FishstatJ (FAO, 2014).

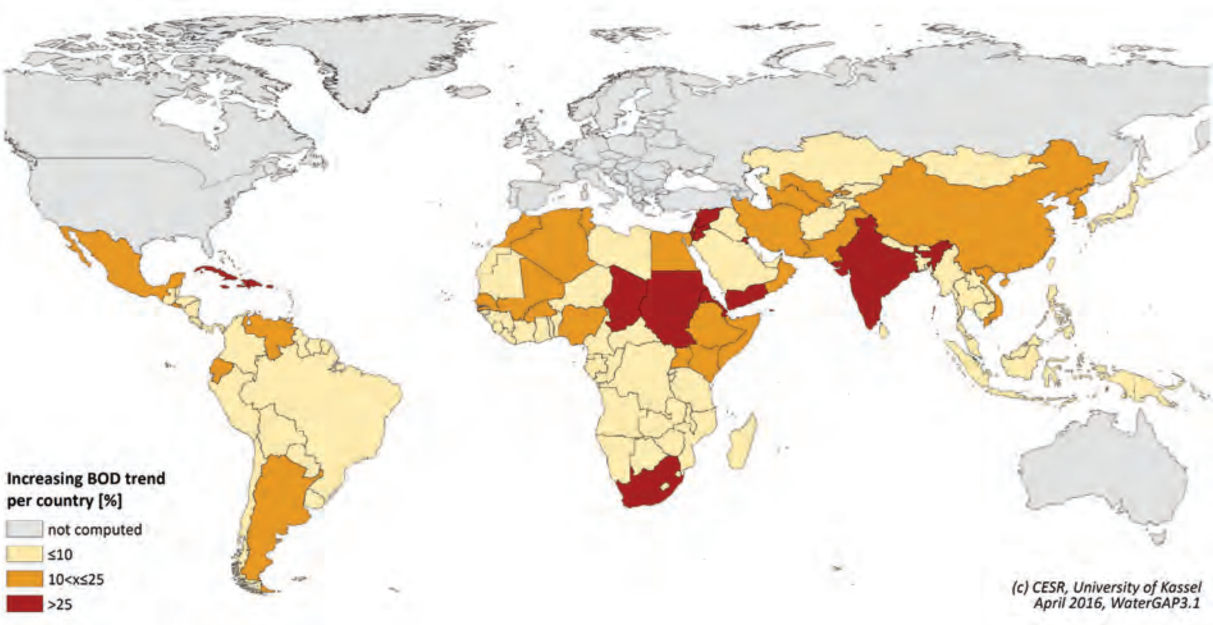


Figure 3.11: Percentage of river stretches in each country with "increasing trend of BOD of particular concern" meaning that in these stretches the pollution level increased into the severe pollution category in 2008–2010, or that they were already in the severe pollution category in 1990–1992 and further increased in concentration by 2008–2010 (cf. Figure 3.15).

Catches are either utilised for direct consumption, used in bartering agreements, or sold at local markets providing additional access and availability to community members not directly involved in the fishery (World Bank, 2010). The large, dispersed scale that inland fisheries typically operate on also helps to maintain supply stability and avoid disruptions on a local scale, as can post-harvest processing such as drying and salting or refrigeration of excess product in more developed areas.

As inland fisheries provide an essential source of protein and micronutrients for millions of people across the developing world, it is of interest where they have the greatest relevance to food security. One indicator is the *national dietary intake of freshwater catches* per capita, which provides an approximation of the level of consumption as well as the potential availability of fishery resources for individuals (Figure 3.9). This indicator assumes all aquatic products from inland fisheries are consumed in-country, which is true for most situations (FAO, 2003). It must also be noted that the consumption of inland fisheries resources are generally higher in rural regions, particularly in communities residing adjacent to lake and river networks, than in major city settlements.

Considering all developing countries with reported inland fisheries catch data, 36 per cent were identified as being at a "higher vulnerability", with most of these countries located in Central and West Africa and Southeast Asia (Box 3.3).

Another important factor relevant to inland fisheries and food security is the *trend in inland fish catches* (Figure 3.10). Global reported inland fisheries catches have been increasing steadily since 1950 at a rate of 2.9 per cent per year (Welcomme, 2011). The country trends of inland fish catches were calculated in order to determine if catches were increasing or decreasing since 1990. Decreasing catches in a country dependent on fish consumption may indicate an increasing risk to food security. Of course, they may also reflect a population becoming more wealthy and preferring not to consume inland fish. Increasing catches may indicate somewhat higher food security. On the other hand, if catches increase beyond the sustainable levels for the fishery, then fish populations may strongly depleted and this would pose an even greater risk to food security. In general, it is difficult to interpret the meaning of a decreasing or increasing catch, and it should be used only as a very preliminary indicator of the status of a fishery.

The national catch trend for developing countries indicates that 62 per cent of the countries considered have increasing catches while 38 per cent reported decreasing ones. An overview of the results shows countries with a decreasing trend in Central Asia and the Middle East, Central America, the Caribbean and some Northern countries of South America as well as in various countries throughout Africa (Figure 3.10).

Box 3.3: Proposed methodology for computing indicators relevant to the status of the inland fishery

One of the main objectives of this pre-study towards a World Water Quality Assessment was to develop a concept for the identification of regions where inland fisheries are vulnerable to water quality deterioration, and where food security may be reduced.

First, preliminary indicators of inland fisheries (Section 3.3.2) and water quality (Box 3.3) are developed. Secondly, these indicators are linked to evaluate how and where water quality degradation has an impact on the capacity of inland fisheries and their relation to food security on a global scale (Figure 3.12). As an example, a preliminary comparison is made in Section 3.3.3 of inland fishery indicators (national dietary intake and national fish catch trends) and a water quality indicator (location of "increasing BOD trends of particular concern").

For preliminary estimates of inland fishery indicators, existing data from international databases such as FAO (Fishery and Aquaculture Global Statistics – FishstatJ), and The World Bank (country population data), were used. The calculations considered only freshwater fish with aquaculture data excluded.

To calculate the indicator "national dietary intake of inland fisheries" (kg/capita/2010), the total reported inland fisheries catch per country was divided by country population. The data were then categorised into "higher" or "lower" intake based on the calculation of the 75th percentile of countries reporting inland fisheries yields. In that regard, countries were classified as being either at a "higher intake" level with ≥ 1.86 kg/capita/yr or a "lower intake" with < 1.86 kg/capita/yr.

The indicator "national inland fisheries catch trend" was calculated by comparing average decadal yields from 1990–1999 with 2000–2010. Decadal averages were used because of large year-to-year fluctuations. This is a very approximate indicator of the possible status of inland fishery resources because it does not indicate the specific reasons for an increasing or decreasing trend. Furthermore, additional factors will be considered including the development level of a country and the occurrence of over-fishing.

The data used for these indicators were only available on a country scale in the FAO Fishstat database. However, there is a need to downscale the indicators to the river basin or lower scale so that they can be related to water quality and other river conditions. This will allow for a more detailed investigation of the threat of increasing water pollution to fish populations of particular importance to food security.

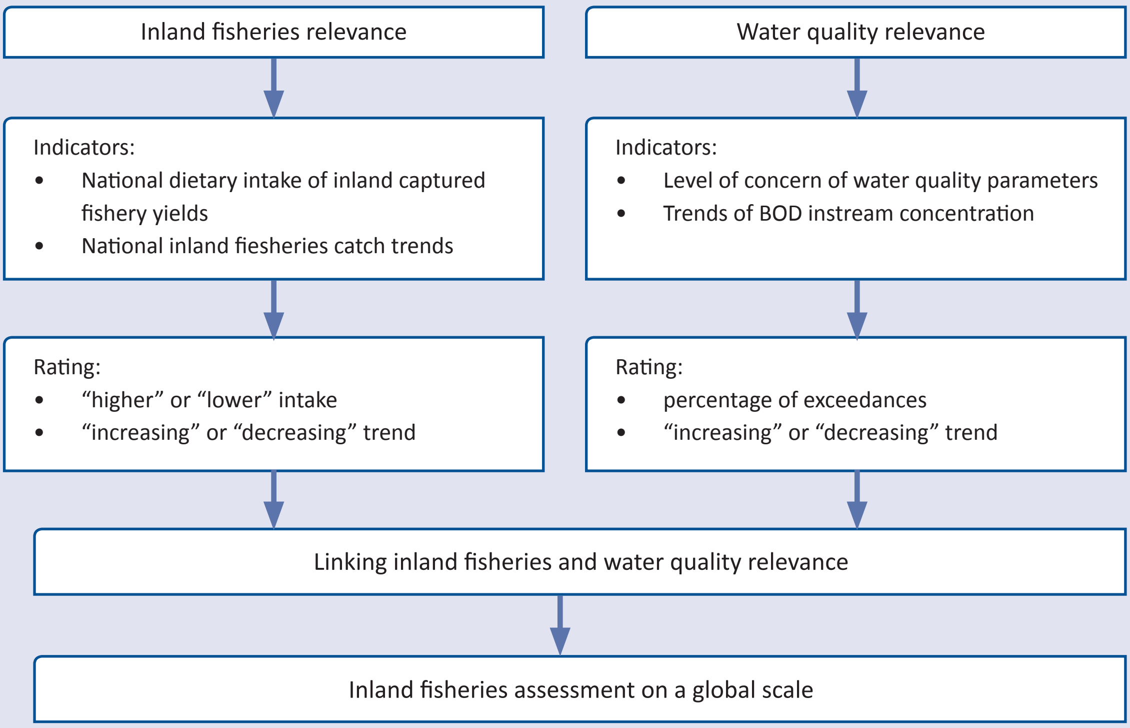


Figure 3.12: Preliminary scheme for assessing the status of inland fisheries with regard to water quality degradation.

3.3.3 What is the level of organic pollution?

As already noted, organic pollution is of particular concern because it threatens the functioning of inland fisheries and aquatic ecosystems in general. Here, results from GEMStat concerning water quality levels in Latin America, Africa, and Asia and how they relate to the health of the inland fishery are examined first. Then a closer look is taken at the spatial and temporal dimensions of one of these indicators, biochemical oxygen demand (BOD).

GEMStat analysis

Certain water quality parameters related to organic pollution are particularly relevant to the health of the inland fishery (see Box 3.4). These parameters are: dissolved oxygen, biochemical oxygen demand (BOD), ammonia, chloride, and pH. The second-to-last column of Table 3.7 presents levels of concern for these five key parameters, with particular consideration given to the tolerance levels of fish. Values outside these limits indicate a high risk to the reproduction, growth, respiration, and feeding of fish. Because of the very wide variety of fish in Latin America, Africa, and Asia; these “levels of concern”[5] are only a very general guide to their tolerance limits.

Table 3.7 presents the percentage of stations where the five key parameters are at levels of concern. Since there is a wide variation in the spatial and temporal coverage of the different parameters, only general conclusions can be drawn from this analysis:

- In Latin America, at least 10 per cent of the measurements for dissolved oxygen, ammonia, and pH exceed levels of concern for these parameters.
- In Africa, at least 20 per cent of the measurements for dissolved oxygen, BOD, and chloride exceed these levels.
- In Asia, at least 10 per cent of the measurements for dissolved oxygen[6], BOD[7], ammonia, chloride, and pH exceed these levels.
- In Table 3.7, ranges are given for the level of concern for BOD. For the more stringent level, 10 per cent of the measured BOD data in Latin America, 40 per cent in Africa, and 15 per cent in Asia are at a level of concern for BOD.

In conclusion, at least 10 percent of measurements from all three continents show levels of concern for at least three out of five water quality parameters of particular importance to the health of fisheries. Together, these results point to an overall picture of concern regarding water quality and the inland fisheries of Latin America, Africa, and Asia.

Modelling analysis

After the examination of results for five water quality parameters with the help of the GEMStat database, the spatial and temporal trends of one of these indicators, BOD, was looked at more closely. BOD is often taken as the principle indicator of organic pollution (Box 3.4). As for faecal coliform bacteria in Section 3.2.2, the WorldQual model is used to compute the monthly concentration of BOD in Latin America, Africa, and Asia from 1990 to 2010.

Based on water quality guidelines from 11 different countries (Appendix B), BOD results were clustered into the three water quality classes shown in Table 3.8. Figure 3.13 shows an example of average monthly levels of BOD for February 2008-2010 clustered into three classes. Severely polluted river stretches include northern and eastern parts of Latin America, northern and eastern Africa as well as many parts of Asia.

Figure 3.13 shows the modelled BOD in-stream concentrations on a monthly average basis for February 2008–2010. However, it is known that levels of BOD vary from month to month because of changing dilution capacity, temperature-related BOD decay, and runoff of pollutants. Figure 3.14 shows the frequency of months each year in which severe BOD pollution levels occur from 2008 to 2010. As for faecal coliform bacteria, it is assumed that the more frequently high BOD levels occur throughout the year the greater the impacts of high BOD levels. Therefore, river stretches with severe pollution during six months or more each year are taken as an indication of hot spot areas. According to this definition, hot spots appear in Central America, eastern South America, Northeast Africa, South and East Asia.

Table 3.9 shows the length of river stretches with different levels of BOD pollution, taking into account the month-to-month variation of BOD. A range of 60,000 to 117,000 km of Latin America’s rivers, equivalent to about one-tenth of its total river stretches, are in the severe pollution class. In Africa, 132,000 to 234,000 km, or around one-sixth of its river stretches, are in the severe river pollution class, and in Asia 168,000 to 268,000 km, or also about one-sixth of all of its river stretches.

Figure 3.15 shows the trend in BOD river concentrations between the early 1990s and late

[5]“Level of concern” in this report is used to mean the pollutant concentration above (or below) which significant negative impacts occur. In this report, these concentrations are derived from water quality standards from official sources such as government departments or UN agencies.
[6]Considering an intermediate value of the range in Table 3.7.
[7]Considering an intermediate value of the range in Table 3.7.

2000s. BOD concentrations have increased in 54 per cent of the river stretches in Latin America, 62 per cent of the river stretches in Africa, and 71 per cent of the river stretches in Asia. In total, 63 per cent of the river stretches on these three continents have an increased BOD concentration.

River stretches marked with red in Figure 3.15 have an "increasing trend of particular concern". In these river stretches, the concentration of BOD increased into the severe pollution category in 2008-2010, or it was already in the severe pollution category in 1990-1992 and further increased in concentration by 2008-2010. These river stretches amount to 6 per cent of the total lengths of rivers in Latin America, 12 per cent in Africa and 13 per cent in Asia and could also be considered hot spot areas. The overlap of hot spot areas according to this definition and the definition used earlier (Figure 3.14 and Figure 3.15) is shown in Table 3.10. River basins listed in this table could be considered as BOD hot spot areas with high confidence since they appear as hot spots according to two different definitions. These areas should be paid particular attention in further monitoring and investigation efforts of organic river pollution.

To sum up the modelling analysis of BOD, results show that the lengths of river stretches with high BOD levels on all three continents are in the hundreds of thousands of kilometres, and that most stretches of rivers also have increasing concentrations.

Preliminary comparison of inland fishery indicators with a BOD indicator

The BOD hot spots ("increasing areas of particular concern") shown in Figure 3.15 are also of importance to inland fisheries because these areas have both a high and an increasing level of BOD. High levels of BOD often coincide with low levels of dissolved oxygen and threaten the local survival of fish and other aquatic fauna (Box 3.4). Figure 3.11 summarizes these data on a country level so that they can be compared to the earlier maps of country-scale consumption of fish and trends in fish catch (Figure 3.9 and Figure 3.10).

A comparison of the three maps indicates two subsets of countries whose inland fisheries may be particularly vulnerable to increasing organic pollution:

- One subset of 10 countries[8] has both a higher consumption of fish from the inland fishery and increasing organic pollution (>10 per cent as indicated by Figure 3.11) (with increasing or decreasing catch).
- A second subset of 16 countries[9] has decreasing catch together with increasing organic pollution (>10 per cent).

The combination of indicators may indicate an increasing risk to the inland fisheries of these countries. At a minimum, it is worthwhile for these countries to be vigilant against increasing water pollution endangering their inland fisheries and the food security and livelihoods they provide.

Box 3.4: Water quality parameters of concern to health of inland fisheries

Dissolved oxygen (DO) is a fundamental water quality parameter (UNEP, 2008) related to the sustainability of freshwater fisheries and aquatic ecosystems integrity. A minimum level of dissolved oxygen is needed to prevent lethal and sub-lethal (physiological and behavioural) effects on fish and other higher organisms (CCME, 1999). While dissolved oxygen is depleted by the decomposition of organic matter and may be completely consumed under excessive organic loads, it also can also show high supersaturation caused by the photosynthesis of algae and other aquatic flora under eutrophic conditions. The solubility of oxygen in water strictly depends on the temperature and decreases with increasing temperatures. Both parameters are ecological key factors which control the occurrence and geographical spread of species. For this reason, two levels of concern for fish communities adapted to cold or warm water are given in Table 3.7.

Biochemical oxygen demand (BOD) is a key indicator of organic pollution (EEA, 2015) and indicates high levels of biodegradable organic matter in the water. High BOD loads usually cause significant depletions of dissolved oxygen and deleterious effects on fish and other biota. One example is the Tietê River in Brazil, presented as a case study in Chapter 4. The Tietê picks up large loads of organic wastes from

[8] Chad, Kenya, Mali, Nigeria, Senegal, Vietnam, Sudan, Turkmenistan, Uganda, Egypt.
[9] Chad, Cuba, Dominican Republic, Ecuador, El Salvador, Haiti, Iran, Israel, Jamaica, Kenya, North Korea, Mexico, Pakistan, Somalia, Turkmenistan, Uzbekistan

domestic and industrial sources as it flows through the city of São Paulo. These loads reduce dissolved oxygen levels in the river to levels as low as 2 mg/l and the low level of dissolved oxygen together with the presence of other pollutants has drastically reduced the number and diversity of fish species in the river around the city.

It should be noted that high BOD *is not always correlated* with low dissolved oxygen and threats to fish *in the vicinity of wastewater discharges.* Dependent on river conditions, dissolved oxygen could be at a satisfactory level at the entry point of BOD discharged into a river because of the time dependent biochemical degradation of the organic matter. Furthermore, under high nutrient loading and eutrophic conditions the biomass of algae or macrophytes may significantly contribute to the BOD loading. However, high levels of BOD in aquatic ecosystems are typically associated with significant oxygen depletion and therefore, the German national water quality guidelines indicate that low oxygen levels and periodic fish kills may be expected at BOD concentrations greater than 8 mg/l (LAWA, 1998).

Another key indicator of organic pollution (EEA, 2015) and of particular concern to fish health is *ammonia*. *Ammonia* exists in two forms in water – un-ionized (NH_3) and ionized (NH^{4+}). Ammonia is taken up as a nutrient by aquatic plants and is typically oxidized to nitrate through the process of "nitrification" which consumes oxygen. In higher concentrations, ammonia is of concern for two major reasons. First, it is toxic to fish, particularly in its un-ionized form (NH_3). The pH of the river or lake plays an important role here, because the higher the pH the higher the percentage of the total ammonia which is dissociated into its toxic un-ionized form. Secondly, the respiration due to nitrification may lower the oxygen levels of running and stagnant waters below ecological thresholds.

Chloride is another parameter of concern to the status of the fishery. High chloride concentrations can impair the "osmoregulation" (internal regulation of water and salts) of fish and other organisms and impair their survival, growth, and/or reproduction (CCME, 1999). Chloride can originate from many sources, including those associated with organic pollution such as domestic wastewater. Hence it is sometimes present in high concentrations when BOD levels are also high. But chloride in rivers and lakes also has other sources not usually associated with organic pollution such as road salts used in developed countries for de-icing roads, drainage flows coming from irrigated farmland, and sea spray.

The *pH* of a river or lake is also of concern to the inland fishery. Above we described that at high pH ammonia is dissociated in its toxic un-ionized form. Water with low pH interferes with the ability of fish to take up oxygen, changes the acid-base regulation at the gills, and has other deleterious effects on the physiology of fish (Matthews, 1998). High pH can reduce the ability of fish to excrete ammonia or regulate their internal ion balance (Carpenter et al., 2012). Low pH in lakes and smaller streams is often not associated with organic pollution, but with another water quality problem, namely acidification. Acidification is caused by "acid deposition", i.e. the atmospheric deposition of acidifying sulphur and nitrogen compounds, into a lake (Heard et al., 2014; Rubin et al., 1992). Acid deposition can stimulate the release of aluminium and other heavy metals from soils into lakes where they pose an additional threat to the health of fish. Exceptionally low or high pH in rivers can result from the discharge of domestic or industrial wastewater containing acidic or alkaline compounds.

Table 3.7: "Levels of concern" of water quality parameters with respect to inland fisheries and percentage of measurements exceeding the levels of concern in Latin America, Africa and Asia in the time period 2000-2010. Data from GEMStat. Water quality standards are listed in Appendix B.

Dissolved Oxygen (mg/l)					
Continent	No. of stations/ 10,000 km²	No. of measurements	Median (all data)	Levels of concern	Percentage of data exceeding the levels of concern
Latin America	0.145	5,200	6.3	x < 5[a] / x < 7[b]	17.1%[a] / 51.9%[b]
Africa	0.002	289	6.9	x < 5[a] / x < 7[b]	23.8%[a] / 40.8%[b]
Asia	0.052	7,380	7.0	x < 5[a] / x < 7[b]	7.1%[a] / 26.3 %[b]
BOD (mg/l)					
Continent	No. of stations/10,000 km²	No. of measurements	Median (all data)	Levels of concern	Percentage of data exceeding the levels of concern
Latin America	0.053	2,957	2.0	4 < x < 8 / x > 8	4.8% / 4.7%
Africa	0.001	236	3.3	4 < x < 8 / x > 8	23.3% / 21.6%
Asia	0.058	5,329	1.7	4 < x < 8 / x > 8	14.7% / 4.8%
Ammonia (mg/l)					
Continent	No. of stations/10,000 km²	No. of measurements	Median (all data)	Levels of concern	Percentage of data exceeding the levels of concern
Latin America	0.216	2,664	0.08	x > 0.3	12.4%
Africa	0.012	1,581	0.04	x > 0.3	6.4%
Asia	0.045	3,045	0.04	x > 0.3	15.7%
Chloride (mg/l)					
Continent	No. of stations/10,000 km²	No. of measurements	Median (all data)	Levels of concern	Percentage of data exceeding the levels of concern
Latin America	0.115	3,541	5.3	x > 120	0.25%
Africa	0.014	1,482	51.7	x > 120	29.0%
Asia	0.042	2,735	17.0	x > 120	12.9%
pH (-)					
Continent	No. of stations/10,000 km²	No. of measurements	Median (all data)	Levels of concern	Percentage of data exceeding the levels of concern
Latin America	0.155	5,449	7.2	x ≤ 6.5 / x ≥ 8.5[b]	20.0% / 1.7%
Africa	0.014	1,639	8.1	x ≤ 6.5 / x ≥ 8.5[b]	0.1% / 13.8%
Asia	0.052	7,615	7.5	x ≤ 6.5 / x ≥ 8.5[b]	4.4% / 5.6%

[a]Criteria for warm water biota; measurements with temperature > 20°C and oxygen < 5 mg/l O_2
[b]Criteria for cold water biota; measurements with temperature < 20°C and oxygen < 7 mg/l O_2

Table 3.8: 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 of 11 countries listed in Appendix B.

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

*derived from the German national water quality guidelines

Table 3.9: Length and percentage of river stretches (km) within various organic pollution classes. The minimum and maximum monthly stretches in the period of 2008 to 2010 are shown.

Water pollution class	BOD concentration (mg/l)	Latin America (min, max)	Africa (min, max)	Asia (min, max)
Low pollution	x ≤ 4	959,000–1,038,000 86–91%	1,238,000–1,349,000 81–89%	1,237,000–1,342,000 78–85%
Moderate pollution	4 < x ≤ 8	33,100–52,000 3–4%	44,000–53,000 3–4%	72,000–77,000 4–5%
Severe pollution	x > 8	60,000–117,000 6–10%	132,000–234,000 7–15%	168,000–268,000 11–17%

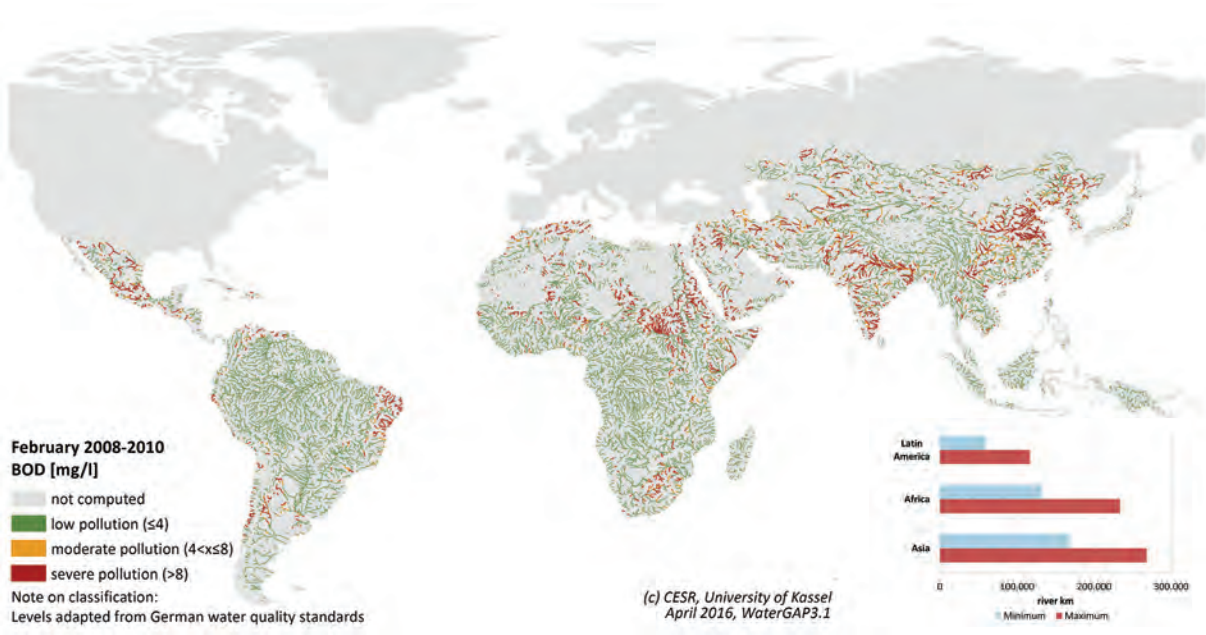


Figure 3.13: Estimated in-stream concentrations of biochemical oxygen demand (BOD) for Latin America, Africa, and Asia for February 2008–2010. Bar charts show minimum and maximum monthly estimates of river stretches in the severe pollution class per continent in the 36-month period from 2008–2010, corresponding to data in Table 3.9.

To sum up, the GEMStat analysis showed that 10 per cent or more of all measurements in Latin America, Africa, and Asia had levels of key water quality parameters that are of concern to the health of inland fisheries. The modelling analysis of BOD on these continents confirmed these results, showing that 6–17 per cent of the river stretches or hundreds of thousands of river kilometres were in the severe pollution class, with the majority of streams having increasing concentration. One overarching conclusion is that countries who rely on their inland fisheries as an important food source should be vigilant about the increasing level of organic pollution.

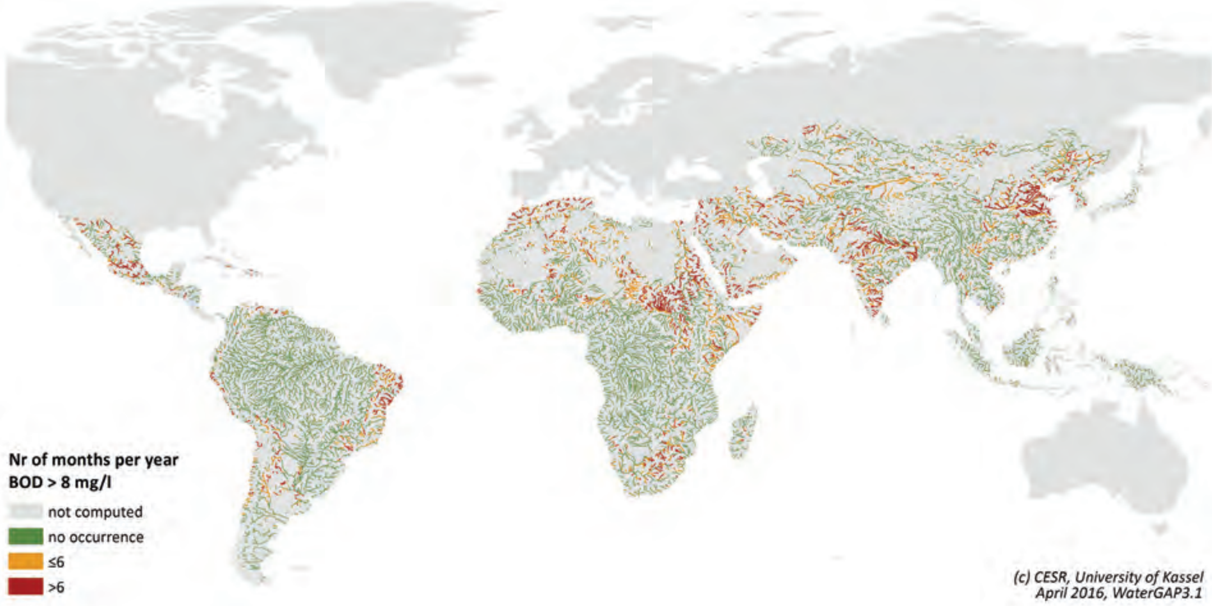


Figure 3.14: Frequency (months/year) in which "severe pollution" levels of biochemical oxygen demand occur in different river stretches over the period 2008–2010.

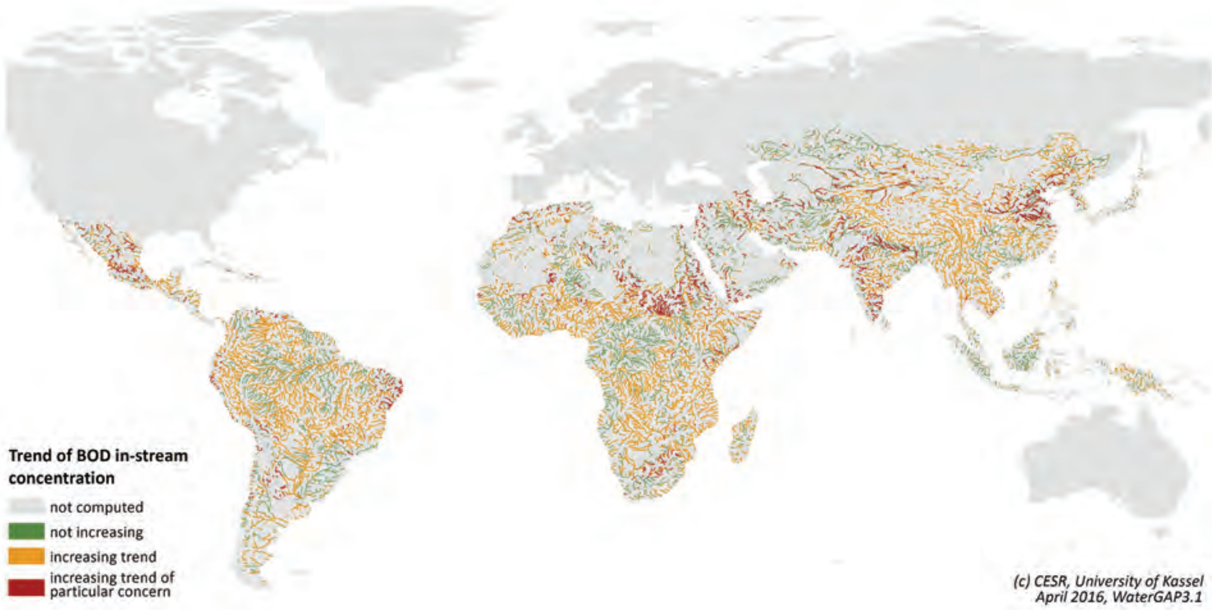


Figure 3.15: Trend in BOD concentrations in rivers between 1990–1992 and 2008–2010. River stretches marked with orange or red have increasing concentrations between these two periods. River stretches marked with red have an "increasing trend of particular concern" meaning that in these stretches the pollution level increased into the severe pollution category in 2008–2010, or that they were already in the severe pollution category in 1990–1992 and further increased in concentration by 2008–2010.

Table 3.10: Selected hot spot areas of organic pollution appearing in both Figure 3.14 and Figure 3.15.

- Central America
- Some river stretches in Northwest Africa
- Vaal river basin
- Limpopo river basin
- River stretches in the Middle East
- Indus river basin
- Ganges river basin
- Some river stretches in Southern India
- Haihe, Huaihe and Yellow river basins

3.3.4 Sources of organic pollution

Several sources of BOD loading are taken into account as shown in Table 3.11. These loadings depend 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. Controlling levels of organic loadings at the source is the key to reducing or preventing anthropogenic wastewater intakes into surface waters (see Chapter 5).

Estimates of loadings of organic pollution on a continental basis for the years 1990 and 2010 are shown in the bar charts in Figure 3.16. As noted earlier, the levels of organic pollution in rivers have been estimated to increase over the last two decades because of increases in loadings of BOD. On the continental average basis, loadings have increased by 30 per cent in Latin America, 65 per cent in Africa, and 95 per cent in Asia. The continental average data, however, mask important differences between sub-regions which may differ depending on the rate of population growth, as well as the extent of agricultural and industrial activities.

The increase in BOD loadings is mainly driven by population growth, urbanisation, increasing generation of industrial wastewater and livestock production. With the help of model results it is not only possible to analyse the change in loadings over time, but also to analyse the causes of high in-stream concentrations and to identify the main contributing sectors.

Figure 3.17 shows the main sources of organic pollution according to the three regions for the year 2010. In Latin America about 60 per cent of the total loadings originated from domestic sewered sources while only 11 per cent can be allocated to the domestic non-sewered sector. Wastewater from manufacturing industries accounts for 28 per cent of the loadings, while the contribution from the agricultural sector and urban surface runoff to BOD loadings is about 2 per cent. High loadings from point sources, like sewered domestic wastewater and manufacturing wastewater, indicate that wastewater is probably collected, but not sufficiently treated.

The main sources of BOD loadings in Africa are non-sewered (49 per cent) and sewered (36 per cent) domestic sources from urban and rural populations. In total 85 per cent of loadings are from domestic sources (Figure 3.17). Approximately 13 per cent of BOD loadings in rivers originate from the discharge of wastewater from manufacturing facilities.

In Asia, the domestic sector contributes 54 per cent to the total BOD loadings in 2010, of which about 29 per cent come from sewered sources and 25 per cent from non-sewered sources. Compared to the other continents, a high share of BOD loadings, namely 45 per cent, comes from wastewater produced in the manufacturing sector.

Table 3.11: Categories of organic pollution loadings accounted for in total BOD loadings.

- Domestic sewered (point sources)
- Domestic non-sewered-hanging latrines (point sources); Domestic septic tanks, pit toilets, open defecation (diffuse sources)
- Manufacturing (point sources)
- Urban surface runoff (diffuse sources)
- Agriculture – livestock wastes (diffuse sources)

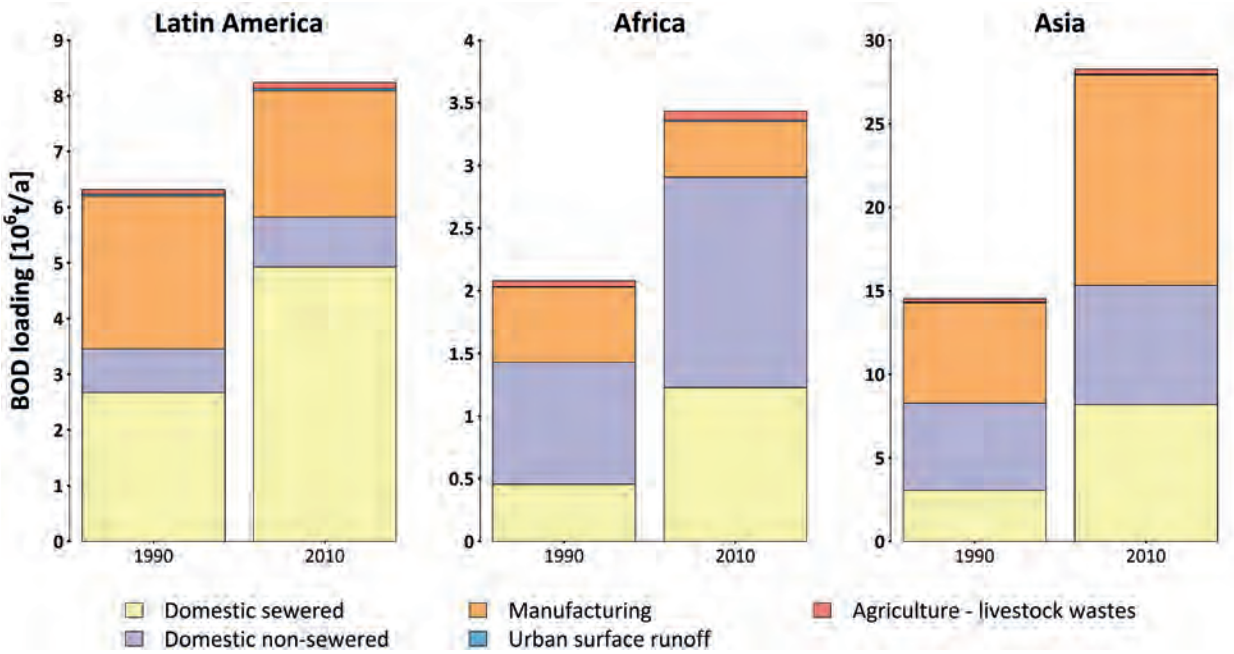


Figure 3.16: BOD loadings for Latin America, Africa, and Asia for 1990 and 2010. Units: tons/year.

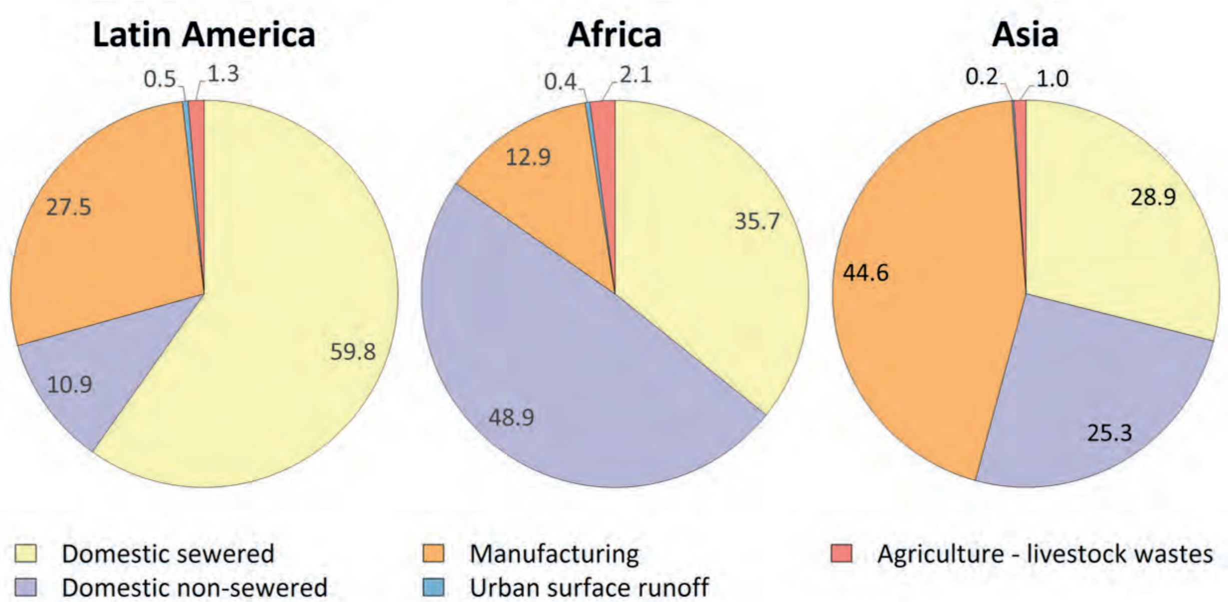


Figure 3.17: Distribution of BOD loadings according to source for 2010. Units: percentage.

3.4 Salinity pollution and impairment of water use

3.4.1 What is salinity pollution and how does it impair water use?

Salinity pollution occurs when the concentration of dissolved salts and other dissolved substances in rivers and lakes is high enough to interfere with the use of these waters. In freshwaters, salinity is commonly defined and measured as the mass of "total dissolved solids" (TDS) in a litre of water, with units of milligrams per litre (mg/l).[10] This is also the approach used in this report.

All freshwaters have a natural background level of salts due to the weathering of soils and rocks in their drainage basin. In drainage basins underlain by granite, the weathering rate is relatively low, and, accordingly, the natural level of salinity in rivers in such areas is low. In drainage basins with clay soils, weathering is much higher, and also water salinity tends to be proportionately higher. Close to the sea, rivers acquire salt by mixing with tidal ocean waters or from precipitation containing traces of sea salt. Therefore, even without human interference, some rivers have relatively high salinity levels. In these naturally saline rivers and lakes, aquatic and riparian ecosystems have adapted to these saline levels.

Society artificially increases the concentration of salinity by discharging domestic, industrial, and agricultural wastes into rivers and lakes. As will be seen in Section 3.4.3, important anthropogenic sources of salinity are irrigation return flows, domestic wastewater, and runoff from mines. A more local and seasonal source, particularly important in developed countries in colder climates, is the wash-off of salt used to melt snow on roadways (Anning & Flynn, 2014).

Salinity pollution can have many important negative impacts. One of the most important impacts is that it can hinder the use of a freshwater supply for irrigation. Only water with a relatively low salinity can be used for irrigation. If water applied to crops has a too high salinity concentration, salts accumulate in the root zone of plants and interfere with the plant's extraction of water from the saline solution. A reduced water uptake can lead to wilting of the plant. While some plants are salt-tolerant, the majority of food crops are not. With this in mind, the Food and Agriculture Organization (FAO) has recommended limits to the use of saline water for irrigation (Table 3.12). Restrictions on use for irrigation start at a concentration of TDS of 450 mg/l, a concentration that is not unusual where waste loadings are significant.

Salinity pollution has wide-ranging negative impacts on aquatic ecosystems at the individual, population, community, and ecosystem levels (Cañedo-Argüelles et al., 2013). Freshwater organisms have a limited tolerance to salinity and usually cannot adapt to salinity concentrations significantly higher than natural background levels.

Salinity pollution is also of concern to certain industries, such as food processing and pharmaceutical manufacturing because they require intake water with very low salinity. High salinity levels also contribute to scaling of pipes and boilers in factories (Salvato et al., 2003).

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 (Vengosh, 2003).

In this report, the FAO recommendations for irrigation given in Table 3.12 are used as benchmarks for the level of pollution.

Table 3.12: Classes of salinity water pollution according to river concentrations of TDS used in this report. These classes correspond to the restrictions on use for irrigation from FAO (1985) shown in the third column.

Water pollution class	TDS (mg/l)	Restrictions on use for irrigation FAO (1985)
Low pollution	< 450	No restrictions
Moderate pollution	450–2,000	Increasing restrictions
Severe pollution	> 2,000	Severe restrictions

[10] Total dissolved solids include both dissolved salts as well as dissolved organic materials. According to the US EPA: "In stream water, dissolved solids consist of calcium, chlorides, nitrate, phosphorus, iron, sulfur, and other ions particles that will pass through a filter with pores of around 2 microns (0.002 cm) in size." US EPA http://water.epa.gov/type/rsl/monitoring/vms58.cfm. Retrieved May, 2015.

3.4.2 What is salinity pollution and how does it impair water use?

GEMSTAT analysis

As for the analysis of faecal coliform pollution and organic pollution (see Sections 3.1.2 and 3.2.2), there are insufficient measurements on the continental scale for Latin America, Africa, and Asia to gain a continental overview of salinity pollution based only on data. Furthermore, the data distribution is geographically biased because of the limited number of countries providing information to the system. Therefore, as in previous sections, all TDS data from 2000 to 2010 were consolidated in individual statistical distributions for each of the three continents (Figure 3.18 and Table 3.13).

While the medians are in the low pollution class, the 90th percentiles for Africa and Asia are above or near 450 mg/l. This indicates that 10 per cent or more of the measurements from these continents have salinity levels that would restrict their use for irrigation to some degree. While Latin America has lower overall measured levels of total dissolved solids, Figure 3.18 (left panel) shows that some measurements do exceed the 450 mg/l guideline value.

Modelling analysis

Figure 3.19 shows an example of the level of TDS for February 2008–2010 according to the classes of TDS in Table 3.12. Areas of severe salinity pollution exist in the upper and lower Nile and Indus basins. Areas of moderate pollution (where use of river water for irrigation is partially restricted according to Table 3.12) include river stretches of the Euphrates, Ganges, and Aral Sea basin.

As was noted previously, faecal coliform bacteria and BOD river concentrations vary from month to month because of the variability of river conditions. River salinity also varies in this way. Table 3.14 shows the length of rivers affected by salinity pollution taking into account the month-to-month variation of river pollution. Around 4,600 to 10,000 km of Latin America's rivers, or about 0.7 per cent of all river stretches, are in the severe pollution class. For Africa, the estimate is around 32,000 to 83,000 km, or around 4 per cent of its river stretches, and for Asia around 28,000 to 65,000 km, amounting to about 3 per cent of its entire river stretches.

Figure 3.20 shows the frequency of months in a year in which river stretches are in the severe pollution category for TDS. In this context, it is assumed that river stretches with severe or moderate pollution six months or more in a year are an indication of hot spot areas.

Figure 3.21 shows the trend in TDS river concentrations between the early 1990s and late 2000s. TDS concentrations have increased in 21 per cent of the river stretches in Latin America, 33 per cent of the river stretches in Africa, and 37 per cent of the river stretches in Asia. In total, 31 per cent of the river stretches on these three continents have an increased TDS concentration.

The areas where salinity pollution has increased to a severe level of total dissolved solids or started at a severe level and became worse are of particular concern. These stretches are shown in Figure 3.21 and can be considered another estimate of hot spot areas.

Table 3.13: Overview of data availability and statistical values for TDS in the period 2000–2010. Data source: GEMSStat. SD = Standard deviation. Units: [mg/l]

Continent	No. of stations/ 10,000 km²	No. of measurements	Median	10th percentile	90th percentile	SD
Latin America	0.04	2,901	52	19	223	119
Africa	0.012	1,687	333	118	1,014	1,820
Asia	0.045	7,441	70	8	445	2,936

Table 3.14: Length and percentage of river stretches (km) in various salinity pollution classes. The minimum and maximum monthly stretches are indicated for the period of 2008 to 2010.

Water pollution class	TDS concentration (mg/l)	Latin America (min, max)	Africa (min, max)	Asia (min, max)
Low pollution	x ≤ 450	1,146,000–1,163,000 95–96%	1,330,000–1,410,000 87–93%	1,367,000–1,473,000 86–93%
Moderate pollution	450 < x ≤ 2,000	39,000–50,000 3–4%	82,000–112,000 5–7%	81,000–150,000 5–10%
Severe pollution	x > 2,000	4,600–10,400 0.4–0.9%	32,000 – 83,000 2–5%	28,000–65,000 2–4%

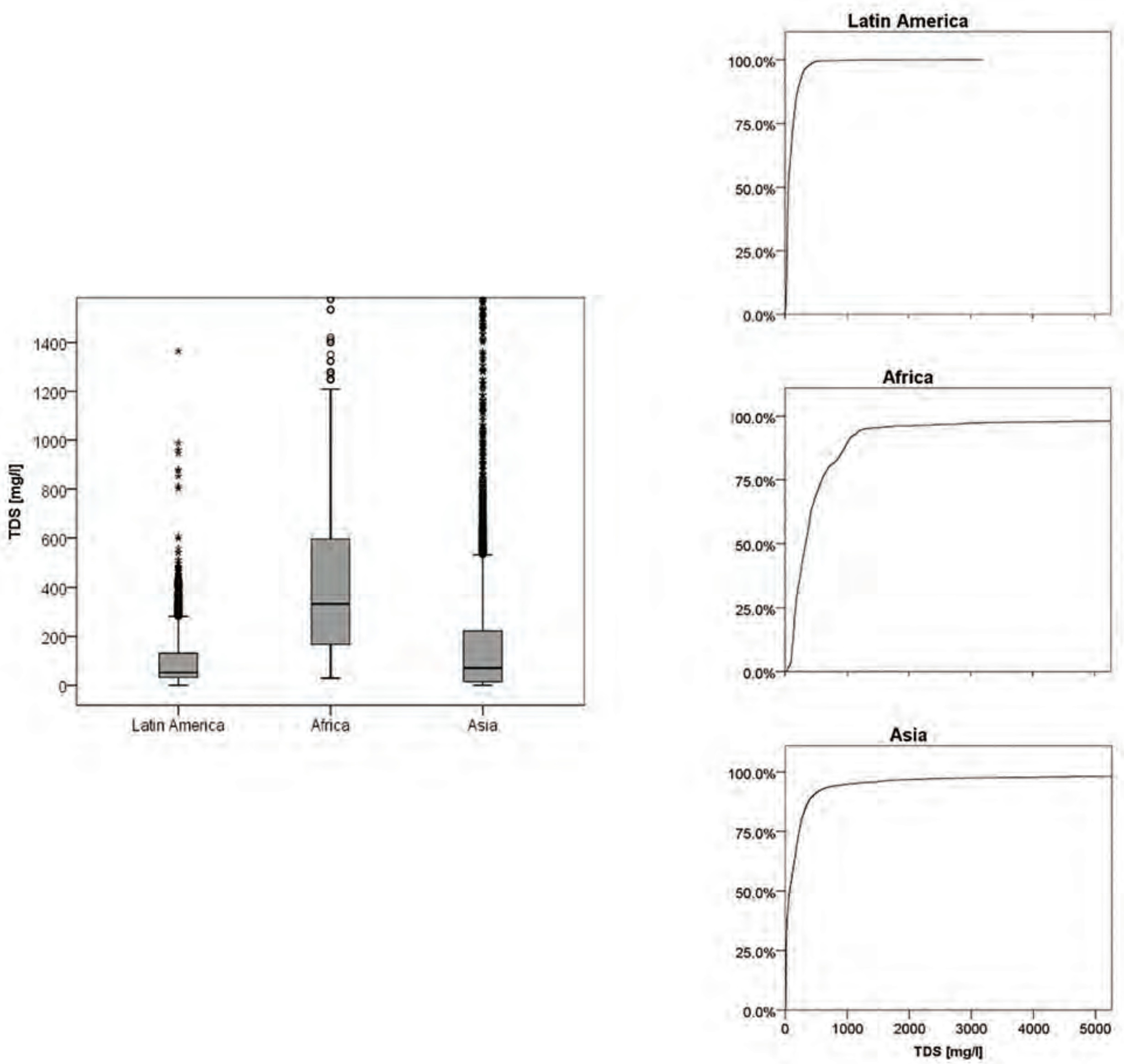


Figure 3.18: Box-and-whisker plots (left) of the distribution and cumulative frequencies (right) of TDS in Africa, Latin America, and Asia in the time period 2000–2010. Boxes show 25th to 75th percentile and median (black line). Data source: GEMStat.

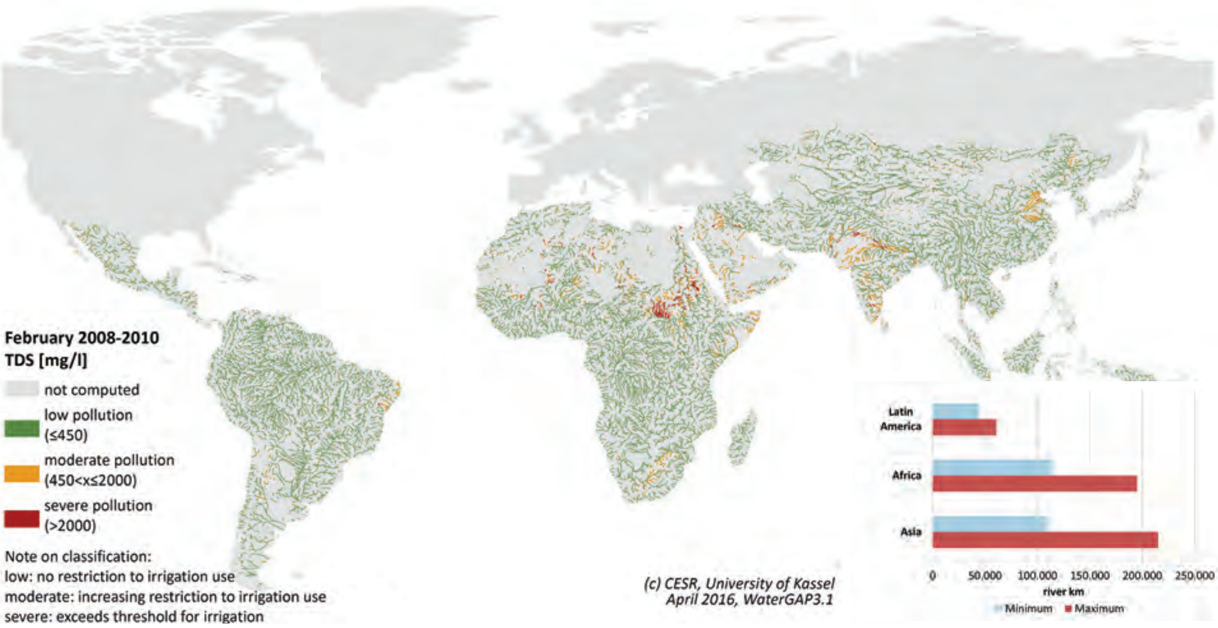


Figure 3.19: Estimated in-stream concentrations of total dissolved solids (TDS) for Latin America, Africa, and Asia for February 2008–2010. Bar charts show minimum and maximum monthly estimates of river stretches in the severe pollution class per continent in the 36-month period from 2008–2010 corresponding to data in Table 3.14.

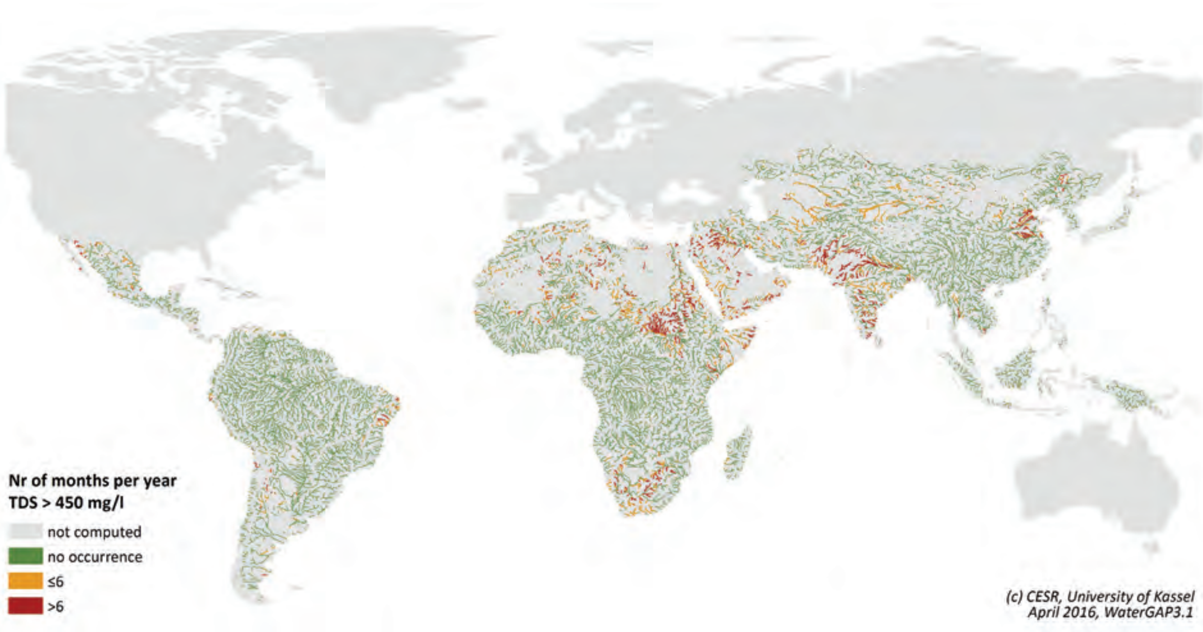


Figure 3.20: Frequency (months/year) in which "moderate or severe pollution" levels of total dissolved solids occur in different river stretches over the period 2008–2010.

Table 3.15: Hot spot areas of salinity pollution (from Figure 3.20 and Figure 3.21).

- Lower Nile river basin
- Euphrates river basin
- Indus river basin
- Ganges river basin
- Aral Sea basin

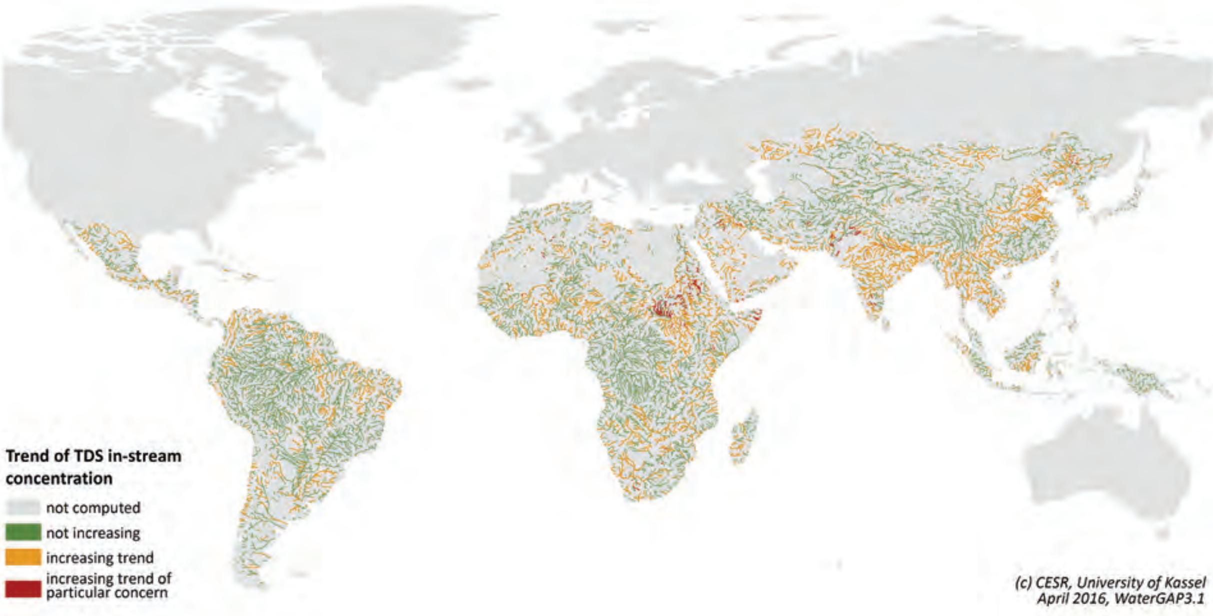


Figure 3.21: Trend of TDS levels in rivers between 1990–1992 and 2008–2010. River stretches marked with orange or red have increasing concentrations between these two periods. River stretches marked with red have an "increasing trend of particular concern" meaning that in these stretches the pollution level increased into the severe pollution category in 2008–2010, or that they were already in the severe pollution category in 1990–1992 and further increased in concentration by 2008–2010.

3.4.3 Sources of salinity pollution

Most of the salinity loading to rivers, including in Latin America, Africa, and Asia, comes from natural background sources (Figure 3.23, upper diagram). In this study, background concentrations of TDS are estimated to range from around 5 to 832 mg/l (Appendix B). However, about 10 per cent of river stretches have a natural TDS concentration of > 450 mg/l (defined here as "moderate" salinity pollution). Exceptions are some arid and semi-arid drainage basins with high weathering rates. But the high salinity areas indicated in Figure 3.19, Figure 3.20, and Figure 3.21 are almost all caused by anthropogenic loadings of total dissolved solids (Table 3.16).

In both Africa and Asia, the main anthropogenic source is return flow from irrigated areas which transfers large amounts of salts from cropping areas to surface waters (Figure 3.22 and Figure 3.23). The second most important category is manufacturing. In Latin America the most important source is manufacturing, followed by irrigation return flows (Figure 3.23). This is because the fraction of continental area devoted to irrigation in Latin America is small compared to Asia. Although the fraction of irrigated area is small in Africa, TDS loadings from irrigation are much larger compared to the other sources, e.g. manufacturing. Loadings from irrigation return flows may be underestimated for the year 2010 because the extent of irrigated area in that year has not been estimated (Siebert et al., 2015), and the coverage of irrigated area for these calculations is assumed to be constant between 2005 and 2010. On all continents, the third most important source was domestic wastewater conveyed by sewers.

Runoff from mining activities is an important source of salinity in some rivers. An example is given in Chapter 4 for the River Vaal. However, it is not included here because of the lack of comprehensive data from the three continents being studied. Therefore, in some river stretches the loadings of total dissolved solids are underestimated. TDS loadings from mining will be included in future studies. Road salt is an important source of total dissolved solids in North American rivers (Anning & Flynn, 2014), but is not expected to be of major importance for the three continents studied here.

Table 3.16: Categories of salinity pollution loadings accounting for total TDS loadings.

- Domestic sewered (point sources)
- Domestic non-sewered – hanging latrines (point sources); domestic septic tanks, pit toilets, open defecation (diffuse sources)
- Manufacturing (point sources)
- Urban surface runoff (diffuse sources)
- Agriculture – irrigation return flows (diffuse sources)
- Agriculture – animal wastes (diffuse sources)
- Background soil/rock (diffuse sources)

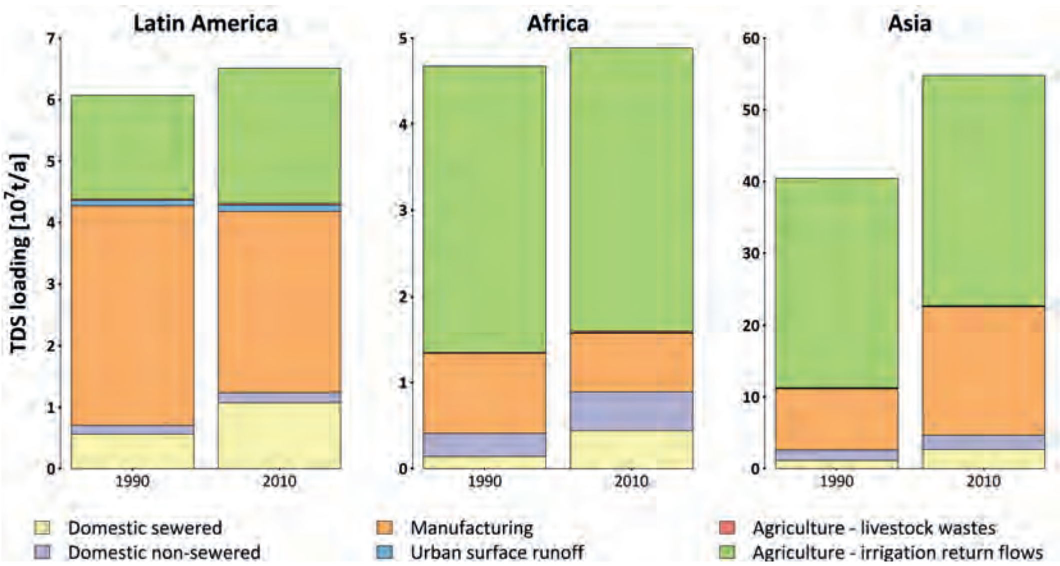


Figure 3.22: Anthropogenic sources of TDS loadings for Latin America, Africa, and Asia for 1990 and 2010. Units: tons/year.

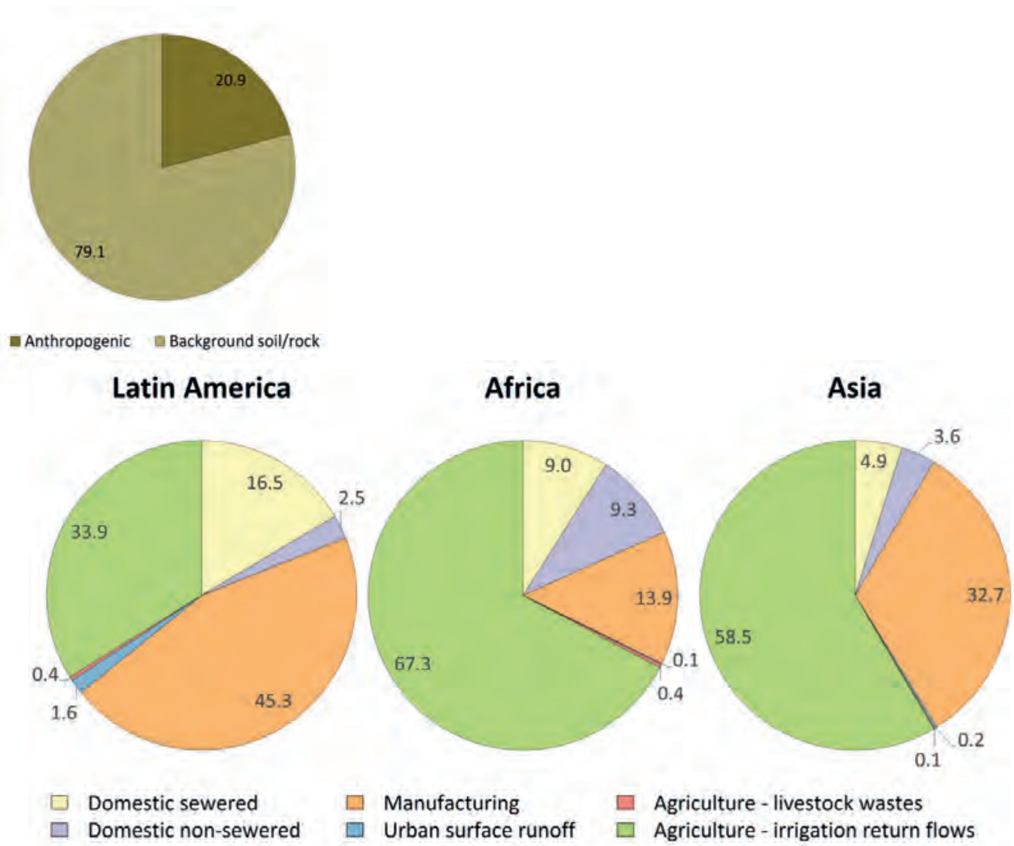


Figure 3.23: Upper diagram: Distribution of total anthropogenic versus background input of TDS to rivers in Latin America, Africa, and Asia. Lower diagrams: Distribution of TDS loadings according to anthropogenic sources for 2010. Units: percentage.

3.5 Eutrophication and nutrient loadings to large lakes

3.5.1 What are eutrophication and other water quality problems in lakes?

Lakes contain around 90 per cent of the liquid freshwater on the earth's surface (ILEC, 2011) and they are an important source of water and food. However, the ability of lakes to provide these and other ecosystem services is threatened by infrastructure development, overfishing, invasive species, and in particular by water pollution. Water quality degradation in lakes takes different forms including eutrophication, pathogen contamination, organic pollution, and chemical pollution. In this study, the focus is on eutrophication because of its negative impacts on lakes, its worldwide scale, and because it may be expanding in scope (e.g. Jin et al., 2005). A few of the many examples of lakes affected by eutrophication now or in the past are shown in Table 3.17.

Eutrophication in lakes is part of a natural process of nutrient accumulation that leads to gradually increasing the plant productivity of a lake. In this case, nutrients originate from natural sources such as the decomposition of organic material, or rock and soil weathering. But in many lakes, anthropogenic inputs of nutrients greatly accelerate the natural process. This is sometimes called "cultural eutrophication". If temperature, light, and other conditions are sufficient, loadings of nutrients stimulate the rapid growth of algae and other aquatic plants. When these large algae populations die off, they are decomposed by bacteria, which deplete the oxygen resources of the lake, threatening the survival of fish and other aquatic organisms. Other impacts of eutrophication in lakes are listed in Box 3.5.

There is a lively discussion in the scientific community about the importance of phosphorus and nitrogen loadings as causes of lake-eutrophication.[11] In this report only the total phosphorus loadings to lakes are taken into account. These loadings were examined in 25 "major lakes" in the world selected because they are of special interest to human society due to their size.[12] Some of these lakes are subject to eutrophication as noted in Table 3.17.

Table 3.17: A selection of past and present eutrophication problems reported for large lakes.

Lake	Main source of nutrient pollution	Selected effects of pollution	Reference
Taihu (China)	Chemical and manufacturing plants, agriculture, domestic waste water	Phytoplankton changed from diatom flora to one dominated by cyanobacteria; algae blooms; Macrophytes disappeared	Stone (2011)
Erie (Canada, USA)	Agriculture, industrial waste water, domestic waste water; reduced phosphorus inputs by mid 1980s	Increase in phytoplankton biomass, algae blooms, eutrophic and hypereutrophic species, fish kills due to anoxia; water quality has been improving since the 1980s.	Allinger and Reavie (2013)
Constance (Germany, Austria, Switzerland)	Agriculture, domestic	Low oxygen concentrations, algae blooms (re-oligotrophication since the 1980s due to massive reduction of nutrient pollution)	IGKB (2002)
Peipsi (Estonia, Russia)	Agriculture, domestic, manufacturing	Low oxygen concentrations, algae blooms	Kangur et al. (2005)
Laguna de Bay (Philippines)	Domestic, agricultural, industrial effluents	Algae blooms (lake wide algae bloom in 1979), low oxygen concentrations which endanger aquaculture	ILEC (2005)
Victoria (Tansania, Uganda, Kenia)	Growth of the predominantly rural human population; agriculture	Phytoplankton changed from diatom flora to one dominated by cyanobacteria; increase of algal biomass; fish kills; more prevalent deep water anoxia; superposition effects by Nile perch introduction	Sitoki et al. (2010)

[11] On the one hand, most scientists agree that under pristine circumstances phosphorus limits the growth of algae. This implies that excess phosphorus causes eutrophication and that its removal from lakes would in turn reduce eutrophication. On the other hand, others believe that in addition to phosphorus, nitrogen also plays a significant role depending on the type of lake, its trophic status, and the season (Kolzau et al., 2014). Still others believe that nitrogen rarely contributes to lake eutrophication (Schindler, 2012).

[12] The "major lakes" sample is made up of 5 of the largest lakes in each of five UNEP "Global Environment Outlook" regions (Africa, Asia, Europe, Latin America, and North America), excluding the Caspian Sea, Aral Sea, and Lake Chad because of their special characteristics. The 25 major lakes are displayed in Figure 3.24 to Figure 3.26.

Box 3.5: Effects of eutrophication on lakes and reservoirs (from Smith et al., 1999)

- Increased biomass of freshwater phytoplankton and periphyton
- Shifts in phytoplankton species composition to taxa that may be toxic or inedible (e.g. bloom-forming cyanobacteria)
- Changes in vascular plant production, biomass, and species composition
- Reduced water clarity
- Decreases in the perceived aesthetic value of the water body
- Taste, odour, and water supply filtration problems
- Possible health risks in water supplies
- Elevated pH and dissolved oxygen depletion in the water column
- Increased fish production and harvest
- Shifts in fish species composition towards less desirable species
- Increased probability of fish kills

3.5.2 What are the phosphorus loadings to major world lakes?

Anthropogenic loadings of phosphorus into lakes originate from domestic sewered wastewater, domestic non-sewered sources, manufacturing, inorganic fertiliser from cropland, animal wastes, and atmospheric deposition. Estimates for the time period 1990–2010 are provided by the WorldQual model, which was also used earlier in this chapter for estimating faecal coliform bacteria, BOD and TDS in rivers (see Appendix B). A fraction of these loadings is assumed to be retained in the watershed of the lake and not enter the lake proper. Loadings of total phosphorus computed by the model have been tested against independent estimates of various lakes and large river basins (Appendix B).

The anthropogenic total phosphorus loads to Qinghai Lake in China (514 kg P/km²/yr) and to Issyk-Kul Lake in Kyrgyzstan (211 kg P/km²/yr) are the highest loadings to the selected major world lakes (Figure 3.24). The loads to Great Bear Lake and Great Slave Lake in North America are very small. The phosphorus loads to African lakes range widely, as do the loads to Asian lakes. It is important to note that the size of the phosphorus load is not necessarily proportional to the degree of eutrophication because other factors have an important influence on eutrophication including temperature and light conditions, the physical attributes of a lake, and average residence time of lake water.

The natural long-term processes of eutrophication are accelerated by anthropogenic inputs of phosphorus. Therefore, it is of concern that in 23 out of the 25 major lakes more than 50 per cent of the total phosphorus loads are from anthropogenic sources (yellow and red circles in Figure 3.24).

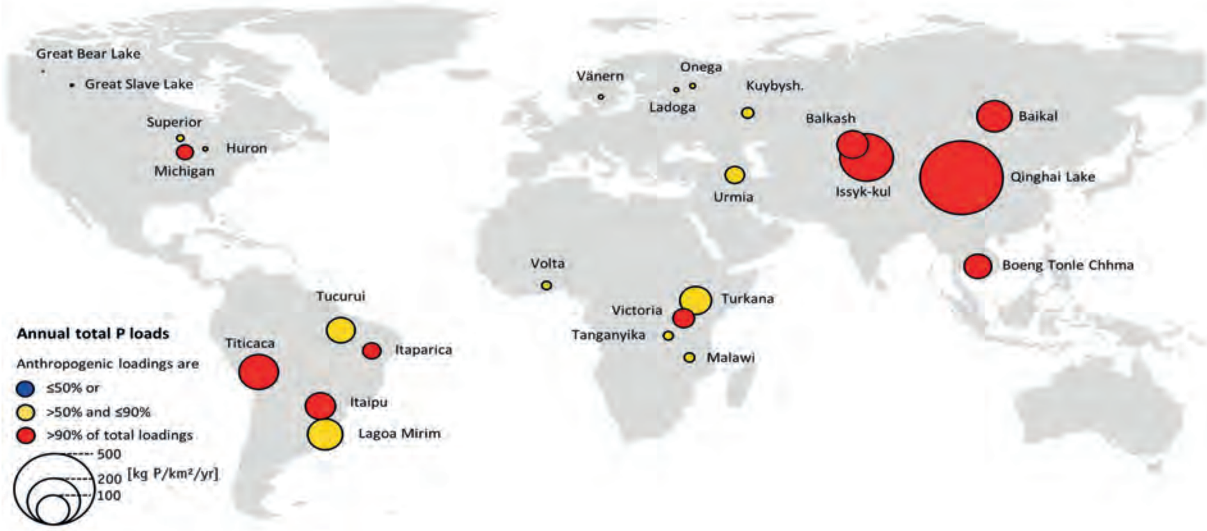


Figure 3.24: Average total phosphorus loads per unit lake basin area and an indication of the anthropogenic versus background loadings for the selection of 25 largest lakes for the period 2008–2010. The size of a circle represents the annual total phosphorus load per unit lake basin area. The colour indicates whether the proportion of anthropogenic loadings exceeds 50 per cent (yellow circles) or even 90 per cent (red circles) of total loadings or falls below 50 per cent of total loadings (blue).

3.5.3 What are the sources of phosphorus?

To avoid or reduce eutrophication in these lakes it is necessary to know what sources of anthropogenic phosphorus are most significant (Figure 3.25). The dominant source in almost all lakes examined here is inorganic fertiliser. Livestock wastes are the second largest source in Africa. Domestic wastewater is an important source of total phosphorus loadings in Europe and North America.

The changes in estimated loadings between the periods 1990–1992 and 2008–2010 are shown in Figure 3.26. Most of the major lakes in Latin America, Africa and Asia have increasing anthropogenic loadings. By contrast, loadings decreased in North America and Europe. Reductions in Western Europe and North America were achieved through reduced usage of phosphorus containing products (e.g. detergents), a higher level of wastewater treatment and reduced fertiliser application. However, fertiliser application is still increasing in South America, in Africa, and in the Asia-Pacific region.

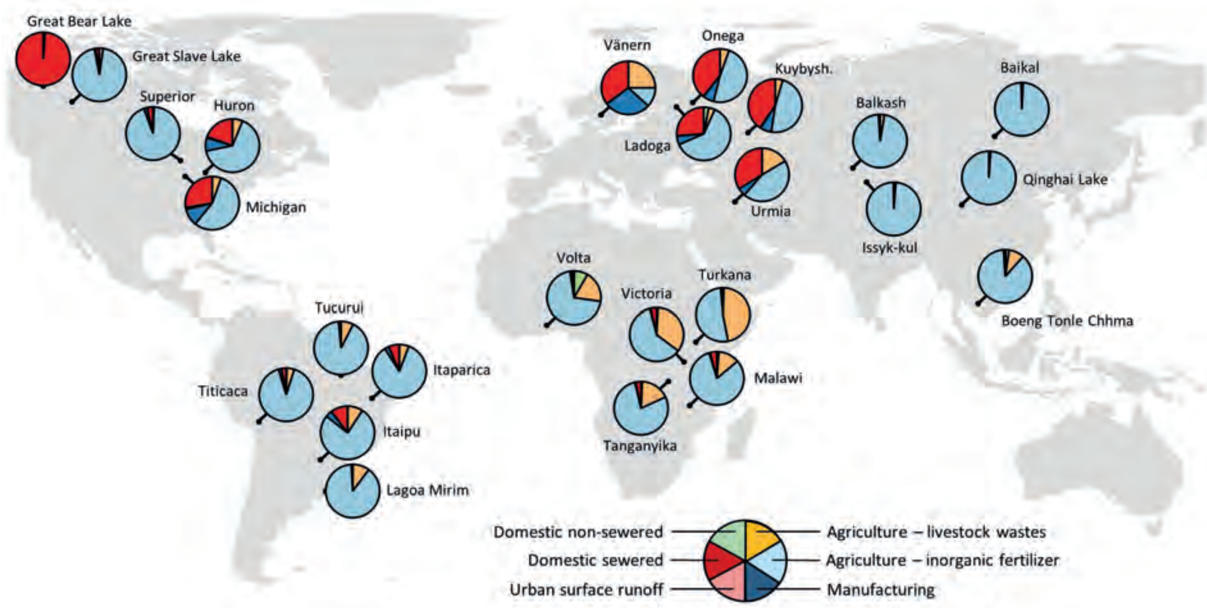


Figure 3.25: Sources of anthropogenic total phosphorus loadings to major lakes. The average percentage contributions to the annual loading for the period 2008–2010 are shown.

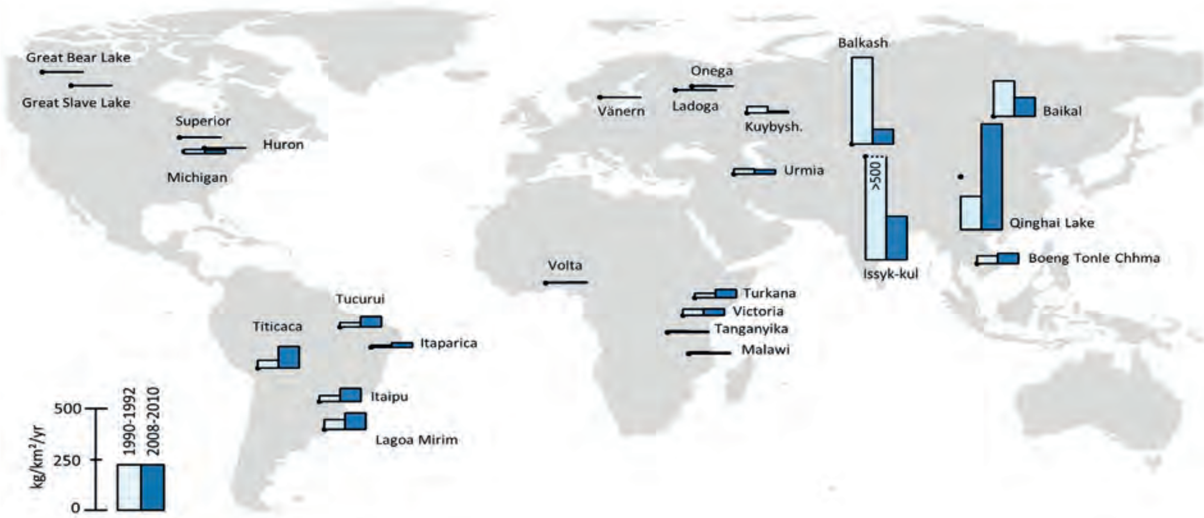


Figure 3.26: Total phosphorus loadings from anthropogenic sources per unit lake basin area for 1990–1992 and 2008–2010. Units: kg/km²/year.

These trends in phosphorus loadings may change the trophic state of a lake (the state of a lake according to the availability of nutrients for aquatic flora). How quickly a lake responds to an increase or decrease in phosphorus inputs will depend, among other factors, on the residence time of a lake (the time it takes the water in a lake to renew itself). Small lakes will respond fairly quickly because they have relatively small volumes and therefore shorter residence times. Larger lakes, as in the 25 lakes examined here, have much longer residence times (e.g. 330 years for Lake Baikal and 23 years for Lake Victoria), and therefore it might take decades or centuries for a lake to respond to changes in phosphorus inputs. Box 3.6 below illustrates a feasible method for estimating the response of small to medium sized lakes to phosphorus inputs.

Box 3.6: Estimating the changes in the trophic state of lakes

The predicted total phosphorus (TP) loads from a lake's basin can be used to classify the corresponding trophic state of the water body by calculating the average equilibrium TP concentration in relation to threshold levels for trophic states according to Vollenweider (1976) (see Figure 3.27). For this plot, small to medium-sized lakes in different continents of the world with coherent data on P loading, lake surface area, and hydrology were selected, which allowed for the calculation of the equilibrium P concentration in the lake as the primary determinant of the trophic state (vertical axis). The horizontal axis represents the hydraulic load (calculated by dividing the annual inflow to the lake surface area) of the system and, therefore, characterises the hydrological setting of the system.

Furthermore, the two time series periods from 1990–1992 and 2008–2010 were compared to identify trends. Most systems showed similar hydraulic loads, except of Lake Taihu and Kariba Reservoir, but marked differences in lake phosphorus concentrations. While European lake systems were predominantly characterised by decreasing P concentrations, most non-European systems showed increasing trends in P concentrations. In case of Lake Constance, Lake Como, and Lake Peipsi even a transition from eutrophic to mesotrophic conditions could be seen indicating the efficiency of water management programs.

Thus, this method can be used for analysing the trajectories of changes in the trophic states of lakes and estimating the relevance of hydrological or water quality related drivers. The plot also illustrates that a large change in TP load does not necessarily need to be associated with a changing trophic state since certain threshold P concentrations have to be reached. The plot also allows for the estimation of a "distance to target". The reduction in TP loadings required to reach mesotrophic conditions for Lake Taihu, for example, would be much larger than for Kariba Reservoir.

A prerequisite for a wider application of this method is an objective survey of lakes of different sizes in a geographic area and requires further hydrological and limnological information including reference trophic states. It must also be stressed that a thorough testing of the phosphorus loading concept is required since this methodology was predominantly developed on temperate lakes and its application to tropical systems needs to be carefully assessed. These aspects are proposed to be part of the full scale World Water Quality Assessment to test the usability of this approach for a global assessment of lake eutrophication.

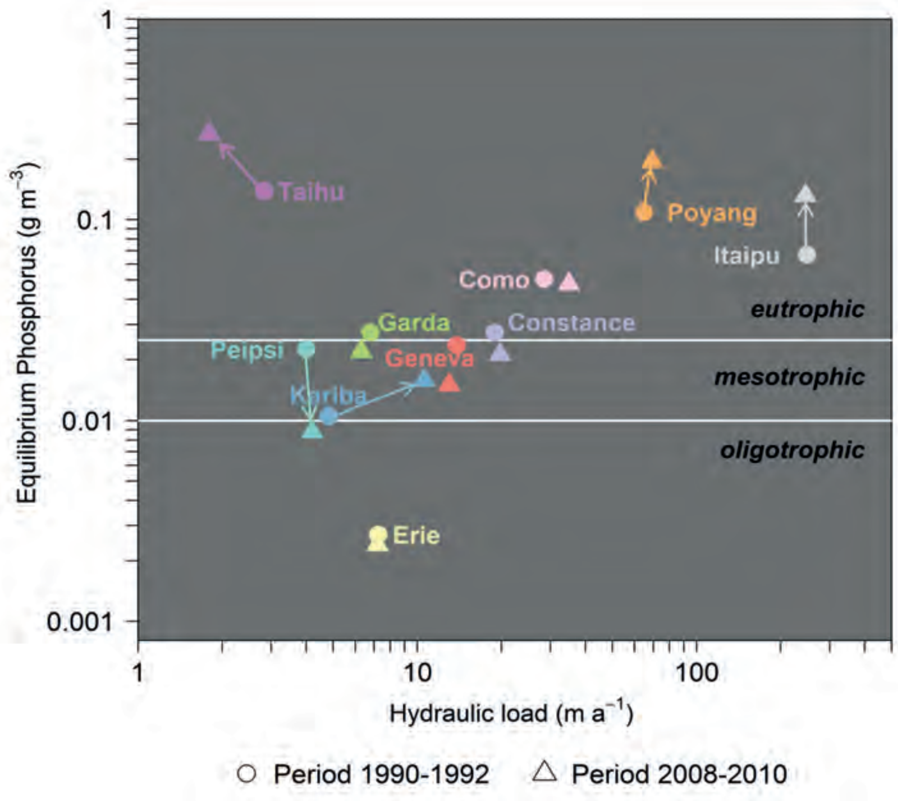


Figure 3.27: Trophic classification of 10 large lakes based on the phosphorus loading model by Vollenweider (1976). Two different periods were used (1990–1992 and 2008–2010) and the simulated TP loadings converted to the corresponding equilibrium phosphorus concentration (y-axis). Critical P concentrations of 10 and 25 mg/m^3 for the transition between oligo-/mesotrophic and meso-/eutrophic systems, respectively, were used. Note the log-log plot.

4 Water Pollution in River Basins

Aim of this chapter

Identifying transferable messages about the world water quality situation with the help of eight river basin case studies.

Main messages

- Similar kinds of water quality challenges are occurring around the world even if the locations and situations are very different. But these challenges sometimes have different immediate and ultimate causes, all linked to unsustainable growth or practices.
- A key to managing water quality is good governance and effective institutions. Barriers to good governance are the fragmentation of authority, lack of technical capacity, and lack of public awareness. These and other barriers can be overcome with action plans, collaborative authorities, and other instruments.
- Coping with the global water quality challenge is closely connected to many other priorities of society such as food security and health. Therefore, actions to protect water quality should be part of efforts to achieve the new Sustainable Development Goals.

4.1 Introduction

After reviewing the water quality situation on three continents in the previous chapter, the water quality situation in eight river basin case studies from around the world (Figure 4.1) is examined in more detail in this chapter. These cases emphasise the diversity of water quality issues (Table 4.1), management actions, and lessons learnt from experience in different river basins. Examples from the Hudson and Elbe rivers show the complete trajectory from articulating a water pollution problem through to its solution. Most of the examples, however, show that much still needs to be done either to restore water quality or to avoid further water quality degradation. The Upper Tietê case, for example, demonstrates how much time it takes from realizing the problem exists to the first signs of water quality improvement.

Each case study first presents an overview of the river basin's physical and governance characteristics. It then reviews the nature of its water quality problems and the current solutions being planned or tried out. Finally, it describes the lessons to be learned from the case study that are relevant to other river basins.

Chapter 4.2 River Basin 1 – Upper Tietê | Confluence of Tietê and Pinheiros Rivers in São Paulo, Brazil
Source: Ricardo Zig Koch Cavalcanti / Banco de Imagens ANA

Chapter 4.3 River Basin 2 – Godavari | Sunset at Godavari
Source: *https://commons.wikimedia.org/wiki/File:Sunset_at_Godavri.JPG*

Chapter 4.4 River Basin 3 – Volta | Transporting sand upstream the Volta for construction
Source: Adelina Mensah

Chapter 4.5 River Basin 4 – Chao Phraya
Source: Dr. Pinida Leelapanang

Chapter 4.6 River Basin 5 – Vaal River | Vaal Barrage
Source: Gordon_O'Brien

Chapter 4.7 River Basin 6 – Medjerda River
Source: Seifeddine Jomaa

Chapter 4.8 River Basin 7 – Elbe River | Valley of Elbe near Děčín.
Source: *https://commons.wikimedia.org/wiki/File:Labe_udoli.jpg*

Chapter 4.9 River Basin 8 – Hudson River
Source: Matthias Manske | *https://de.wikipedia.org/wiki/Hudson_River#/media/File:Hudson_South.jpg*

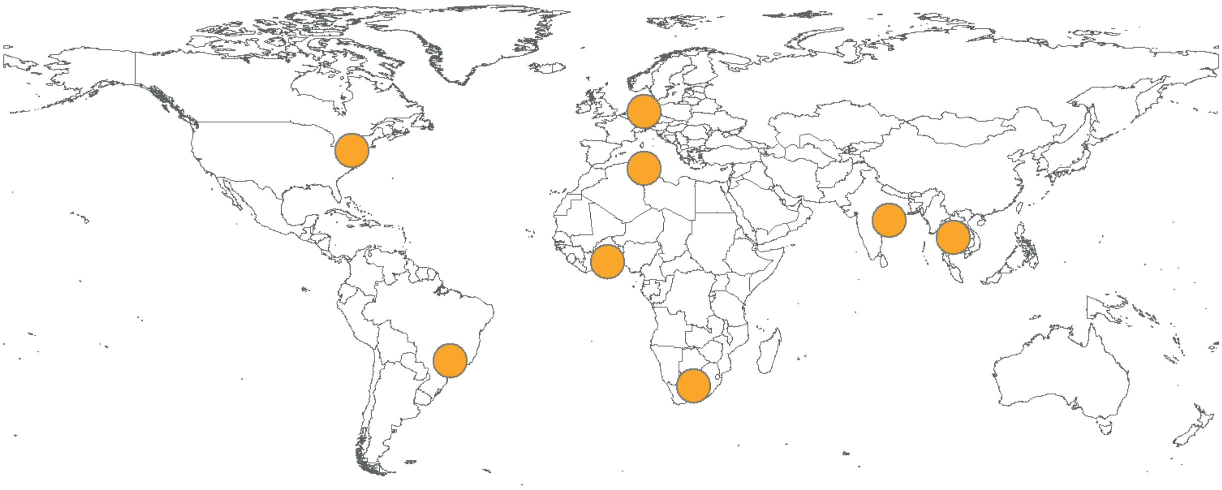


Figure 4.1: Case study locations.

Table 4.1: Case study overview (BOD = biochemical oxygen demand, FC = faecal coliform bacteria, TDS = total dissolved solids, N = nitrogen, P = phosphorus, PCBs = polychlorinated biphenyls).

Continent	River Basin	Typical water quality issue
Latin America	Upper Tietê	Organic pollution (BOD)
Asia	Godavari	Organic pollution (BOD)
Africa	Volta	Pathogen pollution (FC)
Asia	Chao Phraya	Pathogen pollution (FC)
Africa	Vaal	Salinity pollution (TDS)
Africa	Medjerda	Erosion and leaching of salts (TDS) and nutrients
Europe	Elbe	Nutrients (N and P)
North America	Hudson	Synthetic organic chemical pollution (PCBs)

4.2 River Basin 1 – Upper Tietê

The Upper Tietê River flows through the São Paulo Metropolitan Region, south-eastern Brazil, the largest urban and industrial agglomeration of South America. Since the 1950s, the growth of the population and the industrial activities led to a severe deterioration of the Tietê River water quality. In 1991, a Cleanup Programme was launched, and since then, the treatment level of domestic and industrial sewage has significantly increased. The river stretch impacted by severe pollution downstream of the São Paulo Metropolitan Region has decreased from 260 km to 100 km. This is the largest river cleanup project in Brazil and shows the importance of public participation, continuous investments, and the creation of governance and financing mechanisms.

4.2.1 Brief overview of Upper Tietê Basin characteristics and governance

The Tietê River has a total length of 1,136 km and is a tributary of the Paraná River, which is part of the Plata Basin, the second largest basin in South America. It is located entirely within São Paulo State, south-eastern Brazil. The Upper Tietê River flows through the São Paulo Metropolitan Region, the largest urban and industrial agglomeration of South America which includes the city of São Paulo and 38 adjacent municipalities, together responsible for 19 per cent of Brazilian GDP.

The hydrology of the basin is very complex because of many structures for flood control, water supply and flow management that have changed the natural regime of water flow. Human water consumption is larger than the water available in the basin, and a large portion of water (31 m³/s) has to be imported from neighbouring basins.

Upper Tietê River Basin
River Length: 243 km
Drainage area: 5,720 km² (37% urban)
Population: 20 million (2010)
Precipitation: 1,400 mm

Figure 4.2: Location of the Upper Tietê River Basin.

Water quality management in the basin is the responsibility of several agencies. Water quality is monitored by São Paulo Environment Agency (CETESB), which also has the mandate for water pollution control. The São Paulo State Sanitation Company (SABESP) is in charge of domestic water supply and wastewater treatment in most of the municipalities of the basin. The Upper Tietê River Basin Committee was established in 1991 and has, among other responsibilities, the task to approve the River Basin Plan and water quality targets. Civil society, NGOs, and the media have played an important role in the creation and implementation of the Tietê River Cleanup Program, described later.

4.2.2 Typical water pollution problem, causes and impacts

Over the last 50 years, an intense urbanisation process has taken place in Brazil. The population of the São Paulo Metropolitan Region has increased sevenfold since 1950 and its growth was not followed by a proportionate increase in domestic wastewater treatment levels. The intense industrialisation process that occurred during that period also contributed to the increase of water pollution. The location of the São Paulo Metropolitan Region on the upstream reaches of the Tietê River is also an important factor, since the relatively low river discharge here affords only a low dilution capacity for pollutants.

In the 1950s, fishing, rowing, and swimming were important activities at the Tietê River and many clubs were created along the river, some of which still exist. However, since 1972 the high pollution levels in the river have discouraged these activities.

High concentrations of BOD, phosphorus, ammonia-nitrogen, pathogenic microorganisms, and toxic chemicals are observed in the Upper Tietê River, indicating the high contribution of domestic and industrial wastewater (CETESB, 2014). The total domestic organic load in the river is 635 ton BOD/day. The industrial organic load is 26.4 ton BOD/day and the industrial inorganic load is 307 kg BOD/day (FUSP, 2009).

Because of the high BOD loads, the section of the Tietê River that runs through the São Paulo Metropolitan Region frequently has dissolved oxygen concentrations below 2 mg/l, and many tributaries have values close to 0 mg/l. Fish surveys carried out in the river showed a significant reduction of fish diversity as the river flows into the urban areas, and a complete absence of fish when it flows through the city of São Paulo (Barrella & Petrere, 2003).

The uncontrolled growth of the São Paulo Metropolitan Region around two major reservoirs (Billings and Guarapiranga) has degraded water quality because of the release of sewage, garbage, and diffuse pollution. The eutrophication of these reservoirs is a concern for public water supply, requiring the use of algicides to control the high levels of algae, and increasing the costs of water treatment.

Irrigation with polluted water is also a concern on farms because of the contamination of farm produce. Pinheiros River, a tributary of Tietê River, is a large urban breeding ground of mosquitoes. Insecticides are applied in the river margins to eliminate mosquitoes and other vectors, and traces of these insecticides were found on the waters of Pinheiros River (Cunha et al. 2011).

The São Paulo Metropolitan Region is affected by the heat island effect that contributes to the formation of convective storms of high intensity, causing floods in small urban watersheds and extensive runoff that contributes to a significant pollution load. Downstream of the São Paulo Metropolitan Region water pollution causes the formation of excessive foams from detergents, the accumulation of debris, and unpleasant odours.

4.2.3 Solutions and transferable lessons

In the late 1980s, NGOs and the media organized several actions against the Tietê River degradation and a campaign to clean up the river. In 1991, a petition calling on the State government to clean-up the Tietê River was signed by 1.2 million people and in 1992 the São Paulo State Government launched the Tietê River Cleanup Program. The programme is funded through loans from the InterAmerican Development Bank and Brazilian Development Bank, and from resources of the SABESP. The programme includes the construction of new wastewater treatment plants, expansion of existing plants, construction of sewer collection networks, and the control of industrial pollution.

The programme was divided into three phases with a total investment of US$ 3.6 billion. The programme is currently in its third phase, and will finish in 2016. A fourth phase is planned with a total investment of US$ 1.9 billion and the goal to universalise the collection and treatment of sewage in areas attended by the SABESP.

Since 1992, the level of sewage treatment of domestic wastewater has increased significantly from 24 to 84 per cent (Figure 4.3). Sewage collection has increased from 70 to 87 per cent. The expansion of sewage collection networks in poor regions has been a challenge, as some households were unconnected to sewers because people were unable to pay. In these cases, the State government decided to pay for these connections.

With regards to industrial pollution, the CETESB identified 1,250 companies in 1992 that were responsible for 90 per cent of the industrial pollution of the Tietê River. These companies were asked to submit plans for constructing treatment systems and were supported through loans from the World Bank and the Brazilian Development Bank (BNDES). The financing of these plans and imposing of fines between 1992 and 2008 led to a 93 per cent reduction of the industrial organic load and a 94 per cent reduction of its inorganic load (CETESB, 2008).

The main result of the increase in the treatment of domestic sewage and industrial effluents was a decrease of the downstream river reach impacted by pollution. In 1992, a total length of 260 km was affected downstream of the São Paulo Metropolitan Region. In 2014, this was reduced to 100 km. These improvements contributed to the return of fish at some locations and the reduction of unpleasant odours.

Despite the improvement in water quality downstream, the river in the São Paulo Metropolitan Region is still highly polluted. The recovery of the Tietê River is a long process that will need continuous investments over the next years. The Tietê River Cleanup Programme is the largest river cleanup project in the country and shows the importance of public participation and the provision of financing mechanisms.

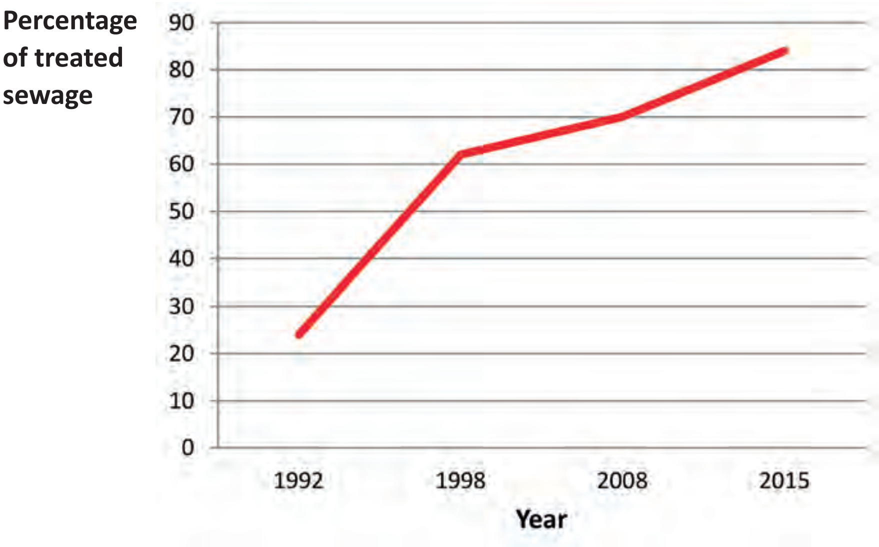


Figure 4.3: Trend in percentage of domestic sewage treated in the Upper Tietê River Basin (SABESP, 2014).

4.3 River Basin 2 – Godavari

In the Godavari river basin, discharge of untreated and partially treated sewage from cities is one of the principal reasons for the river's non-compliance with Indian water quality criteria. A Location Importance Index (LII) has been developed to assess the extent and severity of violations of water quality standards. A High LII indicates frequent pollution stress and thus a need for conducting a detailed pollution inventory and expanding water quality monitoring.

4.3.1 Brief overview of Godavari Basin characteristics and governance

The Godavari River is the second longest river in India and it has the third largest river basin in the country. Godavari originates from Trayambakeshwar in Maharashtra and then flows for about 1,465 km in a generally south-eastern direction before emptying into the Bay of Bengal. The catchment basin area of the river is 312,812 km^2 with agricultural land and forest as the main land use categories in 2005-06 (60 per cent and 30 per cent of the catchment area, respectively) (CPCB India, 2011). Despite its massive catchment area, the river's discharge is not substantial because of the low average annual rainfall in the basin. Its four important tributaries are the Manjira, the Pranhita, the Indravati and the Sabari.

Water is a State subject in India, i.e. the State is responsible for the management of water resources. Responsibilities for water management are shared between the State Pollution Control Boards (responsible for surface and groundwater quality and industrial discharges), the State Groundwater Boards (responsible for ground water estimation, qualitative and quantitative studying and approval of groundwater abstraction), the State Water Resources/Irrigation Departments (responsible for the approval of surface water withdrawal from river systems), and the Urban Local Bodies (responsible for water withdrawal from surface/groundwater bodies, treatment and supply, and treatment of sewage). There is only a modest amount of information sharing and/or cooperation between these agencies (Central Water Commission, 2012).

4.3.2 Typical water pollution problems, causes and impacts

At several locations, the water quality of the Godavari River does not meet the required criteria for Class A ("Drinking Water Source without conventional treatment but after disinfection") including for the parameter biochemical oxygen demand (BOD). Figure 4.5 summarizes the long term trend of BOD from several monitoring stations in the river. While there is a variation in the peaks, mean BOD levels are more or less constant.

Figure 4.4: The Godavari Basin extends across the States of Maharashtra, Karnakata, and Andhra Pradesh.

Discharge of untreated and partially treated sewage from cities is one of the principal reasons for the non-compliance. The sources of water pollution include (a) domestic sewage, (b) industrial effluent, and (c) agricultural non-point sources. The population density in the basin ranges from 25–50 persons/km² to 500–1,000 persons/km². More than 441 towns, 58,072 settlements and 33 cities are located in the basin area. The population of the basin, based on a 2001 census, was 60.57 million, out of which about 75 per cent live in rural and the other 25 per cent in urban areas. Nearly 40 per cent of the workforce is engaged in cultivation, 30 per cent as agriculture labourers, and 30 per cent in mining and manufacturing and other industries (Central Water Commission, 2012). In the absence of a detailed effluent inventory, the sewage load entering the Godavari is calculated based on certain assumptions. Assuming approximately 80 litres of sewage generation per person in urban areas and approximately 50 litres sewage in rural regions, the volume of raw sewage entering Godavari will be approximately 3,000 million litres per day. Further assuming an average BOD concentration of 200 mg/l and an average treatment capacity of 40 per cent, the total BOD load can be estimated at 219,000 t/yr. This would correspond to an average BOD intensity of 409 kg/km/day of river length.

No direct estimate of effluent generation in the Godavari basin or effluent entering the Godavari has been made or is available in literature. In Andhra Pradesh (situated in the lower Godavari basin), sugar and distillery units are large in number in addition to pulp & paper and fertiliser companies. These industries are likely to be massive water consumers and contributors to the deterioration in water quality in the river particularly from Nashik to Nanded in Maharashtra and at Baster in Chhattisgarh and Burgampahad in Andhra Pradesh (CPCB India, 2011).

Pollution due to the runoff of chemical fertilisers is also likely to be a problem. The average annual use of chemical fertilisers in the basin area is 49.34 kg/ha which is more than twice the national average. The total consumption of pesticides is 21,586 t/yr.

4.3.3 Solutions and transferable lessons

In the Godavari basin, there are 34 water quality monitoring stations spread across the States of Maharashtra and Andhra Pradesh. The Water Quality Index (WQI, Abbasi & Abbasi, 2012) is used as a single parameter to (a) communicate water quality to stakeholders and (b) compare water quality across locations over time. CPCB in India has adopted the WQI from the index developed by National Sanitation Foundation (NSF) USA. CPCB's WQI uses parameters such as BOD, DO, faecal coliform bacteria (FC), and pH. The WQI used so far is based on concentrations and does not account for the adequacy of river flow for diluting wastes and supporting the aquatic ecosystem. It would be useful, therefore, to introduce minimum "environmental flows" as an additional benchmark for tracking the health of the Godavari.

As assessment of compliance is one of the key objectives of the water quality monitoring program, it is useful to develop metrics to prioritise the monitoring

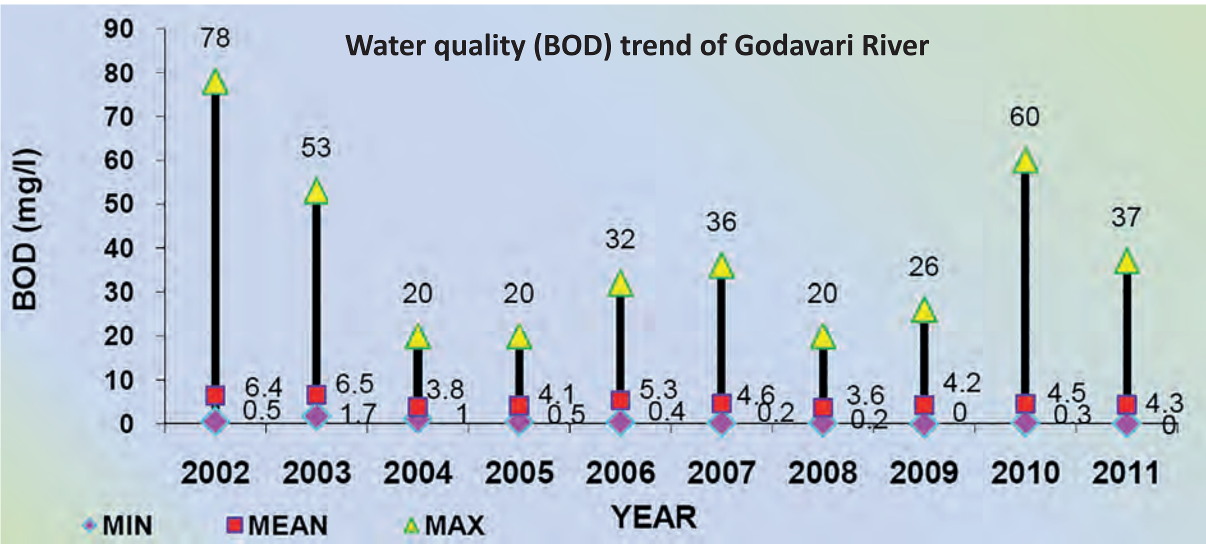


Figure 4.5: Water quality (BOD) trend between 2002 to 2011 in the Godavari River (CPCB India, 2011).

locations. To achieve this objective, a new Index called Location Importance Index (LII) was developed. The LII is a measure to assess the extent (frequency), severity (magnitude) of violations and how contiguous the violations are in relation to standards. To calculate LII, monthly BOD and DO observations from 18 water quality monitoring stations in the State of Maharashtra are used. High LII values, e.g. in the stretch downstream of the city of Nasik, indicate frequent pollution stress and thus a need for conducting a detailed pollution inventory and initiating water quality control measures. Further, these stretches are ideal for the placement of automated water quality monitoring stations. These measures have been recommended to the Maharashtra Pollution Control Board.

There is a need for conducting comprehensive impact assessment going beyond the assessment of in-stream water quality. Such an assessment should cover the entire river basin ecosystem. For a holistic impact assessment, parameters such as water use (domestic, industrial agricultural) non-point pollution loads, agricultural yield, public health indicators, groundwater quality, ground water levels, biodiversity, and top soil contamination should be considered including climate change related vulnerability.

4.4 River Basin 3 – Volta

The resources of the Volta River basin of West Africa are essential to the livelihoods of the predominantly rural communities that inhabit it. Due to limited sanitation infrastructure, faecal coliform contamination has already deteriorated water quality in parts of the basin and this will continue to escalate with increasing population and urbanisation. Transboundary management structures, participatory processes and other innovative solutions are suggested as short and medium term remedies.

4.4.1 Brief overview of Volta Basin characteristics and governance

The Volta River basin has a rich network of diverse ecosystems that provide a wide range of natural resources for its six riparian countries. These resources directly and indirectly support the livelihoods and economic development of its current population of over 20 million. With populations projected to reach 33 million by 2025 and with increasing variability and changes in weather patterns in the basin (Oyebande and Odunuga, 2010), the sustainability of basin resources, especially water (McCartney et al., 2012), is under severe and increasing threat.

The creation of the Volta Basin Authority (VBA) in 2006 and the Convention on the Status of the Volta River and the Establishment of the Volta Basin Authority (signed in 2007, ratified by the six countries in the period 2008-2009) is a transboundary approach towards coordinated management of the basin's resources. The VBA has overall responsibility for implementing an international cooperation for the sustainable management of water resources and promoting better sub-regional economic integration (VBA, 2010). In addition to the VBA mandate, the management of the Volta Basin is characterised by a number of international, regional and national bureaucratic structures, such as ratification of various international conventions, membership in the Economic Community Of West African States ECOWAS, as well as the West African Economic and Monetary Union (Ghana excepted). Traditional management systems are also important, even though the complexities between modern and customary systems can sometimes lead to conflicts (UNEP-GEF Volta Project, 2013).

Brief facts about the Volta River Basin (Source: UNEP-GEF Volta Project, 2013):

- *Situated in the sub-humid to semi-arid West African Savannah Zone and covering 28% (400,000 km^2) of West Africa;*
- *Shared by: Benin (4.1%), Burkina Faso (46%), Ghana (39%), Côte d'Ivoire (1.8%), Mali (2.4%), and Togo (6.4%);*
- *Drained by 4 sub-basins: the Black and White Voltas (from Burkina Faso), Oti River (Benin), the Lower Volta (Ghana), and emptying into the Gulf of Guinea;*
- *The Volta Lake in the Lower Volta, created in 1965 by the construction of the Akosombo Dam for hydropower is the 2nd largest man-made lake by surface area (8,500 km^2) in the world;*
- *Precipitation varies between 1,600 mm (south) and 360 mm (north);*

- *Annual runoff is 56.4 billion m³;*
- *Population density: 72/km² in 2010; 83/km² in 2015; >100 inhabitants per km² by 2025;*
- *Main livelihoods: agriculture (extensive and mostly rainfed), livestock production, fisheries, forestry, and hunting and gathering.*

4.4.2 Typical water pollution problem, causes and impacts

Available data indicates that severe water quality deterioration is not widespread in the Volta Basin. Significant localised problems are more prevalent in the densely populated northern towns which have lower hydrological flows than the south, where the higher flows dilute pollutants (UNEP-GEF Volta Project, 2013). Although requiring more extensive and long-term datasets to be conclusive, reports of surface water quality in the basin indicate generally good water quality (e.g., Andah et al, 2003; Goes, 2005; WRC, 2008) with low average nutrient levels, especially in the Volta Lake (van Zweiten et al., 2011). High nutrient loads from agricultural sources occur in specific locations such as cotton, sugar cane, or commercial oil palm plantations (Programme GIRE Burkina Faso, 2001; Samah, 2012) or from markets (Ofori, 2012), and, to a lesser extent, localised industrial pollution from beverage and textile production (Gampson et al., 2014). Faecal coliform levels are, however, consistently above WHO guidelines for drinking water (e.g., Kankam-Yeboah & Opoku-Duah, 2000; UNEP-GEF Volta Project, 2013). Samah (2012) reports levels between 121±32 cfu/100 ml and 425±181 cfu/100 ml in the Asukawkaw River for March-June 2012 that contributes about 40 per cent to the total volume of the Volta Lake.

The presence of faecal coliform bacteria in the basin have been attributed to increasing domestic inputs from discharge of waste, untreated sewage, and open defecation along the banks of the Volta River by both humans and grazing animals, including in some areas, large flocks of migratory birds (Abdul-Razak et al., 2009). In most parts of the basin, a major economic activity is the extensive production of livestock at high densities (although this tends to decrease from the north at 10 to 20 animals per km² to the south at 1 to 5 animals per km²), which has impacts on water quality (UNEP-GEF Volta Project, 2013). In Mali and Burkina Faso, surface water quality is poor with numerous coliform and bacillus bacteria. In the Sourou Valley of Burkina Faso, shallow wells that are a preferred source of drinking water are highly polluted with coliforms exceeding 1x103 cfu/100 ml for E. coli and 1x104 cfu/100 ml for faecal coliforms (Boubacar et al., 2013). In Burkina Faso and northern Ghana, run-off from inland port communities and urban settlements near river banks and reservoirs also significantly affect water quality.

Rural households in the basin mainly depend on individual or communal latrines or defecate openly in nearby bushes or river banks. In urban areas, the sewerage systems are only able to service a small portion of the population and, as a result, untreated sewage is discharged directly into the environment in a number of larger cities such as Ouagadougou, Bobo Dioulasso, and Abidjan. In Ghana, national assessments identified 70 decentralised wastewater and faecal sludge treatment plants serving less than 10 per cent of the urban wastewater volume, and of these, only 13 per cent were still operating (Murray & Dreschel, 2011). In studies assessing the quality of effluent into the Volta River, an effective reduction of BOD concentrations and total removal of coliform (99.99 per cent) was shown in one study (Hodgson, 2007), whilst another showed that, although the treatment performance of two treatment facilities significantly reduced coliform by 95 per cent, the final effluent still did not meet the Ghana EPA standards and required final disinfection (Kagya, 2011).

The concentration of FC can be influenced by seasonal changes, with high contamination levels at the onset of heavy rains where runoff carries raw sewage and leachate from waste dumping sites into the water bodies. The construction of small, medium and large reservoirs in the basin, primarily used for irrigation, the anticipated rainfall variability and the decrease in average annual basin flow of approximately 24 per cent and 45 per cent by 2050 and 2100, respectively (McCartney et al., 2012; Sood et al., 2013), will have serious hydrological and health implications due to lower dilution flows and increased pollutant concentrations.

The faecal contamination of water in the Volta basin has important implications for urban and rural water supply. The Volta Lake, for example, is a water reservoir for large cities such as Akosombo; and rural communities depend directly on the surface water as they tend to have less access than urban communities to potable water from boreholes, pumps, or piped water taps. Burkina Faso and Ghana have a largely rural population. So, only 37 per cent (in Burkina Faso) to 62 per cent (Ghana) of households have access to safe drinking water (Rodgers et al., 2007). Even where there is access, a large number of people still prefer and continue to use untreated water from the river due to quality perceptions and opportunity costs (Engel et al., 2005).

As a result, waterborne diseases are a threat to the rural communities, with a significant contribution to the 2012 mortality rates of children aged less than 5 years in Benin (10 per cent), Burkina Faso (11 per cent), Ghana (7 per cent), Côte d'Ivoire (10 per cent), Mali (12 per cent), and Togo (9 per cent) (WHO, 2014a). Contaminated water also has implications for aquatic organisms such as clams, a common and inexpensive source of protein and livelihood for the communities at the Volta estuary. Adjei-Boateng et al. (2009) and Amoah et al. (2011) found that the clam *Galatea paradoxa* in these areas was highly contaminated with FCs, due to its capacity to accumulate up to five times the bacterial load in the surrounding water, through its filter feeding activities. The evidence of high microbial contamination of fish caught in polluted waters (Kombat et al., 2013), making it unsafe or undesirable to eat, shows that there are potential impacts to the health and livelihoods of the local communities.

Water contamination by FCs is compounded by poor awareness and education about public health, inappropriate technologies for sanitation, both in urban and rural areas, lack of effective and coordinated legal systems for controlling the discharge of effluents and lack of financial resources. The capacity to address such issues is challenged both at the regional and national levels by (i) limited research and technical capacity, (ii) inadequate implementation of regulations, (iii) complexities of ecosystems and poverty, (iv) the language barrier between Anglophone and Francophone countries, and (v) lack of effective and operational institutional and legislative mechanisms to ensure basin wide action, as well as other factors. However, there are still a number of opportunities and transferable lessons in terms of governance, information flow and technological solutions, which can be used for integrated water quality improvements.

4.4.3 Solutions and transferable lessons

The advantage of having the VBA as a management structure is the regional recognition and respect that it has, which allows for access and collaboration with reputable international and national institutions, projects and programmes. Existing networks of institutions can be enhanced, or new networks created, to enable the development and implementation of both regional and national management solutions. The independent development of national strategies by individual countries is less efficient than a comprehensive regional strategy. However, as this will require time and funds, the sharing of best practices by the countries is needed at this time. A database of related information generated through regional, cross-basin, and national research can support this process. A harmonised method of water quality monitoring techniques, including faecal source tracking, can also provide important information required for evidence-based decision making.

The VBA also encourages countries to financially support improved sanitation and water pollution control. This includes increasing the technical and institutional capacity to collect and interpret relevant data, formulate policy, and implement strategies. Integrated water resources management requires participatory frameworks and processes at all levels to succeed. Institutions from government, civil society (including traditional authorities), academia, and the private sector need multi-stakeholder platforms to communicate, support each other, and coordinate activities. At the local level, community engagement, especially by beneficiaries, and the use of indigenous knowledge, where appropriate, will lead to acceptance and success. The appreciation of gendered roles in water use and sanitation is also essential in the development of management strategies (e.g., Peter, 2006; Figueiredo and Perkins, 2013).

Currently, solutions for effective water management in the Volta Basin tend to focus on strategies for improving sanitation and the provision of safe drinking water. These strategies are applied in addition to traditional wastewater treatment systems at community and household levels for reducing pathogen loading into the environment. Potential innovative on-site technologies, such as anaerobic digestion and biogas generation (Avery et al., 2014), the application of low-tech options using locally available biomaterials, or ecosanitation, where urine and faecal matter are separated to recover nutrients (Mihelcic et al., 2011); could also be explored.

A range of small scale water treatment technologies, from low cost chlorine disinfection systems to more expensive reverse osmosis systems, appropriate storage of water and improved hygiene are required to minimise the potential health impacts of drinking contaminated water. Local ingenuity and simple mechanisms also improve access to safe drinking water; for example, the SODIS method of placing clear bottles filled with water on a piece of metal in full sunlight for a number of hours kills off all microbes (McGuigan et al., 2012). However, local ownership of both the technology development and the treatment system used is an essential element of its success. Demand-driven water treatment systems are far more sustainable than those which are eventually abandoned because community members were not aware of the full capital and operational costs from the start (Rossiter et al., 2010).

In addition to the numerous opportunities for addressing water quality issues of the Volta Basin, promoting community and household level solutions has far-reaching impacts in protecting the health of humans and the ecosystem. Education and awareness creation processes are, therefore, required to build knowledge and gain support, place pressure on local governments to change policy, and enhance enforcement practices in order to support larger scale basin management planning (Palaniappan et al., 2010).

Figure 4.6: Map of Volta basin

4.5 River Basin 4 – Chao Phraya

The Chao Phraya River is considered the lifeblood of Thailand. The river supports 13 million people and is used in a variety of ways, including for drinking water, irrigation, and as the primary water source for the Tha Chin River. Under low to average water conditions, domestic, agricultural, and industrial discharges are greater than the river's capacity for self-purification. The main source of water pollution is untreated wastewater from domestic sources. Existing wastewater treatment plants service only limited areas. Therefore, the construction of new wastewater treatment plants is suggested in order to improve water quality. Moreover, community involvement, through means such as water conservation and waste minimisation programs in Pathum Thani and Nonthaburi, are essential to the success of water quality programmes.

4.5.1 Brief overview of Chao Phraya Basin characteristics and governance

The Chao Phraya River basin is located between latitude 12 01' to 19 45'N and longitude 98 10' to 101 30'E. It covers ca. 160,000 km^2, representing 30 per cent of the country's total area, and 57 per cent of its population. The upper region of Chao Phraya basin is mountainous with agriculturally productive valleys and the lower region contains alluvial plains that are highly productive for agriculture.

The Chao Phraya River basin consists of the upper four tributaries of Ping, Wang, Yom, and Nan; the lower two tributaries of Pasak and Sakae Krang; and the delta of Chao Phraya and Tha Chin (Paramee, 2003). The region is dominated by the monsoon, with a rainy season lasting from May to October and supplementary rain from occasional westward storm depressions originating in the Pacific. The annual precipitation is 1,179 mm with an annual discharge of 196 m3/s. There are two large dams in the Chao Phraya River basin: Bumiphol and Sirikit which control the runoff from 22 per cent of the basin. The whole basin is rich in biodiversity and contains extensive areas of rainforest. The lower part of the basin has extensive irrigation networks, enhancing intensive rice paddy cultivation. However, in recent years, human intervention has been increasing in forest areas resulting in the conversion of forest to agricultural land.

About half of the population of the Chao Phraya River basin is living in the Bangkok Metropolitan Area (BMA) and parts of Samut Prakan, Nonthaburi and Pathumthani. Bangkok and its vicinity has the highest population density with 1,497 inhabitants/km^2. Similarly, the upper Ping River Basin also consists of areas with a highly concentrated population. Increasing human settlement and changes in land cover have caused degradation of water quality, increased frequency of flash floods, erosion and landslides.

Various agencies are responsible for water governance in the Chao Phraya River basin. The Electricity Generating Authority, Thailand (EGAT) controls the water release from the two main reservoirs in the basin and the Royal Irrigation Department (RID) regularly monitors the water level at the lower reach of Chao Phraya at the Chainat diversion dam. The Pollution Control Department (PCD) monitors the water quality of the Chao Phraya Delta. In the Thachin river basin, several environmental agencies and provincial and local governments have been developing policies and action plans to manage and improve water quality.

4.5.2 Typical water pollution problem, causes and impacts

The lower reaches of Chao Phraya River basin are considered to be the most polluted of the basin, and the Tha Chin River one of the most polluted rivers in Thailand. According to the routine water quality monitoring by the PCD, the lower reaches of Chao Phraya and Tha Chin have not met National Surface Water Quality Standards since the 1990s. Based on the 2009 Annual Report on Water Quality Management by PCD, the overall water quality in Thailand has declined significantly during the past 10 years. According to the 2009–2013 water quality index (WQI) data, Bangkok (the Chao Phraya River) has the poorest water quality as shown in Figure 4.8.

Figure 4.7: Map of Chao Phraya basin.

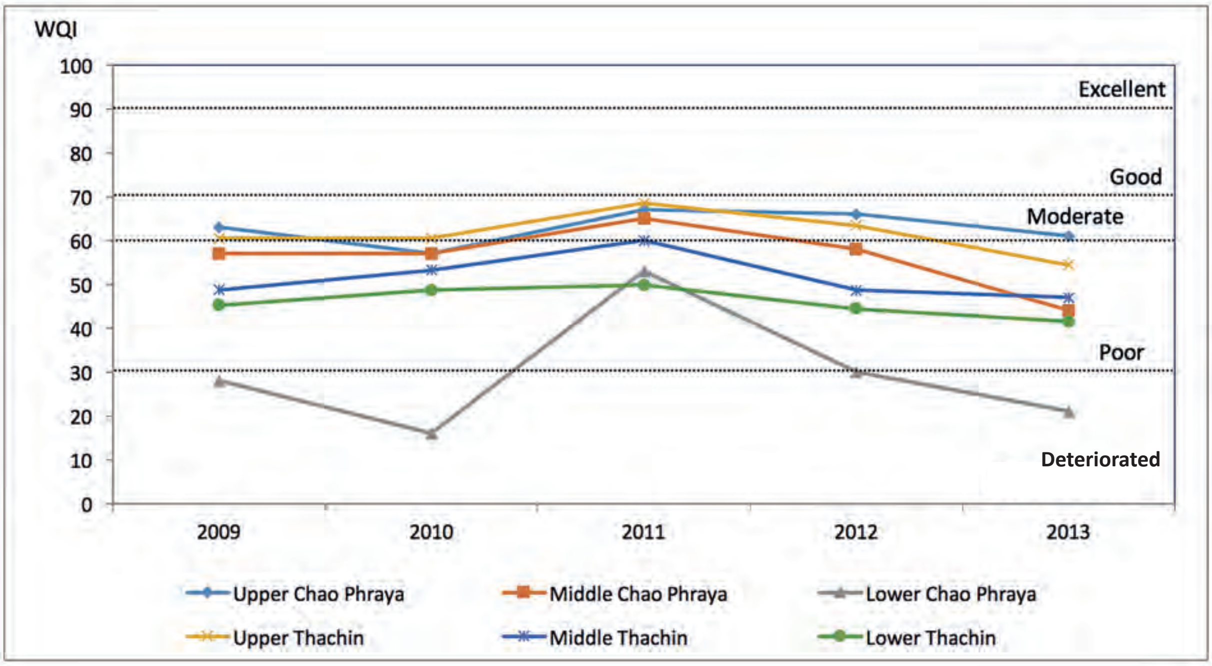


Figure 4.8: Trends of water quality in the Chao Phraya and Tha chin Rivers from 2009 to 2013 (PCD, 2013).

The concentrations of selected water quality parameters in the Upper, Central, and Lower Chao Phraya River and Tha Chin River for the year 2013 illustrate this gradient (Table C.1, Annex C). The parameters indicating poor water quality in the dry season are faecal and total coliform bacteria (FC and TC), NH_3-N, and BOD, whereas those in the rainy season are FC, TC, and NH_3-N. Municipal waste and industrial effluents result in low DO levels and high BOD levels in the lower Chao Phraya and Tha Chin River basins. Industrial wastes contribute to low DO levels below the water quality standard (Kunacheva et al., 2011). The surrounding agricultural areas also contribute to a high amount of NH_3-N and derivatives in the basins. The levels of TC and FC, which reflect the sanitary quality of the river, are degrading because of the discharge of human and animal wastes into the river (Campos & Cachola, 2007).

The major issues of water quality are low levels of DO, frequently below 3 mg/l, high organic matter (BOD), and high FC (Simachaya 2003). Land-based BOD loading into the Upper Gulf of Thailand has increased from 207 t/day in the 1990s to 1144 t/day in the 2000s (PCD, 1997). Total nitrogen loading from the Delta, Chao Phraya and Tha Chin River contributes up to 116,000 t/yr to the Upper Gulf of Thailand (Leelapanang, 2010). As a result, the estuary in the Upper Gulf of Thailand has frequently experienced algal blooms; red tides occurred 18 times at the river mouth during the year 2008 (MCRC, 2009). The Chao Phraya River exhibits serious organic pollution which threatens many species of aquatic life. Similarly, water quality in the Tha Chin River is heavily degraded, due to the combined discharges of industrial, domestic and rural effluents.

In general, the basin is entering a critical period in which small changes in hydrologic conditions can create large socio-economic disturbances. In recent years, land use in the Chao Phraya and Tha Chin River basins has been changing from agricultural to urban and industrial. Due to the increase in population, it is unavoidable that new settlements will be built in areas where water management is difficult. Human impact on water resources, and vice versa, is visible throughout the basin. Native plants acting as surface cover on native land are being destroyed at a rapid pace, causing flash floods, erosion, and landslides. The construction of dams and diversions requires the resettlement of people, usually to unclaimed and infertile areas. In the lower part of the basin where intensive irrigation networks exist, rice is cultivated year-round. Thirty years ago, the same area had a single annual rice harvest. Since then, the number has doubled, then tripled, and today there is continuous cultivation. Clearly, the land is heavily used, with no time for revitalisation.

4.5.3 Solutions and transferable lessons

The National Policy regarding water quality is stipulated in both the National Economic and Social Development Plan and in the National Policy and Plan for Natural

Resources and Environment Management, which set long-term (twenty-year) goals, standards and strategies. In the Eighth Plan, the national goal was to maintain the quality of surface water at the 1996 level (UNESCO, 2003).

The maintenance of river integrity is based on maintaining minimum stream discharges to repel salt-water intrusion in the lower reaches of rivers, dilute pollutants and maintain minimum dissolved oxygen levels to ensure that the quality of the aquatic environment does not fall below acceptable levels. A minimum flow of 16 m^3/s is currently considered sufficient in the lower reaches of the Chao Phraya River to repel salinity intrusion. Pollution control is more problematic. Most of the wastewater discharges of domestic and industrial origin have increasingly been controlled and mitigated through the enforcement of separate effluent standards by various regulating governmental agencies. In addition, the regulation of streamflow in the Chao Phraya River by releases from upstream reservoirs operated by EGAT (Electricity Generating Authority of Thailand) and RID (Royal Irrigation Department) can to some extent improve the poor downstream water quality during the dry season. Allocation of basin water supplies must take into account these needs (Pattanee, 2005).

Thailand has developed master plans of water quality management for major river basins including the Chao Phraya. Construction of wastewater treatment facilities in municipalities is prioritised and recommended as well as a control of wastewater from industrial and agricultural sources. The government has "mobile land doctor units" helping farmers to diagnose and remedy land degradation problems. Charging fees for waste discharges is also being studied and will be applied to many sites in the near future. Four municipalities apply the Polluter-Pays-Principle for wastewater treatment plants and a few more are working towards this policy. Water quality models and geographic information system (GIS) have also been developed and used as tools to help decision-makers in water quality management (Pattanee, 2005).

4.6 River Basin 5 – Setting resource quality objectives for the Vaal River

The Vaal River drains what is effectively the economic hub of Africa, the city of Johannesburg in South Africa. This city was built in the late 1800s and 1900s as a mining city and has innumerable mines dotted around the city, with thousands of kilometres of tunnels beneath the city streets. As mines have been depleted and closed across the Upper Vaal basin, groundwater has risen bringing with it toxic acid mine water which decants onto the surface and into the rivers. Operational mines also pump to void mine water, which also enters the surface water resource. Despite many initiatives to mitigate this issue, even by treatment of the mine water and an active programme to dilute the salinity using inter-basin transfers of cleaner water, the net result is a salinity problem in the rivers downstream. Recent management interventions include the setting of Resource Quality Objectives (RQOs) for the river downstream that are codified in law and become objectives for management action. This study provides an example of how water quality monitoring can be translated into management objectives.

4.6.1 Brief overview of Vaal Basin characteristics and governance

The Vaal River runs through four of South Africa's provinces (Gauteng, Free State, North West, and Mpumalanga), and eventually joins the Orange River which runs into the Atlantic Ocean. This water management area is of major national strategic and economic importance because it hosts economic activity amounting to 20 per cent of South Africa's Gross Domestic Product. It has a catchment area of 197,000 km^2 providing habitation for some 5.6 million people. Water resources in the area have been fully allocated for over three decades, and 54 per cent of water requirements are met through inter-basin transfer schemes primarily from Lesotho via the Lesotho Highlands Water Project, and the Thukela catchment. Owing to such interdependencies between catchments, water infrastructure (numerous dams and inter-basin transfer schemes) is considerable and its management is increasingly key to water supply.

4.6.2 Salinity pollution in the Vaal River, causes and impacts

Poor water quality of surface and groundwater resources is a major issue in the Upper Vaal, both through direct impacts from mining and industry (return flows from mine dewatering) and indirectly from air pollution (coal power stations). The Vaal River Reconciliation study (DWAF, 2009b) identified that salinity (as represented by Total Dissolved Solids, TDS), eutrophication and microbiological water quality are the major water quality issues in the river.

Levels of salinity, as indicated by TDS concentration, are shown in Figure 4.9. The impact of effluent discharges and diffuse sources in the Vaal Barrage catchment is apparent from the substantial increase in TDS concentration between Vaal Dam (VS7) and Vaal Barrage (VS8), where the TDS concentration is 7.3 times greater than natural concentrations (DWAF, 2009a).

The increase in the TDS concentrations from the point VS7 to VS8 is attributable to the highly saline tributaries that drain into the Vaal Barrage but also includes diffuse pollution (DWAF 2009a). The Vaal Barrage sub-catchment is one of the most complex catchments in South Africa. It is highly developed with industries, urban areas and mining activities. In excess of 90 per cent of the dry weather flow is made up of return flow emanating from the respective tributaries. The TDS concentration in the Vaal River levels off at approximately 600 mg/l due to the dilution management rule practiced in the Vaal Barrage, where water from the upstream Vaal Dam is used to dilute and manage the salinity.

4.6.3 Solutions and transferable lessons

The Water Act of 1998 (of South Africa) requires that Resource Quality Objectives (RQOs) be set for all water resources in South Africa, including rivers, wetlands, estuaries, lakes, and groundwater and a procedure was drafted to regulate this process (DWA, 2011). The selection of objectives takes into consideration both, the quantity and quality of water resources, as well as the habitats and biota associated with these water resources. The objectives are selected after the water body is assigned a "management class"; this class is based on the socio-economic and ecological drivers and requirements of the water resource (DWA, 2012). During 2014, the RQO procedure was implemented for the Vaal River, but only the Upper Vaal is described here.

The main steps for determining RQOs are:

1. Delineate resource units (RUs).
2. Prioritise those resource units that have water "issues" (see Figure 4.10).
3. Prioritise those components that would best illustrate these "issues". Components should include quantity, quality, habitat and/or biota.

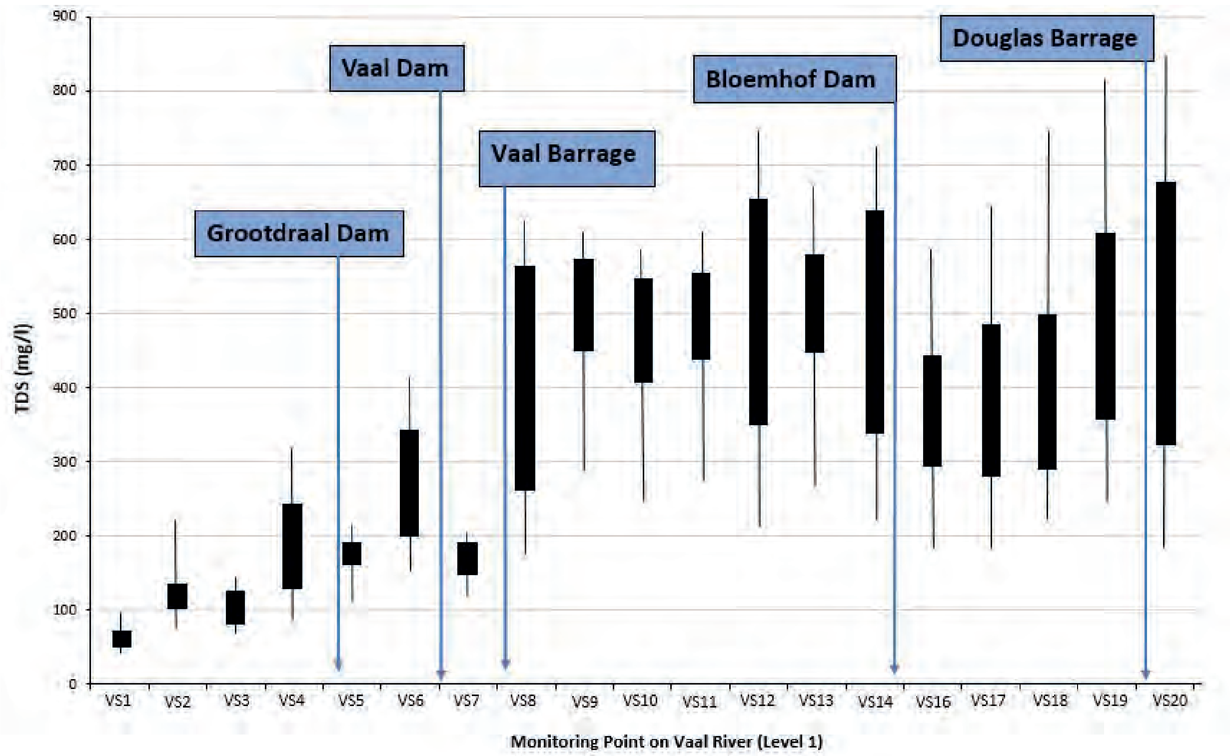


Figure 4.9: TDS concentrations (mg/l) in the Vaal River showing the 5th, 25th, 75th and 95th TDS concentration percentiles (figure redrawn from DWAF 2008).

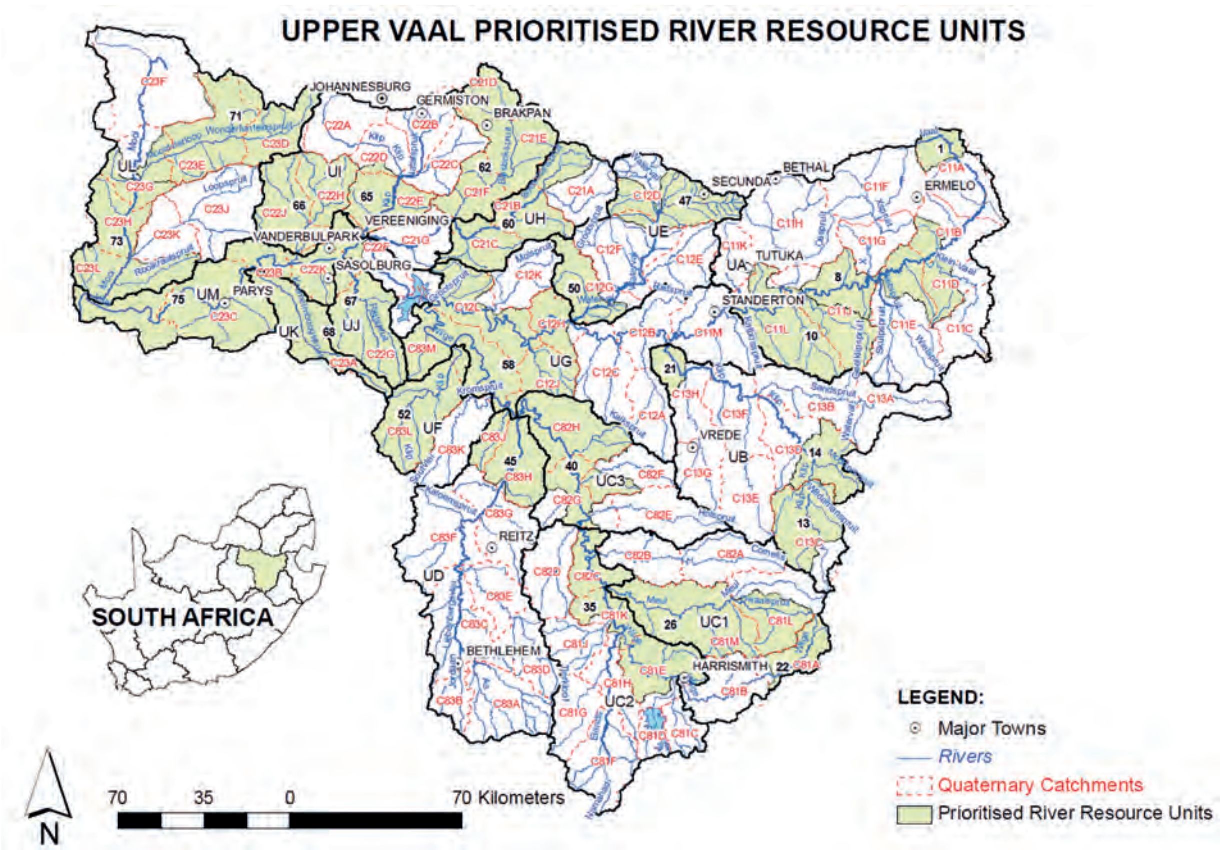


Figure 4.10: Prioritised Resource Units for the Upper Vaal catchment demonstrating the extent of coverage of the legally binding Resource Quality Objectives (DWS, 2014). RQOs are set for each of the indicated Resource Units.

For example, in some areas nutrients may be the driving issue, in others an indicator fish species may be the best indicator of what is happening with the resource, etc.

4. Determine RQOs for each resource unit that would serve to maintain the water resource (quantity, quality, habitat and biota) in a condition that meets the desired Management Class. A key characteristic of the RQO procedure is that the RQOs themselves are essentially narrative and describe the objective in terms that can be accepted by stakeholders. These are then supported by Numerical Limits which are subject to change as knowledge and science improves.

This procedure was implemented for the Upper Vaal (DWS, 2014). While this report documents all of the many issues and the resulting RQOs for the quantity, quality, habitat, and biota for the Upper Vaal (Table C.2, Appendix C), only selected salinity results are illustrated here.

Key features of these RQOs are:

- The RQOs respond to the classification of the water management area (basin) into management classes which addresses both biophysical and socioeconomic needs and influences.
- The RQOs are generally narrative as this allows greater certainty and concordance with stakeholder requirements.
- The RQOs are supported by numerical limits which may be subject to improvement as information and data is added following both monitoring and also developments in understanding.

The RQOs and the numerical limits are gazetted in the Government Gazette and thus become legally binding on all authorities. The Department of Water and Sanitation is required to control sources of pollution and impact so that the RQOs can be met. It does this through a system of Source Directed Controls (licenses).

4.7 River Basin 6 – Medjerda

The Medjerda river basin is the only permanent stream in Tunisia. It originates in the Atlas Mountains of eastern Algeria, crosses Tunisia's Northern region and discharges into the Golf of Utica in the Mediterranean Sea. The continuous increase of pressures on water use in the region for agriculture, industry and urbanisation deteriorate the in-stream and nearshore water quality of the Medjerda significantly. A strategy for joint soil and water conservation measures is needed to identify hot spot and vulnerable areas to reduce sediment loads and their associated impacts. Participative actions for awareness-raising are especially targeting "the new generation" and local population.

4.7.1 Brief overview of Medjerda Basin characteristics and governance

The Medjerda River has an average discharge of 1 billion m^3/yr representing 37 per cent of the total surface water of Tunisia and 22 per cent of the renewable water resources in the country; it provides drinking water, completely or partially, to 60 per cent of the Tunisian population (Jaouadi et al., 2012). The length of the main river basin is about 484 km covering an area of 23,700 km^2, 32 per cent of which is located in Algeria (Figure 4.11). Mean precipitation in the Medjerda river basin ranges from 600–1,000 mm/yr in the north sub-humid region to 300–400 mm/yr in the south semi-arid to arid part of the basin, resulting in an average of about 480 mm/yr. The main economic activity in the basin is agriculture which produces a large fraction of the total national cereal production (70 per cent of the cultivated area). This gives the basin a central role in national food security. As a result, most of the available water in the Medjerda catchment is used for irrigation (80 per cent). Meanwhile, the household and tourist sectors account for 16 per cent of water use, and industry 4 per cent. Several wastewater treatment plants have been serving municipalities near the river since 1994.

A large dam was constructed in 1981 on the main river tributary of the Medjerda following the severe flood of 1973 which saw river discharge reach 3,500 m^3/s. Although the main goal of the Sidi Salem dam is to provide flood protection to downstream inhabitants and agricultural areas, it also makes more irrigation water available to the northern and central parts of the country. In addition, electricity is produced at several hydropower plants using water stored behind the dam. Even though the Sidi Salem reservoir has contributed to the development of the Northern regions (for example, by providing water for expanding irrigated areas), it has also had significant adverse impacts on the natural environment, especially related to the silting of its reservoir. Zahar et al. (2008) reported that the Sidi Salem reservoir has substantially reduced the discharge of the Medjerda, altering the morphology of its cross section, but also reducing the frequency of floods at the downstream part. However, the impact of climate change in the region is thought to have increased the complexity of flood management. Although new guidelines for flood protection have been adopted for the management of the Sidi Salem reservoir, the frequency of flooding remains high and perhaps is even increasing, as indicated by high water events in 2003, 2004, 2005, 2012, and 2015.

Water monitoring in the basin is provided mainly by two agencies: the "Direction Générale des ressources en Eau" (DGRE) for water resources and the Agence Nationale de Protection de l'Environnement" (ANPE) for water quality.

4.7.2 Typical water pollution problem, causes and impacts

Jdid et al. (1999) have reported that water quality in the north-western part of the Medjerda basin is characterised by high heavy metal concentrations, especially arsenic and zinc. The concentration of total dissolved solids (TDS) of surface water is in the range of 0.14–4.2 g/l in most parts of the catchment, except the southwestern part (the Mellègue sub-catchment). Here TDS concentrations reach up to 9.68 g/l during the dry season. Also, an analysis of physico-chemical and bacteriological parameters revealed degradation of water quality: Faecal coliform bacteria reach a concentration of 1,100 cfu/100 ml below the largest cities (such as Jendouba and Beja, Figure 4.11). Also, at some stations nitrogen and phosphorus loads reach values of 330 and 315 kg/day, respectively. From the ecological perspective, measurements of the free-flowing part of the river (Riahi & Ben Thayer, 2008) and the Sidi Salem reservoir (Koumaiti et al. 2010) indicate that the river is mesotrophic.

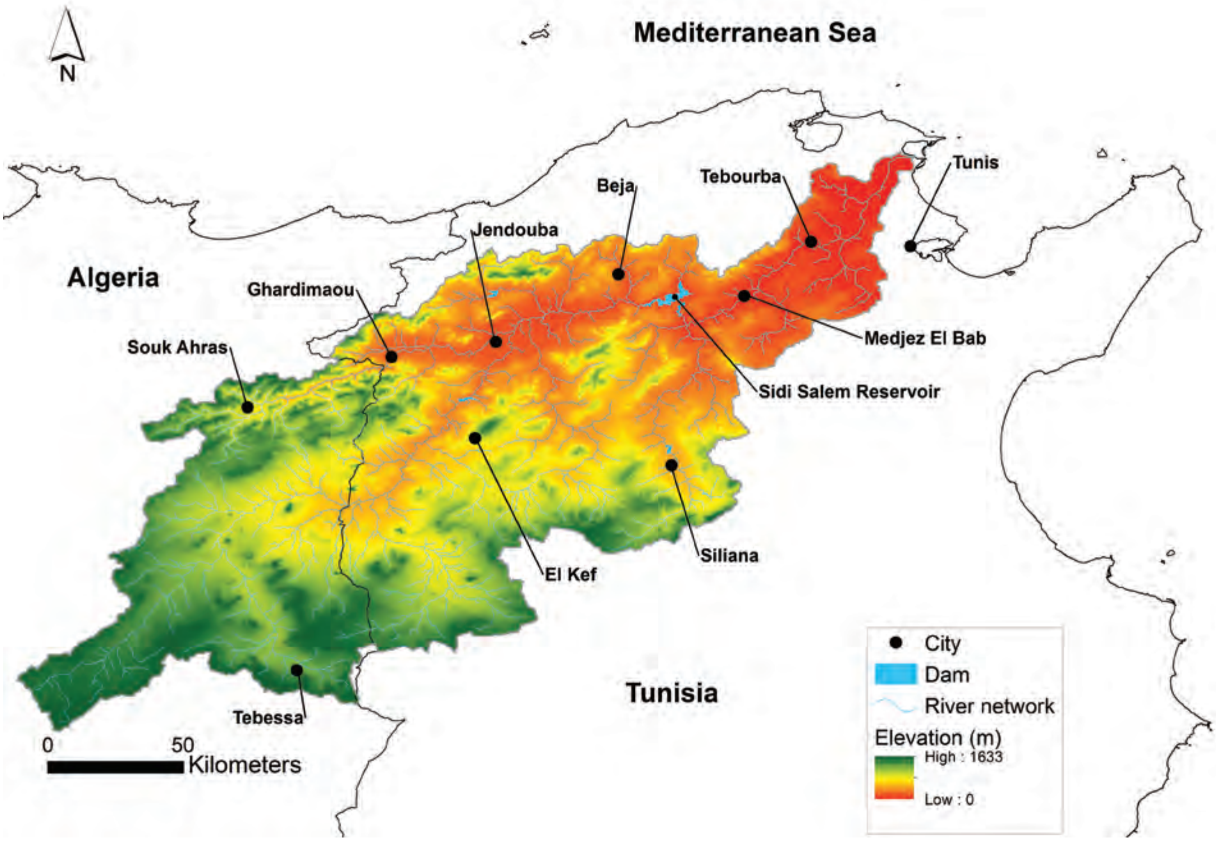


Figure 4.11: The geographical location of the Medjerda catchment and its digital elevation model.

High heavy metal concentrations are caused by leaching from closed mining activities and by the intrinsic geochemistry of the sub-soil, which has high natural concentrations of heavy metals. Bouraoui et al. (2005) have reported that the Medjerda River basin is experiencing an intensification of agriculture and irrigated area is increasing rapidly. In addition to diffuse sources, point sources (e.g., sewage plants) have significantly increased during the last decade. It is estimated that the Medjerda River basin receives 1.27 million m^3/yr of untreated and 12 million m^3/yr of treated wastewater from the sewage systems (DGRE, 2006). The increased use of fertilisers in agriculture during the last decade has also affected shallow aquifers, where nitrate concentrations reach about 300 mg/l near irrigated areas. The catchment is also subject to soil erosion episodes due to heavy rainfall events characteristic of the Mediterranean region. Moreover, it was found that the most severe soil erosion episodes occurred particularly at the beginning of the rainy period (September-October) after a long dry period (hot summer) following the crop harvesting and soil tillage season (Mosbahi et al., 2013).

Agriculture is suspected of being the largest contributor to non-point source pollution. However, its contributions have not been quantified because of the lack of monitoring of in-stream water quality. Also, food industries produce large volumes of wastewater containing high levels of organic pollutants, which affect the aquatic ecosystem of the Medjerda River. Even though many industries have their proper wastewater pre-treatment plant, the lack of maintenance and experienced staff to run these plants means that they do not always operate effectively. An additional threat to the water quality of the river comes from the possible leaching of lead, zinc and other compounds from mine tailings at abandoned mining sites especially in the north-western part of the basin (Mlayah et al. 2009).

Accelerated soil erosion occurred during the last decade due to the increased frequency of flooding and led to siltation in the river. Economic impacts occurred because of losses in soil productivity due to decreases in fertile soil volume, losses of nutrients and organic matter, the need for greater quantities of fertilisers to make up for diminished soil fertility as well as the reduction in the life span of dams and reservoir capacities. Environmental impacts arise from the siltation and increased turbidity of waterways. Environmental impacts are not always restricted to those regions where erosion occurs; high levels of nutrients, associated with erosion of agricultural soils, may be transported to the mouth of the Medjerda River and contribute to coastal eutrophication and possibly hypoxic conditions.

4.7.3 Solutions and transferable lessons

In order to protect the limited resources in the Medjerda catchment, various Tunisian agencies are working together on an ambitious sustainability project. For this, an interdisciplinary framework was established covering environmental, socio-economical and institutional aspects.

Faced with ever-increasing challenges of water resource management in the country, a coherent national water policy is essential. In Tunisia, soils are under serious risk due to long dry periods followed by heavy bursts of intensive rainfall, falling on steep slopes with fragile soils and low vegetation cover. The dams in the Medjerda basin are threatened by siltation. Thus, a strategy for soil and water conservation measures is needed to identify hot spot and vulnerable areas to reduce sediment loads and their associated impacts. Also, for better water quality assessment in the Medjerda catchment, an innovative high resolution monitoring approach is recommended for the future.

Recently, action has been taken in Tunisia to increase public awareness for water resources management and environmental preservation. The association “Research in Action” (REACT) encourages sustainable development by encouraging an easier transfer of scientific results related to water resources management and environmental preservation to different target groups. REACT has aimed to raise awareness about water issues among the youth of the country through lectures, videos and events focused on sustainable water management, and games related to water sharing.

4.8 River Basin 7 – Elbe

The transboundary Elbe River basin is under pressure from point and diffuse sources that cause increased concentrations of nutrients and other water pollutants. Although nitrogen and phosphorus loads have been steadily decreasing, further measures are needed to achieve a range of environmental objectives. Catchment wide management options are planned in the Elbe River Basin Community, which is an association of ten German federal states.

4.8.1 Brief overview of Elbe characteristics and governance

The Elbe River has its source in Krkonoše Mountains in the Czech Republic and discharges after more than 1,000 km into the North Sea via an estuary that widens up to 15 km. Two-thirds of the catchment area of around 150,000 km² are part of Germany. One-third of the catchment is part of the Czech Republic. Minor areas belong to Austria and Poland. Main confluents are the Vltava in the Czech Republic and the Saale as well the Spree/Havel system in Germany (Figure 4.12). This case study will mainly focus on the water management issues in the German part of the catchment. Within Germany, ten federal states cover areas of between 0.9 per cent (Berlin) and 24.4 per cent (Brandenburg) of the catchment area.

The catchment is characterised by a transitional climate from the humid-oceanic climate of Western Europe to the dry-continental climate of Central and East Europe. Average annual rainfall varies from less than 500 mm in the regions of Thuringia and Saxony-Anhalt to 1,800 mm in the Harz Mountains. The catchment wide average rainfall is 628 mm, which is balanced by an average annual evaporation of 445 mm. Typically, the discharge into the Elbe River is high in late winter and spring due to snow storage and snow melt. However, infrequent flooding may also occur in summer. The average annual discharge at the German-Czech border is 311 m^3/s which increases at the catchment outlet to 861 m^3/s. Approximately 60 per cent of the German catchment is used for agriculture, nearly 30 per cent is forest land and less than 10 per cent is covered with settlements. The transboundary catchment has about 25 million inhabitants, 75 per cent of them live in the German part. In addition to Berlin and Hamburg, major cities are Leipzig and Dresden (Figure 4.12).

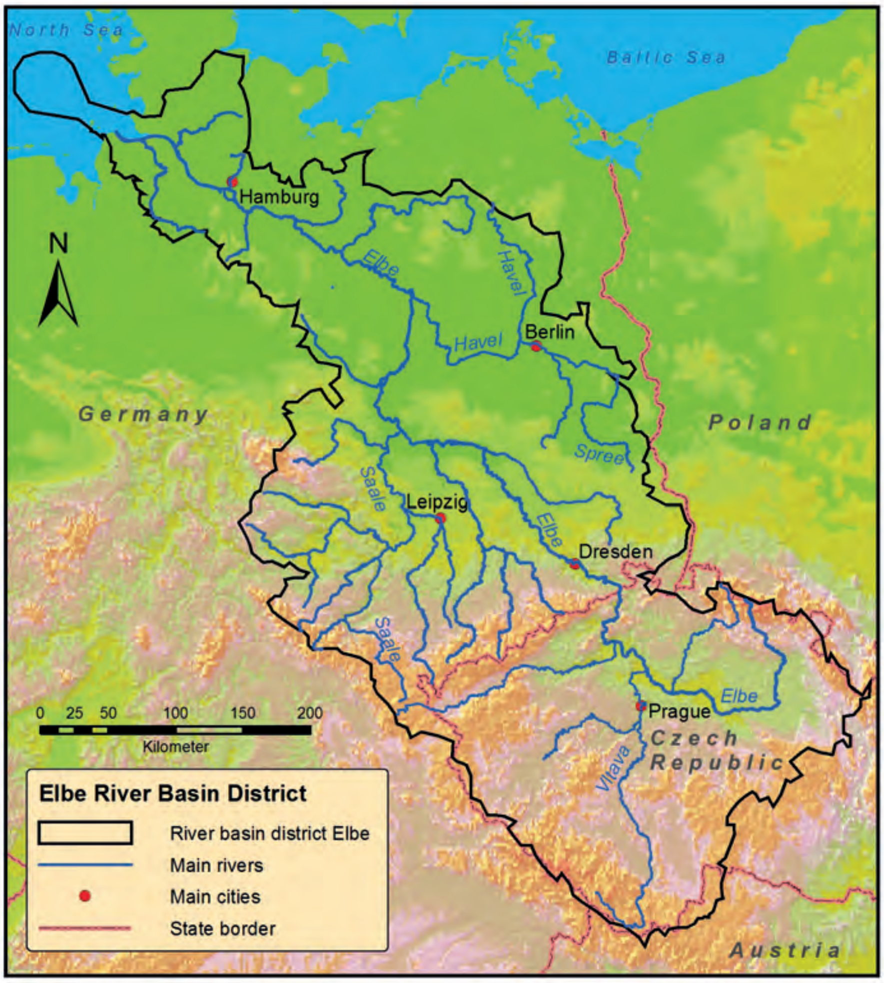


Figure 4.12: Topography of the Elbe River Basin, with its major cities, and the main tributaries of the river.

In 1990, an International Commission for the Protection of the Elbe River was founded. The main objectives of this transboundary organisation are to promote the fair use of river water, especially for municipal users via river bank water extraction and for agricultural water users, while maintaining the health of its aquatic and riparian ecosystems and healthy flora and fauna. The Commission also aims to develop a strategy to decrease the burden imposed on the North Sea ecosystem by the Elbe River basin (IKSE, 1990).

Germany, one of the main riparian nations of the Elbe, has established the Elbe River Basin Community for managing the part of the river basin that crosses German state borders. Members of the Community are the federal government and the ten federal states which share a part of the catchment. The Community mainly focuses on the implementation of the European Water Framework Directive (WFD) and the Floods Directive (FD) (FGG Elbe, 2009). With the exception of Berlin and Hamburg, water management administration in the German states is hierarchically structured on two or three levels. Generally, the supreme authority is a state ministry.

4.8.2 Typical water pollution problems, causes and impacts

In the German part of the Elbe River basin five important management issues are discussed from a catchment wide perspective

- Hydromorphological deterioration and longitudinal continuity
- Contamination with pollutants and nutrients
- Sustainable management of water quantity
- Local impact of mining activities
- Adaption to climate change.

Recent activities mainly focus on the enhancement of hydromorphological conditions and the improvement of fish migration as well as the reduction of contamination by pollutants and nutrients. The latter is also important because of side effects on coastal and marine water bodies. With respect to marine environment protection, a total nitrogen (TN) concentration limit of 2.8 mg/l has been defined for marine and coastal water bodies. This can be compared to a TN concentration of 3.4 mg/l averaged for the years 2009 to 2012 at the monitoring station

Seemannshöft which is located at the catchment outlet. The non-binding target value of total phosphorus (TP) concentration for this monitoring station is 0.1 mg/l, which is exceeded in samples by up to 100 per cent. Figure 4.13 illustrates the general downward trend of TN and TP over a longer period of time. The decrease of nutrient concentration values is typical also for the vast majority of monitoring stations in the German Elbe River basin, which shows a long term trend starting in the 1990s with an initially rapid decrease of nutrient concentrations. However, a slowing of the decreasing trend can be observed in recent years. And, compared to the average, the inter-annual variability is increasing. For TN, an influence of hydrological and meteorological conditions in the winter period is considered to be the main trigger for the observed variations. Also intensification of land use may have caused these changes. In 2013, 29 per cent of the groundwater bodies showed an unsatisfactory chemical status because of accelerated nutrient concentrations.

Measurements in coastal water bodies show that high nutrient concentrations cause chlorophyll concentrations that are up to 400 per cent beyond the target value. Also in the Elbe River and main tributaries, elevated concentrations of chlorophyll and corresponding oxygen concentration depressions are found. In the Elbe estuary, summer oxygen concentrations often are close to a critical value because of nutrient enrichment and eutrophication.

Pressures on single water bodies or on micro/mesoscale catchments can be reduced on the local level with consideration for specific management demands. However, the nutrient concentrations and loads in macro-scale catchments such as the Elbe River and the associated coastal and marine water bodies can only be reduced by coordinated measures to reduce emissions and to increase the retention of nutrients by all responsible upstream authorities. With the implementation of the WFD, the ten riparian states have set up an approach which combines measures for point sources, diffuse sources and nutrient retention. Additionally, synergies with measures to improve structures, e.g., of habitats, are expected. Major options to reduce the nutrient input from agricultural diffuse sources are i) amendment of the Fertilisation Ordinance (Düngeverordnung, DÜV), ii) improvement of crop rotation including intertillage and undersown crops, reduction in intensity of farming practices, iii) fertiliser management, iv) modification of land use including establishment of buffer strips or "living fences" v) tile drain management and vi) mentoring and transfer of knowledge. In detail, these measures are adapted to regional and local requirements. Point source management includes both the improvement of wastewater treatment efficiency, and the management of urban stormwater runoff.

The effect of the measures is estimated on the one hand by expert judgment and on the other hand by nutrient balance modelling and scenario calculations. The combination of these methods increases the reliability of assessments and planning. Nutrient balance modelling with MONERIS 3.0 has identified the main sources and pathways of nitrogen as: groundwater and interflow (40 per cent), tile drains (25 per cent) and waste water treatment (20 per cent). Tile drains are more important as pathways in the northern lowland part of the catchment and urban waste water prevails in cities e.g. of Berlin or Hamburg. For phosphorus, the main sources and pathways are: groundwater and interflow (20–25 per cent), waste water treatment (20–25 per cent), erosion (13 per cent) and tile drains (10 per cent). Erosion is more important in the southern part of the catchment due to its relief. By expert judgment, a significant reduction of nitrate input into surface and groundwater of 10-15 per cent in the German part of the catchment is expected because of the amendments of the Fertilisation Ordinance. Agri-environmental measures to control inputs from drains and improved efficiency in waste water treatment have a high potential for reduction of nitrogen loads. Wastewater treatment is also the main option for reducing phosphorus loads.

Strategies are also developed for the other above-mentioned important management issues that include a status description and options for measures. These strategies are the basis for public discussions. For example, a detailed plan was set up to improve fish migration in the main tributaries at 171 dams, locks and weirs up to 2021. A sediment management concept was compiled that sets up a framework for the evaluation and management of sediment and particle bound contaminants. Such contamination problems are often caused by emissions from contaminated sites but also by reworking of old sediment structures.

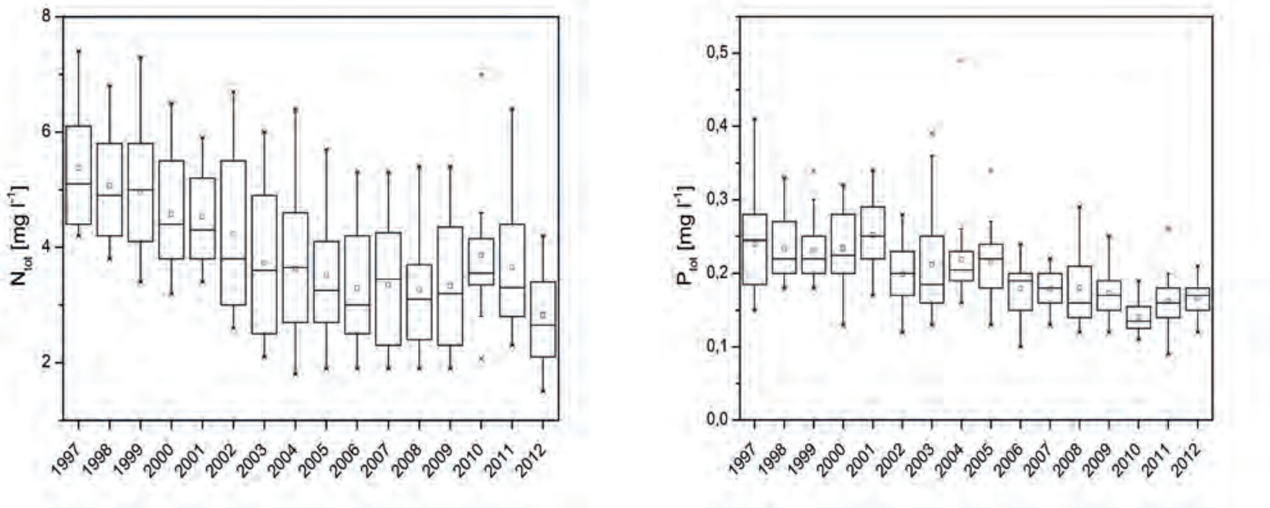


Figure 4.13: Long-term trends of nutrient (Ntot = total nitrogen TN, Ptot = total phosphorus TP) concentrations at the monitoring station Seemannshöft at the mouth of Elbe. Box-and-whisker plot: central bar =median; tops and bottoms of rectangles = 25th and 75th percentile; asterisks = minimum and maximum values.

4.8.3 Solutions and transferable lessons

The nutrient management problem under discussion is at the intersection of different stakeholders and drivers, i.e. agriculture, water pricing, water authorities, and nature conservation, to name but a few. However, the WFD, national laws and regulations, and other international conventions define the target frame. The consideration and acceptance of target values for nutrient reduction in coastal water bodies in inland states is an important step in the achievement of objectives. Modelling results support the identification of nutrient sources as well as pathways and a catchment-wide strategy that includes regional characteristics. Modelling also provides a basis for defining regional (inland) measures that focus on the effective reduction of nutrient input in coastal water bodies. Local pressures are also included at a small scale. On the negative side, modelling results are sometimes not accepted in public discussions about water pollution because models are difficult to understand, and because they sometimes lack adequate input data. The integration of expert knowledge in the discussions can partly compensate for these shortcomings.

After a period with a significant decrease in nutrient loads, the rate of decrease has diminished in recent years both for N and P, despite continuing mitigation measures. This may be caused by inertial effects after the initial strong reduction of nutrient loads, or because the measures are ineffective, or perhaps because the positive impact of the measures is being delayed for unknown reasons. The situation in the Elbe River basin is comparable to that of other rivers with high concentrations of pollutants despite control of pollutant loadings to the river (Dorioz and Tadonléké 2009).

The administrative structure of the Elbe River Basin Community, which coordinates the efforts of the federal states in the German part of the Elbe River catchment, established the basis for an integrated and coordinated plan of action. The Elbe River Basin Community works on the principles of voluntary and consensus decision making, and in this way reflects the federal structure of Germany. The joint identification of management problems at the catchment scale is the prerequisite for a common understanding and defining environmental targets and management options.

4.9 River Basin 8 – Hudson

The Hudson River basin is a typical example of a mixed-use watershed in the developed world. Historically, the trajectory of water quality issues has followed the transition from settlement, deforestation and resource extraction, through agricultural expansion, industrialisation, and urbanisation. Today, the dominant water quality issues reflect the local history of development and its regional variation.

4.9.1 Brief overview of Hudson Basin characteristics and governance

The Hudson River basin, including its major tributary, the Mohawk River, is situated primarily in New York State, with small portions lying in the neighbouring states of Connecticut, Massachusetts, New Jersey, and Vermont. There is a strong gradient of land use/land cover, with the northern Upper Hudson dominated by forest, the Central Hudson/Mohawk by forest, agricultural and suburban lands, and the southernmost portion being heavily urbanised. Two large park areas, the Adirondack Park in the north and the Catskill Forest Preserve in the southwest, help protect a significant portion of the watershed from development and associated potential water quality impacts. The New York City water supply system provides drinking water for the New York City metropolitan area and other towns in the region, but its catchment (within the Hudson and Delaware basins) is protected from excessive development.

Pollution: From the 1800s to the 1960s, the Hudson River was grossly polluted by effluent from river cities and industry, but with programs such as the Pure Waters Bond Act in 1965 and passage of the Clean Water Act in 1972, funding became available for improved sewage treatment, ultimately resulting in the return of sensitive indicator species in the 1990s. Today, while phosphorus loading has diminished largely due to the removal of phosphorus from detergents, the Hudson still remains the most heavily loaded US estuary in terms of nitrogen, the source of which varies from the forested north (atmospheric deposition), through the agricultural centre (farm runoff) to the urban south (wastewater discharge).

Hudson River Facts

- *Hudson/Mohawk basin area: 34,680 km^2;*
- *Hudson River length: 507 km from its primary source in Lake Tear of the Clouds to the tip of Manhattan Island;*
- *Average precipitation: 1000–1275 mm/yr over a significant north/south gradient;*
- *Major regional water supply system: the NYC reservoir system (17 reservoirs, with watersheds straddling the Hudson and Delaware basins) supplies NY City and other cities of the region, and represents an interbasin transfer of water;*
- *Canal system: the New York State barge canal system connects the river to the Great Lakes and Lake Champlain, providing an opportunity for invasive aquatic species.*

Invasives: The Hudson River exchanges biota with neighbouring basins through canals and aqueducts. Among these biota, Eurasian water chestnut (Trapa natans) and water milfoil (Myriophyllum spicatum) became established and invasive. In particular, thick water chestnut beds choke backwaters and embayments. In 1991, zebra mussel (Dreissena polymorpha), which had invaded the Great Lakes in the 1980s via ship ballast, was discovered in the Hudson River, most likely transported on boats. By 1992, zebra mussels represented > 50 per cent of the heterotrophic biomass (Strayer et al. 2014).

Climate change: Effects are already evident in the Hudson River watershed: sea level has risen ~30 cm since 1940, freshwater discharges have increased, and temperatures have been rising since 1930 (Strayer et al. 2014). Although phenological responses in organisms have been moderate, timing/duration of spawning runs of anadromous (sea-run) fishes has been changing, moving toward earlier runs that may not match up well with in-river primary and secondary production. Regional climate projections indicate more concentrated precipitation events, including major storms which result in severe flooding as in 2011 Hurricane Irene and Tropical Storm Lee and in 2012 Hurricane Sandy.

There is no single governance system for the watershed; a number of different agencies and programs from federal to local hold responsibility for water quality regulation. The Hudson River Estuary Program (HREP), funded by New York State and managed by the state's Department of Environmental Conservation (DEC), has a watershed management programme in place to help mitigate impacts from urbanisation, development,

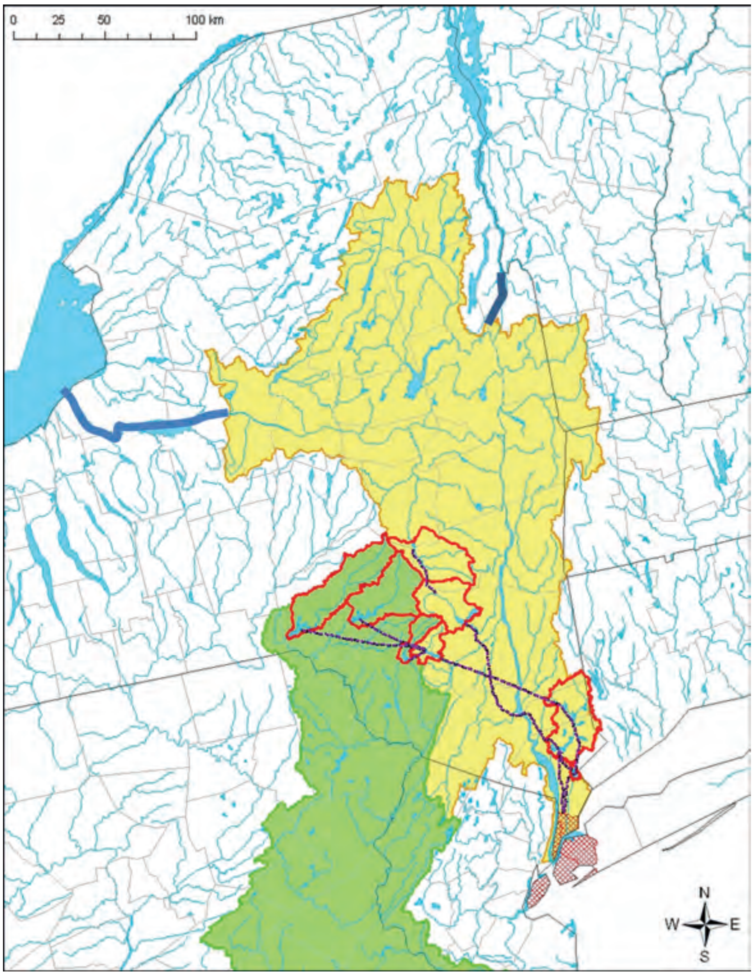


Figure 4.13: Regional map showing the Hudson River watershed (yellow) and other major features of the region including the Delaware watershed (green), the five boroughs (counties) comprising New York city (hatched), the New York City water supply watersheds (red outline) and aqueduct/ tunnel system (purple). Counties of New York and surrounding states are outlined in grey. Inter-basin transfers occur through the Champlain and Erie Barge canals (dark blue).

agriculture, and climate change. The Estuary Program has an active stakeholder advisory board that helps to guide action plans. The New York City Department of Environmental Protection (DEP), a city-level agency, is responsible for monitoring and securing the integrity of the City's water supply system, including its watershed, and its sewage and waste treatment system. As most of the City's sewage is treated and discharged to the Hudson and other waters around Manhattan, the DEP also monitors water quality in the harbour and nearby waters. Non-governmental organisations also play a significant role in monitoring water quality and pollution.

4.9.2 PCBs: causes and impacts

In addition to the above concerns, the largest single toxic contaminant issue in the freshwater portion of the Hudson is that of polychlorinated biphenyls (PCBs). From 1946–1977, the General Electric Corporation (GE) discharged hundreds of tons of Arochlor, a mixture of PCB congeners used in manufacturing electrical capacitors. Although a portion of the discharged PCB mass was removed during maintenance dredging, volatilised off, or transported by the river downstream to the Atlantic, significant portions remained in floodplain soils and river sediment, becoming bio-available and taken up in terrestrial, riverine and estuarine food chains. In 1976, New York State banned all fishing from the source region to the Federal Dam at Troy, NY, and closed commercial fisheries for striped bass in the 250 km of tidal estuary downstream of Troy. Eight years of study later, the US Environmental Protection Agency (EPA) designated the entire stretch from Hudson Falls (320 km from the mouth) to New York Harbor as a Superfund site. Despite that, the complexity of the problem, compounded by a bitter battle between GE and the EPA, led to inaction for decades. In the meantime, a consortium of academics and state agencies monitored the ecosystem, documenting the bioaccumulation of persistent congeners and impacts on fish and wildlife.

The primary impacts of the PCBs in the Hudson River were unacceptable risks to human health and the environment. Since the loadings have stopped, there has been a very slow process of natural recovery of the river ecosystem. Concentrations of PCBs in sport fish and in fish commonly taken by the commercial fishery exceeded both the tolerances set by the United States Food and Drug Administration (FDA) and the concentrations used by the New York State Department of Health (DOH) in advising the public on consumption of wildlife. As a result, the State of New York banned the taking of fish from the 70 km reach between Hudson Falls and the estuary (referred to in project documents as the “upper Hudson”), closed the commercial fishery, and issued an “eat none” advisory for the entire Hudson River from Hudson Falls downstream to the mouth of the river at the Battery in New York.

Following a halt in discharges in 1977, PCBs in water and fish dropped fairly quickly, but levels stabilised in many species by the mid-1980s, particularly in the upper Hudson. PCB concentrations in most species remained well above the FDA tolerance and/or the DOH consumption advisory guidelines. At the request of the DEC in 1989, EPA began a major reassessment of conditions in the Hudson related to GE’s PCB discharges, including extensive monitoring of PCBs in the water column at different flows and times of the year, sampling of known PCB “hot spots” (areas mapped by DEC as containing deposits of concentrated sediment-bound PCBs in discrete locations) to look at changes over time, and annual monitoring of fish at various trophic levels in several locations river wide. EPA also developed a set of predictive tools to inform decisions about various remedial alternatives and conducted quantitative human health and environmental risk assessments. Human health risks identified included both excess cancer risk and risk of non-cancer health hazards associated with consumption of contaminated fish. Ecological risks identified by EPA included population-level effects on piscivorous wildlife, including bald eagle, belted kingfisher, great blue heron, mink, and river otter. Piscivorous mammals were at greatest risk.

EPA’s assessment of river conditions in their 2001 Record of Decision (U.S. EPA, 2001) concluded that trends in PCB concentrations in the water column and fish tissue showed a levelling off with little if any reduction in the last decade. In the Record of Decision, EPA, following the process set in the Federal “Superfund” law, ruled that GE should conduct targeted environmental dredging to remove the highly contaminated sediments from the upper Hudson between the discharge points (in Fort Edward and Hudson Falls) and the Mohawk River confluence at the head of the estuary. This dredging and removal began in 2009 and was completed in 2015.

While EPA was assessing what was necessary to support development of the remedial dredging program, the State of New York, the US Department of the Interior (DOI) and the National Oceanographic and Atmospheric Administration (NOAA), acting as Trustees of natural resources, conducted assessments of potential injuries to a variety of these natural resources. These assessments include measuring impacts of PCBs in the Hudson River ecosystem on American mink (severe reproductive impairment), birds such as tree swallows (growth and development; nesting behaviour), and shortnose and Atlantic sturgeon (survival; growth and development). This assessment work is ongoing

4.9.3 Solution(s) and transferable lessons

EPA’s selection of targeted environmental dredging was intended to accelerate the natural recovery rate of the river ecosystem. EPA concluded in the Record of Decision that two active remedial approaches would be necessary to promote this: control of ongoing sources and removal of the most highly contaminated portions of the river bottom (including the “hot spots”) which acted as ongoing sources to the rest of the river system. Source control at the two capacitor plant sites was achieved before the start of the dredging project in 2009 through implementing a series of remedial actions by GE under State regulatory authority. Actions undertaken at these sites included removal of contaminated sediments near major wastewater outfalls at the sites and groundwater and PCB oil recovery programs designed to limit offsite contaminant migration to the river.

The most significant problems to address in the river were risks to people who consume fish and piscivorous wildlife. To reduce these risks, the PCB body burdens of Hudson River fishes needed to be reduced. Through geochemical evaluations and modelling, EPA determined that fish received their PCB body burdens from both the water column and the food web, from PCBs in surficial and near-surface sediments. To address these pathways, EPA decided to remove the most highly contaminated sediments from areas where significant PCB mass was present and potentially bioavailable or where significantly elevated PCB concentrations occurred at or near the sediment surface. PCB congeners containing three or more chlorines ("tri plus PCBs") were targeted due to their greater propensity for bioaccumulation, environmental persistence, and potential impacts on human health and ecological risk.

Removing targeted sediments and controlling remaining upstream sources of PCB at GE capacitor plants in Hudson Falls and Fort Edward is expected to reduce PCB concentrations in surficial sediments and thus reduce PCB body burden in fish, ultimately decreasing human health risks posed by consuming contaminated fish and ecological risks posed by fish consumption by wildlife. (The routes of exposure to humans and wildlife via floodplain soils will not be abated by the river bottom sediment remediation. To address the ecological and human health risks posed by disposal of PCBs to the Hudson River, a robust investigatory and remedial program, potentially approaching the scale of the sediment remedy, may be required.)

To determine specifically where to remove contaminated sediment, a sediment sampling and analysis programme was undertaken. After using side-scan sonar to map the river bottom by surficial sediment type, a core sampling programme of approximately 8,000 cores, on a triangular grid of 24 m spacing, was undertaken to map the distribution of PCBs in river sediments.

EPA also set three primary "performance standards", for resuspension (impacts on the water column caused by contaminant release during dredging), residuals (the ability of the contractor to meet the project cleanup concentration where dredging was done) and productivity (the rate of sediment removal on a monthly and annual basis). The resuspension standard was set at the drinking water standard for total PCBs of 500 ng/l (http://www.epa.gov/safewater/pdfs/factsheets/soc/tech/pcbs.pdf). The residuals standard was set at 1.5 mg/kg tri plus PCBs.

Once GE's project design team completed the process of delineating the sediments to be removed, and the necessary infrastructure was developed for the project (sediment dewatering and transfer facility, work marinas), the contractor hired by GE performed the first year of sediment removal. This first year ("Phase 1") was planned to be an opportunity for both EPA and GE to better understand project operations in the context of meeting the three performance standards and also in improving the quality of project operations.

Difficulties encountered during Phase 1 included resuspension of PCBs due to several technical issues (e.g. need for repeated dredge passes to meet the residuals standard, inefficiencies in loading/unloading of scows causing delays, presence of debris preventing bucket closures, etc.) and underestimating the areas required to be capped due to underestimation of contaminant depth. After the first year of dredging, a peer-review panel of national experts in remedial dredging was convened to evaluate the project and provide recommendations on project revisions, including revisions to the three performance standards.

During Phase 2, the project has been successful in meeting resuspension standards; the drinking water standard has been consistently met downstream of dredging operations, and the rate of PCB losses has been < 1 per cent of the PCB mass dredged. Sediment removal has significantly increased, with the annual production rate exceeding goals in every year of Phase 2 until 2015. The capping rate has also been low, with less than 8 per cent of dredged areas being capped due to inability to meet the residuals standard.

The primary lesson learned from the dredging programme in the upper Hudson is that a large remedial dredging project can be successfully performed with low resuspension losses, even without controls such as silt curtains or sheet piles, assuming accurate characterisation of site conditions (especially depth of contamination), a sufficiently conservative design approach in setting depth of cut which limits the need for multiple dredging attempts, and properly operated dredge equipment, selected to match site conditions.

4.10 General conclusions from the case studies

Common problems occur around the world

The analysis in Chapter 3 identified the scale of water quality challenges in Latin America, Africa, and Asia from a "top down" perspective. In this chapter, water quality situations were reviewed in eight case studies of river basins from around the world that illustrated in a practical way the realities of these challenges.

The global analysis in Chapter 3 identified that about one-third of all river stretches in Latin America, Africa, and Asia have severe pathogenic pollution. Two rivers in two different locations in the world – the ***Volta*** in West Africa and the ***Chao Phraya*** in Thailand – are different in character, but both have high levels of pathogen pollution linked to the occurrence of waterborne diseases.

About one-seventh of all river stretches on the three continents were identified to have severe organic pollution. The ***Upper Tietê*** River in Brazil and the ***Godavari*** River in India are both affected by organic pollution with high BOD loadings, high BOD river concentrations, and frequent episodes of very low dissolved oxygen. Large stretches of both rivers have few fish and very low diversity.

Tens of thousands of river kilometres on each of the three continents have severe levels of salinity pollution. The ***Vaal*** River in South Africa and the ***Medjerda*** River in Tunisia are both examples for severe salinity pollution. High levels of salinity impede the use of the river for water supply, irrigation water and industrial use.

The ***Elbe*** is an example of a river that has overcome its earlier problems with pathogen and organic pollution but now confronts another type of water quality challenge – high loads of nutrients that lead to eutrophication in its estuary reaches. The ***Hudson*** has also mastered its earlier problems with pathogen and organic pollution while continuing to have high nitrogen loads, but now suffers from the legacy of toxic pollution related to sediment deposits of PCB which have found their way into the aquatic food web.

As can be seen from these examples, similar water quality challenges are occurring around the world even if the locations and situations are very different. Developing countries are experiencing problems that developed countries have overcome, but new problems also persist in developed countries. It is clear that major efforts are needed to achieve sufficient water quality and the ecosystem services it provides.

Similar problems can have different immediate causes

While above it was shown that similar water quality problems occur at very different places around the world, the case studies also showed that similar problems can sometimes have different immediate causes:

- A principal cause of the pathogen pollution in the ***Chao Phraya*** River is the discharge of domestic wastewater from sewers, whereas in the ***Volta*** basin, the main source is not sewers but runoff from inadequate sanitation facilities.
- The salinity pollution in the ***Medjerda*** River is caused largely by return flows from irrigation whereas in the ***Vaal*** River it is mainly from wastewater from industrial sources and runoff from mining activity.

A range of underlying drivers, some common, some specific

The case studies also illustrated that the immediate causes of water quality degradation, such as untreated wastewater discharges, are in turn driven by many different underlying factors, which may vary from river basin to river basin:

- Important underlying drivers of the water pollution of the ***Upper Tietê***, ***Godavari***, and ***Chao Phraya,*** are urbanisation and economic activity which lead to discharges of concentrated, untreated wastewater.
- For the ***Vaal***, the main driver is also economic activity, especially industrial production. As noted above, this leads to the discharge of untreated wastewater and runoff from mining activities.
- For the ***Volta***, the drivers are population growth and inadequate sanitation facilities. At the onset of the rainy season, there is a large wash-off of pollution from inadequate sanitation facilities from the land into the river.
- The water pollution of the ***Medjerda*** and the ***Elbe*** share a common driver: the demand for food. This demand stimulates the irrigation of cropland in the Medjerda basin and this in turn leads to irrigation return flows to the river containing salts

and nutrients. In the Elbe basin, food demand is satisfied mostly by rainfed crops, which are applied with excess amounts of fertilisers, some of which are washed off into the Elbe river.

- For the ***Hudson*** River, the driver of its current PCB pollution has been the demand for industrial products, which may contain dangerous materials that are unsafely disposed of. Another driver of water quality changes in the Hudson River is climate change, which has raised the level of the sea at the river's mouth, increased freshwater runoff, and raised river temperatures, all with potential ecological consequences.

Coping with the water quality challenge

Finally, many valuable lessons about how to cope with the water quality challenge can be derived from the case studies:

- As seen in the ***Godavari***, it is important to avoid fragmentation of authority as this affects the management of river water quality.
- As seen in the ***Elbe*** and ***Volta,*** consolidating authority in an overarching international "commission" can provide an indispensable instrument to deal with international aspects of water quality management. In the case of the Elbe, it was also shown that a wide-reaching national institution (the Elbe River Basin Community) can also provide a valuable platform for gaining the cooperation of all critical actors within a river basin.
- As seen in the ***Medjerda*** and the ***Elbe***, in order to manage water quality, it is essential, under some circumstances, to first manage the *land*. In the case of the Medjerda, management of run-off from agriculture is key to reducing salinity loadings to the river. In the case of the Elbe, an ambitious basin-wide programme is successfully intervening in agriculture in the basin to reduce nutrient wash-off from agricultural land.
- In cases where water quality problems are worsening, sometimes a first important step is to educate the public about the situation. This was the successful approach used in the ***Medjerda*** and ***Upper Tietê*** basins.
- Another effective tool to promote water quality management are basin-wide action plans and targets as in the case of the cleanup programme of the ***Upper Tietê***, the Resource Quality Objectives used in the ***Vaal*** basin, and the water quality master plans developed for the ***Chao Phraya*** basin.
- The ***Volta*** basin also shows that actions to control water pollution require the strengthening of the technical capacity for water quality management in the basin.

The case studies also show that the challenge of protecting water quality is closely link with other important goals of society – providing food, developing the economy, providing safe sanitation. Therefore, over the coming years it will be very important to link goals for water quality with other goals of the Post 2015 Agenda and the new Sustainable Development Goals. This topic is taken up again in Chapter 5.

5 Solutions to the Water Quality Challenge: A Preliminary Review

Aim of this chapter

- To review technical and management options available as solutions to the global water quality challenge.
- To give examples about the practical implementation of solutions.

Main messages

- There are many options available to developing countries for avoiding the water quality deterioration of their rivers and lakes. Among the main technical options are: (i) pollution prevention, (ii) treatment of polluted water, (iii) the safe use of wastewater and (iv) the restoration and protection of ecosystems.
- Apart from established strategies, there are innovative new ideas which were not available or used by developed countries when confronted with similarly deteriorating water quality decades ago. Examples are: pollution prevention in industry, constructed wetlands, and conservation and maintenance of forested headwaters.
- A "one size fits all" option will not work to solve the global water quality challenge. Instead, regionally adapted clusters of measures will be needed to control the diverse types of water pollution and sources of pollution. Some of these packages might be applicable to many different river basins.

Previous chapters have shown that water pollution is prevalent and increasing in rivers in many countries in Latin America, Africa, and Asia. The situation is not completely different from what prevailed several decades ago in North America and Europe when increasing population and economic activity propelled a substantial increase in water pollution. At that time, the accent was on economic development at the expense of environmental quality. After several decades, the intensity of water pollution peaked, and developed countries managed to substantially scale-down the levels of organic pollution, nutrient loading and pathogen contamination in their rivers and lakes (as indicated by sinking river concentrations of BOD, phosphorus, and faecal coliform bacteria) (EEA, 2014; Hogan, 2014; OECD, 2008). Although some types of water pollution persist in developed countries (see Chapters 1 and 4), the water quality of many of their freshwater ecosystems has improved significantly.

Now, as noted above, several countries in Latin America, Africa and Asia are following a similar trend. Yet the majority of river stretches on these continents are still in good condition and countries still have the chance to avoid further pollution and restore already-polluted rivers. The case studies in Chapter 4 give some examples about how this can be put into practice through various management approaches and technical options (Table 5.1). As we see later, these are only a subset of many other technical options available to countries for reducing water pollution. (Many case studies in Chapter 4 mention monitoring as part of solving their pollution problems. Although monitoring is not a technical option in the sense of Tables 5.1 and 5.2 in this chapter, it is a very important step in tackling pollution control, as emphasized in Chapter 2.)

Table 5.1: Technical options mentioned for the specific water quality issues in the case studies (Chapter 4).

River Basin	Upper Tietê	Godavari	Volta	Chao Phraya	Vaal	Medjerda	Elbe	Hudson
Type of pollution	Organic pollution	Organic pollution	Pathogen pollution	Pathogen pollution	Salinity	Erosion, salinity, nutrients	Eutrophi-cation	Organic chemical pollution
Technical options employed								
Pollution prevention							X	X
Treatment of wastewater treatment	X		X	X	X	X		
Safe reuse of wastewater			X				X	X
Protection & restoration of ecosystems				X	X		X	X

Among the most established options is to lay out a network of sewers for collecting wastewater from different sources and delivering the wastewater to a conventional wastewater treatment facility, as developed countries began to do decades ago. This has only been a partly successful strategy in developing countries because of the high energy costs of conventional treatment facilities, the lack of technical capacity to run these plants, and other drawbacks. Moreover, pollutants from diffuse sources such as urban surface runoff and irrigation return flows are difficult to collect and treat, both in developing and developed countries. In other cases, specific types of pollutants, e.g. pharmaceutical residuals and some trace metals, are not effectively removed by conventional treatment. Despite all these drawbacks, gravity driven sewerage and conventional wastewater treatment is often still a favourable option for bringing a water pollution problem under control.

New options have arisen over the last few decades and are worth considering. They complement (rather than replace) conventional wastewater treatment. If wastewater treatment is included, the major options now available for reducing water pollution loads are:

- Pollution prevention
- Wastewater treatment (conventional and unconventional)
- The safe reuse of wastewater
- Ecosystem protection and rehabilitation

Section 5.1 briefly reviews the specific measures that fall under these major categories and how these measures can be used to reduce sources of water pollution. An overview of these measures and how they apply to the different types of water pollution sources is given in Table 5.2. The options are diverse and their feasibility depends on the type, intensity, and quantity of specific water pollutants as well as many other technical factors, which are discussed in the text.

But selecting the right technical option is only one aspect of water pollution control. It is also important to develop effective management and governance strategies. Some of these aspects are discussed in Section 5.2.

Table 5.2: Selected technical options relevant for different sources of pollution. Technical options marked with "+" are relevant to reducing the indicated source of pollution. This is not an exhaustive list of options.

	Source of pollution				
Technical option	Domestic sewered	Domestic non-sewered	Urban surface runoff	Industry	Agriculture and sediment pollution
1. Pollution prevention					
Increasing water use efficiency	+	+		+	+
Reduction of wastes produced	+	+		+	+
Urban green infrastructures			+		+
2. Treatment of wastewater					
Mechanical/primary treatment	+		+		
Biological/secondary treatment	+			+	
Chemical/tertiary treatment	+			+	
Advanced treatment	+			+	
Constructed wetlands & natural treatment systems	+		+		+
3. Safe reuse of wastewater					
Use of stormwater			+		
Reuse of domestic wastewater and sludge	+				
Household greywater recycling systems	+				
Reuse of wastewater in industries				+	
4. Protection and restoration of ecosystems					
Forest conservation / reforestation of river basins			+		+
Using natural wetlands for treatment of wastes	+		+		+
River dilution	+	+	+	+	+
Flow regime restoration	+	+	+	+	+
Targeted environmental dredging				+	+

5.1 Technical Options

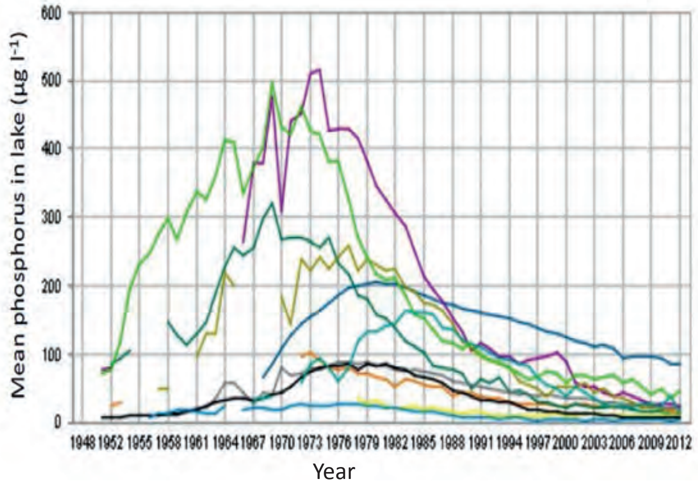
5.1.1 Pollution prevention

"Pollution prevention", or "source control of pollutants", is the banning, avoidance, reduction, or elimination of a contamination at the source. In many circumstances, pollution prevention has been shown to be as effective as conventional wastewater treatment in reducing water pollution loadings.

Best practice example

'Source control of phosphorus'

Prior to 1980, polyphosphates were used in detergents in large quantities because of their ability to bind calcium and magnesium ions and thus soften water. The phosphorus loading of many lakes and rivers, especially in OECD countries, increased dramatically with increasing detergent use after World War II. As a response, the use of phosphate in detergents was regulated in Central Europe beginning in the late 1970s. Consequently, phosphates were replaced by other water-compatible chemicals such as sodium aluminium silicate, and average phosphorus concentrations in wastewater were halved. This action, along with the upgrading of wastewater treatment plants, led to a decline in the phosphorus loading of many Central European lakes to their pre-1950 levels.



Trend of mean phosphorus concentrations in 11 alpine lakes from 1940 through 2012. Data from EEA (2015).

Pollution prevention is achieved in various ways, as explained in the following paragraphs.

Increasing water use efficiency

One way to prevent water pollution is to use water as efficiently as possible so that less wastewater is produced.

- *Households.* Water use can be made more efficient in the household by fixing leaky taps and toilets, using water saving devices in toilet cisterns, taking showers rather than baths, and using water-saving washing machines and dishwashers.
- *Manufacturing and industries.* Measures here include the introduction of water efficient production processes, water recycling and wastewater reuse.
- *Agriculture.* This includes water efficient irrigation, and tailwater return systems.

Reduction of wastes produced

Another pollution prevention strategy is to reduce the amount of wastes produced and thereby reduce the amount of wastes in wastewater. (See box "Best practice example 'Source control of phosphorus'").

- *Households.* One option here is to use compost toilets which do not require water and produce compost (such as the Ecosan systems). Another option is to employ a greywater system which recycles household water used for washing purposes. Technically speaking, it is more practical to include these systems in new buildings than retrofit them into existing buildings. There are many other alternatives, which differ in sophistication and costs. Some options are very feasible and affordable for low income households.
- *Manufacturing and industries.* This includes "Green chemistry" which aims to avoid the release of hazardous substances into the water cycle. One example here is to add equipment at an industrial facility to reduce or recover waste. Another is to modify the production of chemicals so that less waste is produced.
- *Agriculture.* The main options here are nutrient and pesticide management which include minimising fertilizer and pesticide surpluses, changing crop rotation, and reducing surface run-off through tile-drain management.

Urban green infrastructures

Controlling stormwater runoff from city surfaces is an old problem, but new ways are being developed to deal with it. Traditionally, stormwater runoff is collected in large conduits and either delivered to a treatment plant or discharged directly to surface waters. An alternative approach, which is increasing in popularity, is "rainwater harvesting" through which water is stored on the urban landscape in natural depressions or in artificial cisterns and then sometimes used for watering parks and for other non-potable purposes.

Constructing "green roofs" made up of plants that absorb and retain rainwater has become a simple and popular way of lessening the immediate runoff of stormwater. In addition, green roofs make houses cooler in the summer and warmer in the winter and the roofs act as small habitats for a wide range of flora and fauna.

Urban "green infrastructures" also include pavement that enhances stormwater infiltration, and structures that reduce the infiltration of storm runoff into sewers.

5.1.2 Treatment of wastewater

A wide range of different options are available for conventional and non-conventional treatment. Some are single-stage systems; others, such as mechanical-biological-chemical treatment, are a combination of different stages. Some include tailor-made pre-treatment systems. (See box "Fuheis demonstration site as best practice example of 'Treatment of polluted water'").

Fuheis demonstration site as best practice example of **'Treatment of polluted water'**

As part of the project IWRM-SMART (Sustainable Management of Available Water Resources with Innovative Technologies), the Fuheis demonstration site near Amman (Jordan) started operation in the autumn of 2009. Different technologies are operated at the site, including sequencing batch reactors, extended aeration systems, constructed wetlands, a sludge humification system and a sludge screening and anaerobic stabilization reactor. The facilities are used for identifying the combinations of technology that can successfully treat different wastewaters. The facilities are also used for the training of technicians, and to inform managers and decision makers about technical options for dealing with water pollution.

Source: Manfred van Afferden (UFZ)

Mechanical/primary treatment

Primary treatment is used to remove larger particles and some of the finer particles as well, depending on the set-up of the system. The key function of a mechanical system is to settle out particles in the wastewater by gravity. As a stand-alone solution it must be considered outdated but in combination with more advanced treatment it is still very useful. This is because pre-removal of larger particles makes the next steps in the treatment process much more efficient. On average, well run mechanical treatment systems may reduce the amount of organic matter by 30–50 per cent, and nutrients by 10–20 per cent.

Biological/secondary treatment

This type of treatment involves the decomposition of wastes by a wide variety of microorganisms. Secondary treatment helps in removing most of the organic matter and only part of the nutrient load. Hence the effluent from this stage of treatment often still contains substantial amounts of nutrients and other chemicals which require further treatment to be removed. However, the microbiological processes in this stage of treatment can be optimized to boost the removal of nitrogen compounds such as nitrate and ammonia, but only if the processes are controlled correctly, e.g. with alternating periods or zones of high and low oxygen concentrations. One consequence of secondary treatment is that it produces a large amount of sludge which must be disposed of safely.

Chemical/tertiary treatment

This treatment stage typically includes the use of specific additives, such as iron-sulphate, to remove phosphorus and other chemicals. Precipitation of heavy metals is a common method to take the metals out of the water phase and into the sludge phase. Since tertiary treatment targets substances that are not removed by more affordable primary and secondary treatment, it tends to be the most expensive stage of treatment.

Advanced treatment

Research is constantly advancing the state of wastewater treatment. For example, conventional treatment systems require large amounts of land which may not be available in cities; this lack of land has stimulated the development of very compact systems for specific types of wastewater. The principles used in these new types of technology are based on well-known but optimised mechanical/biological methods. Typical clients for new treatment methods are hospitals, industries, and cruise ships. A limitation of such systems is that they are adapted to a particular kind of wastewater having a narrow range of characteristics. Wastewater outside this range could destroy the microorganisms that play an essential role in the treatment system.

Some advanced treatment facilities recover methane, a useful fuel, from the gasification of sludge and other treatment processes. Often this fuel is used for the internal fuel needs of the treatment facility. Some advanced treatment produce an excess of fuel which is sold or utilised in other public facilities.

Constructed wetlands and natural treatment systems

"Constructed wetlands", usually consisting of reeds, are fabricated to mimic the purifying capacity of natural wetlands. Before passing through the wetland, wastewater is usually pre-treated to remove sand and grit. Well-dimensioned and -maintained wetlands can provide the same pollutant removal rates as traditional mechanical/biological treatment systems. Constructed wetlands are mainly used for treating domestic wastewater low in chemicals because a high concentration of chemicals can destroy the biological processes of the wetland. They are particularly suited for rural areas land is available for the wetland. One drawback of constructed wetlands is that they store large quantities of phosphorus, organic material, and heavy metals in their soils and sediments, and this necessitates a periodic renewal of the treatment system.

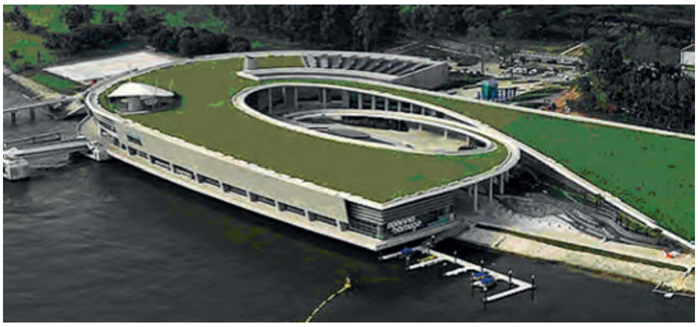
5.1.3 Safe reuse of wastewater

Use of stormwater

There are a number of ways in which the harvesting and subsequent use of stormwater helps to reduce water pollution. First it prevents polluted stormwater runoff from directly entering surface waters. Second, it helps reduce the frequency of stormwater overflows from sewer systems. Third, it replaces some water withdrawals from surface waters and therefore helps maintain more consistent flows in the river system. (See box "Singapore as a best practice example on 'Safe reuse of wastewater'")

Singapore as a best practice example on
'Safe reuse of wastewater'

No other city in the world is harvesting stormwater at the scale of Singapore. As a small island lacking natural aquifers and lakes, and with little land to collect rainwater, the city needs to maximize what it can harvest. With a network of drains, canals and 17 reservoirs of various sizes, two-thirds of the Singapore land area has been turned into a giant water cistern. The harvested water is used for recreational purposes and many other uses.



Source: http://www.anmc21.org/english/bestpractice/images/img/env_wat02_2.jpg

Reuse of domestic wastewater and sludge

The reuse of wastewater, excreta and greywater for irrigating or fertilising crops is widespread and can reduce or avoid water pollution by preventing these substances from directly entering surface waters. But for reuse to be successful it must be carried out in a safe and socially acceptable way, and this depends on how the wastewater and waste is managed and on various ethical, cultural and educational factors. The main task for managers is to ensure that wastewater, and its by-products such as composts and sewage sludge, are treated to a hygienically safe state before further use. Treatment options include long term storage, exposure to very high temperatures, and exposure to UV light.

Another safe way to reuse wastewater from the domestic sector is to use it for cooling or other purposes in closed production cycles in the industrial sector; this minimizes the risk that people will be exposed to unsafe substances or organisms in the wastewater. Depending on the type of wastewater, it may also be safe to use it for watering ornamental plants and fruit-growing bushes and trees, although not for irrigating food crops such as leafy vegetables and root plants.

A continuing problem is that not all dangerous chemical substances in wastewater are removed by conventional treatment. Therefore, the reuse of treated wastewater and sewage sludge may inadvertently convey dangerous substances to soils and groundwater. One solution is for these substances to be removed at the source, through "pollution prevention" actions as described above, before they enter the wastewater stream.

Most treatment systems produce sludge which has to be managed carefully to avoid public health hazards. One safe option is to use sludge as the feedstock for a biogas generator which produces methane-rich gases that can be used for heating, cooking, and other energy uses. The stabilized sludge can afterwards be used as a fertiliser or soil amendment once it is confirmed to be free of dangerous substances. (See box "Best practice example on 'Anaerobic Digestion System (ADS) biogas systems' in Ghana."). As with treated wastewater, a good way to ensure that sludge is free of dangerous chemical substances is to remove these substances at the source through "pollution prevention".

Best practice example on
'**Anaerobic Digestion System (ADS) biogas systems' in Ghana**

Biogas Technologies Africa Limited (BTAL), located near Accra (Ghana), is providing low tech, innovative solutions to convert faecal matter, biodegradable healthcare waste and solid waste into biogas energy and nitrogen-rich plant fertiliser. Numerous institutions, including hospitals, hotels, educational centres, and food processing industries as well as private homes, have benefited from the low cost and low land requirements of the biogas plants. These plants can also be used in areas with unreliable or limited water supply and do not require electricity to operate. With support from UN-Habitat, UNIDO, and UNEP, BTAL is carrying out similar projects in Senegal, Nigeria, Uganda, Mozambique, Tanzania, South Africa, and Kenya.

Source: John Idan

Household greywater recycling systems

Systems for treating and reusing greywater have become relatively common worldwide (Al-Zu'bi et al. 2015, Ghrair et al. 2015, de Gois et al. 2015, Lam et al. 2015). By definition, "greywater" is wastewater from baths, showers, washing machines, dishwashers, and kitchen sinks; "blackwater" is water from toilets (Birks & Hills 2007). Certain studies further divide greywater into "light greywater" (wastewater from bathrooms, showers, and baths) and "dark greywater" (wastewater from washing machines, dishwashers, and kitchen sinks). Sievers et al. (2014) give the following typical concentration ranges for dark greywater in Europe: chemical oxygen demand 102 to 1,583 mg/L, biochemical oxygen demand 56 to 427 mg/L, total nitrogen 3 to 48 mg/L and total phosphorus 0.5 to 15 mg/L.

The degree of sophistication of the recycling system depends on the intended use of the treated greywater (Ghaitidak & Yadav 2015, Teha et al. 2015). In some cases, comparatively simple processes are used such as sand filters (Ochoa et al. 2015) and helophyte treatment plants (Laaffat et al., 2015, Saumya et al. 2015). In other cases, different components from conventional wastewater treatment are combined, for example, ozonisation units, UV disinfection units, adsorption set-ups, and filtration components (Kneer et al. 2009). In still other cases, biological systems, such as membrane bioreactors and biologically aerated depth filters, are used.

Reuse of wastewater in industries

There are many opportunities for wastewater reuse in industry. For example process water can be re-used for sanitation and other water uses at the industrial sites. Depending on the circumstances, wastewater may also be used as boiler feed water or cooling water. Some authors have proposed using industrial wastewater as input to bioenergy production (Ranade & Bhandari, 2014).

As with the reuse of wastewater in other sectors, a prerequisite for reusing industrial wastewater is to treat it to a safe and acceptable level. A wide spectrum of technologies are relevant including precipitation and sedimentation, biological treatment media filtration, membrane filtration, ion exchange, reverse osmosis, and disinfection. Such treatment is used to reduce or remove priority pollutants, pathogens, biodegradable compounds, and metals and other non-biodegradable compounds. A complicating factor for industrial wastewater treatment is the extreme variation of the quality and quantity of wastewater over time. Both treatment and economic efficiency can be improved by eliminating potentially damaging wastewater compounds at the source, before they enter wastewater streams.

5.1.4 Protection and restoration of ecosystems

River networks, lakes, reservoirs, and groundwater are interconnected compartments of the hydrological cycle and closely linked to the terrestrial environment. They provide many essential ecosystem services such as drinking water, flood protection, nutrient cycling, means of transport, energy production, and self-purification. Here we discuss their role as a controller of water quality.

Forest conservation/reforestation in river basins

The headwaters of streams and rivers are typically much steeper than their lowland parts. Therefore, if they are thinly-vegetated they may have more frequent rapid surface runoff and a higher rate of soil erosion than lowland areas. If they are heavily forested they will have a much lower rate of erosion, and a much smaller amount of sediment and nutrients will be transported from the land surface into freshwater ecosystems. Hence, conserving the forest cover of headwaters, or re-introducing this forest cover, can be a very effective way of controlling downstream water quality. (See 'Catskill/Delaware watershed conservation' box).

Using natural wetlands for treatment of wastes

Floodplains, riparian zones, and wetlands play a key role in the integrity, functioning, and biodiversity of aquatic ecosystems. Because they retain water and have alternating dry and wet conditions with steep bio-geochemical gradients, they act as filters of poor quality water that flows into them. Hence, their protection and restoration is an important element of water quality management at regional or catchment scales. (See box 'Danish Action Plan on the Aquatic Environment')

River dilution

Rivers themselves can effectively dilute small loads of non-persistent pollutants when river discharge is high enough and consistent. However, a river cannot safely dilute persistent pollutants, such as organic chemicals, because these substances accumulate in the food web and in sediments. Also it is obvious that rivers with low flows cannot successfully dilute pollutants that are discharged in large volumes.

Flow regime restoration

Removing dams or artificial channels will restore a more natural flow regime to a river and can sometimes mitigate water quality problems. For example, removing a dam on an otherwise free-flowing river may successfully reduce eutrophication and dissolved oxygen problems occurring behind the dam. This is because these problems are most likely related to the long residence time and accumulation of nutrients in the reservoir behind the dam. In this case, removing the dam and restoring the unrestricted flow of the river may remove the water quality problem.

Targeted environmental dredging

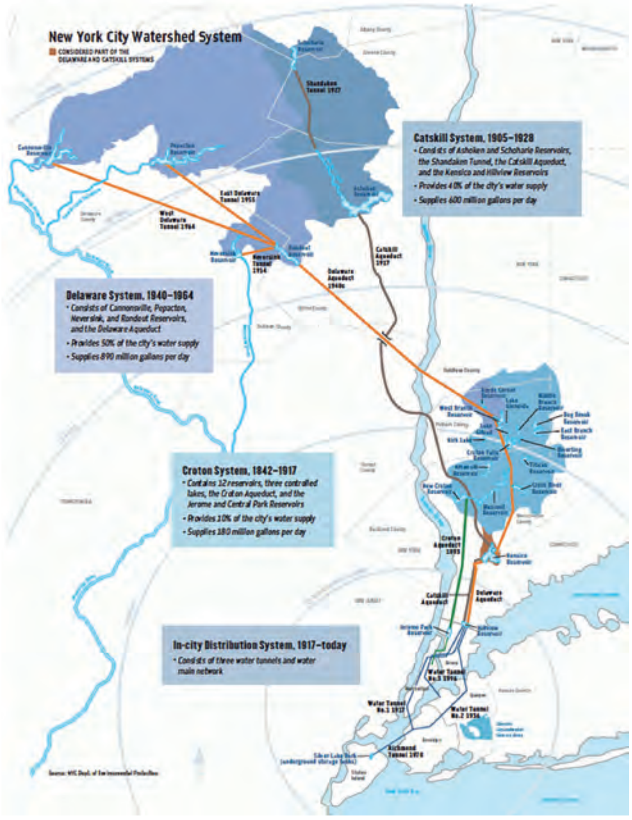
Environmental dredging is used to remove contamination from targeted areas in river beds. This technology is very specific and is designed to minimize resuspension of small sediment particles that may be contaminated with PCBs, heavy metals, or other toxic materials. Resuspension is avoided, for example, with hydraulic dredges or similar machinery which function like large vacuum cleaners to remove contaminated sediments with strong suction pumps.

Best practice example

'Catskill/Delaware watershed conservation'

New York City obtains most of its water from the Catskill/Delaware watershed located upstream from the metropolitan area. Approximately 1.4 billion gallons of water (about 5.3 million cubic meters) are consumed daily by eight million New York City residents and one million upstate customers. At present, all of New York City's drinking water is unfiltered.

In order to maintain the quality of this water supply New York State [annually] spends about 100 million US$ for actively managing the forest catchment areas and compensating the farmers for using less fertiliser and reducing grazing. By comparison, it has been shown that the alternative to these actions – constructing a treatment plant for filtering the raw water to achieve sufficient water quality according to required standards – would require investments of about 7–10 billion US$ with annual operation and maintenance costs of about 110 million US$.



The Catskill watershed and water supply system for New York City (Source: NYC Dep. of Environmental Protection).

Best practice example

'Danish Action Plan on the Aquatic Environment' for controlling nutrient loads

Danish inland and coastal waters deteriorated in the 1970s and 1980s leading to country-wide public and political concern. The cause was the high nutrient loading from point and diffuse sources. Diffuse sources play a major role because more than 60 per cent of the total area of Denmark is cultivated land, and livestock production and density is high. Under the so-called "Action Plan on the Aquatic Environment II", a series of natural wetland rehabilitation projects were carried out to control nutrient losses from agricultural areas to the freshwater and marine environment. These projects included the re-establishment of 16,000 hectares of "wet meadow" to help reduce nitrogen leaching, and 20,000 hectares of formerly removed forests.

It was estimated that nitrogen loads were reduced by 127,000 tonnes N/yr under the action plan, equivalent to a 40 per cent reduction of overall nitrogen discharges into the aquatic environment.

Aerial view of large scale wetland rehabilitation project in the Skjern River watershed under the Danish Action Plan on the Aquatic Environment (Source: Danish Forest and Nature Agency)

5.2 Other issues for protecting water quality

5.2.1 Water quality protection and the Post-2015 Development Agenda

As emphasised throughout this report, water is a key requirement for the sustenance of human life and sustainable development. It is not surprising, then, that water quality issues are strongly linked with other development themes such as poverty, hunger, health, education, gender inequality, and environmental sustainability. In Chapter 3, for example, it was reported that the groups most vulnerable to pathogen water pollution are women and children who still rely on surface waters for their domestic needs. It was also recounted that poor fisher are vulnerable to organic pollution and smallholder farmers to salinity pollution.

The lack of access of poor people to water of adequate quality contributes to socio-economic inequalities. On the positive side, since 1990 more than two billion people have gained access to improved sources of drinking water through programmes associated with the Millennium Development Goals (WHO/UNICEF 2014b). Nevertheless, while access to drinking water has increased, the quality of surface waters used for household water supply in many parts of the developing world continues to deteriorate as articulated in previous chapters. Therefore, it is very significant that the new Sustainable Development Goals (SDGs) under the Post 2015 Development Agenda have ambitious targets not only for access to drinking water, but also for water quality (UN, 2015). A holistic and coherent approach is needed to tackle this and other goals. A concerted global education and awareness-building campaign around water quality issues will be needed, with targeted regional and national campaigns that connect water quality to issues of cultural and historical importance. Explaining the necessity of good water quality to households, the media, policy makers, business owners, and farmers can have a tremendous impact on protecting and restoring water quality.

5.2.2 Precedents for restoration

It is not necessary for developing countries to go through the same cycle of increasing water pollution, widespread degradation of freshwaters, and eventual recovery, that developed countries went through decades ago. The many different technical and management options available for coping with increasing pollution loads are given in Section 5.1 above.

Furthermore, it is possible to begin restoring stretches of rivers and lakes that are already polluted by building on experience from other parts of the world. For example, Chapter 4 presents the example of the restoration of a large segment of the Upper Tietê River in Brazil. Elsewhere in Latin America, the Medellin River in Colombia was restored through the efforts of the Medellin River Sanitation Programme and integrated urban water management (Kraemer et al., 2001). Water quality in the eastern part of Columbia was improved by employing the polluter pays principle which led to an expansion of wastewater treatment (Kraemer et al., 2001). In Africa, the water quality behind the Hartbeespoort Dam in South Africa was restored through biological remediation (Keto, 2013 and Kraemer et al., 2001). Many lakes and rivers have been restored in Europe, including Lakes Norvikken and Mälaren located in Sweden which were revived by reducing phosphorus loadings (Schindler, 2012).

The countries along the Elbe River collaborated successfully in restoring their river through an effective institution called the International Commission for the Protection of the Elbe (see Chapter 4). The Commission championed wastewater treatment in the public sector, conveyed water management reports to the public, and carried out many other activities to promote water quality management in the basin (Dombrowsky, 2008). Meanwhile, the Rhine Action Programme brought together its riparian states in a successful effort to restore the water quality of the Rhine (Raith, 1999; Bernauer, 2002). Similarly, the London River Action Plan was instrumental in restoring the integrity of the Thames River (London Rivers Action Plan, 2009).

One lesson from these and other examples presented in Chapter 4 is that an *action plan*, agreed upon by all the main actors in a river basin, is a key step in restoring rivers and lakes. Another lesson is that it is useful to set up a *collaborative institution*, such as an international commission, for developing and carrying out the action plan.

5.2.3 Financing and governance for protecting and restoring freshwaters

It is generally accepted that the infrastructure for managing water, wastewater and sanitation will require considerable additional investments. Because of the high costs of conventional wastewater collection and treatment, pollution control agencies usually combine financing with cost recovery measures. These might include, for example: direct cost recovery from the user/polluter (also known as ”beneficiary charges”), indirect local taxation (typically using property tax as a vehicle), and subsidies from other government departments. Cost recovery also requires sound regulatory frameworks and policies. Without this enabling environment, the investments needed to support water pollution control will be inaccessible to most developing countries.

Financing of wastewater infrastructure in developing countries comes from various sources including overseas development assistance programmes of donor countries, multinational financial institutions, or international commercial lending and credit agencies.

One way to achieve sustainable financing for water pollution control is to adopt a mix of economic policy instruments that foster an efficient allocation and use of water and protect and reduce the pollution of water resources. As highlighted by the fourth principle of the Dublin statement on sustainable water management adopted by the UN in 1992, all uses of water have an economic value. Managing water as an economic good is an important way of achieving efficient and equitable water use and of encouraging conservation and protection of water resources. The use of economic instruments in water resources management is often more cost effective than other instruments, because it helps internalise the costs of water pollution (Klarer et al., 1999).

Over the years, it appears that the barriers to controlling water pollution have stubbornly remained in place (Camdessus, 2003; UN-Water, 2015a). For example, many governments and institutions from the river basin to country level still have not adopted a strategic approach to wastewater management based on sound planning and evidence. Another important barrier, especially in developing countries, has been the fragmentation of institutional responsibilities for wastewater management which prevents efficient coordination of actions. This was brought up in Chapter 4 in the discussion of water quality management in the Godavari River Basin (Table 5.3). In addition, several case studies in this chapter highlighted the importance of participatory processes, such as “Research in Action” REACT in Tunisia, including community involvement and inclusion of indigenous knowledge.

But there are signs that some developing countries are giving higher priority to wastewater and water resources management. Two examples are the newly adopted Africa Water Vision for 2025 and the establishment of the African Ministerial Council on Water (AMCOW) (Meena, et al, 2010). These steps contribute to the good governance needed to tackle water quality degradation. Good governance, including evidenced-based policymaking and the effective application and enforcement of legal and institutional restrictions on water pollution, will be a prerequisite to meeting the global water quality challenge. Many examples of good governance solutions from the case studies in Chapter 4 are given in Table 5.3.

Table 5.3: Summary of governance solutions mentioned in the case studies (Chapter 4).

Case study	Pollution problem	Governance bodies *	Interest organisations	Programmes and policy instruments
Upper Tietê	Organic pollution	São Paulo Environment Agency	Upper Tietê River Basin Committee	Tietê River Cleanup Program
Godavari	Organic pollution	State Pollution Control Boards, State Groundwater Boards, State Water Resources/ Irrigation Department, Urban Local Bodies		
Volta	Pathogen pollution		Volta Basin Authority	Convention on the Status of the Volta River

Table 5.3: cont.

Case study	Pollution problem	Governance bodies *	Interest organisations	Programmes and policy instruments
Chao Phraya	Pathogen pollution	Electricity Generating Authority, Royal Irrigation Department, Pollution Control Department, Regional Environment Office		National Economic and Social Development Plan, Plan for Natural Resources and Environment Management, Wastewater discharge fees (Polluter-Pays-Principle)
Vaal	Salinity	Department of Water and Sanitation		Water Act of South Africa, Law-binding management objectives (Resource Quality Objectives)
Medjerda	Erosion, salinity, nutrients	Direction Générale des Ressources en Eau, Agence Nationale de Proctetion de l'Environnement		
Elbe	Eutrophication		International Commission for the Protection of the Elbe River, River Basin Community Elbe	European Water Framework Directive, Urban Wastewater Treatment Directive, Nitrate Directive, Hazardous Substances Directive, Floods Directive
Hudson	Organic chemical pollution	Department of Environmental Conservation, New York City Department of Environmental Protection		Hudson River Estuary Program

5.3 Some questions for a full assessment

This chapter has clearly shown that many technical and governance solutions are available to meet the water quality challenge. These include new approaches that were not available to the developed countries some decades ago when population growth and increased economic activity led to a substantial increase in water pollution. It was also shown that no single set of solutions will work everywhere. This is because of the great variation in types of water pollution, sources of water pollution, socio-economic conditions, and hydro-ecological boundary conditions. On the other hand, similar water quality challenges are occurring around the world even if the locations and situations are very different. Therefore, it may be possible to develop different packages of technical and governance options that can be used in many different river basins to deal with similar problems. In order to identify these packages, a full global water quality assessment should address the following questions:

- What are the types and sources of water pollution related to various socio-economic and eco-hydrological conditions?
- What is the efficiency and success rate of existing water pollution measures and programs?
- What are the most important drivers of water pollution?
- For a particular location, what is the relationship between pressures, impacts, and responses to water quality degradation?
- What are effective clusters of technical and governance options for particular archetype water quality problems?
- What are the most useful indicators for tracking progress towards the water quality Sustainable Development Goal?

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