SUBCHAPTER

5.1.1

The Meuse River basin

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5.1.1.1 Introduction

The Meuse is an international river that has been used by man for centuries and it is still the main source of drinking water for large cities in Belgium and the Netherlands. In fact, water quantity and quality have been a major issue between the various riparian countries and political regions. Many kinds of data have been generated in the past decades on various aspects of the river: (a) hydrology for the need of predicting and controlling floods; (b) water chemistry in the context of water pollution assessment and control; and (c) biology and ecology for water quality assessment and studies on aquatic biodiversity community dynamics and ecosystem function.

In contrast to the other rivers of this chapter and despite its relatively short length (905 km), the Meuse is a transboundary river that flows through several countries and regions, mainly France, Wallonia, Flanders and the Netherlands. The total catchment area is 35,548 km^2 with nearly nine million inhabitants. This fact already suggests that the river experiences impacts from human activities and that water and river management are key issues that must be dealt with at international level. To achieve the necessary coordination an international commission for the protection of the river (ICPM International Commission for the Protection of the Meuse) was created in 1995 and redefined in 2000 as the International Commission for the Meuse (ICM) in the context of the implementation of the EC Water Framework Directive (WFD). These international agreements created the International River basin District (IRBD) of the Meuse. A particular feature of the hydrography of the Meuse watershed is that all major tributaries (Semois, Lesse, Sambre, Ourthe) are located mostly in the Walloon Region, so that nearly 36% of the watershed is in this region. The French watershed is comparatively smaller (*ca.* 26%), although it contains more than half of the entire main river.

Besides landscape and ecosystem values, the Meuse fulfills diverse functions and undergoes several kinds of pressures. Its surface waters are treated for the drinking water supply for around six million people, mainly in large cities (e.g., Brussels, Antwerp and Rotterdam). The river is regulated by weirs and navigation dams that allow navigation between the ports of Rotterdam and Antwerp (through the "Canal Albert") and the industrial centers of Wallonia and the southern Netherlands. It provides cooling water for industries and power plants (including two nuclear power plants) and receives thermal discharges. Production of hydroelectricity is carried out by turbines at most dams. In addition, a major part of the land in the watershed is used intensively for agriculture, which implies problems of erosion and diffuse inputs of fertilizers and pesticides to surface and ground waters. These pressures on the river and its water quality, however, do not limit various recreational activities such as angling and boating in some sections (Table 5.1.2).

TABLE 5.1.2 Surface area and number of inhabitants for each state or region of the International River basin District Meuse

	Area (km^2)	Number of inhabitants (×1000)
France	8919	671
Luxemburg	65	43
Belgium (Walloon region)	12,300	2189
Belgium (Flemish region)	1596	411
The Netherlands	7700	3500
Germany	3968	1994
Total	34,548	8808

5.1.1.2 Historical perspective

Progressive changes that profoundly affected river morphology and hydraulics began some 200 years ago when the first large-scale works for controlling floods and improving navigation on the river were undertaken. Micha and Borlée (1989) provided a detailed account of the history of the canalization of the Belgian stretch of the Meuse that occurred in various steps throughout the 19th century. At the same time, encroachment of the floodplain by construction of roads and railways and by human occupation in towns and villages along the river also occurred (Photos 5.1.1–5.1.3).

Further regulation occurred as industry was developed in the beginning of the 20th century and a major phase of riverbed alteration followed the 1926 catastrophic flood, via the construction of new roads and railways, and increased human occupation along the river. Since then, the navigable channel has been deepened to further improve navigation and lower risks from flooding. Today, only a few patchy macrophyte stands exist along the Belgian stretch of the river (Descy, 1987a, 1987b). Among the consequences of this intense regulation and land-use change is a dramatic increase in suspended load for river discharges over 100 m^3/s and regular dredging to remove sediment deposits from the channel. Throughout the 20th century, flow downstream of Liège declined significantly because of water abstraction and exploitation of groundwater.

PHOTO 5.1.1 The Meuse River at Bannoncourt in France (Rkm 194.5) @ G. Thiébaut.

PHOTO 5.1.2 The Meuse River at Namur in Belgium at the confluence with the R. Sambre (Rkm 530) @MRW-DIRCOM – J.-L. Carpentier.

PHOTO 5.1.3 The Meuse River at Monsin downstream of Liège upstream of the border Belgium—The Netherlands (Rkm 600) @MRW-DIRCOM – J.-L. Carpentier.

The French stretch of the river was less affected by regulation and several parts of the river have retained their ecological function and biological potential (Grevilliot et al., 1998). The most natural reach lies in the middle of the French stretch (Photo 5.1.1) where the channel was not regulated and periodically inundated grassland still exists. In the Netherlands, the physical situation of the Meuse is comparable to that in Belgium, having patchy sites with more natural ecological and biological characteristics: a wide river valley offering high potential for restoration and important projects aimed at reconciling the conflicting objectives of navigation, flood control and sustainable ecological function. These projects focus on restoring habitat diversity and floodplain structure where possible.

The ecological status of Meuse tributaries varies by country and region. For instance, most tributaries (*ca.* 85%) in the French and Belgian part of the basin have a natural morphology and hydrological functioning, with the exception of a few large dams and local structural changes for flood control. Relatively few reservoirs were built in the Meuse River basin: most are located in the Walloon region and used for drinking water supply, flow regulation, electricity production and recreation. Canals and highly modified tributaries are found in Flanders and the Netherlands. Overall, 62% of the rivers and 12% of the 150 lakes in the Meuse basin can be considered more or less natural.

5.1.1.3 Geography and geology

Symoens (1957) summarized the biogeographic features of the region. The basin is found in the Baltico—Rhenan sector of the Medio-European domain and has a mostly continental climate. Local contrasts occur in the Ardennes highlands, with cold winters, and in the Lorraine, region with hot summers. The influence of the Atlantic domain in the west also is relatively strong and attenuates thermal variations. Precipitation can be locally high, allowing the development of typical Atlantic plant associations. Seven different ecoregions occur in the basin (ICM, 2005): (1) calcareous regions of tertiary calcareous formations of Trias and Jura in Lorraine and the Eiffel; (2) Famenne of Devonian slate plateau formation adjacent to the Ardennes mountainous region with fast-flowing calcareous rivers; (3) siliceous mountainous bedrock formations of the Ardennes and the Eiffel; (4) hilly regions of Condroz with low areas of chalky massifs and river moraines and terraces; with mixed sediments and rivers with intermediate flow velocities, somewhat alkaline and with high sediment loads; (5) eolic loam region of quaternary loamy plateaus, with incised watercourses with fine sediments and high alkalinity; (6) sandy areas in the Campine region, having Miocene sands and quaternary lowland regions, with streams having sandy riverbeds; and (7) organic peat and clay valleys and moorlands that are drained by small watercourses with high dissolved organic matter.

5.1.1.4 Geomorphology

The Meuse basin has three major geomorphological areas that correspond to the Upper Middle and Lower Meuse. The Upper Meuse stretches from the source on the Langres Plateau to immediately downstream of Charleville—Mézières in France. The Middle Meuse starts downstream of Charleville—Mézières and ends after Liège in Belgium. It covers a large part of the Ardennes Plateau and Walloon part of the basin. The Lower Meuse begins at Liège and ends in the deltaic region of the Netherlands, where the Meuse flows into the North Sea. This section covers the German Flemish and the Netherlands' parts of the basin. The main river flows over calcareous rocks in the upper basin, which strongly influences its chemistry. The main river has been divided into 10 water bodies, in which the three upstream ones are in the Western Highlands and the remaining ones are in the Western Plains (Table 5.1.3).

5.1.1.5 Climate and hydrology

The climate of the basin is a temperate oceanic type, although a continental influence often causes hot dry summers and cold dry winters. An oceanic regime dominates most of the time, resulting in humid weather in all seasons. The average annual rainfall is 700—1400 mm with the highest amount in the high Ardennes. Despite large interannual variation, long-term changes in rainfall have occurred, that are associated with climate change. For instance, there has been an increase in maximal winter rainfall since the early 1980s, parallel to an increase in maximal winter discharge (Tu et al., 2005).

The Meuse is a rain-fed river with considerable fluctuations between seasons and years. Major areas of the watershed are hilly with an impermeable subsoil. In these areas, surface runoff is common, often resulting in flash floods in tributaries and the main river. Low water retention in the middle basin causes low flows during dry periods. High flows generally occur in winter and spring. Variations in flow can be abrupt resulting in floods that last from a few days to several weeks. This was the case for example in 1993 when a maximum flow of 3100 m^3/s was measured in Eijsden, between Wallonia and the Netherlands. Summer and autumn are mainly characterized by long periods of low flow that can range from 10 to 40 m^3/s in Eijsden. The analysis of long-term records (Latli et al., 2017) of discharge at several sites on the river does not show any significant trend in mean annual flow (Fig. 5.1.1). By contrast, over the same period of time, mean annual water

TABLE 5.1.3 Typology of the River Meuse as defined by the International Meuse Commission (2005)

Subecoregions	Meuse sections	Ecoregion and altitude category	Global geology	River type	State/ regions[a]
Haute- Marne Plateau de Langres	1. Le Châtelet-sur-Meuse –Neufchâteau (confluence of the Mouzon)	Western highlands 200–800 m asl	Calcareous	Small river on chalk and marl with mostly calm and cold water	F
	2. Neufchâteau-Nouzonville (confluence of the Gutelle)	Western highlands 200–800 m asl	Calcareous	Large river on chalk and marl with mostly calm and temperate water	F
Ardennes	3. Nouzonville – French/ Belgian border	Western highlands 200–800 m asl	Siliceous	Large siliceous river of the Ardennes massif wide stream with cold and temperate water	F
Condroz	4. French/Belgian border–Borgharen	Western plains <200 m asl	Calcareous	Very large river of the Condroz with small slope (canalized river). Slow flowing river on sand/clay (NL)	B/WL–NL
Kempisch plateau–Limburg hill country	5. Borgharen–Maasbracht Grensmas (border Meuse)	Western plains <200 m asl	Siliceous	Rapidly flowing large river on gravel	B/VL–NL
Kempen	6. Maasbracht – Lith (Zandmaas en Bedi jkte Maas) Sandme use and diked	Western plains <200 m asl	Siliceous	Slowly flowing lower course on sand/clay	NL
Land van Maas en Waal	7. Lith–Waalwijk (Benedenmaas) (Lower Meuse)	Western plains <200 m asl	Siliceous	Fresh intertidal water on sand/clay	NL
Biesbosch–Rhine-Meuse delta	8. Waalwijk–Haringvlietdam (Bergsche Maas Biesbosch Amer-Hollands Diep-Harlingvliet	Western plains <200 m asl	Siliceous	Fresh intertidal water on sand/clay	NL
Biesbosch–Rhine-Meuse delta	9. Krammer Volkerak	Western plains <200 m asl	Siliceous	Medium sized deep buffer lake	NL
Coast	10. Haringvlietdam– 12 miles zone (Northern delta coast)	Western plains <200 m asl	Siliceous	Transitional waters/estuary	NL

[a] F, *France;* B/WL, *Belgium Wallonia;* B/VL, *Belgium Flanders;* NL, *The Netherlands.*

temperature shows a significant increasing trend of over 1°C since 1970 (Fig. 5.1.1; see also Latli et al., 2017).

5.1.1.6 Biogeochemistry, water quality, and ecosystem processes

The Meuse is an alkaline river dominated by calcium and bicarbonate ions with high conductivity (400–600 μS/cm) and a pH between 7.5 and 8.0. Conductivity is highest in the upper river (up to 900 μS/cm) (ICM, 2005), quickly decreasing downstream and remaining constant to the delta where saline intrusions occur. A detailed characterization of the geochemical properties of the river and tributaries can be found in Descy and Empain (1984). They describe five water types ranging from acid streams with low conductivity (<50 μS/cm) to alkaline calcareous streams with

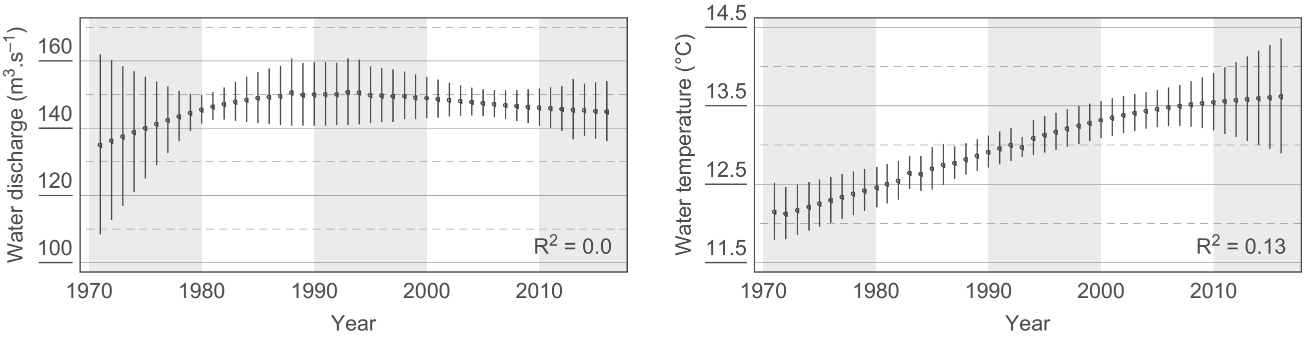

FIGURE 5.1.1 Long-term variation in the annual mean values of water discharge and water temperature modeled with GAM, using data from several sites of the R. Meuse: Saint-Mihiel, Inor, Ham-sur Meuse (France), Tailfer Liège (Belgium), and Eijsden (The Netherlands); between 1971 and 2017 (*dark circle*). Between-sites deviations (= standard deviation bars) are provided.

conductivities reaching 600 µS/cm. Suspended matter are relatively low in the Meuse typically ranging around 15 mg/L in recent years. Longitudinally highest concentrations are in the middle reach, possibly due to sediment resuspension by boats. The analysis of long-term records indicate a relative stability in suspended matter during the 1970s and 1980s, followed by a steady decline (Fig. 5.1.2; see also Latli et al., 2017).

Urban and industrial wastewater treatment has progressively increased over time, so that the river water quality has steadily improved in river sectors that were historically polluted by organic waste and various micropollutants (ICM, 2015). The impact of human activities on the concentrations and composition of dissolved (DOM) and particulate (POM) organic matter (OM) in streams and rivers of the Meuse basin were recently investigated (Lambert et al., 2017). Higher concentrations of dissolved and particulate organic carbon (DOC and POC, respectively) were measured in agro-urban dominated systems and were associated with a more microbial/algal and less plant/soil-derived character in OM pools compared to streams and rivers draining forested ecosystems (Fig. 5.1.3). These changes in OM composition were found to result from the combination of agricultural practices that promoted the decomposition of terrestrial soil organic matter and enhanced in-stream productivity due to higher nutrient levels. Seasonal variations in POC concentrations were related to changes in freshwater discharge along the hydrological cycle and subsequent changes in POM sources from terrestrial sources in winter to autochthonous sources in summer. However, contrary to observations made in other temperate catchments (Graeber et al., 2012; Lambert et al., 2014; Raymond and Saiers, 2010), DOC concentrations were less related to discharge than POC, due to relatively constant and hydrologically independent inputs and greater microbial production of DOM during summer. These inputs of OM from microbial origin especially occur in urban areas and were directly related to population density, supporting the statement according to which urbanization leads to a stream DOM composition distinct from those observed in natural and agricultural catchments (Williams et al., 2016).

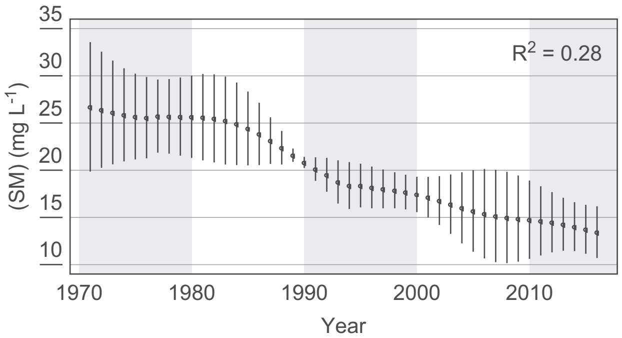

FIGURE 5.1.2 Long-term variation in the annual mean values of suspended matter modeled with GAM, using data from several sites of the R. Meuse: Saint-Mihiel, Inor, Ham-sur Meuse (France), Tailfer, Liège (Belgium) and Eijsden (The Netherlands) between 1971 and 2017 (*dark circle*). Between-sites deviations (= standard deviation bars) are provided.

Inland waters have been recently recognized as important players in the global budgets of long-lived greenhouse gases (GHGs) acting as vigorous sources to the atmosphere of carbon dioxide (CO_2) (Raymond et al., 2013; Borges et al., 2015), methane (CH_4) (Bastviken et al., 2011; Borges et al., 2015) and nitrous oxide (N_2O) (Hu et al., 2016). The distribution of dissolved CO_2 CH_4 and N_2O in the rivers and streams of the Belgian part of the Meuse basin was recently reported (Borges et al., 2018). Stream and river surface waters were oversaturated in CO_2, CH_4, and N_2O with respect to atmospheric equilibrium, acting as sources of these GHGs to the atmosphere although the dissolved gases also showed marked seasonal and spatial variations. Seasonal variations were related to changes in freshwater discharge following the hydrological cycle, with highest concentrations of CO_2, CH_4 and N_2O during low flow, owing to a longer water residence time and lower currents (i.e., lower gas transfer velocities), both

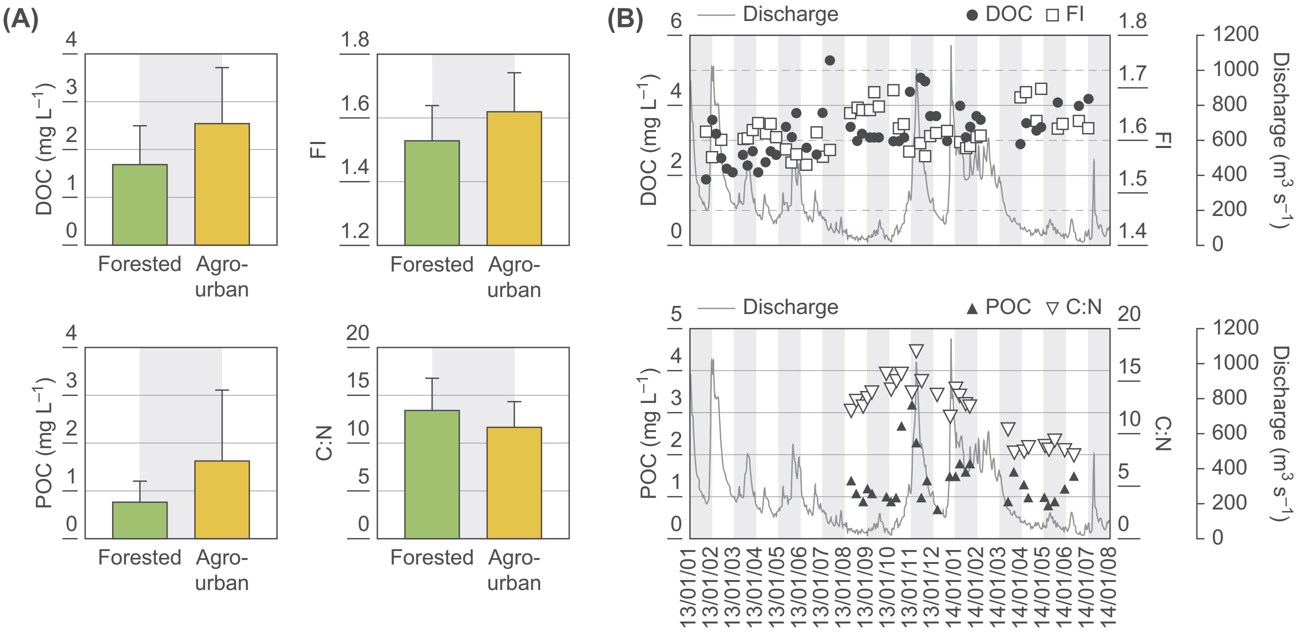

FIGURE 5.1.3 (A) Average DOC and POC concentrations, FI (fluorescence index see Lambert et al., 2017) and C:N ratio in streams and rivers draining forested and agro-urban catchments. Higher FI and lower C:N values in agro-urban catchments indicate higher inputs from microbial and algal sources on the DOM and POM pools respectively. (B) Seasonal variations in the Meuse River at Liège of freshwater discharge, DOC concentration and FI ratio (*upper panel*), and POC concentrations and C:N ratio (*bottom panel*) from January 2013 and August 2014. *Adapted from Lambert et al., 2017.*

contributing to the accumulation of gases in the water column combined with higher temperatures favorable to microbial processes (Fig. 5.1.4). Spatial variations were mostly due to differences in land cover over the catchments, with rivers and streams dominated by agriculture (croplands and pastures) having higher dissolved CO_2, CH_4 and N_2O levels than forested systems (Fig. 5.1.4). This seemed to be related to higher levels of dissolved and particulate organic matter, as well as dissolved inorganic nitrogen in agriculture-dominated systems compared to forested ones (data not shown).

Inputs of nitrogen and phosphorus are still high in the river Meuse even though there has been a substantial decrease of orthophosphate over time (Fig. 5.1.5). By contrast, nitrogen loads have remained rather high with a major contribution from agriculture (~66%), whereas most P inputs are from domestic wastewater (50%), with agricultural (37%) and industrial sources (8%) contributing locally (ICM, 2015).

Phytoplankton development shows a contrasting trend over time (Fig. 5.1.5). In the 1980s and 1990s, chlorophyll *a* concentrations in the river could exceed 100 µg/L, amounting to ~4 mg C/L, representing a major contribution to OM loading. In the 2000s, a dramatic decrease in chlorophyll *a* levels occurred, unrelated to changes in nutrients and suspended sediments (Latli et al., 2017). The recent decline in chlorophyll *a* in the river, which has been attributed to the recent invasion by the filter-feeding Asian clam *Corbicula* sp. (Pigneur et al., 2013), resulted in an apparent decrease of eutrophication with an improvement in water transparency and changes in the dissolved oxygen budget and P cycling.

Several heavy metals (Cr, Cu, Zn, Pb, Cd) contaminated the Meuse, sometimes at significant concentrations, causing concern for drinking water supply. The contamination of bed sediments by heavy metals was also a serious problem especially between Liège and Kinrooi where the highest industrial activity is found. In the past decades, pollution by heavy metals and organic micropollutants, except polycyclic aromatic hydrocarbons (PAHs), has steadily decreased so that a good chemical status has been reached in a large part of the Meuse basin (ICM, 2015).

5.1.1.7 Biodiversity

Studies of aquatic flora and fauna of the Meuse were relatively sparse before the 1970s. Then, a strong interest developed for the river biota, largely triggered by the need to assess the impact of pollution, including thermal pollution and radioactive contamination from power plants on the river. Several surveys and detailed studies of the flora and fauna have been conducted in the past decades, giving a better knowledge of the river

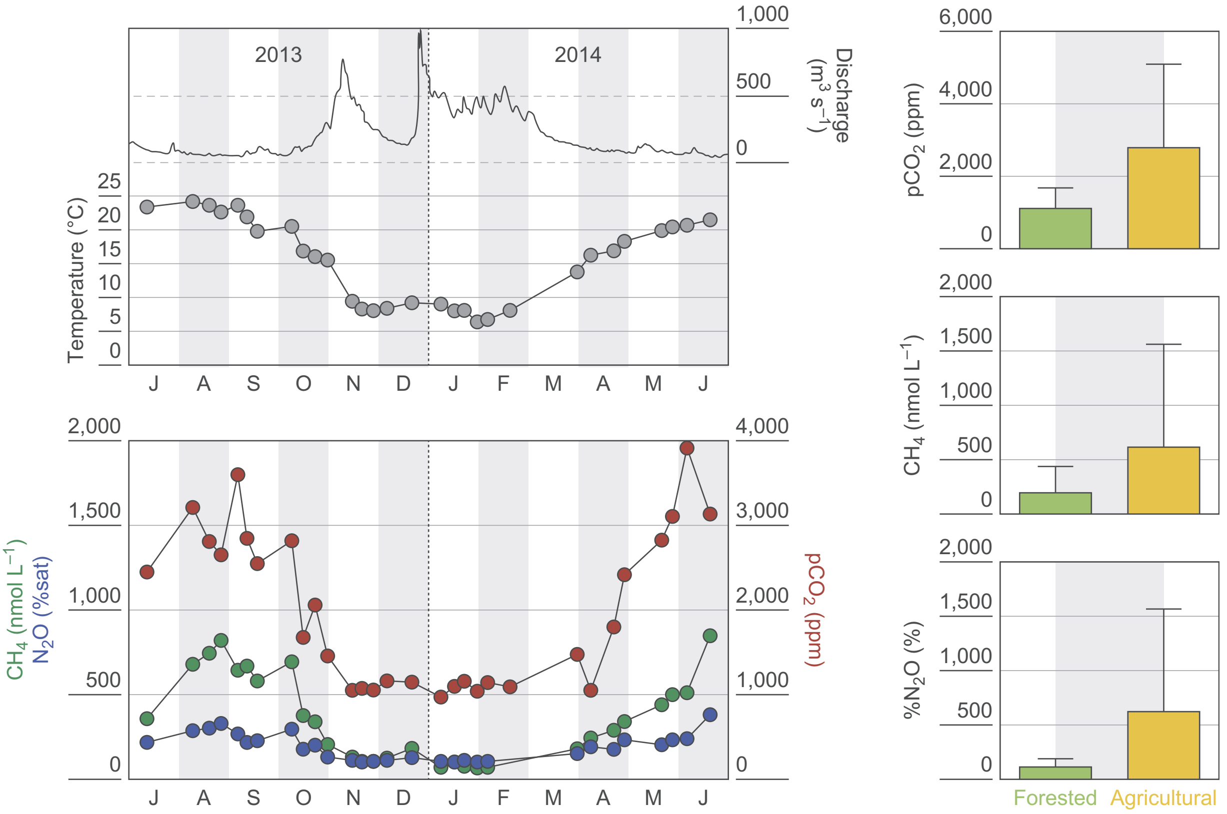

FIGURE 5.1.4 Seasonal variations in the Meuse River at Liège of freshwater discharge, water temperature, partial pressure of CO_2 (pCO_2), dissolved CH_4 concentration and dissolved N_2O saturation level (%N_2O), from July 2013 to June 2014 (*left panels*) and the average pCO_2, CH_4 and %N_2O in streams and rivers with mainly forested and main agricultural land cover on the catchment (right panels). *Adapted from Borges et al., 2018.*

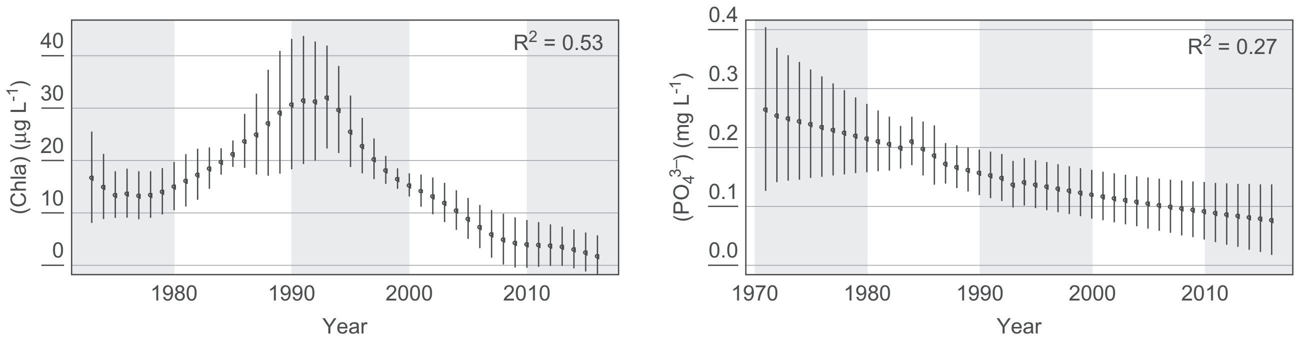

FIGURE 5.1.5 Long-term variation in the annual mean values of chlorophyll *a* and dissolved reactive phosphate, modeled with GAM, using data from several sites of the R. Meuse: Saint-Mihiel, Inor, Ham-sur Meuse (France), Tailfer, Liège (Belgium), and Eijsden (The Netherlands); between 1971 and 2017 (*dark circle*). Between-sites deviations (= standard deviation bars) are provided.

and of the organisms living in it. Due to the lack of earlier surveys, it is still difficult to fully assess the extent of the ecological changes that have occurred in the river as a consequence of alterations resulting from hydraulic management and water and sediment pollution. Major changes occurred in the biocenosis of the River Meuse over time, especially in the 2000s, related to increased river regulation and invasions by exotic species of invertebrates and fish. These invasions have affected river communities to a variable extent and have also had significant effects on ecosystem functions.

5.1.1.7.1 Algae

In the Meuse basin, benthic algae, especially diatoms, have been examined several times since the 1950s

(Symoens, 1957). Because of the wide range in physical—chemical conditions of the river and its tributaries, algal assemblages are quite diverse in the less polluted streams in the catchment. Benthic diatom assemblages were classified at the European scale (Gosselain et al., 2005) and at least four assemblage types of low-impacted streams were identified in the basin.

Diatoms are a dominant component of the phytoplankton in the river and centric species are most common. Rojo et al. (1994) and Reynolds and Descy (1996) gave lists of potamoplankton taxa commonly found in lowland rivers. In the River Meuse, green algae, mainly coccal forms, are often an important group in the phytoplankton (Descy, 1987a, 1987b). Excluding tychoplanktonic forms (i.e., taxa of benthic origin that have detached and remain in suspension), about 150 planktonic taxa are common in the river (Descy, 1987a, 1987b; Descy and Gosselain, 1994; Gosselain, 1998). Green algae represent more than 51% of these taxa while diatoms contribute 28%. Other planktonic algae are most often secondary, although chrysophytes, cryptophytes, cyanobacteria, dinoflagellates and euglenophytes can reach high numbers locally or during particular periods. The diatoms found in the River Meuse are common in eutrophic lowland rivers (Reynolds and Descy, 1996); they may develop large populations all year round or in some seasons and include several species of centrics belonging to the genera *Stephanodiscus*, *Cyclotella*, *Cyclostephanos* and *Aulacoseira*.

Large temporal variation in phytoplankton biomass and composition occurs as a result of variation of discharge, light and temperature. The dynamics were simulated with a non-stationary simulation model (Everbecq et al., 2001) that has also been used for assessing the impact of benthic filter-feeders (Descy et al., 2003; Pigneur et al., 2013) and the ecological impact of power plants. The expansion of exotic filter-feeders has resulted in a dramatic reduction of phytoplankton abundance and production (Pigneur et al., 2013) with several consequences for water quality and the food web (Latli et al., 2017; see below). In parallel to the biomass decline, substantial changes in phytoplankton composition might have occurred but this requires quantitative data that are presently not available.

5.1.1.7.2 Aquatic plants

The status of macrophytes differs considerably depending on the sector of the river considered, for reasons related to natural typology and hydraulic management. In particular, river regulation by hydraulic works for allowing commercial navigation and eutrophication has contributed to the loss or decline of aquatic vegetation in the Meuse downstream of the French-Belgian border. The aquatic vegetation in the French sector is quite abundant and diverse, and contrasts strikingly with that of the Belgian Meuse. The French Meuse has retained its habitat heterogeneity (Micha and Pilette, 1988), and consequently harbors a diverse vegetation of helophytes and hydrophytes.

In the Belgian sector, there has been a strong reduction of habitats for aquatic plants as a result of deepening and widening the navigation channel, limiting plant colonization. Most banks also have been stabilized, further constraining plant development. The decrease in water transparency from eutrophication and excess algal growth and from sediment resuspension by boat traffic has limited macrophyte development in the littoral zone. Nevertheless, 11 riparian types are found in the upper part of the Belgian sector (GIREA, 2004). Further downstream, most hydrophytes had completely disappeared from the Walloon Meuse (GIREA, 1996) but a recovery seems to have occurred in the past decade, following the improved water transparency from diminished phytoplankton biomass (Latli et al., 2017).

5.1.1.7.3 Zooplankton

Most data concern metazooplankton and were collected during the 1990s by Viroux (2000) at a time when phytoplankton abundance was high. Rotifers frequently reached densities >500 ind./L and numerically dominated the few euplanktonic species found in the river. Five species, all from Brachionidae, made up the bulk of this assemblage: *Brachionus calyciflorus, B. angularis, B. urceolaris, Keratella cochlearis* and *K. quadrata*. The Synchaetidae were also well represented, containing several species from the genera *Synchaeta* and *Polyarthra*. This community comprised a combination of opportunistic, largely-algivorous/omnivorous filter-feeders (e.g., various *Brachionus*), detritivores (*Keratella*) and more selective "raptorial" feeders (*Synchaeta, Polyarthra*). Some bacterivorous species (*Anuraeopsis, fissa, Filinia* sp.) were also found at low densities, and the large predator *Asplanchna* was commonly recorded. A total of 44 taxa have been listed for the river.

Cladocerans found in the river were mostly euplanktonic species. Small *Bosmina* were the most abundant, especially downstream, where they could reach up to 50 ind./L. Larger species like *Moina, Ceriodaphnia, Diaphanosoma* and even *Daphnia cucullata* were less common. These taxa typically peaked in late summer, when flow conditions allowed long water residence time (Viroux, 2002). A few planktonic and benthic copepod taxa were also found, and their dynamics resembled those of cladocerans with maximal population density (up to 60 ind./L) in late summer.

In the 2000s, zooplankton abundance dramatically declined in the River Meuse (Latli et al., 2017), following aquatic invasions, either by competition for algal resources, direct predation or both (Pigneur et al., 2013; Marroni et al., 2016). As for biodiversity, while autumn surveys in the lower part of the river (Liège) counted an average of 10 zooplankton species from 1995–2005, only 3 species were found on average between 2007 and 2011. In recent years (2015–17), a slight recovery has been observed with an average of 6 species (Joaquim-Justo, unpublished results).

5.1.1.7.4 Benthic invertebrates

Data on bottom-dwelling microinvertebrates, a largely neglected component of aquatic food webs, are available for the Meuse (Capieaux, 2004). Benthic cladocerans are common in plankton samples, with 10 species of Chydoridae and 1 Macrothricidae (*Macrothrix hirsuticornis*) being identified from sediment samples. Their presence in the plankton is associated with increases in discharge (Viroux, 2002) and, except for *Chydorus sphaericus*, their capacity to survive in the plankton is uncertain.

In the Meuse, there is substantial longitudinal change in benthic macroinvertebrate assemblages as a result of natural typology, but communities have strongly responded to modifications of the river channel for navigation and water pollution, that have mostly affected downstream sections. Whereas insects dominate the French sites in taxonomic richness as well as in abundance, crustaceans become more important downriver, especially in the Walloon and Dutch sector. French sites present many taxa with preferences for fast-flowing reaches, such as caddisflies, mayflies, coleopterans and dipterans, with some slow-flowing reaches containing several species of dragonflies. In contrast, the Walloon and Dutch sectors harbor mostly oligochaetes, achaetes, polychaetes, turbellarians, gastropods and bivalves. Some habitat improvement around the Belgian–Dutch border and the "Border Meuse" allowed the recovery of aquatic insects such as caddisflies (see Usseglio-Polatera and Beisel, 2003). Several exotic species considered as recent invaders increase in numbers downstream and contribute to the total abundance of up to 80% at some sites. For instance, upstream dispersal of the amphipod species *Chelicorophium curvispinum* and *Dikerogammarus villosus* in the River Meuse has been observed at rates of 15 and 30–40 km year^{-1} respectively (Josens et al., 2005).

Several exotic invasive bivalve species are recorded in the Meuse: mainly Dreissenids and *Corbicula* clams. Along the well-known and long-time established zebra mussel (*Dreissena polymorpha*), the quagga mussel (*Dreissena rostriformis bugensis*) has been present since 2007 (first recorded in 2006 in the Hollandsch Diep a part of the Meuse and Rhine Estuary in the Netherlands; Molloy et al., 2007). The quagga mussel has spread upstream along the River Meuse via several fronts based around large rivers and canals (Marescaux et al., 2015). Dreissenids are able to act as ecosystem engineers: the shell beds physically alter freshwater ecosystems, resulting in modifications of benthic macroinvertebrate communities (Marescaux et al., 2016).

Clams of the genus *Corbicula* spp. settled in the Meuse in the early 1990s (Vanden Bossche, 2002). These clams are mainly native to Asia and particularly known for their fast spread and being benthic filter-feeders which can massively reduce phytoplankton density. This has been well demonstrated in the river (Pigneur et al., 2013). Two main morphotypes of *Corbicula* have been recorded in the Meuse: the forms S and R usually identified as *C. fluminalis*, and *C. fluminea*, respectively. However, form R would belong to the genetic lineage of *C. leana* according to mitochondrial DNA data (Pigneur et al., 2011). Forms R and S are genetically characterized as two distinct lineages, each exhibiting virtually no genetic polymorphism and thus being considered as a clonal lineage (Pigneur et al., 2011). Indeed, the invasive lineages found in the Meuse seem to reproduce through androgenesis (Pigneur et al., 2011). In this rare form of asexual reproduction, descendants are clones of their father (reviewed by Pigneur et al., 2012). This reproductive mode, combined with the ability of self-fertilization, could have contributed largely to the invasive success of these clams in the Meuse (Hedtke et al., 2008; Pigneur et al., 2011, 2014).

A study based on 13 years of monitoring data, highlighted the long-term combined effects of global warming, trophic resource decrease, predation risk and water quality variation on the trait-based structure of macroinvertebrate assemblages along 316 km of river (Latli et al., 2017). The reduction of trophic resources in the water column by invasive molluscs (Pigneur et al., 2013) affected the trophic structure of macroinvertebrate assemblages (Latli et al., 2017). Scrapers may have benefited from the increase in water transparency and have become the major feeding guild among invertebrates. Conversely, a reduction of phytoplankton density in the water column has directly affected particulate organic matter supply to the bottom, with an impact on deposit feeders. In the Meuse, the decline of native deposit feeders can be attributed to fish predation but also to competition with exotic crustaceans occupying the same ecological niche. During the 1990s, *C. curvispinum/robustum*, two Ponto-Caspian invasive crustaceans, gradually became dominant (bij de Vaate et al., 2002; Josens et al., 2005). More recently, the exotic amphipod *D. villosus*, first recorded in the Meuse in the early 2000s (Van den Bossche, 2002), has become the most abundant benthic predator and may have contributed to the demise of native gammarid species.

The Ponto-Caspian polychaete *Hypania invalida* (Ampharetidae) escaped from the Danube basin and was first recorded in 2000 in the Belgian section of the Meuse (Vanden Bossche et al., 2001), simultaneously to its rapid invasion of the Main Rhine/Moselle, Seine and Rhône basins (Devin et al., 2006). This euryhaline active filter-feeder living in a muddy tube on various mineral substrates from gravel to silt and mud deposits (Vanden Bossche et al., 2001; bij de Vaate et al., 2002; Woźniczka et al., 2011; Pabis et al., 2017) is widespread in potamal rivers exhibiting hydromorphological alterations and exposed to intensive navigation (Vanden Bossche et al., 2001; Zorić et al., 2011). It rapidly reached high densities (>10,000 ind./m^2) in the river and could significantly contribute to bottom substrate clogging (Vanden Bossche et al., 2001; Devin et al., 2006).

Top-down control had an important impact on macroinvertebrates in the Meuse. The increase of invertebrate-feeding fish was significantly correlated with the diminution of large macroinvertebrates to the benefit of small-sized species with shorter life cycles (including exotic gobies). Finally, water temperature increase seems to have had very little impact on macroinvertebrate traits. However, this effect could be masked by eutrophication and organic pollution that occurred during the 1980s and probably reduced the abundance of many sensitive species. Data are missing for disentangling the effects of global warming from other factors influencing macroinvertebrate communities.

5.1.1.7.5 Fish

The fish fauna comprises 55 species of which 36 are native. Several migratory fishes have disappeared (see below), while exotic fishes represent up to 50% of the assemblage in some parts of the main river (Kestemont et al., 2002). Rheophilic species have relatively high populations in the French Meuse and in the unregulated Border Meuse, whereas limnophilic species are well represented in all sectors. During the last two decades, a proportion of limnophilic species diminished in the Belgian Meuse, mainly due to the decline of roach populations (Otjacques et al., 2016). As for the macroinvertebrates, water pollution and habitat alterations are major causes for low fish diversity in the river particularly in downstream sections.

The number of exotic species is relatively high in the Meuse. Most of these exotics have been voluntarily or accidentally introduced for various reasons (recreational fisheries, restocking, aquaculture), whereas others have migrated from other European river basins through various interbasin canals. An improvement in water quality in the lower river has benefited the movement of some fish as well, such as the recent presence of the asp *Aspius aspius* since 2000. The origin of exotic fishes is mainly from central Europe (e.g., Danube basin), although species from North America and Asia also have been introduced. Until the last decade, some tropical fishes, such as tilapia *Oreochromis aureus* and *O. niloticus*, African catfish *Clarias gariepinus* and pacu *Colossoma macropomum*, were regularly found in some limited areas, usually near heated effluent waters of nuclear power plants. Their survival during winter is doubtful and the closure of a large fish farm that was producing these species induced their decline. Several species have reproducing populations, including the common carp, zander, goldfish, channel catfish and pumpkinseed. Other stocked fish such as rainbow trout, brook trout, common whitefish and peled were introduced many decades ago in streams and reservoirs but they do not have reproducing populations.

Despite the large number of exotic fishes, no species is yet considered as really invasive in the Meuse. However, some exogenous taxa could have a significant influence on native fish communities. For example, the large predatory European wells catfish *Silurus glanis*, which is widely distributed in the river, may have an impact on freshwater and anadromous fish as it has been reported in other European rivers (Syväranta et al., 2009). More recently, three species of Gobiidae (*Proterorhinus semilunaris, Neogobius melanostomus, N. kessleri*) were detected in the Dutch and Belgian parts of the river (Van Kessel et al., 2016). *P. semilunaris* and *N. melanostomus* were also observed in some French locations since 2013 but with low densities (Manné, 2017). A rising number of publications report that gobies in invaded areas, particularly in large rivers, may have negatively influenced native benthic fish. The round goby (*Neogobius melanostomus*) is particularly abundant in artificial habitats with hard substratum where it outcompetes the protected *Cottus gobio* (=*C. perifretum*) (Van Kessel et al., 2011, 2016; Dorenbosch et al., 2017).

Seven native species of the Meuse are extinct, including Atlantic salmon, Allis shad, Twaite shad, European sturgeon, houting, sea lamprey and river lamprey. Flounder, burbot and spiny loach are probably extinct in most parts of the Meuse basin, since they have not been captured in the last decade. Some of these species are present, although rare in the Dutch part of the Meuse. Causes of extinction or endangerment include the building of weirs for navigation (reducing fish migration), industrial and to a lesser extent urban pollution, commercial overfishing and the destruction of spawning and nursery habitats. Only a few species are considered endangered, such as the eel, and many species are classified as vulnerable, including the European brook lamprey, bullhead and several salmonids and cyprinids.

For ensuring free movement of fish in rivers and reintroducing some anadromous fish, several programs have been conducted in the Meuse ("Meuse Saumon 2000" in the Walloon region and "Zalm terug in onze rivieren" in the Netherlands). In the Meuse, large migratory species such as Atlantic salmon and sea trout are of special emphasis. The main management actions conducted consist of removing the main obstacles to fish migration, mapping and restoring adequate breeding sites for adults and nursing areas for juveniles, and restocking young fish (eggs larvae juveniles) from nonnative strains to sustain populations. Since 1980, a significant number of adult salmon were caught in the lower Dutch Meuse and in the fish pass of Lixhe for stocking purposes and increasing a local strain. The number of Atlantic salmon returning has increased since 2012, reaching up to 53 adults in 2015 (Ovidio et al., 2018).

A long-term study based on fish, covering 427 km of the French and Belgian River Meuse over 25 years (Latli et al., 2017), revealed that fish abundance increased at the end of the 1990s but decreased after 2005. On the other hand, species richness, taxonomic equitability and abundance of exotic fishes showed no significant temporal trend over the study period. Fish abundance was correlated with plankton availability in the water column and predation risk due to an increase of great cormorants (*Phalacrocorax carbo*).

In parallel with the chlorophyll *a* decline in the Meuse (Fig. 5.1.5), feeding habits of the fish assemblage also shifted gradually from a community dominated by omnivorous species to invertebrate-feeding species (Latli et al., 2017). Omnivorous fish have been affected by the drastic decrease in zooplankton density following the phytoplankton decline. Otjacques et al. (2016) confirmed that the main cause for the dramatic reduction of the roach (*Rutilus rutilus*) in the Belgian part of the river is the drastic decline in planktonic resources that followed the invasion of the exotic filter-feeders. Top-down control also induced an important modification of fish assemblages in the river; the trait-based structure of the fish assemblage appearing more impaired by predation than that of the benthic macroinvertebrate assemblage. In particular, slow-growing fish species with late maturity and low fecundity (e.g., *Thymallus thymallus, Leuciscus leuciscus, Esox lucius*) significantly declined over the study period, most probably as a result of great cormorant predation. In contrast, changes in macroinvertebrate reproductive strategies are not significantly correlated to fish predation. While predation pressure of cormorants on fish is clear and has been described elsewhere (Engström, 2001; Cech and Vejrik, 2011), the link between predation and macroinvertebrate abundance seems more complex than expected. Although similar patterns in fish communities were observed in different sections of the Meuse, it seems that river channelization strengthened the impact of planktonic limitation and predation (Otjacques et al., 2015, 2016; Latli et al., 2017).

5.1.1.8 Human impact, conservation and management

5.1.1.8.1 Human impact

A major economic use in the Meuse basin is drinking water supply from both surface and groundwater. The total amount of water abstracted for drinking water reaches 964 million cubic meters per year, of which 64% is extracted from groundwater. In the Dutch, German and Walloon areas, between 30% and 46% of the drinking water comes from surface waters. Although groundwater is the major source of drinking water throughout the Meuse basin, less than half of the groundwater bodies have reached good status according to the WFD; the major cause being chemical status because of contamination by nitrate and pesticides, mainly from agriculture (ICM 2015). Water abstraction for agriculture is relatively low in the basin, although industrial usage, cooling water for power plants in particular, can be locally important. Most power plants are located upstream of the French-Belgian border (Chooz nuclear power plant) and downstream in Belgium (Tihange nuclear power plant). Commercial navigation is important on the Belgian Meuse. Most boat traffic takes place to and from the Albert Canal with a total transport of up to 45 million tons/year in 2014. Up to 20 million tons/year were transported in the sector between Liège and the tributary Sambre in 2016. Small hydropower plants have been installed on most navigation dams and flood control has always been a major issue in the basin, making it necessary to develop management plans for reducing flood risks (ICM, 2015).

5.1.1.8.2 Conservation and restoration

Many restoration measures have been conducted on the river in the French sector. Since 1994, measures for restoring ecologically important wetlands were carried out, including environmentally friendly agricultural practices. The objective of these operations was to preserve the status of key sites for maintaining hydrological functions that take into account groundwater recharge, self-purification processes and flood management. These actions have also helped protect the habitat of wetland plants and birds such as the curlew (*Numenius arquata*), crane (*Grus grus*) and corncrake (*Crex crex*). Several restoration projects have been initiated to restore the natural course of the river by connecting side arms or improving lateral connectivity with floodplain water bodies (about 20 between 1994 and 1999, at least 10 between 2001 and 2016) and replanting riparian vegetation along the fluvial corridor. The pike (*Esox lucius*) is monitored to evaluate the effectiveness of lateral habitat restoration. Pike stocking is by itself a restoration action and at least 19 tons of pike were dumped in the French Meuse between 2007 and 2014.

In Wallonia, where hydrologic management has been more extensive, fewer opportunities are available for ecological restoration. Some projects are under way, that include the connection of the main channel with side arms to improve habitat for fishes. Islands, which often retain some natural features, have been classified as natural reserves and thereby protect habitat for flora and fauna, most notably bird nesting sites for kingfisher and great crested grebe. Various projects are now under way for restoring reed stands by replanting semi-aquatic plants in shallow areas. Recently, some riparian zones have been designated as Natura 2000 sites. Several measures for restoring longitudinal and lateral connectivity have been implemented in small tributaries where circulation of sediment and fish was impeded by old hydraulic works: an example is the WALPHY project, supported by the EC LIFE program, which produced guidelines for river restoration in a similar context (Verniers and Peeters, 2013; Castelain et al., 2018). The environment of the lower Belgian Meuse benefited from various projects; for instance, the creation of a new lock at Lanaye included measures for creating plant, fish and bird habitat (GIREA and Royal Haskoning, 2005).

In the Flemish stretch of the river, the “Border Meuse”, an important international restoration project, took place in collaboration with the Netherlands. The project “Levende Grensmaas” consisted of allowing more space for the river by lowering the riverbanks. Acquisition of land along the river allowed the integration of flood protection measures and ecological restoration of the river. In the Netherlands, a similar approach was adopted in the project “De Maaswerken”, which included extending the river channel by widening and deepening. Other conservation actions are the improvement or construction of fish passes, integration of the river as a core zone in primary ecological structures (“Ecologische Hoofdstructuur”), restoration of the riparian zone, (project “Natuurvriendelijke Oevers Maas”) and cleanup of the sediments in the lower Meuse.

International collaboration is needed for the best conservation of riverine species and habitats in the main river and tributaries (e.g., Semois, “Border” Meuse, Rur, Schwalm and Niers) and for border zones that are often surrounded by large natural areas (Gaume, Hautes Fagnes, Maasduinen). In France, large stretches of the alluvial plain of the Meuse are included in the network of protected areas, i.e., French Meuse and Vosges. Protected areas are also found along the tributaries Mouzon and Chiers. Large wetlands lakes and swamps (e.g., Pagny-s-Meuse) are found in Lorraine.

In March 2000, Wallonia designated 165 sites (*ca.* 21,000 ha) as protected areas that include several tributaries and large moorlands (e.g., Hautes Fagnes). In Flanders, eight “‘habitat” areas are within the Meuse basin mainly in tributary valleys and along the floodplain of the Meuse. In the Netherlands, 16 of 79 protected areas under the “birds” directive are in the Meuse basin and many are connected to the main river. Here, 39 of 141 “habitat” areas also are in the Meuse basin. Seven large protected zones are both “bird” and “habitat” protection areas, including the Biesbosch, Groote Peel, Krammer—Volkerak, Meinweg, Haringvliet, Voordelta and Maasduinen. Lastly, there are 52 “habitat” areas in the German river basin of which the largest are the “Kermeter” on the Rur, the “Krickenbecker lakes” on the Nette and the “Lüsekampniederung” on the Schwalm. Further, the “Meuse-Nette-Platte” region, which includes the Grenzwald and Meinweg, is of considerable importance at the international level.

5.1.1.8.3 Management

In many aspects, the Meuse shares the same problems as other Western European rivers, with major issues being sustainable water use by humans and the need for environmental protection or restoration in the context of changing climate and aquatic invasions. In a large part of its course, the river has been regulated for navigation and flood control for about a century. River management has often neglected the environment and aquatic biota, so that plant and animal biodiversity has decreased and floodplain functions are no longer operating, The river has also faced many pressures from anthropogenic activities that have affected the quality of water and sediments. Although large forested areas still exist in the basin, agriculture is a major land use in the catchment. The basin has a large human population that needs drinking water and produces waste, and various industrial and power plants use the river water. Eutrophication is widespread in the Meuse and despite considerable progress being made for wastewater treatment, organic pollution may still affect some stretches in the main river and its tributaries. Thermal pollution may affect the oxygen budget locally and micropollutants contaminate the water and sediments in several places. In the last few years, many invasive species, mostly macroinvertebrates, have entered the river and several have successfully extended their range. There is evidence that global warming has been affecting the temperature of the river but sufficiently detailed historical data are missing, which makes it difficult to assess the consequences for aquatic organisms and ecosystem function and services.

Implementing the WFD on such a river, and in particular achieving the objective of "good status" or "good potential," is not a simple task and necessarily involves coordination at an international level. A significant initiative was a transnational modeling of the Meuse basin carried out (initiative of ICM partners) in 2010 with the PegOpera software (Grard et al., 2014) to demonstrate the ability of the model to provide scientific support for surface water management of international districts.

5.1.1.9 Conclusions and lessons learnt

Overall, a substantial improvement of Meuse water quality, as far as physical and chemical variables are concerned, was already observed since the early 1980s, thanks to sustained efforts at regional national and international levels (ICM, 2015). Similarly, measures taken over decades for restoring connectivity throughout the basin from the river mouth to small tributaries have resulted in encouraging results. A sure sign among others is the return of the emblematic Atlantic salmon. This is a good example how positive results can be achieved when restoration efforts are well-designed, supported by adequate scientific studies coordinated among different countries and regions and sustained over a long period of time.

The impact of numerous exotic species that have appeared in the Meuse since the 1990s remains a major concern. Navigation waterways opened immigration routes for aquatic organisms from different zoogeographic provinces, in particular the Ponto-Caspian area, following the reopening of the Main-Danube canal in 1992 (Leuven et al., 2009). Past invasions have been marked by transition in processes governing ecosystems (Pigneur et al., 2013; Marescaux et al., 2016a) and we have to keep in mind that invasions are still in progress (Beisel et al., 2017). Replacement of native species by new arrivals with original bio/ecological profiles (Marescaux et al., 2015, 2016b) may result in profound changes in the associated community and functioning of ecosystems. With the exponential increase in invasion rate of large hydrosystems (Beisel et al., 2017), we can predict that new exotic species will colonize the Meuse in the future, although nobody knows which species will invade and what will be the consequences of current and future invasions.

Habitat degradation, species invasions, climate change and chemical pollution are the main threats to the Meuse. A paradox is that in this changing world where we promoted the conservation of ecosystem services through the implementation of the Water Framework Directive, we still sorely lack data and integrated interdisciplinary studies. Key environmental drivers, such as temperature or habitat change, have to be monitored with a long-term perspective and a selection of river stretches should be considered as LTER (Long-Term Ecological Research) sites. This will feed knowledge to better define future restoration programs and to evaluate the benefits of implemented actions.

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