CHAPTER

7

The Loire River basin

Florentina Moatar[1], *Jean-Pierre Descy*[2], *Stéphane Rodrigues*[3], *Yves Souchon*[1], *Mathieu Floury*[1], *Cecile Grosbois*[3], *Camille Minaudo*[4], *Maria Leitao*[5], *Karl Mathias Wantzen*[3], *François Bertrand*[3]

[1]**INRAE, RiverLy, Centre de Lyon-Grenoble Auvergne-Rhône-Alpes, Lyon, France;** [2]**University of Liège, Liège, Belgium;** [3]**University of Tours, Tours, France;** [4]**University of Barcelona, Barcelona, Spain;** [5]**Bi-Eau, Angers, France**

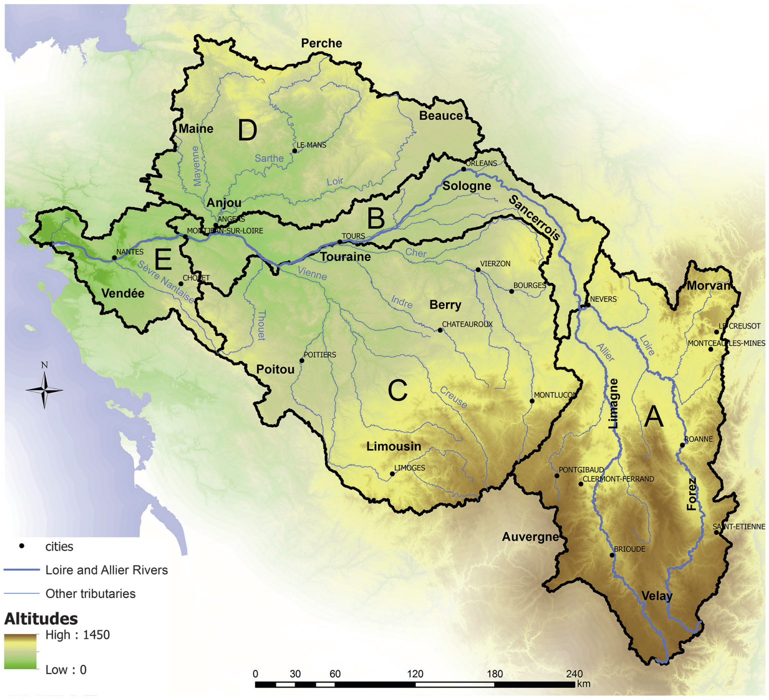
OUTLINE

7.1 Introduction

The 1012 km-long Loire River (source at 1408 m asl) has a catchment of 117,054 km^2 (20% of France) and an annual discharge of 843 m^3/s (mean annual discharge for the period 1863–2018, French Hydro Database www.hydro.eaufrance.fr) at the Montjean-sur-Loire station, the upstream limit of the dynamic tide (Fig. 7.1). The river flows north from the central Hercynian Massif then turns west near the town of Orléans, flowing over a sedimentary plain where it receives several tributaries from the western part of the Massif Central (Table 7.1). Finally, the river drains into the Atlantic Ocean after receiving tributaries from the Hercynian Massif Armoricain.

The Loire River and its first large tributary, the Allier (source at 1423 m asl 410 km long catchment 14,310 km^2), flow almost parallel from the heights of the Massif Central, south to their confluence downstream of the town of Nevers (Fig. 7.1 Area A). The largest urban areas in this upper catchment are Saint–Etienne and Clermont–Ferrand. The Loire then flows for ca 300 km until it merges with the next large tributary, i.e., Cher River (Fig. 7.1 Area B). More than 40% of the human population is concentrated in this valley and the adjacent valleys of the Loire and Allier basins.

Rivers of Europe, Second Edition
https://doi.org/10.1016/B978-0-08-102612-0.00007-9



Alti® 50 m IGN

FIGURE 7.1 Loire catchment and digital elevation model, its main drainage network and urban centers (BD Alti 50 m IGN): (A) Upstream Loire and Allier; (B) Loire Valley; (C) Cher, Indre, Vienne: tributaries rising in the west of the Massif Central; (D) catchment of the Maine; (E) subcatchment of the estuary.

Downstream of Nevers, the river crosses the Val de Loire, the site of the world famous castles and historic towns of Orléans, Blois, Tours and Saumur. Downstream of Tours, there is still a quarter of the river course to go and the network that drains almost 60% (66,000 km^2) of the Loire catchment becomes highly complex. Here, within a distance of ~100 km, the Loire receives water from four major tributaries, thereby increasing the mean annual discharge more than twofold; first the Cher (source at 717 m asl, 367.5 km long, catchment 13,906 km^2), then the Indre (source at 486 m asl 287 km long catchment 3000 km^2) and finally the Vienne (source at 920 m asl 372 km long catchment 21,105 km^2), which rises in the west of the Massif Central (Millevaches plateau, Limousin tables) (Fig. 7.1 Area C).

Here several towns, such as Montluçon, Vierzon and Bourges on the Cher, Chateauroux on the Indre, Limoges and Chinon on the Vienne, contribute to the anthropogenic pressure. The fourth tributary, close to the town of Angers, is the Maine (only 12 km long but with a catchment of 22,194 km^2), which rises in the Massif Armoricain (Fig. 7.1 Area D). Within this part of the catchment, human activities, settlements, industry and agriculture have developed considerably along the main stem and only about 10% of the population is found in subcatchments of the Loire valley. The subcatchment of the estuary begins downstream of Montjean-sur-Loire. This section is homogeneous because it is located entirely within the Massif Armoricain. It is low-lying with an oceanic climate. Land use is similar to that of the basin of the Maine and it is marked mainly by two rapidly expanding urban areas—Nantes (approx. 900,000 inhabitants) and Saint-Nazaire (Fig. 7.1 Area E) (Dupont et al. 2016). In general, land use becomes increasingly intense downstream and toward the west. The human population is expected to increase in the middle and lower Loire and around urban centers, while large upstream regions are likely to become less populated.

In the upper Loire basin, the Loire and Allier flow alternately through gorges (in which several dams have been built) and small alluvial plains. This is a scattered landscape with volcanic and granitic areas favorable for livestock farming, which contrasts with the depressions of the tectonic basins, such as the sediment-filled Limagnes, suitable for agricultural activities. Several towns (Le Puy, Roanne, Digoin, Decize and Nevers on the Loire and Clermont–Ferrand, Vichy and Moulins on the Allier) use water from the rivers. Despite more industrialization than in the middle and oceanic Loire basins, this area is experiencing a decline in agriculture and population size, particularly in the highlands.

From the Allier confluence downstream of Nevers to the Cher, the middle Loire flows over calcareous tables and sedimentary alluvial valleys with meandering stretches, gravel islands and sand banks. This is where the Val de Loire starts and where the channel was

TABLE 7.1 General characteristics of the Loire catchment and its main subcatchments

	Upstream Loire and Allier (Area A)	**Loire valley (Area B)**	**Cher, Indre, Vienne (Area C)**	**Maine (Area D)**	**Estuary (Area E)**	**Loire catchment**
Surface (km^2)	32,616	9,888	43,451	23,984	7,564	117,503
Mean elevation (m)	1009	211	482	216	145	412
Maximum elevation (m)	1850	382	953	416	290	1850
Mean annual precipitation (mm) (1981–2010)	904 (549–2130)	737 (626–981)	830 (562–1567)	748 (600–1303)	839 (659–1101)	811
Mean air temperature in July (°C) (1981–2010)	25.1 (17.4–28.1)	26.0 (25.1–26.9)	25.8 (21.5–27.3)	25.0 (22.1–26.5)	25.1 (22.7–26.3)	25.4
Mean air temperature in January (°C) (1981–2010)	2.2 (−1.9 to 4.4)	3.9 (3.0–4.9)	4.2 (1.4–5.8)	4.4 (3.4–5.6)	5.6 (4.5–6.7)	4.1
Mean annual specific discharge (L/s/km^2)	11.5 (3.7–37.3)	4.6 (3.1–8.4)	7.3 (4.1–24.6)	6.5 (2.8–14.8)	-	7.5
Lakes - volumes (million m^3)	142				96	238
Ponds - volumes (million m^3)	12	14	37	3	10	76
Dams reservoirs - volumes (million m^3)	584		342	10	40	976
Population density (people/km^2)	64	81	42	98	191	72

developed for navigation, although it is little used today. It is also an area that has a rich heritage of abbeys and royal castles. With several cities, three nuclear power plants and extensive agriculture, water use is a major issue here. In the central region, up to 70% of the land is used for agriculture (cereals, sugar beet), which has resulted in a loss of woodland and hedgerows. There are several forests and small lakes in the Sologne and the vineyards of the Loire extend over a large part of the area. Before it reaches the granitic Massif Armoricain, three tributaries (the Cher, Indre and Vienne) flow into the Loire within a distance of 30 km and in Angers it is joined by the Maine. The fourth power plant is located in this stretch of the river. Anthropogenic impact is more pronounced in the granitic Massif Armoricain (livestock production, mainly dairy and pigs) than in the granitic Morvan or Limousin.

7.2 Historical background

The Loire basin has probably been occupied by humans for 500,000 years. Numerous traces of the Bronze and Iron Ages occur along the river. Since prehistoric times, man has made use of the river by fishing, hunting and collecting aquatic vegetation. The prehistoric dugout canoes were replaced by flat-bottomed barges ("gabares" and "toues") and the "Marine de Loire" was active up to the 19th century (Dumont, 2010). Since the Gallo–Roman period, human activities (deforestation, agriculture, livestock farming, establishment of villages and towns, navigation) had direct impacts on the river by increasing erosion and suspended sediments, straightening meanders and isolating side arms (Bravard and Magny, 2002). In the Middle Ages, "turcies" and then levees were built along 530 km of the river for flood protection. There were also a large number of water mills which replaced the 6th-century boat mills that hung from bridges. Canals and aqueducts were also built (Burnouf et al., 2003; Courant and Cussonneau, 2003).

Navigation is now limited to the estuary, but in earlier times the river was largely navigable from the Massif Central, as evidenced by toll payments during the golden age of river navigation (Dubois-Richir, 2003). This was the period when goods such as tiles were shipped upriver from Angers and salt, hemp, and then coal were transported downriver from the upper Loire, while wine from the Auvergne was carried along the Allier (Dumont and Arthuis, 2016). The famous wines from the Val de Loire were transported from Roanne to Nantes. The canals of Briare and Orléans were abandoned at the end of the 19th century, but have recently been restored for tourism. Over the course of time, the river has been transformed by human activities, such as channel clearing, burning trees, draining marshes, straightening meanders and extracting sand from the river bed. The focus today is on sustainable development.

7.3 Geology and paleogeography

The Loire basin is characterized by various lithologies that influence its configuration and the shape of its valley (Alcaydé et al., 1990; Nehlig, 2010). The three identified units are from upstream to downstream: i) the Massif Central (representing part of the Hercynian chain 300 Ma); ii) the Paris basin characterized by sedimentary rocks deposited from the Triassic (250 Ma); and iii) the Massif Armoricain resulting from the Hercynian Orogeny (Fig. 7.2).

These three geological units and their deformation form the basis of the hydrographic network of the Loire and its tributaries and are the source of the sediments they transport and deposit at the surface of the watershed. They also influence the distribution of aquifers in the catchment area. From a hydrogeological point of view, the upstream basin of the Loire (the Massif Central) is characterized by small groundwater aquifers. Nevertheless, some may contain drinking water of good quality (e.g., Volvic). In the Paris basin, larger aquifers are used for drinking water and agriculture. These aquifers comprise the alluvial aquifer of the Loire Valley, the limestone aquifer of the Beauce, the Cretaceous chalk aquifer at Blois, the Cenomanian and Albian sand aquifer in Touraine, and the Jurassic limestone aquifer in Berry. The sedimentary nature of the soil of the Paris basin favors the development of an underground hydrographic network (Karst), whose resurgences feed the sources of some tributaries of the Loire such as the Loiret (Albéric, 2004). In the Massif Armoricain, sedimentary rocks (tertiary formations and recent alluvium), although scarce, constitute substantial water resources. The fractured formations of the Hercynian basement also have some water reserves.

Since the Cenozoic, tectonic constraints led to the establishment of alluvial formations on one-fifth of the Loire basin (see Figure 4 in Nehlig, 2010). The formation of the Limagnes during the Oligocene (30 My) and the uplift of the Massif Central during the Miocene (15 My) induced the north-south and east-west flow and the eccentric positioning of the Loire in its basin (Nehlig, 2010). From the lower Miocene (20 My), some of the solid fluxes from the Massif Central were added to those of Lake Beauce before reaching the "Mer des faluns" in the region of Blois (Rasplus, 1978). In the Pliocene (5 My) and Pleistocene (2 My), the uprising of the southern part of the Massif Armoricain redirected the flow along a south-north axis. The presence of fluvial deposits from the Massif Central indicates possible connections and capture of the Loire flow by the basin of the Seine

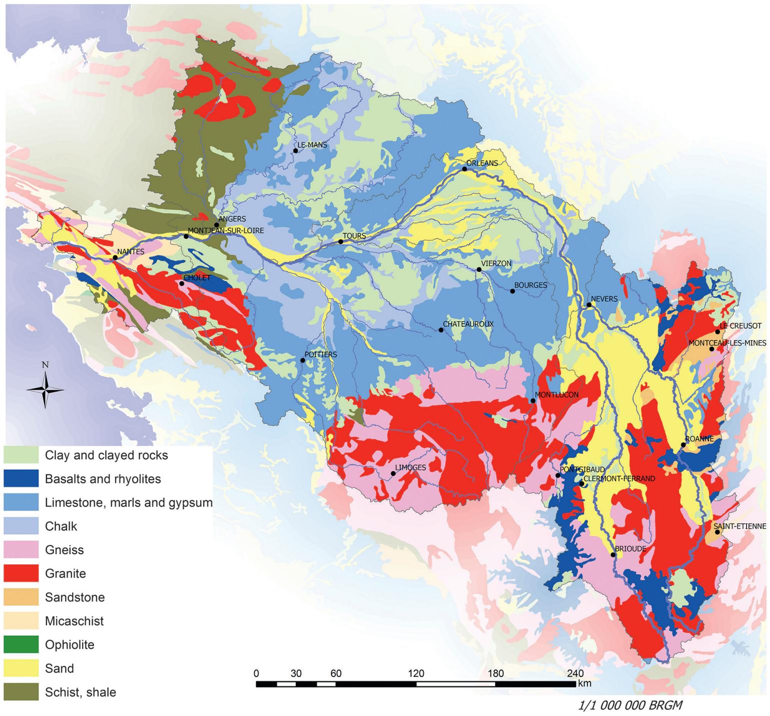


FIGURE 7.2 Various lithologies in the Loire basin.

between the Miocene and the Quaternary (Tissoux et al., 2013). The presence of sands rich in augite (mineralogical marker of the volcanism of the Massif Central) in the Seine basin is evidence of these connections between the two basins. This part of the geological history of the Loire basin is currently highly debated (Etienne and Larue, 2011). In the Pleistocene (Tourenq and Pomerol, 1995), the flow abandoned the south-north route in favor of an east-west route with possible connections to the Vilaine Estuary (Brault et al., 2001).

During the Quaternary period, the erosion and sedimentation phases related to climatic variations and the uplift of the Paris basin (alpine orogeny) led to the general incision of the river network of the Loire and its tributaries and the appearance of terraces (Macaire 1983; Debrand-Passard, 1998; Colls et al., 2001; Voinchet et al., 2010). The river now flows over Weichselian Holocene and submodern alluvial deposits (Brossé, 1982). Climatic variations in the Weichselian and Holocene led to significant changes in solid flows (granulometric nature and quantity) of the Loire and thus its morphology. The development of human societies in the second half of the Holocene also modified the balance between liquid and solid flows in the basin and thus the morphology of the tributaries (Morin et al., 2011) and river (Garcin et al., 1999; Gourry et al., 2003). These dynamics can be illustrated by the Val d'Orléans, where the river changed from a braided style to a meandering style between the Pleniglacial and Holocene (Castanet, 2008) (Photo 7.1).

PHOTO 7.1 A typical riffle-pool succession in the upper Loire in a granitic catchment of the central Hercynian Massif. @ Etablissement Public Loire.

7.4 Fluvial geomorphology and sedimentology

From a geomorphological point of view, in the Massif Central, the Loire and Allier flow in gorges and grabens (tectonic depressions). The gorges of the Loire are carved in the granite while those of the Allier are made of granite and metamorphic rocks. The grabens delimited by north-south faults are characterized by tertiary lacustrine and marine fills (Eocene/Oligocene).

Volcanic rocks are also present in this part of the basin (Cantal, chaine des Puys, Cézallier, Devès, Mont-Dore, Sancy, Velay). From its source to Roanne, the average slope of the Loire is 3.8%. Except in the plain of the Forez, the upper Loire flows through gorges that prevent lateral migration and development of a flood plain. There are two major dams in this section (Grangent and Villerest upstream of Roanne). From Roanne to the confluence with the Allier (Bec d'Allier), the Loire has a wide flood plain with wandering meanders (e.g., between Diou and Imphy), sometimes stabilized by bank protection. The slope of the Loire decreases to 0.7% in this section (the Limagne Bourbonnaise and foothills of the Morvan),. The upstream section of the Allier (from the source to Vielle Brioude) is characterized by slopes between 2% and 10%, coarse granularity of sediment (pebbles) and a sinuous or even meandering channel planform. The slope of the bed then decreases (1.5‰) and the valley widens in the Limagne Brivadoise, allowing significant meandering upstream of Issoire. From Clermont-Ferrand, the Allier flows through the Limagne (slope 1‰). Active meanders (lateral scouring/deposition cut-offs) highlight the energy of the fluvial system in this area and its capacity to maintain ecological succession and floodplain rejuvenation (Geerling et al., 2006).

In the Paris basin, characterized by a monoclinal structure of the Mesozoic and Cenozoic, the Loire is joined by tributaries on the left bank (Cher, Vienne, Indre). After the Bec d'Allier, levees demarcate the embanked bed whose width varies between 500 and 800 m between Nevers and Angers. Downstream of the Bec d'Allier, the fluvial pattern of the Loire is anabranching with many channels and alluvial bars around wooded islands. From the Bec d'Allier to Briare, levees are discontinuous, relatively low and far from the channel. Downstream of Briare, levees are closer, the planform becomes almost straight and the number of channels and width of islands decrease. The slope in this area is close to 0.5%. Upstream of Orléans, the channel has high-amplitude meanders in a relatively large valley (area of Guilly). The single channel configuration continues up to Tours. The valley becomes narrower as it passes through the carbonate complexes of Touraine up to the Bec de Vienne (near Montsoreau). The confluences of the Loire with its large tributaries (Cher, Vienne) occur in a sector characterized by large number of secondary channels, islands and alluvial bars; the slope is 0.4% and the active band near 330 m. In this section, the development of ports and towns has often led to the construction of groynes and facilities to improve navigation (e.g., Givry, Orléans, Tours, Chouzé-sur-Loire).

At Les Ponts-de-Cé, the Loire enters the Massif Armoricain, where it is guided by the undulating terrain formed of granite, gneiss and micaschists, as well as primary sedimentary cover. This section is characterized by the omnipresence of structures to facilitate navigation, as well as islands, often reinforced by riprap. The slope of this section is close to 0.2%, tidal action is felt up to Saint Florent Le Vieil (50 km upstream of Nantes), while the salinity front is located in the sector of Nantes (Le Hir and Menesguen, 2016).

In addition to considerable material from the Paris basin, the sediments of the Loire are mainly siliceous, arising from the supply zones of crystalline and volcanic rocks in the upper basin. The amount of crystalline material has varied over time, mainly due to climatic variations occurring during the Weichselien and Holocene periods (Macaire et al., 2013). Most sediments are composed of coarse sand and gravel, although pebbles are dominant in the upper basin. A mineralogical study of the sands of the Loire riverbed shows that they are composed of at least 21 different minerals, mainly feldspars (about 33%), rock fragments (30%) and quartz (27% on average). Sand mineralogy and granularity of alluvium appear to influence their natural radioactivity (Patryl, 2000). Particle size of the sediments of the bed of the Loire and of its major tributaries varies considerably (Table 6.1 in Rodrigues et al., 2016a) and decreases downstream. In its middle reaches, the Loire is considered a sand-gravel river. Between Decize and Oudon, the mean grain size is 1.6 mm and lateral grain size variability within the main channel is sometimes greater than the longitudinal variability within this morphological unit. The particle sizes mentioned here indicate a high sediment mobility, even for low bed shear stress (Rodrigues et al., 2015). In the middle reaches of the Loire, sediments are therefore in nearly constant motion (at least the sands) and feed the migration of bedforms within the channels (ripples dunes bars). The migration speed of these forms depends on the geometric characteristics of the channel (slope width-to-depth ratio) and hydrology. These bedforms can migrate *ca.* 1 m/day or more during average and low water flow conditions and up to several tens of meters per day for dunes during floods (Claude et al., 2014; Wintenberger et al., 2015b). Sediments passing through secondary channels can be stored for several years, decades and more (Rodrigues et al., 2006, 2012). The river bedload has been calculated by directly measuring solid fluxes using sediment samplers and analyzing bedform migration. For the year 2010, 480,000 t of sediment (i.e., 8.5 t/km^2/year) were transported as bedload in the Bréhémont sector (30 km downstream of Tours) (Claude, 2012; Claude et al., 2012). Solid discharge and sediment transport capacity have recently been quantified, highlighting the major contribution of the Allier and to a lesser extent the Vienne (see Table 6.2 in Rodrigues et al., 2016a).

The active sediment dynamics of the Loire are the basis for its diversity of habitats. In this respect, the Loire differs from other major French rivers by allowing the recruitment of pioneer wood communities (Wintenberger, 2015). The dynamics of sedimentary bars (free [migrating] or forced [nonmigrating] bars) play a major role in this process (Wintenberger et al., 2015a). Feedback from vegetation on both liquid and solid fluxes (Euler et al., 2014) often leads to a particular topographic signature (Rodrigues et al., 2007; Wintenberger et al., 2015a) and to the transformation of bars into islands by sediment storage and accretion. This process is fast in the early stages (Fluvial Biogeomorphic Stage = geomorphic stage) and slow when the island becomes significantly disconnected from the surrounding channels (FBS = ecological stage). In the estuarine section, sediment dynamics vary according to the flow of the river and the tide. The meeting of these water bodies leads to the appearance of high levels of turbidity which extends over about 15 km and whose concentrations in suspended matter can reach 5 kg/m^3 (Mignot and Le Hir, 1997; Rodrigues et al., 2016a). This high level of turbidity can lead to hypoxia, or even anoxia, due to the degradation of organic matter. The high turbidity of water can also prevent primary production and impair water quality for some uses (drinking water supply agriculture industry, etc.) and disrupt the migration of some fish species. The position of this maximum turbidity varies longitudinally according to the river regime and tidal intensity. Its maximum extension upstream (sector of Nantes-Sainte Luce sur Loire) was largely influenced by the incision of the Loire bed in its downstream and middle reaches.

Rapid incision of the main channel is mainly due to human activities in the Loire and its basin: embanking, construction of navigation groynes and river-training structures, massive sediment, mining in the bed up to the mid-1990s, riprapping of the banks and construction of dams on the Loire (Grangent 1956; Villerest 1988) and its tributaries (Poutès, 1941; Naussac, 1983). This incision is accompanied by side effects such as the destabilization of civil engineering structures, disconnection of the main channel, with secondary channels subjected to vegetal development (Rodrigues et al., 2006 2007) and lowering of the alluvial water table. This phenomenon results in a significant decrease in the active width (Latapie et al., 2014; see Fig. 7.2 in Rodrigues et al., 2016b), reflecting an accelerated evolution toward a single channel style and by an overall loss in ecological richness, accompanied by the disappearance of alluvial softwood forests. The widespread incision of the main channel of the Loire was accompanied by a lowering of the low-water line on the order of −1 to −2 m in the plain of the Forez (between 1921 and 2001), from −1 m at Givry −0.5 at Gien -1.5 m downstream of Orléans, -2 m at Tours -0.8 m at Langeais, -1 m at Saumur, -1 m at Montjean-sur-Loire and -3 m at Ancenis between 1900 and 1978 (Gazowsky, 1990). In some areas, excavation of the bedrock associated with this incision has had profound consequences on aquatic habitats. At the same time, intense plant development on marginal areas that are less often flooded (secondary channels, ox-bow channels and alluvial bars) also contributes to the increased risk of flooding by reducing flow capacity during episodes of floods (Photo 7.2).

PHOTO 7.2 The meandering middle Loire and the nuclear power plant of Belleville-sur-Loire (km 500). @ J. Roché.

7.5 Climate and hydrology

Climate of the Loire basin is fairly varied; a mountain climate with Mediterranean influences in the Cévennes in the Massif Central, and mainly oceanic in the middle and downstream reaches. Annual precipitation ranges from 500 to 2100 mm and is below 800 mm (the average for mainland France) across the whole sedimentary basin and sedimentary depressions of the valleys of the Upper Loire and Allier. This variability of climate and geology results in a wide variety of hydrological regimes; 8 of 12 regimes identified in France are found in the Loire basin (Sauquet et al., 2008). More than 50% of the monitoring stations have a pluvial regime with long and marked low-water levels in summer. The flow of some rivers is $< 5\,\mathrm{L\,s^{-1}\,km^{-2}}$ between June and October and can be as low as $2\,\mathrm{L\,s^{-1}\,km^{-2}}$ in August and September. Some rivers in the upper basin of the Vienne and Limoges Plateau and in the lower part of the Massif Central have abundant streamflow between January and May ($27\,\mathrm{L\,s^{-1}\,km^{-2}}$) due to high rainfall and some snowmelt. Rivers in the upper basin of the Loire and Allier have a pluvionival regime, while some of the most upstream rivers are influenced by autumn rainfall of the Mediterranean (Moatar et al., 2016). In the Paris basin, flow of some rivers is sustained during summer by the calcareous aquifer of the Beauce, particularly in the northern part where 83% of the effective rainfall percolates and 86% of this amount is drained by rivers (Monteil, 2011; Baratelli et al., 2016).

The Loire River is characterized by an irregular flow with extreme low water levels in summer (during the historic low water periods in 1870 and 1921 the flow in Orléans was about $10\,\mathrm{m^3/s}$) and significant floods (*ca.* $6000\,\mathrm{m^3/s}$ during the historic floods of 1856) (Dachary, 1996; Duband, 1996, 2010). In the 1980s, two dams were constructed, one on the Loire (Villerest $235\,\mathrm{Mm^3}$) and the other on the Allier (Naussac $190\,\mathrm{Mm^3}$), to create reservoirs to release water during low flows in the Middle Loire and to take in excess water during high flows (Villerest). Releasing water during low flows makes it possible to maintain an objective flow in the Middle Loire of about $60\,\mathrm{m^3/s}$ and $55\,\mathrm{m^3/s}$ in the last few years. The calcareous aquifer of the Beauce also provides input to the Loire between Orléans and Blois with a mean of $6\,\mathrm{m^3/s}$ in summer and $13\,\mathrm{m^3/s}$ in winter; these figures are established by hydrogeological modeling (Baratelli et al., 2016), by energy balance derived from water temperature sensors (Moatar and Gailhard, 2006; Beaufort et al., 2020) and **infrared satellite imaging** (Lalot et al., 2015). Upstream of Orléans, local karstic formations have been identified, giving rise to the Bouillon resurgence (spring of the Loiret River) (Binet et al., 2017; Albéric, 2004).

The capacity of the aquifer system of the Loire basin to sustain flow throughout the summer is relatively weak. Average interannual flow of the Loire at the Montjean-sur-Loire station is $843\,\mathrm{m^3/s}$ and the input from aquifers accounts for only 12% of the total flow. Consequently, the drainage system of the Loire basin is particularly sensitive to climate variations. Trends of various hydrological indicators have been established from time series of flows measured between 1968 and 2008. Some stations, mainly located upstream, indicate a significant decrease in mean annual flow, and minimum annual flow, as well as earlier low-flow periods (Giuntoli et al., 2013). These findings indicate a reduction in the water resource and aggravation of low-flow periods in the Massif Central. In contrast, there was no indication of any significant consistent pattern of regional change in high water levels during this period. However, these results should be seen in the context of the relatively short period of analysis (40 years). Hydrology is a powerful spatial/temporal integrator of meteorological conditions. Hence, time series of flows express meteorological variations not only over short time scales (daily seasonal annual) but also at multidecadal scales (Fig. 7.3). Consequently, significant variations in flow are found at the multidecadal scale. Representation of

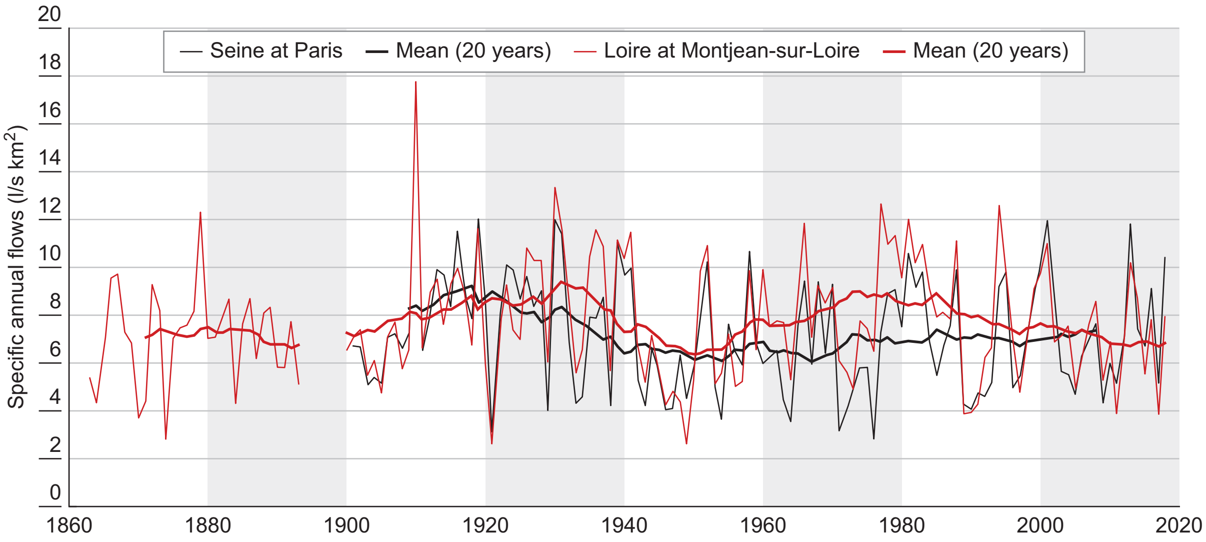


FIGURE 7.3 Illustration of multi-decadal variations on the Loire and Seine through representation of specific annual flows (bars) with their moving averages over 20 years (in *bold lines*).

the specific annual discharge of the Loire and Seine and their moving average over a period of 20 years clearly illustrates cycles lasting approximately 50 years, with changes in flow of nearly 30% mainly caused by the contribution of spring flows (Boé and Habets, 2014).

In the Loire basin, 14 large-scale climate projections, based on several international climate models (GIEC Ar4) for the median emission scenario (A1B) were used to study the possible impact of climate change (Moatar et al., 2010; Vidal et al., 2016). Using a statistical downscaling method, climate projections were integrated into a hydrological model to simulate the possible impact of climate change with two time horizons: 2046−65 (mid-century) and 2081−2100 (end of century). Based on these two horizons, climate change can be characterized across the whole basin by an average annual warming of 2°C (±0.4) at mid-century and of 3°C (±0.7) at the end of the century. It will be greater in summer and autumn, reaching nearly 4°C in August at the end of the century. This warming will be accompanied by an increase in potential evapotranspiration. There will be greater spatial and seasonal variations in changes in total monthly rainfall, with a sharp decrease in summer/autumn, but slight increases in spring, although this signal is much less certain.

To transform climate projections into hydrological projections, we used two hydrological models that were also used in the Seine basin (Habets et al., 2013). At Montjean-sur-Loire (109 930 km^2), the most downstream hydrometric gauging station not influenced by the estuary, the EROS model indicates a 30% decrease in the annual flow with 15% uncertainty. Looking at seasonal variations along the Loire and its main tributaries, the decrease in flow has a greater impact on low water than high water, the latter showing a less marked decrease. The pattern of a decrease in average flow and in flow during low-water periods, and of longer low-flow periods, is found in both hydrological models. Moreover, climate projections also allowed simulation of piezometric levels, showing a decrease in the average level compared to today, on the order of 1 meter at mid-century and 1.8 m at the end of the century for half the basins studied. These drop in level would lead to a decrease of 8%−50% in the input to the Loire from the aquifers compared to the present day. This fall in input would thus lead to a decrease in flow during low-flow summer periods and to a rise in water temperature, which has already been observed in the Middle Loire based on time series measured since 1976 (+2°C in 30 years) and reconstructed time series going back to 1881 (Moatar and Gailhard, 2006; Floury et al., 2012). Based on these climate and hydrological projections, the mean annual increase in water temperature simulated with the median emission scenario (A1B) would be 2°C−3°C at mid-century (Bustillo et al., 2014).

7.6 Biogeochemistry, water quality, and ecosystem processes: status and trends

Nutrients, organic and mineral pollutants input resulting from agricultural, urban and industrial activities in the Loire River drainage basin shape the water quality of the river (Garnier et al. 2018; Grosbois et al. 2012). Stream biogeochemical processes are governed by the drainage basin input from these above-mentioned anthropogenic activities and the timing magnitude of their delivery to the river network (Minaudo et al. 2018). Domestic, agricultural, and industrial wastes discharged into the rivers of the Loire basin cause significant nitrogen and phosphorus pollution (Fig. 7.4). Throughout the basin it is estimated that 20 tons of nitrogen and 3.9 tons of phosphorus are discharged directly into rivers every day from domestic and industrial wastewater treatment plants. Urban pressure is particularly strong near the headwaters in the Upper Loire and Allier basins because the large urban areas of Clermont-Ferrand and Saint- Etienne discharge their waste into water bodies with low dilution capacity. However, point-source discharge of phosphorus has sharply decreased in the last 20 years following new regulations. For example, in the urban area of Tours, daily phosphorus discharge has decreased by a factor of 20 over the past 20 years (i.e., from 400 kg P d^{-1} to 20 kg P d^{-1}). In contrast, non-point sources like agricultural fertilizer use (e.g., in the Paris basin) and livestock pressure (e.g., in the Massif Armoricain) continue to contaminate surface water and groundwater (Minaudo, 2015), which eventually flows to the Loire River.

The Loire basin comprises 708 small agricultural regions that are grouped according to farming practices into three zones called “agro-zones”, each having a unique influence on river biogeochemistry. These agro-zones follow an upstream-downstream gradient and correspond roughly to catchment lithological boundaries (crystalline metamorphic and sedimentary), which further influence the transport of pollutants from the soil to groundwater (Fig. 7.2). A good indicator of agricultural non-point-source pollution is the surplus of nitrogen and phosphorus in soils. A surplus of these two elements in soil represents fertilization compared to uptake by crop production. Soil surpluses exceeding 60 kg N/ha/year and 30 kg P/ ha/year are found in agro-zones of intensive agricultural activity like the Middle Loire (Parisian basin) and the downstream Massif Armoricain (particularly the Maine and Se′vre basins) (Poisvert et al., 2017). The highest levels of nitrogen surplus are found in the Lower Loire, with up to 110 kg N/ha/year for arable land and 150 kg N/ ha/year for permanent pasture. However, not all of this nitrogen makes it to the river because pastureland soils can

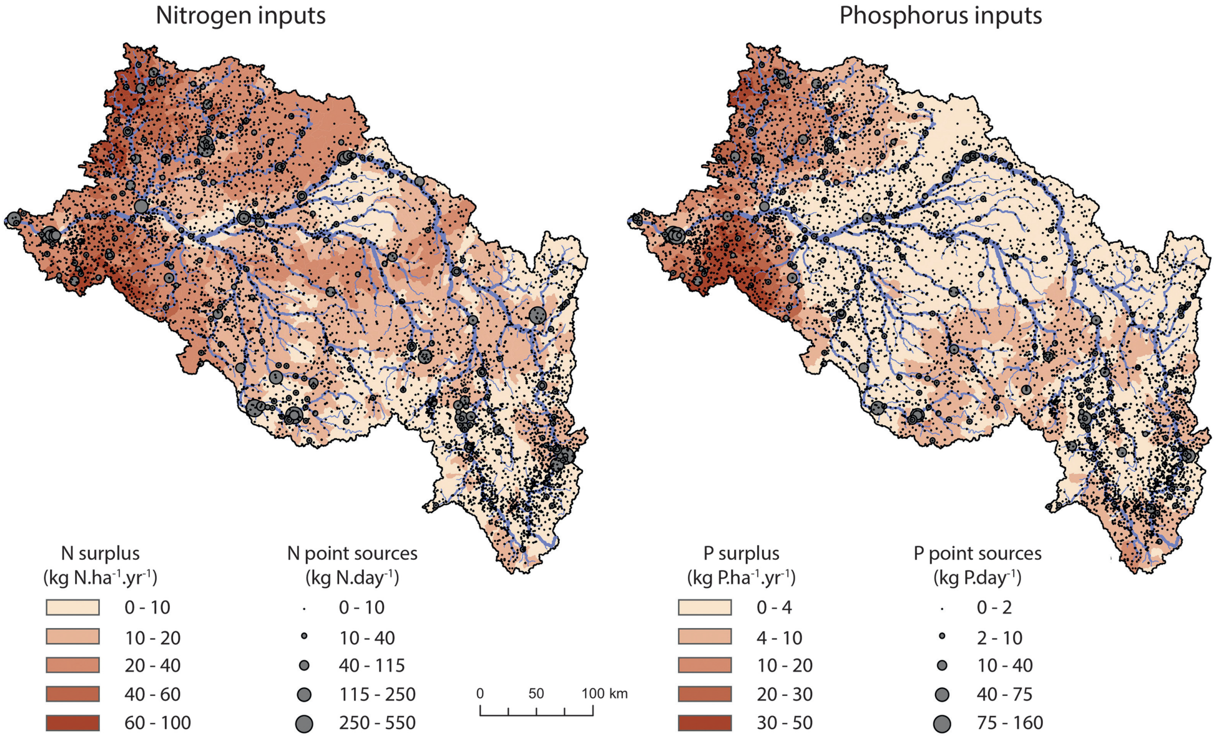


FIGURE 7.4 Anthropogenic input of nitrogen and phosphorus in the Loire basin in 2010. Agricultural surpluses derived from the NOPOLU 2010 model (*left panel*). Discharge from wastewater treatment plants derived from data of the Loire-Bretagne Water Agency (*right panel*).

absorb up to 100 kg N/ha/year of the surplus (Billen et al., 2012; Anglade et al., 2015). Nevertheless, the surplus remains high; most groundwater is polluted by nitrate while soils and sediments are polluted by phosphorus.

The Loire is particularly vulnerable to eutrophication because the summertime low-flows are spread out into multiple channels. This combination of branching geomorphology and hydrology results in shallow, slow moving water, leaving phytoplankton ideal conditions to develop. Eutrophic conditions reached a peak in the late 1970s (Fig. 7.5), with extreme concentrations of phytoplankton (>250 mg/L chlorophyll a during summer) in the Middle and Lower Loire basin (Crouzet, 1983; Moatar and Meybeck, 2005). These eutrophic conditions were associated with a high diversity of phytoplankton species (Leitao and Lepretre, 1998; Abonyi et al., 2012, 2014) and high rates of primary production (daily amplitudes of 12 mg O_2/ L and 1 unit pH (Moatar et al., 1999, 2001). At this peak of eutrophic conditions, the estuary of the Loire was regularly anoxic in summer due to degradation of labile organic matter (Etcheber et al., 2007). During eutrophic periods, approximately 50% of this labile organic matter (measured as particulate organic carbon) available in the estuary was produced by phytoplankton within the Loire River (Minaudo et al., 2015).

Since the mid-1990s, there has been a nearly twofold decrease in orthophosphate concentrations, a clear sign of efforts related to point-source pollution reduction. Following this reduction in phosphorus, indicators of eutrophication such as phytoplankton and cyanobacteria biomass (Minaudo et al., 2020), and daily amplitudes of dissolved oxygen and pH decreased by a factor of 2.5 (Moatar et al., 1999, 2001; Minaudo et al., 2015). These decreases are thus at least partly explained by the strong control of phosphorus on phytoplankton growth (Descy et al., 2011; Minaudo et al., 2018), but may also be explained by *Corbicula* sp. clam colonization starting around the year 2000. *Corbicula* sp. is an invasive filter-feeding bivalve mollusk with a high capacity to reduce phytoplankton concentrations (Floury et al., 2017; Latli et al., 2017). Regardless, this marked decrease in eutrophication consequently reduced organic matter input into the estuary system. Particulate organic carbon generated by phytoplankton has decreased from approximately 100K tons/year in 1994 to less than 25K tons/year in 2012 (Minaudo et al., 2016). However, excess nitrogen input continues to produce “green tides” on the coast and colored water in the coastal area around the Loire Estuary.

The quality of the Loire basin regarding metallic and organic compounds can be seen in its sediment quality. Trace elements have been largely studied in Loire river

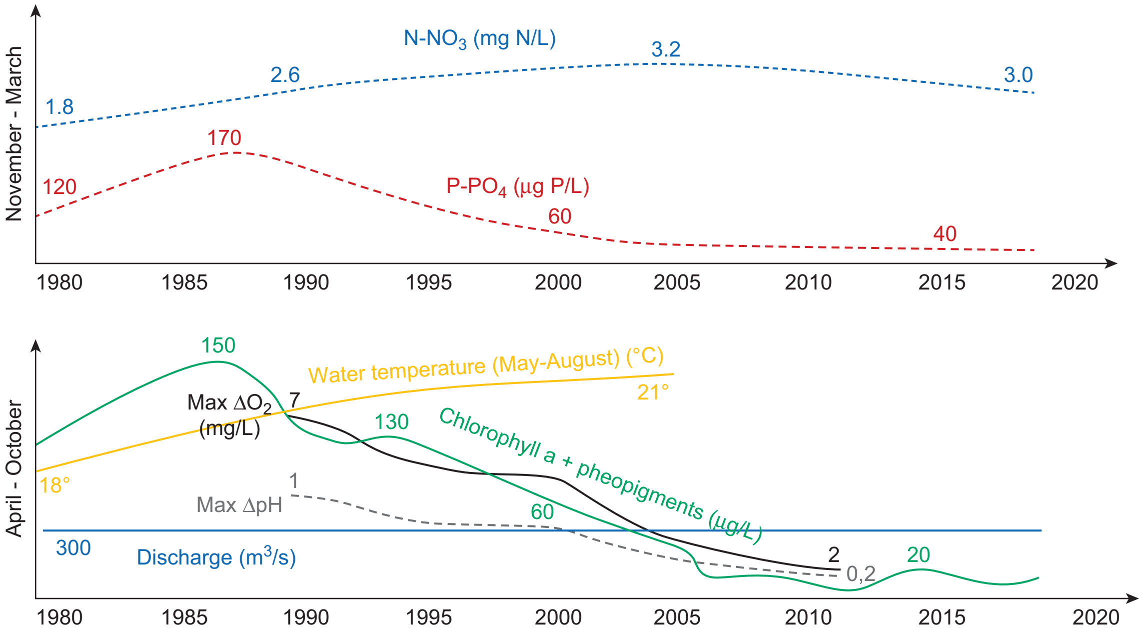


FIGURE 7.5 Conceptual diagram of the development of eutrophication (chlorophyll a daily variations of dissolved oxygen and pH) and its control factors (nutrients, temperature, flow) in the Middle Loire in winter (November to March) and summer (April to October) since 1980.

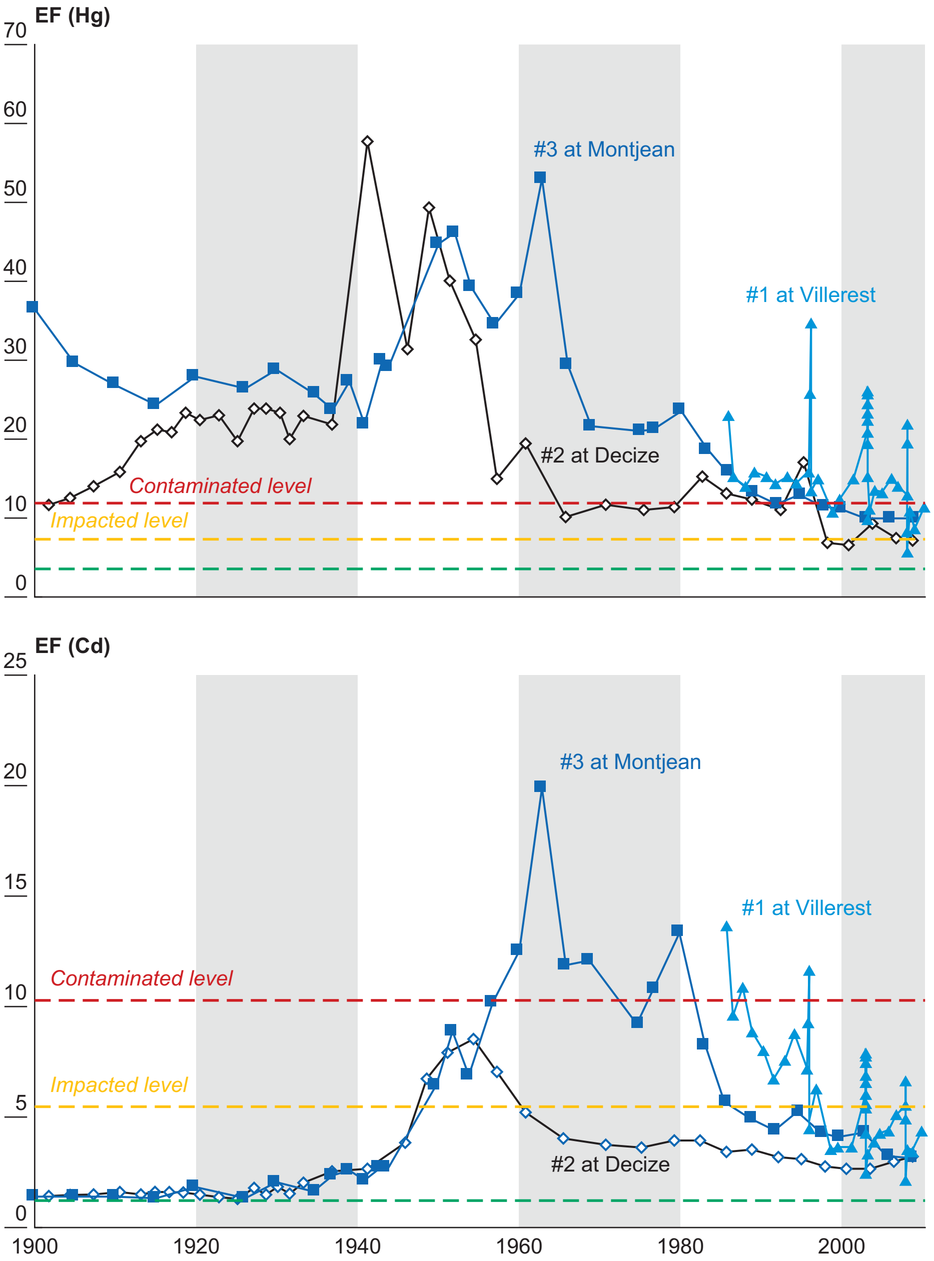
sediments since the late 1990s, while studies on spatio-temporal distribution of organic and emerging compounds only began in the late 2000s (Bertrand et al., 2015; Couderc et al., 2015; Lemarchand et al., 2010), later than in other European basins. For trace elements, mercury and cadmium are the most enriched trace elements in the river bed and bank sediments when compared to pristine concentration levels at the basin scale (Coynel et al., 2016; Grosbois et al., 2012; Dhivert et al., 2015). Some subbasins and the estuary present specific enrichments related to geochemical anomalies and local anthropogenic activities, mostly linked to coal, gold and other ore mining and associated activities. For example, the upstream basins of the Allier and Vienne are enriched with As; there is Sb in the Allier, Mayenne and Vienne subbasins; and Pb in the reach between Saint Etienne and Tours (Négrel and Pételet, 2012). Sediments of the Loire basin can be highly enriched in trace elements but less than in the Seine and other European basins (Grosbois et al., 2012).

The most representative period of these multi-elemental enrichment maxima in the basin was 1945–late 1970s (Fig. 7.6). Trace element concentrations started to decrease by the end of the 1960s in the most upstream part of the basin and during the 1970s further downstream (Fig. 7.6). This decrease is probably connected to the closure of mining and metallurgical activities in France (especially coal and Au-Sb mining), improvements in urban and industrial effluent treatment and reduction of industrial leaks associated with environmental regulations (Dhivert et al., 2016).

In contrast, the Loire is one French river with the highest levels of natural radioactivity (Eyrolle et al., 2008). Together with the Rhône, it was also one of the river pioneers for nuclear electricity production since the late 1950s. Based on the 1987–2008 survey of radioactive elements in sediments, most radioactivity is of lithological origin and more specifically linked to contained in granitic minerals. Levels of radioactive isotopes with an artificial origin (^{60}Co, ^{58}Co, ^{124}Sb and ^{110}Ag) are more than 2 orders of magnitude lower than the natural level (Eyrolle et al., 2008). The ^{40}K level is mainly linked to phosphate and potassium hydroxides mineral fertilizers used in agricultural practices. Nowadays, radioactivity levels due to artificial and agricultural practices have considerably decreased.

One of the most important questions when dealing with contaminants is the potential transfer of contaminants to biota living in surface waters. In the Loire basin some studies have surveyed specific indicator species such as the great cormorant, eel, otter, osprey and catfish to identify the potential influence of river quality on biota. According to Lemarchand et al. (2010, 2014), trace elements are still present in the liver of these sentinel species, whatever their age or sex, and more specifically mercury (more than the potentially toxic level of 4 µg/g Hg). These results show a legacy effect of anthropogenic activities using inorganic contaminants in biota. In contrast, among all the persistent organic pollutants that have been surveyed, only organochlorine pesticides (mainly DDE) and some indicator PCBs had higher levels than recommended toxic threshold values in the

FIGURE 7.6 Temporal evolution of Hg and Cd enrichment in sediments of 3 stations of the Loire basin (#1 the most upstream station in the Villerest Reservoir; #2 the station at Decize, just upstream of the Loire-Allier confluence and #3 just upstream of the estuary at Montjean). The enrichment is calculated as an enrichment factor (double normalization to Al composition and natural geochemical background; Grosbois et al. 2012) and 3 different levels are visualized (poorly impacted, close to a natural origin; moderately and highly contaminated).



basin (Lemarchand et al., 2014; Couderc et al., 2015). In the Loire Estuary, some other organic compounds have also been detected in eels, including PBDE and PFAS. When compared to other large rivers, the ecosystem of the Loire and its estuary are influenced by persistent organic pollutants.

7.7 Aquatic and riparian biodiversity

The Loire River flows partly through two continental ecoregions (Massif Central and southern Bassin parisien) and partly through two Atlantic ecoregions (south Atlantic and Brittany). These interactive components are integrated in the six hydroecoregions delineated by Wasson et al., (2002). These authors underlined that, in the case of the Loire basin, the geomorphological regions show good agreement with the hydroecoregions. The settlement of numerous species, from glacial relicts to warm-area species, was favored by the climate and the habitat diversity maintained by the free hydrodynamic functioning that still occurs from the uplands to the ocean. The flora is particularly rich due to invasive species spreading through the valleys, in addition to mountainous, Mediterranean and Atlantic species. The same goes for fauna, in particular for terrestrial and aquatic invertebrates, which inhabit humid to dry areas from riparian vegetation to banks and from gravel to sand beds. Birds, including migratory species as well as terrestrial and aquatic vertebrates, also exploit this great habitat diversity.

7.7.1 Phytoplankton

Phytoplankton in the Loire has been studied since 1920 but early studies were qualitative and mostly done on downstream stretches (Des Cilleuls, 1928; Germain, 1935). The Loire has the highest phytoplankton diversity in France and probably among other large European rivers (Rojo et al., 1994). During the growing season, at Rkm 640 nuclear power plant, phytoplankton taxonomic richness ranges between 97 and 127 species, with 65–79 green algae, 16–31 diatoms and 10–14 cyanobacteria (optical microscopic observations from 1995 to 2007). Surveys carried out on the rivers Marne, Seine and Oise (Leitao and Rouquet, 2002) reported much lower biomass and diversity than that found in the Loire.

In the middle Loire the most productive groups are diatoms and green algae. The greatest biomass of cyanobacteria occurs mainly in downstream reaches. At high flow ($>800\ m^3/s$) phytoplankton is diluted and biomass low. When discharge decreases to $\leq 300\ m^3/s$, unicellular centric diatoms become common, especially *Cyclostephanos invisitatus, Cyclotella meneghiniana, Stephanodiscus hantzschii* and *Thalassiosira pseudonana*. At low flows ($<100\ m^3/s$), delicate multicellular forms appear, such as *Fragilaria crotonensis, Nitzschia fruticosa*, and *Skeletonema potamos* and are often mixed with green algae typical of summer assemblages. The green algae are either large colonial forms (*Coelastrum microporum, C. reticulatum, Micractinium pusillum*), cells connected by gelatinous threads (*Dictyosphaerium pulchellum, D. tetrachotomum, Dichotomococcus curvatus, Westella botryoides*) or star-shaped colonies (*Actinastrum hantzschii, Ankistrodesmus fusiformis*). Prostrate colonies such as *Scenedesmus* are regularly observed. The most frequent species are *S. bicaudatus, S. intermedius S., opoliensis, S. spinosus* and *S. sempervirens*. The average contribution of green algae to total phytoplankton biomass is on average ~15%, which corresponds to 1.3 mg C/L in the middle Loire.

Leitao and Lepretre (1998) documented the seasonal and longitudinal patterns of phytoplankton abundance from 1991 to 1994 at six stations between km 150–875 upstream of the river source. Samples from the upper Loire were characterized by diatoms, whereas green algae dominated the middle and lower river. Seasonally, diatoms dominated with low diversity at high flows, whereas green algae and cyanobacteria with high biomass were common in summer during low flows. The diatoms *Stephanodiscus hantzschii* and *Cyclostephanos invisitatus* made up most of the spring phytoplankton assemblage, as found in other French (Leitão and Rouquet, 2002) and European rivers (Descy et al., 1994b). Maximal phytoplankton biomass occurred in summer in the middle and lower river and green algae dominated (Minaudo et al., 2020). Tributaries affect the main river phytoplankton community, either by adding species in spring, or causing biomass decrease in autumn through dilution effects. Available data on total algal abundance in the middle Loire (1982–2007) showed that phytoplankton biomass has decreased in the last decade in parallel with chlorophyll *a* concentration in recent years (Minaudo et al., 2016), this being the result of P reduction efforts with a contribution of grazing by the filter-feeding Asian clam (see below), like in the River Meuse (Pigneur et al. 2013; Latli et al., 2017).

7.7.2 Vegetation

The Loire has a wealth of Atlantic, Mediterranean and medio-European flora (Cornier, 2002). Plant diversity along the river is mainly explained by the geographic extension and morphology of the hydrographic network influenced by climate; the relatively natural hydrologic regime; the sedimentary edaphic and geomorphologic characteristics that cause microclimatic variability and the relatively low anthropogenic pressure compared to the majority of other large European rivers. Five main groups of flora corresponding to different phytogeographic regions can be found along the Loire-Allier system (Cornier, 2002; Greulich et al., 2016). The gorges of the upstream valleys leave little riparian space for alluvial-type vegetation. Purple willow (*Salix purpurea*) can be found (below 1200 m) but the predominant species is alder (*Alnus glutinosa*). Aquatic vegetation is very limited.

Further downstream, the alluvial plains offer more dynamic spaces and mosaics of varied habitats that are conducive to a rich flora of European importance. Floodplains between the Forez Plain and upper estuary are home to over 1340 taxa of vascular plants, distributed within 475 genera and 119 families (Cornier, 2002). The most common are herbaceous plants such as *Asteraceae* (155 taxa), *Poaceae* (138 taxa) and *Fabaceae* (92 taxa). Among the woody plants, *Salicaceae* are the most numerous (19 taxa). In the last 10 years, main and secondary channels have become characterized by the presence of beds of submerged hydrophytes, sometimes very extensive and often dominated by water crowfoot (*Ranunculus aquatilis*) (Greulich et al., 2016). Stagnant or slow-flowing water in the main and side channels host a number of plant communities characteristic of neutroalkaline, eutrophic, standing water, comprising submerged plants (*Ceratophyllum demersum, Stuckenia pectinata, Potamogeton perfoliatus, P. crispus, P. nodosus, Najas marina, Myriophyllum spicatum*, etc.) or freefloating plants (*Lemna* spp, *Spirodela polyrhiza*).

The lower course of the Allier River is one of the last remaining free meandering river segments in Western Europe, and thus provides a good example of riparian succession processes of a dynamic temperate river system. Six succession phases can be identified: Water; Bare Soil with <5% vegetation; Pioneer Phase with ruderal stress-tolerant vegetation such as Salicaceae with a vegetation ground cover ∼25%; Herb Phase with patches of short-lived annual and biannual herbs reeds and grassland that can also contain scattered woody pioneer individuals with a vegetation ground cover >25%; Shrub Phase with woody herbs like *Poa pratensis* and *Hypericum perforatum* and small patchy *Prunus* sp*., Crataegus* sp, and Salicaceae shrubs and trees; and finally the Forest Phase with dense woody canopy ground cover, typically more than 60%, and vegetation over 5 m high. Between 1967 and 2005, the study site near Moulins was characterized by a shifting habitat mosaic; floods did not change the overall habitat composition of the riparian corridor but changed their spatial distribution. Since 2005, progression and retrogression processes have been drastically reduced, with increased stability (i.e., no channel migration progression or retrogression of patches) and a concomitant reduction of high and moderate magnitude floods.

Vegetation in the estuary varies according to the degree of salinity and duration of floods. Polyhaline zones (i.e. zones with high levels of salinity) are characterized by the appearance of halophile plants and salt marshes. Plant communities in very saline areas include black rush (*Juncus gerardi*), sea milkwort (*Glaux maritima*) and sea arrow grass (*Triglochin maritima*). Plants in less salty areas include the media sandspurry, (*Spergularia media*) sea aster (Tripolium pannonicum) and sea poa grass (*Puccinellia maritima*). The common reed (*Phragmites australis*) and saltmarsh bulrush (*Scirpus maritimus*) are found among the saltmarsh vegetation.

In the mesohaline zone characterized by less brackish water, there are vast subhalophile thermo-Atlantic wet meadows. Plants in areas of moderate flooding include divided sedge (*Carex divisa*), bulbous foxtail (*Alopecurus bulbosus*), narrow-leaved water dropwort (*Oenanthe silaifolia*) and sea clover (*Trifolium squamosum*). Where prolonged flooding occurs, there are communities with protected plants, such as adder's-tongue spearwort (*Ranunculus ophioglossifolius*) and bigflower clover (*Trifolium michelianum*). In the oligohaline part of the estuary, where the water is considerably less saline, the banks harbor estuary angelica (*Angelica heterocarpa*), which is a protected species both nationally and in Europe. This plant, which is endemic to the large estuaries of the French Atlantic coast, is most prolific on thick compact brackish mud in the midst of tall broad-leaf oligohaline grasses (*Calystegio sepium-Angelicetum heterocarpae, Oenanthetosum crocatae*) and to a lesser extent in softwood forests (Greulich et al., 2016).

During the 20th century and particularly since the 1950s, there has been a sharp increase in woody vegetation in the alluvial plain, notably in the Middle Loire (particularly between Bourbon-Lancy and the confluence with the Vienne). Woody vegetation and more generally terrestrial vegetation has become more widespread in riparian zones or tributaries of the Loire through disconnection from the main channel following incision of the bed (Greulich et al., 2016). Another significant modification concerns meadows; at the end of the 1960s, they were still dominant on the upstream and downstream reaches, but their surface area has decreased by 20%, mainly replaced by arable land. During the same period, wasteland areas appeared in the alluvial bed, increasing from <0.5% in 1969 to 6% in 2000.

The Loire now has nearly 300 nonnative plant species (Cornier, 2002), many of which appeared during the 20th century. In central France, i.e. most of the Middle Loire, there are 58 native taxa and 27 alien taxa among the subset of species characteristic of major rivers. Nonnative species developed first in sand-gravel banks and wetlands, as well as meadows and heathlands away from the low-flow channel (Greulich, 2011; Greulich et al., 2016). In aquatic habitats, major modifications observed concern the rarefaction of communities associated with oligotrophic and mesotrophic environments, including algal communities such as Characeae in riparian areas, or the decline of species such as lesser marshwort (*Helosciadium inundatum*). Moreover, increased development of rapidly growing and highly productive species has been observed. For example, slow-flowing water has been massively colonized since the 1990 and 2000s by two species of water primrose (*Ludwigia peploides* and *Ludwigia grandiflora)* native to South America. From vegetative fragments, they have colonized most of the Loire, with the greatest density observed in the western subdistrict of Val de Loire (Cornier, 2002; Greulich et al., 2016).

In the fast-flowing areas of the Loire, a major change in flora is the recent development of large beds of aquatic grasses largely composed of water crowfoot. These native plants, which were previously relatively scarce, have developed massively in the Middle Loire since the early 2010s. These beds also include other native aquatic species. There still is insufficient data (i) on the effects of morphology and phenology of herbaceous plants on sediment dynamics, (ii) on the effects of recent alien species on the biocenosis and physical environment, and (iii) on the respective roles of orthophosphates and filter-feeding molluscs in the recent decline in phytoplankton abundance and expansion of macrophyte beds in the Loire.

7.7.3 Heterotrophic plankton

Various data on bacterioplankton and protozooplankton are available for the middle Loire (Picard and Lair 2005). Heterotrophic bacteria (up to 14×10^9 cells/L) consisted of cocci (49% on average), rods (35% on average), colonies (12% on average) and filaments (4% on average). Algae were dominated by small forms (0.8–1.2 μm). At densities of up to 9×10^6 cells/L, heterotrophic flagellates described according to shape (spherical or ovoid), size (1–18 μm) and number of flagella, comprised 22 morphotypes. Most were spherical and the >5 μm size-class was most abundant (88% on average). Five classes, 19 families and 22 genera of ciliates have been found in the river and were dominated by Oligotrichs (*Strobilidium, Strombidium*) and Peritrichs (*Vorticella*). Depending on the year, Prostomatids (*Urotricha*), Hymenostomes (*Cyclidium*), Phascolodontes (*Phascolodon*) and Haptorides (*Didinium Mesidinium*) were associated with a few Heterotrichs (*Stentor*), whose distribution varied along the river. Their densities can reach up to 51×10^3 cells/L and small sizes dominate. In 1999, the <50 μm size class represented on average 73% of the assemblage that of 50–100 μm accounted for 20% and those >100 μm comprised the rest.

Metazooplankton was extensively studied in the middle Loire (Lair, 2005, 2006). From 1995 to 2004, 61 species were collected at Dampierre-en-Burly (Rkm 550) and Saint-Laurent-des-Eaux (Rkm 640). The community is dominated by Brachionidae (44% at Dampierre-en-Burly, 34% at Saint-Laurent-des-Eaux) and Trichocercidae (13% and 16%, respectively). Depending on the year, Asplanchnidae (6% and 10%, respectively) can be quite abundant. Also occurring are Notommatidae (6% and 9%), Synchaetidae (7% and 10%) and Epiphanidae, and Lecanidae (5% each at both sites). In some summers, the abundance of Flosculariidae (6% and 4%, respectively) is influenced by the invasion of the warm stenothermal *Sinantherina socialis* (Champ, 1978).

On account of geomorphological changes and dispersal, it is not surprising to collect a mixture of planktonic and epibenthic rotifers. Over 10 years the dominant species sampled included *Anuraeopsis fissa, Asplanchna priodonta, Brachionus angularis, B. calyciflorus, B. leydigi, B. quadridentatus, Cephalodella catellina, C. gibba, Epiphanes macroura, Keratella cochlearis, K. tecta, Lecane luna, Polyarthra dolichoptera, P. vulgaris, Rhinoglena frontalis, Sinantherina socialis, Trichocerca brachyuran, T. pusilla* and *T. similis*. Depending on the year, the density of planktonic species fluctuated from 49% to 69% at Dampierre-en-Burly, and from 41% to 74% at Saint-Laurent-des-Eaux, that of epibenthic species from 31% to 51% at Dampierre and from 26% to 59% at Saint-Laurent. Such results illustrate that rotifer numbers are directly affected by flow conditions in the river, with numbers decreasing at high flows.

7.7.4 Benthic invertebrates

Invertebrate communities of the Loire and its tributaries are relatively diverse, partly due to the particular biogeographic situation of the basin. The biological potential remains high according to Bacchi (2000), who reported a pool of 138 taxa mainly belonging to five dominant insect orders: Plecoptera, Ephemeroptera, Trichoptera, Coleoptera and Odonata. More recently, Wantzen and Richard (2016) sampled a total of 222 taxa in the 27 monitoring stations of the WFD general survey. In addition, by combining different specialized studies often focused on one group or on a particular subregion, the total number of taxa has increased to 456, with 24 Mollusca, 57 Ephemeroptera, 78 Trichoptera, 18 Plecoptera, 132 Diptera (including 115 Chironomidae), 75 Coleoptera, 16 Odonata, 10 Heteroptera and 15 Crustacea. Different taxa representative of these orders can be successively found from the headwaters to the mouth of the Loire. Overall, the general longitudinal biotic organization of the river follows the pattern proposed by Verneaux (1973) as follows. The well-oxygenated headwaters of the Upper Loire, with their granitic and volcanic coarse substrates, host a wide diversity of Plecoptera and most pollution-sensitive Ephemeroptera and Trichoptera. Species such as *Arcynopteryx compacta, Brachycentrus subnubilus* and *Odontocerum albicorne* can be found, highlighting the good quality of the water.

While rheophilous taxa remain abundant downstream, major changes occur in the Loire/Allier system, with the appearance of more tolerant species, such as *Chimarra marginata, Cheumatopsyche lepida Hydropsyche contubernalis, H. exocellata Oligoplectrum, maculatum Potamanthus luteus* and *Raptobaetopus tenellus*, illustrating both the natural biological gradient along the river and the increase in pressure from human activities (Guinand et al., 1996; Ivol et al., 1997; Ivol-Rigaut, 1998; Beauger et al., 2006; Beauger, 2008). Further downstream, successive dams have altered the bed load transport and there is a progressive increase in human impacts along the watercourse. Consequently, the decrease in water quality in the Middle Loire, due to agricultural domestic and industrial inputs, has facilitated colonization by pollution-tolerant species adapted to disturbed environments, potentially replacing native species. In the middle and lower sections, sand dunes develop, hosting typical faunal elements of sandy rivers, such as chironomids and oligochaetes (Wantzen et al., 2014).

As in other European rivers, the Loire has not been spared from invasive benthic invertebrates, even though its near-natural environmental conditions, the lack of bank stabilization with riprap (with the exception of cities and remnants of groynes for navigation) and the improving water quality have lowered their invasive potential. *Corbicula fluminea*, an Asiatic invasive bivalve probably spread by attaching itself to boats sailing up the Loire from the estuary. The "Asian clams" also reached the Allier in 2001 and Cher via canals; in the Auvergne it has been used as fishing bait (Brancotte, 2002). *Corbicula* is adapted to the environmental conditions of the Loire, but may be affected by exceptionally cold winters, as in 2012/13 when the populations decreased to about 10% of the previous year. However, warmer canalized tributaries in urban areas serve as prime sites for invaders such as *Corbicula, Dreissena polymorpha* and *Dikerogammarus villosus* (Hesselschwerdt and Wantzen, 2018), enabling these species to access the main river. *Corbicula* may reach high densities (>2000 ind./m^2) at some sites along the Loire and Vienne. Its occurrence combined with ongoing reduction in P inputs to the river may explain the dramatic decrease in phytoplankton and progressive development of aquatic macrophytes at some sites. While *Corbicula* juveniles are loosely attached to sand grains (pseudobyssus), *Dreissena* mussels have a solid byssus thread by which they attach themselves to solid substrates and floating macrophytes. They are relatively rare in the Loire probably due to the natural sediment movement but they can be found in larger numbers in still-water areas (e.g., at the confluence of the Maine near Angers) and on the shells of living native unionid mussels (*Anodonta anatina*), which they suffocate by overgrowth. The "killer shrimp," *Dikerogammarus villosus*, also seems to be limited by the natural sediment structure of the Loire, but may occur locally in high densities (Wantzen and Richard, 2016), interfering with the native invertebrate fauna (Piscart et al., 2011) and possibly leading to their decline.

The taxonomic diversity of aquatic invertebrates, already high in the headwaters, is greatest between the Allier/Loire confluence and the estuary. This stretch of the river is relatively natural and unregulated and has numerous perifluvial habitats that favor taxa such as coleopterans, which increase significantly in number from the source to the estuary. The Giant River Pearl Mussel (Pseudunio auricularius, formerly: Margarita auricularia) is one of the rarest invertebrate species in the world. The last extant populations are found in Spain and France, including the Vienne, one of the largest tributaries of the Loire (Prié et al., 2017). It was rediscovered when the Maisons Rouge dam was removed. Global populations have declined for a number of reasons, including water pollution, habitat destruction, overharvesting for mother-of-pearl and extinction of the most common host fish, the European Sturgeon (*Acipenser sturio*). Currently, a LIFE + project is dedicated to artificial reproduction and reintroduction of this mussel (Soler et al., 2019).

Notwithstanding the overall longitudinal structure of benthic assemblages, long-term changes in invertebrate communities have occurred over the past decades. In particular, the taxonomic richness of the Middle Loire has significantly increased since the early 1980s, from the dual consequence of hydroclimatic and trophic change (Fig. 7.7A; Floury et al., 2013). On the one hand, the significant rise in diversity has been driven by a growing number of taxa exhibiting biological features adapted to warming and/or discharge reduction (e.g., limnophilic taxa; Floury et al., 2017), including invasive species like the Asian clam *Corbicula fluminea*. On the other hand, it has been supported by a diversification of food resources as a bottom-up response to P-limited phytoplankton (Floury et al., 2017), as reflected by the gradual decrease in filterer and microinvertivorous taxa to the benefit of other feeding types, including taxa scraping on epilithic biofilms (Fig. 7.7A). Similarly, a long-term increase in diversity has been observed in the Upper Loire and Allier, involving analogous climatic and trophic processes (Floury et al., 2018). Furthermore, these functional changes of invertebrate assemblages can have broader consequences on other biological communities, based for instance on the phytoplankton filtration rates of invasive bivalves like *Corbicula* and the high occurrence of benthic invertebrates in fish diets.

7.7.5 Amphibians

Amphibians observed in the Loire basin are reported in Cochet et al. (2002). The fire salamander (*Salamandra*

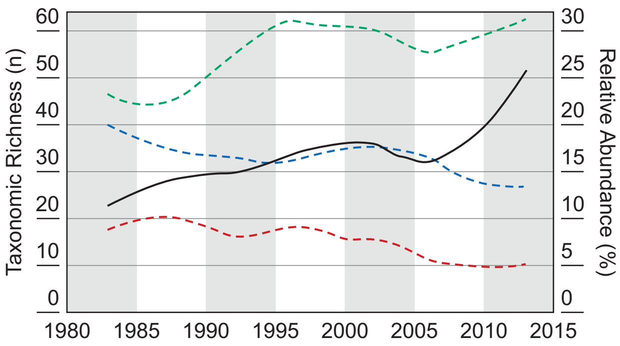


FIGURE 7.7 Long-term trends in the invertebrate community of the Middle Loire: taxonomic richness (*solid black line*) and relative abundance within the whole assemblage (*dotted lines*) of scraper (green), filterer (blue) and microinvertivorous (brown) taxa.

salamandra) is the most widespread species in the basin. Five new species are found in France: the great crested newt (*Triturus cristatus*), marbled newt (*Triturus marmoratus*), common newt (*Lissotriton (Triturus) vulgaris*), Alpine newt (*Ichthyosaura (Triturus) alpestris*) in the stagnant waters of the upper basin, and palmate newt (*Lissotriton (Triturus) helveticus*). The common toad (*Bufo bufo*) is found in slow-flowing water, the midwife toad (*Alytes obstetricans*) is found occasionally in the floodplain and more frequently in the uplands. The Natterjack toad (*Bufo calamita*) is found in oxbows and gravel pits, the common spadefoot (*Pelobates fuscus*) and western spadefoot (*Pelobates cultripes*) are occasionally found in the lower basin, and the Parsley frog (*Pelodytes punctatus*) is found throughout the basin apart from some tributaries. The yellow-bellied toad (*Bombina variegata*) is relatively common in the upper basin and the common tree frog (*Hyla arborea*) is found throughout the basin. The green frog (*Rana temporaria*) is found throughout the Loire basin, whereas the agile frog (*Rana dalmatina*) is limited by altitude and found mostly in the lower basin. The edible frog (*Rana esculenta*) and Iberian green frog (*Rana perezi*) are found mostly in the south, the marsh frog (*Rana ridibunda*) mostly in the north and the pool frog (*Rana lessonae*) is most common in stagnant waters in the floodplain.

The African clawed frog (*Xenopus laevis*), native to Southern Africa (from the Cape to the plateaus of Nigeria and Cameroon), was introduced in France in the 1950s for biological research purposes and spread accidentally from the basins of the Thouet and Argenton, in the Deux Sèvres department in the 1980s. Currently, it is only found in the north of the Deux Sèvres department and in the south of the Maine-et-Loire department (ONCFS Sarat 2012). The American bullfrog (*Lithobates catesbeianus)* was brought deliberately to the Gironde from the USA in 1968 and it was also introduced in the Sologne where it was discovered in 2002. Currently, it is found across the entire southwest of France the second largest area in Europe where it is found. However, in the Loire basin it is restricted to three villages of the Loir-et-Cher department (ONCFS Sarat 2012).

7.7.6 Fish

Around 60 fish species from 20 families are present in the Loire basin (Souchon, 2002; Tomanova et al., 2014; Boisneau and Feunteun, 2016). A remarkable feature is that numerous migratory and anadromous fish still occur: 11 of these species use the Loire/Allier system to complete their life cycle, which comprises both marine and freshwater stages. The Atlantic salmon (*Salmo salar*) forms the last wild European population migrating into a large river system. The sea trout (*Salmo trutta*) is recorded but lacks good population records. The shad (*Alosa alosa*) is common and is more frequent than the twaite shad (*Alosa fallax*). Sea lamprey (*Petromyzon marinus*), European river lamprey (*Lampetra fluviatilis*) and smelt (*Osmerus eperlanus*) spawn in freshwater habitats. The catadromous eel (*Anguilla anguilla*) colonizes the whole basin up to the upper Loire-Allier River. The flounder (*Platichthys flesus*) and two species of flathead mullet (*Mugil* ssp.) forage in freshwater habitats near the mouth. The European sturgeon (*Acipenser sturio*), present until 1940, is the only native fish that has gone extinct within the Loire basin.

Except for a few species with a Mediterranean affinity or central European origin, the Loire basin comprises almost all the fishes found in the freshwaters of France. Species richness is highest (20−25 species) in sections where the channel is wide and diverse with secondary channels, such as the Middle Loire, lower Vienne and rivers Allier, Creuse and Cher. Streams of the upper Loire-Allier, Sarthe and upper Mayenne host almost intact fish populations with species sensitive to pollution or habitat degradation such as brown trout (*Salmo trutta* Atlantic lineage, Berrebi and Schikorski, 2016), sculpin (*Cottus gobio*) and the European brook lamprey (*Lampetra planeri*). The ecologically and hydromorphologically intact area near the Allier-Loire confluence plays an important role with respect to the protection and biodiversity of the Loire basin. Near the Loire-Allier confluence, the canal between the Loire and Rhône (canal du Nivernais) opened an immigration route for species from the Rhône basin such as sander (*Sander lucioperca*), nase (*Chondrostoma nasus*), wels catfish (*Siluris glanis*) and some potentially endangered species like grayling (*Thymallus thymallus*), sofie (*Chondrostoma toxostoma*), burbot (*Lota lota*) and bitterling (*Rhodeus sericeus*).

The grayling (*Thymallus thymallus*) is native to the Loire basin since the end of the tertiary it is found in the Upper Allier in the departments of the Loire and Puy du Dôme, and on the Ance du Nord and on the Lignon du Forez, tributaries on the left bank of the Loire (Grès, 2017). It is also found in the Upper Vienne upstream of Limoges, in the Vienne and two of its tributaries (the Combaldead the Maulde). Genetically, these three populations belong to a large Loire group, distinct from those of the Danube, Rhône and Rhine. Differences between them show that they come from local ancestral stock, with low genetic diversity, unresponsive to various breeding attempts and which have not been in contact since the last ice age i.e. nearly 10,000 years.

An overview of the change in fauna over the last 25 years can be obtained by examining time series of the monitoring networks set up since the 1990s (Eau France, 2013). During this period, rivers have undergone not only changes in thermal regime, but also concomitant changes that affect hydrological regimes and the physical and chemical composition of the water (a gradual decrease in phosphorus reduction of black spots with high nitrite rates stable or increase in nitrates). From a selection of 48 species widely found across France, Poulet et al. (2011) analyzed the temporal changes to their occurrence. Overall, the trend is toward an increase in the number of species per station, from an average of 8.1 species in 1990 to 9.5 species in 2009. Of the approximately 100 sampling points in the Loire basin, 57% gained species (11% significantly so). The overall trend is thus a moderate change. Diversity has declined most in the Vienne basin, while several points in the upstream basin of the Loire and Allier have seen an increase in richness. The wels catfish (notably in the downstream Indre and middle Loire), schneider, common barbel and chub have significantly increased in number, while the common trout (across the whole basin), catfish, common bream and tench have decreased. These trends do not all seem to show the same processes. The reduction in distribution areas favorable for trout, on the fringe of the currently occupied zone, can in all likelihood be attributed to the effect of a rise in the thermal regime resulting in an upstream shift of the thermal niche that it thrives on (optimum for growth between 12.8°C and 19.5°C; Elliott, 1976). In contrast, more warm-water species, such as the bitterling and Schneider, have become more widespread. For other species such as the wels catfish, a warm-water species not native to the basin, it could be part of the continuation of a process of colonization, taking advantage at the same time of a favorable temperature.

7.7.6.1 Trends in the Loire basin

Long-term monitoring at the five nuclear power plants located along the Loire and Vienne rivers provides trends in large river fish communities over the past 20–30 years. Studies by Daufresne and Boët (2007) and Maire et al. (2019) identified strong increases in species richness and total fish abundance, concomitant with a gradual increase in water temperature. The strongest signal underlying observed community change was an increase of warm water species, and these trends were driven by native rather than nonnative species. Increases in the relative abundances of warm water species, such as the bitterling and pseudorasbora, have been observed to the detriment of historically dominant species, such as the roach and white bream. Several species, such as the asp, crucian carp and spined loach, have appeared in these systems over the study period, whereas only the black bullhead has disappeared. The changes that have been observed reflect modifications in the trophic functioning of the river, parallel to those described for macroinvertebrates (Fig. 7.7B); benthivorous species increase over time to the detriment of plankton-consuming species. This reinforces the hypothesis of change in the spatial distribution of primary producers from pelagic to benthic, following a general increase in light conditions.

7.7.6.2 Focus on migratory species: Eel

The eel, once very abundant, declined at the end of the 1970s. At that time, professional fishermen caught more than 100 tons of glass eels per year, compared to only 24 tons in 2014. The glass eels rapidly colonized the estuary of the Loire, its tributaries and major wetlands (Grand Lieu lake Brière Lavau marsh) and then the upstream reaches of the river. Within a few weeks, the glass eels could reach the confluence with the Vienne (Feunteun et al., 2003), but the majority settled as soon as possible in the first vacant habitat they came to, preferably in the estuary. The migratory process could last for years. For this reason, the average size and age of the eels tended to increase with distance from the sea; the youngest and smallest eels, and also the males, were far more numerous downstream. Their numbers have fallen considerably since 2007 in the upstream reaches of the basin (Vichy/Allier) (Bach et al., 2017), both on the upstream run (yellow eels) and the downstream run (silver eels).

There are multiple causes of this decline. Anthropogenic factors such as overfishing, the destruction of wetlands, certain levels of pollution (metals organophosphates), eutrophication or the presence of dams have restricted the geographic distribution and continental reproduction of the eel. At the same time, the rise in temperature in the continental zone does not seem to be implicated yet, insofar as the eel likes water that is over 20°C and up to 30°C and even thrives under those conditions (optimum 22–23°C; Deelder, 1985). The profound changes in oceanic and atmospheric conditions are also a disadvantage, by (1) reducing the conditions for successful larval growth due to the decrease in marine production of prey organisms, or (2) altering ocean currents used by leptocephalus larvae to migrate from breeding grounds in the Sargasso Sea to colonize the European coast (Miller et al., 2016). Work by Pacariz et al. (2014) on modeling ocean currents, their changes and effects on the passive transport of larvae, led to the conclusion that the second hypothesis could not on its own account for the decline in eel populations. On the other hand, Bonhommeau et al. (2008) provided strong evidence to support the first hypothesis by linking the recruitment of eels to primary production in the Sargasso Sea, negatively correlated with its temperature (relationship established on a time series of 11 years between 1994 and 2004). Variation of 0.4°C

(21.4–21.8°C) in 1980 was enough to bring about the collapse of the recruitment index three years later (Recruitment Index decreasing from 2.4 to 1.3 in the Loire basin with parallel changes in other European basins). A second thermal stage ensued at the start of the 2000s (21.8–22.1°C).

7.7.6.3 *Atlantic salmon*

The Atlantic salmon colonizes the Loire and its main tributary the Allier (81% of the total population Bach et al., 2015), and also the Vienne-Gartempe system and Arroux (12%). At the European level, salmons that migrate the furthest (several hundred kilometers), overcoming a large number of barriers in order to reach their breeding grounds, are genetically largely unmixed (Perrier et al., 2011). Spawning populations comprise essentially large individuals that have spent 2–3 years at sea, which migrate in winter and spring. Historic data and population census at the fishpass at Vichy on the Allier (653 km from the sea 50% of the potential spawning grounds along the whole river) since 1997 show that the number of adults on the upstream run has declined sharply since the early 1980s, falling from 2000 to 3000 individuals per year to less than 1000 in 1989, when there was a significant drop. These figures are in line with European trends of catch rates in the fisheries of the North Atlantic, with a decline from 8000 tons in the 1980s to 1000 tons in 2014 (ICES, 2015). An unusual migratory behavior occurred in the two hot years of 2003 and 2015; a sharp increase in the number of salmon going through Vichy (1238 and 1187 salmon, respectively) was recorded before the high temperatures. In an analysis of the migratory behavior in 2003 in various French basins, Travade and Carry (2008) found that the migratory numbers stopped abruptly when the average daily temperature of the water reached 25°C, and that there was no further migration upstream beyond that threshold. This phenomenon was marked in the Garonne-Dordogne system, notably with the definitive absence of salmon that had spent one year at sea. In the Loire, spawning individuals were older and migrated upstream earlier, and were less affected by the conditions in 2003.

To explain the decline of Atlantic salmon populations, it is necessary to analyze the causes that penalize it in both the continental and marine stages of its cycle. Changes in thermal regime can influence the phenology of migration, its sexual maturity and the whole phase of juvenile growth in freshwater and at sea. Temperature changes can affect the concomitance, such that spring hatching on the continent or maturing at sea are out of phase with the availability of suitable prey. Regarding the marine phase, Beaugrand and Reid (2003) and Beaugrand et al. (2015) found that the phase of decline coincides with a rise in sea temperature in areas where salmon mature, resulting in a change in the nature and abundance of phytoplankton and zooplankton, negatively affecting the growth and survival of the salmon. Two marked shortage periods were observed in 1986/87 and 1996/97. For the continental phase, there is a current lack of similar knowledge; thermal stress for the parr seems to be between 22°C and 28°C (Elliott and Elliott, 2010), but the preferred temperature for the continental growth phase is lower between 9°C and 17°C (Alabaster and Lloyd, 1982).

A model of the salmon population dynamics on the Allier, upstream of Vichy, based on data sets available since the 1970s and using a large variety of data (river habitats, fish catches, sampling, head count at passes, stocking) (Dauphin et al., 2013) revealed: i) a sharp drop in the return rate of 0+ juveniles to adults at the end of the 1980s, with no real recovery; ii) large geographic differences in the natural recruitment of juveniles; on average it is two times higher from Langeac to Poutès Monistrol and upstream of the Poutès dam than elsewhere; iii) a very low return rate of farming smolts at Vichy; and iv) a measurable contribution of new 0+ juveniles to the recruitment of salmon with three winters at sea. Without stocking, the population would not have disappeared, but the number of adults returning to Vichy would have been 80% lower on average in the last 10 years.

7.7.6.4 *Shad*

The two species of shad found along the Atlantic coast, the allis shad (*Alosa alosa* L.) and twaite shad (*Alosa fallax* Lacépède), encounter the same problems as salmon in the Loire Estuary during their breeding migration. The allis shad are the most abundant and migrate further upstream (Boisneau et al., 2008). Although it does not go quite as far upstream as the Atlantic salmon, it is found in a larger number of tributaries, with the largest numbers counted at the fishpasses of the Vienne (89%), compared to only 11% at the passes on the Loire (Bach et al., 2015). Shad stocks started to recover after major spawning areas became accessible during spring floods. Besides these periodic exceptions, the shad population remains stagnant and at low levels compared to the natural potential of the river. There is a stark contrast between 2007, when 30,800 spawners were counted in the Vienne basin (50% of the number in the whole basin) and the following years, when numbers barely exceeded 2000 individuals. Other hypotheses attribute the fall in numbers to strong predation pressure by wels catfish (Boisneau, 2015).

7.7.6.5 *Lampreys*

Lampreys recently started to recolonize the Creuse River. Sea lampreys migrate upstream to their spawning grounds between February and June at an average speed of 15 km per day (Gadais et al., 2013). When the conditions are bad, for example due to mud blockages as in May 2010, lampreys that do not interrupt their migration die of asphyxiation. Most of the migratory stock colonizes the Vienne basin, with a large number of spawners counted notably in 2007 (93,000), 2012 and 2015 (50,000). By contrast, 2017 was a catastrophic year for this species, with only 1200 individuals counted.

7.7.7 Aquatic mammals: status and trends

Populations of the European beaver (*Castor fiber*) and Eurasian otter (*Lutra lutra*) are constantly expanding (Bouchardy, 1998); the former following deliberate reintroduction between 1970 and 1996 from Rhône stock, the latter as a result of a gradual spread from the center of the basin (particularly the Creuse) and wetlands of the Atlantic coast, where relict populations exist. Most of the basin has now been colonized, starting from the main drainage basin and gradually spreading to secondary networks (Dewas et al., 2012). At the end of 2014, beaver was found in stretches of river totaling nearly 6196 km, corresponding to 58% of the area surveyed Hurel and Marchadou, 2016. Van Looy et al. (2014) modeled the Loire network connectivity, showing how the European otter colonized the Loire basin over 25 years, based on large data sets of riparian corridor, land use and the hydromorphological characteristics of a river network covering 17,000 km. Channel straightening and riparian forest fragmentation were shown to be key elements in functional connectivity. Road infrastructure was identified as a critical habitat factor, but not a major obstacle for species movement in the riparian corridor.

The little-known southwestern water vole (*Arvicola sapidus*) is found and is thought to be in decline, but there has been little research on this species. The Loire basin is also one of three sites in France where the raccoon (*Procyon lotor*) is found (the North-East; Auvergne, essentially the Haute Loire and Puy de Dôme; and Bordeaux) (Hurel and Marchadou, 2016). This North American animal breeds and is currently expanding its area, mainly in the Allier valley. The European mink (*Mustela lutreola*) is considered to be extinct in the Loire basin and is now only found further south in the Charente and Charente Maritime Departments. Nonnative species such as the coypu (*Myocastor coypus*), originally native to temperate South America (Argentina in particular), and the muskrat (*Ondatra zibethicus*), native to North America, have been widespread in the Loire basin since 1995, following escapes from fur farms.

7.8 Management and conservation

7.8.1 Changes in environmental problems

Historically, water quality of the Loire was quite good in the 18th century. Various references note that its waters were recommended for better health because of its salt composition. A report in 1786 writes that a person of Orléans affected by early stages of chronic disease was told by a famous Parisian physician to "Promptly return to Orléans and for any remedy, make use of water of the Loire." However, the Loire did not escape the degradations from intense economic development in the 19th century, which resulted in heavy pollution related to industrial activities (tanneries, retting of plant fibers, paper mills and mining). These activities declined finally at the beginning of the 20th century, resulting in an improved water quality by the 1950s, followed by further degradation by forms of pollution that appeared as a result of urban growth, intense agriculture and development of the food industry.

A study by Des Cilleuls (1928) showed that at the beginning of the 19th century, development of phytoplankton in the Loire was poor, similar to other freeflowing rivers. Although phosphorus data before the 1980s are lacking to show the beginning of eutrophication, it was evident already in the 1960s that nutrient inputs had considerably amplified phytoplankton growth. A study of the Loire in 1967 suggested that the river was experiencing eutrophication at that time, and river quality monitoring carried out since 1980 showed that phosphorus concentrations and chlorophyll *a* levels were very high. From the late 1940s to the 1980s, enrichment of phosphorus was noted in Loire sediments, and river eutrophication was well marked by the general increase in endogenic calcite (Manickam et al., 1985). Total organic carbon in studied sediments started to increase in the early 1950s (Grosbois et al., 2012). Since 1990–2000, summer phytoplankton biomass has been reduced threefold in the Loire and its tributaries, alongside the overall twofold drop in concentrations of bioavailable phosphorus. Improved treatment of discharge from wastewater treatment plants has had a significant effect on this level of phosphorus, notably in the upstream reaches of the basin.

Today, the Loire is still classified as eutrophic because a considerable quantity of phytoplankton can develop, but more fleetingly, such as the 140 μg/L peak of chlorophyll measured during summer 2010, but which only lasted a week, and during the periods of very hot weather in 2018 and low flow. Eutrophication still affects the quality of the ecosystem and could increase in the coming years following a rise in water temperature and appearance of longer and more severe low-flow periods in summer. Eutrophication in reservoirs, particularly upstream, not discussed in this chapter, is an issue of current concern. The phenomenon of localized eutrophication in the reservoirs of Naussac, Grangent and Villerest should be monitored because it could take different forms (recurrent cyanobacteria blooms, development of macrophytes). Temperature has also been considered as a triggering factor for cyanobacteria blooms (e.g., *Microcystis aeruginosa*) in the reservoir of Grangeant (Latour et al., 2007; Sabart, 2009).

Nitrogen pollution of ground and surface water remains a major issue in the Loire basin, its estuary and coastal area, as in the northwestern corner of France that is subject to strong regional specialization of crop production in the agricultural zone of the sedimentary basin, and livestock production in the Massif Armoricain. While there are still margins for maneuver in terms of wastewater treatment and improvement of agricultural practices to reduce the environmental loss of nitrogen underlying this pollution, it is clear that only structural changes in the agro-food chain and eating habits will ultimately enable pollution levels to return to levels that are compatible with environmental quality objectives.

In addition to this long-term degradation in physical and chemical water quality, the Loire had other problems that contributed to its deterioration. These included the construction of retention structures and migration obstacles for fish, other hydromorphological alterations particularly from hydraulic developments, and the discharge of toxic substances such as pesticides. Pesticides were found at most sampling sites, sometimes in concentrations thought to affect biological diversity. Estimates of the pesticide input from agricultural sources support these findings, although non-agricultural contributions may be also important.

The migratory potential of the Loire basin for fishes is limited by distance from the sea as a natural constraint and frequency of artificial migration obstacles such as dams and habitat degradation. The degree of environmental change can be characterized by the extent of water level regulation by dams. Rivers with low slopes, such as the Mayenne, Sarthe and Loir (Sarthe tributary), and numerous dams have been particularly affected. The cumulative impacts become especially manifest during the spawning season because dams retard migration and enhance mortality via the clogging of sediments. Channel excavation of the Loire disrupted lateral fluvial dynamics and caused an alarming decline in the pike population. Headwater catchments in the Massif Central are less impacted because agricultural pressure is still relatively low. Some impacts result from the increase in the number of ponds in the Limousin area that affect water temperature (Seyedhasemi et al., 2020), dissolved oxygen and water quality in general, and the permeability of surface bed sediments by clogging. Hydraulic works in the 1970s—1980s strongly modified the rivers as well, especially in the Massif Central where the impacts on fish populations were statistically evident. Rivers in the Maine basin and central region have been remarkably transformed by a chain of impoundments. A reduction in river slope caused a simplification of riverine habitat, with a loss of fast-flowing zones and associated fish, such as the barbell, common dace (*Leuciscus leuciscus*) and spirlin (*Alburnoides bipunctatus*). Nonetheless, the Loire, Allier and lower Vienne still contain a variety of riverine habitats and stretches of free-flowing and braided reaches (Photo 7.3).

7.8.2 Conservation and restoration policies

In the 1980s, two visions of Loire development were confronted: “develop nature” by protecting against floods and developing the economy through protective infrastructure (dams); and “living with the river”, through integrated ecological management of the Loire basin by seeking alternatives to dams, developing a

PHOTO 7.3 Structures to facilitate navigation in the downstream part of the Loire River at Béhuard (Maine-et-Loire) @ Ph. Graindgorge/Gerpho.

culture of flood risk, circulation of highly migratory fish, protection of salmon and preservation of Loire diversity. In the 1990s, the Loire basin played a pioneering role in terms of testing a new watercourse management policy, through the implementation of the Loire Grandeur Nature Plan. This comes after a conflict period over a water development program for the Loire and its tributaries planning several dams to fight against flooding. This program was finally abandoned in favor of the "Plan Loire Grandeur Nature," an action plan under the authority of the State, which is the first program of its kind on a river in France. It aimed to reconcile human security, environmental protection and economic development, turning its back on the logic of heavy protective measures (Huyghues Despointes, 2008). A new management method for the French rivers has gradually developed in the Loire basin over the past 20 years (Rode, 2009).

The "Plan Loire grandeur nature", initiated in 1994, led in particular to the restoration and establishment of fishpasses. As mentioned above, a total ban on salmon fishing was implemented in 1994 and two dams were removed in 1998 within this plan framework. Before, a LIFE program (a financial instrument of the European Community supporting environmental and nature conservation projects) supported by environmental associations initiated the "Loire Nature" in 1992 that aimed to preserve free space along the Loire and Allier. The project focused on 8 sites that were the most remarkable from an ecological perspective. This action was continued in a second LIFE program "Loire Nature 2" (2002–2006) involving public and private actors working together to protect ecosystems. The LIFE program "Great Loire Salmon" was also conducted from 2001 to 2004. Special protection zones have been designated within the framework of Natura 2000, an ecological network of the European Community to protect the most endangered habitats and species in the basin. In the context of mammals, there now exist management plans of habitats for the European beaver and Eurasian otter, restoration of fish migration pathways in the rivers to reconnect the food chain, and control of nonnative nutria and muskrat.

In the Loire basin, the 1990s marked a turning point in the management and perception of the river. Several strong measures to protect the environment and promote natural and cultural heritage were implemented. First of all, the interregional Plan "Plan Loire Grandeur Nature" marked an inflection and an innovation in watercourse management policies at the national level. Then two dates mark the beginning of a heritage enhancement of the middle Loire: in 1996, creation of the natural regional park Loire-Anjou Touraine (situated between Tours and Angers) and in 2000, registration of the Loire valley between Sully-sur-Loire and Chalonnes (280 km long and 800 km^2) on the UNESCO list of World Heritage sites (creation of the "Val de Loire World Heritage" Mission in 2002). At the same time, other protection and conservation policies were implemented in the Loire basin. The European network "Natura 2000" covers 25% of the surface area of the Loire catchment added with properties of conservation organizations such as the CORELA (Regional Conservation Center for the banks of the Loire and its tributaries).

Several ZNIEFF (Natural Areas of Fauna Flora and Ecological Interest) and ZICO (Important Areas for Bird Conservation) have been delimited, underlining the interest in the biodiversity offered by the river and encouraging scientific research. The second phase of the Loire Plan (2000–2006) integrated the regions as a full partner actor and extends its missions to heritage and tourism development. The third and fourth phases of the Loire Plan (2007–2013 then 2014–20) benefit from European support through the ERDF (European Regional Development Fund). Over time, the objectives of the Loire Plan are set in an evolving national and European context, in favor of the preservation of water quality and biodiversity, prevention of flood risks and enhancement of heritage. The last two phases of the Loire Plan, since 2007, are significant for this strong trend, with the support of Europe. The Loire Plan has been a model for the implementation of other river plans in France: a Rhône Plan and Seine Plan were developed in the 2000s.

7.9 Conclusions and lessons learnt

The Loire River is bordered by levees since the Middle Ages downstream of the Loire/Allier confluence and presents an incised bed due to sediment extraction since the middle of the 20th century. Nevertheless, the Loire River still has numerous reaches with active fluvial dynamics and offers a remarkable biological diversity. This illustrates the capacity of resilience of this exceptional ecosystem. The present high biological diversity results from a large variety of geological and climatic features of the Mediterranean, continental and Atlantic regions. Moreover, there exist several hotspots of biodiversity such as the Loire/Allier confluence, where a wide range of habitats hosts a high diversity of plants and birds.

Although ignored for a long time, aquatic environments have seriously deteriorated due to sediment extraction and the construction of sills and barrages that deeply modified aquatic habitats and biotic communities. The number of impounded reaches is high in many tributaries of the lower Loire basin, and although there are few in the main stem of the Loire, all are obstacles to fish migration. Fish populations have been affected by the deepening of the river bed, e.g., the status of the pike is in question, and the ecological consequences are visible in plant communities through accelerated growth of hardwood forests. Lateral dikes along the middle Loire also stabilized channels and islands. Pollution impacts cumulate in the estuarine zone where conditions for fish are poor during certain periods of the year. In the future, some effects of climate change, such as increases in water temperature and the appearance of longer and more severe low-flow periods in summer, may exacerbate water quality problems such as eutrophication.

Under European and national influence over the past 20 years, public policies for Loire management have shifted to a more sustainable approach focusing on continuity and eco-systemic functionalities. While emphasizing the good ecological status of rivers, the Water Framework Directive (WFD) noticeably modified the priorities of European water policy. While once focused on the reduction of industrial and domestic pollution, and more recently on the control of pollution from diffuse sources, management is now aimed toward the good functioning of aquatic environments. The primary goal of the WFD of reaching a good ecological status of aquatic environments should enhance the restoration of aquatic environments. Many efforts have been made to mobilize the public and stakeholders to assist in habitat improvement and assure financial funding. Much debate on the revision of the management and water master plans require the input from the public and stakeholders. Implementing the fifth phase of the "Plan Loire Grandeur Nature" should add to this discussion, while improving the ecological status of the Loire basin remains a primary goal.

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