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27 The Seine, the River dedicated to Paris

Lestel, Laurence¹, Meybeck, Michel¹, Carré, Catherine², Belliard, Jérôme³

¹ UMR 7619 METIS, Sorbonne Université-CNRS-EPHE, Paris, France

² LADYSS, Université Paris 1 Panthéon-Sorbonne, Paris, France

³ HYCAR Research Unit, INRAE, Antony, France

Summary

In France, the Seine River was already being used as a waterway some 6000 years ago. It has favored the development of Paris since the Romans founded the city as Lutetia. In the Middle Ages, the transportation of timber rafts and food supplies on the river, river mills, and direct use of the water supply sustained the growth of the capital city. New river uses were developed in the mid-19th century: the river was gradually channelized and equipped with locks for navigation and received insufficiently treated urban wastewater. During the same period, the Seine riverscape was immortalized by impressionist painters. From 1870 to 1970, the river quality downstream of Paris continued to worsen in a context of urban development: few fish species survived, due to severe hypoxia in the Lower Seine, until a giant wastewater treatment plant, Seine-Aval, was constructed in the 1940s–1990s. This effort led to an improved basic environmental quality in the 1990s, which allowed the gradual restoration of fish populations downstream of Paris. The longitudinal and transversal connectivity of the river was again reduced after World War II: major reservoirs were built in the headwaters for flood control and sustaining low flows in the river reach within Paris, and the original floodplain wetlands were transformed into several hundred artificial sand pits. Today, migratory fishes are now gradually returning, including salmon in the lower part of the river, thanks to specific fishways which partially restore migration pathways.

From 1960 to 2010, Parisians had very little contact with their river: fluvial navigation, flood control, sand extraction, river bank car traffic, and poor water quality were the limiting factors. The inscription of the banks of the Seine in Paris by UNESCO on the World Heritage list in 1991, signaled a reversed trend in the expectations of the riverside residents concerning their river. Associations and officials have since requested the ecological restoration of urban rivers, including the Seine, and the conservation of the few remaining natural wetlands. Recreational amenities were re-established from the 2000s onwards, and the swimming competitions, planned for the Paris Olympic Games in 2024, are a driver to reach a better bacteriological river quality. However, the Seine River, impacted by a metropole of seven million people and its related impacts, is set to remain a highly modified river, and will continue to be regulated to provide the economic functionalities and restored to provide the ecological functionalities expected today; coordinated governance at the scale of the whole river basin, successful in terms of water quality, has yet to be realized in other domains such as flood security or habitat restoration.

27.1 Introduction

The Seine River and the City of Paris have been closely connected over 2000 years (Beaudouin 1993). The complex relations between the river, the city that became the capital of France in the 13th century, and the population of the river

basin, encompassed various and evolving cultural elements. These elements include the use of the river and its floodplain to meet the needs of inhabitants (drinking and washing) and their economic activities (urban expansion, industry, transport and energy), their demands for flood

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control and recreational uses. Each of these elements had different kinds of impacts on the river and/or its floodplain (reversible/irreversible, low intensity/high intensity), and express different people's perception of the river (fig. 27.1).

Paris, one of the big cities of the world, is situated in the center of the Seine basin. From the Gallo-Roman times, when the city, at that time Lutetia, expanded under the reign of Julian the Apostate (4th century), Paris' population and its urban area have increased by three orders of magnitude, reaching today seven million out of the 18 million people living in the Seine Basin (fig. 27.2). It exerts a strong pressure on its river, in part because of the limited dilution capacity of the Seine relatively to Paris population, with a sustain low water discharge of only $150 \text{ m}^3 \text{ s}^{-1}$ in August and September at the Paris-Austerlitz flow gauging station (Flipo et al. 2020a). The complex impact of the city extends over the whole river course, from

the headwaters at the *Source de la Seine*, downstream to the river mouth (fig. 27.2) (Meybeck and Lestel 2017). The natural river system has become progressively affected by multiple types of alteration in combination, such as: changes in land use on the floodplains; channelization of the river course, loss of transverse connectivity, regulations of river discharge, water level, and water depth; obstacles to fish migration (navigation locks); introductions of non-native species; organic pollution and eutrophication, generating hypoxia, impacts on aquatic biodiversity, changes in biogeochemical cycles, contamination by toxic substances, and other emerging water quality issues (Garnier et al. 2020). The changes in the last 200 years have particularly been studied by the Piren-Seine, a research program initiated in 1989 (Mouchel et al. 1998, Flipo et al. 2020b) and, since 1995, by the GIP Seine Aval Program (Fisson et al. 2014).

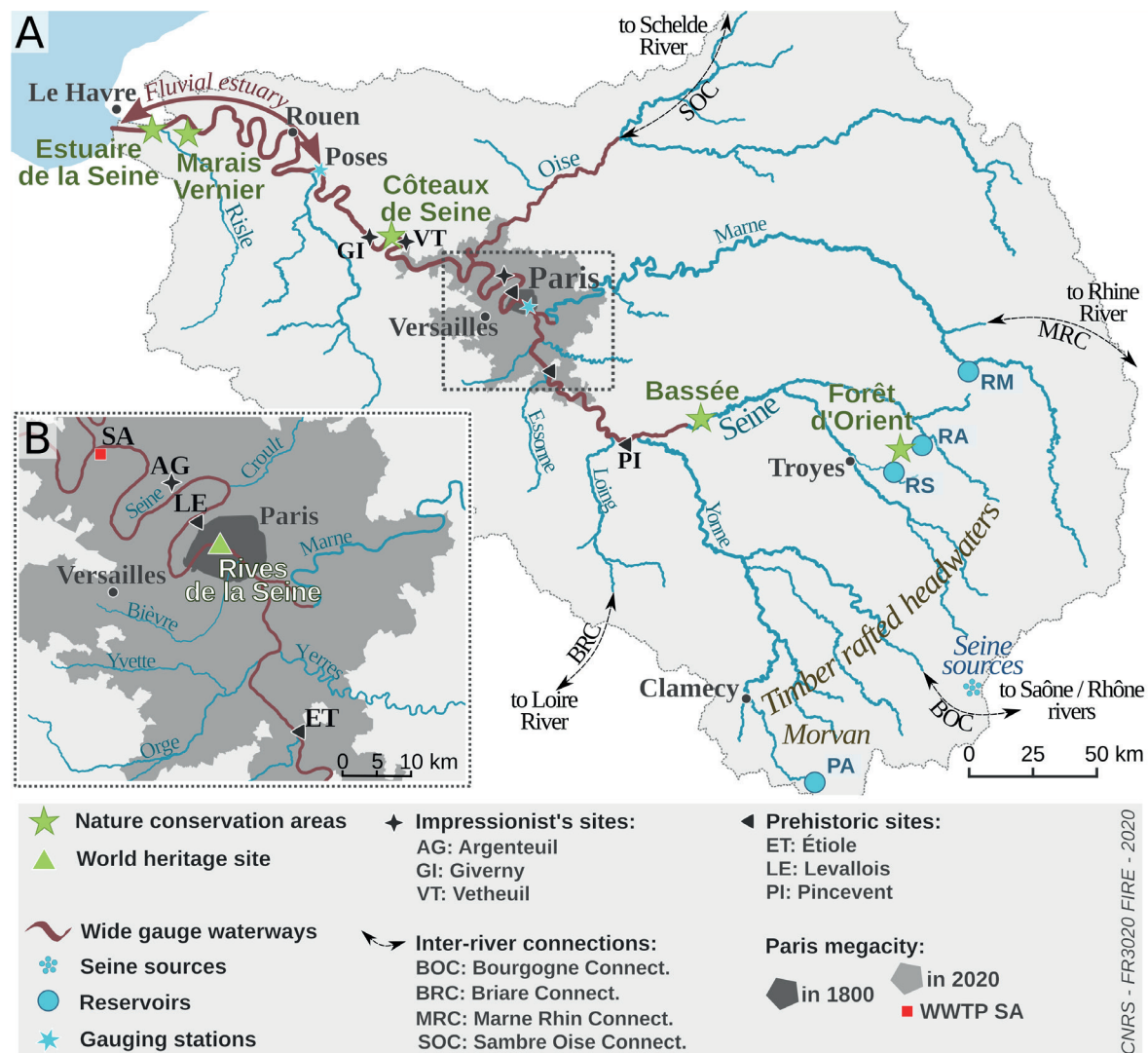


Fig. 27.2 The Seine River Basin showing the whole basin extent (A) and the urban area expansion between 1800 and 2020 (B), with its principal hydrological, natural and cultural features mentioned in the text. Map: Marie Silvestre, with permission

Today, the modified river course is narrower and deeper than that of the 19th century, with few remaining islands. The original riparian wetlands, once covering the whole alluvial and estuarine plains, have markedly decreased, often replaced by new artificial water bodies, the sandpits. The Seine remains somewhat polluted, despite the construction of wastewater treatment plants, with a significant drop in some water quality indicators downstream of Paris (Flipo et al. 2020b). Water from the Seine, Marne and Oise rivers is still used to produce domestic drinking water, distributed to 5.5 million metropolitan residents. However, in the Rouen sector (240 km downstream of Paris, fig. 27.2), the water supply comes from groundwater, due to the much-degraded quality of the Seine.

Another specificity of the relationship people have with the Seine River is the degree of control of the river. Its modification began in the 13th century with the installation of mills, diversions and thresholds, often located in every kilometer of the first-order streams. The claim of Paris on the river course became prevalent in the 19th century, with priority given to navigation, to the extent that today the Seine is the French river that has the highest transportation activity (20 Mty⁻¹). The navigable Seine River is now a succession of low slope river reaches delimited by locks, and the river banks in Paris have been stabilized by high and low quays that were constructed in the 19th century. This demand for regulation is particularly marked for the water levels of the Seine and its tributaries, whether to maintain low water levels or, conversely, to limit flooding. In 1910, a historical flood affected Paris during two months. As a consequence, a series of reservoirs located 250 to 300 km upstream of Paris, on the Yonne, Cure, Aube, Upper Seine and Marne rivers (fig. 27.2) were built between 1930 and 1990. Today they partially lower the high-water levels in Paris by few dozens of centimeters during the highest flows and sustain the summer low flows by adding 50 m³s⁻¹ and more (fig. 27.3). Despite that, flooding is still the major natural risk to which the cities bordering the Seine are exposed.

The perception of the river by Parisians has also evolved considerably (fig. 27.1). For instance, in the second half of the 19th century, the Seine riverscape (with its small villages, recreation areas on the river banks (*guinguettes*) and river baths) was favored by the Impressionists, who initiated in situ landscape painting. In contrast, from 1950 to 1990, there was a lack of connection between the river and the Parisians. After World War II, the banks of the Seine were

largely occupied by fluvial port facilities and urban highways, and the river was left to river traffic and wastewater discharge; meanwhile the river quality, severely degraded, allowed only a few tolerant fish species to persist.

The construction of wastewater treatment plants (WWTPs) between 1970 and 2000 initiated the restoration period and progressive change in people's perceptions and values of the river. The last 20 years are showing a reversal of the people perception with the inscription of Paris river banks, with their historical buildings, on the UNESCO World Heritage list in 1991 (UNESCO-WH 1991), the re-allocation of part of the banks to the public promenade in 2002, and the promotion of enhanced river contact through new educational and cultural associations.

However, the river is still in search of social re-appropriation. Activities on and around the river remain moderate, compared to the mobilization occurring with other urban rivers such as the Rhône (Bouleau and Fernandez 2012). Moreover, it is necessary to note the present lack of governance at the scale of the Seine as a whole system, in contrast to the situation for other French rivers such as the Loire (see chapter on the Loire, this volume) and Rhône rivers.

27.2 Geographic setting: a medium-sized but significant river for regional development

The Seine River, having a length of 775 km from its headwaters to its mouth, is a middle-sized river draining a 76,000 km² basin entirely located in northern France (fig. 27.2).

The source of the Seine was established very early, in Gallo-Roman times. Downstream, the limit between the Seine River and its estuary varies according to points of view: in such a macro-tidal estuary (more than 2 m of tidal range), hydrologists observe tidal fluctuation of the water level up to Poses, i.e. in freshwaters far upstream of the brackish/freshwater limit located 20 km upstream the river mouth (fig. 27.2). Therefore they set the estuarine limit at Poses, while the administrative maritime limit has varied, from Rouen to Berville, depending on the period (Le Sueur 2015). But for riverside residents and in the common sense of society, the Seine is still considered a river until the estuary mouth at Tancarville near Le Havre.

The major tributaries to the Seine are the Yonne and Cure, in the Morvan Mountains, and the Aube, Loing, Marne and Oise rivers (fig. 27.2). The bedrock in the basin comprises essentially carbonate rocks (61.2% limestones

Table 27.1 Main characteristics of the Seine River from headwaters to its mouth

Seine River	
Countries in the catchment	France
Catchment size (km ²)	65,000 at Poses, upstream of the estuary, and 76,238 at the Seine mouth
Length (km)	607 river + 170 fluvial and saline estuary
Mean (min/max) annual discharge (m ³ s ⁻¹)	Average annual discharge: 280 at Paris Austerlitz; and 485 at Poses. Maximum recorded discharge around 2,600 (Flipo et al. 2020a) and minimum around 30 before regulation
Hydrological/sedimentological patterns	Pluvial/oceanic regime with high flows in winter (January and February) and low flows in summer (August and September); low-energy river with sandy bottom in most parts of the network
Degree of naturalness	The Seine River is heavily modified from natural, based on its physical habitats, hydrological regime, chemistry, and biodiversity
Natural landscape types	Lowland meandering river course incising carbonate rock plateaus. Alluvial plains (covering 14,000 km ² of the basin), once rich in lateral wetlands are today mostly disconnected from the river or filled-in; the wetlands have been replaced by new, deep and steep, sand-pits
Physical impacts	Channel deepening and channelization (controlled water levels for 400 km of navigable reaches and 29 major locks (Seine mainstem); 3 main (and other smaller) lateral reservoirs constructed along the river course for discharge regulation; artificial banks within urbanized reaches (around 100 km)
Largest cities (inhabitants)	Seine River: Paris metropolitan area (Greater Paris, 7 million people), including Paris (2 million); Troyes, Montereau, Melun, and Mantes (each around 50,000–100,000); Seine Estuary: Rouen metropolitan area (500,000), Le Havre metropolitan area (270,000); 18.2 million across entire basin (2018)
Urbanization	Early Celtic settlements along the Upper Seine River; Roman settlements (<i>Lutetia</i>); gradual expansion of urbanized river reaches within Paris and suburbs, from 2 km (12 th century) to 100 km today
Protected natural areas	National nature reserves: Forêt d'Orient (15.6 km ²) Bassée (8.5 km ²), Côteaux de Seine (2.7 km ²), Marais Vernier (1.5 km ²), Estuaire de la Seine (85 km ²); Regional nature reserves: Côtes de la Fontaine (0.1 km ²), Boucle de Moisson (3.1 km ²); National wildlife and hunting protection area : Lac de Der (56.6 km ²); i.e. around 1% of the river corridor
Prevailing use form in the catchment	Intensive agriculture on plateaus (56.5% of basin area); managed forest (partly planted) 25.9%; urbanized and industrialized areas (7.5%), grasslands (9.5%). Industries are located along the river course, from agro-industries upstream of Seine-Yonne confluence, to heavy industries in Paris suburbs and estuary
Famous elements of biodiversity	Migratory fishes (e.g., salmon), being recolonized; Bassée floodplain wild grapevine, more than 500 plant species in the Côteaux de Seine
Famous elements of River culture	Banks of Seine UNESCO World Heritage, in the historic center of Paris; Seine R. waterscape celebrated by painters (Impressionists), poets, songs writers; former recreation areas (guinguette dance bars, bathing and aquatic sports areas), now revitalized

and chalk) and sandy formations (12.8%), while the river valleys are filled with alluvial deposits (22.0%). This generally low-energy river, with limited average slope (20 cm km^{-1}) and stable, seasonal discharge regime (winter high flows and summer low flows) (fig. 27.3), does not cross rocky outcrops or other natural obstacles to navigation but has now cascading locks and few major dams in its headwaters.

The original natural morphological dynamics of the meandering Seine River, incising the calcareous plateaus, resulted in 1 to 10 km-wide floodplains filled with Quaternary sand and cobbles. The Bassée Floodplain upstream of Paris (fig. 27.2), once an alluvial forest wetland, constitutes a major aquifer that today is an essential source of sand and gravel. Historical maps of this area allowed an estimation of the slow shifting rate of the Seine River meanders: 5 m every 100 years (Lestel et al. 2019). As the basin was not ice-covered during the last Glacial Period, Holocene climate fluctuations were then the main drivers of the morphological changes in the river and its estuary, such as island and sand bar formation, and bank erosion. The present-day average specific runoff ($7.5 \text{ L s}^{-1} \text{ km}^{-2}$) and fine sediment supply ($10 \text{ t km}^{-2} \text{ y}^{-1}$ of clay and silt) of the Seine are typical of many other western European rivers (Garnier et al. 2020).

The main cities of the Seine Basin are located in the floodplains of the Seine and its tributaries. In the Lower Seine Basin, plateaus dominate the floodplain, rising above it by one to 200 m, generating a characteristic landscape (see fig. 27.6, column 1, low). This landscape is composed successively of cities next to the river, villages on the hill slopes, and plateaus with agricultural and forestry land use, which are nowadays partly replaced by urban sprawl.

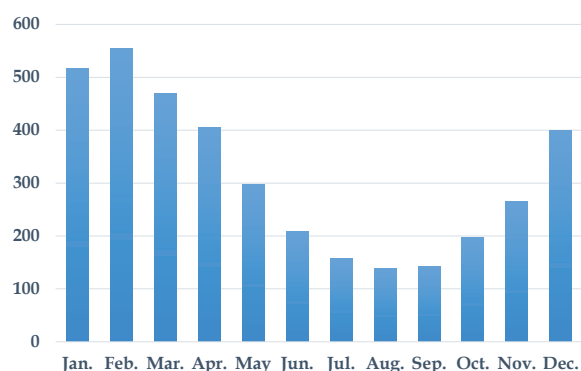


Fig. 27.3 Average monthly discharge ($\text{m}^3 \text{ s}^{-1}$) of the Seine River calculated on the period (1970–2010) at Paris Austerlitz after the creation of reservoirs. Graph: Laurence Lestel, based on data by Banque Hydro, Eaufrance website (2020)

Following its modification to facilitate river navigation, the Seine has become a succession of low slope river reaches delimited by locks, and is one of the main logistic axes in France with 20 million tons of freight transported each year. Today, the ports of Le Havre, Rouen and Paris are jointly managed by a public entity, HAROPA (HAROPA website 2020).

27.3 Historical evolution towards an irreversible artificialization

The rich information that exists on the Seine River of the past and its cultural elements, uses, perceptions, and expectations, is derived from many sources: archeological excavations in the floodplain, historical records, pioneer chemical analyses, and archives from the institutions in charge of river management and surveys. Their chronology (fig. 27.1), with our current understanding of the past, present, and likely-future of the Seine River as a socio-ecological system, has been mostly generated within the last 30 years from the interdisciplinary Piren-Seine and GIP Seine aval scientific research programs (PIREN Seine website 2020, GIP Seine Aval website 2020), now parts of the Zone-atelier Seine of the CNRS (ZA-Seine website 2020).

27.3.1 Early occupation of the Seine Valley (Prehistoric to Roman times)

According to archeological records, people have settled on the Seine River banks since prehistoric times and in the alluvial plain over the last 100,000 years, from the Paleolithic to the Neolithic period. The Levallois stone knapping (Levallois is a commune in the inner suburbs of Paris), described in the late 19th century, is now universally used to qualify the flint tools of the Mousterian culture (c. 160,000–40,000 BP). The Magdalenian culture (c. 17,000 – c. 12,000 BP) is also fully documented in Pincevent and Etioilles, two famous sites located on river-floodplain silt deposits, regular occupation sites of hunter-gatherers as revealed by archives (Fritz and Tosello 2011). The well-preserved dugout canoes found at Noyen-sur-Seine (Mesolithic, 8,000 BP) and at Bercy (Neolithic, 5,000 BP), today a site in the center of Paris, attest to the very early navigation on the river.

During the Gallo-Roman period (1st–5th centuries), the headwaters of the river were dedicated to *Sequana*, the river deity (name of uncertain origin) from which the name for the Seine is derived, also given the name of Sequanians to the people living along the Seine. A set of dozens of wood *ex-votos* (i.e. an offering given in order to

fulfil a vow) have been found in the Source de la Seine (Martin 1965), attesting the sacred nature of the river (fig. 27.1: 1). In this period, Lutetia was built on Île de la Cité, the heart of Paris, and a powerful corporation, the *Parisii Nautes*, managed fluvial transport (de Izarra 1993).

27.3.2 Historical uses of the Seine River (Middle-Ages to the beginning of the 19th century)

In the 13th century, Paris became the capital of France and a major European city, fed by its rich hinterland thanks to fluvial navigation. Many of the initial modifications of the river course were a result of the demand for food, wood for fuel and construction, and other commodities largely transported by waterways (fig. 27.1: 2–5, 7–8). Stone embankments appeared in Paris at the beginning of the 14th century. Timber rafting, a major river use initiated in the 16th century, peaked around 1800, with a total transported volume of 1–1.5 million m³ of timber per year; this industry declined rapidly during the second half of the 1800s, then stopped after 1900. Timber, originating from the Morvan Forest, was first conveyed on small tributaries, whose discharges were artificially increased by the operation of specific headwater ponds, during winter as free logs around 1 m (3.5 feet long) (fig. 27.2) (Poux et al. 2011). The logs were then re-assembled and finally transported to Paris as timber rafts (Bruley 1995). Rivers of the Seine system also provided an essential energy source through mills of all kinds, fixed and floating. It has been estimated that 6,000 mills were present on streams and rivers in the Ile-de-France region alone, an area of some 12,000 km² within the basin (Boët et al. 1999).

In 1800, Paris accounted for 11% of the Seine Basin's total population of 4.5 million inhabitants, with its 500,000 people, heavily reliant on the rest of the basin for food and energy (Billen et al. 2009). The Seine River was already connected with the Loire River since 1632, through the Briare Canal, France's first canal (BRC, fig. 27.2). Under Napoleon I, the French state began to develop navigation facilities on state-owned navigable rivers, with harbors, artificial banks and docks, and the system of high and low quays in Paris (Guillermé 1990). The Ponts et Chaussées state corps of engineers was in charge of the construction and management of this infrastructure.

The claim of Paris on the river course became clearer when Napoleon I named the Paris administrative territory after the river, and in 1864, this claim was formalized by Napoleon III, though a symbolic representation of Sequana, the roman

river deity, at the official location of the Seine source owned by the capital city.

27.3.3 Contemporary river features (19th - 20th centuries)

The progressive modification and channelization of the Seine and its tributaries has been fully documented, thanks to the archives of a river-dedicated corps of engineers (Ponts et Chaussées) and other river dedicated institutions (Lestel et al. 2020). This physical alteration occurred in the whole navigable reach, in the main channel, the river banks and in the floodplain, with a maximum artificialization in the Parisian reach and in the estuary (fig. 27.1: 11, 13–14).

When motorized river transport began to develop, the Seine – and Paris – became quickly connected to the Scheldt River (Belgium) through the Oise River, a transboundary tributary of the Seine, and St. Quentin Canal (built in 1829, SOC, fig. 27.2), as well as to the Saône and Rhône rivers through the Bourgogne Canal (1832, BOC, fig. 27.2). The 1837 Law for the improvement of navigation on the Seine River resulted in the channelization of the river course, with dozens of sluices and locks, and a deepening of the river at 1.6–2 m navigation gauge (Merger 1994, Brennetot 2019) (fig. 27.6, column 4, up). The construction of dikes and the channel deepening resulted in the drying up of the adjacent alluvial floodplains (Lestel et al. 2019). During a second stage of development, in the 1950s–60s, a much deeper navigation gauge was adopted (to 3 m). Today, the stepwise profile of the river is characterized by a succession of reaches with very limited slopes over a 400 km stretch, and delineated by 29 weirs and locks between La Bassée and Poses (fig. 27.4).

The river waterways also facilitated passenger transportation on new steamboats between Paris and Le Havre, a service, which lasted about 100 years. The famous Bateaux-Mouches, developed for the Paris World Fair in 1867 (fig. 27.6, column 2, up), are a contemporary legacy of this activity and are still one of the best ways to visit Paris. Over the same period, the emerging railways initiated an alternative, competing and parallel form of transport for people and goods.

In the 19th century, Parisian urban development accompanied the industrial revolution, which led to the installation of many factories on the banks of the Seine, for transport and access to water. A century later, when the Paris region was deindustrialized, urban areas replaced these industrial ones. The urbanized areas increased by two orders of magnitude, from 75 km² in 1850 to 2,850 km² today (Esculier and Barles 2020)

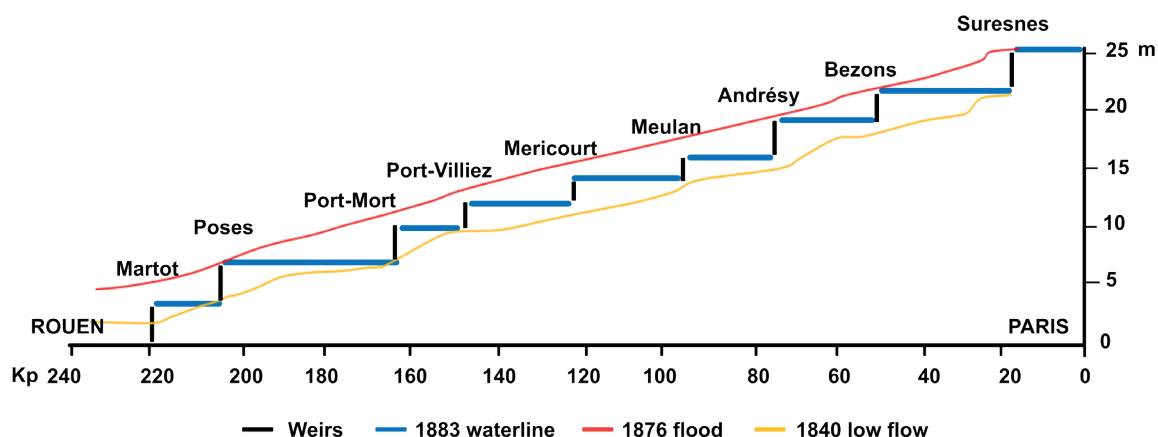


Fig. 27.4 The 1883 longitudinal river bed profile (altitude in m above sea level) on the lower Seine reach, 240 km from Rouen (Martot lock) to Paris (Suresnes lock) resulting from the staircase transformation of the navigated Seine in the mid-1800s. Graph: Laurence Lestel, based on data from Pont et Chaussées engineers (AN CP/F/14/10078 File 2, 51a)

(fig. 27.2). These built areas, which have greatly reduced the expansion zone of flooding, are thus more vulnerable to inundation nowadays. Most of these transformations are considered irreversible (fig. 27.1: 11, 13).

27.3.4 Water quality degradation – a long-lasting story (1850–1990)

Water uses of the Seine have evolved with time and the related pressures on the river have continued to increase, with consequences for the Seine's water quality (fig. 27.1: 9–10, 18–20).

The Seine water has been the essential water resource for Parisians for a long time. The most spectacular facility was the Samaritaine, an enormous hydraulic water pump, powered by a water wheel under the Pont Neuf in Paris, which lifted water up from the Seine River, between 1608 and 1813, for use in the royal Louvre Castle and its Tuileries Gardens. In the late 1700s, the excellent quality Seine River water, directly withdrawn and distributed by individual water carriers, was still being celebrated for its organoleptic properties and was adequate for cooking and cloth cleaning (Parmentier 1787, Backouche 2000). Fifty years later, the water of the Seine was analyzed by pioneer water chemists, Boutron and Boudet, in 1854, to establish the first-ever water quality scale, for water hardness (Carbonaro-Lestel and Meybeck 2009). Meanwhile, in reaction to the cholera epidemics of 1832 and 1854, and other increasingly studied waterborne diseases, wastewater collection became a matter of concern in the second half of the 19th century. Eugène Belgrand (1810–1878), the Paris city chief engineer working with Georges-Eugène Haussmann (1807–1891), established the sewage collection system of Paris during the Second Empire (1852–1870) (Deutsch and Gautheron 2013). The collection led to a marked degradation in

river water quality, shown by indicators such as ammonia, nitrite, dissolved oxygen, organic matter, dissolved salts, nitrate and faecal coliforms (Meybeck et al. 2018). These early water quality indicators, developed by chemists and microbiologists, such as Gérardin, in 1874, and Dienert, in the 1890s, were used for the first time to quantify the impacts of a city on its river, over a section of river extending from Paris to 100 or 250 km downstream (Meybeck et al. 2017, Dmitrieva et al. 2018). These indicators are still used for high-frequency monitoring surveys by the water institutions of Paris, establishing some of the longest records of river water chemistry.

In the 1870s, collected wastewater was spread over "sewage farms" near Paris, where it served as fertilizer for agricultural production, i.e. a short nutrient cycle where farm products were then used by Parisians. This technique, which lasted more than 100 years, was however insufficient to efficiently treat the growing volume of wastewater. A single wastewater treatment plant (WWTP), using anaerobic digestion, was established in 1940, at the sewage farm of Achères, 60 river km downstream of central Paris. However, less than 10% (200,000 m³ d⁻¹) of the total volume of sewage was treated in the 1950s (fig. 27.1: 10, fig. 27.2: SA).

France's first Water Law (1964, L64-1245) resulted in a paradigm change for wastewater treatment. Six river basin authorities were established, including the Agence de l'Eau Seine-Normandie (AESN), which could then establish and raise taxes on water users, mainly cities and industries, and in turn redistribute the tax revenues for the development of WWTPs across the whole basin. The extension of the Achères WWTP, today the Seine-Aval facility, allowed the treatment of 2.1 million m³ d⁻¹ water in the mid-1980s, corresponding to eight million inhabitant-equivalent

(Meq) in terms of oxygen demand load (as officially defined in the 1960s). It was then the largest in Europe and became reduced to 6 Meq when other WWTPs were constructed in the 1990s, redistributing the impact of Paris WWTPs over 100 river kilometers. The lag between sewage collection and the adequate treatment of oxygen-consuming organic pollution from Paris was only resolved in the mid-1990s (Meybeck et al. 2018), aiding the restoration of fish populations in the lower Seine River (Belliard et al. 2020, Le Pichon et al. 2020) (see fig. 27.5). Today, efforts to improve water quality include the control of improper wastewater connections and the construction of storm-water overflow storage facilities, with the aim to restoring, maybe, swimming in the Seine River.

27.4 Biotic diversity: the recent biological recovery of a severely altered river ecosystem

This historical analysis shows the enormous influence of the City of Paris on the whole Seine River, from headwaters to estuary, including: (i) the artificialization of the river course, (ii) the hydrological and hydraulic alteration of flow regime (discharge, water level, water depth and velocity), due to reservoirs and to the cascade of locks, (iii) the degradation of physical habitats (of suburban and urban reaches and floodplain wetlands), (iv) the degradation of the chemical and bacterial water quality of the Lower Seine downstream of Paris, resulting in a loss of biodiversity, particularly of fishes.

Most of the physical modifications are considered irreversible, having detrimental impacts on natural aquatic habitats. The Seine River channel-

ization induced the gradual disappearance of the many islands of the river between 1850 and 1950 (Lescure et al. 2011). This has been quantified by the comparison of 1830s and contemporary river maps (Lestel et al. 2019, 2020): along the 340 km from the Seine-Yonne confluence to Rouen, 405 islands have been lost, some razed, many attached to the river banks by filling the secondary arms of the river. For the navigated channel, the geomorphological braiding index has markedly decreased, from 2.5 in 1890 to 1.5 today, reflecting the loss of shallow spawning grounds favored by many fish species.

27.4.1 Migratory and freshwater fish species

The history of the fish populations of the Seine River Basin has been reconstructed as far back as medieval times, from archeological remains (e.g., food remains) and various types of historical documents, complemented by recent electrofishing data (Belliard et al. 2018), with some caution (archaeological remains provide insight into the past occurrence of species, some of them were actually caught in distant waters, such as the rare commercially valuable species (Beslagic and Belliard 2014)).

Before human intervention, the native fish fauna of the Seine River system likely included up to 23 strictly freshwater species, as well as an additional 11 diadromous (migratory) species (table 27.2). Humans gradually modified this native fauna through their early fishing activities, documented since prehistoric times, their ability to transport living fish and, more broadly, their impacts on their environment.

Fish assemblages were impacted by river mills, since the 13th century, and timber rafting

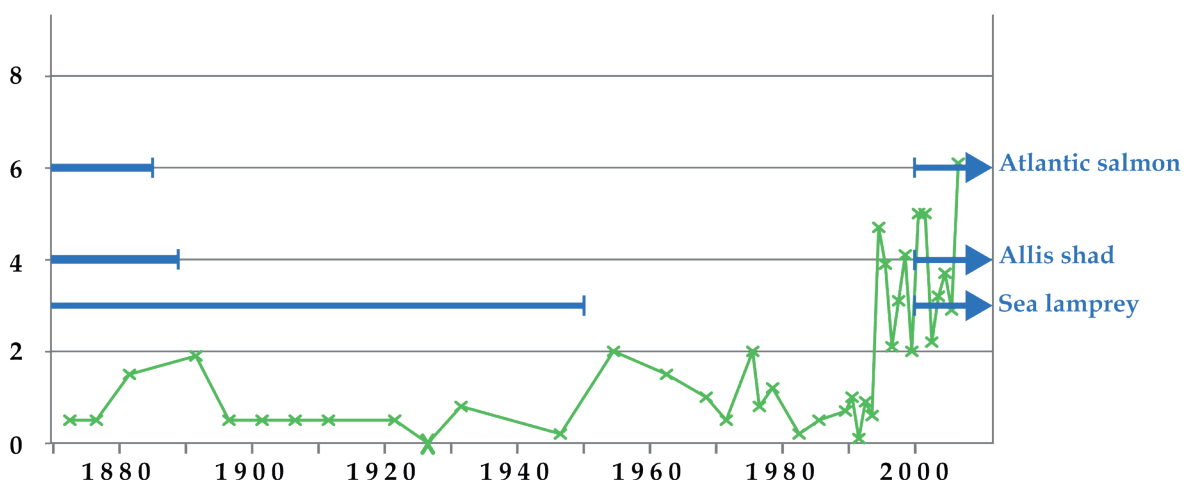


Fig. 27.5 One-hundred-and-forty years of minimum oxygen (O_2) content in the Lower Seine in July (left axis: dissolved O_2 ($mg\ L^{-1}$, green line). Blue arrows indicate periods of presence/absence of three fish species observed in the Lower Seine. Limits in oxygen contents representing chemical barriers for Sea lamprey, Allis shad and Atlantic salmon are 3, 4 and 6 $mg\ L^{-1}$ respectively. Graph: Laurence Lestel, modified after Meybeck et al. (2018), Le Pichon et al. (2020)

Table 27.2 Key elements of biodiversity of the Seine River and its floodplains

Key element	Link to the natural flow regime	Ecosystem services	Human use and threats
Migratory fish species: Atlantic salmon (<i>Salmo salar</i>), sea trout (<i>Salmo trutta</i>), allis-shad (<i>Alosa alosa</i>) and twaite shad (<i>Alosa fallax</i>), sea lamprey (<i>Petromyzon marinus</i>), and river lamprey (<i>Lampetra fluviatilis</i>), European eel (<i>Anguilla anguilla</i>), thinlip mullet (<i>Liza ramada</i>), flounder (<i>Platichthys flesus</i>), smelt (<i>Osmerus eperlanus</i>), European sturgeon (<i>Acipenser sturio</i>)	Migration period in the Seine River depends on fish species. Allis shad and sea lamprey: March–June; Atlantic salmon: three periods in March–May, June–July, September–November (Le Pichon et al. 2020)	Indicator of "good ecological quality" of water and sediments (salmonid fry lives in the hyporheic zone), ecosystem engineers marker (salmon redds), lamprey and sturgeon are important host fish for unionid mussel larvae (Soler et al. 2019)	Allis shad: critically endangered; sea lamprey: endangered; Atlantic salmon: nearly threatened (Le Pichon et al. 2020). Disappearance of these species between 1900s – 1990s. Changes in use from a source of food for riparian people to a psychological positive experience (well-being)
Wild grape vine (<i>Vitis vinifera</i> spp. <i>silvestris</i>)	In the Bassée Floodplain, the widest alluvial sector upstream of Paris. An alluvial forest indicator	One of Europe's most important stands of <i>V. vitifera</i> in Europe, identified only in the 1980s (Arnal and Zanre 1990)	Protected by the creation of the Bassée National Nature Reserve (RNN155) in 2002 (854 ha)
Rouen violet (<i>Viola hispida</i>), and more than 500 plant species in the Côteaux de Seine (e.g., orchids, Pasque flowers (<i>Pulsatilla vulgaris</i>), St. Bernard's lilies (<i>Anthericum liliago</i>), silky spike melic (<i>Melica ciliata</i>))	Specific habitat of the calcareous river valley cliffs (Arnal 2013)	Priority conservation species (Annex II Habitat Directive 92/43/EEC)	Its protection has led to the relocation of a motorway project bypassing the city of Rouen.

in the 17th–19th centuries, which were altering the river banks and fish habitat, meanwhile the thousands of artificial ponds were also warming headwaters.

The first documented introduction of non-native species is that of the common carp (*Cyprinus carpio*), through farming ponds in the 13th century (Middle Ages) (Hoffmann 1995, 1996).

A sharp decline in migratory species such as salmon populations was already noted during the 13th century, as a consequence of the development of water mills, which prevented access to spawning grounds and also presumably facilitated overfishing (Lenders et al. 2016). However, in the mid-1800s, Atlantic salmon (*Salmo salar*) could still go upriver for 690 km, sea lamprey (*Petromyzon marinus*) for 610 km, and the shad (*Alosa alosa*) for 550 km (Le Pichon et al. 2020).

The 1850–1900 period is considered a turning point, with the widespread construction of barriers in waterways used for commercial naviga-

tion, the severely anoxic conditions downstream of Paris, and the introductions of non-native species. All of these factors resulted in altered fish assemblages, especially the disappearance of migratory species.

In 1858, the construction of Settons Dam on the Cure River definitively closed off salmon access to the best spawning grounds upstream (Moreau 1898). Meanwhile, on the lower Seine River, the construction of the Martot Weir in 1864, just upstream of Rouen (dismantled in 1939, after a major straightening of the Seine River for navigation), followed by Poses Weir a few kilometers further upstream (1886, and at 4 m high, the highest navigation dam at that time, still in operation today), considerably reduced fish access to the Seine river network (Le Pichon et al. 2020) (fig. 27.6, 1st column, up). Within only a few years, this led to a collapse of the most vulnerable species. As a result, European sturgeon, salmons, and allis shad, were extinct in the Seine

River Basin by the beginning of the 20th century. Species such as twaite shad and smelt, able to reproduce further downstream, were less adversely affected.

After the 1860s, summer hypoxia periods (defined as less than 2 mg O₂ L⁻¹ downstream of Paris) and frequent low-oxygen events (< 5 mg L⁻¹), contributed significantly to population declines for all fish species, and generated frequent fish kills, especially after heavy summer rainstorms over Paris, due to the overflow of untreated combined sewers. Gradually, in the 1970s, the hypoxic zone could extend more than 150 km along the Lower Seine River (Meybeck et al. 2018). After World War II, a second hypoxic zone (< 2 mg O₂ L⁻¹) was measured for 200 to 300 days every year within the estuary, sometimes with periods of total anoxia in summer and autumn. This zone was due to the release by Rouen of untreated urban sewage directly into the river, coupled with the nitrification of ammonia released by Paris' water treatment works (Fisson et al. 2014, Billen et al. 2001). As a result, the populations of smelt and twaite shad, two fish species that are able to reproduce in the lower parts of the river, collapsed during the 1950s and were presumed extinct throughout the basin in 1970. Altogether, only four anadromous species were remaining within the Seine Basin, *Lampetra fluviatilis*, *Anguilla anguilla*, *Salmo trutta trutta* and *Platichthys flesus*, by the end of the 1970s, with sparse populations (Rochard et al. 2009).

The major introduction of non-native species took place in the 1800s, in line with a collective desire of public authorities to "improve the production of natural systems" with species from other countries, facilitated by technical and scientific progress in fish breeding in France (Belliard et al. 2020). After a decline in alien species introductions during the first half of the 20th century, due to two World Wars and gradual awareness of their potentially detrimental ecological consequences, the rate of introductions increased again from 1950, due to the development of recreational fishing. In recent decades, introductions of pikeperch (*Sander lucioperca*), grayling (*Thymallus thymallus*) and wels catfish (*Silurus glanis*) were favored by anglers (Belliard et al. 2020).

Other introductions occurred accidentally. The establishment of navigation channels connecting the Seine River with neighboring European rivers (fig. 27.2), acted as an accelerator for exotic aquatic species, including mollusks (e.g. zebra mussel, *Dreissena polymorpha*) and aquatic plants, from Central and Eastern Europe. This mode of colonization seems to be involved in a few fish, such the common nase (*Chondrostoma*),

observed as early as the 19th century, and more recent arrivals in 2015, the ide (*Leuciscus idus*), asp (*Leuciscus aspius*) and round goby (*Neogobius melanostomus*) (Manné 2017).

Native fish populations started to recover in the mid-1990s, when the considerable efforts to treat sewage (initiated post-1970), succeeded in restoring the river oxygen balance from Paris down to the estuary (fig. 27.5, Meybeck et al. 2018). Many species returned, including some diadromous fishes, such as twaite shad and smelt, both species now regularly reproducing in the Lower Seine. A second recovery phase was associated with the gradual installation of fish passes on navigation weirs: in the early 2000s, salmon and allis shad, species migrating further upstream, began to recolonize the river system, without restocking (Belliard et al. 2009, Perrier et al. 2010).

27.4.2 Floodplain wetlands and emblematic riparian plants

Wetlands, initially abundant in the forested floodplain, have gradually decreased since the mid-1800s due to agriculture, deforestation, channelization, urbanization and sand extraction (Bendjoudi et al. 2002, Ecosphère 2005).

Sand mining, for example, generated a shift in wetland habitats in the floodplain. Originally, they were shallow water bodies, as abandoned arms and other slack waters, mostly activated and connected during medium and major floods (> 5-year return period). The extraction increased dramatically after 1950 to up to 10 million ty⁻¹, for construction materials for the rapid expansion of Paris as a megacity, for new highways and railways, and for the Nogent-sur-Seine nuclear power plant in the Bassée floodplain located 150 km upstream of Paris (see fig. 27.2, Meybeck et al. 1998). The Seine floodplain deposits provided an adequate, cheap solution, and could be easily transported by the waterway. The extraction, which is ongoing, has resulted in hundreds of sand-pits, upstream and downstream of Paris, 2 to 5 m deep, with steep banks, filled with alluvial groundwater, either hydrologically isolated from the river mainstream or sometimes connected via channels.

The Bassée is the major alluvial plain of the Seine Basin, covering 320 km² (fig. 27.2). The evolution of its land cover over the last 180 years can be quantified using an analysis of historic maps (Lestel et al. 2020). The remnant patches of alluvial floodplain forest are high in floral diversity. They harbor the indigenous wild grapevine (*Vitis vinifera*) (fig. 27.6, column 1, middle), one of its few habitats in Europe (along with the Rhine

and Danube floodplains, see chapters in this volume) and the white elm (*Ulmus laevis*) (Arnold et al. 1998); a survey of 374 ha of remaining alluvial forest revealed the wild grapevine was present in 4.5% of it (Ecosphère 2005).

Other emblematic plant species of the Seine River are found on the steep, calcareous cliffs (Coteaux de la Seine) of the Lower Seine Valley. Both Bassée and Coteaux de la Seine are now nationally protected areas (see fig. 27.2). The presence of Rouen violet (*Viola hispidula*) and of an endangered butterfly marsh fritillary (*Euphydryas aurinia*) on the calcareous cliffs near Rouen has long postponed the motorway bypass in the east of the city of Rouen, making it necessary to propose an alternative route.

27.5 Cultural assets of the Seine River and its celebration, a complex history

The Seine River and its basin are very rich in cultural elements, material and intangible, many of them located on the banks of the river in Paris. The natural, tranquil river landscape also inspired a revolution in art history, the Impressionism of the 1870s to 1890s, which initiated in situ landscape, recreation areas and river baths painting (fig. 27.1: 12). This inspiration fell away with the disappearance of social activities on the Seine and its banks after World War II. At that time, the banks were largely occupied by river port facilities and urban highways, the river was left to the transport of goods, and river water quality was degrading. People no longer had personal contact with the river (fig. 27.1: 15).

The last 20 years show a reversal of this situation, however, with the inscription of Paris river banks and their historical buildings on the UNESCO World Heritage list (UNESCO-WH 1991), and the reassignment of some areas along the river banks to urban recreation (fig. 27.1: 16).

27.5.1 The Seine river banks in Paris, a part of UNESCO World Heritage

In the historical heart of the city, the Seine river banks in Paris, inscribed in 1991 on the UNESCO World Heritage list, comprise 23 bridges, the quays and banks of the Seine between the Pont de Sully and the Pont d'Iéna, the Ile de la Cité and the Ile St. Louis. In this 365 ha area, archaeological elements and architectural masterpieces reflect a history of over two thousand years: the Roman baths of Lutetia, the medieval religious monuments (Notre Dame and Sainte Chapelle), and the many royal and civil buildings (Louvre, Grand and Petit Palais, Gare d'Orsay and Eiffel

tower), along the river course. This ensemble, regarded as a geographical, cultural and historical entity, forms an exceptional and well-preserved example of urban riverside architecture, where the different layers of the history of Paris are harmoniously superimposed (fig. 27.6, column 2, up). Unlike the center of Rouen, which was heavily damaged during World War II, these banks remained intact. They host bouquinistes, open air antiquarian booksellers, which are typical of the Seine banks.

The Seine River Basin also holds a great number and variety of other World Heritage monuments and sites, many of them connected or close to the river course: Vezelay Basilica, Fontainebleau and Versailles castles, Provins medieval city and the new Le Havre city, reconstructed in the 1950s, which marks the ultimate boundary of the estuary. The medieval city of Troyes and its multiple Seine canals is currently proposed as an addition to this world heritage list. For two centuries, Versailles, the chateau-city built by Louis XIV in the 17th century, was fed by the Seine River waters. This was achieved using the unique Machine de Marly, a technological marvel of its time that lifted on average 3,200 m³ of water per day from the river to the Versailles plateau (162 m elevation), with the help of 14 water wheels (Brandstetter 2005). In the second half of the 19th century, the degraded water quality of the river, due to Paris sewage, forced Versailles to shift its supply to alluvial groundwaters (Dmitrieva et al. 2018).

27.5.2 The Seine River landscape generated the Impressionism revolution in art

In the 19th century, the Seine River landscape attracted the pioneer en plein air landscape painters of art history: first Turner, a precursor in 1834/35, then Corot in the 1850s and 1860s, and the Impressionists in the 1870s (Monet, Renoir, Sisley, Pissarro, Guillaumin), the Neo-impressionists in the 1880s (Van Gogh, Seurat and Signac), and then the Fauves in the 1900s (Matisse, Vlaminck and Marquet). They often resided in small villages on the river between Paris and Le Havre: Gennevilliers, Bougival, Vetheuil and Giverny, and painted other locations, among them Asnières, Levallois, Chatou, Rouen and Le Havre; all sites that today are world-famous among art connoisseurs (Chable and Sibout 2003) (fig. 27.2 and fig. 27.6, column 2, middle). Tributaries, such as the Oise River for artists Corot and Van Gogh, the Yverres River for Caillebotte, and the Grand Morin Valley, also named 'the valley of painters', were also inspiring spots for these painters.

These artists celebrated the intrinsic beauty of the riverscape – in all seasons, from sunrise to sunset, and during floods and ice jams. Sometimes, the river banks, bridges, villages and bathing areas are barely visible in the paintings, in a play of light on the water and the infinite color tones of the aquatic vegetation, e.g. as in the waterlilies series (*Les Nymphéas*) by Monet. These works, today present in the world's leading art museums, are considered as masterpieces of art history, and include: *Impression, soleil levant* (Le Havre) by Monet (1872), *Un après midi à la grande Jatte* (at Levallois, near Paris) by Seurat (1884/85), and the *Déjeuner des canotiers* by Renoir (1881), representing the *Fournaise guinguette* – a riverside recreation area – at Chatou, during summer times. Actually, these representations were sometimes misleading about the real state of the river: when Renoir painted this last scene, river water quality was very poor, as recorded by the Parisian Observatoire de Montsouris, due to Parisian wastewater outlets releasing untreated water at Asnières and Clichy (Meybeck et al. 2017, Dmitrieva et al. 2018).

Activities on the Seine and its banks also inspire photography (for example, by famous photographers Cartier-Bresson, Riboud and Doisneau), retracing the Paris of quays, bridges, islands, following painters, such as Guillaumin and Signac, who immortalized the smoking chimneys of industries on the river banks or the river traffic – both symbols of progress at that time, but today considered as negatively impacting environmental quality. The river traffic has also been filmed, for films such as *L'Atalante* ('The Passing Barge') in 1934, by French writer-director Jean Vigo. The Seine River is also celebrated in many poems known to many (e.g., *Le pont Mirabeau* by Guillaume Apollinaire 1912), and songs (*La Seine*, sung by Vanessa Paradis 2011). The Ponts des Arts, a pedestrian bridge across the Seine, celebrated in another song by Georges Brassens (1954), is today a favorite romantic spot for visitors to Paris.

27.5.3 Lost and re-appearing recreation areas on the banks of the Seine

The Seine River was already a place for recreational canoeing in the 18th century (Delaive 1998). At the end of that century, the first bathing establishments were developed on the river within Paris. Barges were converted into swimming pools, filled with water directly pumped from the Seine River without filtration, such as the famous Deligny pool at the Orsay bank (Duhau 2007). On the Seine and its tributary, the Marne River, open-air dancing cafés on the

riverbanks, called *guinguettes*, attracted thousands of people every summer weekend for decades. Access to river recreation areas and the many riverside weekend 'anglo-norman style' mansions, which were built in the 19th century, was facilitated by the new railways and special train fares (Chaïb 2019). The estuarine zone of the Seine, too, was a place of recreation for Parisians. Before the 1860s, there was a famous tidal bore on the Seine at Caudebec, which was so spectacular that special trains were chartered from Paris Saint-Lazare station at the time of high tides. The bore was nearly eliminated in the 1960s following the drastic modification of the Seine channel and extensive dredging in the estuary and river. Today reduced to a single wave, nicknamed "*le flot*", appreciated by surfers and canoeists, it still remains in memories (fig. 27.6, column 2, below) (Foussard et al. 2010).

During the first Paris Olympics, in 1900, swimming, sailing and canoeing competitions were organized on the river (Devron 2000). Aquatic sports culminated during the interwar years, but rapidly declined thereafter when bathing and other water-contact sports began to be limited, due to commercial activities on the river. It was not a deterioration in instream water quality that initiated the ban on bathing in the Seine (in 1867 in Paris, in 1923 in the nearest suburbs), but rather, the difficulty of reconciling the presence of swimmers with barge traffic. Thus, the bathing establishments started to be pulled out of the water and installed on river islands (Charbit 2006), then later transformed into swimming pools, which were gradually relocated away from the river. After World War II, suburban cities, upstream and downstream of Paris, started to dump collected wastewaters in the river system. New sanitary regulations for river-contact activities, and the associated water quality surveys showing increased fecal contamination, led to a definitive ban on bathing in the Seine River in 2003, only, in the Val-de-Marne department upstream of Paris (Mouchel et al. 2020). While swimming in the Seine is still forbidden today within Paris, many hope that, with the city hosting of the 2024 Olympic Games and planned swimming competitions in the river, river bathing will be reinstated.

Another human use of the Seine banks disconnected Parisians from the river in the 1960s, namely, the automobile traffic on those parts of the river banks not used as fluvial harbors (e.g., in Gennevilliers). A 13 km-long urban expressway, the Voie Georges Pompidou, was created

within Paris and, in many suburbs, river banks also became dedicated to urban traffic. Except for some hundred meters in the historic center (e.g., Ile de la Cite and Ile St Louis), direct pedestrian access to the river was hampered.

The relation of Parisians with the Seine River changed after 2002, starting with the temporary creation of artificial beaches each summer along the Seine River in the center of Paris (the Paris-plages project – Perrinjaquet and Paravicini 2012), including recreation and open-air sports installations along 3.5 km. Later, in 2016, the river banks in Paris were designated permanently pedestrianized zones.

27.6 Current trends: Ongoing use management of the Seine

Today, commercial transport still remains the priority use of the Seine waterway and river banks, especially in the Lower Seine (Fourneyron and Revet 2016). The urbanization of floodplains continues, making recurrent debates on flood risks, especially in Paris metropolitan area, and on the role of the Upper Seine for the protection of flood zones. Public authorities are also trying to make room for emerging needs, such as tourism, passenger transport and the development of water sports, but without coordinated integration.

27.6.1 Continuous transformation of the Seine riverscape

The HAROPA port authority (managing the ports of Le Havre, Rouen and Paris) and Voies navigables de France (VNF, french waterway authorities), both public institutions, are continuing the hydromorphological transformation of the Seine River (fig. 27.1: 11).

In the Lower Seine, a new bridge, the Normandie bridge, was built over the estuary in 1995 and the extension of the port at Le Havre was commissioned in 2006, for which a polder has been built, narrowing the estuary over 2 km. Dredging of the sediments of the Seine River continues, to facilitate navigation. A planning contract was signed in 2015 between the State and the Normandie and Ile-de-France regions to promote transport along the Seine River (CPIER 2015).

In the Paris metropolitan area, industrial river ports are planned at Achères for construction and public works, and at Vitry-sur-Seine, as a logistics platform for planned urbanization works (e.g., the Grand Paris Express metro lines), to divert part of the road transportation to the river.

The Upper Seine is concerned by a navigation project to deepen the gauge in the Bassée flood-

plain (from Bray-sur-Seine to Nogent-sur-Seine; VNF 2012) (fig. 27.2).

27.6.2 Continuous urbanization of the floodplain

Since the early 1980s, when a specific national flood risk prevention policy was launched (see Law L82-600 on the compensation of victims of natural disasters, and Law L87-565 prescribing the establishment of flood risk prevention plans PPRI), more than 100,000 housing units have been built in flood-prone areas in Paris metropolitan area, half of them in the inner suburbs (Hauts-de-Seine and Val-de-Marne departments). Deindustrialization has freed up large areas along the Seine that are well equipped with transportation facilities. The demand for housing is leading to densification, with collective housing and offices gradually replacing warehouses and pavilions. Today, a total of 435,000 housing units (around 8% of the units of Paris metropolitan area) are at potential risk of flooding, mainly in the corridors of the Seine mainstem (81% of them) and the Marne tributary (15%). Faced with the challenge of insufficient housing, which is particularly acute in the metropolitan area of Paris, this densification process is likely to continue, with a significant increase in the number of flood-exposed housing units by 2030 (Faytre 2016). Indeed, the risk of flooding is the major river-related risk to which the cities bordering the Seine are exposed. In the event of extreme flooding, the difficulties likely to arise (highly degraded functioning of urban networks, particularly electricity and sewage collection, or lack of infrastructures to evacuate all flooded populations) have not been fully taken into account to date (Reghezza 2009).

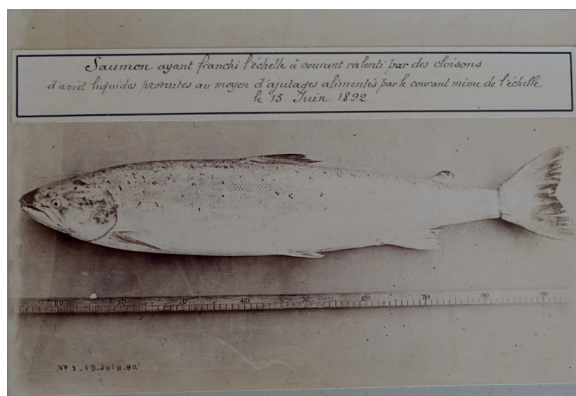
However, medium flood damages have been partially addressed. The State services and the elected representatives of local authorities agreed to mitigate them through the application of common construction rules in these areas (e.g., floodable parking and non-habitable ground floors). They share the view that protection against flooding is provided locally by a discontinuous line of dikes (the quays of the Seine) (fig. 27.6, column 3, low), and upstream by retention dams, although both elements offer limited protection from centennial floods.

27.6.3 Evolving role of the Upper Seine River reservoirs

The first major dam, the 20 m high Settons Dam, in the Morvan Region, on the Cure River, a tributary of the Yonne River (fig. 27.2), was built in

Table 27.3 Key elements of cultural diversity of the Seine River

Key element (on main channel of Seine River)	Link to the natural flow regime	Ecosystem services	Threats and recovery
Archeological artifacts	Dugout canoe (6800 BP) (Carnavalet Museum, Paris)	Valued heritage in museums (e.g., the Museum of Prehistory of Nemours)	Loss of archeological artifacts during major river works in the 19 th century
Sequana deity	Sequana source celebrated	Primacy of the Seine over the Yonne as a river (despite larger discharge of the Yonne)	A not well-known and uncelebrated place today
Water supply facilities	Historical water supply facilities (Marly Machine for Versailles, Samaritaine for Paris)	Major technical achievements of their time that have now disappeared	Today totally disappeared from the memory of the inhabitants
Artistic representation	Artistic works of painters, writers, poets, musicians and photographers, inspired by the aesthetic and/ or uses of the river, particularly in and around Paris.	These productions have made the Seine known all over the world, with a romantic vision which changes the river perception by people and has established a proximity to the river. Current policies use this alleged past proximity as evidence of a necessary reconnection to the Seine.	A universal heritage little threatened by oblivion. But the Orsay and Louvre Museums are in flood-risk zones. Their unexposed collections are in the process of being moved to safer locations
Quais de Seine in Paris	Riparian built architec- ture (17 to 20 th centuries), bouquinistes, bridges (e.g., Pont-Neuf)	A visual reference, a geographical landmark shared by Parisians and tourists who get around the city. Reappropriation of the low quays in Paris as a place to walk.	High road traffic with the transfer of traffic from low quays to high quays
Sport and recreation areas	Guinguettes, aquatic sports during inter-war period, Paris-plages	The memory of a popular place of leisure allowing social mixing and outdoor exercise	Swimming is forbidden for sanitary reasons
River use for transportation along the whole Seine River	Fluvial transport (péniches) and passengers boats (bateaux-mouches)	An additional mode of transport, for tourism, with a festive and local dimension. The symbolic setting of the Armada event in Rouen. River cruises well developed between the estuary and Paris	Fluvial transportation for the local residents remains very limited in Paris



Atlantic salmon caught at the Martot fish ladder in 1892 (AN/F/14/13605). Photo: Laurence Lestel



The indigenous wild vine, *Vitis vinifera subsp. sylvestris* found and protected in the Bassée floodplain. Photo: AGRENABA, with permission



Typical Lower Seine River landscape showing the incised plateau, its rocky slope and the Seine cultivated floodplain. Photo: Laurence Lestel



The Seine River banks in Paris, UNESCO World Heritage. Photo: Laurence Lestel



Seine River landscape at the Bennecourt Ginguettes immortalized by impressionist painter Monet. Photo: Wikimedia Commons, Public Domain



The original tidal bore at Caudebec at the beginning of the 20th century. Historical post card: Pouchin-Perré Imprimeur Libraire

Fig. 27.6 Left column: iconic examples of biological diversity, right column: iconic examples of cultural diversity



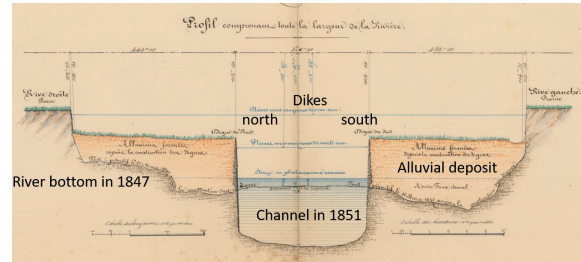
The June 2016 flooding in Paris (Zouave at the Pont de l'Alma). Photo: Wikimdia Commons, CC BY-SA 4.0



Typical urban river bank devoted to car traffic. Floating debris captured by the sewage treatment institution. Photo: Laurence Lestel



Suburban concrete river banks left as industrial waste-land along the channelized river devoted to fluvial traffic. Photo: Catherine Carré



River cross cut showing drastic modification of the navigated channel at Villequier (Lower Seine) in the mid-1800s (Pont et Chaussées engineers, AN F/14/6745). Photo: Archives Nationales, with permission



Europe's largest wastewater facility, the Seine-Aval plant at Achères, near the Seine-Oise confluence. Photo: SIAAP Emmanuel RICHE ODYSSEE_V360 Mrs ZZ, with permission



Typical river rehabilitation, with wooded slope and pedestrian walkway (Seine at Sartrouville). Photo: Laurence Lestel

Fig. 27.6 (continued) Left column: iconic examples of threats, right column: iconic examples of sustainable management

1858 to release flows for timber rafting. Then, other dams were constructed on Morvan headwaters from 1931 to 1985 to control the floods of the Cure River; their elevation range between 37 and 49 m. Today, the related reservoirs are important sport fishing spots, but also constitute the ultimate obstacles to the migration of fish, including salmon, that once spawned in the Morvan headwaters.

After the exceptional one-century-return 1910 flood, which damaged Paris and its suburbs and prevented the functioning of the capital city for two months (Gallois 1911), the issue of flood storage reservoirs was raised. Until the 1940s, the river level within Paris was not regulated and extreme low flows could be observed in summer, exacerbating poor water quality downstream of Paris. A specific river level control was therefore set, at ± 0.35 m, within the Parisian sector, thus minimizing river discharge variations (Barles and Guillaume 2014). This was achieved by the construction of large storage and flood control reservoirs between 1966 and 1990 on the Champagne plateaux, some 250 km upstream of Paris, which are fed by diverted and pumped river waters (RS, RM, and RA on fig. 27.2): the Seine (23 km²), Marne (48 km²) and Aube (23 km²) reservoirs, totalling 841 million m³.

All these facilities, financed by the four departments of Paris and its suburbs are managed by Seine Grands Lacs, a specific territorial public institution initiated in 1969. They regulate floods and have gradually increased the summer low flows of the Seine in Paris from 25 m³s⁻¹ – the natural extreme low-flows – up to 100 m³s⁻¹. As such, they have contributed to the dilution of treated wastewater inputs of the Paris conurbation (totalling 30 m³s⁻¹ downstream of Paris).

These reservoirs now provide a sense of flood protection, especially as, since their operation, no flood has occurred to equal that of 1910, a situation which has allowed continuous urbanization in the Seine River corridor after World War II. However, in the May and June 2016 Seine flood, an exceptional period for the Seine River, where floods are generally observed from December to March, two people died and 17,500 had to be evacuated from their homes (DRIEE 2016) (fig. 27.6, column 3, up). This flood event additionally resulted in more than € 1 billion in damages and caused major disruption to transport networks.

Despite the controversy about the ability of the river storage facilities to protect the Parisian metropolitan area from a one-century return flood, the construction of new artificial water storage compartments has been proposed by of-

ficial river authorities in the Bassée floodplain, some 100 km upstream of Paris (Seine Grands Lacs website 2020, Deroubaix et al. 2016). Ten compartments, totaling 23 km² for the whole project, are planned, separated by 58 km of artificial dikes, up to 4.7 m high. As a whole, the project has been submitted to official public debate in 2011–2012 (CNDP website 2020) but its impact on the natural functioning of the Bassée floodplain and biodiversity remains uncertain.

27.6.4 Multiple river uses: a spatial partitioning without coordinated integration

The large number of problems encountered in urban rivers, and the difficulties inherent in co-operation among the many administrative units created to tackle them, is a global issue (Wantzen et al. 2019). As for other rivers, direct uses of the Seine River tend to be approached as a cascade in terms of priority setting, from commercial to passenger transport (river shuttles and pleasure craft), and finally to other uses (rowing and fishing). Coexistence works on the principle of a spatial partitioning of the dominant activities, linked to technical constraints and safety rules specific to each activity.

The specialization of river uses among the downstream, central, and upper reaches of the Seine River, shows that energy production occurs outside the Paris metropolitan area, while yachting and residential housing are mainly located within the metropole borders (fig. 27.7). While the Nogent-sur-Seine nuclear power plant upstream of Paris is still in operation, the Porcheville thermal power plant downstream of the city was closed in 2017. Passenger river transport is divided: the bateaux-mouches in Paris are mainly for tourists from outside of the region; one-day trips in the Île-de-France region are intended for local residents; and river cruises are designed for distant destinations (Rouen – Paris, Paris – Loing).

For a few decades already, the Seine River has been experiencing a recovery in many ways, due to urban programmes (Carré and Deutsch 2015) and the creation of conservation areas. For example, the riverscape architecture project "Réinventer la Seine" targets the greening of 40 urbanized areas, with different river and bank structures already realized within Paris, and others which are planned to facilitate the proximity of the public with the river, including floating barges that serve as gardens (Re-invent the Seine website 2020). These initiatives generated a cultural transformation concerning people's perceptions of the river. Parisians living downtown

and in the suburbs are beginning to reconcile with the river that historically made Paris. They are demanding more "natural environments", and more specifically, the restoration of the river banks (Daniel and Bordes-Pagès 2010) (fig. 27.1: 17). Some of them are new anglers and many others are expecting that the 2024 Olympics will oblige the authorities to achieve an acceptable river water quality standard for full contact recreation (fig. 27.1: 21). Parisians also want greater flood security, after two recent flooding episodes in 2016 and 2018 (fig. 27.1: 6).

27.7 Future management: How to meet society's new expectations?

Facing the new challenges of the 21st century will require new regulations and forms of river management, from local to basin scales, for at least the following issues: emerging water quality issues, bathing and new river care, flood management under climate change, and restoration of highly impacted areas.

27.7.1 Tackling emerging water quality issues requires a new consensus

Now that point sources of pollution (industrial and urban wastewaters) have been considerably reduced, and that the eutrophication issue has been handled through the installation of phosphorus and nitrogen treatment units in waste water treatment plans (Meybeck et al. 2017), other water quality issues, some due to diffuse sources, particularly those linked to agriculture, others due to urban wastes (drug uses, hospital wastewaters), are on the political and management agendas: pesticides and nitrate contamination; pharmaceutical residues and other endocrine disruptors; and microplastics detritus (as detailed in Flipo et al. 2020b, and see detailed references on pesticides, PAH and new contam-

inants therein). Their resolution requires different kinds of waste treatment and/or regulation at the state level and a national consensus among actors, e.g. in the agricultural sector.

Additionally, the legacy of past contamination by micropollutants is still present, as evidenced by the polychlorinated biphenyls (PCB) crisis in 2008, resulting in the prohibition by the authorities of fishing for hyper-accumulative species (top predators) in the Seine. The PCB contents exceeded the current standards for edible fish. Actually, PCB production was banned in 1971, but these chemicals were still used by industries for a further two decades, and are still present in sediments. The irony is that the crisis arose when PCB contamination levels, as measured on fine river particulates, were one to two orders of magnitude lower than their peak in 1970 (Meybeck et al. 2018, Ayrault et al. 2020).

27.7.2 Going back to the river: swimming requires a new river care

The reopening of the river baths, promised in 1988 by Jacques Chirac, at that time mayor of Paris, should have taken three years. Actually, despite a marked improvement in microbiological water quality in the past 30 years in the urban reach within and downstream Paris, fecal contamination in 2020 is still above the threshold set by the bathing quality standard. This objective is now strongly reactivated with the venue of the summer Olympic Games in Paris in 2024. Triathlon and open water swimming competitions are planned in the Parisian reach. Reopening the baths would send a symbolic signal that water quality restoration has occurred along with a return of salmon species across Paris. The Lower Marne River management institution (Marne Vive) braves the current bathing ban every year, through a collective symbolic 'Big jump' into the river (Marne Vive website 2020).

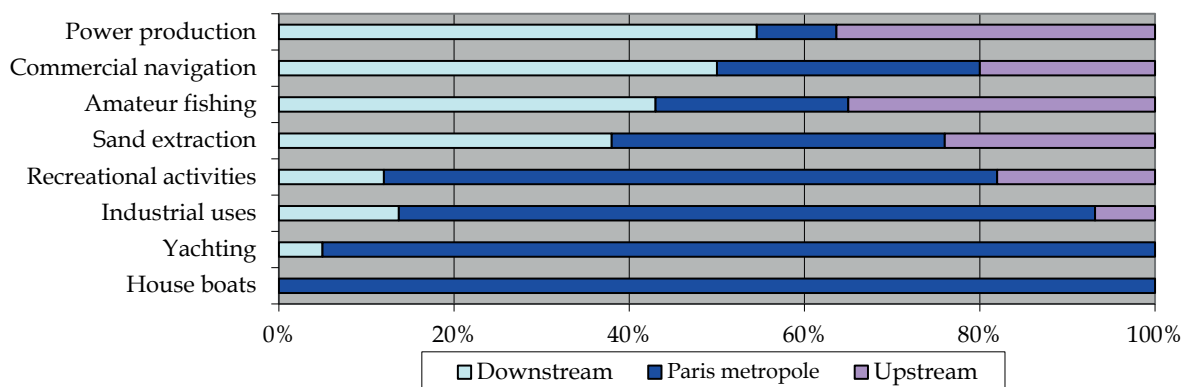


Fig. 27.7 Relative occurrence of multiple river-derived resources and services at the turn of the 21st century in the Upper Seine, the Paris metropolitan area, and the Lower Seine. Graph: Catherine Carré, based on various studies by Agence de l'eau Seine-Normandie

The first type of response is a technical one, through the improvement of wastewater treatment, even beyond the levels required by the regulations, (fig. 27.6, column 3, middle and column 4, middle). However, the attainment of water of sufficient quality for river bathing will only be possible if a new "river care" is established. In addition to more stringent public policies and technical measures, this social solution requires changes in individual practices. Enhanced education can also favor increased knowledge, common pride, shared values, and basin solidarity. Since 1987, the Seine basin authority (AESN) has convened 'water classes' curricula, from kindergarten to university level, taken by 1748 classes in 2018 alone. Also, a teachers' association has developed remarkable teaching tools dedicated to western European river basins, including the Seine (Fleuves Grandeur Nature website 2020). These initiatives should be generalized, to propose and promote a specific river culture (Wantzen et al. 2016) for the Sequanians, as already found for other basins (Loire and Rhine, see respective chapters).

27.7.3 Dealing with changing water regime in the context of climate change

Climate change impacts on the Seine Basin include extended summer dryness, more intensive rains and changes in flood regimes (Flipo et al. 2020a). Their impact on the hydrological balance of the basin and its water resources has also been investigated (Ducharne et al. 2011, Habets et al. 2013). Even if predictions very much depend on the global climate models used, the general trend is a decrease in the water resources of the rivers and of the water table in aquifers.

Increase in flood frequency and intensity on the Seine basin could have dramatic consequences. For instance, hydrologists estimated that the flood of June 2016 had a 1,000 year return period on the Loing River, a tributary of the Seine, 100 km South of Paris, with river runoff intensity exceeding $100 \text{ L s}^{-1} \text{ km}^{-2}$ (Flipo et al. 2017). If the center of the multi-day rainstorm that generated the flood had been located in the heart of Paris, there would have been catastrophic damage. The estimates of the population at risk vary between one and six million people, all of whom would have to be evacuated for several weeks or even months. 51 municipalities of more than 10,000 inhabitants will face the degradation or destruction of their public services and economic activities, as well as an obligation to respond to the needs of their residents without means of evacuation and/or accommodation (Fujiki and Renard 2018). The economic cost of the potential

flood damage is estimated at € 30 billion in direct costs (OECD 2014), to which must be added the impact of the halt in city activity on the other French metropolises, the dynamism of which depends significantly on Paris. Despite significant efforts to improve risk prevention governance in Paris, a fragmented institutional structure prevents commitments are made for specific long-term goals (OECD 2018).

Agricultural water scarcity is projected to increase: on average, in 2050, the annual river runoff would decrease by 14% and the aquifer water table would be lowered by 2.5 m, associated with increased irrigation demand (Habets et al. 2013). These trends are expected to lead to increased groundwater withdrawal, with over-abstraction already resulting in losses in perennality in summer for smaller streams and rivers in the central part of the basin (Beauce and Brie) (Onde website 2020). An increase in the Seine River water temperatures in summer could also compromise the cooling of the atomic power station of Nogent-sur-Seine, requiring temporary shutdowns (ASN 2020).

27.7.4 Restoration of a highly anthropized river system needs an overall plan and new tools

The past and projected development trajectories of the Seine River and its basin (Meybeck et al. 2018, Billen et al. 2020, Flipo et al. 2020c), make it an excellent and rare example of the evolution of a river socioecological system at the Anthropocene for over more than 150 years (Barles 2015, Meybeck and Lestel 2017, Meybeck et al. 2019), studying both the impacts on the river, the social responses and the ever-increasing river controls.

The controls exerted on the river course and aquatic ecosystem by Paris now far exceed the natural hydromorphological and hydraulic variations in many ways: the hydrological regime is now largely controlled through regulation (see 27.7), water quality downstream of Paris is largely engineered by the wastewater treatment plants (it was demonstrated in July 2019 when massive fish kills were once more observed, following an accidental fire at the Seine-Aval WWTP that restricted its operations for several days).

The fish biodiversity is also largely dependent on anthropogenic controls (e.g., pollution, barriers, and species introductions). The indicator for fish biodiversity (an indicator of river good ecological status under the European Union Water Framework Directive of 2000, EU WFD 2000/60/EC) shows that recovery is occurring. However, opportunities for the restoration of physical

aquatic habitat, required according to the 1992 Water Law (L92-3) and then by the EU WFD, are limited. Many of the existing transformations – channelization, bank artificialization, floodplain sand mining, and damming – might be considered permanent, given the current management policy in the Seine basin, which still gives priority to navigation.

The existing protected areas, created mostly for migratory and resident bird populations, concern artificial waterbodies and part of the estuary. The Seine and Aube reservoirs are now included in the Forêt d'Orient National nature reserve and are valued as bird refuges (fig. 27.2). The 48 km² manmade Der-Chantecoq Lake (the Marne reservoir), visited annually by 200,000 to 350,000 common cranes (*Grus grus*), is managed as a National wildlife and hunting area. The Marais Vernier, a former estuarine ox-bow wetland and the adjacent Risle Valley in Normandy, are a joint national natural reserve, totaling 1.5 km², restored by landscape engineering (e.g., the creation of ponds). In the estuary, a national protected wetland area of 85 km², the Réserve naturelle nationale de l'estuaire de la Seine, was created in 1997, particularly for waterfowl, to compensate for the extension of the port of Le Havre.

The renaturalization concerns dikes along the Seine River, once heavily concreted, today partly revegetated (fig. 27.6, column 3, low, and column 4, low) (DIGUES project 2020). In addition, some towpaths have been transformed into pedestrian and cycle paths. The continuity of the Paris-Le Havre cycle route is already reaching 87% and is set for full completion (Brennetot 2019). The reappropriation of the banks of the Seine also makes progress through the study of its landscapes (Antoni et al. 2017) and the creation of an observatory of the Seine landscapes in 2019 (Vallée de la Seine website 2020).

The lack of coherence among the different policies affecting the river remains problematic. Most of the important public or private institutions that manage the Seine River and its basin do so from Paris: the fluvial ports institution HAROPA; the waterways public institution (VNF, Voies Navigables de France) which manages the locks; the Seine reservoirs institution (Grands Lacs de Seine); the Paris metropole sewage management syndicate SIAAP; the private companies for sand and gravel extraction; the private and public water utilities companies; and finally the Seine Normandie River Basin Authority (AESN). In the past decades, these institutions have been responsible for large parts of the anthropogenic transformations of the river.

Today, their engineers are in charge of its ecological restoration and environmental management. A new river management challenge is the expected harmonization of their objectives at the basin level, within the regional water management plan (Schéma directeur d'aménagement de l'eau, SDAGE), which must be established every six years, as asked by the EU WFD in 2000.

The pollution and artificialization of the Seine River did not lead to the same social mobilization to defend the river as observed for the Loire and Rhône rivers during the 1970s and 1980s, respectively. Greater mobilization and basin-wide awareness can push politicians and river managers towards a more unified stakeholder vision of the river. This could be enhanced in the future through special events, such as an annual Sequana day, mixing popular, historic, and cultural events, as is done for the Loire River in Orléans each September (see chapter on the Loire, this volume). This event could be set up at locations along the river, from the Sequana Source to the estuary, and bring together many existing activities presently scattered throughout the basin. During the Rouen Armada events, dozens of historical ships, from all continents, mainly sailing boats, gather in the estuary. The seven armadas held since 1989 are a successful example of the reconnection of local people to their fluvial environment and to the rest of the world, through cultural heritage (Féménias et al. 2013).

Meeting the new challenges of the 21st century (whether from climate change, or new societal expectations, such as recreational bathing and bank restoration) will require the development of river care, more integrated management, overall plan and better coordination among the different institutions in charge of the river and its functions. Facing the increasing urbanization of the Seine corridor, the enhanced celebration of the river's heritage could provide an increasing positive view of the river and generate a better quality of life for its people.

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Fig. 27.6 Monet's Seine River Landscape: [https://commons.wikimedia.org/wiki/File:Claude_Monet_River_Scene_at_Bennecourt,_Seine_\(2\).jpg](https://commons.wikimedia.org/wiki/File:Claude_Monet_River_Scene_at_Bennecourt,_Seine_(2).jpg)

Fig. 27.6 June flooding: [https://commons.wikimedia.org/wiki/File:Zouave_Pont_de_1%27Alma_Seine_6m05_\(7\).jpg](https://commons.wikimedia.org/wiki/File:Zouave_Pont_de_1%27Alma_Seine_6m05_(7).jpg)