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A Western European River in the Anthropocene

The Seine, 1870–2010

Michel Meybeck and Laurence Lestel

When Paul Crutzen, an atmospheric chemist, coined the term “Anthropocene” (Crutzen and Stoermer 2000), he was referring to a period when human control of the earth system, at the global scale, became equivalent to natural forces. River basins can be used to validate the Anthropocene concept: they are a key component of earth system analysis (Garrels, Mackenzie, and Hunt 1975; Berner and Berner 1996), providing information on regulating processes of the surficial earth (climatology, hydrology, production of vegetation, erosion, and weathering) and on the fluxes of material, water, nutrients, sediments, and so on, from continents to oceans. The Anthropocene concept was rapidly adopted within the scientific community; for example, the International Geosphere and Biosphere Programme (IGBP) has used it to describe rivers across multiple scales, from the local to the global (e.g., the biogeochemical cycles of carbon, nitrogen, and phosphorous; sediment fluxes and coastal morphology; water systems at the scale of continents) (Meybeck 2002, 2003; Vörösmarty and Meybeck 2004; Vörösmarty, Maybeck, and Pastore 2010; Seitzinger et al. 2005; Syvitski and Kettner 2011).

Another vision of river basins has been developed by environmental historians and geographers. It focuses on the multiple relations between rivers (and more generally water resources) and the development of societies since the Neolithic period. River basins have been essential to the development of agriculture, transportation, communication, food and fiber resources, and security. For this, rivers have been tamed, used, regulated, transformed, and sometimes diverted from one basin to another. In the pioneering book, *The Earth as Transformed by Human Action* (Turner et al. 1990), river basins such as those of the Thames and Nile were selected to illustrate *longue durée* interrelations (> 100 years) between humans and their environment. Other studies have focused on river uses and transformations over

the past two hundred years (Mauch and Zeller 2008; Castonguay and Evenden 2012) or on the contemporary period (Arnaud-Fassetta, Masson, and Reynard 2013).

River-related activities can be reconstructed using data from historical and/or archeological archives as well as from the sedimentary archives in floodplains, deltas, and estuaries. This work has been done for a number of systems, including the Chesapeake Bay (Cooper and Brush, 1993) the Seine, the Spree, the Po, and the Zenne (Lestel and Carré 2017). In recent decades, environmental concern about rivers and their “quality” (i.e., their capacities to fulfill society uses in addition to our contemporary vision of what a “good ecological state” should be) has been developing. This has led to the Water Framework Directive (WFD 2000), which aims to restore all European Union (EU) rivers. The criteria for what constitutes a “good ecological state” are determined by societies, and they have evolved over the past 160 years. Well-documented river systems for which we have data on earth system processes (e.g., soil erosion, primary production) as well as social processes (e.g., population dynamics, ways of living, security needs) are particularly convenient for studying the evolution of the relationship between a river and society over the *longue durée*.

The Seine River basin (France), 65,000 km², fulfills these criteria: the Piren-Seine program, started in 1989, is studying the present-day functioning of the river basin, particularly the river quality, from its headwaters to the estuary, and its evolution over 140 years under changing demography, economic activities, water institutions, water quality regulations, and water sanitation. The program is highlighting the enormous influence of the megacity of Paris on the Seine basin and the major physical and chemical transformations that have greatly evolved over time (Meybeck, de Marsily, and Fustec 1998; Barles 1999; Garnier and Mouchel 1999; Barles and Mouchel 2006; Billen et al. 2007; Meybeck et al. 2007; Meybeck et al. 2016; Lestel and Carré 2017).

We consider first the distribution of the maximum physical and chemical impacts in the river basin at selected periods, first by stream order, a hydrological concept, second by the upstream/downstream impacts of Paris megacity. Then we analyze the general mass-balance of nutrients and material flow of metals in the basin, in comparison to their natural circulation rates in “pristine”—or preindustrial—conditions. The Seine *longue durée* analysis (1870–2010) shows large-scale trajectories and reveals both reversible and irreversible alterations of the basin. Finally, we propose a general scheme showing the stages of societal response to Anthropocene river basins, highlighting the remaining irreversible changes of basins, their regulations by societies, and their interconnections with other world basins through global trade and global economy.

THE SEINE BASIN

Today the Seine basin encompasses the major economic activities, except mining, that have increasingly put pressure on rivers and their basins over the last p40

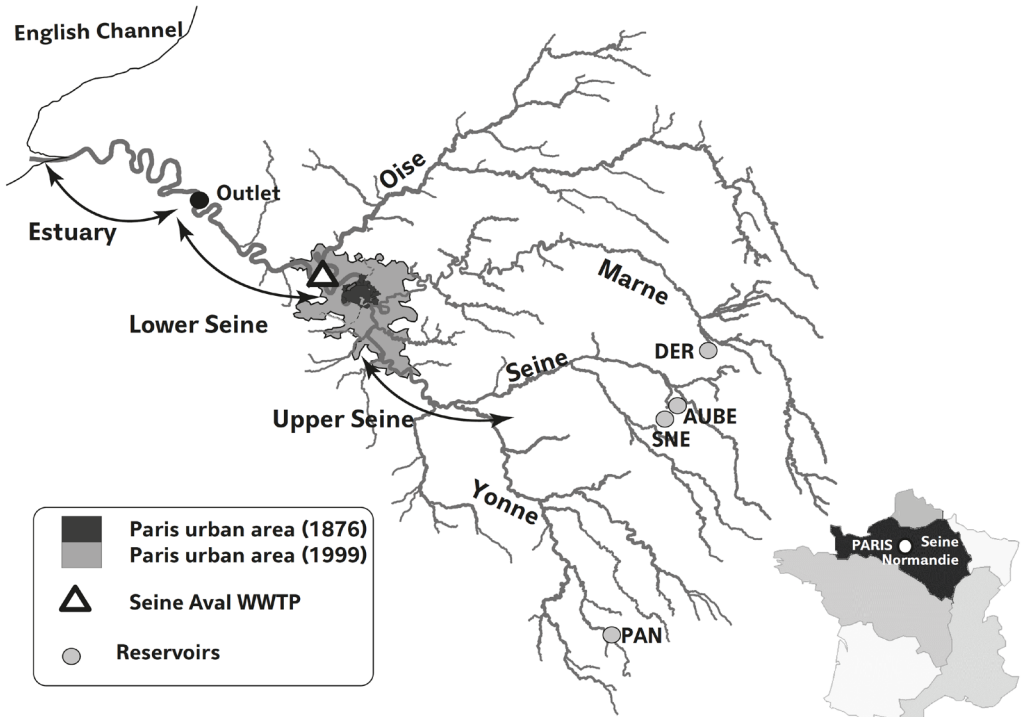


FIGURE 7.1. Main components of the Seine River basin and Paris urban growth between the 1870s and the 2000s. The river network corresponds to stream orders 3 to 7.

years: industrial, urban, agricultural, river transportation, and damming (Billen et al. 2007; Mouchel and Billen 2008–15).

The river basin upstream of its estuary covers 65,000 km². It had approximately 7 million people (Mp) in the 1870s; it has 17 Mp today. One important characteristic of the basin is the population pressure gradient, which has changed from fewer than 20 people/km² in half of the basin to more than 2,000 p/km² in the Paris suburban river basins (Orge, Bièvre), with an average of 250 p/km² for the whole basin at the mouth. Paris megacity is a prominent feature of the basin, which delineates the Upper Seine and the Lower Seine (fig. 7.1). The natural dilution power here is very limited, making the Seine sensitive to point sources of pollutions compared to most EU rivers. This is especially important given the fact that Paris's treated wastewaters total more than 30 m³/s, equivalent to a medium-sized river.

The Seine basin is also characterized by intensive agriculture. The development of agriculture at first paralleled the growth of Paris and its food demand over the last centuries (Billen et al. 2012). Then a major turning point in land use took place in the 1960s, when grasslands were converted to cropland and nitrogen fertilizers were used intensively. Further affecting the river has been the

demand for deeper, larger, and more extended navigated reaches in the basin and the increased sand and gravel extraction in the floodplain, which has been used for Paris urban growth.

Industries are mostly located in Paris megacity, along the Lower Seine industrial corridors, and along one of its main tributaries, the Oise. Until the 1970s, industrial waste waters were barely treated on site and then discharged directly to the closest rivers, with the assumption that they would be diluted and self-cleaning. Until the late 1980s, the level of toxic substances in the river, the fluxes released by both the city and its industries and their effects on receiving waters, was largely ignored by French scientists and authorities (Meybeck et al. 2016).

Greater Paris (the Paris urban area) has evolved from 2.5 Mp over 480 km² in the 1870s to 10 Mp over 2,500 km² today (see fig. 7.1). In the 1870s, the collected waste waters started to be spread in sewage farms near Paris. Wastewater treatment plants (WWTP) were then gradually built in the past fifty years as a result of the 1964 Water Law. One of the sewage farms at Achères, located at 60 river km downstream of Paris, was converted between 1930 and the 1980s to the Seine-Aval WWTP, treating up to 8M equivalent-people in the 1970s. Since then, new WWTPs have been built around Paris (Lestel and Carré 2017).

PHYSICAL AND CHEMICAL IMPACTS ON THE RIVER NETWORK, A STREAM ORDER ANALYSIS, AND THE WEIGHT OF PARIS MEGACITY

The spatial representation of alterations to river and stream courses is difficult for several reasons: the increasing size of hydrological entities from headwater streams to the estuaries; the discrete nature of the information, collected at fixed stations; and the integration of water and sediment chemistry over the basin upstream of the station. In the classical way of representation, used by river authorities, stations are mapped as dots that are color-coded according to quality levels. This representation combines visually, and often statistically, the stations on small streams (basin area 100 km²) with those on great basins (100,000 km² or more). Stream orders, used by hydrologists and river ecologists (Naiman 1983), allow assessment of the quality of basins by their hydrological importance. The hydrological network is organized from the first permanent headwaters streams (order 1) to the river mouth (order 7 for the Seine). In many Piren Seine models the physical properties of the network, width, depth, water discharge, are considered similar within the same order and increase when two streams of similar n orders meet to form an $n+1$ order.

Figure 7.2A shows the distribution of the maximum physical alterations of the aquatic system by stream order. Unless otherwise noted, these date to 2015. The impacts are graded in four categories, according to their relative intensity on watercourses within a given stream order. These alterations have been gradually developed through time. In headwaters (orders 0 to 1 and 1 to 3) agriculture is the

main cause of the alteration through wetland draining, ditch construction, and stream course straightening. The urban development of Greater Paris has generated the disappearance of many urban rivers, particularly at the turn of the nineteenth century (e.g., the Bièvre River). After 1950, channelization and dredging of the Seine River for navigation, excavation of dozens of large sand pits for gravel and sand mining, and regulation by locks are responsible for a major artificialization and regulation of the lower river reaches over several hundred kilometers, including the estuary. In addition, four main water reservoirs were constructed 250 river km upstream of Paris in the 1930s through 1980s (Pannecière [PAN], Seine [SNE], Aube [AUBE], and Der [DER]; see fig. 7.1). These were financed by the city of Paris for flood protection and low-water discharge regulation, increasing the summer low flows from 25 m³/s at Paris up to 100 m³/s for an increased dilution of treated Paris waste waters.

Other physical modifications also had an impact on orders 1 to 4 before the 1800s. These included multiple ponds—more than 2,550 for the whole Seine basin, mostly on first-order streams (69 percent) (Passy et al. 2012)—and water mills—up to 6,000 over 12,000 km² in the Ile-de-France region (Boët et al. 1999). The higher orders remained comparatively untouched and featured multiple islands. These islands, in turn, gradually disappeared between 1850 and 1950: in the 5 to 7 stream orders about 25 percent of the river bank length has been lost when comparing pre-1850 and contemporary maps (Lestel et al. 2015).

As such, the whole Seine River network is physically modified, with the exception of some forested streams. Meanwhile, land use has greatly evolved since 1950. For instance, in the middle reach of the Seine, upstream of Greater Paris, artificialized land cover (intensive agriculture, urban area, sand pits, channelized river course) increased from 51 to 74 percent, and more natural cover (forest, grassland) decreased from 49 to 26 percent. The sand pits excavated in the floodplain went from 0.1 to 7.6 percent (Bendjoudi et al. 2002). Mills, sills, and ponds can be considered semireversible features at secular time scales, but great reservoirs, loss of islands, channelization, and artificial embankments can be considered irreversible alterations that have modified the river ecology—for example, for fish (Boët et al. 1999; Tales et al. 2009).

The chemical (e.g., metals) and biogeochemical (eutrophication, hypoxia) alterations are here presented at their maximum stage (see references in Meybeck et al. 2016) (fig. 7.2B). Eutrophication developed when the river course was slowed down and/or in navigated reaches (stream orders 5 and up). Heavy metal (Cd, Cu, Pb, Zn) contamination is also organized by stream orders, the highest being the most degraded (Meybeck 1998, 2002). Small urban streams within Greater Paris did not follow the stream order progression as their high population was not always connected to treatment plants: they were more degraded than the Seine River itself. Also, in contrast to the general upstream-downstream degradation of the river chemical quality, following the population density distribution, the

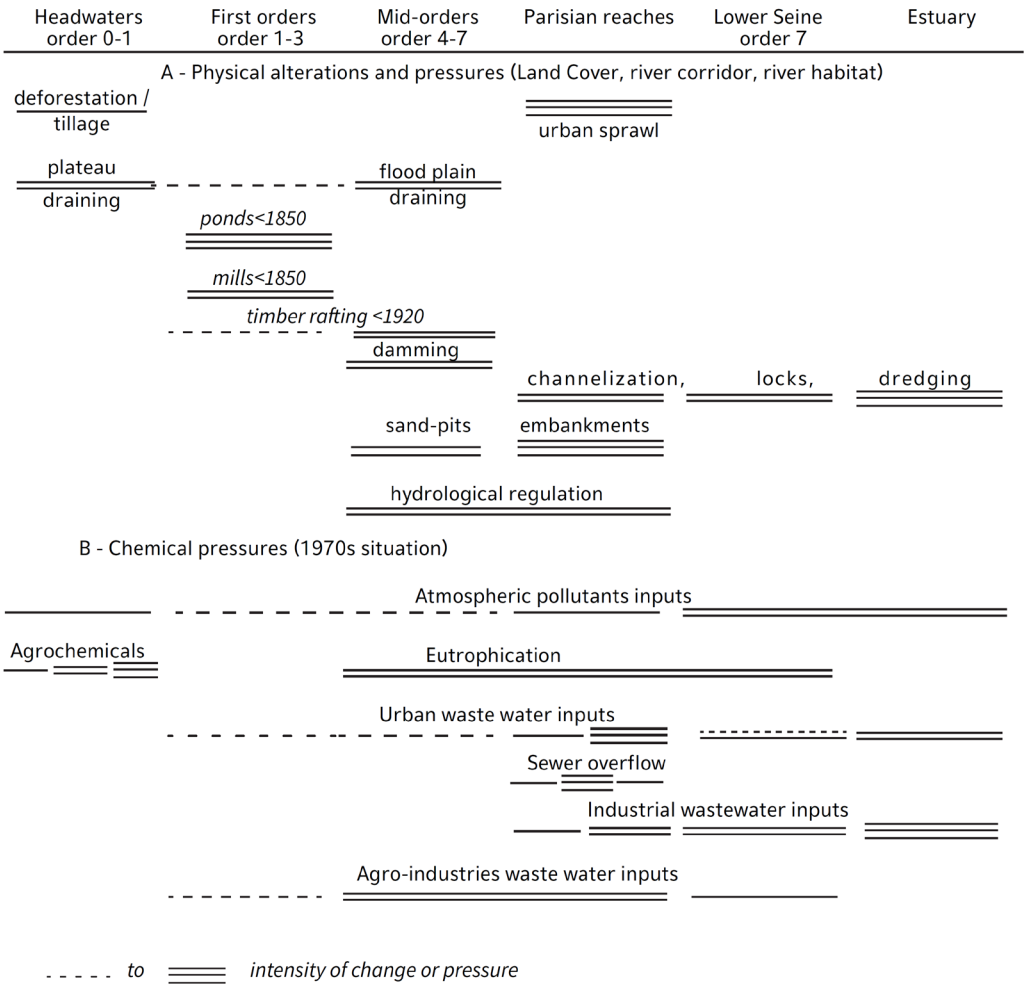


FIGURE 7.2. Spatial distribution of maximum alterations of the Seine River hydrological network, presented by stream orders 1 to 7. A: Physical alterations, as in 2015, otherwise noted. B: Chemical pressures as in the 1970s.

nitrate level in unpopulated streams draining intensive agriculture was already—and still is—at its highest level in the basin.

Our studies also reveal the historically enormous influence that Paris megacity has had on its river (Lestel and Carré 2017) (fig. 7.3). The hyperconcentration of population and industrial activities, and the subsequent releasing of their treated wastes from 1950 to the 1990s (Lestel and Carré 2017) (figs. 7.3, 7.1a), may have had impacts far downstream to the estuary. These include delayed nitrification (3) of

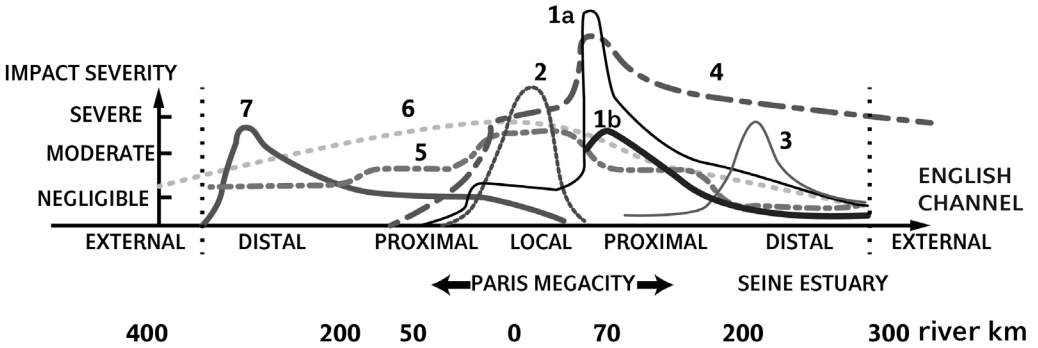


FIGURE 7.3. Schematic longitudinal profiles of the impacts of Paris megacity on the Seine River main course at various periods. 1a, 1b: Organic pollution in the 1960s and 1990s. 2: Occasional overflow of combined urban sewers (until the 1990s). 3: Estuarine hypoxia due to estuarine nitrification (until the 2000s). 4: Metal contamination (in 1990). 5: Physical habitat degradation (2015). 6: Atmospheric pollution (1980s). 7: Timber rafting (1600–1920)

the released ammonia with subsequent estuarine hypoxia (Garnier et al. 2007). This effect has been augmented by the fact that for several decades most collected waste waters were treated in a single location, the Seine-Aval WWTP (see fig. 7.1). In addition, many suburban wastes were discharged directly into the river, as was the case for industry. Today oxygen balance has been greatly improved (1b). Until the 1990s, during storm events, the impact of combined sewage overflow affected the Paris city center, generating hypoxia and fish kills (2). Authorities have since made a great effort to store these untreated waters then release them to WWTPs after the storm event. The metal level in particulates downstream of Paris was near its maximum in the 1970s (Meybeck et al. 2007) (4) and contributed to the general contamination of the English Channel and the North Sea.

Paris's impact is also observed in its distal upper course. Prevailing winds may carry atmospheric pollutants to other river basins (6). Water discharge regulated by its four major reservoirs actually constrains the river flows of the Yonne, Upper Seine, and Marne (5). For three hundred years until 1920, the Yonne-Seine River reach conveyed timber for fuel and construction wood to Paris (7); its impact on river ecology—wood debris, bank abrasion—has not yet been estimated.

ACCELERATED CIRCULATION AND OUTPUTS OF MATERIALS IN THE SEINE RIVER BASIN

River basins are traditionally used by geochemists and earth system scientists to establish the circulation of elements at the earth's surface in natural conditions and to understand its regulation. They determine (i) the natural composition of river

solutes (mg/L, $\mu\text{g/L}$); (ii) the relative contents of elements in river particulates (% to parts per millions, or ppm; i.e., $\mu\text{g/g}$); and (iii) the exportation of these products by the river, rated by the basin area, also termed specific loads (mass per unit time and unit area: $\text{t km}^{-2} \text{y}^{-1}$). These metrics are used to quantify the natural earth system and reconstruct its past evolution in geologic eras.

The human impact on river fluxes has been recognized early, from the local to the global scale (Garrels et al. 1975; Meybeck and Helmer 1989; Berner and Berner 1996). Over the course of fifteen years, this field greatly expanded (Meybeck 2003; Vörosmary and Meybeck 2004; Seitzinger et al. 2005; Vörosmary et al. 2010; Syvitski and Kettner 2011), revealing major transformations of the earth's system on continents during the Anthropocene epoch: (i) the accelerated circulation of elements with regard to the preindustrial conditions, (ii) the retention of river particulates in the countless small to very large reservoirs built since 1950, and (iii) the related loss of water by irrigation, mostly in semiarid regions. The Seine River basin can be used to illustrate the river flux increase since retention in reservoirs is limited (Meybeck, de Marsily, and Fustec 1998). The Piren-Seine scientists have determined the evolution of river fluxes by combining several approaches (Meybeck et al. 2016): (i) the analysis of forested streams without any human impacts, for background levels of major ions and nutrients (Meybeck 1986); (ii) the analysis of Neolithic river floodplain deposits for background metal contents in river particulates (4000 BP, Meybeck et al., 2007); (iii) the reconstruction of the medieval circulation of nutrients in rural conditions (Billen et al. 2009); (iv) the reconstruction of river sediment composition, over the past eighty years, based on sedimentary archives in the Lower Seine floodplain (Meybeck et al. 2007; Le Cloarec et al. 2011) (see fig. 7.4, lower right cartoon); (v) the current circulation of nutrients and metals in the basin since 1950 through the compilation of economic data on fertilizer use, phosphorus use in detergents and other products, and the metal used in various sectors (as raw metal, metal containing products, recycled metals) (Meybeck et al. 2007; Thévenot et al. 2007; Lestel 2012; Billen et al. 2012; Garnier et al. 2015; Romero et al. 2016). In some cases, the data were only available at the national level, and a 30 to 40 percent proportion has been applied to convert those for the Seine basin—in proportion to its overall agricultural, demographic, and industrial weight. The limitations of these estimations are discussed by Lestel et al. (2007).

The river-borne fluxes at the river outlet (river budget station, monitored since the 1970s; see figs. 7.1 and 7.4) have been established for nitrogen, phosphorus, and heavy metals and compared to the economic flows of materials containing these elements over the 65,000 km^2 of the Seine basin. Several indicators are defined: (i) the *circulation ratio* of contemporary elemental circulation over natural (pre-industrial) river flux: $I_1 = U_{\text{eco}}/F_{\text{bgr}}$; (ii) the *concentration ratio* of the contemporary concentrations or contents over the estimated natural levels $I_2 = C_{\text{river}}/C_{\text{bgr}}$;

TABLE 7.1. Indicators of the alteration of natural elemental fluxes in river basins, resulting from a mass flow and river flux comparison. The Seine River example. I_1 to I_4 : see text. WQC_i/C_{BGR} , water quality criteria over background concentration, established by geochemists.

(1) River fluxes based on dissolved material around 2000s. (2) River fluxes based on particulate matter at the maximum contamination period (ca. 1960). (3) In $g\ capita^{-1}\ y^{-1}$. DL: dimensionless ratio. WQC_i/C_{BGR} defines the deviation from the pristine state accepted by river managers (Ministère de l'écologie 2012; Oudin and Maupas 1999 for metals) (see fig. 7.5).

	Nitrate NO_3^-	Phosphorus P	Cadmium Cd	Copper Cu	Mercury Hg	Lead Pb	Zinc Zn
I_1 (DL) (max)	40 (1)	280 (1)	3000 (2)	13000 (2)	5000 (2)	6000 (2)	2000 (2)
I_2 (DL) (max)	(25) (1)	(50) (1)	150 (2)		500 (2)	23 (2)	22 (2)
I_3 1960s (3)			3.3	39.6	0.61	52	156
I_3 2000s (3)	4400	400	0.07	5.3	0.06	5	11.1
I_4 (%) 1960s			11.6	0.35		0.94	1.9
I_4 (%) 2000s	15	7	0.4	0.04	(10)	0.08	0.25
WQC_i/C_{BGR}	10 to 50	3 to 5	4	1.8	23	1.1	2.3

(iii) the *per capita excess loads* in the river $I_3 = (F_{riv} - F_{bgr})/Pop$, calculated by subtracting the natural exports at river mouth (F_{bgr}) from the measured or reconstructed river loads (F_{riv}) at given periods, defining excess loads, then rating it to the basin population (Pop) during these periods (expressed in $g\ capita^{-1}\ y^{-1}$); (iv) the *leakage rate*, that is, the ratio of excess river load (annual mass) to the elemental circulation (annual mass) over the basin, $I_4 = (F_{riv} - F_{bgr})/U_{eco}$ (Table1); (v) the ratio of the contemporary water quality criteria defining the good state over the natural background (WQC_i/C_{BGR}).

As none of these indicators is affected by the size of the basin, they allow making comparisons between river basins and elements, particularly as concerns I_1 , I_2 , I_4 , which are dimensionless. The (I_1) indicator, expressing the flow of economic materials with regard to natural processes in the earth system within a river basin territory, ranges here from 40 to 13,000. The concentration ratios (I_2) measure the rate of deviation of concentrations from the pristine river state, an indicator often used by geochemists, which reached maximum values from 20 (nitrogen, zinc) to 500 (mercury). It depends on the natural dilution power of the receiving river: for a given pressure, for example, a great city, I_2 is lower when the receiving river has a higher water discharge or sediment flux, as with the Rio Negro for Manaus and the Rhône River for Lyon, respectively; in the Yellow River it is barely possible to find evidence of metal contamination, due to the enormous sediment load of the river, a thousand times that of the Seine. The *per capita excess loads* (I_3) depend on the use of material, on the efficiency of the environmental responses (e.g., recycling and water treatment). Between the 1960s and the 2000s, they have been divided tenfold for Cu, Hg, Pb, and Zn, and by fifty-fold for Cd, the use of which is now greatly restricted. The per capita river export of nitrate-nitrogen is eleven-fold that

of phosphate-phosphorus. The leakage rate to the aquatic system (I_4) is an indicator of the environmental performance of the society within the basin (Meybeck et al. 2007). This is still important for N and P but is today very limited for most metals (from 0.04 to 0.4 percent), except mercury, which still affects the river despite its complete ban for most uses. Within the WFD, the management of river basins, targeted on concentrations that define the “good ecological state” (WQC_1), may not reflect the environmental efforts, better described by I_3 and I_4 . It must be noted that the WQC_1 set by French water authorities are often much higher than the natural background values (C_{BGR}) as estimated by scientists (see table 7.1 below), and that current water management is not based on the environmental impact indicator, I_2 , or on the indicators of environmental performance, I_1 , I_3 and I_4 .

THE OPENING OF THE SEINE BASIN DEMONSTRATED BY THE MATERIAL FLOW ANALYSIS

For earth system scientists, natural fluxes within river basins are derived from the erosion and weathering products of surficial rocks and from the uptake of atmospheric carbon and nitrogen occurring within the basin. For ecological economists, the material flow analysis over a given territory reveals the metabolism of the anthroposphere (Baccini and Brunner 2012). The comparison of both approaches reveals that the circulation of many economic products used in the Seine River basin is one to two orders of magnitude more than the natural fluxes, as for the heavy metals (Lestel 2012). Most of these products are actually recycled, and the river is receiving a minor leak of these. Also, the economic circulation of products in the Seine River basin is now totally opened: the basin exports a great quantity of agricultural and food products and manufactured products and consumes a large quantity of fossil fuels, mining products, and manufactured products; it also emits long-range atmospheric pollutants that may reach other basins.

The material flow analysis of heavy metals in the Seine basin is schematized in figure 7.4. It illustrates the spatial and temporal complexity (Lestel et al. 2007; Thévenot et al. 2007; Lestel 2012): mining (1) only occurred in the 1700s, and inherited contamination is expected in floodplain sediments of the Upper Seine and Marne (see fig. 7.1); metal smelting (2) was located throughout most of the nineteenth and twentieth centuries in Paris and along the rivers (Oise, Seine) (Lestel 2012); metal transformation by industries (3) is now located mostly in Greater Paris; the use of metal and of metal-containing products is very much related to the urban population (4); the recycling of metal products, such as pipes and car batteries, a great provider of metal leaks, was first realized in Paris suburbs prior to 1950 (5a) and then externalized outside of the Seine basin (particularly in the north of France, where it generated extreme contamination, and finally outside the country) (5b). The state of contamination of river reaches generated by these activities depends on their location and on the ratio pressure/river dilution power.

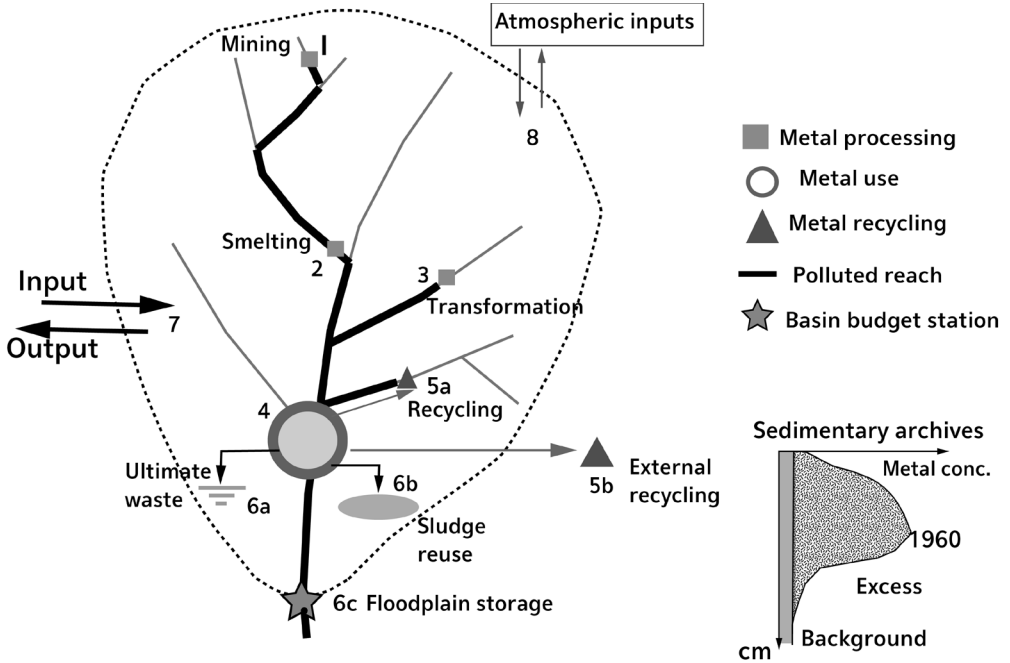


FIGURE 7.4. Schematic representation of the circulation of material within a river basin at the Anthropocene and reconstruction of past contamination from floodplain sediments at the basin outlet. The metal example. See text for explanations.

Since most of the heavy metal flux is associated with particulates, their storage over centuries can be important in urban infrastructures (4), in soils contaminated by industries, in former landfills and dredged sediments (6a), in agricultural soils fertilized by the recycling of Paris WWTP treated sludge, once highly contaminated (<1990) (6b), and in floodplain sediments, which provide records of the contamination (6c).

Changing biogeochemical cycles are also illustrated by nitrogen circulation. For centuries, Paris city growth depended on its fertile hinterland. Organic wastes from animal and human populations were collected and recycled in suburban market gardening, at a short distance from the city. The use of industrial fertilizers, mostly after the 1950s, and the development of sewage collection and treatment reduced the recycling loop of carbon, nitrogen, and phosphorus (Barles 2005; Billen et al. 2009; Billen et al. 2012), and is recently being reconsidered.

Finally, global trade should now be considered in the analysis of environmental impacts by societies (figs. 7.4, 7.7). For instance, today imported products are present in all sectors: soya food for cattle, tropical fruits and grains, palm oil, tropical woods, fuels, metallic ores, metal-containing products, and so on. These generate

substantial environmental degradation where they originate but are rarely taken into account in the environmental assessment of the receiving river basins. In turn, the nitrogen circulation at the global scale shows that the export of food produced within the Seine basin is a significant nitrogen input into other basins (Lassaletta et al. 2014). Atmospheric exchanges (8) may also be considered in river basin budgets.

REVERSIBILITY AND IRREVERSIBILITY OF RIVER QUALITY IN THE LOWER SEINE RIVER BASIN

Analysis of the physical, chemical, and biochemical impacts that occur in the Seine River over the *longue durée* shows various trajectories (Meybeck et al. 2016), some reversible, others irreversible, that can be schematized using the “impair-then-repair” model (Meybeck, de Marsily, and Fustec 1998; Vörösmarty et al. 2015) (fig. 7.5). This model starts with a period of *insignificant impact* on the earth system or on the water resources (OA, stage 1). The next stage is a period of *accelerated degradation* of the aquatic environment and of water resources (AB, stage 2), often faster than population increase in the river basin, reaching first the level of water quality (WQC_1) at which water resources are impaired, then often followed by a severe level of water quality (WQC_2). When the technical and regulatory measures taken by a society become efficient a *proactive rehabilitation phase* is observed after a maximum impact stage (BC, stage 3). When a satisfactory state is finally achieved, reaching the level of quality WQC_3 , the *regulation stage* ensures a stable quality even if the population and economy of the basin continue to grow (CD, stage 4). In the Seine River, the impact of untreated wastewater combined with sewer overflow—a historical heritage—is now minimized by the management of sewage works during storm events in Greater Paris (Tabuchi et al. 2013). If environmental management is insufficient, the impact can reach *permanent degradation* (BE, stage 5) stabilized at an altered level ($>WQC_2$), and the change can be considered irreversible.

The duration of the moderate environmental degradation (ED_1), from the societal perspective, is defined here by the exceedance of WQC_1 ; and the duration of the severe degradation (ED_2), by the exceedance of WQC_2 . Water quality scales, WQC_1 and WQC_2 , defined for each of the issues recognized by the society may evolve over time, therefore changing the environmental assessments it makes. From an earth system perspective, the analysis may be quite different: any significant deviation from the pristine state, as defined by the background concentrations (C_{BGR}), is expressing an alteration of the earth system (ES_A) and may generate a change in receiving waters—for instance, along the coastal zone. The WQC_1/C_{BGR} figures (table 7.1) in which WQC_1 is the contemporary threshold of the good ecological state used by French authorities, range from 1 to 50, depending on elements: they are much higher for nitrate than for metals, reflecting differing societal perspectives on the most toxic substances.

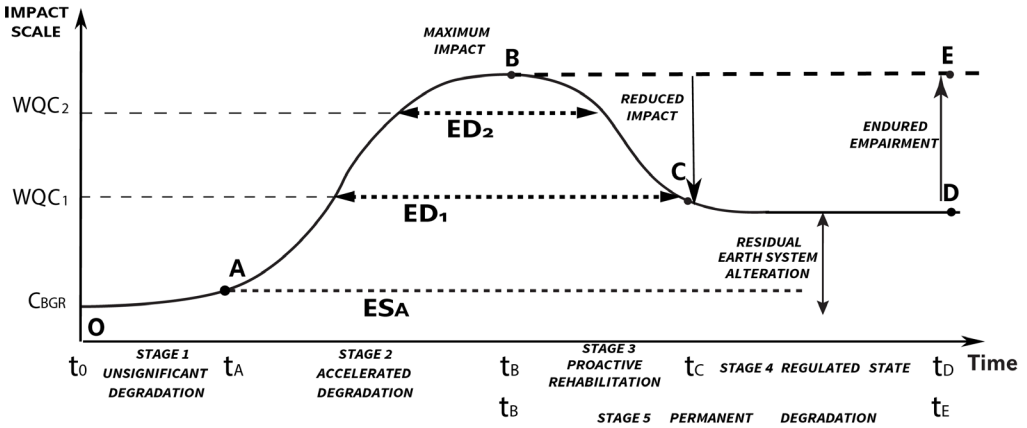


FIGURE 7.5. The impair-then-repair scheme and the five stages defining river quality trajectories, applied to North American and Western European river basins (adapted from Meybeck 1998; Vörösmarty et al. 2015). WQC₁ and WQC₂: Water quality criteria established for water management. CBGR: Pristine state concentrations. ESA, ED₁, ED₂: Respectively, duration of Earth System alteration, of the impaired state and severe degradations of the river, as defined by river basin societies.

In the Seine River basin this scheme has been applied to analyze the 1870–2010 trajectories of some river quality issues, including physical alterations, nitrate pollution, eutrophication, “organic pollution” (leading to hypoxic waters), heavy metals contamination, and bacterial contamination. Many of them are detailed in a companion paper (Meybeck et al. 2016).

The physical alteration of the Seine River network, at any stream order, is mostly irreversible (>100 years), and therefore at stage 5 (see fig. 7.2). However, ancient mills and ponds are semireversible: many fish ponds have been filled from 1800 to 1950, and the many sills left by water mills have been dismantled in response to the Water Framework Directive, which favors fish circulation (stage 4). In contrast, the major water works (locks, channelization, artificial banks, sand pits, dredged reaches and reservoirs) have barely been studied and can be considered irreversible changes that have generated the loss of five migratory fish species in the basin. This alteration developed gradually between the late Middle Ages (t_A, fig. 7.5) and 1990 (t_B), when the last reservoir was constructed. The most critical period (ED₂) started in the 1900s when the salmon disappeared.

The chemical alterations of solutes—dissolved nutrients, organic matter—are reversible, provided that adapted technical or regulatory responses are applied (Meybeck et al. 2016). For organic pollution (river hypoxia, ammonia pollution), the river is now reaching stage 4. The maximum hypoxia period is observed at least between the 1870s and 1990s (ED₂), until the completion of WWTPs in the whole

basin. As concerns river eutrophication, controlled by dissolved phosphate, the river network is currently at stage 3–4 and the ED₂ period extends from the 1960s to the 2000s, when detergent phosphates were finally banned and tertiary treatment of phosphorus was established in Seine-Aval WWTPs and others. The nitrate pollution issue is still highly debated by basin actors, depending on the perspective considered and the WQC₂ chosen by the society. The impaired state (ED₁, 1960–present) started after deep changes in land uses and agricultural practices. Since then, the nitrate concentration has gradually increased and reached a river maximum near 2000, after which it has remained stable. From the sanitary perspective, which prevailed for the basin authorities from the 1970s to the 2000s, the current situation in the river is not severe: nitrate is around 25 mg/L, compared to the 50mg/L WHO guideline; however, many wells have exceeded this guideline and have been closed. From the point of view of coastal eutrophication, bathing and seafood consumption, nitrates are much too high, producing green tides and toxic algal blooms, and the river threshold established by coastal scientists is 10mg/L. From this perspective, the river has been at stage 5 since 1970, and stage 3 will not be initiated unless drastic changes in fertilizer use are made. And even with such changes, the nitrate contamination of groundwater may last half a century (Meybeck et al. 2016). The 10mg/L threshold still corresponds to a tenfold increase in nitrate load as regards pristine conditions, an increase factor that cannot be accepted from an earth system perspective for oceans such as the North Atlantic.

The bacterial contamination trajectory in the Middle Seine River, upstream of Paris city, can be assessed, thanks to very early surveillance in the 1900s. It shows a marked degradation between the 1950s, when sewage collection was generalized in Paris suburbs, and the 1990s, when treatment capacity for Paris and its suburbs became sufficient (Servais et al. 2007) (stage 4). For the Lower Seine the ED₂ period extended for more than 140 years, and the trajectory is currently at stage 3–4.

The chemical alteration of heavy metals, as measured in river particulates, shows irreversible impacts in contaminated soils and floodplain sediments. Their levels greatly depend on sediment quality criteria that have been divided up to tenfold since the 1980s. The general trajectory of metal contamination as archived in river sediments (see fig. 7.4) is a general decrease in content since the 1960s (t_b , fig. 7.5) in the Seine basin, mostly due to industrial transformations (Meybeck et al. 2007; Lestel 2012). The duration of severe degradation (ED₂) was at least from the 1920s to the 1990s for mercury and cadmium, though this duration was shorter for copper, lead, and zinc. Today metal levels in river particulates have decreased (stage 3 or 4, depending on metals) but are often much higher than the pristine state established by using 4,500-year-old sediments. This is particularly the case for mercury. The Seine River has been and continues to be a major source of metal contamination of the North Sea. Contaminated sites in soils and sediments will last for millennia, unless specifically addressed.

Other micropollution issues are now addressed in the Piren-Seine program (endocrine disruptors, drugs, pesticides): most of their trajectories correspond to stage 2. The above description of the historical impacts of Paris on the Seine River has parallels in other cities, including Berlin, Milan, and Brussels (Lestel and Carré 2017). The severe degradation period (ED_2) of the Spree, Lambro, and Zenne Rivers also lasted for one hundred years for most issues. We should expect similar impacts in many other fast-developing megacities.

CONCLUSION

Although the “good state” targeted in Europe (WFD 2000) leads us to believe that the goal of society is now to bring the river basin back to its natural conditions, this is by no means the case from an earth system perspective (fig. 7.6). First, many changes are already (or are becoming) irreversible—at least for many generations with regard to land use changes (deforestation and agriculture, urban growth, reservoir construction); degradation of the aquatic habitat throughout the river continuum, from headwaters to estuary; soil and sediment contamination; and aquifer pollution. Second, the circulation of elements in such river basins can be greatly modified.

From the earth system perspective, the natural circulation of elements within river basins might be multiplied by more than one order of magnitude when megacities are present. Leaks into river basins can range from 0.1 to 10 percent, depending on the elements and the societies’ stages of development, and can dramatically modify natural concentrations and fluxes in rivers. Leakage rates are not stable: metals in the Seine River basin have decreased over the past fifty years, by one order of magnitude. This was due first to important changes in the industrial sector and then to environmental regulations—even while the use of most metals was increasing (Lestel 2012; Meybeck et al. 2007). Meanwhile the per capita excess loads carried by the river have decreased, reflecting both economic development and environmental responses.

From the perspective of water resources used by societies, human impacts on river basins should be analyzed from multiple points of views, considering the spatial heterogeneity and the multiple trajectories over the *longue durée*. For instance, the stream order approach should be complemented by the upstream/downstream impacts of the megacity. Past activities (mining, industrial, urban, and even agricultural cadmium-containing phosphorus fertilizers) have a bearing on present contaminations of river and soil particulates. Cumulative past alterations of the physical habitat, started one hundred years ago or more, undertaken to secure water resources, meet navigation needs, develop agriculture, and flood security, are mostly permanent and generate irreversible impacts, such as the loss of migratory fish communities. In contrast, organic pollution, river eutrophication, and bacterial contamination have the potential to be repaired.

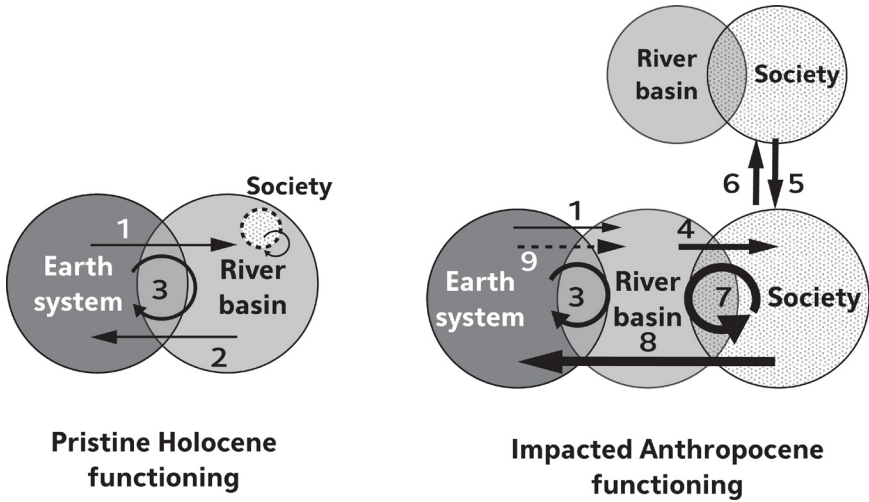


FIGURE 7.6. General scheme of circulation of material within pristine basins (left) and impacted basins at the Anthropocene. See text. Atmospheric transfers are not presented here.

Further, the impact of a megacity on a river basin is not necessarily proportional to its population: at some stage of environmental concern, economic and technical development, societies may improve the recycling rate of their economic materials, waste collection and treatment, modify the use of toxic substances (arsenic, mercury, cadmium, atrazine herbicide in the Seine basin), and improve markedly the chemical and biogeochemical quality of their rivers. The river biota, also exposed to species introductions and invasions, reflect these multiple impacts and their trajectories. Thus river-society interactions are spatially and temporally complex and can be addressed only by means of a multidisciplinary approach in which contemporary hydrologists, geochemists, hydrobiologists, and geographers are collaborating with environmental historians (Lestel and Carré 2017).

The evolution from natural to Anthropocene conditions is hypothesized in figure 7.6. The nonindustrial agrarian society is biogeochemically in equilibrium with the basin resources mostly controlled by the earth system (fig. 7.6, left, 1). The fluxes exported by rivers to oceans (2) contribute to the general balance (3) of the earth system. The Anthropocene is characterized by the globalization of river fluxes and their controls (fig. 7.6, right). In populated and industrialized river basins, the circulation of economic materials (7), extracted within the basin (4) and/or imported (5), may exceed by an order of magnitude or more the natural state (1) (e.g., nitrogen, phosphorus, and heavy metals in the Seine basin), resulting in additional river fluxes and concentrations (8). The most developed basins affect the least developed ones, sometimes far away, to meet their own mining,

agricultural, or energy needs (e.g., hydropower dams) and may transfer their own wastes to these basins.

Environmental measures aim to minimize the leaks from the anthroposystem to the river system (8) but actually accept a variable level of deviation from the pristine state (WQC_1 vs. C_{BGR} , table 1; stage 4, fig. 7.5); the long-term impact (centuries to millennia) is still poorly known. The regional and global water and sediment fluxes to oceans are already modified, and the most sensitive biogeochemical cycles—nitrogen, phosphorus, silica—are likely to modify the earth system and, in turn, generate global changes that will affect all river basins (Meybeck 2003; Seitzinger et al. 2005; Vörösmarty et al. 2010; Syvitski and Kettner 2011).

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