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Nicolas Flipo, Laurence Lestel, Pierre Labadie, Michel Meybeck,
and Josette Garnier

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Abstract The Seine River basin in France (76,238 km², 17 million (M) people) has been continuously studied since 1989 by the PIREN-Seine, a multidisciplinary programme of about 100 scientists from 20 research units (hydrologists, environmental chemists, ecologists, biogeochemists, geographers, environmental historians). Initially PIREN-Seine was established to fill the knowledge gap on the river functioning, particularly downstream of the Paris conurbation (12 M people), where the pressure and impacts were at their highest in the 1980s (e.g. chronic summer hypoxia). One aim was to provide tools, such as models, to manage water resources

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and improve the state of the river. PIREN-Seine gradually developed into a general understanding and whole-basin modelling, from headwater streams to the estuary, of the complex interactions between the hydrosystem (surface water and aquifers), the ecosystem (phytoplankton, bacteria, fish communities), the agronomic system (crops and soils), the river users (drinking water, navigation), and the urban and industrial development (e.g. waste water treatment plants). Spatio-temporal scales of these interactions and the related state of the environment vary from the very fine (hour-meter) to the coarser scale (annual – several dozen km). It was possible to determine the trajectories (drivers-pressures – state-responses) for many issues, over the longue durée time windows (50–200 years), in relation to the specific economic and demographic evolution of the Seine basin, the environmental awareness, and the national and then European regulations. Time trajectories of the major environmental issues, from the original organic and microbial pollutants in the past to the present emerging contaminants, are addressed. Future trajectories are simulated by our interconnected modelling approaches, based on scenarios (e.g. of the agro-food system, climate change, demography, etc.) constructed by scientists and engineers of major basin institutions that have been supporting the programme in the long term. We found many cumulated and/or permanent hereditary effects on the physical, chemical, and ecological characteristics of the basin that may constrain its evolution. PIREN-Seine was launched and has been evaluated since its inception, by the National Centre for Scientific Research (CNRS), today within its national Zones Ateliers (ZA) instrument, part of the international Long-Term Socio-Economic and Ecosystem Research (LTSER) network.

Keywords LTSER, PIREN-Seine, Seine basin, Seine River, Socio-ecosystem, Zone Atelier Seine

1 Introduction: River Systems in the Anthropocene

Water resources are indispensable for social development. Human needs shaped rivers and river basins, leading to a drastic modification of the global water cycle. Changes due to human activities are so large nowadays that they override natural processes, leading to the end of a geological era and the beginning of a new one called “the Anthropocene” first conceptualized by Crutzen [1, 2]. Using this concept first proposed by the Earth science community, and increasingly considered by the human sciences [3, 4], makes it possible to highlight multiple and profound changes in the watersheds: (1) the physical environment is largely modified compared with its initial state; (2) terrestrial, aquatic, and estuarine environments are increasingly managed by societies, according to their interests and their representation of nature: flows, river morphology, summer temperature, water quality, and biodiversity are now largely controlled by dedicated institutions according to specific criteria; and (3) some of the factors influencing such management are located within the

catchment area, but the external components have been increasing steadily for 50 years (national and European regulations, national and European markets for agricultural products, decline or recovery of industry and mining, as well as the evolution of international trade, etc.).

River system refers primarily to the hydrosphere, i.e. the water circulation over a well-delineated area, the basin watershed. It includes the atmospheric inputs and water flow components of the drainage network and is separated into (1) the surficial hydrographic network, from headwater streams to the estuary, including stagnant systems such as ponds, wetlands, lakes, reservoirs, and canals, (2) shallow and deep aquifers and their related unsaturated zone. It also includes the terrestrial biosphere and the pedosphere, which regulate water circulation and provide the river-borne and groundwater materials, and the aquatic biosphere, from micro-organisms to fish populations. Finally, the system also includes all the controlling factors that regulate these fluxes of water and materials and their composition: internal factors, either natural (e.g. hydrological regime, river morphology) or anthropogenic (e.g. water abstraction, pollution, hydrological control, and artificialization of river course), and external factors (e.g. climate change, trans-basin trade, species introduction, etc.). It can therefore be considered as a socio-ecosystem in the sense of Haberl [5].

Among the six hydrographic basins of metropolitan France, the Seine-Normandie basin is the most human-impacted (see Sect. 2 of this chapter). It receives the highest anthropic pressure, due to its industry and agriculture linked to the development of the urban area of Paris, which has been and still is the economic and social heart of France. The very poor chemical and ecological status of water in the 1980s led a small group of researchers to propose a PIREN-Seine, i.e. an interdisciplinary environmental research programme launched by the French National Centre for Scientific Research (CNRS), as had already been put in place for the Rhône River, the Garonne River, and the Alsace plain in 1979 [6]. It was created in 1989 in a context of insufficient wastewater treatment in the Paris conurbation and new investment projects in sanitation facilities [7]. Its first achievement consisted in developing a model, Riverstrahler [8], to dynamically represent the biogeochemical fluxes of carbon, nitrogen, phosphorus and then silica, for each body of water in the basin, from headwaters to the Seine outlet, according to constraints such as geomorphology, hydrography, agricultural diffuse sources, and urban discharges. Another modelling tool, ProSe, was also developed with a transient hydrology on the lower Seine more dedicated to the Paris conurbation domestic load [9–12]. These tools have made it possible to bring together research teams on a common object of study, the entire Seine watershed; the programme has also been a forum for dialogue between the basin's institutional partners and researchers, enabling the latter to make management proposals to establish investment priorities based on the results of these models [13]. Despite the fact that PIREN programmes have been replaced by other interdisciplinary programmes, the PIREN-Seine programme has continued to exist, financially supported by the institutions in charge of the Seine basin management. Over the past 30 years, it has generated a vast number of publications, more than 100 PhD theses, hundreds of publications in scientific journals and as many communications in international workshops and conferences, as well as

special issues [14–16] and several booklets [17]. Nevertheless, the collective visibility of this group of scientists and institutional partners is relatively low internationally, since most publication credits are given to individuals, to their laboratories, or to their research institutions. Moreover, the names of these laboratories and institutions have also evolved over time, making the recognition of this collective effort even more difficult. This book provides the opportunity to present a selection of some of the most salient results of the programme, obtained within the framework of our current socioecological approach of relevant environmental issues in the Seine River basin. Most of the results will be presented as trajectories that relate environmental changes and societal changes. A number of the trajectories identified within the Seine basin will be presented in Sect. 3 of this chapter.

These studies of socioecological systems are by nature interdisciplinary; the proposed conceptual frameworks such as material flow analysis (MFA) [18, 19], the driver-pressure-state-impact-response (DPSIR) concept recommended by the European Environment Agency [20–22], the human-environment systems (HES) framework [23], or the social-ecological systems framework (SESF) [24] are means of structuring this research or proposing a common language for the different disciplinary components used to analyse the complexity of these human-environmental relationships, with each of the methods having its objectives and limitations [25]. These approaches are increasingly present within the PIREN-Seine, which has been included in the Zone Atelier Seine (ZA Seine) and the Long-Term Socio-Economic and Ecosystem Research (LTSER) programmes, as presented in Sect. 4 of this chapter. The spatial and temporal scales of the trajectories described in the following 14 chapters are presented at the end of this introduction.

2 Multiple and Heavy Pressures on the Seine River System

In a basin like that of the Seine River which has long been populated, deforested, and industrialized and where the large urban conurbation of Paris and highly productive agriculture areas coexist, human control of the system, its water, and the material fluxes often exceeds natural controls. This makes the Seine River system a case study in which complex interactions between societal and biophysical processes can be examined. The next subsections summarize the present situation in terms of land use, water use, as well as human pressures and their dynamics since the beginning of the twentieth century.

2.1 *The Hydrological Features of the Seine River Basin*

The Seine River basin extends over 76,000 km², of which 65,000 km² are upstream of its estuary, with the outlet of the basin located at Poses (Fig. 1). It lies 97% within the sedimentary Paris basin, the largest groundwater reservoir in Europe (Triassic to

tertiary, Fig. 2a). The lithology of the basin encompasses carbonates (69.6%) and sandy formations (13.6%), interbedded by poorly permeable clayey and marl units (9.1%) and covered by alluvial deposits (5.4%) (Fig. 2b) [27]. The sedimentary basin is covered by carbonated loess in its western and central parts [28].

The river network can be described using the Strahler stream order concept [29], which is used throughout the morphological, hydrological, and biogeochemical modelling of the Seine basin. The total length of the river network is 27,500 km, mostly composed of first and second Strahler orders. The main tributaries of the Seine River are the Yonne River, the Marne River, and the Oise River. The Seine River reaches the seventh Strahler order after its confluence with the Yonne River.

The hydrological regime of the Seine River basin is pluvial/oceanic. The mean rainfall over the basin is 800 mm year^{-1} and exhibits some spatial variability, with a maximum of around $1,200 \text{ mm year}^{-1}$ along the coastal shoreline and in the Morvan mountainous range and only 650 mm year^{-1} in its central part [30–32]. For the past 50 years, the Seine discharge at the last gauging station before the estuary at Poses has had an average value of $485 \text{ m}^3 \text{ s}^{-1}$ but reached $2,280 \text{ m}^3 \text{ s}^{-1}$ in winter, with summer minimums at $80 \text{ m}^3 \text{ s}^{-1}$ (low flows sustained by reservoirs). In addition to

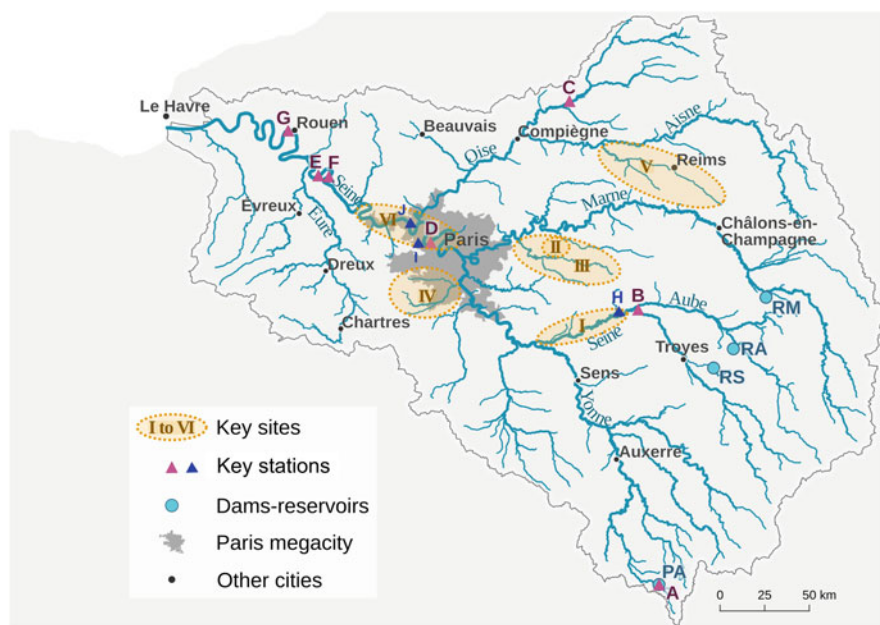


Fig. 1 The hydrological network (Strahler orders 3–7) of the Seine and the main experimental sites that have been studied. I Bassée floodplain, II Orgeval stream experimental area, III Grand Morin River, IV Orge River, V Vesle River, VI Lower Seine sector. Core sites [26]: A Pannecières reservoir, B Troyes Seine canal, C Chauny Oise River, D Chatou Seine sluice, E Muids Seine floodplain, F Bouaffes Seine floodplain, G Rouen Seine estuary dock. Sampling stations: H Marnay, I Bougival, J Triel. Reservoirs: PA Pannecières, RA Aube reservoir, RS Seine reservoir, RM Marne reservoir

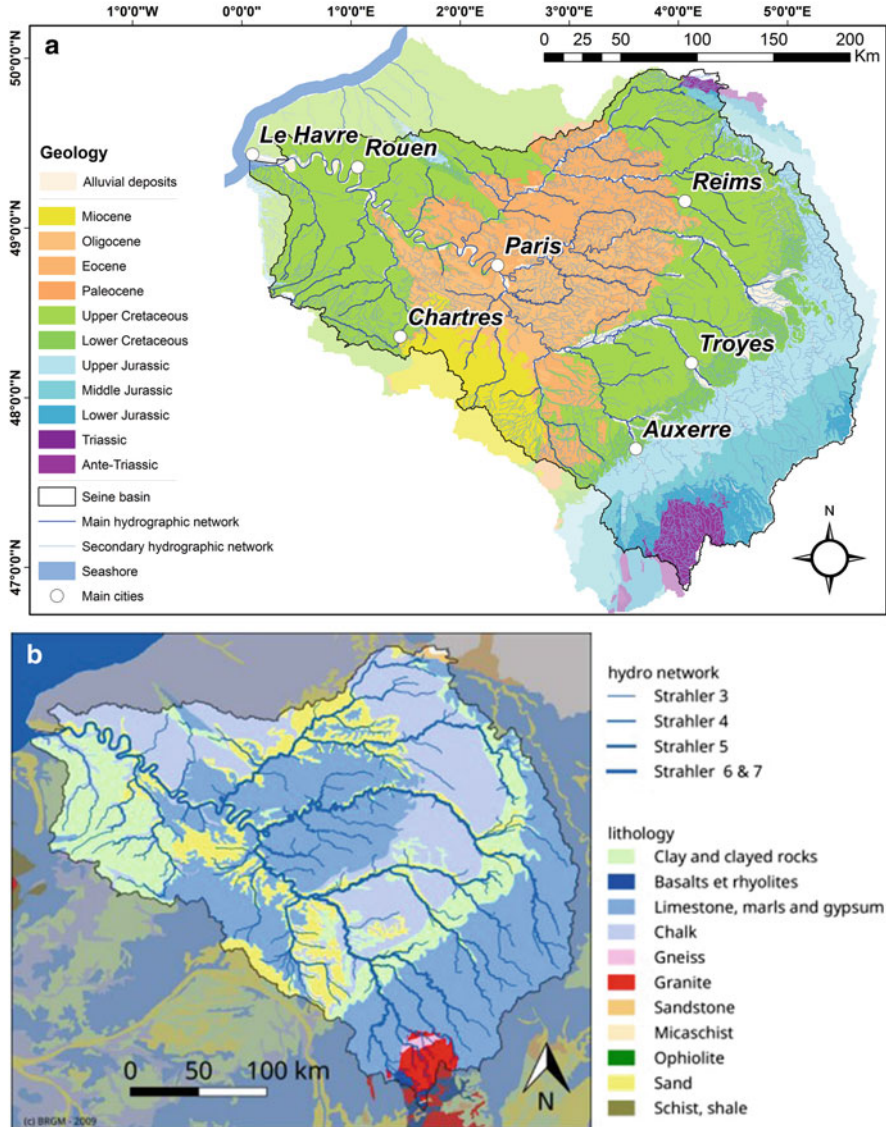


Fig. 2 (a) Geological structure of the Seine basin. (b) Lithology of the Seine basin

these seasonal river flow variations, a 17-year cycle associated with the North Atlantic Oscillations (NAO) structures the long-term temporal variability of stream discharges [33], as well as groundwater levels [34].

The rainfall exhibits virtually no seasonality, meaning that the river flow regime derives from seasonal variations in real evapotranspiration, thereby resulting into winter high flows and summer low flows; these are naturally sustained by numerous

sedimentary aquifers, and, for the middle and lower reaches of the Seine and Marne rivers, by large reservoirs that were built between 1931 and 1990 (Fig. 1) [35]. These reservoirs, totalling 841 Mm^3 , regulate floods and can provide more than 50% of the river flow in summer, thus contributing to dilute wastewater inputs of the Paris conurbation (i.e. $25 \text{ m}^3 \text{ s}^{-1}$ discharge downstream of Paris). Water management is therefore a key factor of the current Seine River discharge profile [32]. It should be noted that the relative natural dilution power of the Seine River in relation to Parisian wastewaters is very limited, making the Seine River sensitive to point source pollution compared with most large European rivers.

The PIREN-Seine programme focuses mainly on the Seine River basin upstream of its estuary, the latter also being studied by the long-term programme, Seine-Aval, which started in 1995 [36]. The main experimental sites studied within the Seine River basin and the coring sites presented in Ayrault et al. [26] are shown in Fig. 1 and will be discussed in further detail in the following chapters.

2.2 *Evolution of the Basin Population*

Paris, the largest megacity in Europe, has developed on the Seine River in the central part of the basin, near the confluence of the Marne River and upstream of the confluence with the Oise River. This location once represented a favourable factor for the long-distance transport of food, timber, and construction materials. The urbanized part of the basin has been growing over the past two centuries. Paris megacity increased from 75 km^2 in the 1850s (Paris area) to $2,850 \text{ km}^2$ today [37]. In 2015, it was home to 12.4 million (M) of the 16.7 M inhabitants (inhab.) within the basin. The population density of the Seine basin in 1901, 1954, and 2016 is provided in Fig. 3, showing the increasing population in the Ile-de-France region, around Paris, and downstream along the lower Seine. The population density near urban tributaries in the Paris area ranges between $1,000$ and $5,000 \text{ inhab km}^{-2}$, while it is much lower ($<20 \text{ inhab km}^{-2}$) in the upstream areas, with an average of $250 \text{ inhab km}^{-2}$ for the whole basin.

The urban pollution generated by the city of Paris, and later by the Parisian conurbation, which impacts the lower Seine and the estuary has been a major concern of the authorities for over a century [37–39]. Water quality has been severely degraded in terms of oxygen levels, ammonia, and nitrite concentrations, as well as the occurrence of faecal bacteria over a section of river extending from 100 to 250 km downstream from Paris [40]. In the 1870s, the collected wastewater started to be spread over sewage farms near Paris. Wastewater treatment plants (WWTPs) were then gradually built but insufficiently to treat the volume of wastewater generated by the Paris conurbation [41]. One of the sewage farms at Achères, located at 60 km downstream from Paris, was converted into the Seine-Aval WWTP between 1930 and the 1980s, treating up to 8 M inhab. equivalents in the 1970s [35]. The lag between sewage collection and its adequate treatment was only bridged in the 1990s [42].

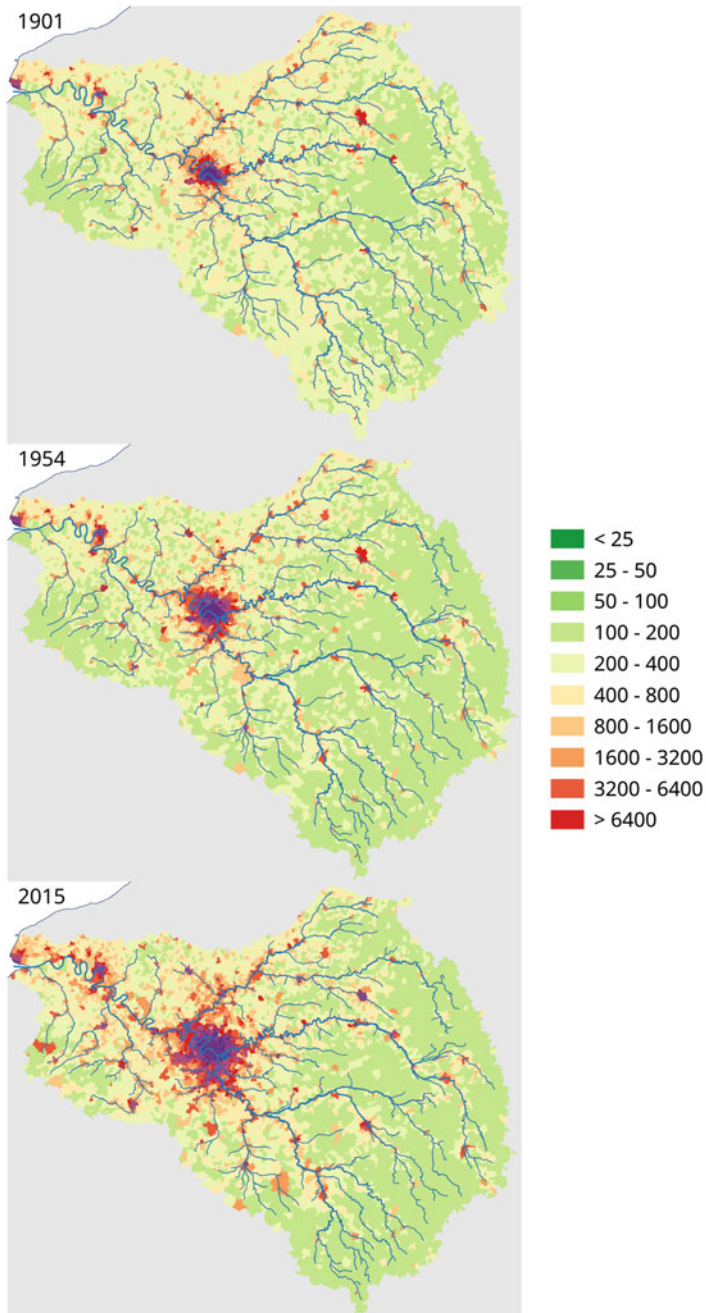


Fig. 3 Population density of the Seine basin in 1901, 1954, and 2015

2.3 The Land Cover

Nowadays, the Seine River basin is characterized by a relatively high proportion of urbanized area (7.6%), compared with grasslands (9.5%), forested areas (25.6%), and croplands (56.5%). Wetlands and water bodies represent low surface areas (Fig. 4).

Paris is surrounded by areas of high-intensity agriculture, oriented towards specialized intensive production of cereal and industrial crops. The development of agriculture initially paralleled the growth of Paris and its food demand in recent centuries [43]. Then a significant turning point in land use took place in the 1960s, when nitrogen fertilizers were applied intensively to croplands and converted grasslands [44, 45]. A major socioecological transition of the Seine system is thus identified at that time.

The PIREN-Seine has documented these changes in great detail (e.g. crop rotation, fertilizers applications, livestock density, etc.) from agricultural censuses conducted since 1850 at the level of the French departments and also by enquiries at the scale of small homogeneous agricultural areas (PRA, petites régions agricoles; originally defined in the 1950s). This information supported the reconstruction of nutrient circulations (nitrogen and phosphorus) in the basin at a fine spatio-temporal resolution [46]. Changes in land cover since the beginning of the twentieth century were also used to reconstruct the evolution of the Seine basin water budget [32].

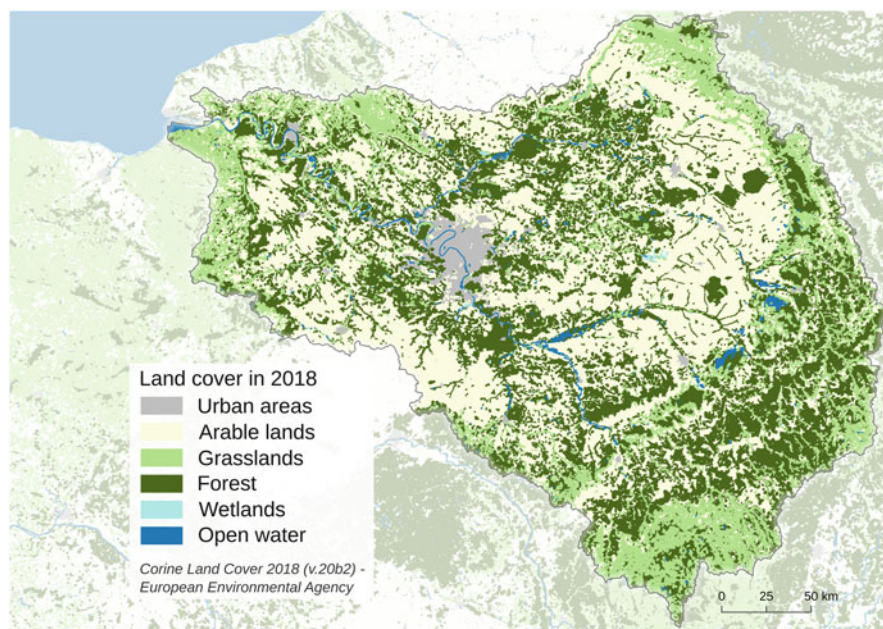


Fig. 4 Land cover distribution (2018) of the Seine River basin

2.4 Industries and Navigation

Heavy industrialization began in Paris and its suburbs on the eve of the nineteenth century. Until the end of the “Thirty Glorious Years” (1946–1975), industries were mostly located in Paris megacity, along the Lower Seine industrial corridors and along one of its main tributaries, the Oise River (see Fig. 1). Industrial wastewaters were barely treated on site and were discharged directly to the closest rivers, with the official assumption that they would be diluted and that rivers had enough self-cleaning potential. Deindustrialization and industrial wastewater treatment promoted by the Seine-Normandie Basin Agency (AESN) led to an improvement in the quality of the Seine River’s water. 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 were largely ignored by French scientists and authorities [26, 42, 47].

A further factor affecting the river has been the demand for deeper, larger, and more extended navigated reaches in the basin, specifically after the 1837 law for the improvement of navigation on the Seine River, allowing increased sand and gravel extraction in the floodplain, transported by waterway and used for Paris urban growth [48].

3 PIREN-Seine Research on the River Basin Trajectories

An investigation of the trajectories of this highly modified hydrosystem in the *longue durée* is the main focus of this book. The study of river systems over several centuries using historical data or sediment core analysis reveals a dynamic that contemporary observation – over a few years or decades – is not able to capture. It allows for the construction of trajectories that link societal evolution and changes in the overall state of the river. These trajectories represent simplified expressions of our understanding at a given stage of (1) the spatial description of the system state and its functioning, (2) its temporal evolution in the *longue durée*, (3) the relationships between river/water actors, and (4) the evolving position of river basins within the Earth system, particularly within the new Anthropocene concept [42, 49]. Trajectories bridge the gap between natural scientists and social scientists and make some results more readily available to our partners and to the public [50]. When possible, the usage of numerical models leads to quantitative results that help to define trajectories. A few examples are provided here. Their time window exceeds the 50 years of environmental monitoring in France and extends to two centuries and even more, owing to particularly abundant archives and historical data for the Seine River basin.

Within the PIREN-Seine, the ways of studying the trajectories of the Seine basin have evolved over time. The first representations were spatial: a catchment area in which a human dimension was introduced to reconstruct water and material flows within the whole catchment (e.g. metals) or to model the biogeochemical cycles of

selected major elements (e.g. nitrogen). The opening of the biogeochemical cycles due to multiple factors has led to more systemic approaches combining the following trajectory components: (1) state indicators; (2) controlling factors and pressures indicators, generally economic; and (3) a set of social indicators, such as scientific knowledge and social awareness, inclusion of issues on the political agenda, environmental surveys, as well as regulatory and technical responses.

This work is complex, since both water and river systems are at the same time a resource, an economic good, and a cultural and symbolic asset, subject to different regulations according to these various functions. Each function generates specific actors or sets of actors and is perceived differently by each of these actors according to the numerous and variable reading grids over time.

3.1 Circulation of Material Within the Basin

The main advantage of river systems is the possibility to carry out material balances by monitoring material fluxes at the outlet of the basin. This approach provides integrated information for the entire territory of the basin and its population, at various time steps. Deciphering all the complexity and heterogeneity of the multiple fluxes requires specific studies for the past and present situations. For almost 30 years, river systems have been recognized for this complexity and studied in an interdisciplinary way owing to it, such as in the PIREN-Seine programme since 1989 or in other programmes [51].

For geologists and geochemists, natural material fluxes within river basin fluxes 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 environmental chemists, the river-borne material contamination results from waste discharges and runoff and from the erosion of soils contaminated by diffuse sources. For environmental economists, material flow analysis over a given territory reveals the metabolism of the anthroposphere, the storage of left-over products, the growing pattern of infrastructures, and the recycling of products and goods [16]. The comparison of additional river fluxes – compared with estimated natural material fluxes – reveals that the circulation of many economic products used in the Seine River basin is between one and two orders of magnitude greater than the natural material fluxes, as for the heavy metals [52]. This new view of territorial functioning is schematized in Fig. 5, in which the system is described by a set of natural and/or anthropogenic reservoirs between which there is a continuous circulation.

The river receives a share – between 0.1 and 40% depending on products and periods – of this economic circulation (e.g. 0.1% for metals [55], 7% for phosphorus [56], and 40% for nitrate [57]). The specific circulations and their impacts on river exports vary over time and may relate to different locations in a river basin (see Fig. 6 for metals).

The reconstruction of these fluxes and of their evolution over time makes it necessary to correlate the knowledge on the circulation of substances in the anthroposphere (manufacturing, importation, consumption, and evolution of uses)

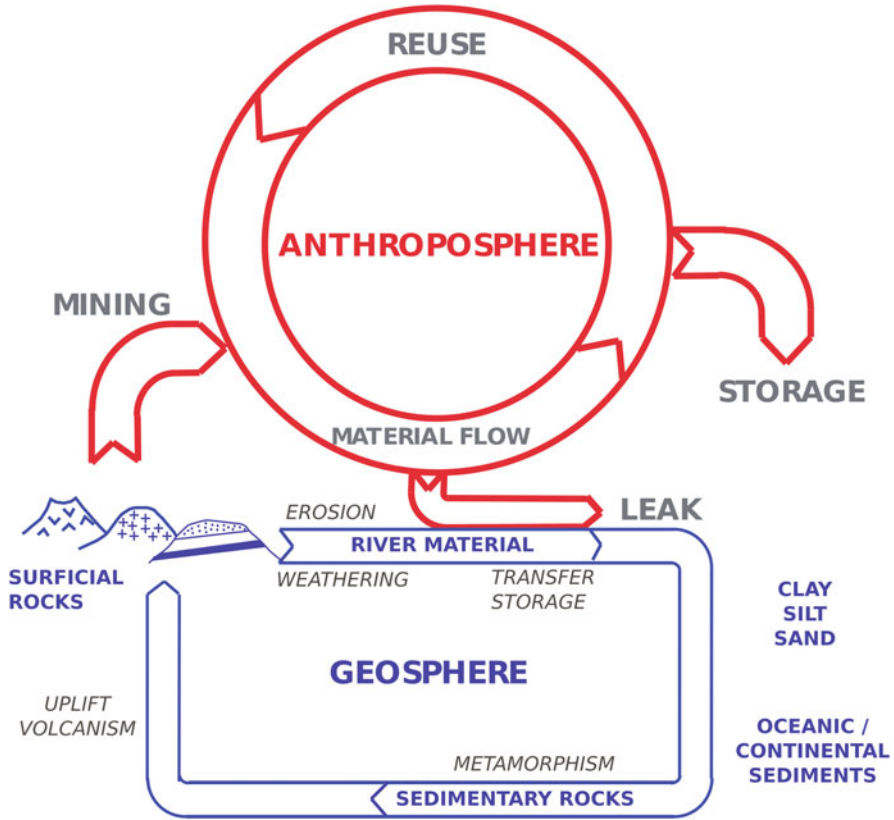


Fig. 5 Schematic circulation and storage of material within an impacted river basin: material flow within the river basin territory and its leaks into the aquatic system (based on [53, 54])

with field data provided by official water surveys or collected by the teams involved in the PIREN-Seine programme. Mass balances at the scale of the Seine River basin were undertaken for nitrogen [58], non-ferrous metals [59], and polycyclic aromatic hydrocarbons (PAHs) [60].

The lack of available sources, either spatial or temporal, makes a retrospective modelling approach to fill the gaps essential. Widely developed within the PIREN-Seine, e.g. for water budget [32], oxygen budgets [41], or nitrogen circulation at the watershed level [46], this approach remains original within the scientific community.

For centuries, the Seine River basin system was relatively closed, excepted for some imported products carried through the river waterway. Nowadays, the socio-economic system has been widely opened through massive imports and exports. The basin exports a great quantity of agricultural, food, and manufactured products, and it consumes a large quantity of imported animal feed, fossil fuels, mining, and manufactured products. It also emits and receives atmospheric pollutants to and from other basins through long-range transport.

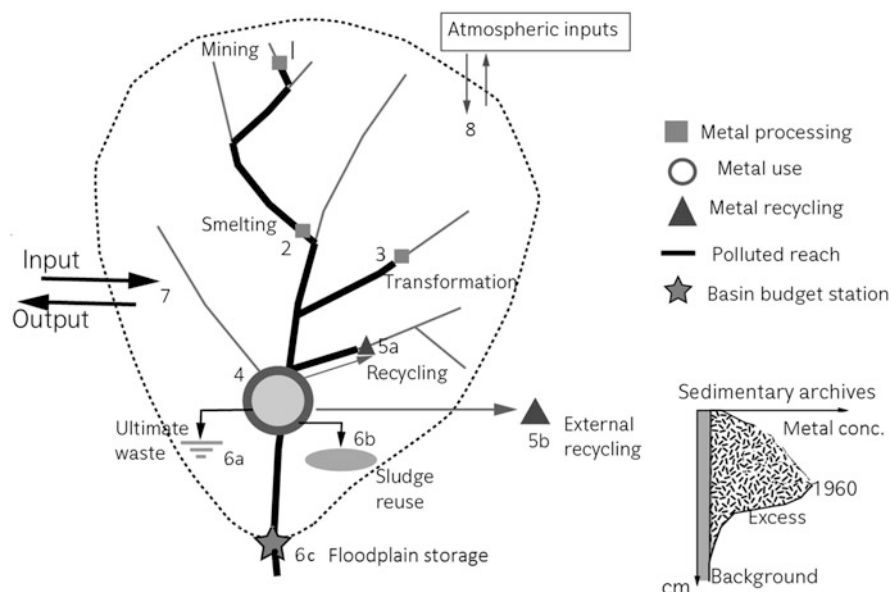


Fig. 6 Circulation of products and materials within impacted basins: (1) mining (very limited, occurring in the 1700s); (2) metal smelting, mostly in Paris and along the Seine and Oise; (3) metal transformation, mostly in Greater Paris; (4) use of metal and metal-containing products; (5) recycling of metal products such as batteries and pipes, first carried out in Paris suburbs prior to 1950 (5a), then outside the basin, and finally outside France (5b); and (6) storage in contaminated soils and landfills (6a); recycling of Paris WWTP sludge, once highly contaminated (<1990) (6b); and storage in floodplain sediments providing sedimentary archives of contamination (6c) (from [49])

This link with other river basins has been evidenced for the nitrogen and phosphorus circulation; it is also obvious for heavy metals, as there are no mines of non-ferrous metal in the basin. The strong impact of the Seine basin on the eutrophication of the Bay of Seine to the English Channel, and of the North Sea, has also been well documented [41], representing an example of the interest in considering the land-to-sea continuum, from headwaters to the coastal zone and eventually to oceans. These studies also showed the growing role of society in the control of rivers during the Anthropocene era [49]. These controlling factors are detailed in the following section.

3.2 Multiple Long-Term Trajectories of River Control Factors

For nearly 150 years, the social response to manage the uses of the river (navigation, flood control, and recreational purposes) or of its waters (drinking or agricultural water resources, dilution of the residual pollution from wastewater treatment plants)

has taken place in successive stages [61]. It followed changes in paradigms (all-sewer sanitation), triggers (catastrophic floods), increasing water needs, new uses (cooling of nuclear power plants, agricultural irrigation), new awareness of water quality, wetland functionality, and aquatic biodiversity. A marker of these social responses are the laws concerning aquatic environments. The main laws for France are those of 1807, 1858, and 2014–2017 (flood prevention); 1829, 1865, and 1984 (river fishing laws); 1837, 1846, 1878, and 1880 (Seine River navigation improvement) and 1956 (Code for Waterways and Inland Navigation); and 1898, 1964, 1992, and 2006 (water quality and general river management).

It has been possible to undertake such a study on the Seine River basin due to the fact that it is an exceptionally rich territory in terms of environmental archives:

1. We have been able to reconstruct the nitrogen circulation and the related water quality, going as far as back in the Middle Ages, based on quantitative economic archives from ecclesiastic records [62].
2. A cartographic database on the river course and its corridor showing its evolution since the end of the eighteenth century has been set up, thanks to the archives of Ponts et Chaussées engineers [48].
3. We benefit from historical data (e.g. the nutrient chemistry and microbiological analyses; river hydrological records), which started in the second half of the nineteenth century – the chemical and bacteriological analyses of Seine water are one of the earliest ever made and have been regularly surveyed since the late nineteenth century [63].
4. We have also used sediment archives to reconstruct the river contamination by numerous and diverse legacy pollutants (heavy metals, PCBs, etc.), over 50–80 years, while the reliable surveys of these substances only started after the 2000s [26].
5. We have analysed historical agricultural censuses from 1854 to the present [45] and their associated greenhouse gas emissions [64].
6. We have also reconstructed the evolution of the fish population, a key integrative ecological indicator within the basin, from historical and archaeological archives collected over more than two centuries [65, 66].

The Seine River basin, therefore, provides an exceptional array of quantitative information, since it has provided water, energy, and food to Paris, France's capital city, for centuries. Reliable documentation dating back to the First Empire (early nineteenth century), when systematic mapping, population censuses, and economic statistics were started, is available.

To further address the interactions between the Seine basin society and its river over the longue durée and to understand these changes, we need access to the evolution of several controlling factors of the river basin system such as hydro-climate evolution (so far addressed from the second half of the nineteenth century [67]), changes in agricultural practices, industrial activities, population distribution and sanitation history, river navigation structures and other river uses, the introduction of aquatic species, etc. A schematic view of these trends is presented in Fig. 7. They show a wide spectrum of evolution, rarely linear and regular, varying from a uniform increase in population over the past 200 years to plateau features, bell shapes

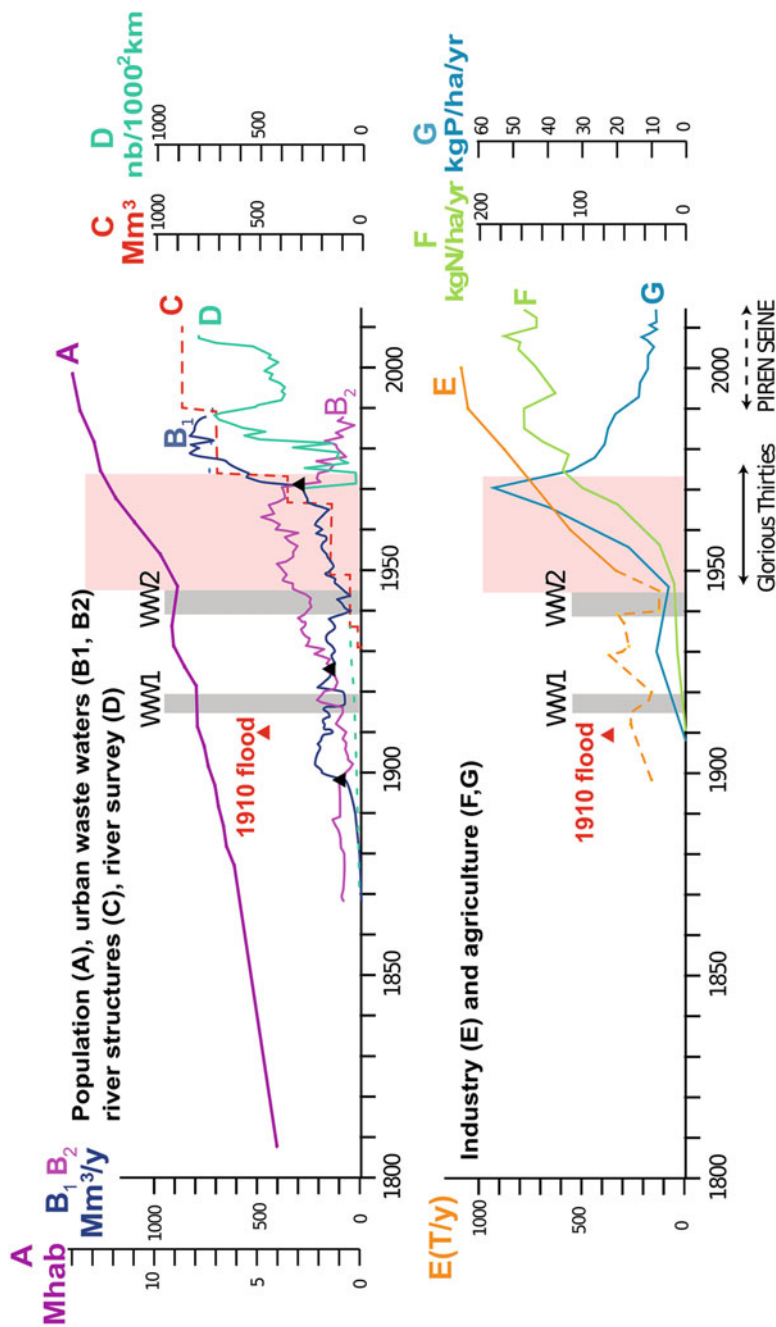


Fig. 7 Elements of the Seine River trajectories construction: evolution of controlling factors on the Seine River basin (1800–2010). A, total population; B1 and B2, collected and treated volumes of wastewaters from Paris [38] (triangles: tipping points at curve intersects); C, total capacity of reservoirs; D, density of river quality survey stations (nb/1000 km²); E, total metal use in France (Cu + Pb + Zn) (from [52, 55]), extrapolated before 1950 from industrial indicators; F, Nitrogen fertilizers applications; and G, Phosphorus fertilizer. Chronological markers: 1910, centennial flood; WWI and WWII conflicts; 1944–1974, period of rapid post-war development; 1989, start of the PIREN-Seine programme

(urban inputs), ruptures, and stepwise variations in the construction of infrastructures (WWTPs and reservoirs) but also in terms of regulations (laws, pollutants bans), notch patterns particularly for World War I and II or the 1929 economic crisis, as well as tipping points (e.g. the collected/treated wastewater ratio). The comparison of the trajectories of pressures/responses shows a temporal lag, sometimes over several decades, typical of each issue [42].

3.3 Trajectories of River State and Societal Response to River Issues

Analysing the trajectories of the river state indicators and their control factors and investigating river-society interactions are now important topics of the PIREN-Seine, which complement the description, functioning, and modelling of the hydrological and biogeochemical functioning of the Seine River system. Indeed, these trajectories combine physical, ecological, chemical, and social attributes. They make it possible to convert our relatively narrow window of observation (i.e. one to five decades) into the *longue durée* observation (100 years and sometimes far more) with which the complex relationships between man and river should be studied. In such a time window, the severe chemical pollution of the river that characterized the twentieth century is becoming a transient phenomenon for many issues.

Knowledge on the river basin shows a non-linear progression, with periods of disinterest in the river and its functioning. This complex social response is schematized in Fig. 8 using the “impair-then-repair” model [61, 68]. This model starts with a

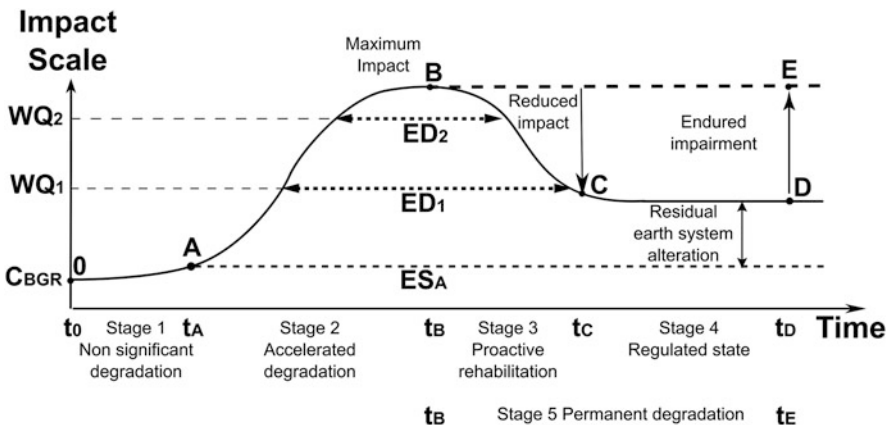


Fig. 8 The impair-then-repair scheme and the five stages defining river quality trajectories, applied to North America and Western European river basins (adapted from [61, 68]). WQC_1 and WQC_2 , water quality criteria established for water management. C_{BGR} , pristine state concentrations. ES_A , ED_1 , ED_2 , duration of Earth system alteration, of the impaired state, and severe degradations of the river, respectively, as defined by river basin societies

period of *non-significant impact* on the Earth system or on 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 growth in the river basin, first reaching the level of water quality (WQC_1) at which water resources are impaired, often followed by a very poor 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 stage of maximum impact (BC, stage 3). When a satisfactory state is finally achieved, reaching the desired level of quality WQC_1 , the *regulation stage* ensures a stable quality even though the population and economy of the basin continue to grow (CD, stage 4). If environmental management is insufficient, the impact can reach a *permanent degradation* (BE, stage 5) stabilized at an altered level ($>WQC_2$), which can be considered as irreversible.

The duration of the moderate environmental degradation (ED_1) from the societal perspective is defined here as exceeding WQC_1 , and the duration of severe degradation (ED_2) as exceeding WQC_2 (Fig. 7). Water quality scales, WQC_1 and WQC_2 , defined for each of the issues recognized by the society may evolve over time, thereby changing the environmental assessments made by societies. 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 in the Earth system (ES_A) and may generate a change on receiving waters – for instance, along the coastal zone.

4 Structuration of the Socioecological Research in the Context of the PIREN-Seine

At the beginning of the programme in 1989, originally launched by hydrologists, environmental chemists, biochemists, and engineers, only the natural processes, as modified and sometimes regulated by present and past human activities, were considered. After the seven stages of the programme, the interactions between the society and its environment now account for a major aspect of our research. In some projects we even aim to understand the generation and regulation of these activities, a turning point that has been taken gradually in the second and third stages of the programme. This comprehensive study of the Seine basin territory, a hydrological and a social system, over a well-defined spatial entity, enables us to generate river functioning models, which now implicitly include a number of socio-economic variables (e.g. agricultural practices, consumers habits, and water use) and technical changes or innovations (e.g. for wastewater treatment). Finally, in the last sixth and seventh stages of the programme, the future state of the river has been explored on the basis of narrative scenarios indicating the evolution of controlling factors, sometimes coupled with the hydrological response to various climate change scenarios. These scenarios have been implemented in the modelling approaches.

4.1 *Evolution of Main Research Themes*

Although the PIREN-Seine programme was not initially planned to last as long as it has or to encompass so many different topics, it gradually became apparent that it was very well suited to study many environmental issues far beyond the initial water resources issues.

The gradual changes in the main themes, as presented in annual reports to our financial sponsors, are schematized in Fig. 9. The colour coding makes it possible to represent the permanent themes, such as hydrology and water circulation, biogeochemistry, ecology, basin history, sediment contamination, as well as agricultural and urban impacts. The main models (Figs. 9 and 10), Riverstrahler [8, 70], ProSe [9, 12, 71, 72], STICS-MODCOU [73, 74], and ANAQUALAND [75], integrate many of these subjects. All these models are mechanistic in nature and evolved towards the next generation for Riverstrahler and MODCOU, now called pyNuts-Riverstrahler [76] and CaWaQS [32], respectively. They have been continuously improved, by integrating new processes, new interactions with the basin society, and refining the space or time resolution. These models can be considered as general tools that encapsulate most of the knowledge gained by the programme at a given stage (see [50]).

In fact, this representation conceals highly specialized scientific work: There is a great variety and specificity to the research topics published in scientific journals, such as surface water and groundwater motion, behaviour and transfer of microbial and chemical contaminants across the river continuum, denitrification processes in riparian zones, greenhouse gas emissions, analytical improvements for trace contaminant analysis, ecotoxicology or microbiological activity in field-based and laboratory experiments, databases construction, water use and treatment history, evolution of environmental concerns, changes in agricultural practices, etc.

4.2 *Present Structuration of the PIREN-Seine Research Programme*

The PIREN-Seine programme includes about 100 researchers from 22 research teams, belonging to research institutions (universities, CNRS, INRA, IRSTEA, MINES ParisTech, École des Ponts ParisTech, EPHE, to mention the major ones) that ensure their remuneration and evaluate their research (typically every 1–5 years).

The PIREN-Seine programme by itself is evaluated every 4 years by its financial partners. The permanent partners since the beginning of the programme in 1989 are basin actors for water quality management such as the Seine-Normandie Basin Agency (AESN) coupled with French authority DRIEE, or the EPTB Seine Grands Lacs, and services for drinking water supply (SEDIF – Syndicat des Eaux d’Île-de-France-, Eau de Paris, SUEZ Eau France) or wastewater treatment (SIAAP, Sewage

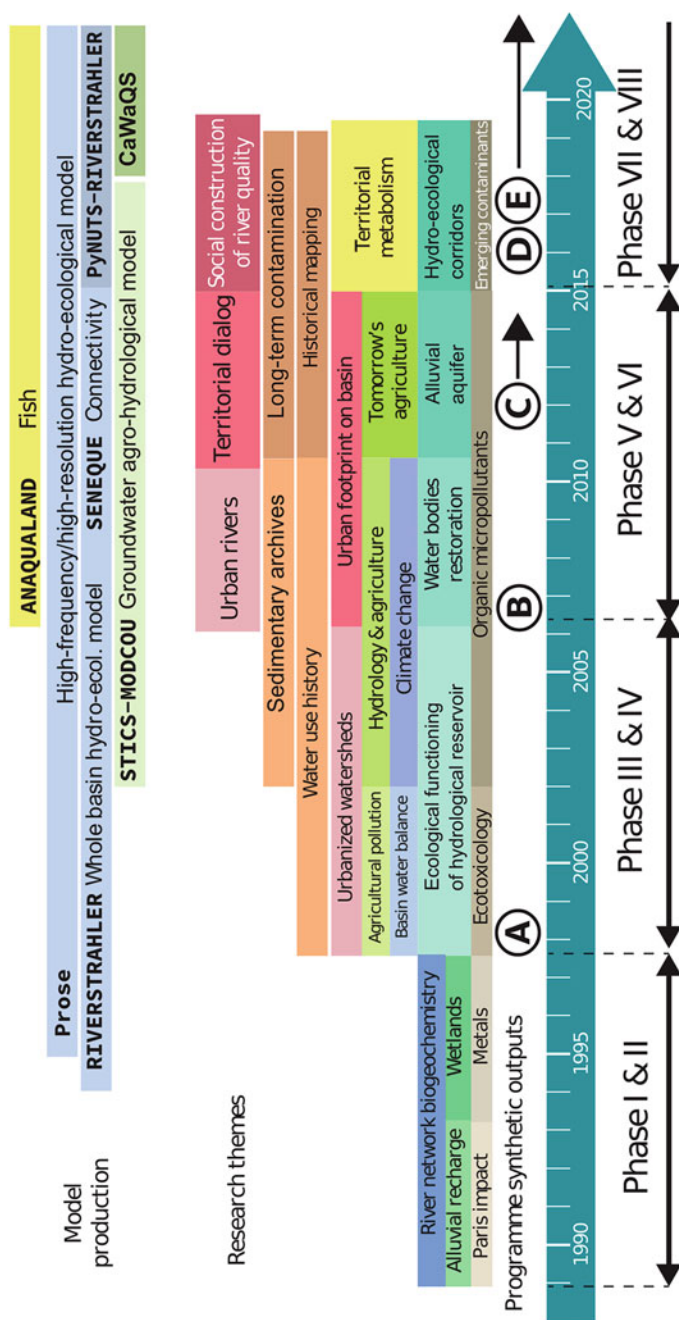


Fig. 9 Gradual development of research themes and modelling tools of the PIREN-Seine programme (1989–2019). A, [14]; B, [15]; C, [17]; D, [16]; E, [69]. For model references, see Sect. 4.1

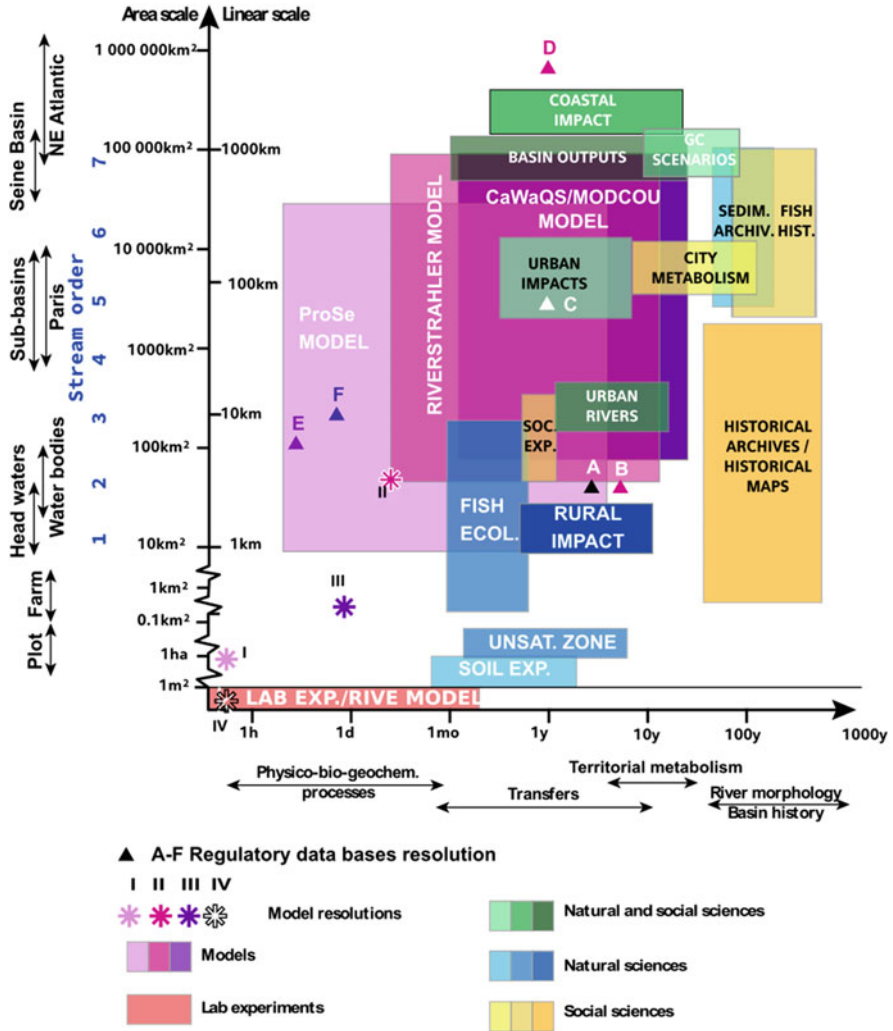


Fig. 10 Main research themes mobilized to describe, understand, and model the Seine River basin and its social interactions, presented in a spatio-temporal diagram. The resolutions of models (I, ProSe; II, Riverstrahler; III, CaWaQS/MODCOU; IV, RIVE) and of regulatory databases (A, population census; B, agricultural census; C, economic statistics (administrative districts); D, economic statistics (national); E, meteorological data; F, hydrological data) are distinguished from the scales of the research items

Public Company of the Greater Paris), VNF, Voies Navigables de France, and the CNRS via the Zones Ateliers network [77]. Funding is used to support specific projects and scholarships to address the main scientific questions collectively arising for the PIREN-Seine scientific and actor partners and stakeholders.

The PIREN-Seine has gradually managed to build up permanent communication gateways and meeting places where all these parties can meet, communicate, and exchange their experience. Over 30 years, numerous scientists, trained under the programme, have reached the public or private sectors dealing with environmental management; some of them are now involved, together with their former PhD advisors, in the stakeholders' meetings of the programme, sharing their views and knowledge, as well as their concepts and tools.

Another set of products comprising leaflets and booklets that have been produced since 2009 is directly targeted at French end users: technicians of the water and/or river institutions, environmental engineers, associations, and educators. These are written by PIREN-Seine scientists and were first published jointly with the AESN and now with ARCEAU Idf [78]. They are freely available [17, 69]. Each one deals with a specific topic. The 40–60-page booklets – a total of 18 in 2019 – can be considered as a whole book on the Seine River basin and its evolution, on river functioning, and on river-society interactions.

The PIREN-Seine is now embedded in the interdisciplinary instrument Zone Atelier (ZA) Seine of the CNRS [79], which comprises two other projects on Parisian urban waters and on the estuary. These ZAs, including the ZA Seine, are part of the national and international LTSER network [80]. Through the network of ZAs, the Seine River programme is connected to other collaborative river research programmes (Rhône, Moselle, Loire, and Garonne).

In addition to these written products, the PIREN-Seine scientists also deliver an annual oral reporting of their main results to their partners. These meetings, established at the outset and opened to associations and journalists, are attended by around 200 people over a 2-day period. They have greatly contributed to establishing mutual trust and shared visions among scientists and partners. These meetings are also attended by the doctoral and post-doctoral students of the programme who also present their main results. The great variety of presentations covering the entire spectrum of our research promotes the interdisciplinary vision built up by the PIREN-Seine community. The programme has also carried out social experiments: They bring together PIREN-Seine social scientists and modellers with groups of citizens, association members, and water institutions technicians, who meet several times to present their visions of river functioning and uses. These experiments, which last at least 1 year, allow the social scientists to explore how the territorial dialogue can be built. Some of the model tools that have been adapted to the territorial conditions can be used to explore local-scale scenarios (e.g. for conflicting river uses, restoration of fish migration, reshaping the agricultural waterscape) (see examples in [50]). At the scale of the whole basin, other scenarios are being developed between scientists and partners, exploring possible future perspectives, particularly in terms of sanitation, agriculture, water demand, and flood security demand (future water storage) [32, 64, 81, 82].

5 The Spatio-Temporal Scales of the Research Themes Selected in This Publication

The selected research themes presented here encompass a wide range of space and time scales schematized in Fig. 10. In addition to laboratory analyses (e.g. characterization of organic matter [83], analysis of contaminants [60, 84], ecotoxicology [85], microbiology [40]), the field activities range from agricultural plot studies to interannual river exports assessed at the basin outlet. Various intermediate time and spatial scales are considered, depending on the scientific or societal question being addressed. They include numerous experimental sites (Fig. 1) that are selected to cover a wide range of impacts, which are generally studied over periods of 3–30 years. At the process scale, the functioning is, for instance, studied in first-order catchments of the rural Orgeval site (II on Fig. 1), an experimental site established in the early 1960s, initially for hydrology and drainage impacts and then for nutrient budgets and pesticides [86]. Recently, continuous records have been set up for hydrological, and especially stream aquifer interactions [87, 88], and biogeochemical monitoring as part of innovative national equipment for the critical zone [89]. Other experimental sites include mid-order streams (3 and 4), such as the Grand Morin River (III on Fig. 1), for which social experiments among river users have been undertaken [50, 90], and the Orge River, a suburban river in the Paris region with a high population density, where many analyses of legacy and emerging contaminants have been carried out (IV in Fig. 1) [85]. The Paris station on the Middle Seine (order 7), just downstream of the Seine-Marne confluence, is located near the laboratory facilities and is used in particular to study the seasonal variability of river chemistry, with a handful of other key stations on upper stream orders, including the Seine reservoirs (5–7, Fig. 1). The Lower Seine course, downstream of Paris (VI on Fig. 1), corresponds to the maximum degradation sector of the Seine River. The impact of the Paris conurbation on this section of the river is present in almost all the following chapters (see, e.g. [37, 40]). The basin output is considered at the Poses station (Fig. 1), just upstream of a weir preventing tide propagation from the estuary. This station at Poses integrates all information on the whole basin upstream. An original feature of the PIREN-Seine programme was to take into account the whole continuum from small streams to the Seine mouth since the outset of the programme [32, 41, 46, 66].

The PIREN-Seine has gradually developed numerous models [50]. These are schematized in Fig. 10 into items with different space and time resolutions: (1) the biogeochemical RIVE model embedded in the Riverstrahler model, which describes the river continuum (10 days, 1 km river reach) [41], and in the ProSe model devoted to a two-dimensional description of the Parisian river sector (15 min, 0.1 km) [12, 91], and (2) the CaWaQS model (formerly MODCOU model), devoted to groundwaters (1 day; 1–5 km²) [32, 92]. These models are actually interconnected and are also connected to another set of estuarine and coastal models. The trajectory of the Seine River has been modelled for retrospective and climate change scenarios for both a hydrological [32] and a biogeochemical perspective [41, 76].

The longue durée evolution of the Seine basin is studied over 50–500 years. Sedimentary archives [26] are used to reconstruct the records of dozens of metals and persistent contaminants that were not adequately surveyed before the twenty-first century. Their interpretation is aided by the historical research on archives for past pressures, water quality analyses, and social responses dating back more than 150 years. The historical maps [48] enable a description of geomorphological modifications in the river course since the eighteenth century, which can be very slow (as with most natural processes) or stepwise (channelization, damming).

All these areas of research are presented here as belonging to the natural sciences (e.g. hydrology, environmental chemistry, biogeochemistry, etc.), the social sciences (history, geography, economics), or their combinations (agronomy, social experiments based on river models, scenarios of basin evolution, etc.). These distinctions are now less and less marked, in particular with regard to the scenarios run with the models and the analysis of socioecological trajectories.

The field, laboratory, and archive research activities are jointly analysed and processed with many regulatory databases and geographic information system (GIS) representations, thereby allowing a description of the entire basin and its evolution. Many of these databases were not set up for environmental studies, but for economic purposes, and, apart from the river discharge measurements, none of them is generated with hydrological boundaries, but rather at administrative levels [52, 53]. All are established at various space and time resolutions, from the daily-subdaily scale and 10 km² for the hydro-meteorological data (Fig. 10, database A) to the yearly statistics of the national economy (database D). These databases are a precious asset of the Seine River basin, with some of them starting at the beginning of the nineteenth century.

Despite the diversity of the spatial and temporal scales shown here, the joint work carried out over 30 years has one common goal: to show the evolution of the Seine basin and its possible future, given the construction of the past trajectories and possible future scenarios that are presented in the following chapters.

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