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Long-term water quality in the lower Seine: Lessons learned over 4 decades of monitoring

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ABSTRACT

The Seine River is a highly artificialised catchment in Europe, comprising both productive agricultural areas and intense industrial and commercial activity. Due to its strategic importance, monitoring programs in the river started as early as the 1970s. The present study compiles and analyses this valuable data set (1970–2014), thoroughly describing the riverine section downstream of Paris and the estuary. We identify long-term trends and shifting patterns in nutrients and oxygen, and pay special attention to the river's evolution after the year 2000, when the European Water Framework Directive came into force. The study has a manifest management perspective, and the results are discussed on the basis of the environmental quality standards proposed in current environmental regulations. The data show that water quality has improved remarkably over the past two decades, with sharp reductions of ammonium and phosphate and a progressive increase of dissolved oxygen levels. The amelioration is prominent in the estuary, where summer anoxic episodes have nearly disappeared. As a result, these three parameters are nowadays in good or very good condition throughout the year. The successful abatement of point sources contrasts, however, with the low effectiveness of the measures provided for the control of nutrients from diffuse sources. Nitrate concentration has increased by 150% since the early 1980s, and only very recently has the upward trend been reversed. Bold agri-environmental management measures are required if we are to prevent chronic pollution problems and truly restore the good ecological status of rivers.

1. Introduction

The Seine River is a highly artificialised catchment in Europe. The upper Seine drains extensive, productive agricultural areas, while the lower part flows across the Paris conurbation, with over 10 million inhabitants, and the Rouen–Le Havre axis, which hosts intense industrial and commercial activity (Meybeck et al., 1998; Billen et al., 2001). The river plays a critical role in numerous aspects of human activity, providing resources (water, food, raw materials) and transportation, and these strategic advantages account for the presence of large human settlements in the region for several centuries (Billen et al., 2007 and references therein).

The importance of the river and its related resources has sparked monitoring activities since the 1950s, which evolved into regular surveys with a bi-monthly frequency after 1970. As a result, the Seine River offers a unique and very complete database that allows a thorough examination of the river's evolution during the past half-century, coupling changes in water quality with major socio-economic and technological changes. Billen et al. (2001, 2007) used the Riverstrahler model to assess the biogeochemical functioning of the basin and presented an overview on the dynamics of the river system, although none or very few data were included on the estuary. Herein, we do not adopt a mechanistic approach, but rather scrutinise the actual quality data set with a number of statistical techniques, including not only the riverine

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section downstream of Paris, but also the estuary. We aim to detect trends, turning points and shifting patterns, providing a complete description of the lower reach of the river. We track concentrations over a long period of time (1970–2014) and establish trajectories that can be paralleled to the trajectories observed in human systems. Furthermore, we have updated the analyses until the most recent years and pay special attention to the evolution after the year 2000, when the application of the Water Framework Directive (hereafter, WFD) promoted new advances in the basin's wastewater treatment plants (e.g. in Achères, the largest sewage facility, phosphorus abatement was implemented in 2000, nitrification in 2007 and denitrification in 2011).

The study has a manifest management perspective: we use the concentration ranges recommended in European and French national regulations and discuss the corresponding quality status categories. The WFD requires all waters to reach 'good ecological status' by 2015, so our results may contribute to verifying the compliance of this demand for the Seine. Our ultimate goals are to assess the efficacy of the water management measures applied thus far, identify major weaknesses and suggest potential improvements.

An additional asset of the study is the integrated assessment of the river stream and the estuary, considering the interplay between the freshwater and the marine reaches. Given the complexity of estuarine systems, policies focused on river water quality rarely consider the effects and synergies with the river mouth and the nearby coastal strip. The role of estuaries in buffering the nutrient load to coastal waters, however, can be significant (e.g., Canton et al., 2012; Soetaert et al., 2006). In the Seine Bight, Garnier et al. (2010) found that the estuary is able to retain (either as permanent or temporary storage, or as definitive elimination) nearly 7% of the annual N inputs (the abatement reaching 40% during the summer months), 4% of dissolved silica inputs and over 30% of inorganic P inputs. Moreover, transit through the estuary changes not only the concentration of inorganic nutrients, but also many other compounds, including a myriad of micropollutants in their dissolved and particulate forms. The results presented here—comprising data from 22 estuarine stations—allow testing some of the conjectures put forward in previous studies on the role of the Seine estuary (Even et al., 2007; Garnier et al., 2008; Némery and Garnier, 2007), namely the low retention capacity with respect to the upstream nutrient fluxes. The next step will be the use of these data to calibrate a functional model to represent the biogeochemical processes occurring in estuarine waters more closely and to quantify the retention/export of the different elements in the estuary, given that the Seine is a good representative of the macrotidal estuaries typical of the European Atlantic façade. For that purpose, the ecological modelling chain used in Passy et al. (2016) to represent the land–sea continuum will take into account the estuarine compartment.

2. Materials and methods

2.1. The study area

A few basic characteristics of the Seine basin (as a whole and for the specific river stretch under study) are presented in Table 1. Briefly, the river and its estuary drain an area covering 76,260 km^2, and the main branch is over 760 km long. After Paris, the river flows to the northwest and drains its water into the English Channel (Fig. 1). The region presents a typical temperate-oceanic climate, with a mean annual precipitation of 680 mm uniformly distributed throughout the year.

The lower Seine River, from Paris to Poses, is about 360 km long and is strongly influenced by the Paris conurbation, which accommodates ca. 12 million inhabitants. Urban effluents from the city are treated in various wastewater treatment plants (WWTPs), whose capacity and types of treatment have been deeply modified during the last decade. The largest one (Seine Aval, located in Achères, 74 km downstream of Paris) treats about 1.67 million m^3 d^{-1} (i.e. 6.5 million equiv. inhab.), the rest of the wastewater being distributed among three other facilities (0.6, 0.3 and 0.24 million m^3 d^{-1}).

The estuary itself occupies 50 km^2 (the third largest estuary in France), and the intra-estuarine basin accounts for ca. 6% of the total surface of the catchment ($\sim$4515 km^2, Garnier et al., 2013a). The population of the estuarine basin is about 1 million inhabitants. A large wastewater treatment unit (Émeraude WWTP) treats the wastewater from Rouen city and its conurbation (0.085 million m^3 d^{-1}, i.e. 0.7 million equiv. inhab.). The estuary is composed of two major sections: a freshwater tidal sector—from Poses to Caudebec—and a lower part affected by a salinity gradient (Fig. 1). The tides influence the estuary up to Poses, where a lock prevents further tidal propagation (Fisson et al., 2014; Garnier et al., 2010). Broadly, tidal amplitudes vary between 3–7 m at Honfleur and 1–2 m at Poses, and the mean residence time in the estuary spans from 17–18 days for a discharge of 200 m^3 s^{-1} at Poses to 5–7 days for a discharge of 1000 m^3 s^{-1} (Even et al., 2007; Le Hir et al., 1999). The estuary is also characterised by the formation of a turbidity maximum zone (TMZ). The TMZ is mostly located between Honfleur and Tancarville, but it can move upstream depending on both the tide cycle and the river discharge. During winter flood events, the TMZ is usually flushed out into the Seine Bight (Etcheber et al., 2007; Garnier et al., 2008, 2010).

Numerous morphological alterations have taken place during the past century aiming at facilitating navigation (Foussard et al., 2010; Lafite and Romaña, 2001; Lafite et al., 2007). A number of dikes and locks have been installed, and many canals have been dredged to increase the depth of the waterways. In addition, huge engineering works designed to improve the access of the Rouen and Le Havre harbours have led to a large amount of sediment removal (Lesourd et al., 2001; Némery and Garnier, 2007).

Despite the large human settlements located in the lower reaches of the river, the Seine catchment and its estuary are mostly composed of agricultural land, notably cereals and industrial crops.

Table 1
Basic characteristics of the Seine basin (stream length, population, population density, wastewater treatment capacity). *SEINE* refers to the whole basin, while *LOW ST* refers to the lowest stream reach (our study area), from Paris down to the estuary.

	Length (km)	Population (10^6 inhab.)	Density (inhab./km^2)	WWT capacity (10^6 equiv. inhab.)
SEINE	767	17	195[a]	11.3[c]
LOW ST	360	12	230[b]	7.6[a]

[a] Garnier et al., 2010; Naeher et al., 2015.
[b] Passy et al. 2016.
[c] Billen et al., 2001.