FACT SHEET: Seine River Basin

The Seine River crosses several important urbanized areas of France. With a length of 754 km, it originates near Dijon, flows through Paris, and discharges to the English Channel. The basin drainage area is approximately 75,976 km². The average rainfall of the watershed is 666 mm/yr. At the Poses Station, the mean annual discharge is about 600 m^3/s. The population is more than 16.5 million inhabitants. Table 1 presents the main characteristics of the basin.

Figure 1 Seine River drainage basin.

Table 1. Seine River Basin characteristics

Seine
COUNTRIES: FRANCE
Pedo-climate: Atlantic region; Atlantic Central zone
Drainage Area 75,976 km^2
Maximum altitude: 906 m
Annual average rainfall 666 mm/year
Main land uses: Agriculture 62%; Forest 30%, and Urban/other 7%
Population in 2015: 16,696,391
River length 754 km
Strahler Order – 7
Discharge at outlet 611 m^3/s
Outlet coordinates: 49° 26' 2" N, 0° 12' 24" E

About 62% of the basin is used for agriculture; the basin hosts 25% of the French agricultural activity and 25-30% of the national industrial activity. Rainfed winter wheat is the dominant crop in the basin. Other crops include rapeseed, barley, and peas or faba bean, but also maize and beet. The total water resource demand is approximately 1.8 billion m^3/yr. About 55% of water abstractions are from groundwater, with the remaining from surface water. Most of the groundwater is pumped for drinking water production (74%), for industrial purposes (16%) and for irrigation by the agricultural sector (10%). Figure 1 presents a map of the Seine River Basin.

Agriculture and water in the Seine Basin

Concentration and flows of nitrogen compounds in freshwaters associated with agriculture have increased during the last decades in the Seine basin, although recently the situation seems stable or even in small reversion (Romero et al., 2016). However, even with a generalization of nutrient management practices that is now required by regulations, meeting drinking standards of 50 mg NO_3^-/L (11 mg N/L) would not be fully guarantee (Billen et al., 2013; Anglade et al., 2015). In parallel, phosphorus pollution has dropped, especially due to improvements in wastewater treatments and the ban of phosphates in household detergents (Romero et al., 2016, Garnier et al., 2019a).

Nitrogen flows from cereals systems are well reported (Constantin et al., 2011; 2012; Benoit et al., 2014; Anglade et al., 2017; Garnier et al., 2016; Autret et al., 2019). Several management strategies may potentially reduce nitrate leaching, like the use of cover crops, improving fertilization, organic farming, etc. The best agro-environmental strategy should be based on the local agro-environmental conditions. Nitrate leaching can be significantly affected by soil physical characteristics (e.g. texture, infiltration rate, field capacity, humus content; Arauzo and Valladolid, 2013), climatic conditions, intensity of soil mineralization and nitrification, residual effect of past fertilization, and crop residues management. Indeed, a history of poor management could affect water quality today. Lag time for previous management could take decades due to the legacies effect in long residence time aquifers (Sebilo et al., 2013).

Cover crops (CC) provide multiple benefits to agroecosystems and their integrated management can generate win/win agro-environmental outcomes. CC can be useful to reduce nitrate leaching but if they are non-legume crops, they could immobilize nitrogen, affecting crop yields. This is related to high carbon/nitrogen (C:N) ratio (e.g. barley) or to a lack of synchronization (e.g., maize uptake). The highest C:N leads to the lowest mineralization (Constantin et al., 2011). Legume cover crops could avoid that problem. The combination of a reduction of nitrate leaching and the boost of nitrogen sequestration, together with the increase of nitrogen mineralization could reduce fertilization rates by 30-55% without affecting yields (Constantin et al., 2012). CC management has to be adapted to local weather (Constantin et al., 2015). Bispecific CC mixtures (legume, non-legume) is the most efficient combination to catch nitrogen and to provide it as green manure (Tribouillois et al., 2016). Indeed, the increase of nitrous oxide (N_2O) emissions that could occur after cultivation of legume cover crops could be offset through integrated management by combining or alternating legume and cereal CC (Quemada et al., 2020).

Organic farming (OF) is recognized as a good approach to reduce nitrate leaching. However, although increasing in the Seine Basin, OF still represents less than 10% of the utilized agricultural surface. Systemic approaches considering the whole rotation have to be considered since different crops have different leaching rates, from alfalfa (the lowest) to crops fertilized after fall or after legumes (the highest; Benoit et al., 2016). In general, lower nitrogen losses (leaching and N_2O) for OF on the whole rotation are associated with more crop diversification and less fertilization. In both systems, organic and conventional, there is an important margin for improvement through better fertilization, legumes and catch-crops (Benoit et al., 2015; 2016). The leaching per hectare observed for OF is lower when compared to conventional farming of the Seine Basin, and for some crops it is in the same range when scaled to yield (Benoit et al., 2014; 2016). Anyhow, when the whole rotation is considered, there is no difference in yield due to high yields of some crops such as alfalfa. For this reason, in OF systems with long rotations including legumes (9 years) would be important to valorize legume forages with local animals (Anglade et al., 2015; Garnier et al., 2016). Autret et al. (2019) found similar leaching for four contrasted practices from conventional to organic. The highest yield was observed in conventional, and best greenhouse gas balance (even a negative budget) for OF. The most impacting factors boosting nitrate leaching in both OF and conventional systems are the use of exogenous organic matter, the lack of catch crops before spring, and the proportion of legumes in the rotation (Benoit et al., 2016). It is also important to know the share of nitrogen surplus that is effectively leached because part of it can be retained in the soil organic matter promoting carbon and nitrogen sequestration instead of pollution (Autret et al., 2019).

The effect of conservation tillage (no-tillage – NT, and minimum tillage - MT) on reducing nitrate leaching is not always clear. Oorts et al. (2007) found same nitrogen mineralization and leaching between NT and conventional tillage. If conservation tillage practices are combined with cover crops, there is a significant reduction of the available nitrogen during the drainage period but also higher N_2O emissions could occur (Constantin et al., 2010). NT with mulching can increase carbon sequestration but could also increase the risk of leaching (Coppens et al., 2006; 2007).

Several studies go beyond the farm scale, exploring territorial and structural strategies. The basin-scale as a base to develop recommendations is also advocated (Romero et al., 2016). The good use of the available organic resources is paramount to increase nitrogen use efficiency at the territorial scale, particularity in areas with high animal density where fertilization much above the optimum is common. To stimulate circular economy and proper reuse of animal manures with a direct impact on water quality, a structural change oriented to reconnect crops and animals has been recommended (Garnier et al., 2016). Promoting denitrification in different compartments of the system is a well-known strategy to reduce the load reactive nitrogen into the system. In agricultural soils, the combination of anoxia, nitrate and labile carbon stimulates denitrification; therefore, some practices such as conservation tillage or compost application may reduce leaching and promote carbon sequestration. If the soil quality is improved, i.e. through compost applications, crop productivity could also be increased. However, these curative solutions could trigger N_2O; therefore preventive measures at the farm scale are also recommended (Garnier et al., 2014).

The Seine basin groundwater system comprises ten major aquifers developed in karstic Jurassic limestone, lower Cretaceous sand, and Upper Cretaceous chalk. Ledoux et al. (2007) modelled the fate and transport of nitrate in the Seine River basin in surface and groundwater, comparing simulations with nitrate concentration measured in the three main aquifers (Oligocene, Eocene and chalk) from 1970 to 2000. The groundwater data show a linear increase in the median nitrate concentration from ~ 20 mg NO_3^-/L in 1974 to ~29 mg NO_3^-/L in 1988, i.e. an increase of 0.64 mg NO_3^-/L/y. The modelling provided probability maps per municipality of exceeding the 50 mg NO_3^-/L level in the aquifers. Lopez et al. (2015) assessed temporal trends of water quality in groundwater for the Seine and Normandy river basins. The basins are predominantly agricultural, 90% of their area is classified as Nitrate Vulnerable Zone, and about 30% of the water bodies fail to achieve good ecological status due to high nitrate content. The authors used 77,978 nitrate concentration data measured from 1971 to 2009 at 5962 springs and wells of the three main aquifers to create maps of nitrate trends at sampling point and at regional scale. From the 668 time series analyzed, 27% showed a downward trend, 10% were stable, and 420 (63%) an upward trend. Maps of the Seine basin groundwater show nitrate concentration in 2010 from less than 25 mg NO_3^-/L to more than 100 mg NO_3^-/L (Tavakoly et al., 2019). The highest mean nitrate concentrations are for the Oligocene aquifer, followed by the chalk, and then by the Eocene aquifer.

The fate and retention of reactive nitrogen in the basin was studied using nitrogen budget approaches (Billen et al., 2009). The main sources of reactive nitrogen input in the basin are fertilizer application (8950 kg N/km²/y), crop N_2 fixation (845 kg N/km²/y), and atmospheric deposition (550 kg N/km²/y). Fertilization accounts for 87% of the total nitrogen inputs. Nitrogen is exported from the basin in the form of commercial products (4380 kg N/km²/y) and river discharge to the sea (1950 kg N/km²/y). The net storage and reaction within the basin is 4015 kg N/km²/y. The storage in the aquifers and unsaturated zone goes from 360 kg N/km²/y in a dry hydrological year to 710 kg N/km²/y in a wet year. Sebilo et al. (2003) analyzed the nitrate isotopic composition of surface and groundwater of the Seine basin to determine the extent of denitrification, and concluded that riparian denitrification is more significant than in the benthic zone.

Doussan et al. (1998) looked at ammonium and organic pollution in the Seine river-groundwater exchanges with alluvial aquifers in the well field of Rangiport island, 40 km downstream from Paris. The well field has a water production capacity of 150,000 m^3/day and the aquifer is fissured Senonian chalk. Groundwater nitrate and nitrite in observation wells were found below detection limit; however, the ammonium concentration was high (24 mg NH_4/L) near the river, decreasing to about 5 mg NH_4/L in the production well, 140 m away from the river. The ammonium concentration profiles increase significantly in the pore water of the sediments in the top 50 cm, with concentration ranging from 30 to 300 mg NH_4/L. The origin of ammonium is primarily due to the organic load of the sediments and their mineralization.

Flipo et al. (2007) assessed nitrate pollution in the Grand Morin aquifers. The two main geological formations are the Oligocene limestones and the Eocene sandstones. Intensive agriculture accounts for 76% of the basin land use, with the remaining 19% forest and 5% urban areas. The main agricultural crops are wheat (42.2%), barley/winter barley (10.3%), colza (10.4%), and maize (8.2%). The study monitored 6000 sampling points from 1972 to 1995. The mean infiltrated flux of the Grand Morin is estimated at 3440 kg N/km²/y (18 mg N/L), about 40% of which is stored in the two aquifers. The mean annual nitrate concentration in the Eocene aquifer increased from 33.16 mg NO_3^-/L in 1977 to 40.23 mg NO_3^-/L in 1988. Conversely, in the Oligocene aquifer mean annual nitrate concentration decreased from 40.17 mg NO_3^-/L in 1977 to 36.95 mg NO_3/L in 1988.

The impact of intensive cereal farming to surface and groundwater in the Orgeval watershed was assessed by Garnier et al. (2014). The land use is predominantly agricultural (82% - cereal crops) and the remaining 17% forest and 1% urban. The basin is covered by 10 m deep loess soils underlain by two tertiary aquifers, the Brie limestone Oligocene formation and the deeper Champigny limestone Eocene formation. The two aquifers are separated by a grey clay layer. The soils are waterlogged, and have been tile-drained since the 1960s. Three piezometers were installed along a 6% agricultural slope with wheat, barley and maize rotation with a fertilization rate from 120-160 kg N/km^2/y. Soil water was sampled for nitrate and N_2O to assess the impacts to the Brie aquifer. The nitrate concentrations in the Brie aquifer ranged from 13.2 mg N/L uphill to 8.6 mg N/L downhill. Measurements suggest the predominance of denitrification. Nitrogen budgets point to nitrate originating from the nitrogen surplus in agricultural soils. Floury et al. (2018) studied the impact of farming on the chemical weathering of the basin at the Orgeval Critical Zone Observatory. Sampling was conducted from 2013 to 2015 in surface and ground waters. The nitrate concentrations in the springs of the basin ranged between 2.6 mg N/L and 19.5 mg N/L. Seven out of the 10 springs have nitrate concentrations greater than the 50 mg NO_3^-/L drinking water standard. Isotope analysis identified two spring groups: those with low nitrate content but rich in sulfate, which suggests coupling of denitrification and sulfur, and those with high nitrate content coming from fertilizer surplus.

Impact on coastal areas

The links between the Seine basin and its coastal zone, integrating agricultural activity in the mainland to impacts of diffuse nutrient loadings delivered at the coastal zone have been documented in several works (Cugier et al., 2005; Lancelot et al., 2011; Passy et al., 2016; Desmit et al., 2018; Garnier et al., 2019).

In general, phosphorus is the limiting nutrient in freshwaters, while nitrogen is the limiting one in marine systems (Elser et al., 2007). The important decrease in phosphorus due to improvement of wastewater treatments and reduction of phosphorus detergents (Romero et al., 2016) is consistent with the observation of a strong reduction of eutrophication in the Seine River (Garnier et al., 2019a). Nitrogen delivery of the Seine River to the coastal zone has increased by 10-20 %, whereas phosphorus has decreased by 55% (Passy et al., 2013; Billen et al., 2001; Garnier et al., 2019a). Thus, eutrophication in marine coastal zones persists, with episodic eutrophication crisis in the Seine Bight (Passy et al., 2016; Menesguen et al., 2018; Garnier et al., 2019b; Thorel et al., 2017). Eutrophication takes various forms with development of harmful algal blooms (HAB), with accumulation of dinoflagellates, and Pseudo-Nitzschia mainly, possibly producing toxic substances, respectively Diarrhetic Shellfish Poison (*DSP*) and Amnesic shellfish poisoning (*ASP*).

Eutrophication risk does not only depend on nitrogen and phosphorus, but also on silica, which is required by diatoms. Eutrophication potential can be quantified with the indicator for coastal eutrophication potential ICEP (Billen and Garnier, 2007; Garnier et al., 2010) which measures the excess of nitrogen or phosphorus over silica (Redfield et al., 1963; Conley et al., 1989). An ICEP value close to zero indicates equilibrium between nitrogen or phosphorus and silica, whereas positive or negative values mean nutrient excess or deficit with respect to silica. In the Seine coastal zone, the ICEP-N value is high, currently estimated at 14.2 kg C/km^2/d. Notwithstanding riverine phosphorus delivery reductions, ICEP-P is still slightly positive, 0.27 kg C/km^2/d. Thus, while a balance has been reached between phosphorus and silica, ICEP-N is still large and potentially conducing to eutrophication. Additionally, the residence time of nutrients in the coastal zone, about 125 days on average, increases the risk of eutrophication, and helps explaining the high phytoplankton biomass reported in the Seine coastal zone.

Overall, the Seine basin is significantly impacted by agriculture. Excessive fertilization and organic pollution are major sources of nitrogen in the ground- and surface water. Remedial measures will not have immediate effect in groundwater due to the long retention time of nitrates in the groundwater systems of the basin (Ledoux et al., 2007).

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