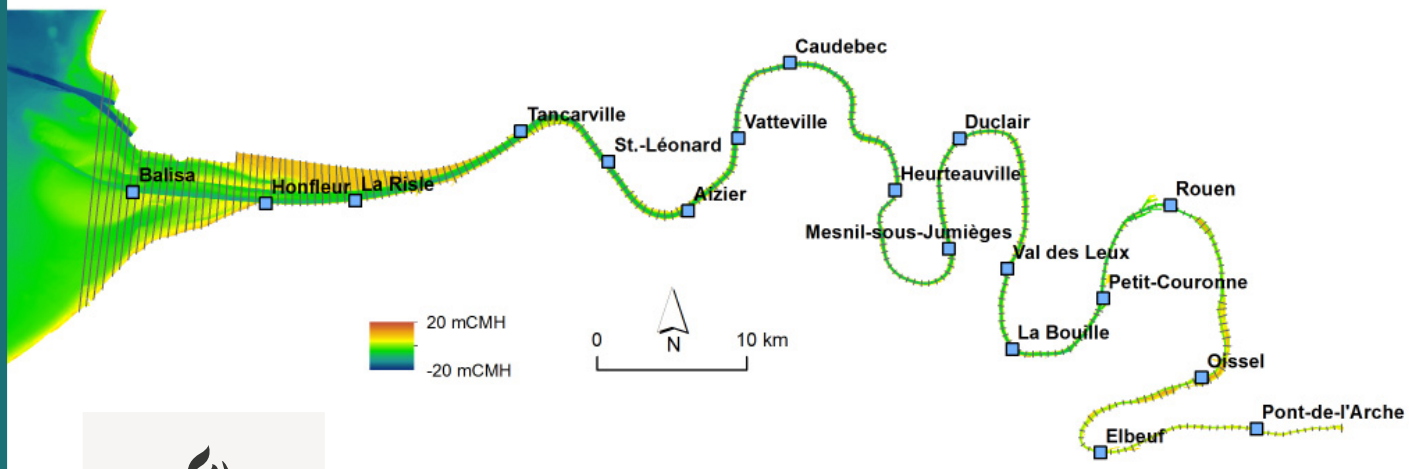

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Interestuarine comparison and historical evolution

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Interestuarine comparison and historical evolution

Vandenbruwaene, W.; Plancke, Y.; Mostaert, F.

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Abstract

Present report studies the hydro-geomorphology of the Seine estuary, and is the second report of Flanders Hydraulics Research within the ANPHYECO project. The hydro-geomorphological characterisation of the Seine is based on data analysis and follows the methodology as applied in the TIDE project (Vandenbruwaene et al., 2013). This enables the comparison of the Seine estuary with other European estuaries in terms of tidal amplification/damping and morphology, hydrodynamics and suspended particle matter, and residence times. The interestuarine comparison demonstrates that: (1) the low convergence of the Seine leads to tidal damping along the estuary despite the large estuary depth, (2) the SPM pattern in the estuary is to a great extent determined by the tide and the freshwater discharge regime, and (3) the residence time for the Seine estuary can be considered as low. With regard to the historical evolution of the Seine we observe an important deepening of the estuary between 1960 and present. Moreover, we observe a significant decrease in SPM over the period 1955-2013, in combination with an increase in the freshwater discharge.

Contents

Abstract III
Contents V
List of tables VII
List of figures VIII
1 Introduction 1
2 Methodology 2
2.1 Main parameters 2
2.1.1 Topo-bathymetry 2
2.1.2 Tide 3
2.1.3 Salinity 3
2.1.4 Freshwater discharge 3
2.1.5 SPM 3
2.2 Derived parameters 3
2.2.1 Morphological parameters 3
2.2.2 Flow velocity, tidal discharge and tidal volume (“Cubage” technique) 5
2.2.3 Residence time 5
3 The Seine estuary 7
3.1 Morphology 7
3.2 The tide 8
3.3 Salinity 10
3.4 Freshwater discharge 10
3.5 Flow velocity 11
3.6 Suspended particle matter 13
4 Interestuarine comparison 14
4.1 Tidal amplification/damping and morphology 14
4.1.1 Amplification or damping? 14
4.1.2 Estuary depth and convergence 16
4.1.3 Relation between tidal amplification/damping and morphology 18
4.2 Hydrodynamics and SPM 19
4.3 Residence time 22
4.3.1 Parameters determining residence time 22
4.3.2 Residence time under mean discharge conditions 24

5 Historical evolution 27
5.1 Morphology 27
5.2 Freshwater discharge 28
5.3 Salinity 30
5.4 SPM 31
6 Conclusions 34
6.1 The present Seine 34
6.2 Historical evolution of the Seine 34
7 References 35
Appendix A: Topo-bathymetries A1
Appendix B: Cross-sections A3

List of tables

Table 1 – Overview of the main hydro-geomorphological parameters collected for the Seine estuary. 2

Table 2 – Summary statistics for the freshwater discharge at Poses in 2010 11

Table 3 – Residence time (in days) from up-estuary boundary to $mouth_{geo}$ under conditions of mean, low and high freshwater discharge (river flow), calculated according to the fractal freshwater method. 26

Table 5 – R^2- and p-values for the linear regression models of the different discharge percentiles. Q10, Q50 and Q90 are presented in Figure 37. Q5 = the 5^{th} percentile discharge, Q25 = the 25th percentile discharge, etc.. 30

Table 4 – R^2- and p-values for the linear regression models presented in Figure 35 and Figure 36. 31

Table 6 – R^2- and p-values for the linear regression models presented in Figure 39 and Figure 40..... 33

List of figures

Figure 1 – Constructed cross-sections along the Seine for the 2010 and 1975 situation plotted against the 2010 topo-bathymetry. 4

Figure 2 – Constructed cross-sections along the Seine for the 1960 situation plotted against the 1960 topo-bathymetry. 4

Figure 3 – Width along the Seine estuary at MHWL and MLWL for the 2010 situation, presented with and without the mouth area (resp. A and B)..... 7

Figure 4 – (A) Cross section-averaged depth along the Seine estuary at MHWL and MLWL. (B) Thalweg depth along the Seine estuary at MHWL and MLWL. 8

Figure 5 – Cross-sectional area along the Seine estuary at MHWL and MLWL, presented with and without the mouth area (resp. A and B) 8

Figure 6 – The mean high water level (MHWL), mean low water level (MLWL), and thalweg depth along the Seine estuary for the 2010 situation. 9

Figure 7 – The mean tidal range along the Seine estuary for the year 2010 9

Figure 8 – Longitudinal mean (grey), winter (blue) and summer (orange) salinity profiles along the Seine estuary calculated over the period 1970-2001, with indication of the low and high water envelopes for winter (P0.2 and P30) and summer (P70 and P99). 10

Figure 9 – The daily freshwater discharge at Poses for the year 2010. 11

Figure 10 – The maximum flow velocity (top) and mean flow velocity (bottom) along the Seine estuary for conditions of mean tidal range and mean freshwater discharge (see also Plancke et al., 2016) 12

Figure 11 – Difference in mean and maximum flow velocity between ebb and flood phase..... 13

Figure 12 – Median suspended particle matter (SPM) along the Seine estuary representative for the present situation (2009-2013). Error bars represent the 25th and 75th percentile values. (A) The entire Seine estuary, (B) zoom of the upper 100 km of the estuary. 13

Figure 13 – 10-yearly averages for the tidal range (2001-2010) along the TIDE estuaries (Vandenbruwaene et al., 2013). For the Humber and Seine, data are averaged over a time period of 1 year (respectively 2005 and 2010)..... 14

Figure 14 – Dimensionless presentation of the tidal range defined by TR_x/TR_0 (with TR_x = tidal range at distance x in the estuary; TR_0 = tidal range at mouth 15

Figure 15 – Tidal range gradient along the 5 estuaries, calculated over 5 km blocks..... 15

Figure 16 – Cross-section averaged depth at MLWL along the 5 estuaries, calculated over 5 km blocks..... 16

Figure 17 – Width at MHWL along the 5 estuaries, calculated over 5 km blocks..... 17

Figure 18 – Convergence (based on 1/b value, see estuary convergence in §2.2.1) and friction (based on the cross-section averaged depth at low water) for the 5 estuaries 17

Figure 19 – The cross-section averaged depth at MLWL versus the observed gradient in tidal range. For gr(TR) < 0 tidal damping, for gr(TR) > 0 amplification. 18

Figure 20 – Relationship between the estuary convergence and the cross-section averaged depth, based on the observed gradient in tidal range. The threshold between amplification/damping is based on the intersections of the regression lines at gr(TR) = 0 (see Figure 19). 19

Figure 21 – Median surface SPM (2007-2010) along the Seine estuary for neap and spring tide conditions. Error bars represent the 25th and 75th percentile values. 20

Figure 22 – Median surface SPM (2007-2010) along the Seine estuary at low and high riverine discharge. Error bars represent the 25th and 75th percentile values. 20

Figure 23 – Median surface SPM (1971-2015) along the Schelde estuary. Error bars represent the 25th and 75th percentile values. 21

Figure 24 – Relation between tidal range and surface SPM (1996-2015) along the Schelde estuary (Vandenbruwaene et al., 2016). 21

Figure 25 – Relation between riverine discharge and surface SPM (1996-2015) along the Schelde estuary (Vandenbruwaene et al., 2016). 22

Figure 26 – Estuary volume V (over 5 km) and fractional freshwater concentration f for the Seine and the TIDE estuaries. 23

Figure 27 – The total volume of fresh water (V_f = V*f) in each estuary segment (over 5 km), calculated according to the fractional freshwater method (Dyer, 1973). 23

Figure 28 – Mean freshwater discharge for the Seine and the 4 TIDE estuaries. Error bars are representative for typical high (P95) and low (P5) freshwater discharge values. 24

Figure 29 – Residence time for each estuary segment of 5 km along the different estuaries. Solid lines represent the residence time under mean freshwater conditions, envelopes (dashed lines) represent high and low freshwater discharges (respectively P95 and P5 values). 25

Figure 30 – Total residence time (from up-estuary boundary to $mouth_{geo}$) under mean freshwater discharge conditions (bar), and for high and low freshwater discharges (P95 and P5). 25

Figure 31 – The historical evolution of the Seine estuary width (at 0 mCMH), represented with and without the mouth area (resp. A and B) 27

Figure 32 – The historical evolution of the cross-section averaged depth (A) and the thalweg depth (B) of the Seine estuary at 0 mCMH. 28

Figure 33 – The historical evolution of the cross-sectional area of the Seine estuary (at 0 mCMH), represented with and without the mouth area (resp. A and B) 28

Figure 34 – The mean yearly discharge at Poses for the period 1941-2013. 29

Figure 37 – The 10th percentile (Q10), the median value (Q50), and the 90th percentile (Q90) discharge per year for the period 1941-2013. Lines represent the corresponding linear regression models (full line = significant trend; dashed line = no significant trend, see also Table 5) 29

Figure 35 – The median PSU value per year for the station Honfleur over the period 1970-2001. Error bars represent the 25th and 75th percentiles. 30

Figure 36 – The median PSU value per year for the stations Heurteauville and Rouen over the period 1970-2001. Error bars represent the 25th and 75th percentiles. 31

Figure 38 – Historical evolution of SPM along the Seine estuary 32

Figure 39 – The median SPM value per year for the station Honfleur over the period 1955-2013. Error bars represent the 25th and 75th percentiles. 32

Figure 40 – The median SPM value per year for the stations Heurteauville and Rouen over the period 1955-2013. Error bars represent the 25th and 75th percentiles. 33

Figure 41 – Seine topo-bathymetry for the 2010 situation A1

Figure 42 – Seine topo-bathymetry for the 1975 situation A1

Figure 43 – Seine topo-bathymetry for the 1960 situation..... A2

Figure 44 – Constructed cross-sections along the Seine for the 2010 and 1975 situation plotted against the 2010 topo-bathymetry – section Balisa-Tancarville..... A3

Figure 45 – Constructed cross-sections along the Seine for the 2010 and 1975 situation plotted against the 2010 topo-bathymetry – section Tancarville-Duclair..... A3

Figure 46 – Constructed cross-sections along the Seine for the 2010 and 1975 situation plotted against the 2010 topo-bathymetry – section Duclair-Rouen..... A4

Figure 47 – Constructed cross-sections along the Seine for the 2010 and 1975 situation plotted against the 2010 topo-bathymetry – section Rouen – Pont-de-l'Arche A4

Figure 48 – Constructed cross-sections along the Seine for the 1960 situation – section Balisa-Tancarville A5

Figure 49 – Constructed cross-sections along the Seine for the 1960 situation – section Tancarville-Duclair A5

Figure 50 – Constructed cross-sections along the Seine for the 1960 situation – section Duclair-Rouen A6

1 Introduction

The GIP Seine-Aval recently outsourced a study to advise what kind of (innovative) ecological restoration measures could be introduced in the Seine estuary to improve the functioning of the system (ANPHYECO project). GIP Seine-Aval contacted hereby the University of Antwerpen (UA) since they are experienced in ecological restoration projects in estuaries. A first number of meetings led to the conclusion that an ecological study of the Seine estuary requires a thorough understanding of the hydro-geomorphology of the estuary. Flanders Hydraulics Research (FHR) has already executed studies on the hydro-geomorphology of other European estuaries (e.g., TIDE project) and was therefore involved (together with IFREMER) within the working group GIP Seine-Aval – UA.

A hydro-geomorphological study of the Seine estuary can be approached in several ways. It can be based on the analysis of available data or it can be based on a modelling study. Between the partners involved in the research it has been agreed that FHR will focus on the analysis of data, while the IFREMER institute will study the hydro-geomorphology based on modelling. It should be pointed out that an extensive data analysis already has been carried out by GIP Seine-Aval. The objective of the study by FHR is to extend this data analysis by applying some of the techniques that were used within the hydro-geomorphological study of the TIDE project (Vandenbruwaene et al., 2013). Firstly, these techniques will be applied to characterize the present hydro-geomorphological situation of the Seine estuary (chapter 3). The present situation of the Seine will hereby be put in an interestuarine context (chapter 4) by comparing the estuary with the TIDE estuaries (i.e. Elbe, Weser, Humber and Schelde). Secondly, historical data (1950-1960 and 1975) will be analyzed to study the long-term (i.e. decades) morphological evolution of the Seine estuary (chapter 5).

2 Methodology

2.1 Main parameters

Main parameters are parameters which are directly measured in the estuary. In this study we focus on the present and the historical hydro-geomorphological situation of the Seine estuary. Data were provided by GIP Seine-Aval. An overview of the collected data is given in Table 1.

Table 1 – Overview of the main hydro-geomorphological parameters collected for the Seine estuary.

Parameter	Timestep / period	Measuring frequency	Number of stations
Topo-bathymetry	1960, 1975, 2010	-	-
Water level	2007-2010	5 minutes	18
Salinity	1970-2001	Variable, 2 weeks to 2 months	22
Freshwater discharge	1941-2013	Daily	1 (Poses)
Suspended particle matter (SPM)	1955-2010	Variable, monthly to yearly	39

2.1.1 Topo-bathymetry

A topo-bathymetric grid of an estuary represents the elevation of the subtidal, intertidal (tidal flat and tidal marsh) and supratidal areas of the estuary, located within the dyke lines. In general, the bathymetric grids (based on multibeam or singlebeam measurements) cover the subtidal and lower intertidal parts of the estuary, while the topographic datasets (based on LIDAR data or topographic surveys) cover the higher parts of the intertidal areas.

Seine bathymetric data were provided for the years 1960, 1975 and 2010. The vertical reference level of the data is meter Cote Marine du Havre (mCMH), the horizontal projection system is RGF93 – Lambert93. The 2010 dataset is a 5 x 5 m topo-bathymetric ESRI raster ranging from the Seine mouth up to Poses (Appendix A: Topo-bathymetries, Figure 41). The 1975 situation was delivered as a 25 x 25 m topo-bathymetric ESRI raster ranging from the mouth up to Rouen (Appendix A: Topo-bathymetries, Figure 42). The 1960 data were provided as xyz-files by Ifremer (partner within ANPHYECO) where the mouth area up to La Risle is covered by points arranged as a square grid, and the area La Risle up to Rouen as point transects. The point inter-distance for the square grid is 100 m, while the point-interdistance at the transects ranges from 10 m up to 100 m. The distance between the transects is about 1 km. In order to derive morphological parameters (§2.2.1) for the 1960 situation, a 10 x 10 raster was created by IDW interpolation (Appendix A: Topo-bathymetries, Figure 43). Concerning the area La Risle up to Rouen,

the IDW interpolation only gives accurate results at the point transects. As a consequence the cross-sections in §2.2.1 were only constructed at the point transects. The point transects between La Risle and Rouen only cover the subtidal. The point grid downstream La Risle also covers the intertidal.

2.1.2 Tide

Continuous 5-minute water level data over the period 2007-2010 were provided for in total 18 tidal gauge stations (Table 1 and Figure 1). Daily high and low water levels were derived for analysis (§3.2) by applying the R-package 'Tides' (Cox et al., 2017) on the continuous water level data.

2.1.3 Salinity

Monthly along-estuary conductivity values are available for the period 1970-2001 (Table 1**)**. Conductivity is measured at 22 stations along the estuary using a YSI multiparameter probe. The provided conductivity values were converted to salinity values (in PSU) by applying the UNESCO formula (Fofonoff and Millard, 1983).

2.1.4 Freshwater discharge

Daily freshwater discharge values at the Poses station were provided for the period 1941-2013.

2.1.5 SPM

SPM values are based on the filtration and weighting of water samples. The water samples were taken at 39 locations along the estuary, over the period 1955-2010, with a variable measuring frequency of 1 month up to 1 year. The sampling depth is about 2 m below water surface, and the time of sampling is at the beginning of the flood phase.

2.2 Derived parameters

2.2.1 Morphological parameters

Width, depth and cross-sectional area

Along the Seine estuary, cross-sections were defined at which the width, the cross-section averaged depth, the thalweg depth and the cross-sectional area were determined. These morphological parameters could be derived by constructing cross-section profiles. The construction of the cross-section profiles is based on the topo-bathymetric data and was done in the software package MikeGIS. For the 2010 and 1975 situation the distance between the cross-sections is about 500 m and the same cross-sections were used (Figure 1, for detailed zooms see Appendix B: Cross-sections). For the 1960 situation the cross-sections were constructed at the point transects (see §2.2.1) and the inter-distance is about 1 km (Figure 2, for detailed zooms see Appendix B: Cross-sections).

The MikeGIS software automatically derives the width and the cross-sectional area at any reference level. The cross-section averaged depth is then calculated by dividing the cross-sectional area with the width, the thalweg depth by extracting the deepest point along the cross-section. For the 2010 situation morphological parameters were derived at MHWL and MLWL (§3.1). However for the historical situations no water level data were digital available. Moreover, the 1960 dataset only contains data on the subtidal, and this for a large part of the estuary (La Risle up to Rouen). Consequently the morphological parameters for the historical part of the study (§5.1) were derived at the level of 0 mCMH.

Figure 1 – Constructed cross-sections along the Seine for the 2010 and 1975 situation plotted against the 2010 topo-bathymetry.

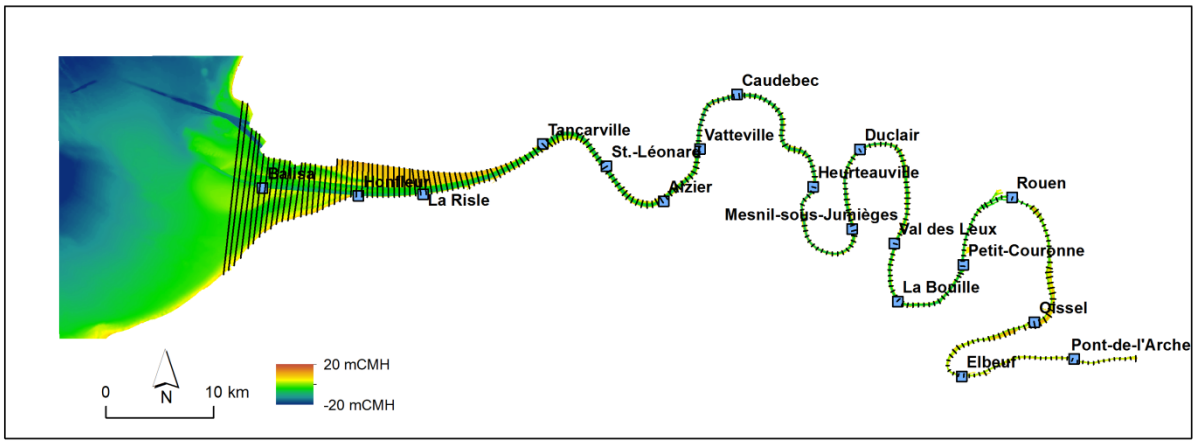
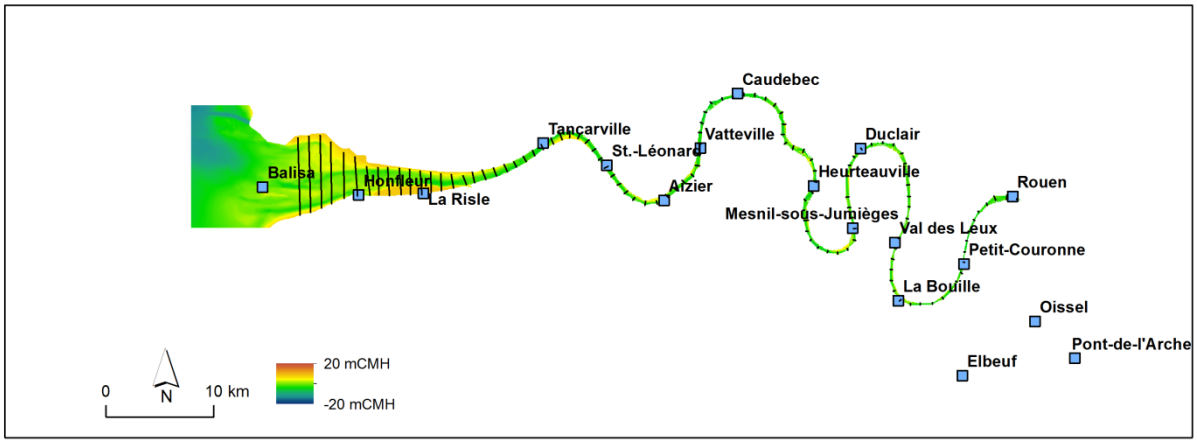


Figure 2 – Constructed cross-sections along the Seine for the 1960 situation plotted against the 1960 topo-bathymetry.



Estuary convergence

The estuary convergence is described by the width convergence length (b). This parameter is determined based on the following equation (Savenije, 2001):

$$B = B_0 . e^{-\frac{x}{b}}$$

With: B = the average cross-sectional and tidal-average width (m)

B_0 = the width at the estuary mouth (m)

x = the distance from the mouth

The slope of the relationship between ln(B) and x then returns -1/b. The larger 1/b, the more convergent the estuary is.

2.2.2 Flow velocity, tidal discharge and tidal volume ("Cubage" technique)

Flow velocities, tidal discharges and tidal volumes for the Seine were derived by applying the "cubage" technique. The "cubage"-technique ("kubatuur" in Dutch) is a relatively simple technique to calculate the hydrodynamics in an estuary (Smets, 1996; Plancke et aL, 2011). It requires only topo-bathymetric data and water levels at different stations to calculate discharges and cross-sectional averaged flow velocities starting from the conservation of mass formula. In contrast to numerical process models, this technique does not require any flow resistance ("roughness") coefficients to calibrate the model. Where the cubage technique uses mass conservation (which is an exact relationship) the error of the method is solely related to the error in water level and topo-bathymetric data.

Flow velocities for the Seine estuary were calculated for the 2010 situation. The cross-sections at which flow velocities were calculated are more or less perpendicular to the fairway, and have an inter-distance of about 500 m (Figure 1). For more information on the Seine "cubage" calculation we refer to the "cubage" study executed within the ANPHYECO project (Plancke et al., 2016).

2.2.3 Residence time

Introduction

Different simplified methods can be used to calculate residence times. A comparison between the different methodologies was made by Ides (2011). It was found that for estuaries with a strong salinity gradient, the most appropriate method to calculate residence times is the fractional fresh water method (Dyer, 1973). As the Seine estuary has a strong salinity gradient, the fractional fresh water method was applied, in which the residence time is defined as:

$$T = f \frac{V}{R}$$

With: T = residence time (days)

f = the fractional fresh water concentration = (Ss – Sn)/Ss

Ss = salinity at the mouth (PSU)

Sn = salinity in a given segment of the estuary (PSU)

V = volume of the estuary segment (m^3)

R = river discharge (m^3/s)

Implementation

The defined estuary segments were based on the cubage cross-sections (see Figure 1). For each estuary segment a fractional fresh water concentration was attributed based on the corresponding salinity profile. The segment volumes were calculated based on the mean cross-sectional area multiplied by the segment length. The mean cross-sectional area is hereby calculated as the average of the cross-sectional areas at MHWL and MLWL at both ends of the segment. For the river discharge the freshwater discharge at Poses was used. The residence time along the Seine estuary was eventually calculated by summing up the calculated residence times of the individual estuary segments.

3 The Seine estuary

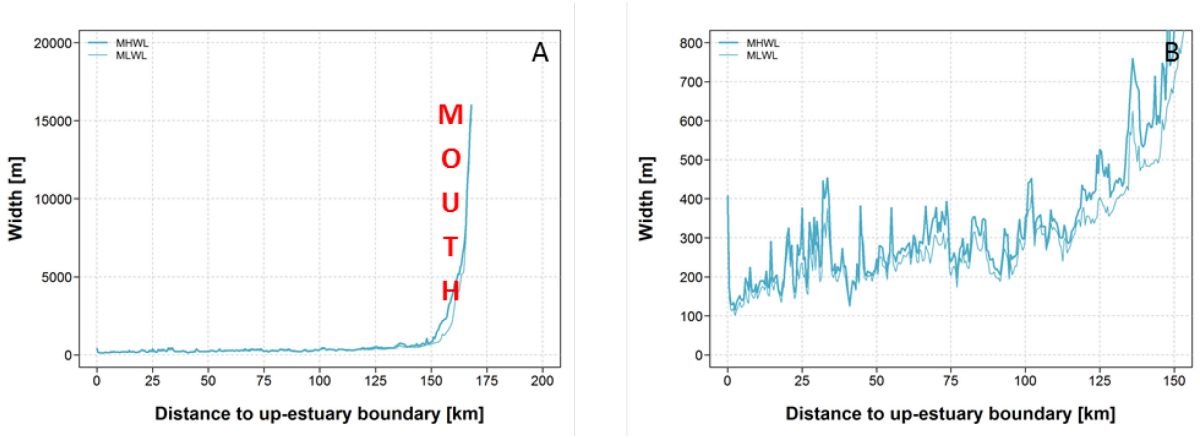
3.1 Morphology

The Seine estuary is a converging estuary with a strong decrease in width along the mouth area (Figure 3a), and a gentle decrease in width along the section Honfleur towards the up-estuary boundary (Figure 3b). In the mouth area the width ranges between 15 km and about 1 km, while upstream Honfleur the range is between 800 m and 100 m. From 125 km up to 160 km the difference in width between MHWL and MLWL is the largest (Figure 3a and b), demonstrating that this section has the largest area in tidal flats.

The cross-section averaged depth at MHWL is for the largest part of the Seine estuary around 10 m (Figure 4a). Only upstream Rouen there is a strong decrease in cross-section averaged depth with values around 5 m. This difference in depth can be explained by the deepening and maintenance of the fairway downstream Rouen, in order to make the harbour of Rouen accessible for vessels. The change in thalweg depth[1] along the Seine estuary (Figure 4b) is comparable with the change in cross-section averaged depth. In general the thalweg depth is a few meters up to 5 m larger than the cross-section averaged depth (cf. Figure 4a and Figure 4b). The thalweg depth at the 0m CMH level is presented in Figure 32b.

The change in cross-sectional area along the Seine estuary is very comparable with the change in estuary width. In the mouth area there is a strong decrease in cross-sectional area, whereas upstream Honfleur the decrease is more gentle (Figure 5). The width determines to a large extent the change in cross-sectional area, since the change along the estuary is several orders of magnitude larger than the change in estuary depth.

Figure 3 – Width along the Seine estuary at MHWL and MLWL for the 2010 situation, presented with and without the mouth area (resp. A and B)



[1] The thalweg depth of a cross-section is the depth at the deepest point in the cross-section

Figure 4 – (A) Cross section-averaged depth along the Seine estuary at MHWL and MLWL.
(B) Thalweg depth along the Seine estuary at MHWL and MLWL.

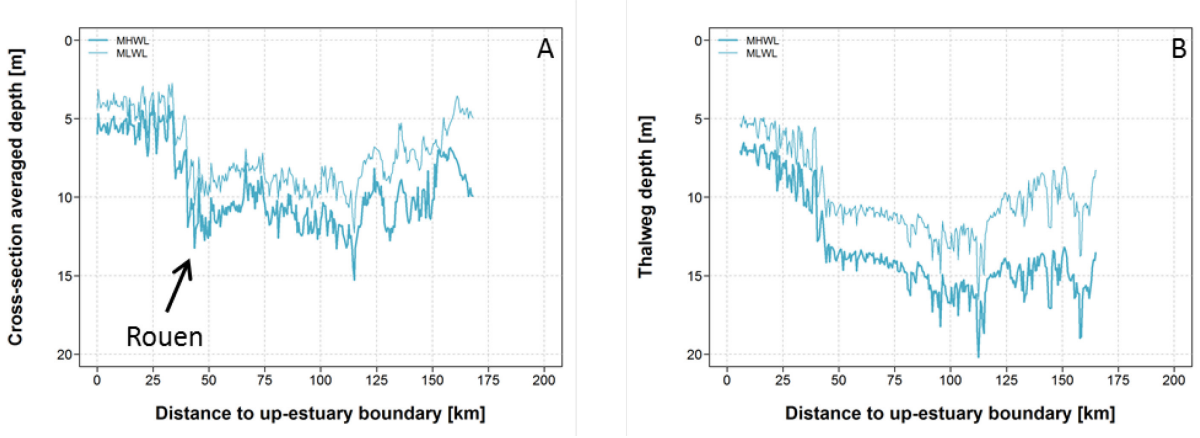
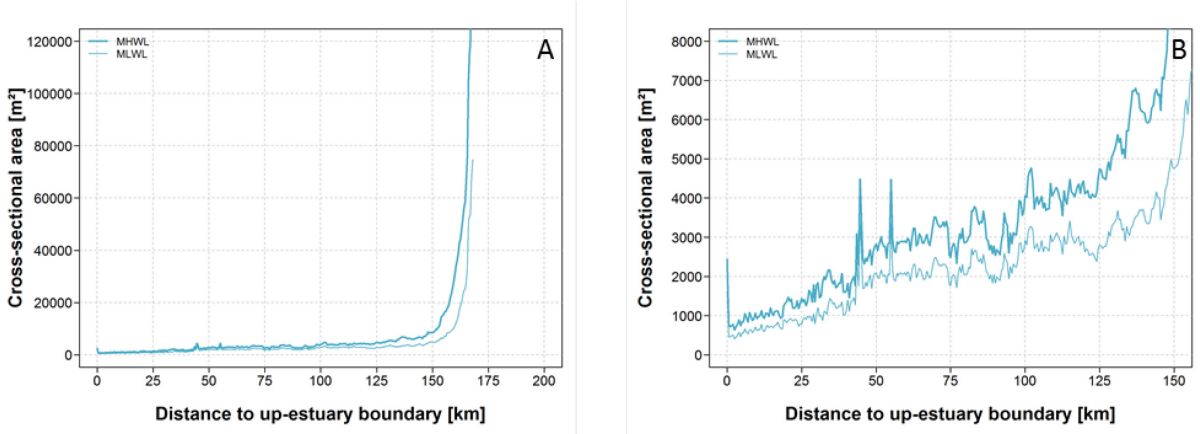


Figure 5 – Cross-sectional area along the Seine estuary at MHWL and MLWL,
presented with and without the mouth area (resp. A and B)



3.2 The tide

The MHWL is more or less constant over a large part of the Seine estuary. Only upstream Rouen (Rouen at km 41) there is an increase in MHWL (Figure 6). With regard to the MLWL there is an increase in the upstream direction, with the strongest increase for the sections Balisa – Caudebec and Petit-Couronne – Pont de l'Arche, and a more gentle increase in the middle part of the estuary between Caudebec and Petit-Couronne (for tidal gauge locations see Figure 1). The increase in MLWL and the constant MHWL results in a decrease of the tidal range in the upstream direction. At the mouth the tidal range is about 5 m and it gradually decreases towards 2 m at the up-estuary boundary, demonstrating that the Seine estuary is dominated by tidal damping. The topic on tidal damping is elaborated in §4.1 where the relation between tidal damping and morphology is discussed.

Figure 6 – The mean high water level (MHWL), mean low water level (MLWL), and thalweg depth along the Seine estuary for the 2010 situation.

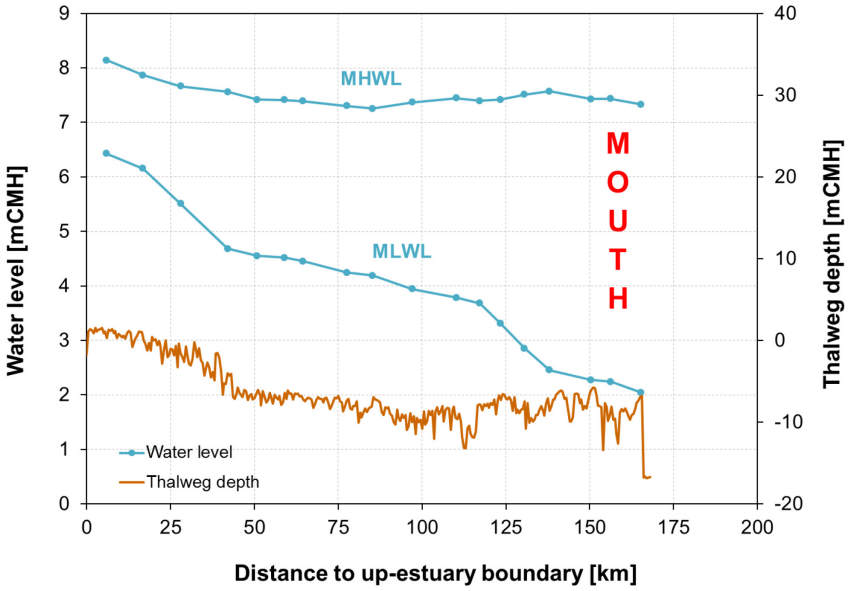
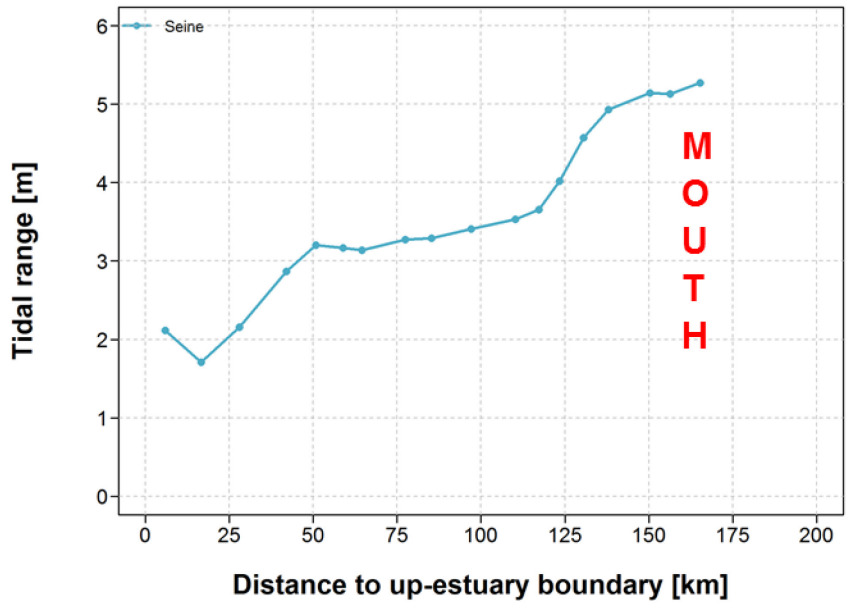


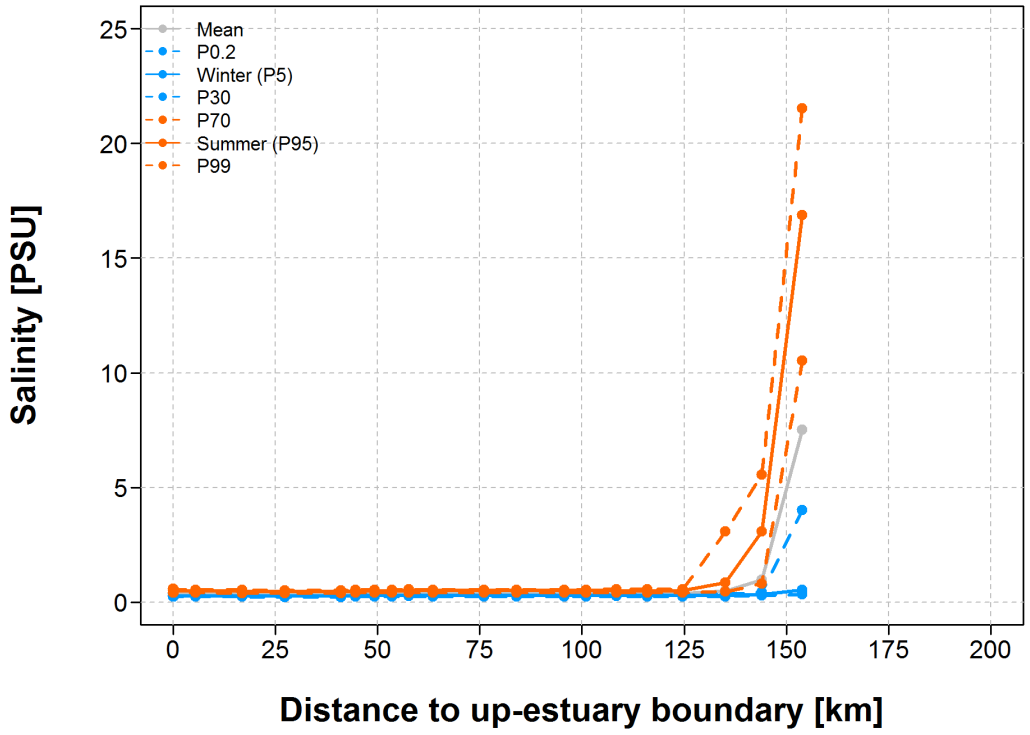
Figure 7 – The mean tidal range along the Seine estuary for the year 2010



3.3 Salinity

Along the mean salinity profile the two most downstream measuring locations have a PSU value larger than 0.5, while for the rest of the estuary the PSU value is below 0.5. This means that almost the entire Seine estuary belongs to the freshwater zone (according to Venice classification system), and that the salinity front only reaches the most downstream part of the estuary (just downstream Tancarville, Figure 8). The amount of salt intrusion is however influenced by the freshwater discharge and the tidal conditions. We observe the strongest salt intrusion during summer (low freshwater discharge) at high water slack conditions. In this scenario the salinity front moves upstream over a distance of about 15 km in comparison with the mean salinity profile (Figure 8). In the scenario where salt intrusion is most restricted (winter conditions and low water slack), no increase in PSU value is observed at the most downstream location (Honfleur), demonstrating that the salinity front does not enter the estuary and is located within the mouth area.

Figure 8 – Longitudinal mean (grey), winter (blue) and summer (orange) salinity profiles along the Seine estuary calculated over the period 1970-2001, with indication of the low and high water envelopes for winter (P0.2 and P30) and summer (P70 and P99).



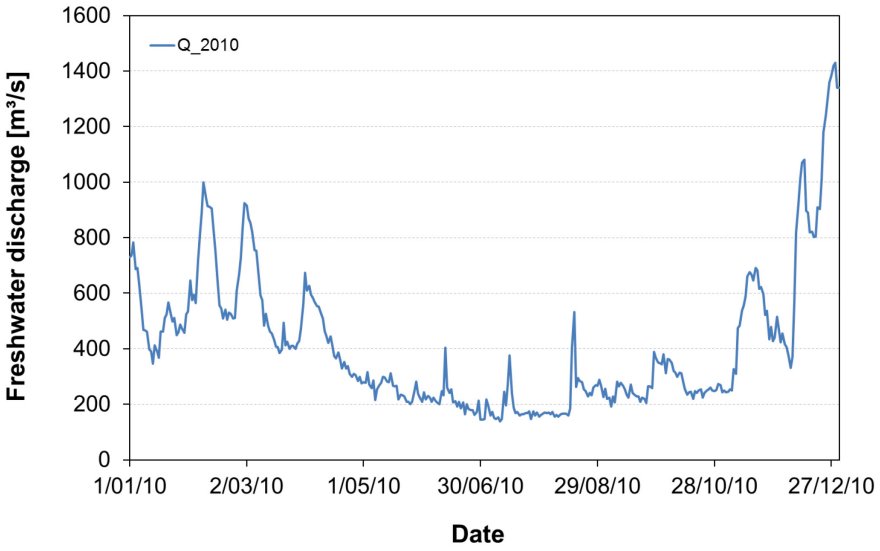
3.4 Freshwater discharge

The mean freshwater discharge in the Seine estuary measured at the Poses station is 414 m³/s (Table 2). For a dry event in 2010 the discharge is 173 m³/s (10th percentile value, see Table 2), while for a flushing event the discharge amounts 794 m³/s (90th percentile value). The freshwater discharge in the Seine estuary is characterized by a typical seasonal variation, with low discharges during summer and clearly higher discharges during winter (Figure 9).

Table 2 – Summary statistics for the freshwater discharge at Poses in 2010

Parameter	Freshwater discharge [m³/s]
10th percentile	173
25th percentile	233
Median	314
Mean	414
75th percentile	526
90th percentile	794

Figure 9 – The daily freshwater discharge at Poses for the year 2010.



3.5 Flow velocity

The flow velocity along the Seine estuary increases from the mouth area up to La Risle (147 km from up-estuary boundary), and then gradually decreases towards the up-estuary boundary (Figure 10). At La Risle the maximum flow velocity is 1.75 m/s and the mean flow velocity is around 1m/s. Note that the mean flow velocity over the ebb phase is somewhat higher than over the flood phase (Figure 10). In general, the mean flow velocity along the Seine estuary is higher over the ebb phase than over the flood phase.

This is not the case for the maximum flow velocity where flow velocities are for a large part of the Seine estuary higher during the flood phase (Figure 11). In the upstream part of the estuary the flow velocity during flood is zero. This is due to the high freshwater discharge which results in the absence of a flood flow over 0-20 km, and clearly higher flow velocities during ebb than during flood over the section 20-40 km (Figure 11).

Figure 10 – The maximum flow velocity (top) and mean flow velocity (bottom) along the Seine estuary for conditions of mean tidal range and mean freshwater discharge (see also Plancke et al., 2016)

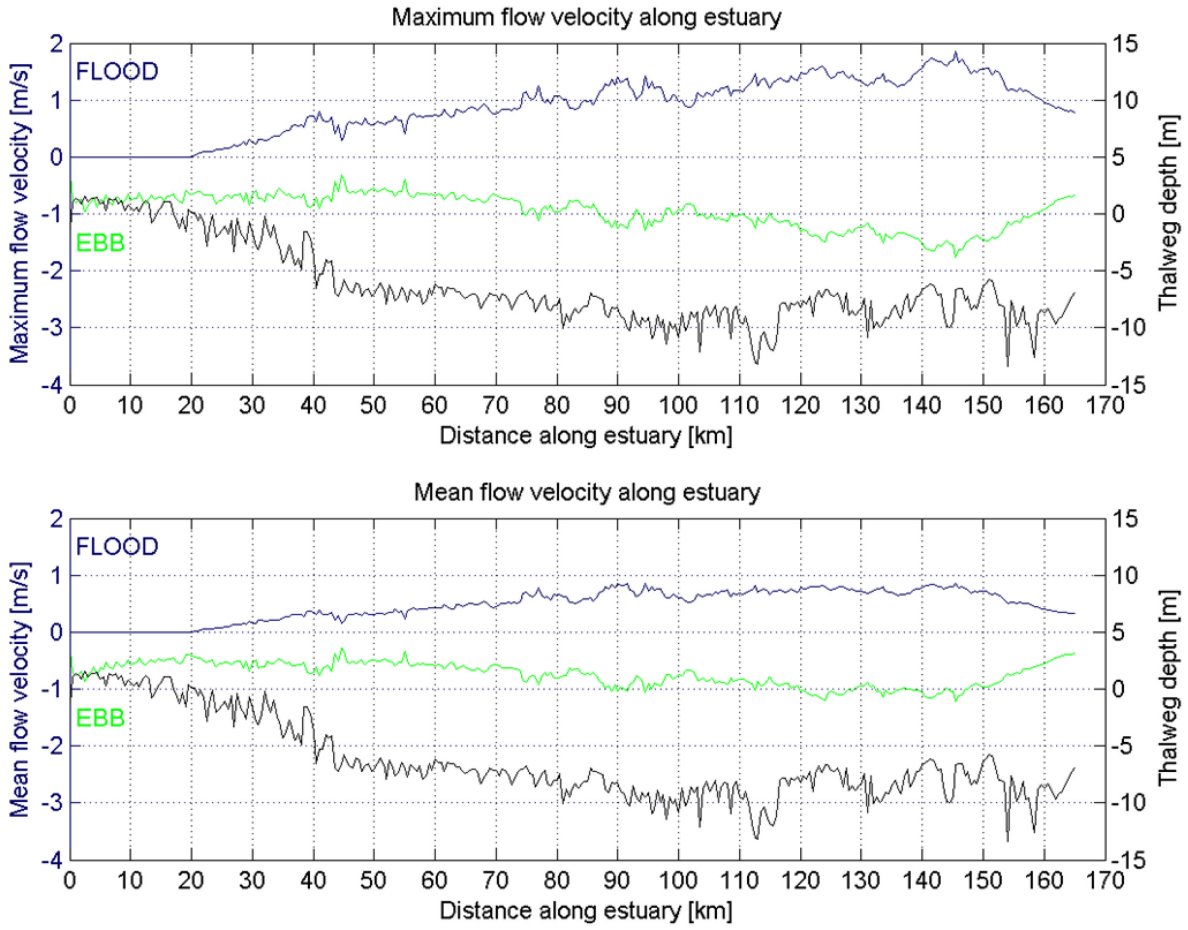
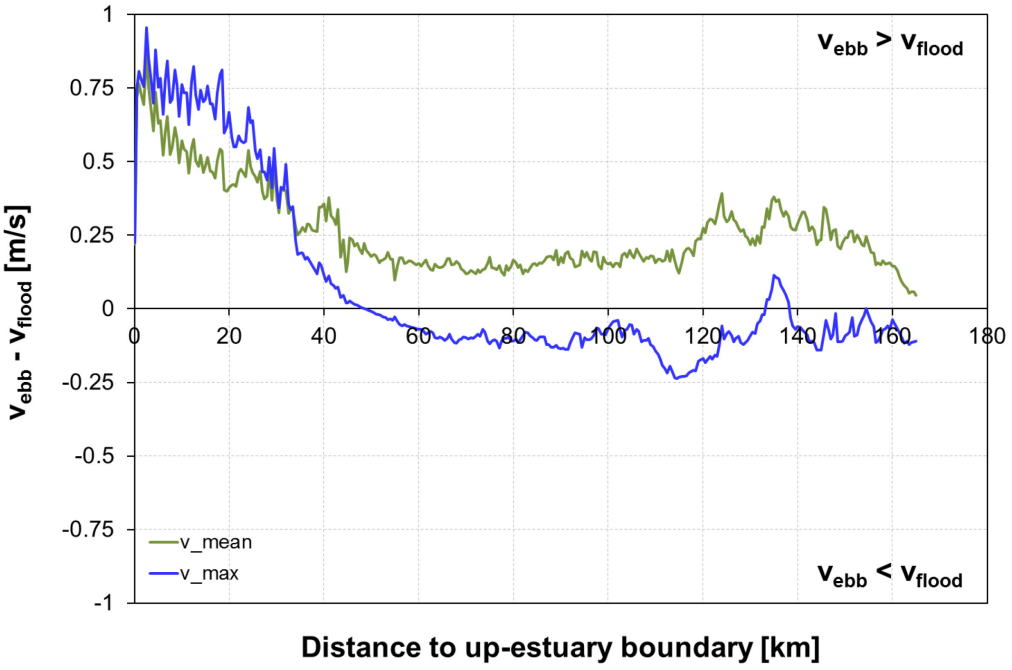


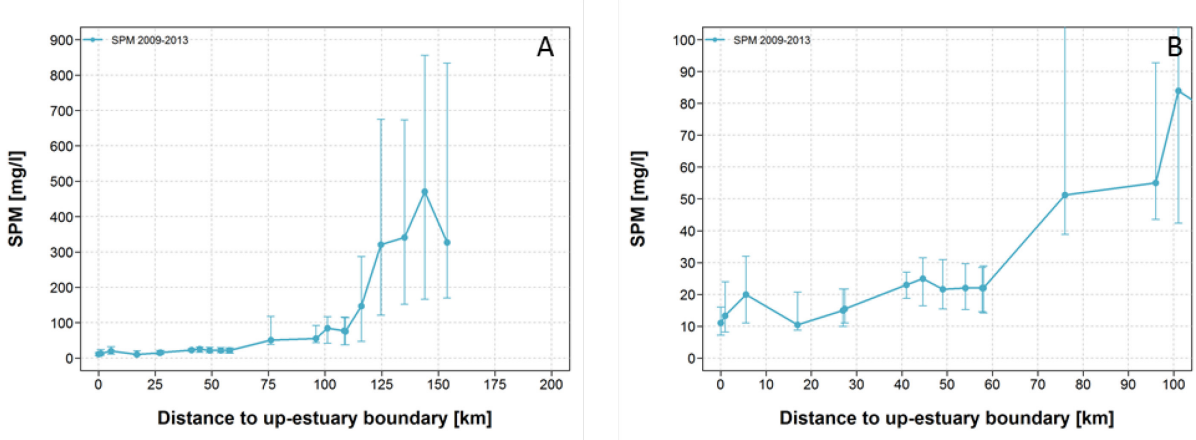
Figure 11 – Difference in mean and maximum flow velocity between ebb and flood phase.



3.6 Suspended particle matter

The Seine estuary has a distinct estuarine turbidity maximum (ETM) near La Risle, with median SPM values up to 500 mg/l (Figure 12a). The 75th and 25th percentile values are respectively around 850 and 175 mg/l, demonstrating that the variation in SPM is large at the ETM. Upstream La Risle the SPM quickly decreases and becomes lower than 100 mg/l for the section Vateville up to the weir in Poses. For the most upstream 60 km the median SPM does not exceed 30 mg/l (Figure 12b).

Figure 12 – Median suspended particle matter (SPM) along the Seine estuary representative for the present situation (2009-2013). Error bars represent the 25th and 75th percentile values. (A) The entire Seine estuary, (B) zoom of the upper 100 km of the estuary.



4 Interestuarine comparison

4.1 Tidal amplification/damping and morphology

4.1.1 Amplification or damping?

Tidal amplification or damping in an estuary is determined by the change in tidal range along the estuary. In case of tidal amplification there is an increase in tidal range in the upstream direction, in case of tidal damping there is a decrease in tidal range. The tidal range characteristics are unique for each estuary and are determined by a number of factors: (1) the tidal range at the mouth, (2) the maximum in tidal range (magnitude and location), (3) the number of kilometres with increase/decrease in tidal range, and (4) the strength of the increase/decrease in tidal range (i.e. the tidal range gradient).

Compared to the TIDE estuaries (Vandenbruwaene et al., 2013) the Seine estuary has the largest tidal range at the mouth (5.3 m for mean tidal conditions, Figure 13). Therewith, this is the location where the maximum in tidal range occurs, or in other words, at no location in the Seine estuary the tidal range is larger than the tidal range at the mouth (Figure 13 and Figure 14). From the Seine mouth to the weir in Poses there is only a decrease in tidal range, and hence the Seine can be considered as entirely dominated by tidal damping. This is in contrast with the TIDE estuaries where both tidal damping and tidal amplification occur. The strength in tidal damping (i.e. tidal range gradient) for the Seine is not constant and varies along the estuary. Tidal damping is the largest 20-40 km from the mouth, and around 120 km (Figure 15).

Figure 13 – 10-yearly averages for the tidal range (2001-2010) along the TIDE estuaries (Vandenbruwaene et al., 2013). For the Humber and Seine, data are averaged over a time period of 1 year (respectively 2005 and 2010)

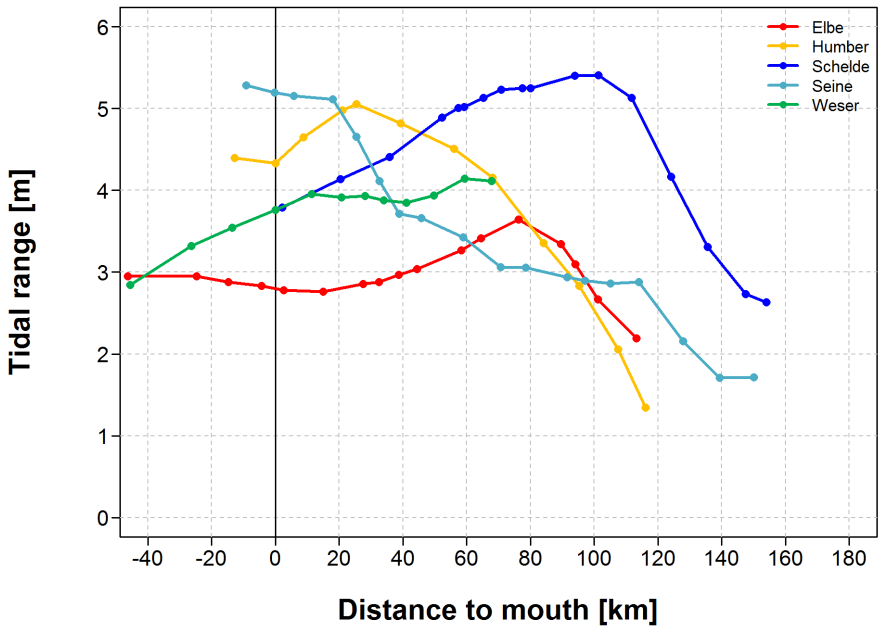


Figure 14 – Dimensionless presentation of the tidal range defined by TR_x/TR_0
(with TR_x = tidal range at distance x in the estuary; TR_0 = tidal range at mouth

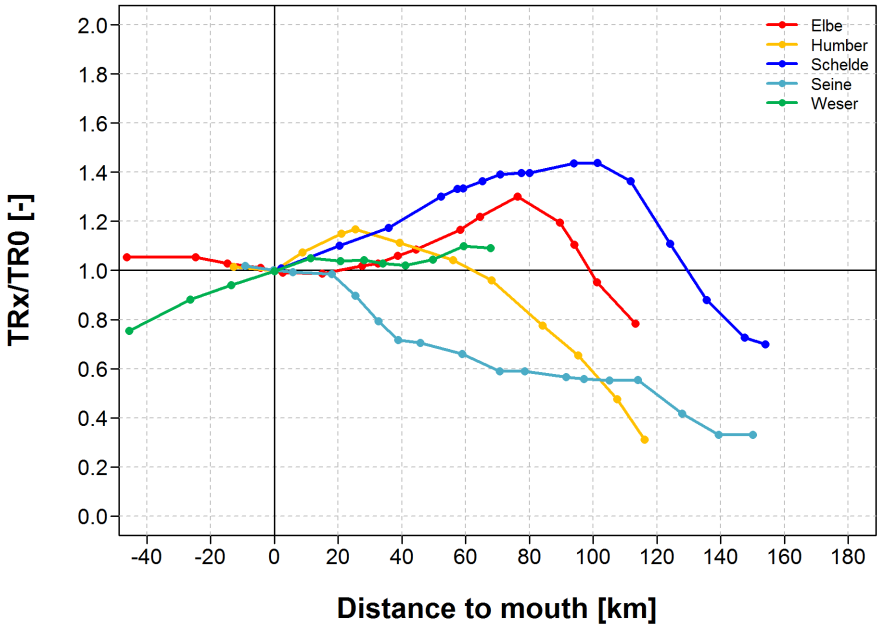
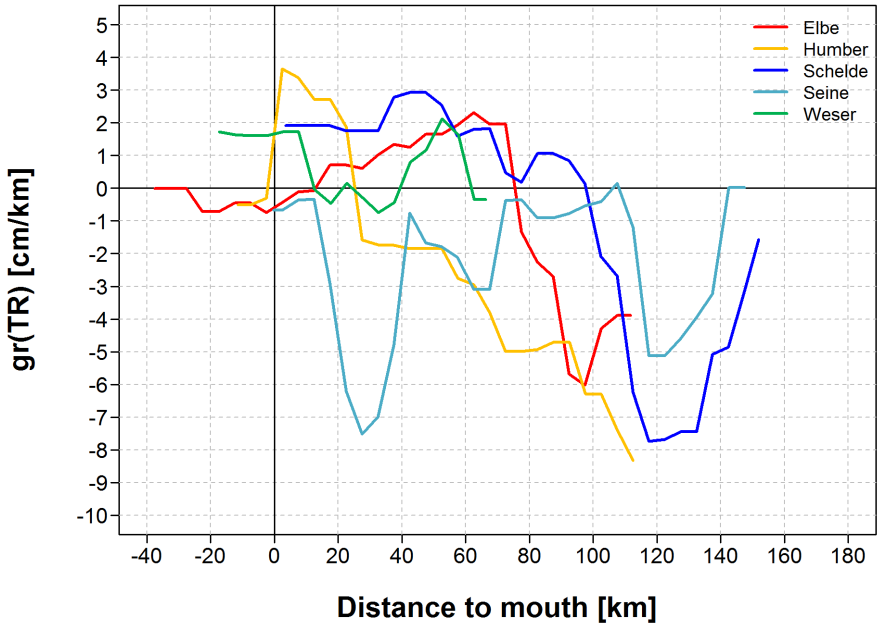


Figure 15 – Tidal range gradient along the 5 estuaries, calculated over 5 km blocks



4.1.2 Estuary depth and convergence

As for the Schelde, Elbe and Weser, the Seine estuary has an important inland port (Rouen) at large distance from the mouth. This requires a sufficiently deep fairway to enable vessel navigation. The cross-section averaged depth between the mouth and Rouen ranges between 7 and 10 m, comparable with the other estuaries that have important inland ports. Upstream Rouen, where no deepening and maintenance of the fairway is necessary, the estuary becomes much more shallow with a cross-section averaged depth around 4 m.

The convergence of an estuary is determined by the change in width along the estuary (see also §2.2.1). The width change gradient along the Seine estuary is small in comparison with the other TIDE estuaries (Figure 17). As a consequence the 1/b value (§2.2.1) is small and the Seine estuary is the least convergent estuary in comparison with the TIDE estuaries (Figure 18).

Summarized, the Seine can be considered as an estuary with a low convergence, but with a significant estuary depth. The depth is hereby comparable with other estuaries that have important inland ports at large distance from the mouth (Figure 18). In general, strong convergent and deep estuaries promote tidal amplification, while shallow estuaries with a low convergence promote tidal damping (Figure 18). The relation between tidal amplification/damping and morphology is further elaborated in the subsequent paragraph (§4.1.3).

Figure 16 – Cross-section averaged depth at MLWL along the 5 estuaries, calculated over 5 km blocks

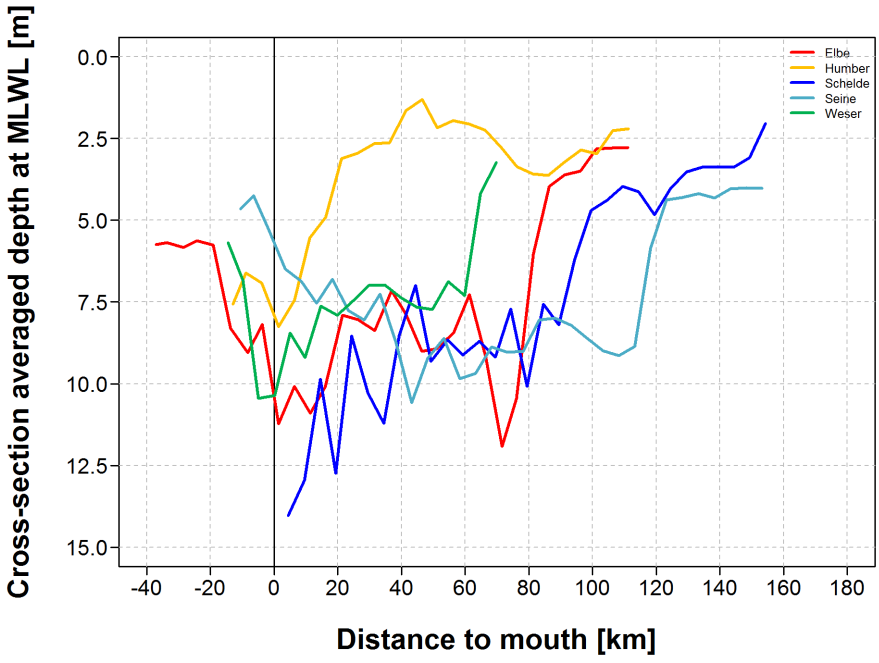


Figure 17 – Width at MHWL along the 5 estuaries, calculated over 5 km blocks

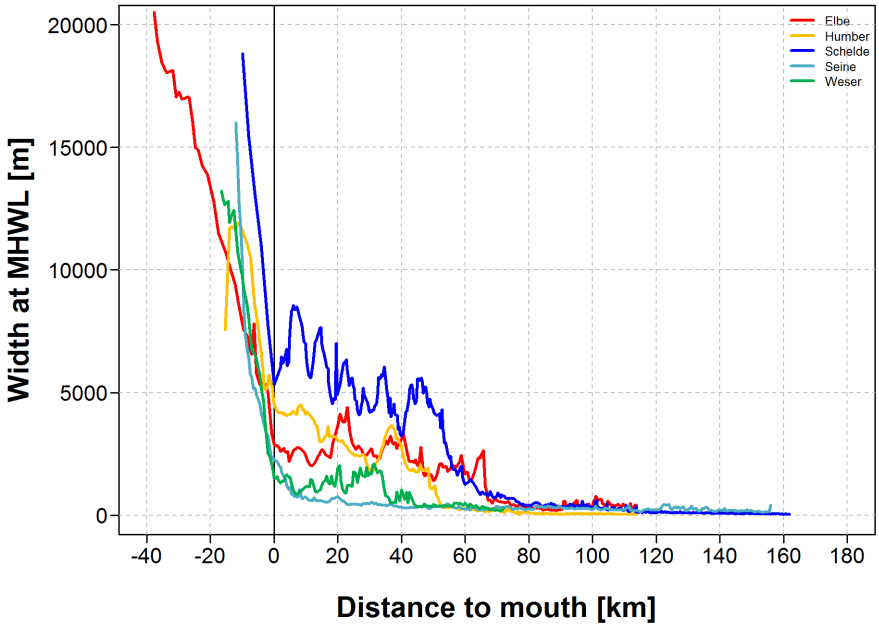
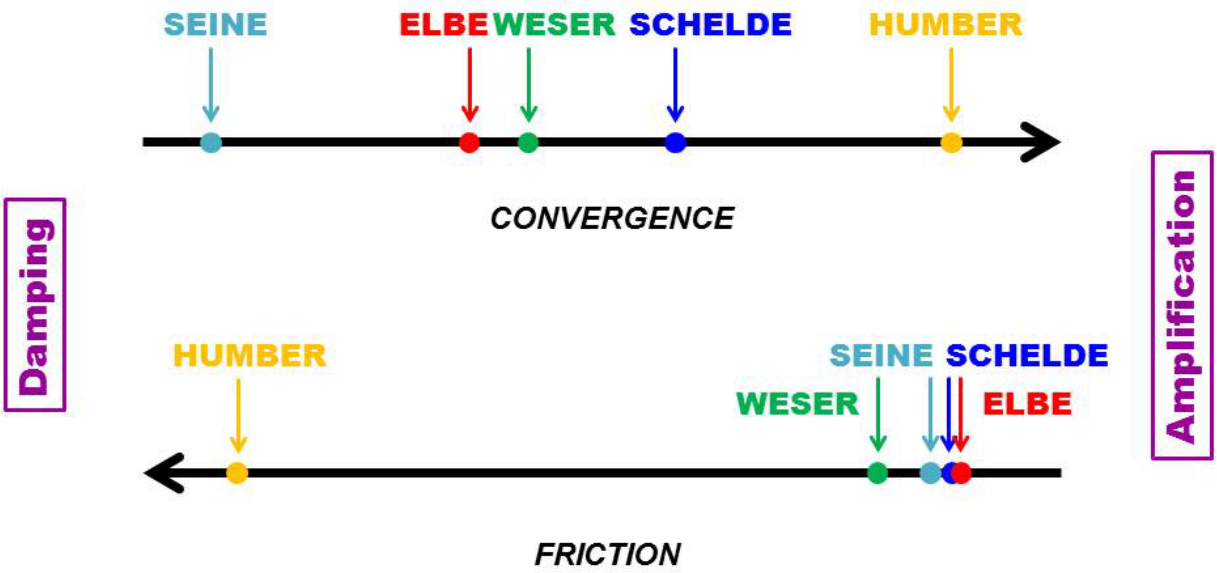


Figure 18 – Convergence (based on 1/b value, see estuary convergence in §2.2.1) and friction (based on the cross-section averaged depth at low water) for the 5 estuaries



4.1.3 Relation between tidal amplification/damping and morphology

It is assumed that the convergence of an estuary is an important driver for the tidal amplification, while limited water depth will cause friction and lead to damping of the tidal range. In this paragraph we present threshold values in estuary depth, for which we can expect tidal amplification/damping, taking into account the estuary convergence.

For each individual estuary we observe that tidal amplification (gr(TR) > 0) prevails for estuary segments with larger depths, while tidal damping (gr(TR) < 0) occurs most frequently along shallow estuary segments (evaluated over 5 km blocks, Figure 19). The observed relationship between the cross-section averaged depth at LW (measure for the friction) and the observed tidal range gradient (gr(TR)) shows that for the most convergent estuary (Humber, Figure 18) tidal amplification (gr(TR) > 0) occurs at a cross-section averaged depth > 5.7 m and that tidal damping (gr(TR) < 0) occurs at a cross-section averaged depth < 5.7 m (i.e. based on an exponential model of the form $y = a(1-be^{-kx})$). For the least convergent estuary (Seine, Figure 18) the critical threshold value for the cross-section averaged depth occurs at 14.2 m (after extrapolating the model), and for an estuary with intermediate convergence (Scheldt, Figure 18) at 7.1 m. This demonstrates that also convergence has an influence on the tidal amplification and damping. Based on the found threshold values for the cross-section averaged depth (Figure 19) and the estuary convergence (Figure 18), tidal amplification and tidal damping in an estuary can be described in function of the estuary convergence and the estuary depth. We observe that for more convergent estuaries, amplification occurs at more shallow conditions compared to less convergent estuaries (Figure 20). We mention that the found threshold value for the Seine should be interpreted with care, since only tidal damping occurs in the system (threshold value based on extrapolation).

Figure 19 – The cross-section averaged depth at MLWL versus the observed gradient in tidal range.
For gr(TR) < 0 tidal damping, for gr(TR) > 0 amplification.

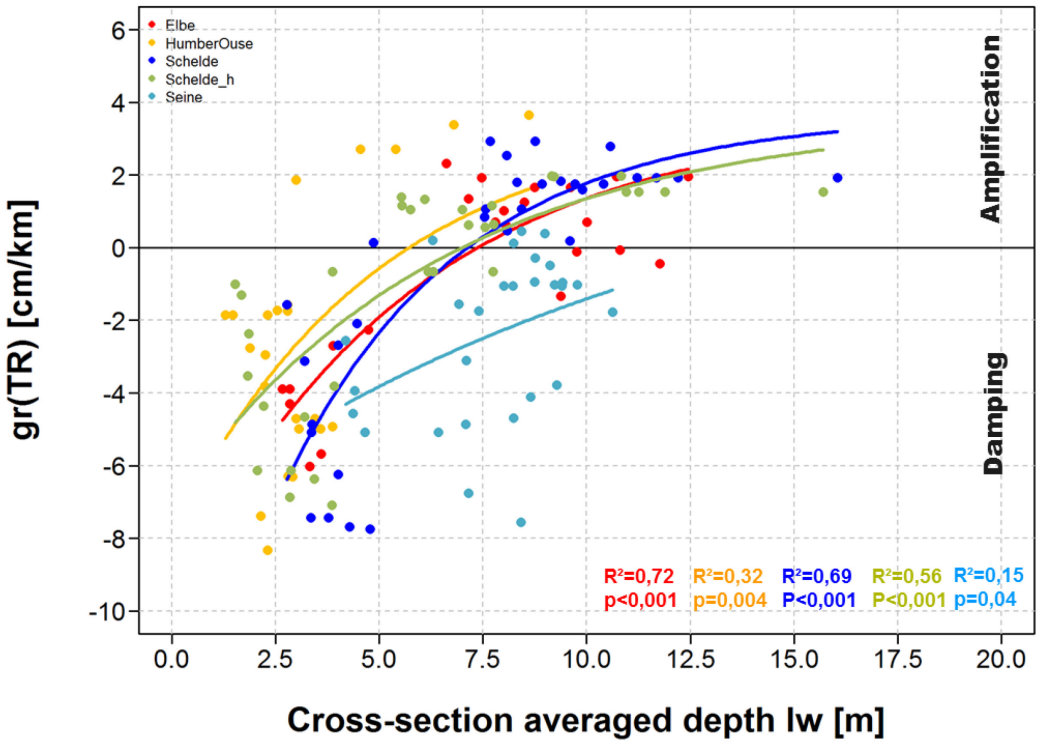
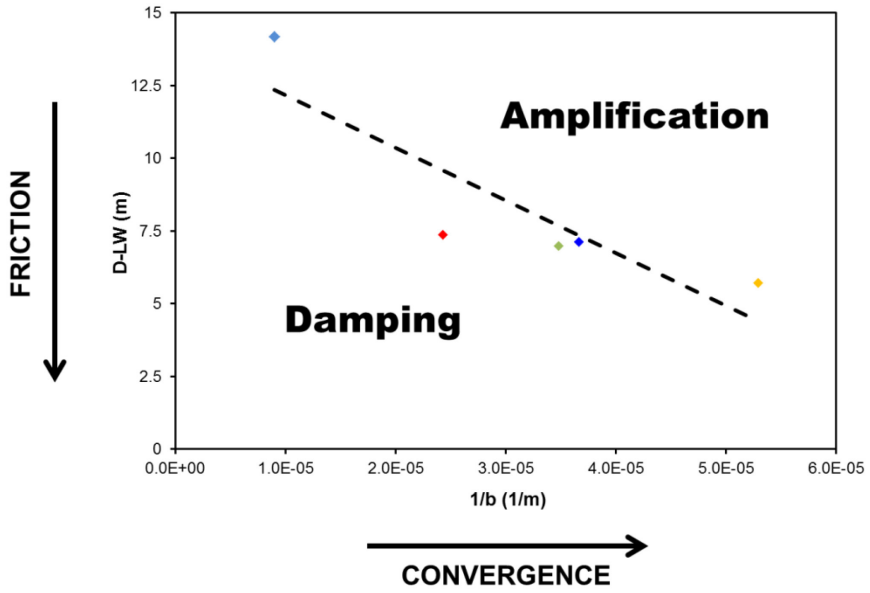


Figure 20 – Relationship between the estuary convergence and the cross-section averaged depth, based on the observed gradient in tidal range. The threshold between amplification/damping is based on the intersections of the regression lines at gr(TR) = 0 (see Figure 19).



4.2 Hydrodynamics and SPM

The amount of SPM and the location of the ETM in an estuary are to a large extent determined by the tide and the freshwater discharge. It is expected that the amount of SPM is higher for spring tide conditions due to the larger tidal range and thus the higher flow velocities. High freshwater discharge on the other hand leads to an export of suspended systems, and hence to a decrease in SPM.

Along the Seine estuary there is a clear effect of tidal range on the SPM signal. In case of spring tide conditions[2] the amount of SPM is clearly higher in comparison with neap tide conditions[3] (Figure 21). This effect is the largest near the mouth where the median SPM value is more than 10 times higher during spring tide in comparison with neap tide (1250 mg/l versus 100 mg/l). In the upstream direction the difference between spring tide and neap tide gradually decreases, but still remains significant, to finally become very small in the most upstream 50 km.

With regard to freshwater discharge we observe a distinct ETM at low discharges[4] (Figure 22). The location of the ETM is near the mouth, but in comparison with mean hydrodynamic conditions it is located slightly more upstream (cf. Figure 12a and Figure 22). In case of high discharges[5] the suspended particles are exported out of the estuary, and the ETM clearly shifts towards the mouth area.

Comparing the Seine with the Schelde estuary demonstrates that the location of the ETM is very different for both systems. For the Seine the ETM is located near the mouth (Figure 12, Figure 21 and Figure 22), while for the Schelde the ETM is located in the upstream part of the estuary (Figure 23).

[2] An observation belongs to a spring tide in case the nearest HW is larger than the 75th percentile HW calculated over the period 2007-2010.
[3] An observation belongs to a neap tide in case the nearest HW is smaller than the 25th percentile HW calculated over the period 2007-2010.
[4] An observation belongs to 'Low Q' in case the discharge is smaller than the 25th percentile Q.
[5] An observation belongs to 'High Q' in case the discharge is larger than the 75th percentile Q.

Freshwater discharge plays here an important role since the mean freshwater discharge for the Seine is much higher than for the Schelde (respectively 414 m³/s at Poses versus 34 m/³s at Melle). With regard to the effect of hydrodynamics on SPM some similar mechanisms occur. Both in the Seine and the Schelde an increase in tidal range leads to an increase in SPM (Figure 21 and Figure 24). Concerning the freshwater discharge we observe in both estuaries a shift of the ETM in the downstream direction in case of higher discharges (Figure 22 and Figure 25).

Figure 21 – Median surface SPM (2007-2010) along the Seine estuary for neap and spring tide conditions. Error bars represent the 25th and 75th percentile values.

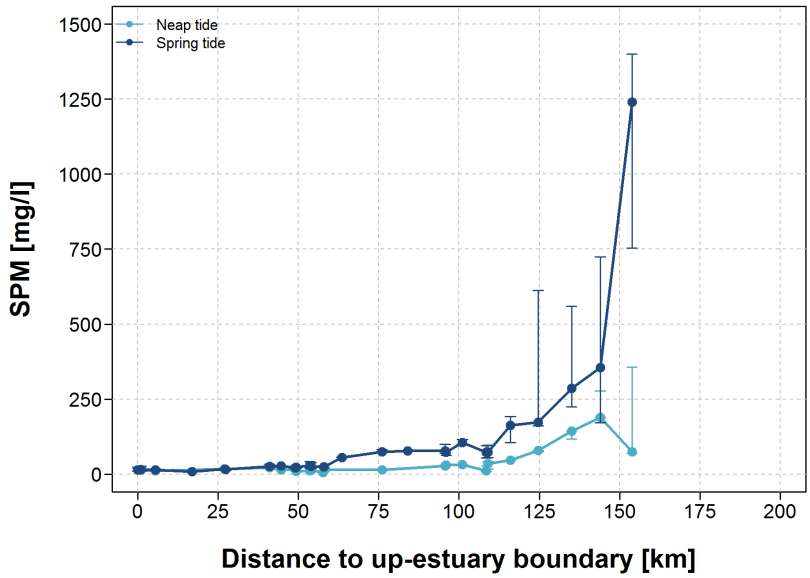


Figure 22 – Median surface SPM (2007-2010) along the Seine estuary at low and high riverine discharge. Error bars represent the 25th and 75th percentile values.

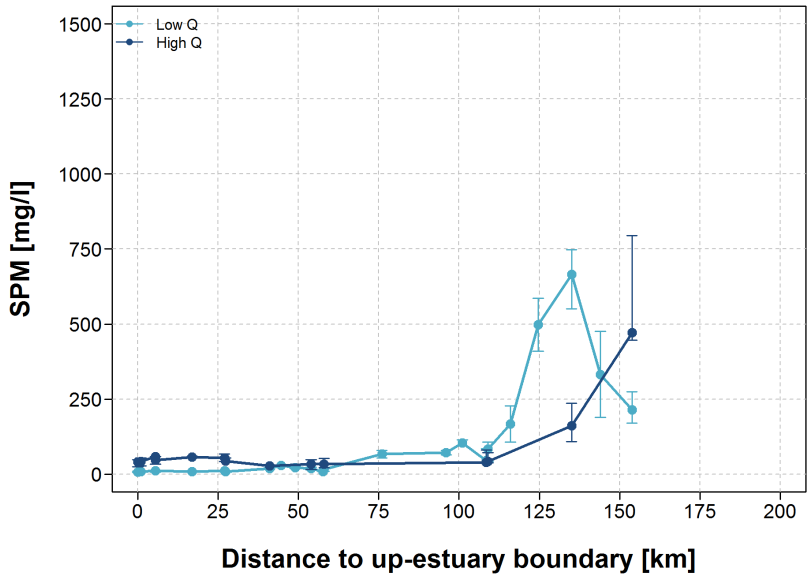


Figure 23 – Median surface SPM (1971-2015) along the Schelde estuary. Error bars represent the 25th and 75th percentile values.

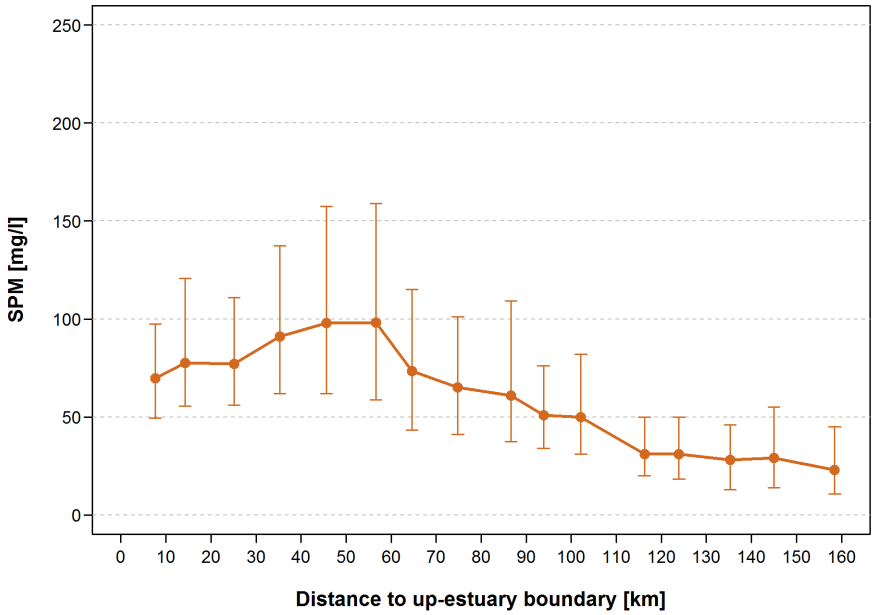


Figure 24 – Relation between tidal range and surface SPM (1996-2015) along the Schelde estuary (Vandenbruwaene et al., 2016).

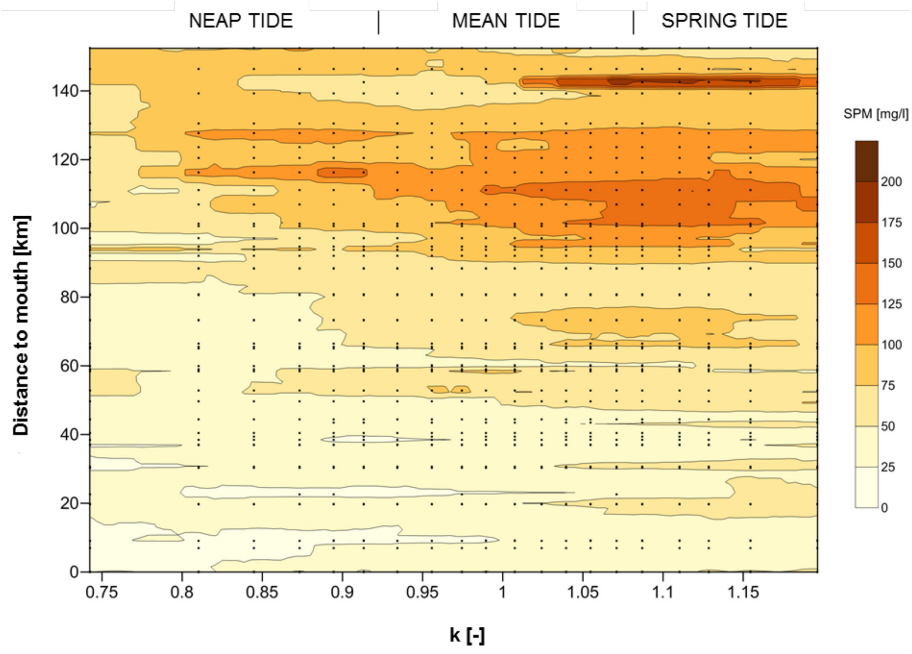
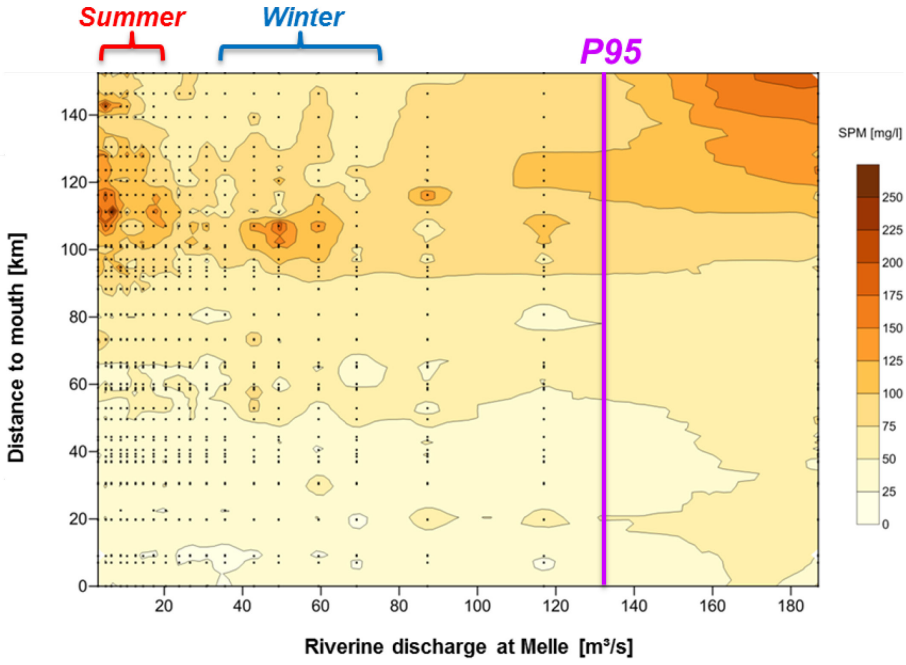


Figure 25 – Relation between riverine discharge and surface SPM (1996-2015) along the Schelde estuary (Vandenbruwaene et al., 2016).



4.3 Residence time

4.3.1 Parameters determining residence time

An overview of the parameters used to calculate residence times according to the fractal freshwater method (see §2.2.3) is given in Figure 26, Figure 27 and Figure 28. The Scheldt has clearly the largest estuarine volume, but in general has lower fractional freshwater concentration values f (for definition of f, see §2.2.3) along the length axis of the estuary (Figure 26). Lower f values along the length axis imply higher salinity values which means that for the Schelde the tidal intrusion is relatively more important than the freshwater discharge, compared to other estuaries. The Elbe for example is characterized by high freshwater discharges (Figure 28) and a rather low tidal range at the mouth (limiting tidal intrusion, see Figure 13). As a consequence f-values are high over the entire estuary (f > 0.7, excluding the mouth area, Figure 27). The Seine estuary can be considered as an estuary with a relatively high freshwater discharge (Figure 28), a high tidal range at the mouth, and tidal damping over the entire estuary (Figure 13). This leads to high f-values over a large part of the estuary, with a sharp decrease close to the mouth area (Figure 26).

Figure 26 – Estuary volume V (over 5 km) and fractional freshwater concentration f for the Seine and the TIDE estuaries.

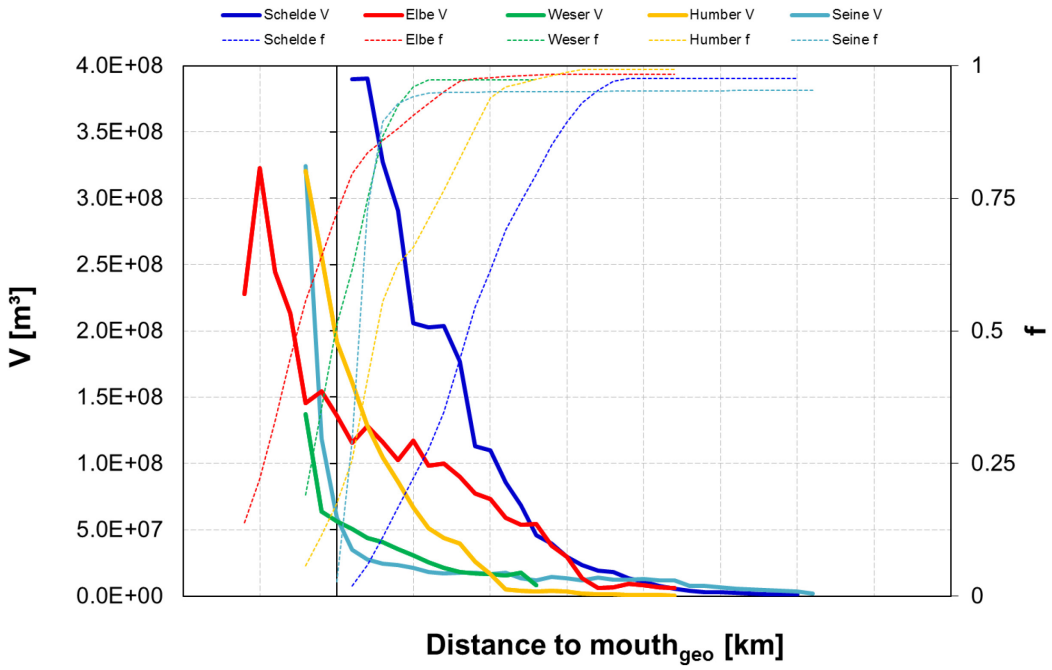


Figure 27 – The total volume of fresh water ($V_f = V^*f$) in each estuary segment (over 5 km), calculated according to the fractional freshwater method (Dyer, 1973).

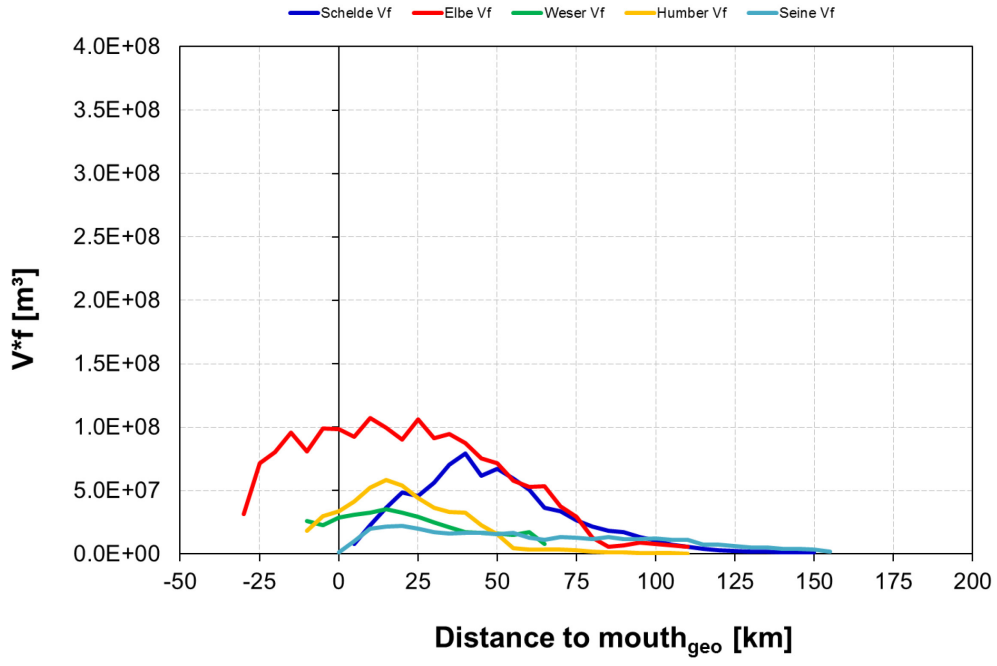
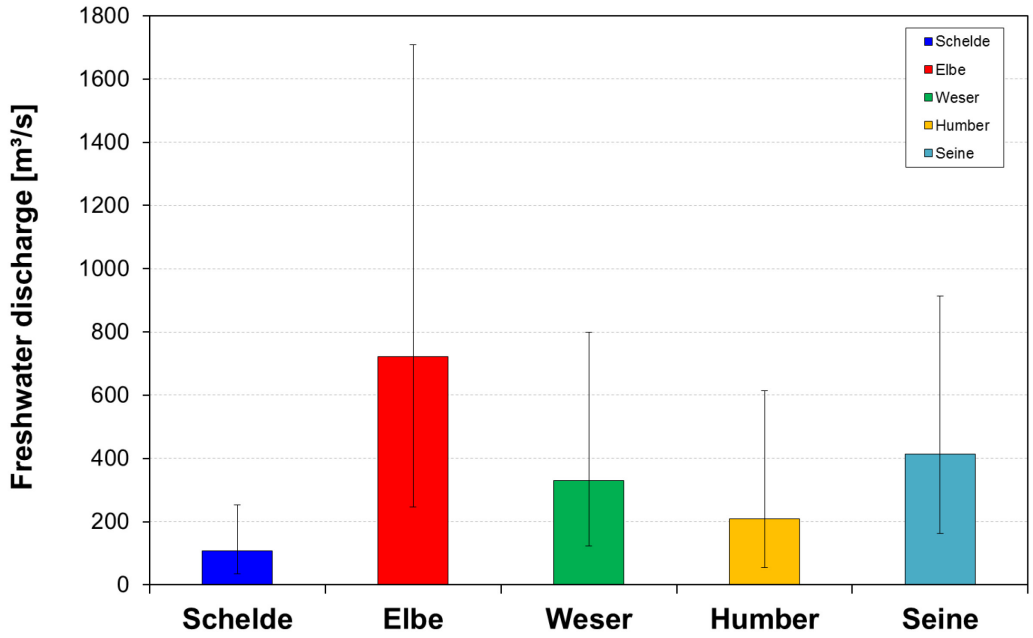


Figure 28 – Mean freshwater discharge for the Seine and the 4 TIDE estuaries.
Error bars are representative for typical high (P95) and low (P5) freshwater discharge values.



4.3.2 Residence time under mean discharge conditions

The freshwater volume is the highest for the Schelde and Elbe (Figure 27), however calculated residence times for the Schelde are clearly higher than for the Elbe (Figure 29) due to the much lower discharges in the Schelde (Figure 28). Or in other words, it takes in the Schelde much more time to replace the available fresh water volume due to the low freshwater discharge. The Seine and Weser estuaries are characterized by a low estuarine volume (Figure 26), low freshwater volumes (Figure 27), and an intermediate freshwater discharge (Figure 28), and consequently have lower residence times compared to the other estuaries.

Cumulating the calculated residence times for each estuary segment from the up-estuary boundary to the $mouth_{geo}$ (Figure 29) returns the total residence time for each estuary. This is thus the time needed for a water molecule to flow from the up-estuary boundary to the $mouth_{geo}$. For the Seine and Weser the residence time is low, for the Elbe and Humber intermediate, and for the Schelde high (Figure 30 and Table 3). The bars in Figure 30 represent the residence times under conditions of mean freshwater discharge, while the error bars represent the residence times for high (P95 value) and low (P5 value) freshwater discharges (respectively lower and upper error bar). During summer conditions freshwater discharges are generally lower than the mean freshwater discharge and residence times will range between the mean residence time and the upper error bar. During winter residence times will range between the mean residence time and the lower error bar.

Figure 29 – Residence time for each estuary segment of 5 km along the different estuaries. Solid lines represent the residence time under mean freshwater conditions, envelopes (dashed lines) represent high and low freshwater discharges (respectively P95 and P5 values).

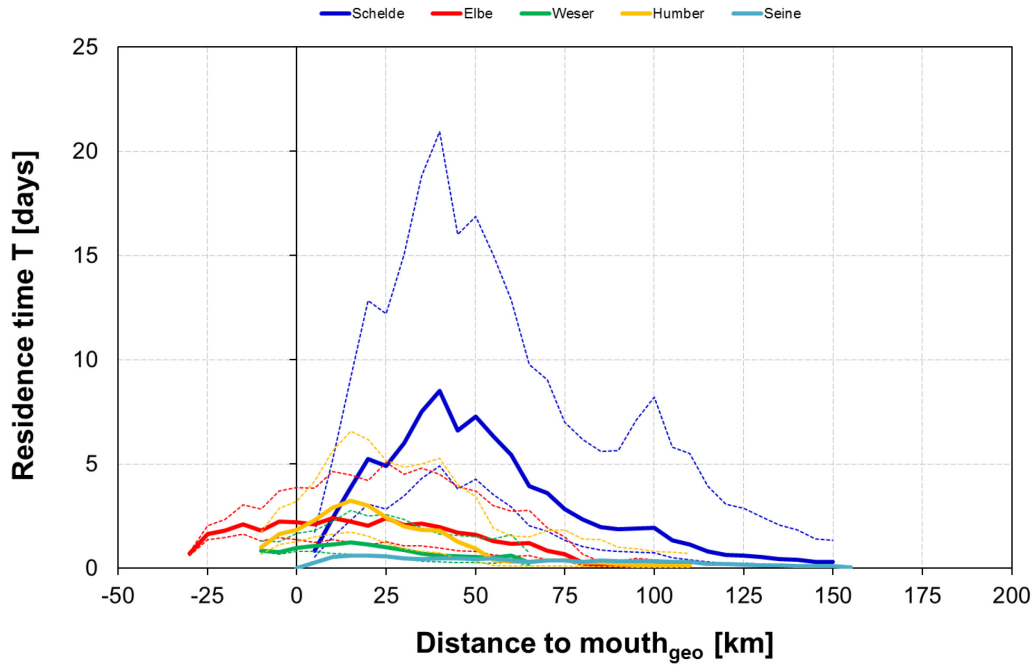


Figure 30 – Total residence time (from up-estuary boundary to mouth$_{geo}$) under mean freshwater discharge conditions (bar), and for high and low freshwater discharges (P95 and P5).

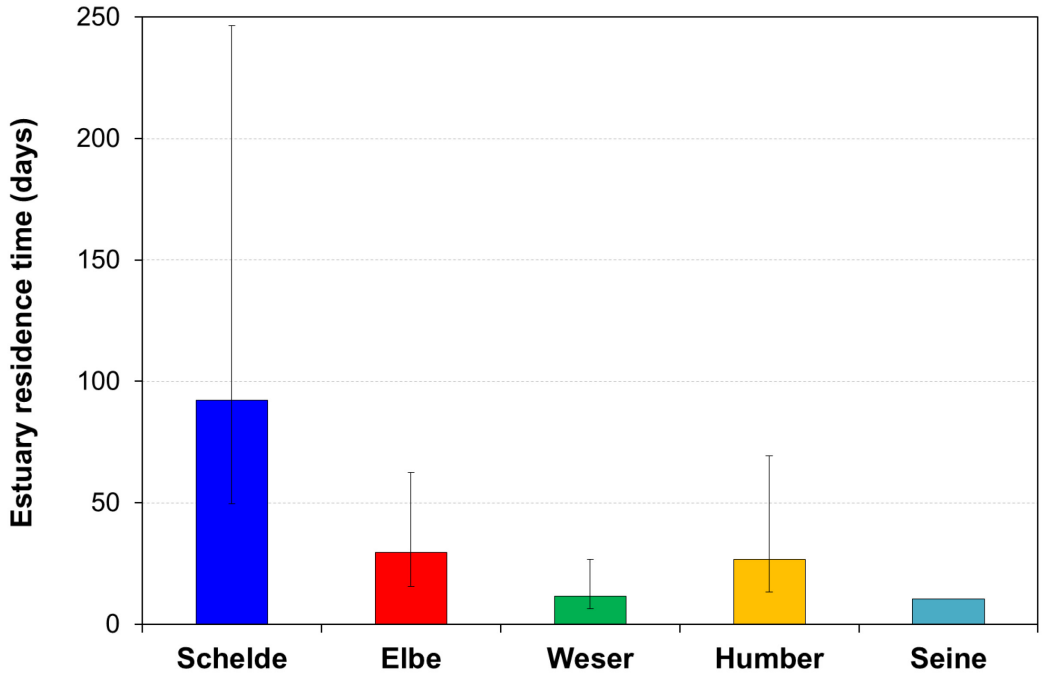


Table 3 – Residence time (in days) from up-estuary boundary to $mouth_{geo}$ under conditions of mean, low and high freshwater discharge (river flow), calculated according to the fractal freshwater method[6].

River flow	Scheldt	Elbe	Weser	Humber	Seine
High	50	16	7	13	-
Mean	92	29	11	27	10
Low	247	63	27	69	-

[6] For the Seine estuary the residence time is only available for conditions of mean river flow since the cubage calculation (delivers input parameters for the residence time calculation) was only calculated under mean river flow conditions.

5 Historical evolution

5.1 Morphology

The morphological evolution of the Seine estuary is characterized by important changes in the estuary depth, and only minor changes in the estuary width (Figure 31 and Figure 32). Between 1960 and 1975 the cross-section averaged depth increases with almost 2 m over the entire estuary. The depth increase continues over the period 1975-2010, but is smaller compared to the period 1960-1975. Only for the section 50-75 km the increase in cross-section averaged depth is comparable with the period 1960-1975. While the deepening takes place over almost the entire Seine estuary, the width changes are rather local. The most important changes are observed along the section 145-160 km, where the Seine narrows over the period 1960-1975. (Figure 31a). Between 1975 and 2010 no important changes in estuary width are observed (Figure 31). Due to the increase in estuary depth the cross-sectional area enlarges (Figure 33). Since the width changes are minor, the change in cross-sectional area is thus mainly governed by the depth changes. For more information on the historical morphological evolution of the Seine estuary we refer to Foussard et al. (2010).

Figure 31 – The historical evolution of the Seine estuary width (at 0 mCMH), represented with and without the mouth area (resp. A and B)

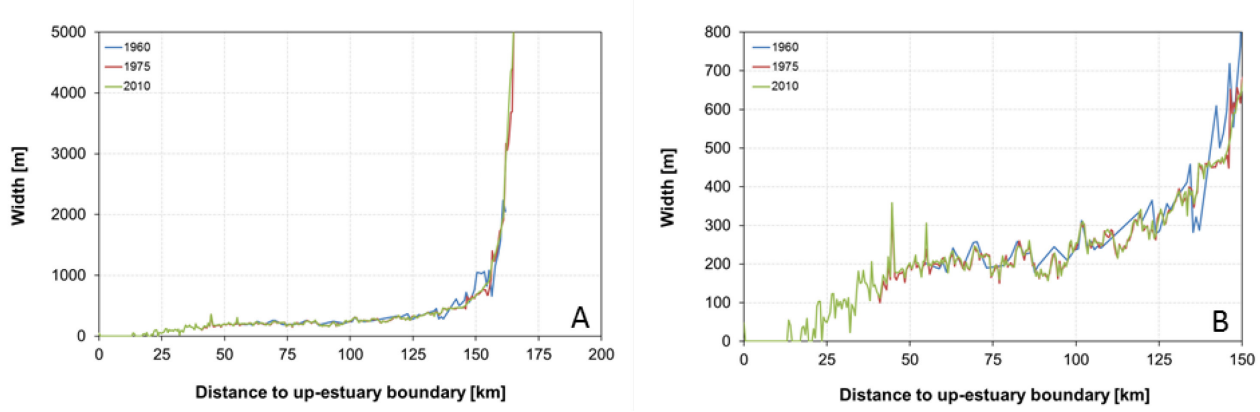


Figure 32 – The historical evolution of the cross-section averaged depth (A) and the thalweg depth (B) of the Seine estuary at 0 mCMH.

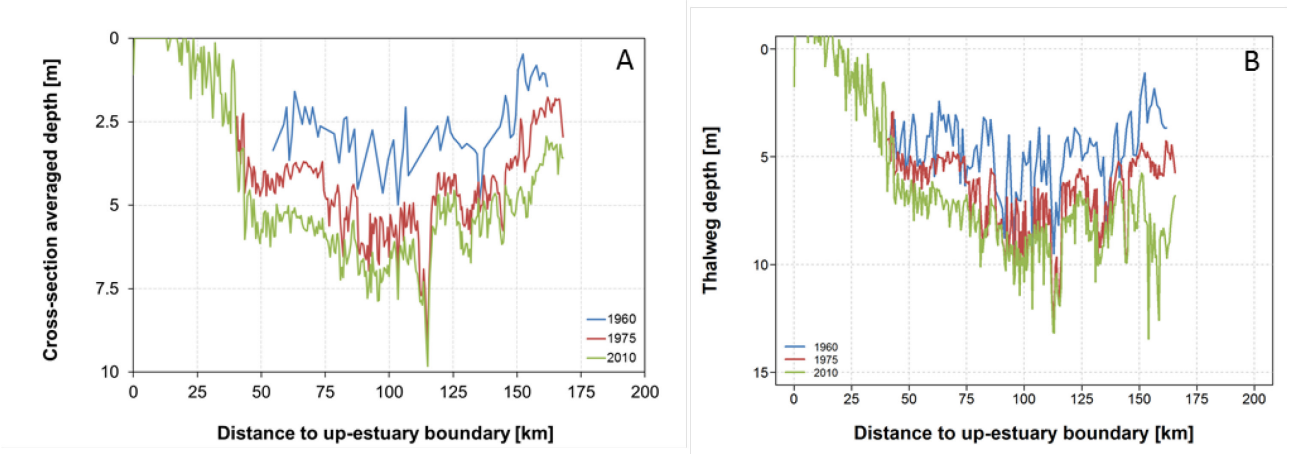
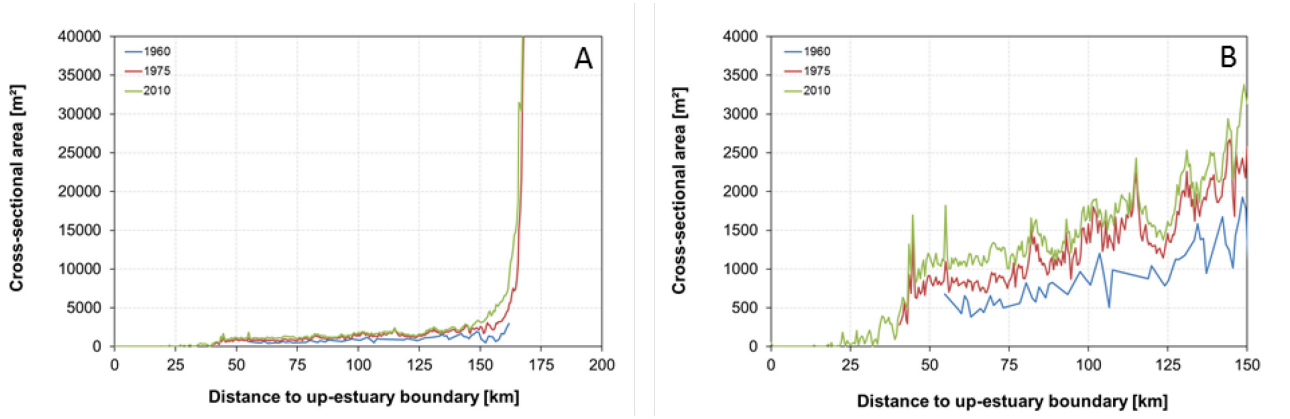


Figure 33 – The historical evolution of the cross-sectional area of the Seine estuary (at 0 mCMH), represented with and without the mouth area (resp. A and B)



5.2 Freshwater discharge

The historical evolution of the mean yearly discharge over the period 1941-2013 shows an alternation between dry an wet years (Figure 34). To evaluate any significant long-term change in the freshwater discharge, percentile values were calculated for each year and a linear model was fitted for each percentile value. This analysis demonstrates a significant increase for the 5th up to the 75th percentile value, although the correlation can be considered as rather weak (Table 5 and Figure 37). For the higher percentile values no significant changes are observed (Table 5 and Figure 37). In other words, we observe for the Seine a long-term significant increase in freshwater discharge for dry periods and mean discharge conditions, but no significant changes for wet periods and flushing events.

Figure 34 – The mean yearly discharge at Poses for the period 1941-2013.

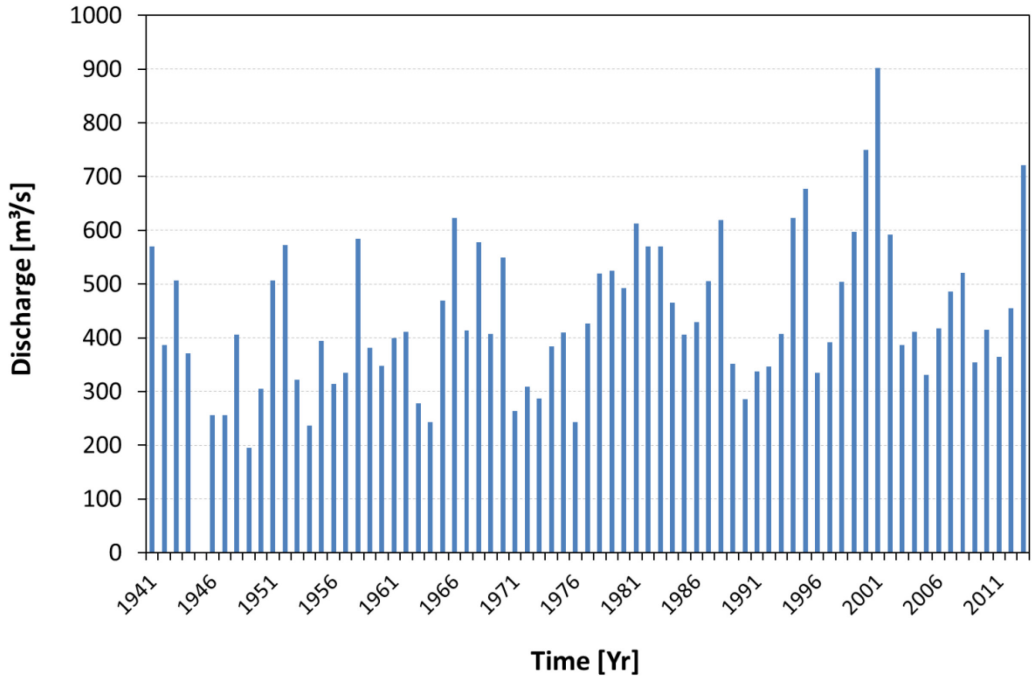


Figure 35 – The 10th percentile (Q10), the median value (Q50), and the 90th percentile (Q90) discharge per year for the period 1941-2013. Lines represent the corresponding linear regression models (full line = significant trend; dashed line = no significant trend, see also Table 5)

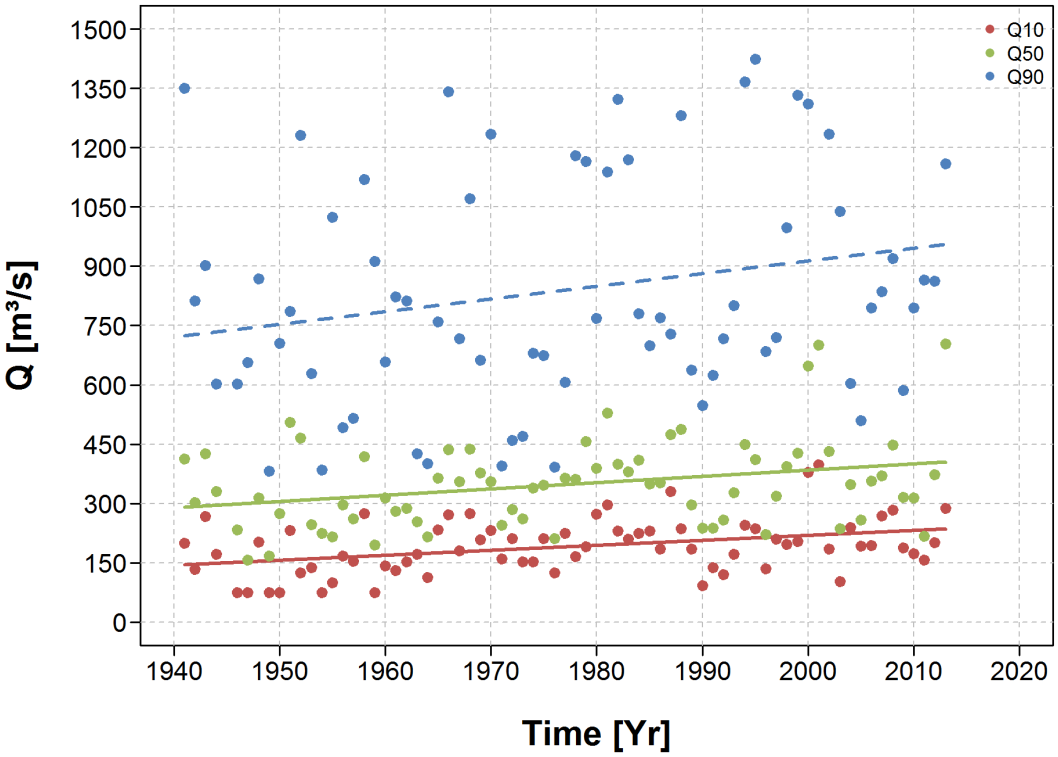


Table 4 – R^2- and p-values for the linear regression models of the different discharge percentiles. Q10, Q50 and Q90 are presented in Figure 37. Q5 = the 5th percentile discharge, Q25 = the 25th percentile discharge, etc..

Discharge percentile	R^2	p-value
Q5	0.12	0.0015
Q10	0.13	< 0.001
Q25	0.13	< 0.001
Q50	0.09	0.011
Q75	0.08	0.009
Q90	0.04	0.07
Q95	0.02	0.12

5.3 Salinity

The historical evolution of the salinity was evaluated for a downstream location (Honfleur), a location in the middle of the estuary (Heurteauville) and an upstream location (Rouen). For each of the locations a lineair regression was performed over the period 1970-2001. At Honfleur there is a significant decrease in salinity, although the correlation can be considered as rather weak (Figure 35 and Table 4). Based on the linear model the salinity decreases from 9 PSU in 1970 towards 5.5 PSU in 2001. For the more upstream locations we observe no significant change in salinity at Heurteauville, and a significant increase at Rouen (Figure 36 and Table 4). As for Honfleur, the correlation at Rouen can be considered as rather weak. However, at Honfleur the PSU value decreases with almost a factor 2, while at Rouen the increase is much smaller.

Figure 36 – The median PSU value per year for the station Honfleur over the period 1970-2001. Error bars represent the 25th and 75th percentiles.

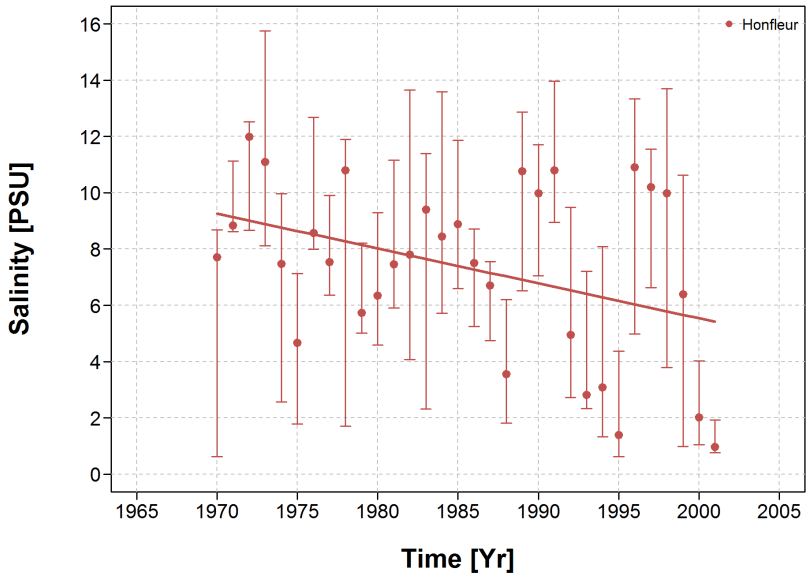


Figure 37 – The median PSU value per year for the stations Heurteauville and Rouen over the period 1970-2001. Error bars represent the 25th and 75th percentiles.

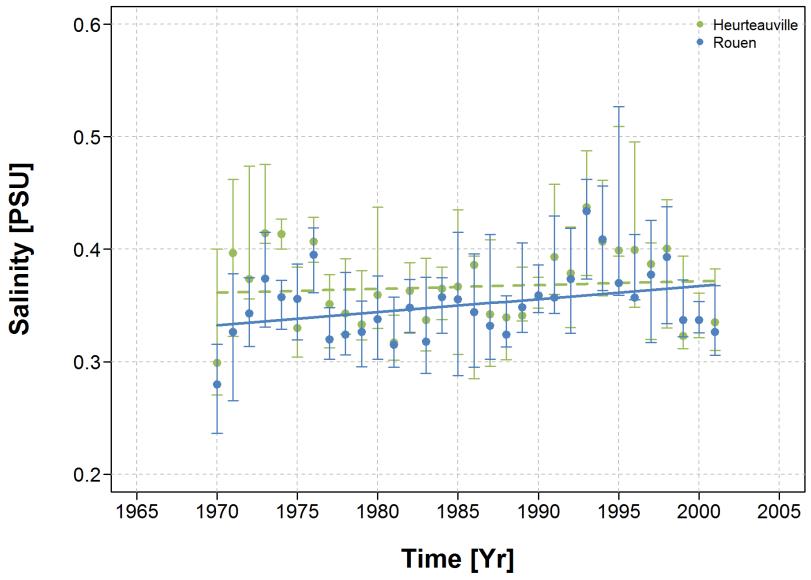


Table 5 – R^2- and p-values for the linear regression models presented in Figure 35 and Figure 36.

Station	R^2	p-value
Honfleur	0.11	0.032
Heurteauville	< 0.01	0.6
Rouen	0.1	0.045

5.4 SPM

The SPM signal along the Seine estuary is not constant in the long-term. At some time periods the amount of SPM is higher compared to other periods. This is especially the case at the ETM location, close to the mouth area, where large variations in SPM occur (Figure 38). To evaluate any significant long-term trend in SPM, a linear regression was performed on the median SPM values at Honfleur, Heurteuaville and Rouen. For all 3 stations we observe a significant decrease in SPM (Figure 39, Figure 40 and Table 6). The strength of the correlation is larger than for the long-term trends in salinity at the same stations (§5.3), and can be considered as weak to moderate (Table 6). Based on the linear models, the decrease in SPM over the period 1955-2013 is considerable for all 3 stations. At Honfleur SPM decreases from 1600 mg/l towards 250 mg/l, while at Heurteauville and Rouen SPM decreases from respectively 215 mg/l and 45 mg/l towards 20 mg/l.

Figure 38 – Historical evolution of SPM along the Seine estuary.

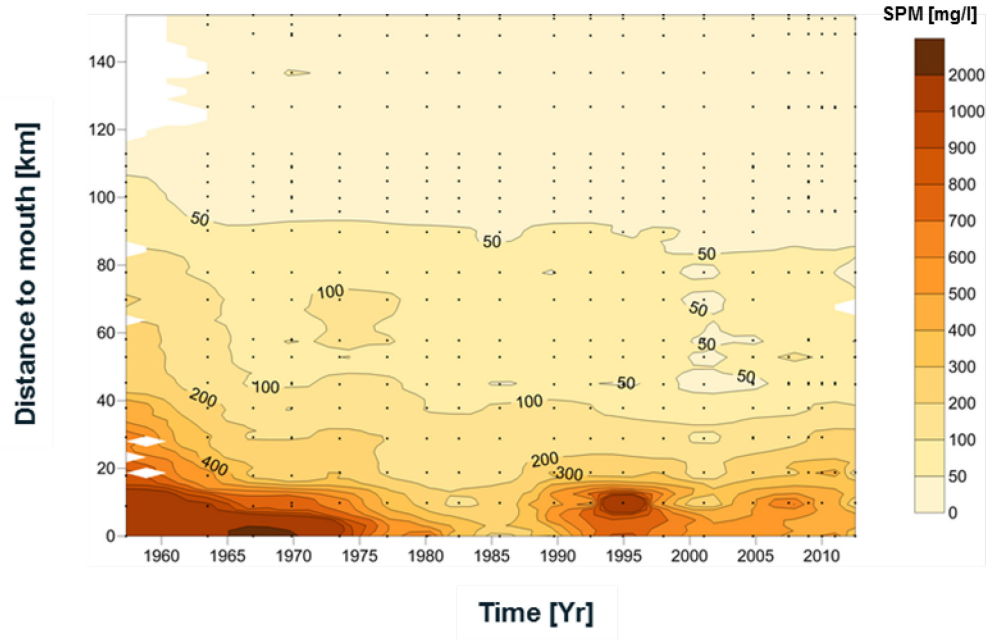


Figure 39 – The median SPM value per year for the station Honfleur over the period 1955-2013.
Error bars represent the 25th and 75th percentiles.

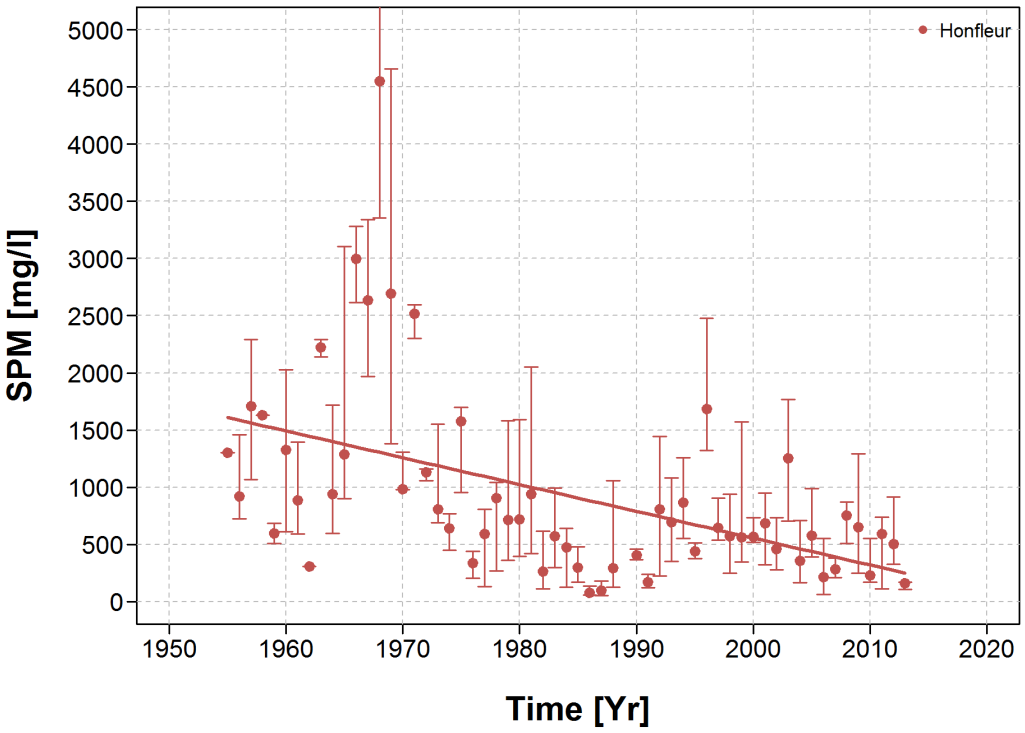


Figure 40 – The median SPM value per year for the stations Heurteauville and Rouen over the period 1955-2013. Error bars represent the 25th and 75th percentiles.

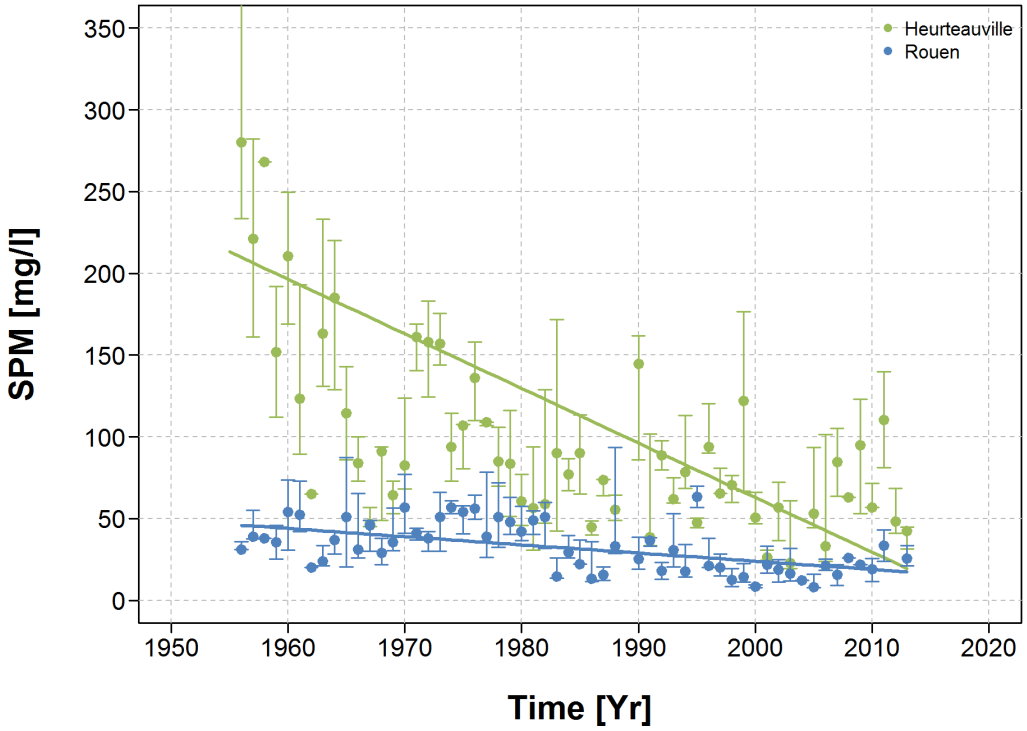


Table 6 – R^2- and p-values for the linear regression models presented in Figure 39 and Figure 40

Station	R^2	p-value
Honfleur	0.23	< 0.001
Heurteauville	0.19	< 0.001
Rouen	0.3	< 0.001

6 Conclusions

6.1 The present Seine

From a morphological point of view we can characterise the present Seine as an estuary with a low convergence and a large estuary depth (Figure 18). In general, the convergence of an estuary can be considered as an important driver for tidal amplification, while limited water depth will cause friction and damping of the tidal range. Despite the significant estuary depth of the Seine, the convergence of the estuary is so low that tidal damping is dominant (Figure 13 till Figure 15). Moreover, the Seine is a strong meandering estuary, which may lead to additional friction and damping of the tidal wave.

The Seine has a distinct estuarine turbidity maximum (ETM) at the salinity front which is located near the mouth (Figure 8 and Figure 12). During spring tide conditions the surface SPM at the ETM reaches values over 1 g/l (Figure 21). The tide and freshwater discharge have a clear influence on the location of the ETM, and the amount of SPM in the estuary. With increasing tidal range there is significant increase in SPM, and this over a large part of the estuary. The increase in SPM is the largest near the mouth area, and gradually decreases in the upstream direction (Figure 21). With regard to the freshwater discharge, there is a shift of the ETM in the downstream direction. At high discharges the suspended particles are flushed out of the estuary and transported towards the mouth area. At low discharges the ETM shifts in the upstream direction and becomes located in the downstream part of the estuary (Figure 22).

Since the Seine has a relatively large freshwater discharge and a small estuarine volume, residence times for the Seine are low (Figure 29 and Figure 30). This implies that water molecules, suspended solids and nutrients are transported quickly from the upstream parts of the estuary towards the mouth area. By comparison, under mean discharge conditions it takes in the Seine estuary 10 days for a water molecule to go from the up-estuary boundary towards the mouth, while in the Schelde estuary this is 92 days (Table 3).

6.2 Historical evolution of the Seine

Between 1960 and 1975 there is an important increase in the depth of the Seine estuary. This depth increase is over the entire estuary (up to Rouen), and continues between 1975 and 2010, however at a slower rate (Figure 32). In general, the width of the Seine did not change significantly between 1960 and present, and is rather limited to some local variations (Figure 31). The observed increase in cross-sectional area between 1960 and present (Figure 33) is thus to a great extent explained by the increase in estuary depth.

Between 1955 and 2013 we observe a significant decrease in SPM, and this for different locations along the Seine estuary (Figure 39 and Figure 40). We may explain this decrease in SPM by the change in discharge regime. Between 1941 and 2013 we observe a significant increase in the freshwater discharge at low and mean discharge conditions (Figure 37 and Table 5). Since an increase in freshwater discharge leads to the export of suspended particles (Figure 22), this may explain the historical decrease of SPM in the Seine estuary. An increase in freshwater discharge may not only influence the amount of SPM in the estuary, but also affects the salinity. At Honfleur we observe a significant decrease in salinity over the period 1970-2001 (Figure 35). This is not observed for the 2 upstream locations (Figure 36), but this can be explained since they are located in the freshwater zone. There, an increase in freshwater discharge will not affect the PSU values in the same amount as locations in the oligohaline or mesohaline zone.

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Appendix A: Topo-bathymetries

Figure 41 – Seine topo-bathymetry for the 2010 situation

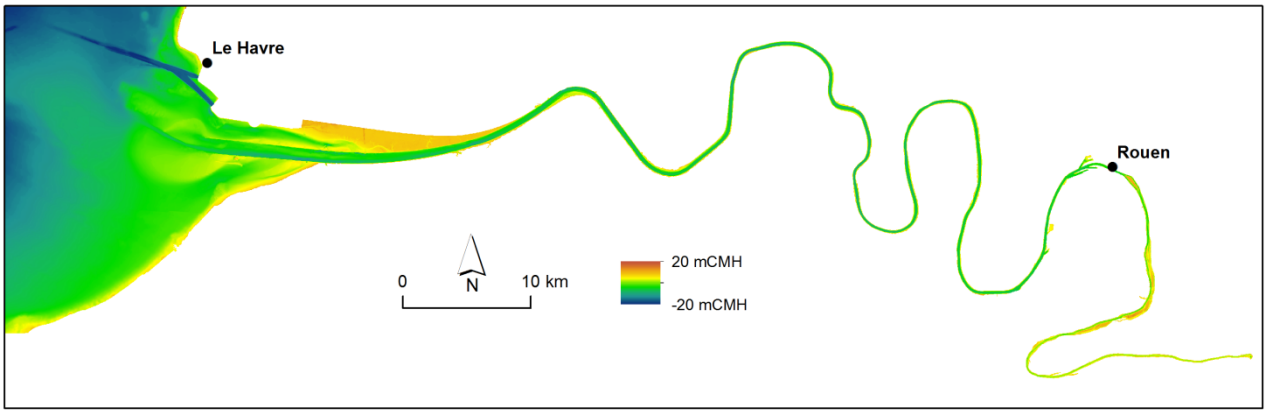


Figure 42 – Seine topo-bathymetry for the 1975 situation

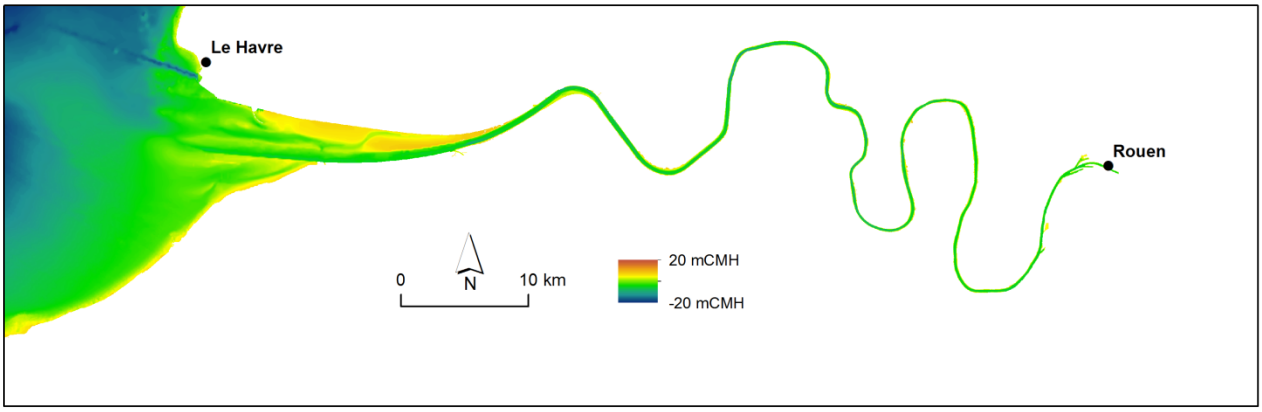
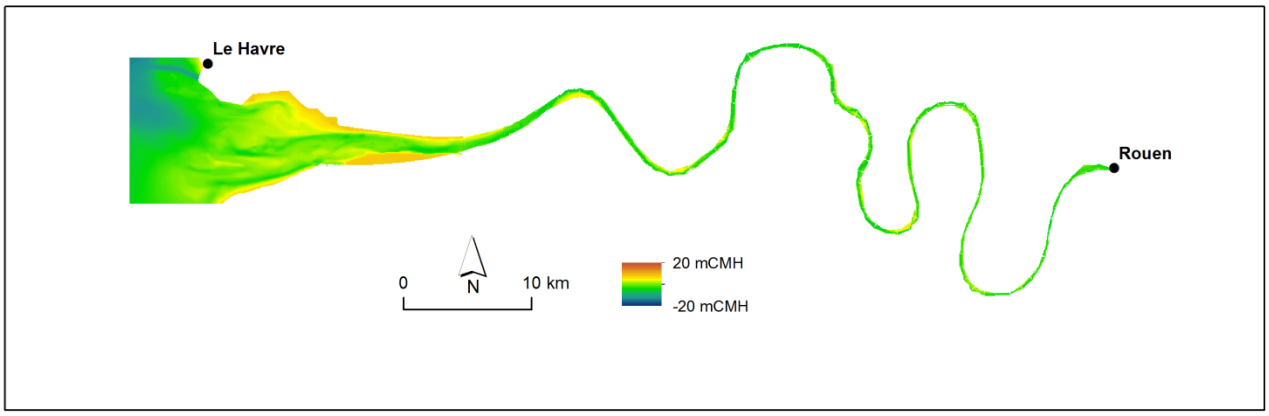


Figure 43 – Seine topo-bathymetry for the 1960 situation



Appendix B: Cross-sections

Figure 44 – Constructed cross-sections along the Seine for the 2010 and 1975 situation plotted against the 2010 topo-bathymetry – section Balisa-Tancarville.

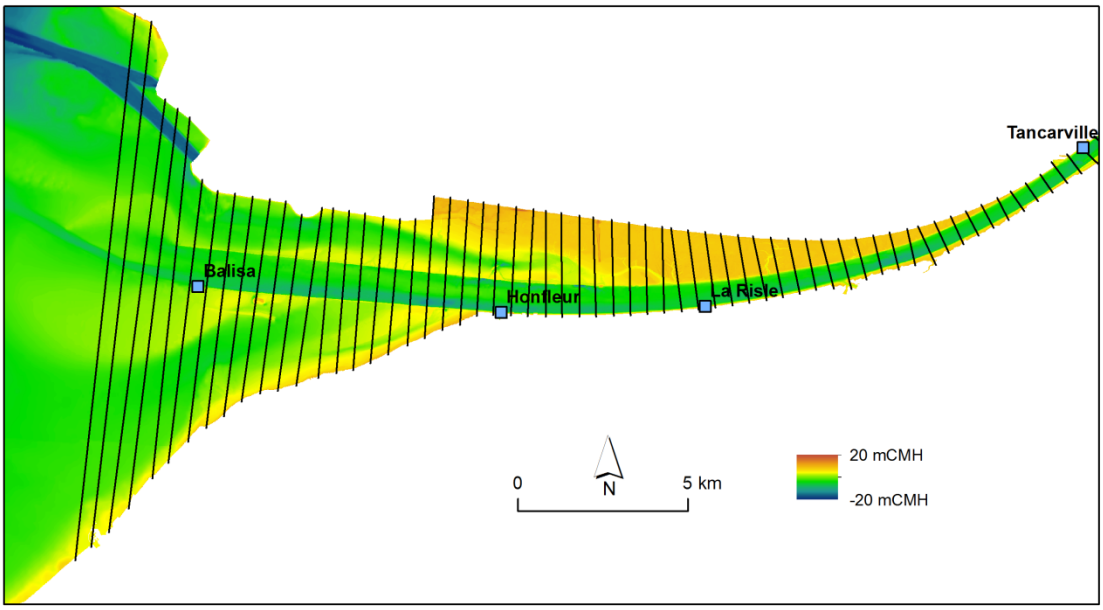


Figure 45 – Constructed cross-sections along the Seine for the 2010 and 1975 situation plotted against the 2010 topo-bathymetry – section Tancarville-Duclair.

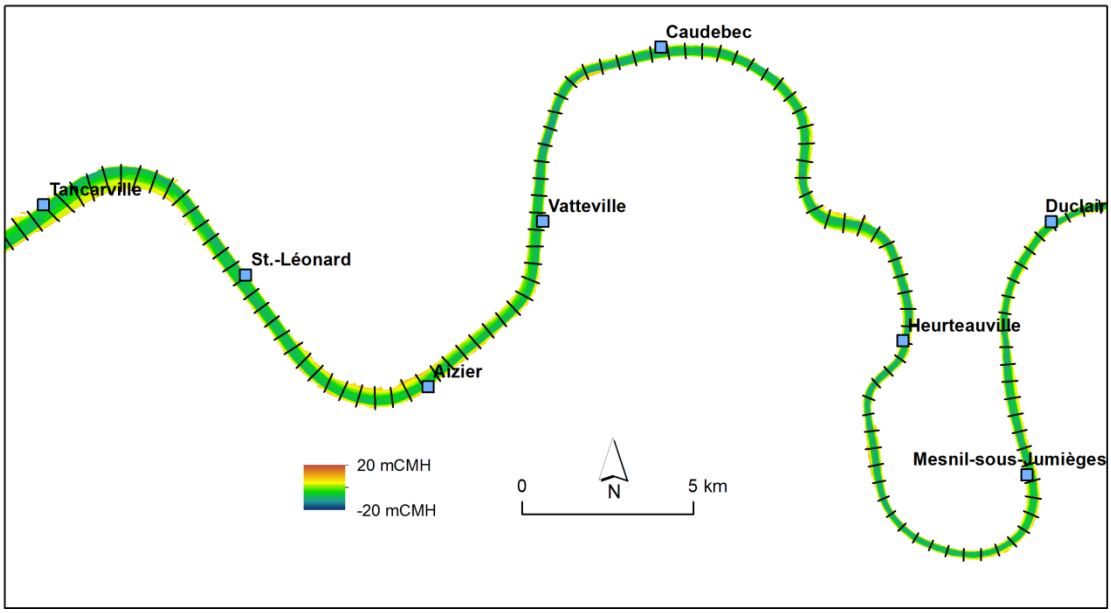


Figure 46 – Constructed cross-sections along the Seine for the 2010 and 1975 situation plotted against the 2010 topo-bathymetry – section Duclair-Rouen.

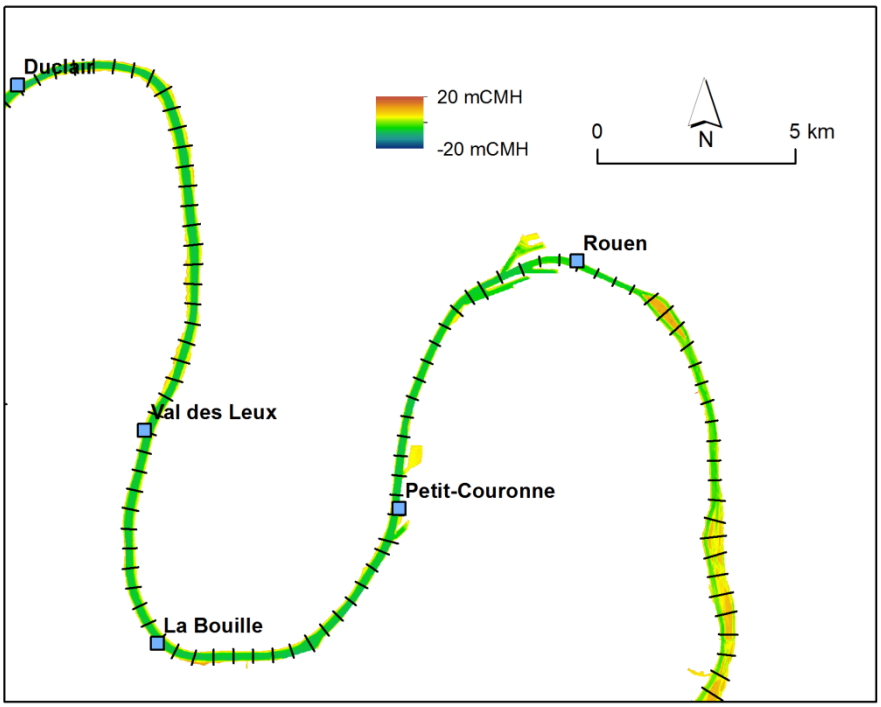


Figure 47 – Constructed cross-sections along the Seine for the 2010 and 1975 situation plotted against the 2010 topo-bathymetry – section Rouen – Pont-de-l'Arche

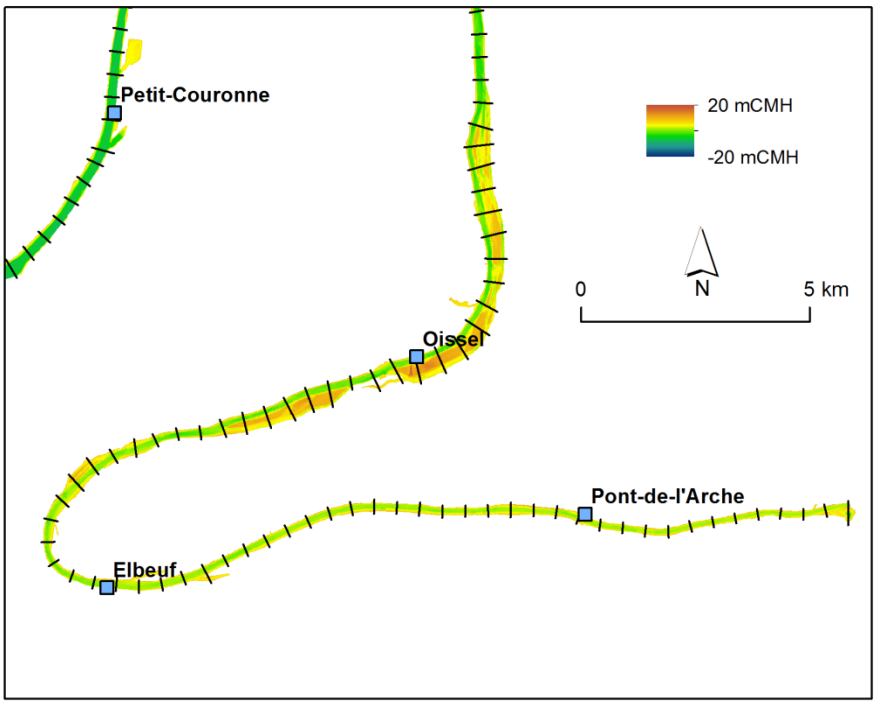


Figure 48 – Constructed cross-sections along the Seine for the 1960 situation – section Balisa-Tancarville

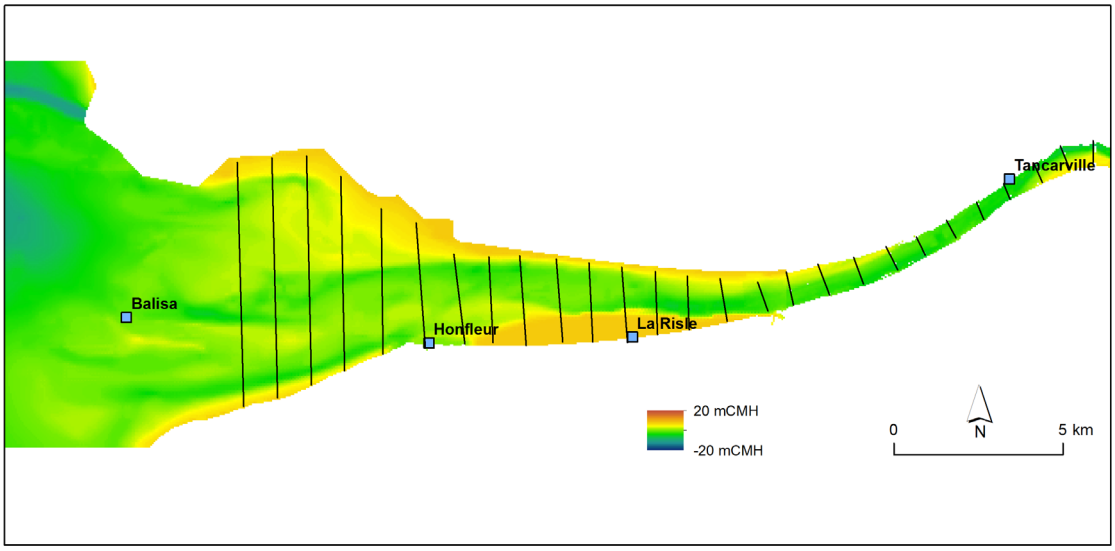


Figure 49 – Constructed cross-sections along the Seine for the 1960 situation – section Tancarville-Duclair

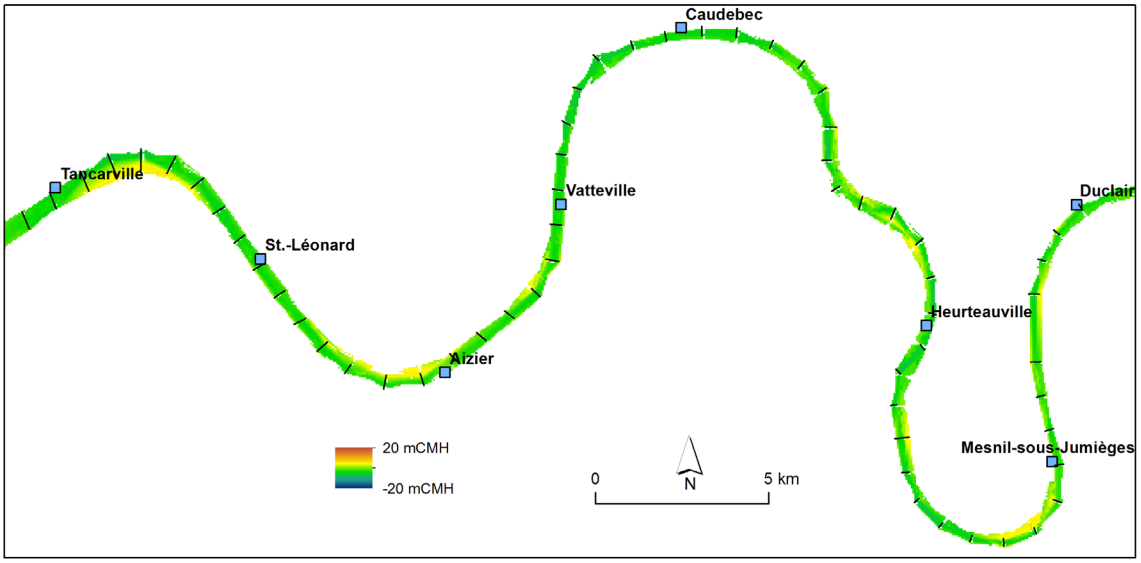
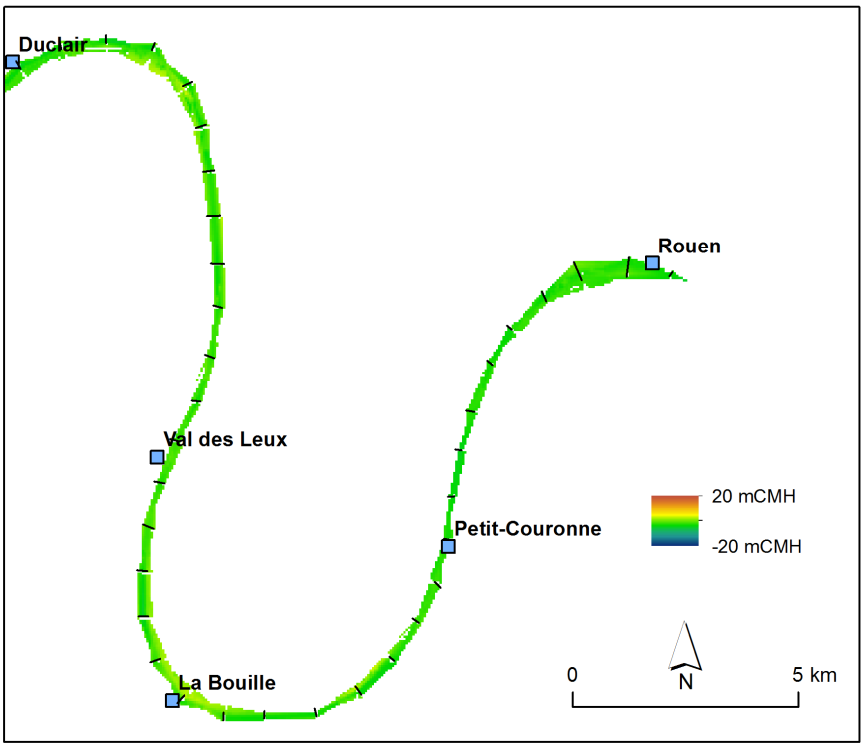


Figure 50 – Constructed cross-sections along the Seine for the 1960 situation – section Duclair-Rouen



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