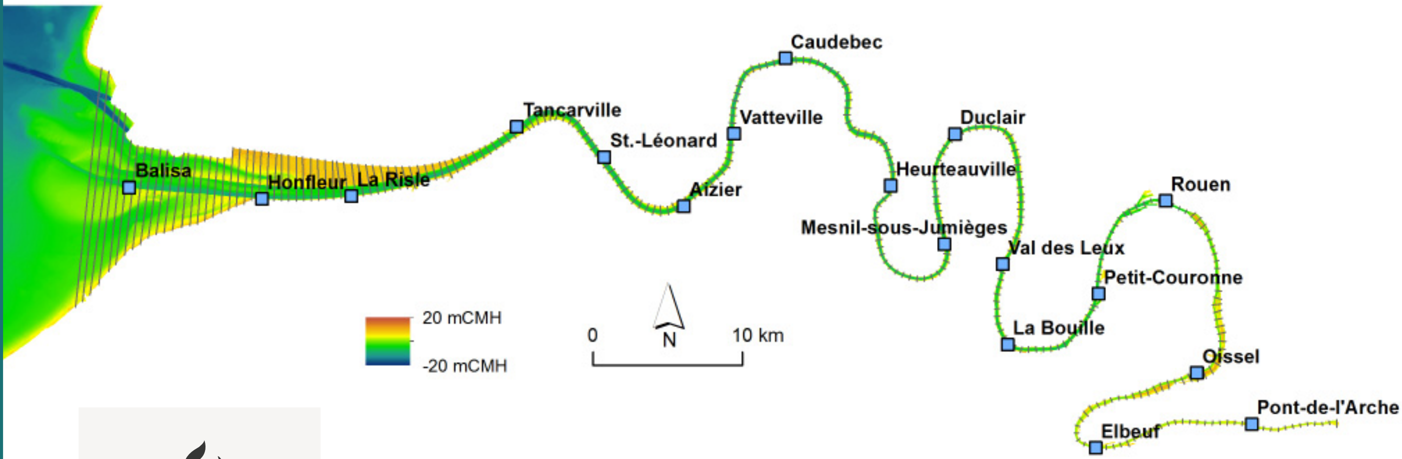

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ANPHYECO-Seine – Hydro-geomorphology of the Seine estuary

"Cubage" calculation

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ANPHYECO-Seine – Hydro-geomorphology of the Seine estuary

“Cubage” calculation

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Abstract

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). In order to perform an ecological study of the Seine estuary, a thorough understanding of the hydro-geomorphology of the estuary is necessary. Flanders Hydraulics Research has already executed studies on the hydro-geomorphology of other European estuaries (e.g. TIDE project).

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. The second approach will be done by IFREMER, while this report describes the results of one part of the data-analysis. From existing tidal and topo-bathymetric parameters, discharges and flow velocities are calculated using the so called “cubage”-technique, a relative simple method that was applied within the TIDE-project. This report describes the results of this “cubage”-calculation for a more or less recent situation of the Seine estuary (i.e. the year 2010).

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1 Introduction

1.1 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, Vandenbruwaene et al., 2013) 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.

From existing tidal and topo-bathymetric parameters, discharges and flow velocities can be calculated using the so called “cubage”-technique, a relative simple method that was applied within the TIDE-project. This report describes the results of this “cubage”-calculation for a more or less recent situation of the Seine estuary (i.e. the year 2010). For a more extensive hydro-geomorphological characterisation of the Seine estuary (in an estuarine context) we refer to the second report of the FHR study within the ANPHYECO project (Vandenbruwaene et al., 2018).

1.2 Outline

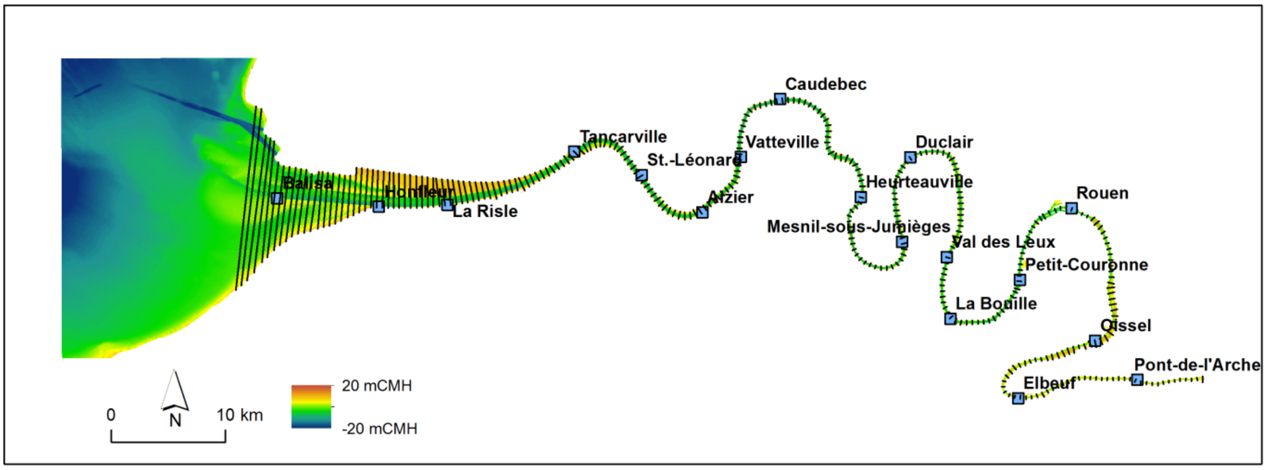
In chapter 2 a brief description of the Seine estuary is given. In chapter 3 the methodology behind the “cubage”-technique is described, while chapter 4 presents the data that were used within this study.

2 Seine estuary

The Seine River has a length of 777 km and drains an area of about 78 650 km². The Seine rises in Burgundy and has its mouth in the Bay of Seine near the city of Le Havre. The Seine watershed is characterized by intensive agricultural activities and by the presence the city of Paris of one of the largest in Europe. Sea-going navigation is possible over the most down-estuarine 105 km, up to the city of Rouen (this reach is called "Seine maritime"), while river boats can go as far as Bas-sur-Seine, 560 km from the mouth.

The final 160 km (Figure 1) are characterised as a macrotidal estuary where fresh water discharges and tides interact. The tidal penetration is blocked by a dam at Poses, which forms the starting point of the cubage calculation presented in this report (KM 0). The estuary can be divided in 3 zones: (1) the fluvial, or upstream, estuary from Poses (KM 0) to Vieux Port (KM 123) is characterised by freshwater, (2) the middle estuary from Vieux Port to Honfleur (KM 156) is characterised by a mixing zone of varying salinity levels and (3) the marine, or downstream, estuary from Honfleur to the Bay of Seine which is characterised by saltwater. More information can be found at the Seine-Aval website: http://seine-aval.crihan.fr/web/

Figure 1 – Overview Seine estuary – location of the tidal stations and the cross-sections



3 “Cubage” technique

The “cubage”-technique (“kubatuur” in Dutch) is a relative simple technique to simulate the hydrodynamics in an estuary. (Smets, 1996; Gosh, 1998; Plancke *et al.*, 2011) It requires only topo-bathymetric data and water levels at different stations to calculate discharges and cross-section averaged flow velocities by using 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. Moreover since 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. In the following paragraphs the main principles and parameters of this methodology is described.

3.1 Methodology

The hydrodynamics in a river or estuary can be described in a one-dimensional way using following equations:

(1) Conservation of mass: $$\frac{\partial Q}{\partial x} + B(x).\frac{\partial z}{\partial t} - f = 0$$

(2) Dynamic equation: $$\frac{\partial z}{\partial x} + \frac{u}{g}.\frac{\partial u}{\partial x} + \frac{1}{g}.\frac{\partial u}{\partial t} + \frac{u.|u|}{C^2.R} = 0$$

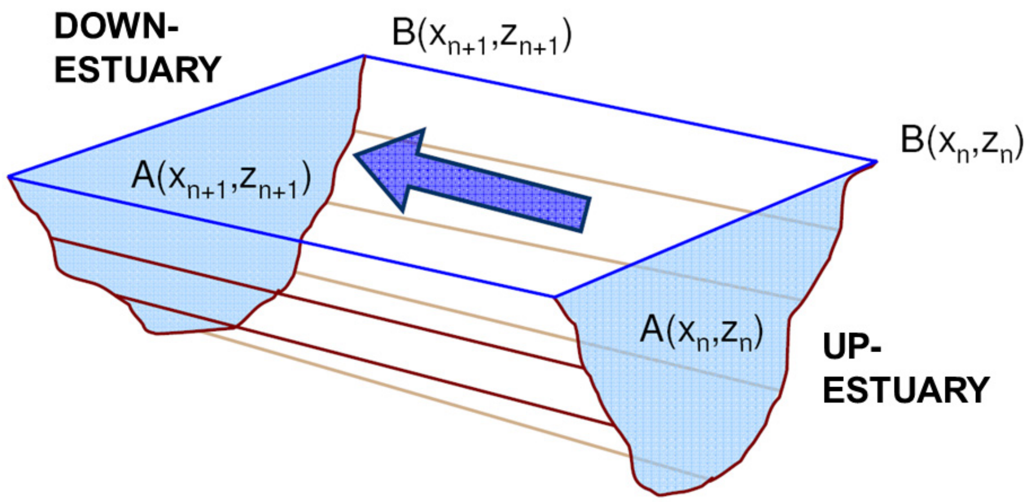
with:
x: abscise of a cross-section in the estuary
z: water level to horizontal reference plain (in this case Côte Marine du Havre (CMH))
t: time
Q: total discharge (ebb = negative | flood = positive)
A: wet section of a cross-section x at water level z: A(x,z)
B: width of a cross-section x at water level z: B(x,z)
u: section-averaged flow velocity: u = Q/A
g: gravitation acceleration (9,81 m/s²)
C: flow resistance coefficient Chézy
f: discharge (including possible tributaries)

The “cubage”-technique is based on the integration of the conservation of mass equation in a segment of the estuary between 2 consecutive cross-sections (Figure 2). Stating from a known discharge curve at one cross section (due to practical considerations this cross section is chosen at the up-estuary boundary), the discharges at the other cross section can be calculated. Application of the trapezoidal rule leads to following equation:

$$Q_{n+1} - Q_n = -\frac{1}{2}.\left[\frac{B_n^{t+1} + B_n^t}{2}.\Delta z_n^{t,t+1} + \frac{B_{n+1}^{t+1} + B_{n+1}^t}{2}.\Delta z_{n+1}^{t,t+1}\right].\Delta x.\frac{1}{\Delta t}$$

with:
Q_n: discharge in cross-section n (up-estuary)
Q_{n+1}: discharge in cross-section n+1 (down-estuary)
B_n^t: width of cross-section n at time step t
$\Delta z_n^{t,t+1}$: change in water level for cross-section n, between time step t and t+1
Δx: distance between 2 consecutive cross-sections n and n+1 (~ 500 m)
Δt: time interval between 2 time steps
(i.e. temporal resolution of water level measurements = 5 minutes)

Figure 2 – Schematisation of cubage technique in a segment of the estuary



3.2 Derived parameters

The "cubage"-technique allows for the calculation of the discharges between every 2 consecutive cross-sections in the estuary. From this parameter following additional parameters can be derived:

(a) Maximum ebb and flood discharges

$$Q_{ebb}^{\max} = \max_{SHW<t<SLW} \left|Q(x,t)\right| \text{ and } Q_{flood}^{\max} = \max_{SLW<t<SHW2} \left|Q(x,t)\right|$$

(b) Ebb and flood discharges averaged over one tidal cycle

$$\left\langle Q_{ebb} \right\rangle = \frac{\left|\int_{SHW}^{SLW} Q(x,t).dt\right|}{SLW - SHW} \text{ and } \left\langle Q_{flood} \right\rangle = \frac{\left|\int_{SLW}^{SHW2} Q(x,t).dt\right|}{SHW2 - SLW}$$

(c) Ebb and flood tidal volumes

$$V_{ebb} = \left|\int_{SHW}^{SLW} Q(x,t).dt\right| \text{ and } V_{flood} = \left|\int_{SLW}^{SHW2} Q(x,t).dt\right|$$

(d) Evolution in time of section-averaged velocity

$$v(x,t) = \frac{Q(x,t)}{A(x,z)}$$

(e) Maximum ebb and flood velocity

$$v_{ebb}^{\max} = \max_{SHW<t<SLW} \left|v(x,t)\right| \text{ and } v_{flood}^{\max} = \max_{SLW<t<SHW2} \left|v(x,t)\right|$$

(f) Mean ebb and flood velocities: velocity averaged over ebb or flood part of one tidal cycle

$$\langle v_{ebb} \rangle = \frac{\left| \int_{SHW}^{SLW} v(x,t).dt \right|}{SLW - SHW} \text{ and } \langle v_{flood} \rangle = \frac{\left| \int_{SLW}^{SHW2} v(x,t).dt \right|}{SHW2 - SLW}$$

3.3 Application to the seine estuary

The "cubage" technique uses water level data and topo-bathymetric data to calculate the discharges and the derived parameters. Therefore water level data are necessary in all measurement stations, while geometric characteristics have to be calculated from topo-bathymetric data. Finally fresh water river discharges have to be specified at the up-estuarine boundaries to be able to perform to calculation. All the necessary data are described in the following paragraphs.

3.3.1 Tides

Within the project it was chosen to perform the cubage calculation for mean tidal conditions. In a first step the mean tidal parameters (HW and LW) were derived for 2010 for three stations: Pont de l'Arche, Le Mesnil-sous-Jumièges and Balisa. Where the cubage technique requires a continuous time series of water levels, one period with several tidal cycles was chosen from the continuous measurements, which had the best agreement with the mean values of the year 2010. The mean parameter values for the year 2010 and the selected period (January 15th and 16th 2010) is shown in Table 1. For this period, water level measurements for all tidal station (Table 2) were selected as input for the cubage calculation. All this data were received from GIP Seine Aval. Table 2 gives an overview of the available water level stations. Figure 3 gives an overview of the water levels over the selected period for all stations.

Figure 3 – Water levels for all tidal stations

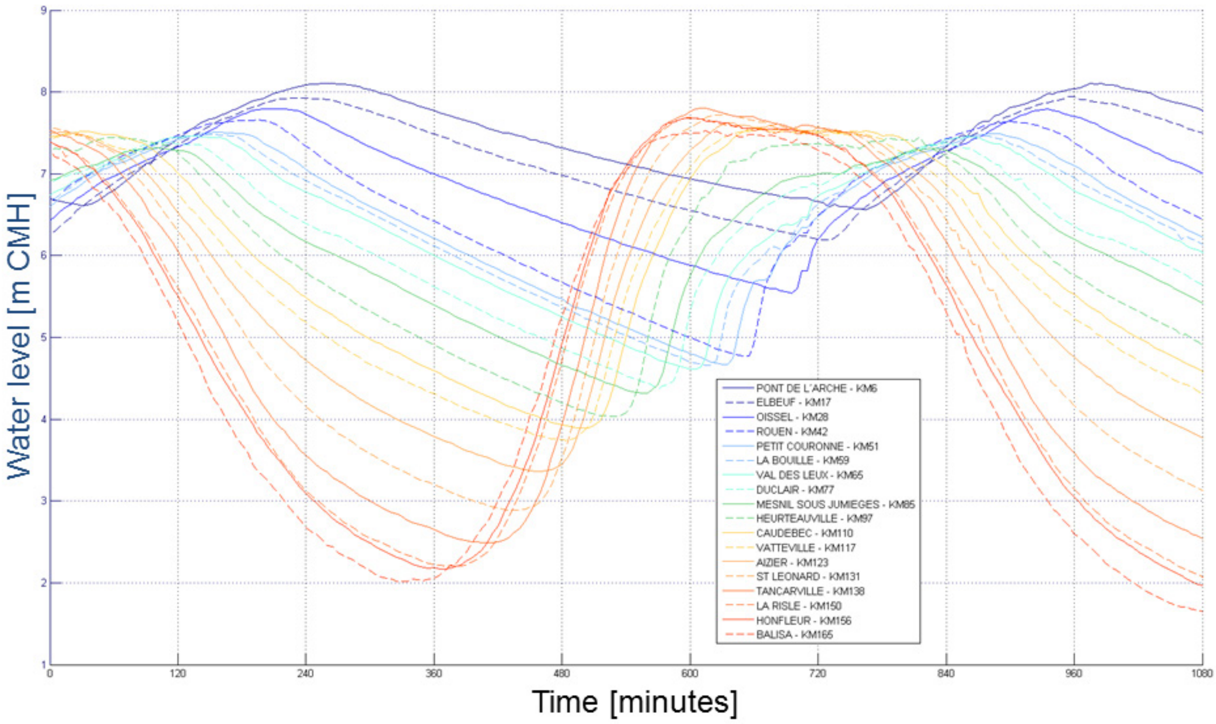


Table 1 – Comparison of mean tidal parameters for 2010 and selected tide

	Distance from weir [km]	HW [cm CMH]	LW [cm CMH]	TR [cm]	Time faling [minutes]	Time rising [minutes]
PdlA –2010	5.9	854	642	211		
PdlA – cubage		811	640	171	475	250
MSJ –2010	85.3	727	398	329		
MSJ – cubage		732	414	318	455	270
BAL –2010	165.2	734	207	527		
BAL – cubage		753	164	589	490	235

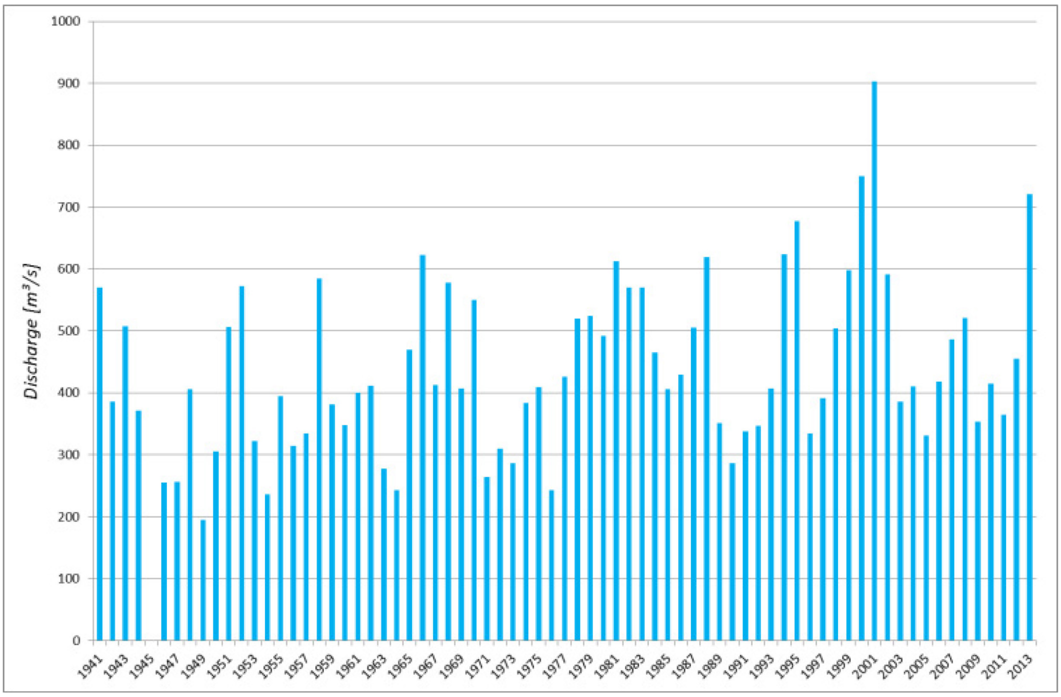
Table 2 – Overview of tidal stations (distance to Poses)

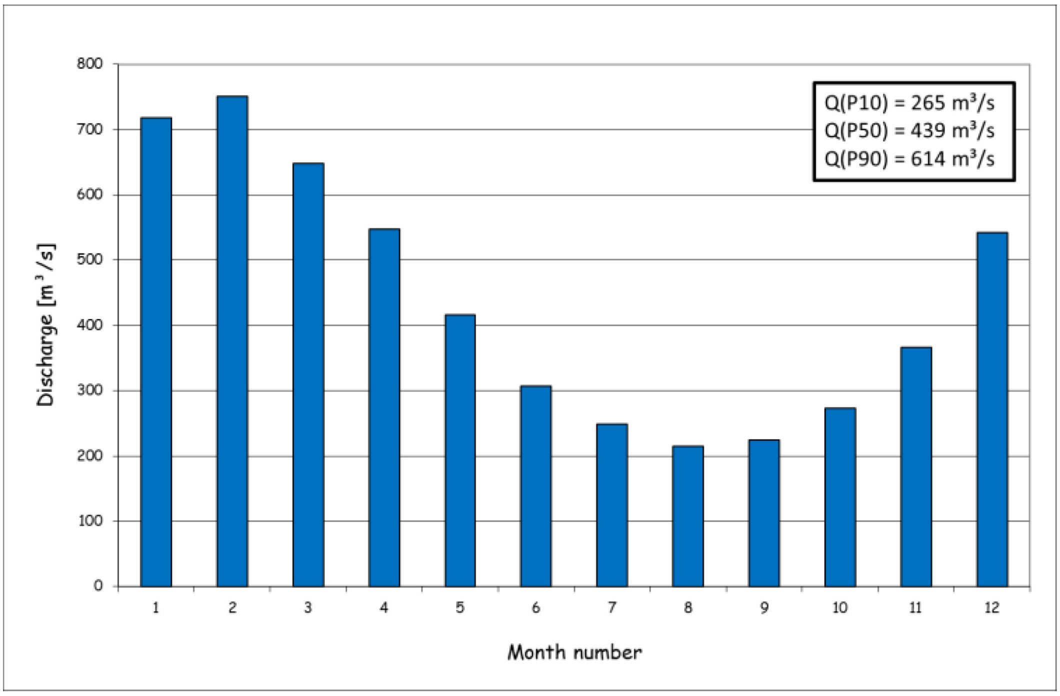
Tidal station	Location [KM]
PONT DE L´ARCHE	6
ELBEUF	17
OISSEL	28
ROUEN	42
PETIT COURONNE	51
LA BOUILLE	59
VAL DES LEUX	65
DUCLAIR	77
MESNIL-SOUS-JUMIEGES	85
HEURTEAUVILLE	97
CAUDEBEC	110
VATTEVILLE	117
AIZIER	123
ST LEONARD	131
TANCARVILLE	138
LA RISLE	150
HONFLEUR	156
BALISA	165

3.3.2 Fresh water discharge

At the up-estuarine boundaries the “cubage” technique requires the implementation of a fresh water discharge. For the Seine estuary this discharge is represented by the fresh water discharge at Poses, which is located ca. 160 KM upstream of the mouth. Based on the monthly values of the period 1941-2013, three characteristic fresh water discharges were calculated: Q(10%) representing a “summer” condition, Q(50%) representing a yearly averaged values and Q(90%) representing a “winter” condition. These values are presented in Figure 4.

Figure 4 – Fresh water discharge at Poses (up-estuarine boundary) over 1941-2013
Annual mean (top) and monthly average (bottom)



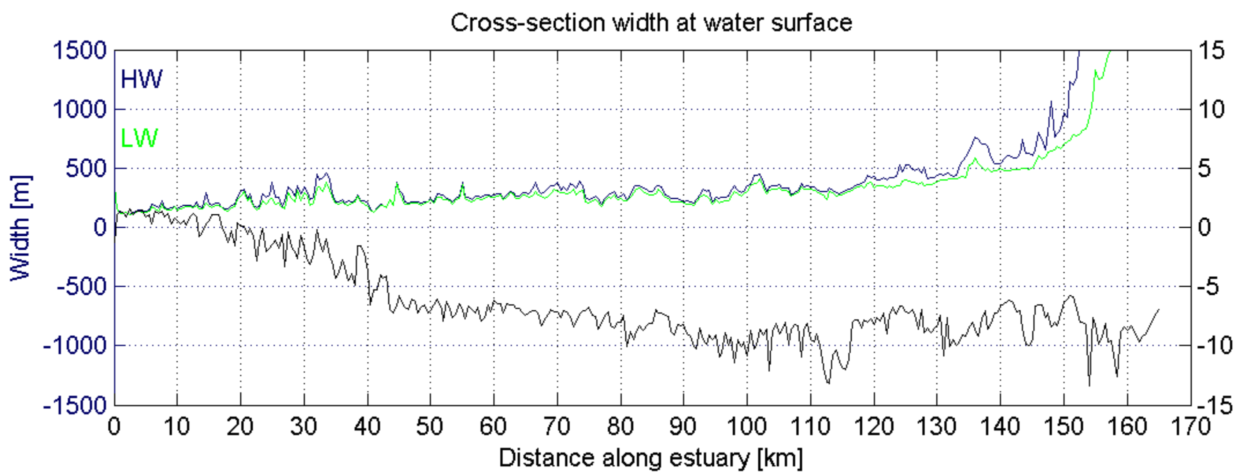


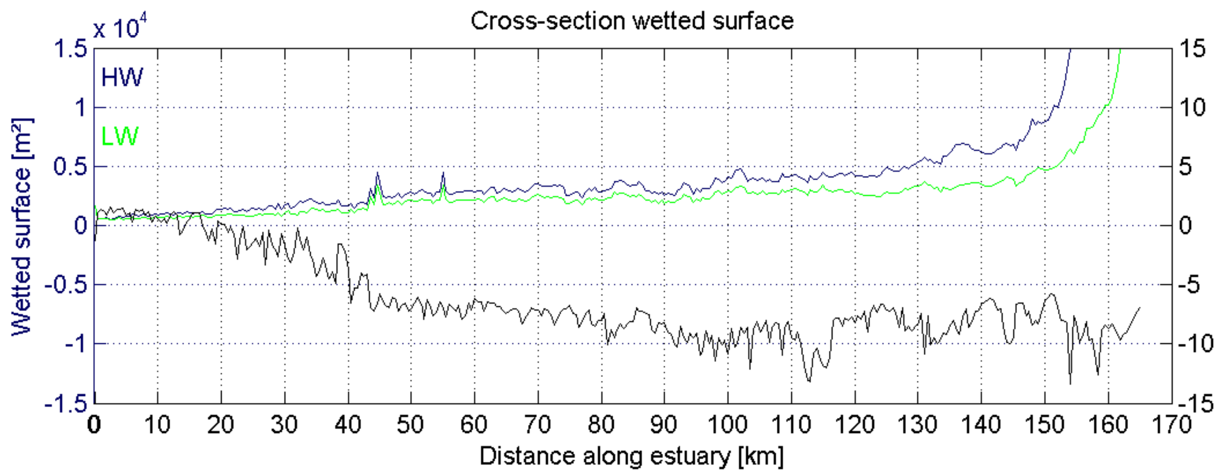
3.3.3 Topo-bathymetry

The 2010 topo-bathymetric data for the Seine estuary was provided by the GIP Seine Aval. For the "cubage" calculation the topo-bathymetry was implemented by attributing the geometric properties to cross-sections perpendicular to the thalweg (Figure 1). The thalweg is defined as the longitudinal profile linking the deepest points of each cross section. On each of the following longitudinal graphs the thalweg is shown in black. The distance between two sections was chosen 500m: this resolution was on the one hand sufficient to be able the represent the topo-bathymetry, while on the other hand the number of cross section remained acceptable. These cross sections were exported in a MIKE11-format. In the final step the different cross sections were imported in MIKE11 and the necessary parameters for each cross section were derived automatically within this software:

- Wet cross section area at different heights; Figure 5 (top) gives an overview of this parameter at the level of mean low water and mean high water.
- Width at different heights; Figure 5 (bottom) gives an overview of this parameter at the level of mean low water and mean high water.

Figure 5 – Overview of wet cross section area (top) and width (bottom) for LW and HW along the estuary





4 Results

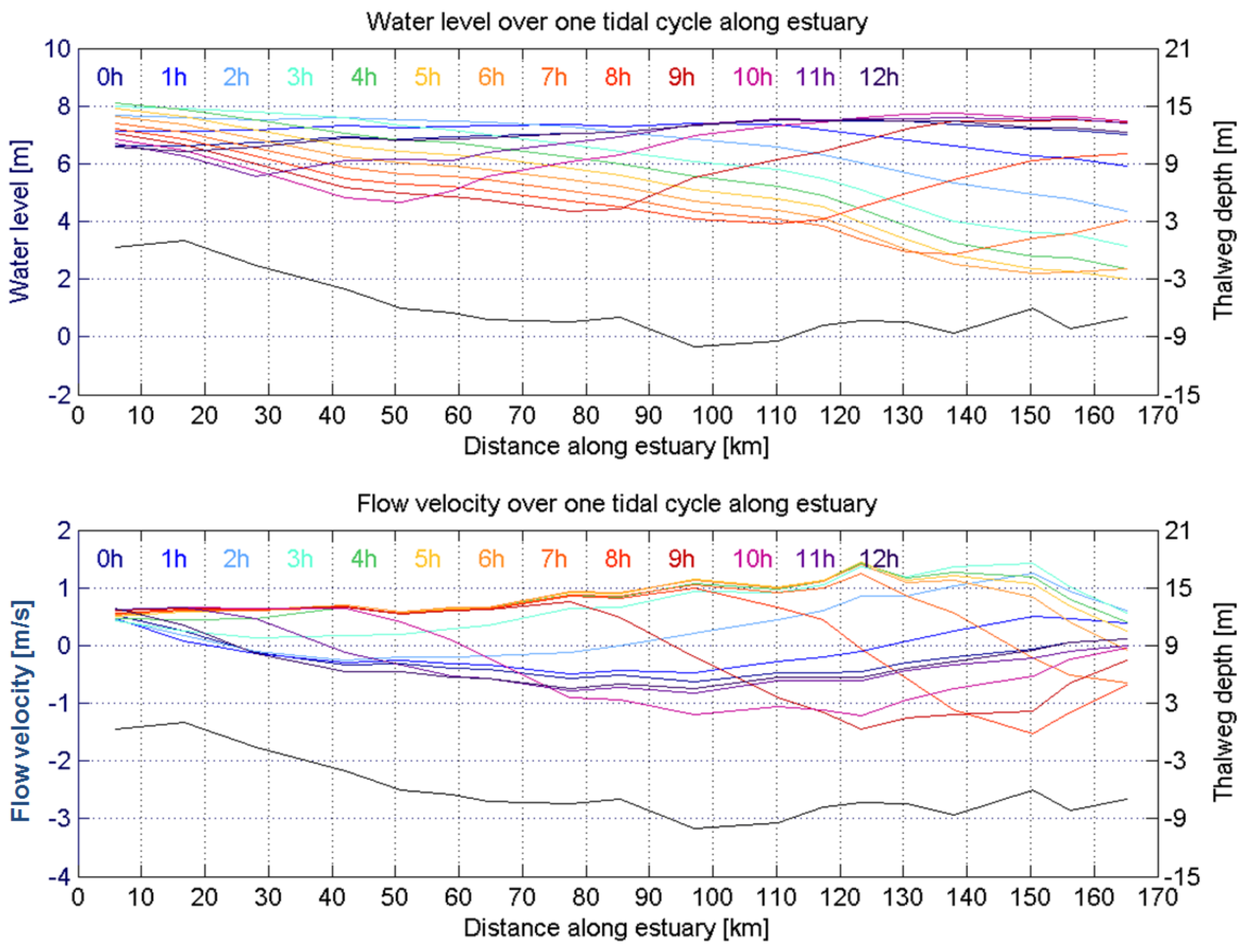
The “cubage” technique allows the calculation of different hydrodynamic parameters. Where the best agreement for the continuous water levels with the mean values for the year 2010, was found on January 15th and 16th 2010, the 50%-percentile value for the fresh water discharge (i.e. 439 m³/s) was implemented at the up-estuary boundary. The down-estuary boundary was chosen at most down-estuarine tidal station (Balisa, KM 165).

In the following paragraphs the main parameters along the longitudinal axis of the estuary are presented. In Annex A the variation in time of both the discharge as the flow velocity is presented for each of the tidal stations.

4.1 Instantaneous water levels and flow velocities

Figure 6 presents the instantaneous water level and flow velocity (ebb = positive | flood = negative) lines for the Seine estuary. Each line represents the instantaneous water levels/flow velocity along the estuary at one certain moment of the tidal cycle. The different lines are shown with an interval of one hour (0h00 is high water at Balisa).

Figure 6 – Instantaneous water level (top) and flow velocity lines (bottom)

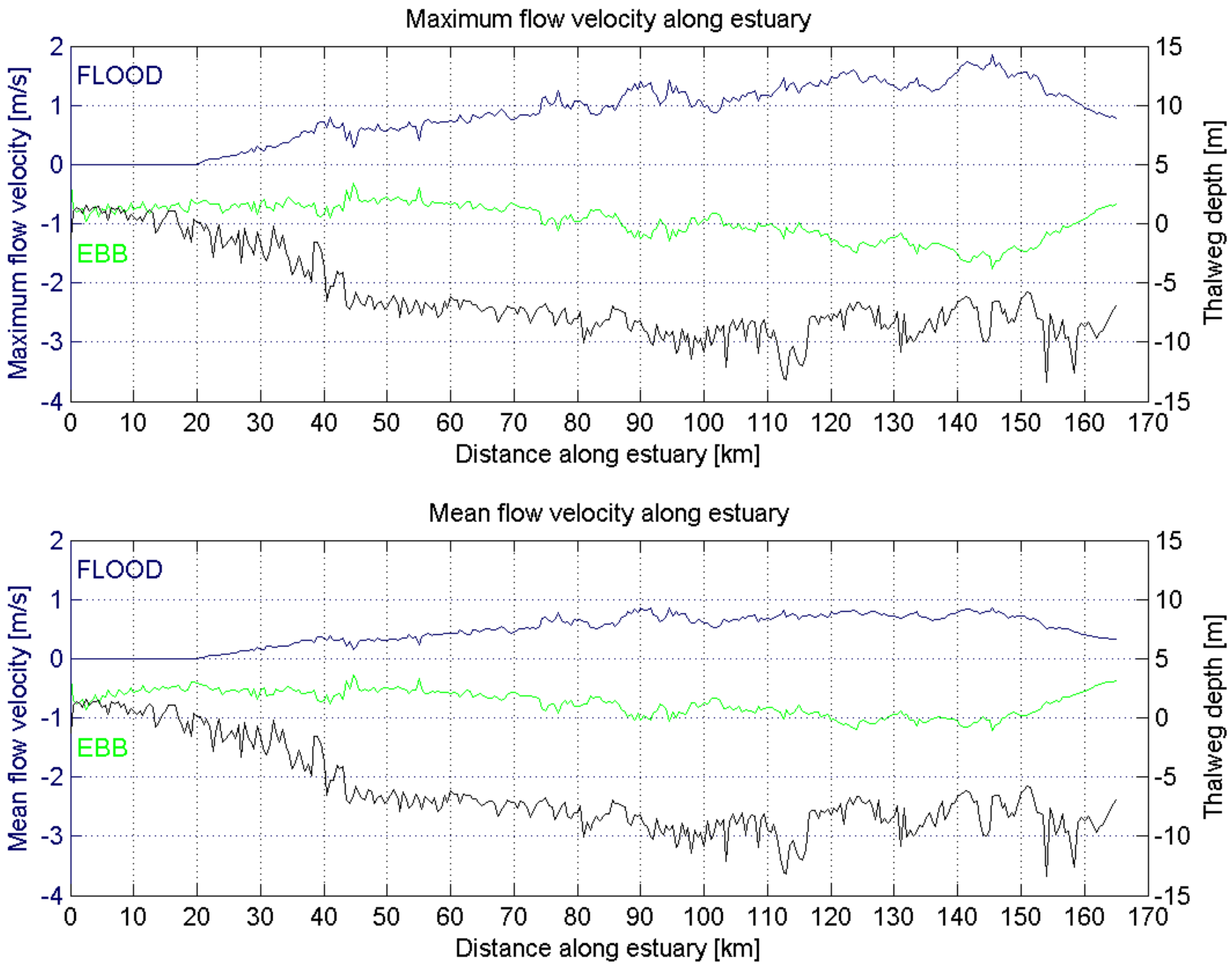


4.2 Flow velocities

Beside the instantaneous flow velocity lines, mean and maximum flow velocities during a tidal cycle are derived along the estuary. Figure 7 (top) shows the maximum ebb and flood flow velocity over the selected tidal cycle, while Figure 7 (bottom) presents the mean ebb and flood flow velocity over the selected tidal cycle.

Time series of flow velocity and discharge are presented in Annex A for all tidal stations.

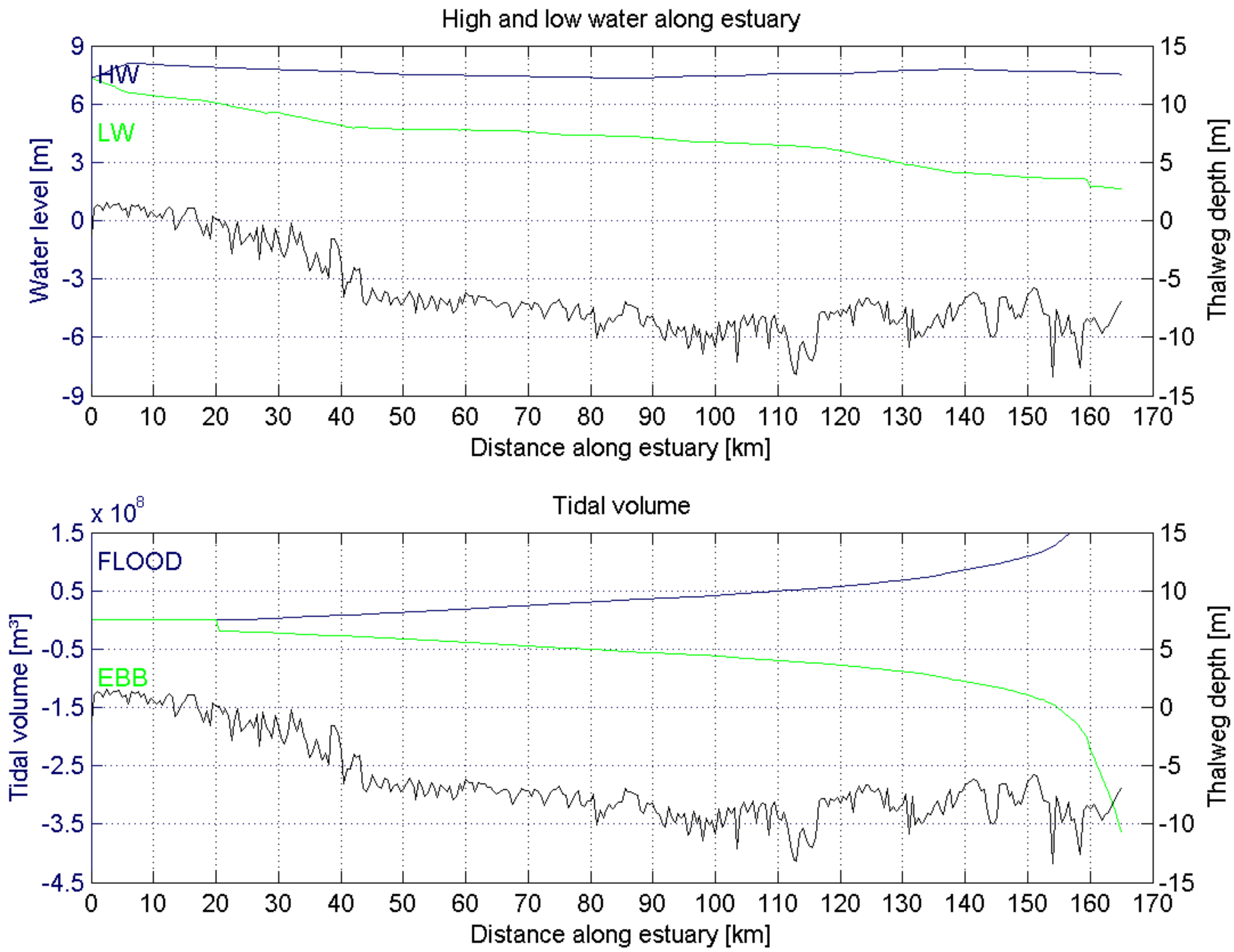
Figure 7 – Maximum (top) and mean (bottom) ebb and flood flow velocities (averaged over one tidal cycle) along the estuary



4.3 Tidal volumes

Figure 8 presents the tidal volumes (over the selected tidal cycle) along the estuary. Where no flood currents/discharges occur, no tidal volumes were calculated (most up-estuarine 20 KM).

Figure 8 – High and low water (top) and tidal ebb and flood volumes (bottom) along the estuary



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Appendix A

Figure A1 – Flow velocity (top) and discharge (bottom) from cubage at tidal station Pont de l'Arche

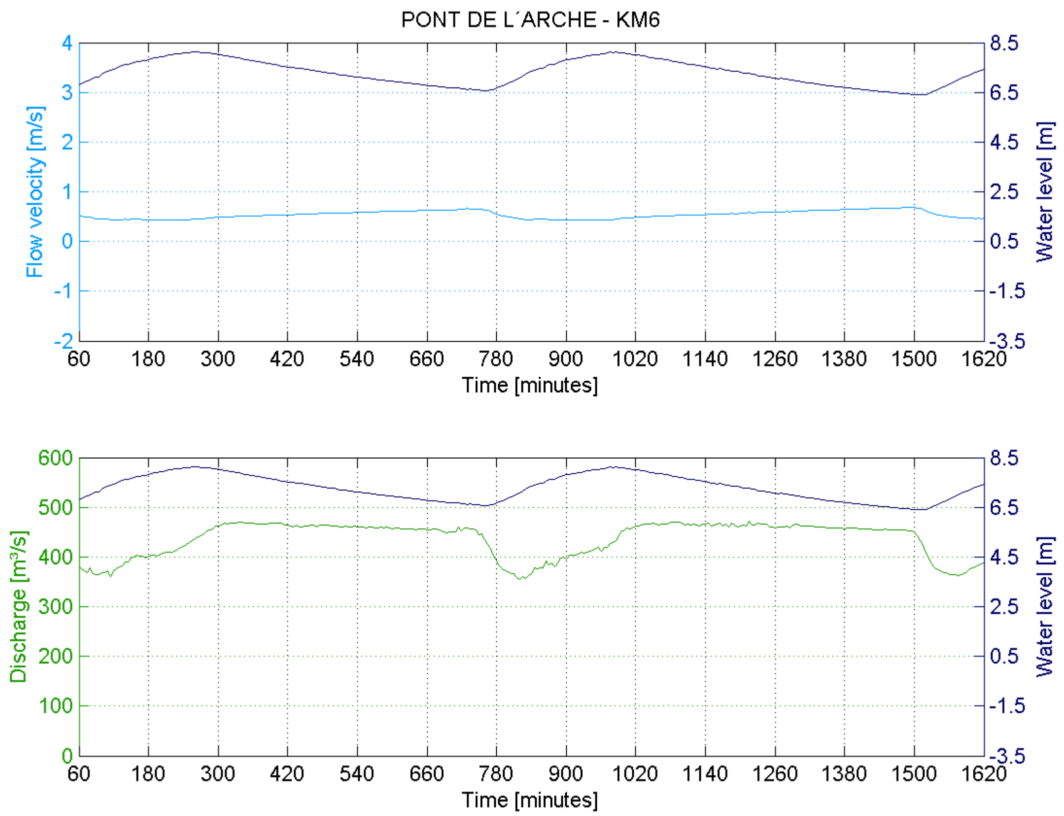


Figure A2 – Flow velocity (top) and discharge (bottom) from cubage at tidal station Elbeuf

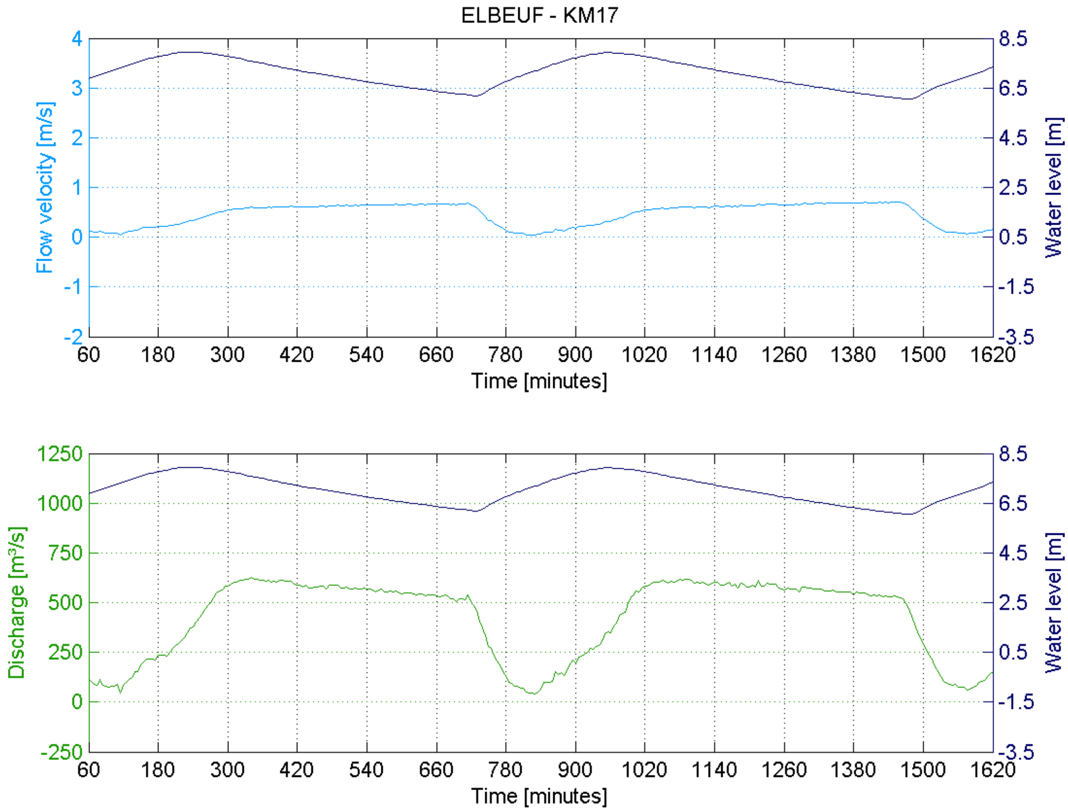


Figure A3 – Flow velocity (top) and discharge (bottom) from cubage at tidal station Oissel

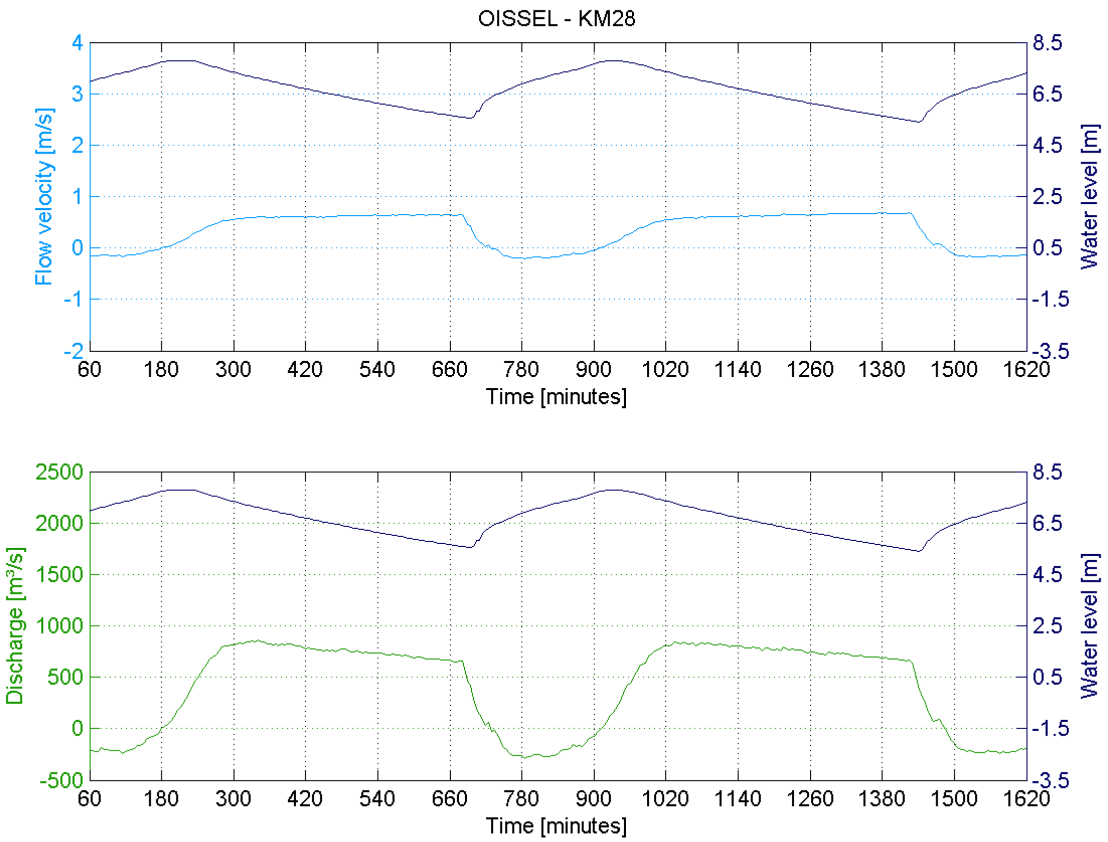


Figure A4 – Flow velocity (top) and discharge (bottom) from cubage at tidal station Rouen

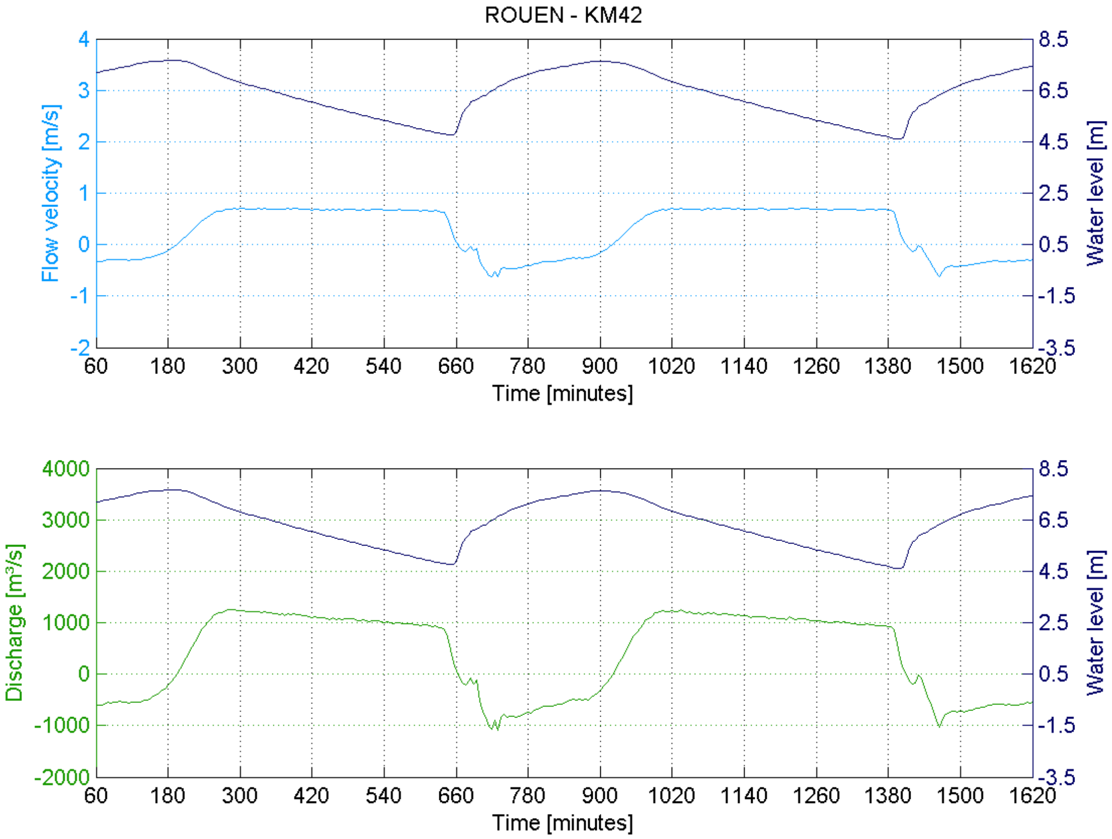


Figure A5 – Flow velocity (top) and discharge (bottom) from cubage at tidal station Couronne

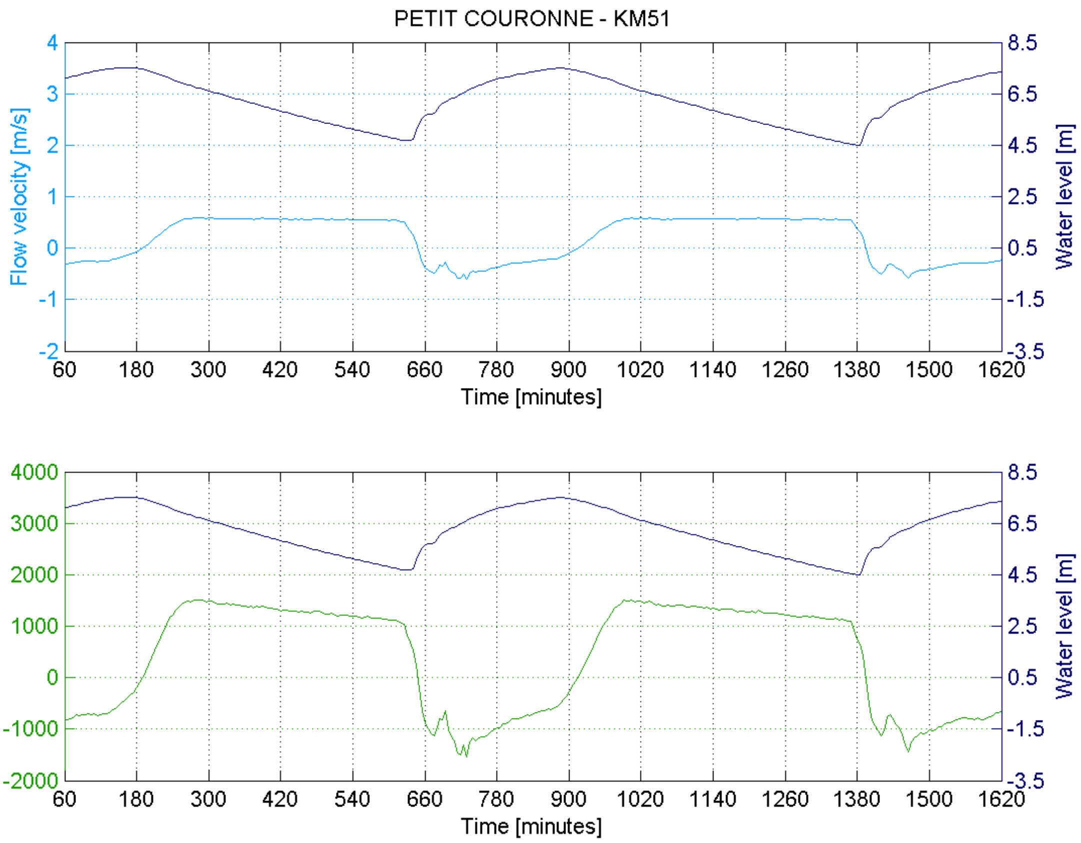


Figure A6 – Flow velocity (top) and discharge (bottom) from cubage at tidal station La Bouille

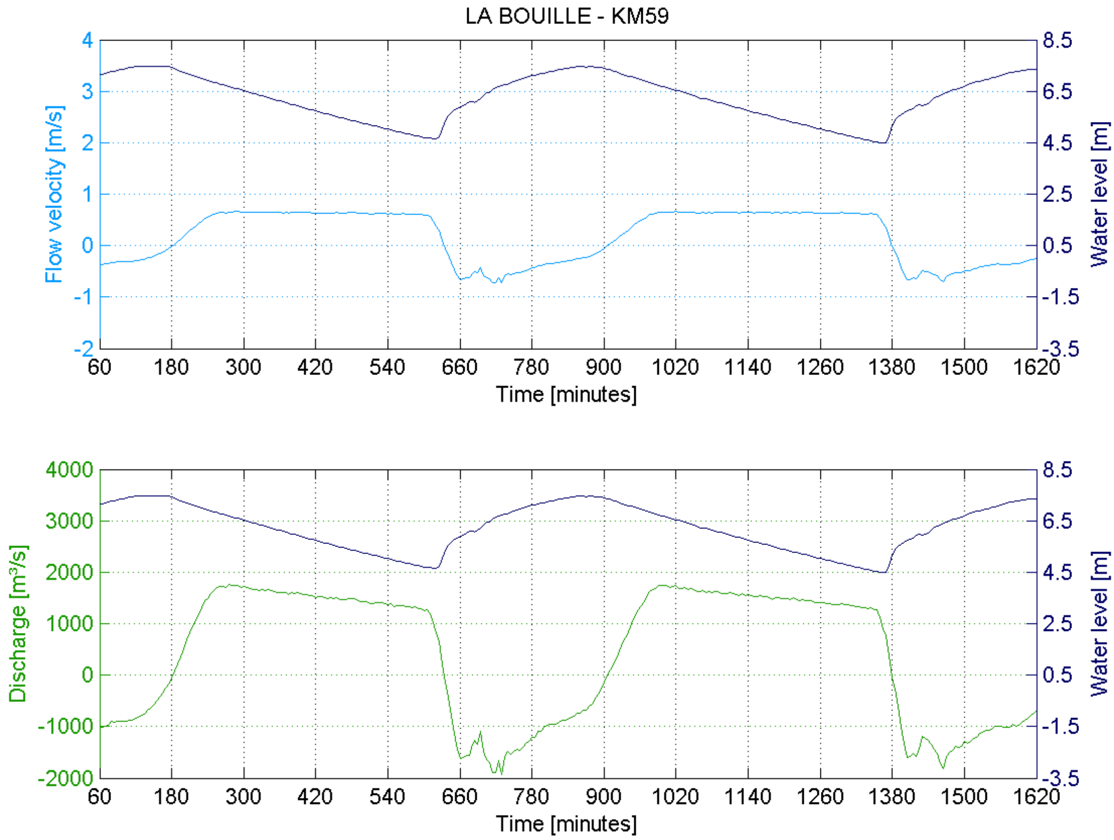


Figure A7 – Flow velocity (top) and discharge (bottom) from cubage at tidal station Val des Leux

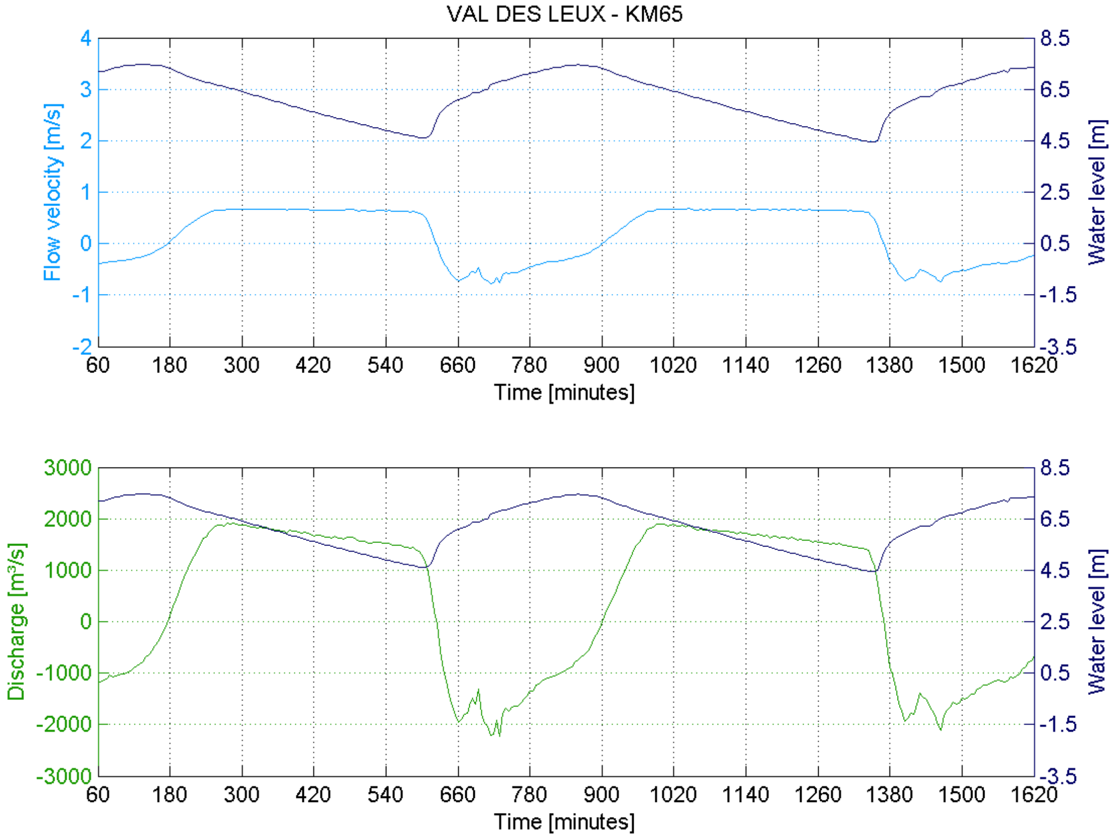


Figure A8 – Flow velocity (top) and discharge (bottom) from cubage at tidal station Duclair

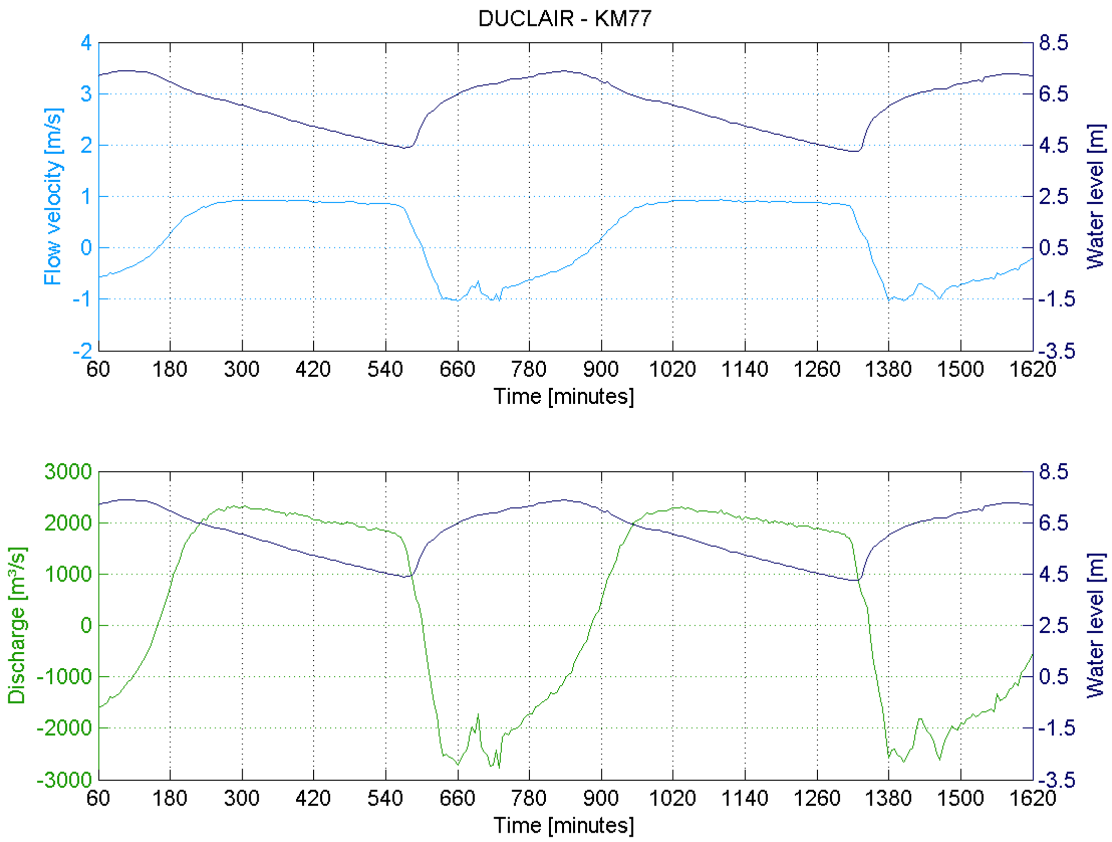


Figure A9 – Flow velocity (top) and discharge (bottom) from cubage at tidal station Mesnil-sous-Jumièges

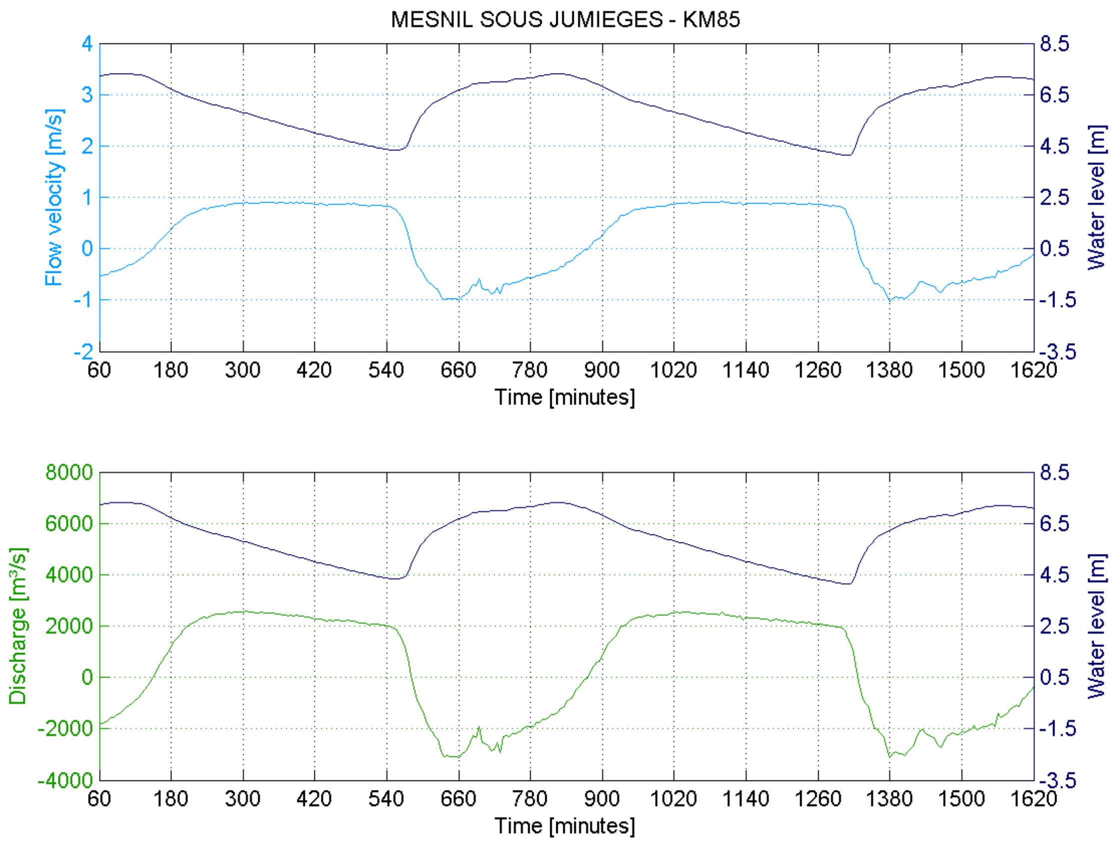


Figure A10 – Flow velocity (top) and discharge (bottom) from cubage at tidal station Heurteauville

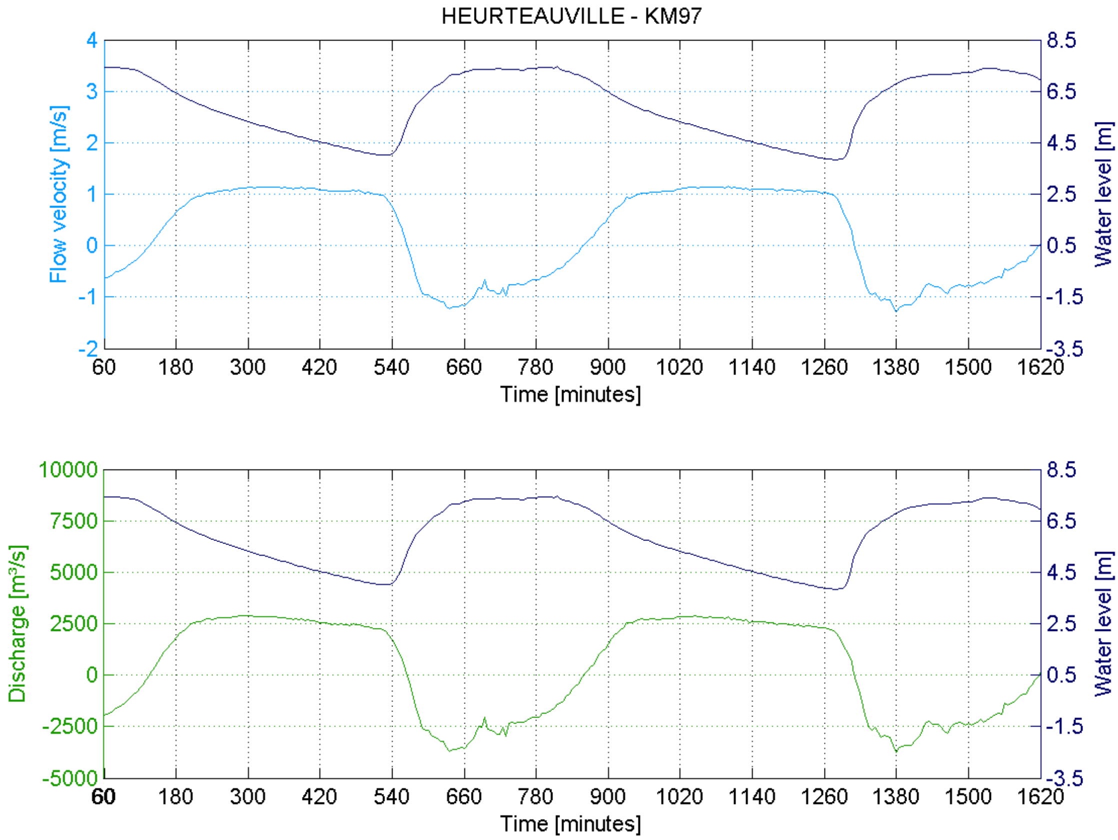


Figure A11 – Flow velocity (top) and discharge (bottom) from cubage at tidal station Caudebec

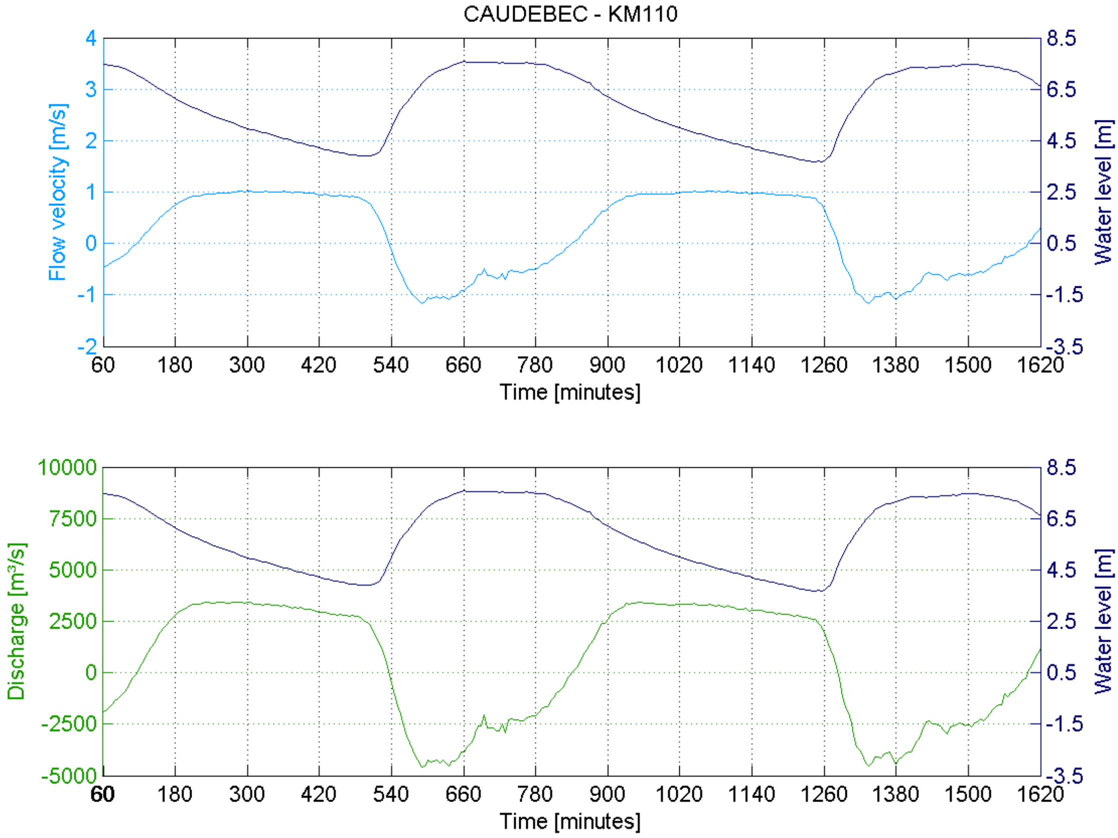


Figure A12 – Flow velocity (top) and discharge (bottom) from cubage at tidal station Vatteville

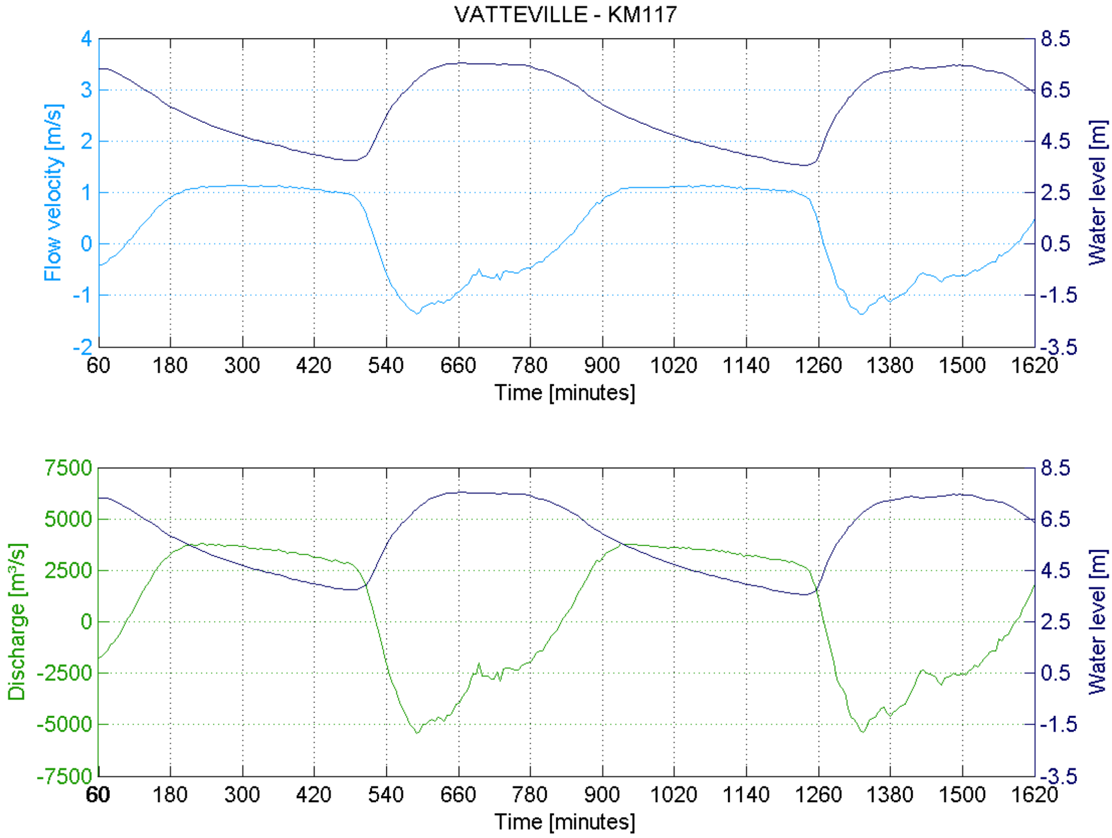


Figure A13 – Flow velocity (top) and discharge (bottom) from cubage at tidal station Aizier

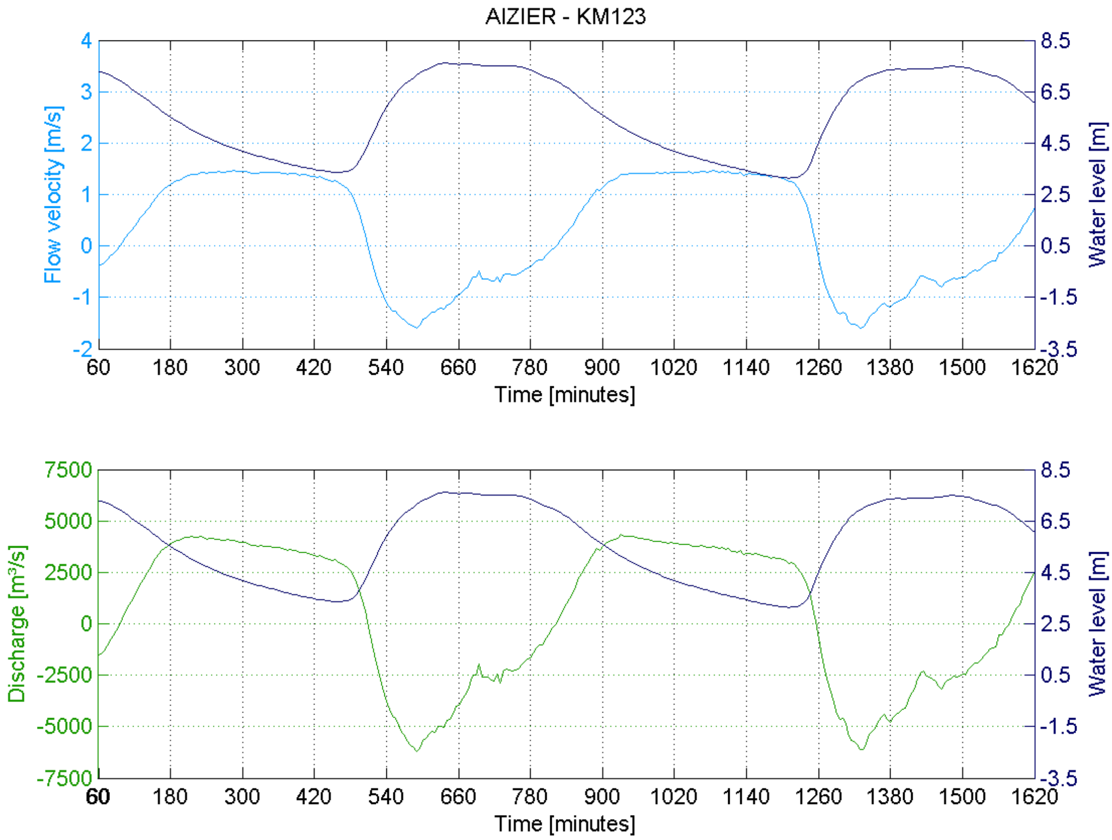


Figure A14 – Flow velocity (top) and discharge (bottom) from cubage at tidal station St Leonard

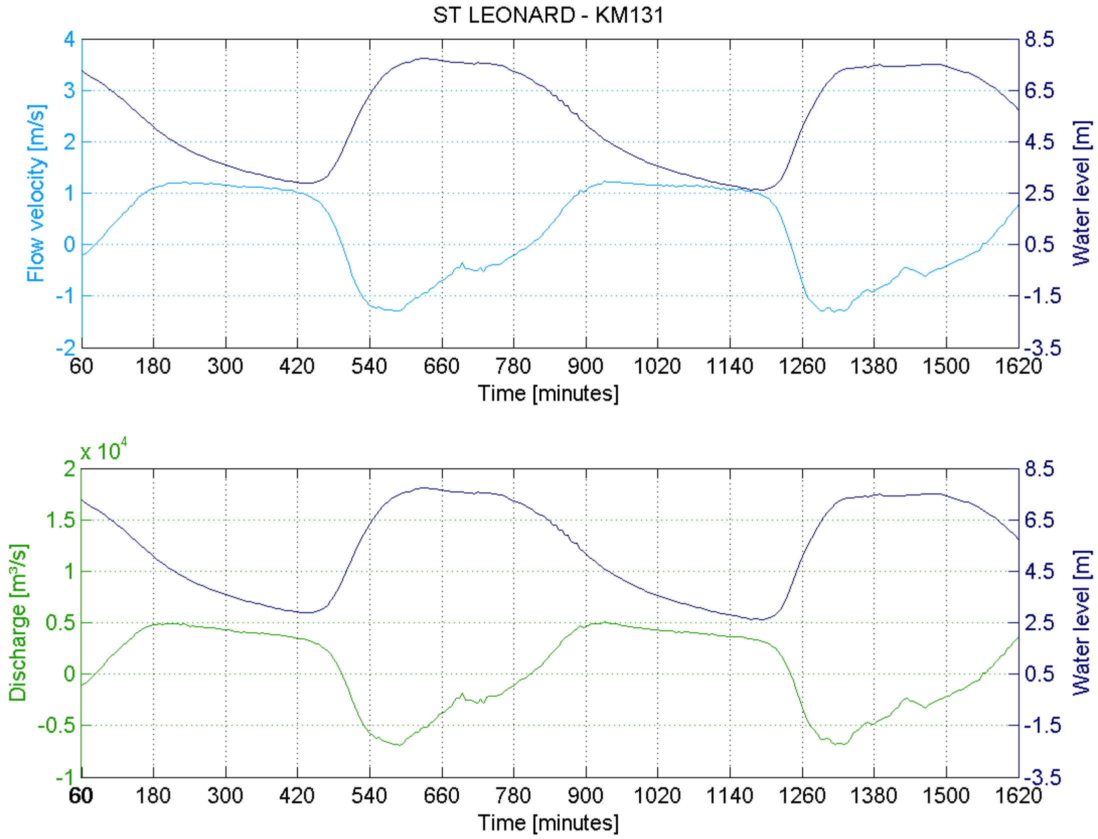


Figure A15 – Flow velocity (top) and discharge (bottom) from cubage at tidal station Tancarville

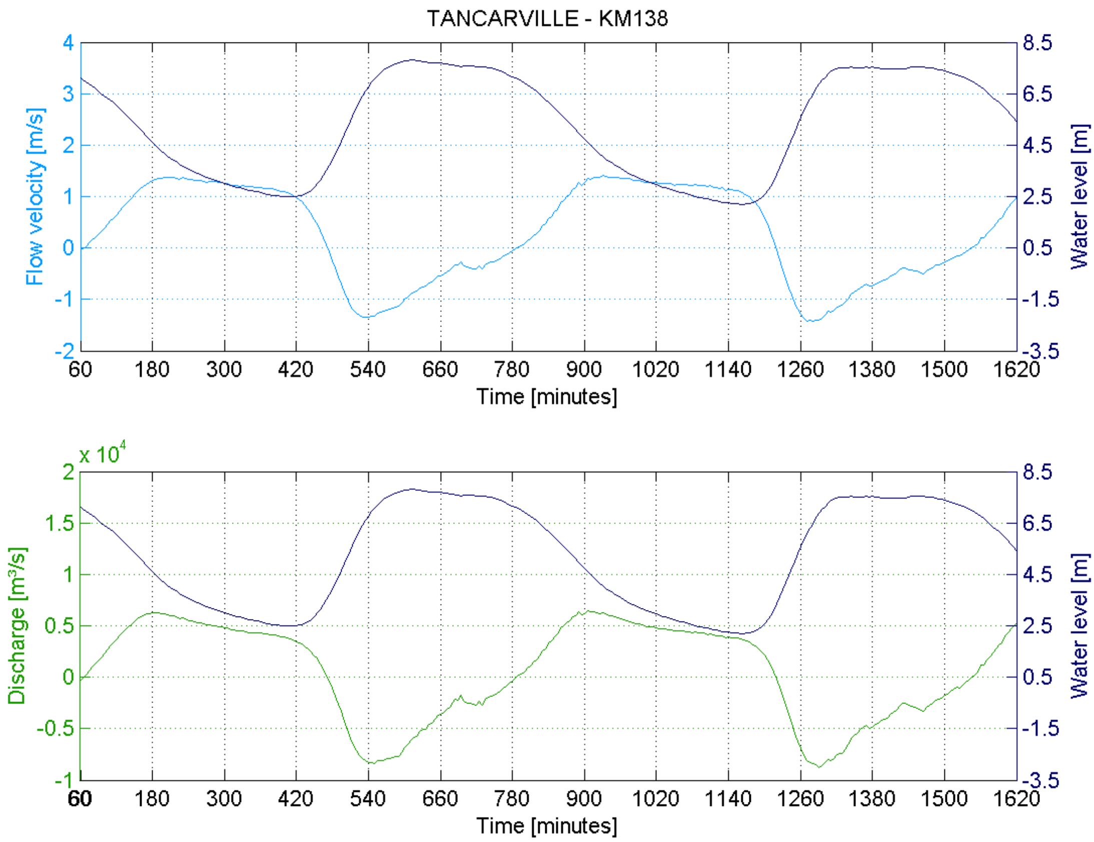
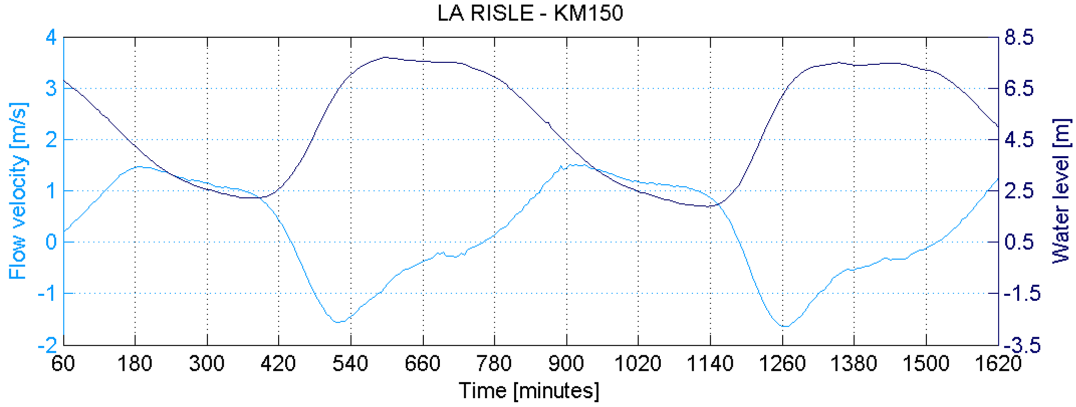


Figure A16 – Flow velocity (top) and discharge (bottom) from cubage at tidal station La Risle



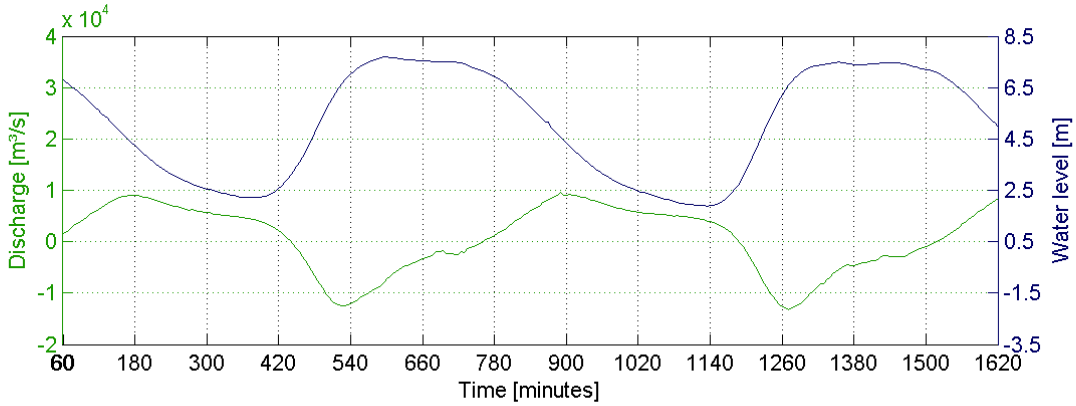


Figure A17 – Flow velocity (top) and discharge (bottom) from cubage at tidal station Honfleur

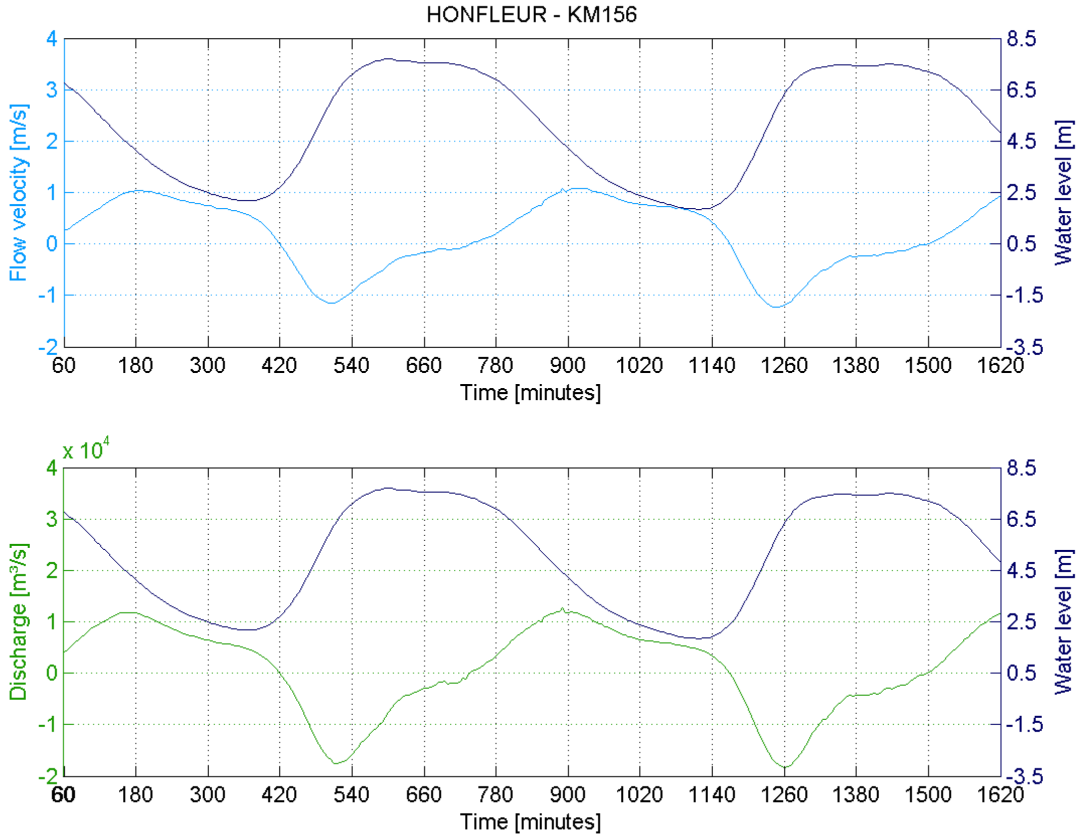
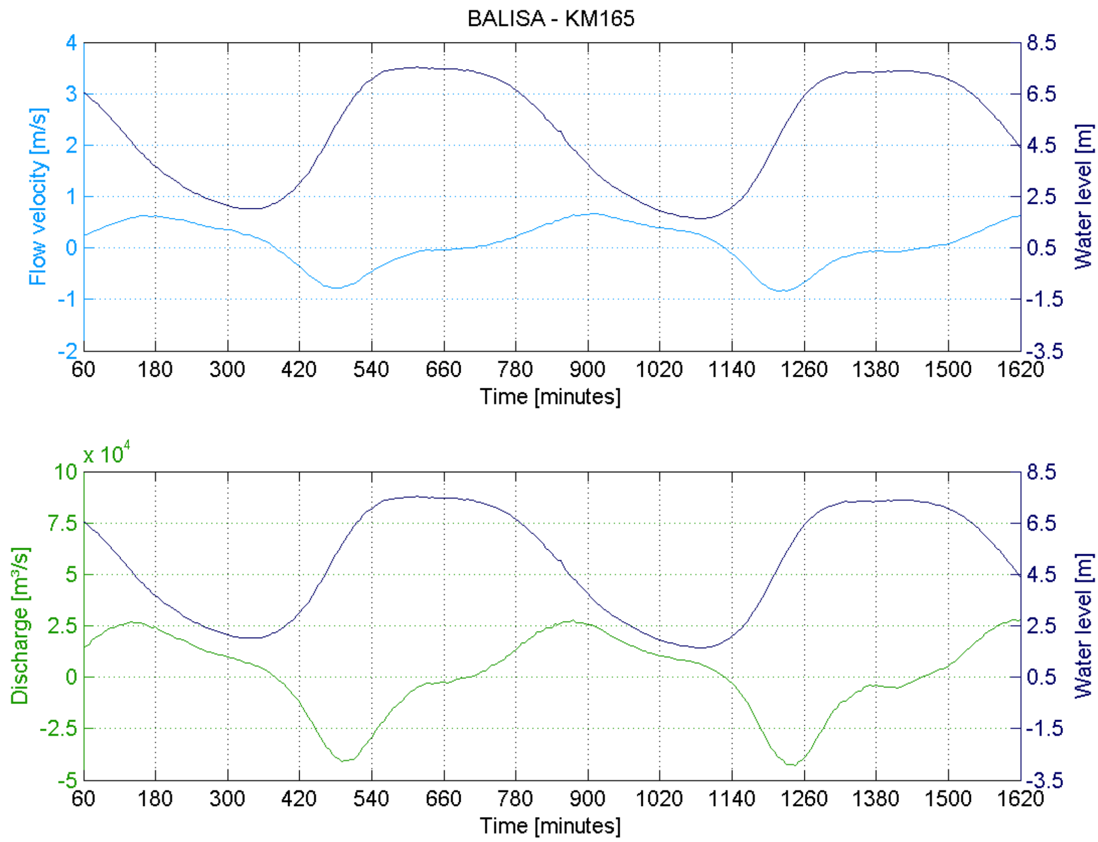


Figure A18 – Flow velocity (top) and discharge (bottom) from cubage at tidal station Balisa



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