



HAL
open science

Hydrodynamics of a hyper-tidal estuary influenced by the world's second largest tidal power station (Rance estuary, France)

Rajae Rtimi, Aldo Sottolichio, Pablo Tassi

► **To cite this version:**

Rajae Rtimi, Aldo Sottolichio, Pablo Tassi. Hydrodynamics of a hyper-tidal estuary influenced by the world's second largest tidal power station (Rance estuary, France). *Estuarine, Coastal and Shelf Science*, 2021, 250, 10.1016/j.ecss.2020.107143 . insu-03678683

HAL Id: insu-03678683

<https://insu.hal.science/insu-03678683>

Submitted on 3 Feb 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

Hydrodynamics of a hyper-tidal estuary influenced by the world's second largest tidal power station (Rance estuary, France)

Rajae RTIMI^{1,2}, Aldo SOTTOLICHIO², and Pablo TASSI^{1,3}

¹Electricité de France, Research and Development Departement (EDF R&D). Address: 6 Quai Watier, 78400 Chatou, France. Email: rajae.rtimi@edf.fr; pablo.tassi@edf.fr

²EPOC Laboratory CNRS, University of Bordeaux. Address: Allée Geoffroy Saint Hilaire, 33615 Pessac, France. Email: aldo.sottolichio@u-bordeaux.fr

³Saint-Venant Hydraulics Laboratory. Address: 6 Quai Watier, 78400 Chatou, France.

Abstract

The Rance estuary is a relatively small low-discharge steep-sided *ria*, located along the Brittany coast in northern France, with a maximum spring tidal range of 13.5 m. Taking advantage of this hyper-tidal regime, the first and currently the second largest operational tidal power station in the world was built at the estuary's mouth and has been in operation since the 1960s. Despite the well-known effect of damping of estuarine water levels, little attention has been given to quantifying the influence of the plant on the propagation and asymmetry of the tidal wave inside the estuary. In this study, hydrodynamics and tidal wave patterns were analyzed in this anthropogenically influenced estuarine system. A two-dimensional depth-averaged numerical model of the Rance estuary was developed. Two scenarios without the tidal power plant involving the dam's pre- and post-construction bathymetry (1957 and 2018 respectively) and present-day conditions scenarios were designed, to highlight the impact of bed evolution and the tidal power station on hydrodynamics and tidal asymmetry. Numerical results showed that, without the structure, bathymetric evolution did not substantially influence estuarine hydrodynamics. Nevertheless, on the estuary-side of the dam, the presence of the tidal power plant induced (i) a decrease in both tidal range and tidal prism, (ii) an increase of low water levels, and (iii) a decrease in both flood and ebb currents. Contrastingly, the region close to the structure reacted differently to plant operating modes, with an increase in flood currents (ebb currents) upstream of

25 the sluice gates (downstream of the turbines). For both the natural condition and the artificially-induced
26 hydrodynamic forcing due to the presence of the plant, numerical results showed that the Rance estuary
27 mainly exhibits flood-dominant behavior, with a longer duration of falling than rising water and stronger
28 peak flood currents than ebb currents. Spanning a period of approximately 60 years, this study presents a
29 quantitative analysis of the influence of the tidal power station on the hydrodynamics in the Rance estuary,
30 and its possible consequences for sediment dynamics. This approach is novel for this particular enclosed
31 water body, characterized by the presence of a dam at its mouth and a lock at its uppermost limit.

32 **Keywords:** Tidal power station, Rance estuary, hydrodynamic processes, tidal asymmetry, numerical mod-
33 eling.

34 1 Introduction

35 Hyper-tidal estuaries exhibit large tidal range (i.e., mean tidal range > 6 m) and strong tidal currents, making
36 them ideal for tidal renewable energy projects. Tidal energy is a form of hydro-power with potential as
37 one of the future sources of renewable energy. However, a tidal power project can modify local hydrody-
38 namics significantly, with impact on sediment dynamics, water quality and ecosystems [1, 2, 3]. Therefore,
39 understanding the impact on hydrodynamics induced by tidal projects is crucial for predicting possible en-
40 vironmental impacts.

41 In estuaries, hydrodynamic behavior is influenced by several factors [4, 5, 6, 7]: (i) the gravitational forces
42 of the Moon and the Sun combined with the rotation of the Earth; (ii) the estuary's morphology, and (iii)
43 the freshwater input discharge. In macro-tidal estuaries, hydrodynamics is mainly governed by tides which,
44 have a profound impact on residual sediment dynamics and consequently on morphological evolution [8].
45 As examined by several authors [9, 10, 11, 12, 13], tidal asymmetry plays an important role, causing residual
46 sediment transport in estuarine systems [14, 15, 16], and can be computed from flow velocity and water
47 elevation [11, 12, 17]. The former identifies the nature of the asymmetry: *i.e.*, ebb- or flood-dominance in
48 the estuary. The latter compares the durations of rising and falling tides. This indicates the predominant
49 direction of residual transport of coarse sediment (gravel and sand) carried by bedload and of fine sediment
50 (silt and clay) carried by suspension. Asymmetry in low and high slack water duration is also relevant to
51 the net transport of the finer sediment fraction in the water column [18]. A human intervention such as a
52 dam located at a seaward boundary modifies the hydrodynamic regime and significantly alters non-linear

53 tidal interactions [9, 10, 19, 20], which can be relevant to sediment transport and accumulation in highly
54 anthropized estuarine systems.

55 Located on the Brittany coast of northern France (Figure 1.a), the Rance estuary is a relatively small steep-
56 sided, 20 km long *ria* [21]. Its maximum perigean spring tidal range reaches 13.5 m at the mouth (Saint
57 Servan, Figure 1.b). Taking advantage of this hyper-tidal regime, the first ever tidal power station in the world
58 was built at the estuary mouth (Figure 1.b). The plant has been in operation and managed by Electricité
59 de France (EDF) since 1966 and is currently the second largest operational tidal power station in the world
60 [22]. With a peak (mean) output capacity of 240 MW (57 MW), it supplies 0.12% of the power demand in
61 France, which is equivalent to a medium-size city such as Rennes (*c.* 225,000 inhabitants) [23].

62 Experimental and numerical studies were conducted, mainly focusing on qualitative analysis of sediment
63 dynamics or ecosystem evolution in the estuary, without prior investigation of how hydrodynamics was
64 influenced by the tidal barrier [3, 24, 25, 26, 27]. Despite a well-known effect on estuarine water levels
65 [24], little attention has been given to quantifying the influence of the plant on the propagation, and vertical
66 and horizontal tidal asymmetry of the tidal wave. The first numerical hydrodynamic model of the Rance
67 estuary was developed in 2001 [26]. It consisted in a two-dimensional (2D) model used to separately study
68 the sea-side and estuary-side regions of the dam. The aim was to determine hydrodynamic parameters for
69 morphological simulations [27]. Although it provided good results with respect to measurements [26], the
70 approach did not evaluate the influence of the power plant on flow characteristics and tidal asymmetry, which
71 could have significant implications for sediment dynamics and morphological changes in the estuary. In
72 2018, 2D and 3D numerical models were developed, to evaluate bacteriological impact in the estuary [28].
73 The study area included both the basin and the offshore region. However, mesh resolution was constant over
74 the computational domain, which was insufficient to capture flow structure close to the plant and between
75 Mordreuc and Chatelier lock (Figure 1.b). The main conclusions of this study were based on the 2D model
76 results, without any further hydrodynamic analysis.

77 Both 2D and 3D numerical models are used to assess hydrodynamic impacts of existing or planned tidal
78 power plant projects. With the third highest tidal range in the world (15m maximum in spring tide), the
79 Severn estuary (United Kingdom) would be an optimal location for tidal power projects. A 2D numerical
80 model was developed by [1] to estimate the impact of three renewable-energy projects: Cardiff–Weston,
81 Fleming lagoon and Shoots dams. The basic dam operation regime adopted was ebb generation only. It
82 was concluded that the Fleming Lagoon project would have little influence on hydrodynamic processes in

83 the Severn estuary, however dam construction would have significant environmental impact [1]. Young *et*
84 *al.* developed a 2D hydrodynamic model to highlight the impact of the world's largest tidal power station,
85 the Sihwa Lake tidal power plant in South Korea [29]. The tidal energy scheme of this plant is a single
86 flood-generation mode. The study established that limiting water surface elevation would modify the estu-
87 ary's ecosystem [29]. Another optimal location for a tidal power plant would be the Bay of Fundy, located
88 on the Atlantic coast of North America, where tidal range can exceed 16 m during spring tides. 2D and 3D
89 hydrodynamic models [30, 2] simulated a range of hypothetical development scenarios with three different
90 operating modes: ebb generation only, flood generation only, and ebb-flood generation. It was concluded
91 that operating mode had considerable influence on local velocities near the lagoon, and particularly near the
92 powerhouse, but seemed to have little influence on the magnitude of far-field hydrodynamic impact [30, 2].
93 One common feature of these studies was that they were all conducted ahead of plant construction, and
94 consequently the impact assessments were only estimations.

95 The main objective of this paper is to analyze how the hydrodynamics of the Rance estuary is influenced
96 by the world's second-largest tidal power station through basic flow characteristics and tidal asymmetry
97 [12, 11]. For this, a two-dimensional depth-averaged model was developed corresponding to both ebb
98 generation and flood-ebb generation schemes (section 3). The numerical model was first calibrated and
99 validated on measurement datasets (section 4.1) and then employed to assess present-day hydrodynamic
100 conditions in the Rance estuary (section 4.2). Application of the numerical model on diverse scenarios
101 involving past/present bed elevations and presence/absence of the dam analyzed the impact of the plant on
102 flow patterns and tidal asymmetry (section 4.3). Finally, section 5 discusses the impact of the Rance tidal
103 power station on hydrodynamic processes and its potential impact on sediment dynamics.

104 **2 Study area**

105 **2.1 Rance tidal power station**

106 The main characteristics of the Rance tidal power plant are as follows (Figure 1.c): (i) a 65 m lock, with
107 20,000 vessels per year passing through; (ii) 24 Kaplan bulb turbines appropriate for very low head and high
108 flow rates [31], 323 m long and 33 m wide, each unit producing 10MW; (iii) a rockfill dyke 165 m long; (iv)
109 6 sluice gates composing 114x15 m dam; and (v) a road on which 30,000 (60,000 in summer) vehicles per
110 day travel between the cities of Dinard and Saint Malo. The particularity of the Rance tidal power plant is

111 its ability to produce electricity during both falling and rising tides (Figures 1.d & 1.e), operating by one-
112 and two-way generation modes thanks to the capacity of its Kaplan bulb turbines to rotate in both directions
113 [32, 29]. The Rance River drains a small catchment area, with an average river discharge of $7 \text{ m}^3/\text{s}$, low
114 water flow rate of $0.5 \text{ m}^3/\text{s}$ and a decennial flood of $80 \text{ m}^3/\text{s}$. These magnitudes are small compared to the
115 tidal flux observed upstream of the plant, with about $9,000 \text{ m}^3/\text{s}$ maximum in neap tide and $18,000 \text{ m}^3/\text{s}$
116 in spring tide (Figure 1.b). Further information on the estuary's morphology, sedimentary and hydrological
117 characteristics can be found in [24].

118 **2.2 Evolution of bed elevation between 1957 and 2018**

119 During the last 58 years, between 1960 (before plant construction) and 2018, the Rance estuary has been
120 subject to natural and artificial sedimentary processes governing its morphological evolution. In the present
121 study, two bathymetry configurations were used for digital elevation models (DEMs), corresponding to the
122 available datasets. The first DEM corresponds to the year 1957, prior to the plant's construction (Figure 2.a),
123 and the second to the year 2018, which is the most recent bathymetric survey (Figure 2.b). For both 1957 and
124 2018 datasets, spatial coordinates were expressed according to the World Geodetic System 1984 (WGS84).
125 Altitude was adjusted to the zero-level provided by the National Hydrograph Service (chart datum).

126 Bathymetry for 1957 was reconstructed using historical maps and data surveyed by EDF, consisting of
127 isobaths and echo-sounder point data at specific locations. To build the Digital Elevation Model, isobaths
128 and point data were vectorized using Global Mapper® and projected in 3D by TerraModel®. The estimated
129 horizontal and vertical uncertainties were of the order of 1m and 0.1m, respectively [33].

130 From May 29 to June 6 2018, a field survey was carried out to collect bathymetric and topographic data
131 in the estuary. High-frequency multibeam echo-sounder measurements were performed to map the estuary
132 bottom. Intertidal zone topography was measured on a light detection and ranging system (LIDAR) [34].
133 The mean uncertainties of the horizontal and vertical measurements were of the order of 0.01m.

134 Downstream of the tidal power station, both DEMs employed the same bathymetry, extracted from the SHOM
135 HistoLitt® surveys carried out between 1970 and 2005 [35]. For seabed depths up to 50m, vertical resolution
136 ranged from 0.3m to 1m and horizontal resolution from 1m to 20m. Beyond 50m, vertical resolution ranged
137 from 1‰ to 2‰ of depth and horizontal resolution was few tens of meters [35].

138 According to bed evolution depicted in Figure 2.c, there was an erosional zone upstream of the sluice gates.
139 Conversely, in the lower part of the estuary, sediment accretion occurred in the meandering reach downstream

140 of Mordreuc. Furthermore, in the middle-estuary region between Ton peak and Saint Hubert port, little
141 difference was observed between the 1957 and 2018 bathymetries. The changes in bathymetry may present
142 inaccuracies due to measurement uncertainty in the older maps.

143 **3 Numerical modeling**

144 **3.1 Hydrodynamic model**

145 The TELEMAC-2D module, belonging to the open-source TELEMAC-MASCARET modeling system
146 (www.opentelemac.org) was used to study hydrodynamics in the Rance estuary and to investigate changes
147 in flow characteristics induced by the tidal power plant. This module solves the two-dimensional, horizontal
148 shallow water equations (2DH), which implicitly assume hydrostatic pressure distribution, constant fluid
149 density and depth-averaged velocity components [36, 37]. This modeling approach has been applied to other
150 shallow and vertically well-mixed estuaries [38, 39, 40, 41, 2]. The numerical tool has been assessed in
151 applications in several coastal and estuarine cases [42, 43, 44, 45, 46]. Two relationships were specified
152 to close the governing equations: a classical squared function dependency on depth-averaged velocity for
153 bed resistance, and the Boussinesq approximation for turbulence parameterization [36]. This study used the
154 Strickler law for bottom friction and a zero-equation turbulence model with constant eddy viscosity. The
155 Strickler coefficient and eddy viscosity values were assumed to be constant over the whole computational
156 domain. They were calibrated using Acoustic Doppler Current Profiler (ADCP) observed data from 2012
157 [47] and validated with measurements of water surface elevation from tidal gauges during 2019. The
158 computational domain covered the sea-side and the estuary-side areas extending from the oceanic open
159 boundary (~ 20km from the tidal power plant) to the upstream limit (Chatelier lock). It was discretized with
160 an unstructured mesh generated by the BlueKenue® pre- and post-processing tool [48]. The mesh consisted
161 of 399, 512 triangular elements and 204, 565 nodes with variable resolution ranging between 1000m offshore,
162 250m near the coastline, 50m around the estuary mouth, 20m inside the estuary and 5m close to power station
163 and within the lower estuary between Mordreuc and Chatelier lock, see Figure 1 [49]. The topo-bathymetric
164 information contained in the DEM was projected onto the finite element mesh using the inverse distance
165 weighting interpolation algorithm [50]. Boundary conditions were set as follows:

166 (i) At the oceanic open boundary (offshore), water levels and velocity component values were imposed

167 through 11 tidal constituents (M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4 and MN4) from the OSU
168 TPXO European Shelf 1/30 regional model [51].

169 (ii) At the upstream limit (Chatelier lock, Figure 1), freshwater input from the Rance river was set up as
170 varying between $5\text{m}^3/\text{s}$ and $30\text{m}^3/\text{s}$. The configuration of this boundary is complex: in addition to
171 the lock, 2 sluice gates maintain constant water level at the port located upstream of the Chatelier lock.
172 As the flow passing through these structures is not measured, flow discharge was estimated from the
173 mean Rance river flowrate, collected from the nearest hydrometric station located $\sim 33\text{km}$ upstream
174 of Chatelier lock.

175 (iii) The tidal power station was represented by two weirs: the first depicts the turbines structure and the
176 second depicts the sluice gates structure. Unlike existing tidal power station models (TPS models)
177 [52, 2, 1], the operation modes of the turbines and sluice gates were calculated by an external
178 optimization algorithm Software named AGRA [53] and not by the head difference seen on TELEMAC-
179 2D. AGRA Software, based on the dynamic programming method [54], is used by operators in charge
180 of the plant to simulate optimal energy generation and the resulting hydraulic conditions (flowrates,
181 start and stop times, *etc.*), notably according to head difference and equipment availability [53]. In
182 order to be consistent with the actual regime of the power plant, the AGRA output was used as input
183 in the TELEMAC-2D model to define the operating mode of the turbines and sluice gates. Following
184 studies by [1, 2, 52], the turbines and sluice gates were treated separately with their corresponding
185 flowrates, to ensure good representation of the complex flow structure in the zone around the dam;
186 the approach of imposing a single flowrate throughout the whole plant boundary was not adopted. In
187 TELEMAC-2D, a weir is considered as a linear singularity, represented by an island in the mesh [55].
188 Standard weir discharge equations already exist in TELEMAC-2D [55], but were adjusted as follows
189 to suit the Rance tidal plant's operation:

- 190 • Flowrate through turbines was computed by three methods depending on operating mode: (a)
191 For direct-, inverse-turbining and direct pumping (D.T., I.T. and D.P. in Table 1), flowrate was
192 interpolated using discharge data generated by the AGRA Software, based on hill charts where
193 flowrate is computed according to turbine blade incidence, which in turn depends on real head
194 difference and tidal power. (b) For filling and draining phases (F.O. and D.O. in Table 1), flowrate
195 $Q_{turbines}$ was computed according to standard orifice equation 1. (c) For Turbines Off phase

(T.O. in Table 1), flowrate $Q_{turbines}$ was set to 0.

$$Q_{turbines} = N_{turb} \cdot A(|\zeta_{estuary} - \zeta_{sea}|)^{1/2} \quad (1)$$

- Flowrate through sluice gates in the Gates Open stage (G.O. in Table 1) was computed by equation 2, adjusted from the standard orifice equation ($Q \propto C_d H^{0.5}$) using a variable instead of a constant discharge coefficient. This approach was adopted since the sluice gates in the Rance power plant are large and appropriate for low head differences, and thus the discharge coefficient varies significantly according to downstream water level. For the Gates Closed stage (G.C, Table 1), flowrate $Q_{sluices}$ was set to 0.

$$Q_{sluices} = N_{sg} (B \zeta_{downstream}^{1/4} - C) (|\zeta_{estuary} - \zeta_{sea}|)^{1/2} \quad (2)$$

In the above equations, $\zeta_{estuary}$ and ζ_{sea} are surface water elevations at Saint Suliac and Saint Servan respectively (see Figure 1 for locations). N_{turb} and N_{sg} are numbers of available turbines and sluice gates respectively. A , B and C are discharge coefficients and $\zeta_{downstream}$ is downstream water surface elevation. Table 2 summarizes values of these parameters (A , B , C , $\zeta_{downstream}$) according to tidal phase (flood and ebb).

Turbine flowrate, $Q_{turbines}$, was then distributed homogeneously across the 24 turbines. Likewise, for sluice gates, $Q_{sluices}$ was distributed homogeneously across the 6 sluice gates. This assumes that all the plant's equipment is available, which is not always the case. However, given that the outage rate for hydroelectric units is low, this assumption would not significantly influence the numerical results. In this study, both water surface elevation and bottom elevation are relative to the chart datum.

- (iv) The rest of the domain contour was represented by a closed solid boundary.

3.2 Tide analysis

To analyze in depth the influence of the plant on the hydrodynamics in the estuary, four complementary metrics were evaluated:

- (i) Tidal prism (TP), defined as the volume of water leaving the estuary at ebb tide [56]. This parameter was deduced from flowrate passing through the TPS section ($Q_{\Sigma TPS}$) located upstream of the plant

221 (Figure 1.b) and was calculated from Eq.3:

$$222 \quad TP = \int_{t \in ebb} Q_{\Sigma TPS}(t) dt \quad (3)$$

223 Tidal prism was further analyzed over a fortnightly tidal cycle to assess its evolution over neap/spring
224 tidal periods.

225 (ii) Mean residence time (T_r), defined as the time taken by a water parcel to leave a defined region through
226 its outlets to the sea [57]. Following studies by [58, 59, 60], mean residence time can be computed
227 from the theoretical tidal prism method as in Eq.4:

$$228 \quad T_r = \frac{VT}{(1-b)TP} \quad (4)$$

229 where V is the mean volume of water in the system, T is the tidal period, TP is the tidal prism, and b
230 is the return-flow factor, defined as the fraction of ebb water returning to the system during the flood
231 tide ($0 < b < 1$) [58].

232 (iii) Ebb/flood tidal current asymmetry $\gamma_0(n = u)$, and tidal duration asymmetry $\gamma_0(n = \frac{\partial \zeta}{\partial t})$, were
233 quantified by computation of skewness as defined by Nidziedo & Ralston [12]:

$$234 \quad \gamma_0(n) = \frac{\mu_3(n)}{\mu_2^{3/2}(n)} \quad (5)$$

235 where the m -th moment about zero, μ_m , is:

$$236 \quad \mu_m(n) = \frac{1}{N-1} \sum_{i=1}^N n_i^m \quad (6)$$

237 and N is the number of samples n_i and ζ is the water surface elevation.

238 The Rance estuary does not have a single along-channel velocity direction. For instance, the flow is
239 mainly aligned north-south upstream of Ton peak, and east-west downstream. Hence, the current field
240 can be defined as the velocity magnitude affected by the sign of the North-South velocity component.
241 Parameters ($\gamma_0(u); \gamma_0(\partial \zeta / \partial t)$) were computed as the median over a neap-spring tidal period to analyze
242 their spatial distribution upstream and downstream of the plant; Nidziedo & Ralston [12] showed that

243 the tide is ebb dominant for $\gamma_0(u) < 0$ and flood dominant for $\gamma_0(u) > 0$. They reported that the
244 duration of falling water is shorter than rising water for $\gamma_0(\frac{\partial\zeta}{\partial t}) < 0$ and longer for $\gamma_0(\frac{\partial\zeta}{\partial t}) > 0$.

245 (iv) Asymmetry metrics were analyzed by computing the amplitude ratio $\alpha = a_{M_4}/a_{M_2}$ and phase differ-
246 ence $\beta = 2\phi_{M_2} - \phi_{M_4}$ on both water surface elevation (ζ) and current (u). As the Rance estuary is
247 dominated by the M_2 semidiurnal tide, this approach is appropriate for quantifying tide asymmetry.
248 According to Friedrichs & Aubrey [11], the amplitude ratio α indicates the degree of non-linearity:
249 *i.e.*, the capacity of the estuary to generate/amplify secondary harmonics (M_4 , M_6 , *etc.*). As for phase
250 difference β , it illustrates the asymmetry direction, flood or ebb dominance. Least squares harmonic
251 analysis of water surface elevation and current was performed on a record of 20 days using the T-TIDE
252 toolbox [61]. Asymmetry metrics were then computed at selected locations in the estuary and further
253 analyzed with Nidzieko & Ralston [12] asymmetry parameters ($\gamma_0(u); \gamma_0(\partial\zeta/\partial t)$).

254 4 Results

255 In this section, the numerical model was calibrated and validated using respectively ADCP measurements
256 collected for five tide cycles in 2012 and a water level dataset recorded from tidal gauges for a period of
257 a fortnight in 2019 (subsection 4.1). Numerical model results were then analyzed to better understand the
258 hydrodynamics in the estuary and to highlight the influence of the power plant on the estuarine system.
259 Subsection 4.2 provides a description of the hydrodynamics in the estuary today. Tide propagation and
260 asymmetry are analyzed for three scenarios in subsection 4.3.

261 4.1 Model calibration and validation

262 To calibrate the numerical model and validate its capacity to predict water surface elevation and tidal currents,
263 two datasets from 2012 [47] and 2019 were used. Firstly, the numerical model with the recent bathymetry
264 of 2018 (Figure 2), was calibrated using a dataset consisting of Acoustic Doppler Current Profiler (ADCP)
265 measurements for five tide cycles (June 4 – 6 2012) collected at three locations near the power station:
266 upstream of the turbines (ADCP 1), upstream of the sluice gates (ADCP 2) and downstream of the power
267 station (ADCP 3). Secondly, the numerical model was validated using a larger dataset of water surface
268 measurements from tidal gauges for the period August 15 – 28 2019. This validation was needed to assess
269 the capacity of the model to propagate the tide along the estuary from upstream (Chatelier Lock) to mouth

270 (Saint Servan), over a continuous period of a fortnight. For velocity validation, Root Mean Square Error
271 (RMSE) on current magnitude and direction was calculated. To validate water surface elevation, RMSEs
272 were computed on the entire water-level signal, at high- and low-water levels. Since the model was further
273 used for harmonic analysis, water level validation was complemented by error computation on the amplitude
274 and phase of the M2 and M4 tide constituents.

275 **4.1.1 Model calibration and validation for the year 2012**

276 Imposing a Strickler coefficient of $60 \text{ m}^{1/3}/\text{s}$ and constant eddy viscosity of $10^{-4} \text{ m}^2/\text{s}$ over the whole
277 computational domain, numerical results were compared with ADCP measurements at three locations
278 indicated in Figure 3. As shown in Figures 3.a;b;c, the model effectively reproduced water surface elevation
279 with $\text{RMSE} \approx 8 \text{ cm}$ upstream of the TPS and $\approx 5 \text{ cm}$ downstream (Table 3). High- and low-water levels are
280 also effectively computed by the model with RMSE below 4 cm upstream of the dam and 3 cm downstream
281 of the structure (Table 3). For both stations upstream of the TPS (ADCP1 and ADCP2), high-frequency
282 oscillations of the order of $\sim 10\text{cm}$ are clearly seen at low and high water, and the tidal range is approximately
283 50% less than in the station downstream of the TPS. The numerical model effectively represented water-level
284 oscillations and tidal wave damping inside the estuary caused by the operation of the TPS. It is also able to
285 reproduce satisfactorily velocity magnitude and direction at the three ADCP locations, with RMSE values
286 below 0.2 m/s for current magnitude and 12° for current direction, as shown in Figures 3.d-i) and Table 3.
287 Upstream of the turbines and downstream of the TPS, flood-currents are stronger than ebb-currents, while
288 they are equivalent upstream of the sluice gates. For the latter, the velocity magnitude decreases by 15%
289 and 6% during flood and ebb respectively with respect to velocity magnitude in the sea-side of the dam.
290 However, this reduction is greater upstream of the turbines (ADCP 1), at 48% and 62% for flood and ebb
291 currents respectively. The flood-current measurements exhibited a peak at the beginning of the flood, which
292 is clearer at stations ADCP 2 and ADCP 3 (Figures 3.e;f). The peak upstream of the plant, directly related to
293 turbine operation, is well represented by the numerical model. However, the peak observed downstream of
294 the TPS (ADCP 3), which could be generated by a combination of TPS operation modes and hydrodynamic
295 forcing (*i.e.*, wind and waves) not considered in this study, is not captured by the model. For the three ADCP
296 locations, ebb currents are mainly oriented north-west and flood currents are mainly directed south-east.

297 **4.1.2 Model validation for the year 2019**

298 To assess numerical model reliability and robustness with respect to the current operating mode of the
299 power station, a numerical simulation was performed over a period of a fortnight from August 15 – 28 2019.
300 For this scenario, only water surface measurements were available. Figures 4.a;b;c;d present a comparison
301 between numerical results and measurements at Saint Servan, upstream of the TPS, Saint Suliac and Chatelier
302 Lock respectively (see Figure 1 for tidal gauge locations). The numerical model demonstrated its ability
303 to reproduce satisfactorily the tidal distortion caused by the TPS, as well as to correctly propagate the tidal
304 wave along the estuary, with RMSE below 10 cm (Table 3). Although the model's error on low water levels
305 is slightly higher than error on high water levels, it is still below 10 cm, which is considered satisfactory.
306 Furthermore, the reduction in tidal range inside the estuary is well represented. The model is also able to
307 reproduce the seiche-like oscillations, which are stronger at stations upstream of TPS and Chatelier Lock.
308 Moreover, the amplitude and phase of the M2 and M4 components are well computed, with error below 5 cm
309 and 9° for amplitude and phase respectively (see Table 4).

310 **4.2 Present-day conditions of the Rance estuary**

311 This section focuses on the fortnight's simulation in August 2019. Numerical results were validated for a
312 large dataset of measurements and represent the current mode of plant operation. High and low tides, mean
313 water level and tidal range along the estuary's channel were analyzed. Then, the evolution of the water
314 surface elevation and currents was studied at particular locations in the estuary for both neap and spring
315 tides.

316 Figure 5.a shows a comparison between spring and neap tide for low water (LWL), high water (HWL) and
317 mean water (MWL) levels along the estuary channel, defined respectively as minimum, maximum and mean
318 water surface elevation during one tide cycle (12 h 25 min). These results suggest that the estuary could be
319 divided into two zones: one from the Chatelier lock to the TPS (~ 18 km) and one from the TPS downstream
320 to the sea (~ 5 km). In the latter zone, there is a difference between HW levels (blue lines) at spring and
321 neap tide (and similarly for LW levels, red lines), while, for the same tidal conditions, MW levels (green
322 lines) remain constant. In the former zone, HWL at spring tide is naturally higher than HWL at neap tide
323 (blue lines); however, LW levels (red lines) are nearly coincident. Therefore, MW level (green lines) is not
324 constant between spring tide and neap tide in this zone. In fact, the operating mode of the TPS requires

325 keeping the yacht harbor upstream of the Chatelier Lock navigable, so a minimum of 2 meters is required
326 in the channel [62], and thus, minimum water level in the estuary channel could not reach its natural value,
327 in contrast to the zone downstream of the TPS. Moreover, LWL, HWL and MWL are always higher in the
328 estuary side than in the sea side. This difference is more significant for LWL, and mainly at spring tide.
329 Consequently, tidal range (Figure 5.b) is decreased in the zone upstream of the TPS by nearly 50% at spring
330 tide and 33% at neap tide compared to the sea-side region.

331 Water surface elevations and currents were analyzed simultaneously with power station operating modes
332 during a spring tide period (Figures 6.a-h). As seen previously, tidal range is reduced in the estuary and
333 high-frequency oscillations are observed at high and low tide during the Off period of both turbines and
334 sluice gates (T.O. and G.C. stages, Table 1). These oscillations are stronger at the Chatelier Lock, considering
335 the tidal wave reflecting on the upstream boundary condition [63]. Moreover, a lag of ~ 2 hours is observed
336 at high and low tides (and similarly for ebb and flood currents) between Saint Servan (sea) and the other
337 locations along the estuary. After reaching the natural water level maximum ($t = 2.4$ d), the pump units
338 raise the estuary water level (D.P. phase) to allow a greater drop in the next low tide, maximizing electricity
339 production (D.T. stage). For the same purpose, the high water (resp. low water) slack period lasts for
340 ~ 1 h 20 minutes (resp. ~ 25 minutes), allowing operating modes to be switched from direct pumping to
341 direct turbinning (resp. direct turbinning to inverse turbinning). During spring tide, the TPS can operate in
342 two-way generation, so that the electricity is produced not only during ebb (D.T. stage) but also during
343 flood (I.T. stage). Furthermore, Figures 6.e;f;g show that the TPS amplifies the peak-flood current in the
344 estuary, mainly by the opening of the sluice gates (G.O. stage). This amplification is then reduced toward
345 the estuary's upstream limit (Chatelier Lock). Moreover, flood currents are stronger than ebb-currents on
346 both sea and estuary sides, except near Chatelier Lock (Figure 6.h) where river currents (negative currents)
347 are dominant.

348 A similar analysis was performed for a neap tide period, as shown in Figures 7.a-h. Since tidal range in the
349 sea side is naturally lower than in spring tide, the operating mode of the TPS is obviously different to ensure
350 electricity production during neap tides as well. Presently, the TPS operates only in one-way generation
351 during this period, so electricity is produced only during ebb (D.T. stage). Thus, in order to meet navigation
352 requirements and ensure a sufficient drop between sea and estuary levels for a long enough time, the direct
353 pumping stage (D.P.) is longer than in spring tide. Consequently, the high-water level in the estuary is clearly
354 higher than in the sea. In addition, the maximum flood-current upstream of the TPS is amplified by pumping

355 through the turbines and sluice gates rather than the sluice gates only, as is the case at spring tide. However,
356 this amplification is quickly dissipated, since currents at Saint Suliac (~ half the estuary) are weaker than
357 those at Saint Servan (Figures 7.e;g).

358 **4.3 Influence of the tidal power station on hydrodynamics and tide asymmetry**

359 To evaluate the impact of the tidal power station on hydrodynamics and tide asymmetry, three configurations
360 were designed (Table 5) for the fortnight of August 15 – 28 2019. The first (C1) was based on the DEM
361 for 1957 (Figure 2.a). It represents a real configuration of the estuary in the past, specifically before the
362 construction of the dam. The second (C2) is a virtual configuration: the present estuary configuration but
363 without the power station. It was recreated from the DEM for 2018 by removing the dam and smoothing
364 the bottom elevation upstream and downstream of the TPS. The third configuration (C3) represents the
365 present estuary configuration, with the TPS and the DEM for the year 2018 (as presented in section 4.2).
366 Comparison between C1 and C2 scenarios highlights the influence of the bathymetry, spanning ~ 52 years of
367 TPS operation. Comparison between the C2 and C3 configurations emphasises the impact of the TPS over a
368 period of a fortnight. These comparisons are complemented by asymmetry analysis, providing preliminary
369 insights at a larger time scale.

370 All three numerical simulations were performed using the same hydrological condition (river discharge at
371 Chatelier lock), the same tidal condition (mean sea level and tidal amplitude and phase), and the same physical
372 parameters. The scenarios were first analyzed in terms of hydrodynamic variables along the estuary's main
373 channel. Then, tidal wave propagation and the spatial distribution of currents at neap and spring tide were
374 discussed. Finally, asymmetry parameters were compared for the three configurations to quantify the tidal
375 distortion caused by both artificial hydrodynamic forcing by the TPS and the estuary's morphology.

376 **4.3.1 Hydrodynamic variables**

377 Morphological changes in estuaries may have an important influence on hydrodynamic variables such as
378 low, high, and mean water levels (LWL, HWL, MWL respectively) and tidal range. These quantities were
379 compared along the estuary's channel at spring tide between the configurations without the TPS: C1 with
380 the bathymetry for 1957 and C2 with the bathymetry for 2018 (Figures 8.a-b). Overall, bathymetry does not
381 have a significant impact on the spatial distribution of water level indicators or on tidal range. However, it is

382 noteworthy that the estuary could be split into two parts in which hydrodynamic variables behave differently.
383 In the first zone, between Chatelier lock and Saint Hubert port ($\sim 6 \text{ km}$), the channel is partially uncovered
384 at low tide but keeps the same level at high tide; thus the tidal range is variable and increases according
385 to bottom depth. At spring tide, where differences between low and high tide are large, the limit of tidal
386 range rise occurs approximately at the Saint Hubert port, in contrast to neap tide, where the limit is slightly
387 ($\sim 2 \text{ km}$) upstream. In the second zone, from Saint Hubert port to the mouth ($\sim 17 \text{ km}$), the channel is
388 always covered, at both neap and spring tides. Moreover, despite some local changes in the channel bottom
389 between 1957 (before the dam construction) and 2018, for instance directly upstream of the TPS, the water
390 level indicators and tidal range do not seem to be influenced. Furthermore, tidal range in this second zone is
391 variable (variation of $\sim 0.5\text{m}$ at spring tide and $\sim 0.1\text{m}$ at neap tide), as it slightly decreases according to
392 bed position.

393 As presented in section 4.2, values of LWL, HWL, MWL and tidal range are highly sensitive to dam
394 operations. Comparison of these values for configurations C2 and C3 (respectively with and without the
395 TPS, in Table 5) provides a deeper overview of the influence of the TPS on water level indicators (Figures
396 8.c-d). Downstream of the dam, the impact of the TPS on water levels and tidal range seems to be negligible,
397 but is more significant upstream. In the last region, the plant amplifies the high-water level (continuous blue
398 line in Figure 8.c) at neap tide by $\sim 10\%$ but maintains approximately the natural maximum level at spring
399 tide. Thus, the dam does not necessarily influence the flooded areas. Low-water level (red line), is strongly
400 increased by the TPS and kept constant along the basin. It nearly reaches the natural mean water level without
401 the structure (green dashed line). Thus, the region between Chatelier lock and Saint Hubert port switches
402 from being an intertidal zone in the configuration without the TPS (C2) to a permanently flooded zone in the
403 configuration with the TPS (C3). In the current study, a mean spring tide cycle was chosen; hence the area
404 between Saint Hubert port and the plant was continually submerged. This behavior might be influenced by
405 the TPS, and especially the area directly downstream of Saint Hubert port (between 8km and 12km from the
406 Chatelier lock), which may be naturally uncovered during an extreme spring tide but switched to a flooded
407 zone by the plant. Therefore, the dam ensures the continuity and uniformity of water level at low tide along
408 the estuary's channel for the purpose of maintaining navigation to the yacht harbor located upstream of the
409 Chatelier lock. Moreover, mean water levels (green lines) at both spring and neap tidal periods are amplified
410 by the presence of the plant. Furthermore, in the area upstream of the TPS, the difference in tidal range
411 between configurations without and with the dam (Figures 8.b & 8.d) increases according to bed elevation,

412 peaking at $\sim 5.25m$ at spring tide near Saint Hubert port. Thus, the dam reduces the tidal range by at least
413 $\sim 13\%$ at neap tide and at most $\sim 50\%$ at spring tide.

414 **4.3.2 Tide and current distributions and propagation**

415 The construction of the tidal power station at the estuary's mouth induces a considerable decrease in tidal
416 range, reducing water volume entering and exiting the basin. Also, the Rance dam operates in both one-
417 and two-way generation modes. Therefore, maximum tidal current at both flood and ebb are potentially
418 influenced by the TPS. It is interesting to compare maximum flood and ebb current distributions between
419 scenarios with different bathymetries (C1 and C2 in Table 5), and configurations with and without the dam
420 (C2 and C3 in Table 5), over a spring tide cycle (Figures 9.a-f).

421 Bathymetry does not seem to have a major impact on maximum flood current distribution (Figures 9.a;b).
422 However, a slight amplification of maximum ebb current occurs in the main channel of the upper estuary from
423 Ton Peak to Saint Servan (Figures 9.d;e). This amplification may be caused by the channel's morphological
424 development over the past 52 years: construction of the TPS to 2018, the main channels upstream of the dam
425 expanded slightly and deepened (Figure 2), allowing faster ebb-current propagation.

426 Scenarios with and without the TPS showed that the maximum flood current is amplified by the dam directly
427 upstream of the sluice gates, but significantly reduced in the rest of the estuary (Figures 9.b;c). Maximum
428 flood currents upstream of the sluice gates increased from $0.8m/s$ without the TPS to $1.75m/s$ with: *i.e.*, an
429 amplification factor of ~ 2.2 . In other words, locally in the region upstream of the dam, the main channel
430 with maximum flood current is controlled by both the modified bathymetry and geometry, and the artificially-
431 induced hydrodynamic forcing by the plant. Nevertheless, the maximum flood current is decreased in the
432 rest of the estuary, from $1.75m/s$ without the TPS to $1.25m/s$ with: *i.e.*, reduction by a factor of ~ 0.7 .

433 The same behavior applies for maximum ebb-current: amplification by the TPS directly downstream of the
434 turbines by a factor of ~ 3.1 and reduction in the rest of the estuary by a factor of ~ 0.4 . Complementary
435 comparisons of current differences between the three modeled scenarios are given in appendix A.

436 On the basis of the foregoing remarks, four locations (downstream of TPS, upstream of TPS, Ton peak
437 and Saint Hubert port, Figure 1) were selected to further analyze the influence of dam operating modes on
438 current distribution. The temporal evolution of water surface elevation and currents was analyzed for a mean
439 spring tide on the three scenarios (C1, C2 and C3: Table 5, Figures 10.a-h). As expected, differences are
440 negligible between configurations C1 and C2, with different bottom elevation levels (red and green dashed

lines) on both water surface elevation and currents. Comparison between configurations C2 and C3, without and with the TPS (green dashed line and blue continuous line, respectively) showed that, while the dam does not modify water surface elevation downstream of the TPS (Figure 10.a), it distorts the currents. At this location, peak ebb current is equivalent to peak flood current in the absence of the TPS, while the presence of the TPS leads to a substantially higher peak ebb current than peak flood current. Also, maximum ebb current occurs during the D.T. phase of electricity generation by the turbines, with sluice gates closed. This explains the amplification of maximum ebb current by the TPS directly downstream of the turbines rather than downstream of the whole structure (cf. Figure 9.f). Furthermore, upstream of the TPS, peak ebb current is higher than peak flood current for the configuration without the dam, while the opposite is true for the configuration with the dam (green dashed line and blue line in Figure 10.f). Flood current is maximized by opening the sluice gates during flood (G.O. stage). This is explained on the one hand by the fact that the estuary is filled mostly via sluice gates rather than turbines, and on the other hand sluice gates width (114m) is considerably smaller than turbines width (323m). Since higher flow through a smaller section induces higher velocity, flood currents upstream of sluice gates are faster than upstream of turbines. Similarly, peak flood currents are significantly greater with the TPS than without. However, this amplification caused by the TPS is remarkably reduced further upstream (for instance, at Ton Peak and Saint Hubert port), as a result of the reduction in tidal range and hence in tidal prism (Figures 10.g;h). In addition, the difference in current magnitude between scenarios with and without TPS also decreases along the estuary, from 0.65m/s at Ton Peak for maximum flood current (0.4m/s for maximum ebb current) to 0.25m/s at Saint Hubert port for maximum flood current (0.25m/s for maximum ebb current). Moreover, a lag of approximately 2 hours is caused by the TPS for both water elevation and current on the estuary side of the dam. This time lag is related to the elongation of high- and low-water slack periods induced by the operating mode of the turbines to enable efficient electricity generation (see section 4.2). The high-tide slack period changes from 20 minutes for the scenario without the TPS to 1 hour 20 minutes for the scenario with TPS, although the difference is less significant for low-tide slack period. These analyses were carried out over a spring tide period, where the dam operates on two-way generation. Next, a similar analysis was performed over a neap tide period, where the plant is in one-way generation mode (Figures 11.a-h). Overall, the TPS induces a similar impact on water surface elevation and currents during neap and spring tide, except for a few details presented hereafter. On the estuary side of the dam (for instance, upstream of the TPS: Figure 11.b), there was no difference during flood between configurations without (green dashed line) and with the TPS (blue continuous line),

471 unlike during the spring tidal cycle (Figure 10.b). Thus, at neap tide the plant could operate only on one-way
472 generation, which means electricity is generated only during ebb (D.T. stage) and not during flood as is the
473 case during spring tide. Moreover, to ensure a sufficient water head between the basin and downstream sea
474 level, the D.P. phase is longer during neap than spring tide, resulting in a high tide that is greater than the
475 natural high tide (configuration C2 without TPS). Furthermore, peak flood current upstream of TPS (Figure
476 11.f) for the configuration with TPS (C3) occurs at the junction between the D.P. phase of the turbines and
477 the G.O. phase of the sluice gates (Table 1) and not during an electricity production phase (D.T. or I.T.) as
478 is the case at spring tide.

479 To complement tidal current analysis, investigations were conducted on the temporal evolution of flowrate
480 across the section upstream of the TPS (Figure 1) and on tidal prism during a neap-spring tide period for the
481 three simulated scenarios (Figures 12a-d). Over the fortnight period, the TPS reduces discharge both entering
482 (flood) and exiting (ebb) the estuary. Particularly, at spring tide (Figure 12.b) maximum flood discharge (ebb
483 discharge) decreases from $10,600\text{m}^3/\text{s}$ ($-7,500\text{m}^3/\text{s}$ at ebb) without the TPS to $7,000\text{m}^3/\text{s}$ ($-5,000\text{m}^3/\text{s}$ at
484 ebb) with the TPS: *i.e.*, a reduction of 34% (33% at ebb). At the neap tide (Figure 12.c), the decrease induced
485 by the dam is slightly less: at most 25% at flood and 22% at ebb. It should be borne in mind that the estuary
486 is filled mostly via the sluice gates at spring tide, whereas at neap tide the contributions of sluice gates and
487 turbines are equivalent. Moreover, bathymetry did not seem to have a significant influence on tidal prism
488 (red and green lines in Figure 12.d). However, the presence of the dam (blue line) induces a major decrease
489 in tidal prism, from $1.22 \times 10^8 \text{ m}^3$ without the structure over spring tide ($0.6 \times 10^8 \text{ m}^3$ over neap tide) to
490 $0.8 \times 10^8 \text{ m}^3$ with ($0.4 \times 10^8 \text{ m}^3$ over neap tide). To evaluate flushing rate in the estuary, tidal prism needs
491 to be compared to the volume of water contained in the basin at high tide, estimated at $1.84 \times 10^8 \text{ m}^3$. Thus,
492 tidal prism accounts for 66% without the TPS at spring tide (33% at neap tide) versus 43% with the TPS at
493 spring tide (22% at neap tide). Theoretical mean residence times in the estuary for scenarios without and
494 with the dam showed that the presence of the TPS could multiply the natural water residence time by a factor
495 of 1.52 at most. Therefore, the presence of the plant causes a lower flushing rate and longer water residence
496 time.

497 4.3.3 Tide asymmetry parameters

498 To quantify the distortion and asymmetry of the tidal signal as it crosses the dam and propagates along
499 the basin, two complementary approaches were applied in the three scenarios: C1 configuration from 1957

500 before TPS construction, C2 configuration of 2018 without the TPS, and C3 configuration of 2018 with the
501 TPS (Table 5).

502 The first approach focuses on tidal velocity and duration skewness [12]. These parameters ($\gamma_0(u); \gamma_0(\frac{\partial \zeta}{\partial t})$)
503 were computed as the median over a neap-spring tidal period to analyze their spatial distributions in the three
504 scenarios (Figures 13.a-f). Despite the presence of the dam and the morphological evolution in the Rance
505 estuary, tide is flood-dominant in the main channel and ebb-dominant in the secondary channels (Figures
506 13.a-c). The presence of the power plant slightly decreases the flood-dominance by 5 – 7% throughout
507 the estuary. Nevertheless, local impacts of the plant on maximum flood and ebb currents (Figures 6; 7 &
508 9); also appears in the spatial distribution of velocity skew near the plant: (i) upstream of the sluice gate,
509 the tide is switched from ebb-dominant without the TPS to flood-dominant with, (ii) downstream of the
510 turbines, the tide is switched from flood-dominant without the dam to ebb-dominant with. Complementary
511 comparisons of velocity skew ratios are given in appendix A. Furthermore, in the Rance estuary, with and
512 without the TPS, duration is always longer for falling than rising water. As expected, bathymetry does
513 not induce any significant changes in duration skew. Likewise, the plant does not influence tidal duration
514 asymmetry downstream of the TPS, as seen previously in Figures 6.a & 7.a. Although upstream of the TPS
515 the magnitude of this typical skew is substantially decreased by the TPS, it still maintains the same trend.
516 This behavior could be related to the operating modes of the plant, which tend to extend high tide and low
517 tide slack periods, so that the temporal variation in water surface elevation $\frac{\partial \zeta}{\partial t}$ is equal to zero over this
518 period, in turn decreasing duration asymmetry (cf. Figures 6.b-d & 7.b-d).

519 The second approach quantifies tidal asymmetry through harmonic analysis using the amplitude ratio $\alpha =$
520 a_{M_4}/a_{M_2} and phase difference $\beta = (2\phi_{M_2} - \phi_{M_4})$ [11]. This method is suitable for the present case study, as
521 the Rance estuary is a system dominated by the M2 semidiurnal tide [64]. Asymmetry metrics derived from
522 harmonic analysis of both water surface elevation ($\alpha_\zeta; \beta_\zeta$) and currents ($\alpha_u; \beta_u$) were computed over the
523 spring-neap tidal period using the T-TIDE toolbox [61], for the three configurations at six locations: Saint
524 Servan, downstream of TPS, upstream of TPS, Ton peak, Saint Hubert port and Chatelier lock (see Figure
525 1 for locations and Table 6 for asymmetry metrics). As expected, bathymetry does not have any significant
526 impact on these tidal distortion parameters. For configurations without the TPS (C1 & C2), tide is hardly
527 distorted along the estuary, with α_ζ between 0.048 and 0.05. Moreover, the presence of the plant does not
528 affect asymmetry metrics related to water surface elevation ($\alpha_\zeta; \beta_\zeta$) for stations on the sea side of the dam
529 (Saint Servan and downstream of TPS). However, phase difference related to currents (β_u) in this zone is

530 modified from 352° without the TPS to 171° with. Hence, location downstream of the TPS switches from
531 flood dominant ($0^\circ < \beta_u < 90^\circ$ or $270^\circ < \beta_u < 360^\circ$) to ebb dominant ($90^\circ < \beta_u < 270^\circ$) [11]. Upstream
532 of the TPS, the presence of the dam modifies the tide from ebb dominant with $\beta_u = 173^\circ$ without the plant
533 to $\beta_u = 355^\circ$ with. Furthermore, Table 6 indicates that the dam induces a substantial decrease in both
534 amplitude ratios α_ζ and α_u by $\sim 70\%$ in the basin side of the plant, but does not modify the flood-dominance
535 behavior of the estuary, except locally near the TPS. These findings are in agreement with the analysis based
536 on Nidziko and Ralston's parameters [12].

537 **5 Discussion**

538 Investigations carried out based on comparison of hydrodynamic and asymmetry parameters between three
539 scenarios with different DEMs and with presence/absence of the TPS, helped to evaluate the impact of the
540 plant on hydrodynamics in the Rance estuary. It was shown that high tide is slightly increased by the presence
541 of the dam in the estuary side of the plant (Figures 5 & 12). However, this amplification occurs specifically
542 at neap tide. At present, maximum water level upstream of the plant is limited to 12 m [62]: *i.e.*, although
543 during an extreme spring tide where maximum high-water level seaward is above 12 m, the high tide inside
544 the estuary will not exceed 12 m. Hence, the plant effectively protects the estuary from storms and risk of
545 marine flooding. This was also seen in studies of other tidal power plant projects: *e.g.*, the Sihwa Lake TPS
546 [29], the Severn dam, the Flemming Lagoon, the Shoots dam [1] and others [41]. The plant's impact on low
547 tide, however, is more significant. The higher low-water level in the configuration including the TPS (Figures
548 5 & 12) modifies a large part of the intertidal areas in the basin (present in the scenario without the TPS),
549 which are permanently submerged: *e.g.*, the area between Chatelier lock and Saint Hubert port. This could be
550 directly related to the evolution of the estuary's ecosystems. Kirby & Retière [3] discussed the post-closure
551 environmental effects of the Rance dam and measurements demonstrated that an increase in permanent
552 subtidal area leads to changes in the estuary's ecosystem, with richer biodiversity, increased habitat variety,
553 greater abundance of fish species and greater variety and density for birdlife. Moreover, higher low tide
554 allows navigation to the yacht harbor next to the Chatelier Lock during ebb. As the tide passes through
555 the dam and propagates along the estuary, it becomes more distorted and more asymmetric. This effect
556 has both natural and artificial origins, due to the estuary's morphology and to hydrodynamic forcing by the
557 plant. Simultaneously analyzing tide propagation (Figures 10 & 11), skewness parameters (Figure 13) and

558 asymmetry (Table 6), shows the area near the dam (~ 1.5km upstream and ~ 0.5km downstream) to be highly
559 sensitive to the presence of the TPS. Amplification of flood current upstream of the sluice gate can cause
560 local bed scouring, which may explain the high erosion rate seen in the same area in Figure 2. Furthermore,
561 with and without the dam, the Rance estuary is mainly flood-dominant with longer duration of falling than
562 rising water and stronger peak flood current than peak ebb current [12, 11, 9, 10]. All this enhances the
563 tendency of residual sediment transport to be in the landward direction: *i.e.*, sediments are carried from the
564 coast toward the estuary [15]. It noteworthy that similar behavior is observed before TPS construction, as
565 confirmed by the C1 results presented in Figure 13. Thus, the plant does not impact the source of sediments
566 present inside the basin. These results are in agreement with measurements performed 15 years after TPS
567 construction, showing that more than 90% of the Rance estuary's sediments came from the sea [65, 24, 27].
568 In addition, flow velocity away from the TPS zone is substantially lowered by the presence of the dam. This
569 may significantly reduce in the suspended sediment concentrations and thus impact the dynamics of the
570 estuarine turbidity maximum (ETM). Furthermore, prolonging high- and low-water slack periods, due to the
571 presence of the power plant, may impact tidal transport of fine sediment with consequences for the settling,
572 re-suspension and diffusion of fine particles in the water column [18]. However, these interpretations need to
573 be analyzed closely with respect to local conditions of sediment bed composition, since the suspended load
574 carried in the seawater is related to tidal current magnitude if the bed includes unconsolidated sediments
575 [66, 67]. Therefore, the impact of the dam on sedimentation needs further investigation. Furthermore,
576 analysis of tidal prism and flowrate passing through the TPS (Figure 12) showed that the plant significantly
577 reduced flushing rates and hence increases the resident time of water containing suspended sediments and
578 pollutants. This was also reported in other tidal power plant projects [29, 1, 2]. On the other hand, since a
579 greater volume of sediment enters from the sea, reducing the water volume flowing into the estuary during
580 flood might reduce the amount of sediment entering the basin. These interpretations need to be supported
581 by complementary sediment transport simulations or *in-situ* observations.

582 **6 Conclusions**

583 This study presents a detailed analysis of the hydrodynamics of the Rance estuary, influenced by the world's
584 second largest tidal power station. This closed-estuary type exhibits an original configuration due to (i) the
585 presence of the Chatelier lock upstream of the basin and the tidal power station downstream and (ii) the plant's

586 hybrid tidal energy schemes of ebb-generation and ebb-flood generation. A two-dimensional depth averaged
587 model of the Rance estuary was developed and successfully validated against water level observations and
588 velocity field measurements for many tidal stations throughout the estuary. The model was then applied to
589 simulate the tidally-driven hydrodynamic processes for the present-day conditions of the Rance estuary and
590 two other scenarios featuring: 1) an artificial condition of the estuary without the dam and 2) the historic
591 conditions of the basin (in 1957), before the dam's construction. Then, the simulations were analyzed in
592 terms of basic flow characteristics and tide asymmetry parameters. Numerical results indicated that, in the
593 absence of the TPS, bathymetry does not have any significant impact on hydrodynamics. However, the
594 presence of the dam substantially modifies tidal patterns. The main consequences of the presence of the dam
595 at the estuary mouth can be summarized as follows. (i) A major decrease in tidal range and tidal prism along
596 with the amplification of the estuary's low-water level switches a large part of intertidal zones, which become
597 permanently submerged, which seems to help the estuary's ecosystem. (ii) A limitation of the high-water
598 level inside the estuary up to 12m protects the basin against marine flooding. (iii) There is an overall decrease
599 in tidal currents in the estuary, except upstream of the sluice gates and downstream of the turbines. (iv) Flood
600 currents and ebb currents are locally amplified upstream of the sluice gates and downstream of the turbines
601 respectively. The study also revealed that the Rance estuary, with and without the TPS, is flood-dominant,
602 with a shorter duration of rising than falling water. These findings suggest that sediment transport tends to
603 be in the landward direction: *i.e.*, the plant does not impact the source of sediment present inside the basin.
604 Finally, the study highlights the need to couple hydrodynamics to sediment transport processes to further
605 quantify the impact of the dam on sediment dynamics and morphological changes in the Rance estuary. The
606 effect of sea level rise, estimated to be $\sim 10\text{cm}$ between 1957 and 2019 [68], could also be evaluated to have
607 a more consistent overview of the long term evolution of this particular estuarine system.

608 **Acknowledgments**

609 The authors are grateful to Christophe Cochet and Malo Lambert for providing the preliminary version of the
610 model used in this work. Antoine Libaux, Marion Duclercq and Florian Boucard are warmly acknowledged
611 for supplying data from the AGRA Software and feedback on the tidal power station operating modes. We
612 would like to acknowledge Chi-Tuân Pham and Sébastien Bourban for giving advice on the tidal model's
613 validation. Finally, we thank the three reviewers, whose comments and suggestions helped improve and

614 clarify this manuscript.

Appendices

A Complementary comparisons between the three modeled scenarios

To complement analyses performed in Sections 4.3.2 and 4.3.3 for the three modeled scenarios, plots of current differences and velocity skew ratios are shown in Figures 14 & 15. Scenario C2, corresponding to the bathymetry of 2018 without the tidal power station (see Table 5), is set as reference. Figures 14.a;c show that sediment deposition zones observed near Mordreuc (see Figure 2.c) could significantly impact the velocity magnitude in the main channel, where currents are reduced by $\sim 0.25m/s$. Figures 14.b;d show that the presence of the dam reduces the current velocities in the estuary main channel by $\sim 0.5m/s$. However, it amplifies flood (ebb) currents directly upstream of sluice gates (downstream of turbines) by $\sim 1m/s$.

Velocity skewness ratio depicted in Figure 15.a shows that estuarine morphological changes between 1957 and 2018 near Mordreuc might have switched the ebb-dominance seen in 1957 to flood-dominance in 2018, although this finding may present inaccuracies due to measurement uncertainty in the older maps. Figure 15.b shows that the tidal power station decreases flood-dominance by a factor of ~ 0.9 along the estuary main channel. Moreover, velocity skewness changes are visible in the area surrounding the dam, where the ebb dominance (flood dominance) upstream of the sluice gate (downstream of the turbines) switches to flood dominance (ebb dominance) due to the presence of the TPS.

Notation

Σ = channel cross-sectional area (m^2);

Q = Flow rate (m^3/s);

Q_{river} = River flow rate (m^3/s);

$Q_{turbines}$ = Flow rate passing through turbines (m^3/s);

$Q_{sluices}$ = Flow rate passing through sluice gates (m^3/s);

A, C = Discharge coefficients ($m^{5/2}/s$);

B = Discharge coefficient ($m^{9/4}/s$);

$Q_{\Sigma TPS}$ = Flow rate passing through section upstream of the TPS (m^3/s);

ζ, WSE = Water surface elevation (m);

T_r = Mean Residence Time (s);

V = Mean volume of water in the system (m^3);

T = Tidal period (s);

b = Return flow factor (-);

TP = Tidal Prism (m^3);

μ_m = The m-th moment about zero ($(m/s)^m$);

$\gamma_0(u)$ = Tidal current asymmetry (-);

$\gamma_0(\frac{\partial \zeta}{\partial t})$ = Tidal duration asymmetry (-);

$a_{M_2}(\zeta)$ = M2 amplitude of water surface elevation (m);

$a_{M_4}(\zeta)$ = M4 amplitude of water surface elevation (m);

$a_{M_2}(u)$ = M2 amplitude of current (m/s);

$a_{M_4}(u)$ = M4 amplitude of current (m/s);

α_ζ = Surface amplitude ratio (-);

α_u = Current amplitude ratio (-);

$\phi_{M_2}(\zeta)$ = M2 phase of water surface elevation ($^\circ$);

$\phi_{M_4}(\zeta)$ = M4 phase of water surface elevation ($^\circ$);

$\phi_{M_2}(u)$ = M2 phase of current ($^\circ$);

$\phi_{M_4}(u)$ = M4 phase of current ($^\circ$);

β_ζ = Surface phase difference ($^\circ$);

β_u = Current phase difference ($^\circ$);

REFERENCES

- [1] Xia, J., Falconer, R., and Lin, B. (2010). “Impact of different tidal renewable energy projects on the hydrodynamics processes in the Severn estuary, UK.” *Ocean Modelling*, 32, 86–104.
- [2] Cornett, A., Cousineau, J., and Nistor, I. (2013). “Assessment of hydrodynamic impacts from tidal power lagoons in the bay of Fundy.” *International Journal of Marine Energy*, 1, 33–54.
- [3] Kirby, R. and Retière, C. (2009). “Comparing environmental effects of Rance and Severn barrages.” *Proceedings of the Institution of Civil Engineers - Maritime Engineering*, 162(1), 11–26.
- [4] Stark, J., Smolders, S., Meire, P., and Temmerman, S. (2017b). “Impact of intertidal area characteristics on estuarine tidal hydrodynamics: A modelling study for the Scheldt estuary.” *Estuarine, Coastal and Shelf Science*, 198, 138–155.
- [5] Stark, J., Meire, P., and Temmerman, S. (2017a). “Changing tidal hydrodynamics during different stages of eco- geomorphological development of a tidal marsh: a numerical modeling study.” *Estuarine, Coastal and Shelf Science*, 188, 56–68.
- [6] Thurman, H. (1994). *Introductory Oceanography*. NY: Macmillan, New York, 7th edition.
- [7] Sumich, J. (1996). *An Introduction to the Biology of Marine Life*. Dubuque, New York, 6th edition.
- [8] Zhang, W., Cao, Y., Zhu, Y., Zheng, J., Ji, X., Xu, Y., Wu, Y., and Hoitink, A. (2018). “Unravelling the causes of tidal asymmetry in deltas.” *Journal of Hydrology*, 564, 588 – 604.
- [9] Aubrey, D. and Speer, P. (1985). “A study of non-linear tidal propagation in shallow inlet/estuarine systems Part I: Observations.” *Estuarine, Coastal and Shelf Science*, 21, 185–205.
- [10] Speer, P. and Aubrey, D. (1985). “A study of non-linear tidal propagation in shallow inlet/estuarine systems Part II: Theory.” *Estuarine, Coastal and Shelf Science*, 21, 207–224.
- [11] Friedrichs, C. and Aubrey, D. (1988). “Non-linear tidal distortion in shallow well-mixed estuaries: a synthesis.” *Estuarine, Coastal and Shelf Science*, 27, 521–454.
- [12] Nidziko, N. and Ralston, K. (2012). “Tidal asymmetry and velocity skew over tidal flats and shallow channels within a macrotidal river delta.” *Journal of Geophysical Research*, 117.

- 656 [13] Guo, L., Brand, M., Sanders, B. F., Fofoula-Georgiou, E., and Stein, E. D. (2018). “Tidal asymmetry
657 and residual sediment transport in a short tidal basin under sea level rise.” *Advances in Water Resources*,
658 121, 1–8.
- 659 [14] Wang, Z., Jeuken, C., and De Vriend, H. (1999). “Tidal asymmetry and residual sediment transport in
660 estuaries.” *Delft Hydraulics report Z2749*.
- 661 [15] McLachlan, R., Ogston, A., Asp, N., Fricke, A., Nittrouer, C., and Gomes, V. (2020). “Impacts of tidal-
662 channel connectivity on transport asymmetry and sediment exchange with mangrove forests.” *Estuarine,*
663 *Coastal and Shelf Science*, 233.
- 664 [16] Mandal, S., Sil, S., Gangopadhyay, A., Jena, B., and Venkatesan, R. (2020). “On the nature of tidal
665 asymmetry in the gulf of Khambhat, Arabian sea using HF radar surface currents.” *Estuarine, Coastal*
666 *and Shelf Science*, 232, 106–481.
- 667 [17] Bolle, A., Bing Wang, Z., Amos, C., and De Ronde, J. (2010). “The influence of changes in tidal
668 asymmetry on residual sediment transport in the western Scheldt.” *Continental Shelf Research*, 30, 871–
669 882.
- 670 [18] Dronkers, J. (2005). *Dynamics of coastal systems*, Vol. 25. World Scientific.
- 671 [19] Vellinga, N., Hoitink, A., van der Vegt, M., Zhang, W., and Hoekstra, P. (2014). “Human impacts on
672 tides overwhelm the effect of sea level rise on extreme water levels in the Rhine–Meuse delta.” *Coastal*
673 *Engineering*, 90, 40 – 50.
- 674 [20] Hoitink, A. J. F., Hoekstra, P., and van Maren, D. S. (2003). “Flow asymmetry associated with
675 astronomical tides: Implications for the residual transport of sediment.” *Journal of Geophysical Research:*
676 *Oceans*, 108(C10).
- 677 [21] Evans, G. and Prego, R. (2003). “Rias, estuaries and incised valleys.” *Marine geology*, 196, 171–175.
- 678 [22] Pelc, R. and Fujita, R. (2002). “Renewable energy from the ocean.” *Marine Policy*, 26, 471–479.
- 679 [23] EDF (2020). “L’usine marémotrice de la Rance”, <[https://www.edf.fr/groupe-edf/produire-
680 une-energie-respectueuse-du-climat/accelerer-le-developpement-des-energies-renouvelables/usine-
681 maremotrice-rance/decouvrir-et-comprendre](https://www.edf.fr/groupe-edf/produire-une-energie-respectueuse-du-climat/accelerer-le-developpement-des-energies-renouvelables/usine-maremotrice-rance/decouvrir-et-comprendre)>.

- 682 [24] Bonnot-Courtois, C., Caline, B., L'Homer, A., and Le Vot, M. (2002). *Mont-Saint-Michel Bay and the*
683 *Rance estuary*. Bull. Centre Rech. Elf Explor.
- 684 [25] Guesmia, M. (2001). "Régime hydrodynamique et sédimentaire de l'estuaire de la Rance" (June).
- 685 [26] Guesmia, M., Cheviet, C., and Macur, O. (2001). "Modélisation hydrosédimentaire de l'estuaire de la
686 Rance – modélisation courantologique bidimensionnelle" (May).
- 687 [27] Thiebot, J. (2008). "Numerical modelling of the processes which govern the formation and the
688 degradation of muddy massifs -application to the Rance estuary and to the Sèvre Niortaise river banks."
689 Ph.D. thesis, Sciences of the Universe, AgroParisTech,
- 690 [28] Chevé, J. and Le Noc, S. (2018). "VibRance : Evaluation des impacts bacteriologiques dans l'estuaire
691 de la Rance" (May).
- 692 [29] Young, H., Kyeong, O., and Byung, H. (2010). "Lake Sihwa tidal power plant project." *Ocean*
693 *Engineering*, 37, 454–463.
- 694 [30] Cornett, A., Durand, N., and Serrer, M. (2010). "3-D modelling and assessment of tidal current
695 resources in the bay of Fundy, Canada." *Proc. 3rd Int. Conf. on Ocean Energy*.
- 696 [31] Hydrelect (2012). "La turbine Kaplan." *hydrelect.info*.
- 697 [32] Charlier, R. (2007). "Forty candles for the Rance river TPP tides provide renewable and sustainable
698 power generation." *Renewable and Sustainable Energy Reviews*, 11, 2032–2057.
- 699 [33] Trubert, B. and S., I. (2016). "Estuaire de la rance de l'écluse du Chatelier à la mer" (june).
- 700 [34] EDF (2018). "Rapport de fin d'intervention de la campagne 2018" (june).
- 701 [35] SHOM (2015). "Dalles bathymétriques fra-14581 et fra-14582" (March).
- 702 [36] Lane, S. N. (1998). "Hydraulic modelling in hydrology and geomorphology: a review of high resolution
703 approaches." *Hydrological Processes*, 12(8), 1131–1150.
- 704 [37] Vreugdenhil, C. B. (2013). *Numerical methods for shallow-water flow*, Vol. 13. Springer Science &
705 Business Media.

- 706 [38] Xie, D., Gao, S., Wang, Z. B., Pan, C., Wu, X., and Wang, Q. (2017). “Morphodynamic modeling
707 of a large inside sandbar and its dextral morphology in a convergent estuary: Qiantang estuary, China.”
708 *Journal of Geophysical Research: Earth Surface*, 122(8), 1553–1572.
- 709 [39] Angeloudis, A. and Falconer, R. A. (2017). “Sensitivity of tidal lagoon and barrage hydrodynamic
710 impacts and energy outputs to operational characteristics.” *Renewable Energy*, 114, 337 – 351.
- 711 [40] García-Oliva, M., Djordjević, S., and Tabor, G. R. (2017). “The impacts of tidal turbines on water
712 levels in a shallow estuary.” *International Journal of Marine Energy*, 19, 177 – 197.
- 713 [41] Neil, S., Angeloudis, A., Robins, P., Walkington, I., Ward, S., Masters, I., Lewis, M., Piano, M., Avdis,
714 A., Piggot, M., Aggidis, G., Evans, P., Adcock, T., Židonius, A., Ahmadian, R., and Falconer, R. (2018).
715 “Tidal range energy resource and optimization - Past perspectives and future challenges.” *Renewable*
716 *Energy*, 127, 763–778.
- 717 [42] Bi, Q. and Toorman, E. (2015). “Mixed-sediment transport modelling in Scheldt estuary with a
718 physics-based bottom friction law.” *Ocean Dynamics*, 65(4), 555–587.
- 719 [43] Brown, J. and Davies, A. (2010). “Flood/ebb tidal asymmetry in a shallow sandy estuary and the impact
720 on net sand transport.” *Geomorphology*, 114(3), 431–439.
- 721 [44] Santoro, P., Fossati, M., and Piedra-Cueva, I. (2013). “Study of the meteorological tide in the Río de
722 la Plata.” *Continental Shelf Research*, 60, 51–63.
- 723 [45] Van, L. A. (2012). “Numerical modelling of sand-mud mixtures settling and transport processes: appli-
724 cation to morphodynamic of the Gironde estuary (france).” Ph.D. thesis, Université Paris-Est, Université
725 Paris-Est.
- 726 [46] Orseau, S., Huybrechts, N., Tassi, P., Pham Van Bang, D., and Klein, F. (2020). “Two-dimensional
727 modeling of fine sediment transport with mixed sediment and consolidation: Application to the Gironde
728 estuary, france.” *International Journal of Sediment Research*.
- 729 [47] Bizien, H. and Soenen, A. (2012). “Mesures de courants aux abords de la centrale marémotrice de la
730 rance" (June).

- 731 [48] Barton, A. (2019). “Bluekenue enhancements from 2014 to 2019.” *Proceedings of the 26th TELEMAC-*
732 *MASCARET User Conference*, 1–9.
- 733 [49] Cochet, C. and Lambert, M. (2017). “The Rance tidal power plant model.” *Proceedings of the 24th*
734 *TELEMAC-MASCARET User Conference*, 191–196.
- 735 [50] Achilleos, G. (2011). “The inverse distance weighted interpolation method and error propagation
736 mechanism – creating a DEM from an analogue topographical map.” *Journal of Spatial Science*, 56(2),
737 283–304.
- 738 [51] Egbert, G. and Svetlana, Y. (2002). “Efficient inverse modeling of barotropic ocean tides.” *Journal of*
739 *Atmospheric and Oceanic Technology*, 19.2, 183–204.
- 740 [52] Angeloudis, A., Falconer, R., Bray, S., and Ahmadian, R. (2016). “Representation and operation of
741 tidal energy impoundments in a coastal hydrodynamic model.” *Renewable Energy*, 99, 1103–1115.
- 742 [53] Libaux, A. and Drouot, J. (2020). “Remplacement de la conduite de la Rance - Présentation du package
743 RANG 3-AGRA Version 0.7.0” (July).
- 744 [54] Bellman, R. (1954). “The theory of dynamic programming.” *Bulletin of the American Mathematical*
745 *Society*, 60, 503–515.
- 746 [55] Telemac-Mascaret Modelling System (2018). *TELEMAC-2D User’s Manual*.
- 747 [56] Davis, R. and Fitzgerald, D. (2004). *Beaches and Coasts*. Blackwell Science, Malden, MA.
- 748 [57] De Brauwere, A., De Brye, B., Blaise, S., and Deleersnijder, E. (2011). “Residence time, exposure
749 time and connectivity in the Scheldt estuary.” *Journal of Marine Systems*, 84, 85–95.
- 750 [58] Sanford, L., Boicourt, W., and Rives, S. (1992). “Model for estimating tidal flushing of small embay-
751 ments.” *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 118, 635–65.
- 752 [59] Marsooli, R., Orton, P., Fitzpatrick, J., and Smith, H. (2018). “Residence time of a highly urbanized
753 estuary: Jamaica bay, New York.” *Journal of Marine Science and Engineering*, 6, 44.
- 754 [60] Monsen, N., Cloern, J., Lucas, L., and Monismith, S. (2002). “A comment on the use of flushing time,
755 residence time, and age as transport time scales.” *Limnol. Oceanogr.*, 47, 1545–1553.

- 756 [61] Pawlowicz, R., Beardsley, B., and Lentz, S. (2002). "Classical tidal harmonic analysis including error
757 estimates in MATLAB using T-TIDE." *Computers and Geosciences*, 28, 929–937.
- 758 [62] Caude, G., Clément, P., Pillet, D., and Vindimian, E. (2017). *Gestion sédimentaire de l'estuaire de la*
759 *Rance* (in French).
- 760 [63] Duclercq, M. (2020). "La Rance: Impact du nouveau mode dechargeur sur l'intumescence dans
761 l'estuaire en cas de declenchement" (February).
- 762 [64] Bauer, H. A. (1993). "A world map of tides." *Geographical Review*, 23, 259–270.
- 763 [65] LCHF (1982). "Étude sédimentologique de l'estuaire de la Rance". (in French).
- 764 [66] Van Rijn, L. (1984). "Sediment transport, Part II: Suspended load transport." *Journal of Hydraulic*
765 *Engineering*, 110, 1613–1641.
- 766 [67] Falconer, R. and Chen, Y. (1991). "An improved representation of flooding and drying and wind stress
767 effects in a 2D tidal numerical model." *Institution of Civil Engineers*, 2, 659–672.
- 768 [68] SHOM (2020). "Permanent Service for Mean Sea Level",
769 <<https://www.psmsl.org/data/obtaining/stations/454.php>>.

770
771
772
773
774
775
776
777
778
779
780
781

List of Tables

1	Operating modes of sluice gates and turbines.	33
2	Turbines and sluice gates flowrate parameters	34
3	Root Mean Square Error (RMSE) computation between numerical results and measurements for years 2012 and 2019.	35
4	Computation of harmonics amplitude and phase errors based on tidal constituents of water surface elevation between numerical results and measurements for year 2019. All results were obtained with the T-TIDE toolbox [61]	36
5	Modeling scenarios	37
6	Asymmetry metrics derived from the harmonic analysis of water surface elevation (ζ) and current (u) at six selected positions along the estuary (Figure 1 for locations) for the three modeling scenarios (Table 5). All results were obtained with the T-TIDE toolbox [61]	38

TABLE 1. Operating modes of sluice gates and turbines.

Structure	Sluice gates		Turbines					
Operating mode	G.O.	G.C.	F.O.	D.O.	I.T.	D.T.	D.P.	T.O.
Definition	Gates Open	Gates Close	Filling On	Draining On	Inverse Turbinning	Direct Turbinning	Direct Pumping	Turbines Off
Tidal phase	Flood Ebb	Flood Ebb	Flood	Ebb	Flood	Ebb	Flood	Flood Ebb

TABLE 2. Turbines and sluice gates flowrate parameters

Tidal phase	A	B	C	$\zeta_{downstream}$
Flood	-132.61	-948.22	-900.9	$\zeta_{estuary}$
Ebb	161.98	960.96	912.73	$\max(1, \zeta_{sea})$

TABLE 3. Root Mean Square Error (RMSE) computation between numerical results and measurements for years 2012 and 2019.

Data set year	2012			2019			
	ADCP 1	ADCP 2	ADCP 3	Saint Servan	upstream of TPS	Saint Suliac	Chatelier Lock
Water Surface Elevation (cm)	8.11	8.13	5.04	6.22	9.12	8.74	8.08
High Water Level (cm)	4.44	4.46	3.08	5.42	4.38	4.24	4.05
Low water Level (cm)	2.41	2.26	2.05	9.58	8.24	8.78	—
Current magnitude(m/s)	0.1	0.18	0.2			—	
Current direction (°)	12	11	8			—	

TABLE 4. Computation of harmonics amplitude and phase errors based on tidal constituents of water surface elevation between numerical results and measurements for year 2019. All results were obtained with the T-TIDE toolbox [61].

Tidal constituents	M2		M4	
	Amplitude (cm)	Phase (°)	Amplitude (cm)	Phase (°)
Saint Servan	3.02	3	2.41	8
upstream of TPS	4.21	4	3.89	9
Saint Suliac	4.15	4	3.77	9

TABLE 5. Modeling scenarios

Name	Bathymetry	Type
C1	1957	Without power station
C2	2018	Without power station
C1	2018	With power station

List of Figures

783	1	The Rance estuary: (a) location map, (b) zoom on the estuary with filled contours of 2018 bathymetry, (c) zoom on the tidal power station (TPS). Vertical plan view of the turbine generators during (d) flood and (e) ebb. Sketches (d) and (e) © EDF (modified).	41
784			
785	2	(a) Bathymetry of 1957 (before the construction of the tidal power station). Blank area represents the zones where the bathymetry is less reliable. (b) Bathymetry of 2018. Bathymetry evolution between 1957 and 2018.	42
786			
787	3	Comparison of numerical results and measured data from data set of 2012: water surface elevation, current magnitude and current direction respectively at positions (a;d;g) ADCP 1 upstream of the turbines, (b;e;h) ADCP 2 upstream of the sluice gates and (c;f;i) ADCP 3 downstream of the tidal power station (see locations in Figure 1).	43
788			
789	4	Comparison of water surface elevation between numerical and measured data, over a period of a fortnight from August 15 to 28 2019, at (a) Saint Servan, (b) upstream of tidal power station, (c) Saint Suliac and (d) Chatelier lock (see locations in Figure 1). Red lines and black dots indicate respectively numerical results and measured data. The measurements are not reliable at low tide at Chatelier Lock station because of technical difficulties of the gauge.	44
790			
791	5	Comparison of (a) low, mean, high water levels and (b) tidal range at neap and spring tide along the estuary channel (see Figure 1 for channel position). The black line indicates bed elevation.	45
792			
793	6	Hydrodynamic variables during spring tidal period: water surface elevation and currents respectively at locations (a;e) Saint Servan, (b;f) upstream of TPS, (c;g) Saint Suliac and (d;h) Chatelier Lock. Black dots and red lines indicate respectively measurements and numerical simulation. Gray solid- and dashed-lines represent operating modes of the TPS (see Table 1).	46
794			
795	7	Hydrodynamic variables during neap tidal period: water surface elevation and currents respectively at locations (a;e) Saint Servan, (b;f) upstream of TPS, (c;g) Saint Suliac and (d;h) Chatelier Lock. Black dots and red lines indicate respectively measurements and numerical simulation. Gray solid- and dashed-lines represent operating modes of the TPS (see Table 1).	47
796			
797	8	Spatial comparison of hydrodynamic parameters between configurations C1, C2 and C3 along the estuary channel at spring tide (see Figure 1 for channel location). (a;b) For low, mean, high water levels and tidal range respectively between configurations C1 and C2. (c;d) For low, mean, high water levels and tidal range respectively between configurations C2 and C3. Black dashed- and solid-lines indicate bed elevation in 1957 and 2018 respectively.	48
798			
799	9	Spatial distribution of (a;b;c) maximum flood currents and (d;e;f) maximum ebb currents for the three studied scenarios respectively. Dry zones at ebb are blanked.	49
800			
801	10	Hydrodynamic variables of the three scenarios during spring tidal period: water surface elevation and currents respectively at locations (a;e) downstream of TPS, (b;f) upstream of TPS, (c;g) Ton Peak and (d;h) Saint Hubert Port. Gray solid- and dashed-lines represent operating modes of the TPS (see Table 1).	50
802			
803	11	Hydrodynamic variables of the three scenarios during neap tidal period: water surface elevation and currents respectively at locations (a;e) downstream of TPS, (b;f) upstream of TPS, (c;g) Ton Peak and (d;h) Saint Hubert Port. Gray solid- and dashed-lines represent operating modes of the TPS (see Table 1).	51
804			
805			
806			
807			
808			
809			
810			
811			
812			
813			
814			
815			
816			
817			
818			
819			
820			
821			
822			
823			
824			
825			

826	12	Temporal evolution at TPS section of (a) flowrate during a fortnight period, (b) zoom on	
827		flowrate during spring tide (two-way generation mode), (c) zoom on flowrate during neap	
828		tide (one-way generation mode) and (d) tidal prism for the three scenarios. (see Figure 1 for	
829		section location).	52
830	13	Spatial distribution of (a;b;c) velocity skewness parameter $\gamma_0(u)$ and (d;e;f) tidal duration	
831		asymmetry parameter $\gamma_0(\frac{\partial \zeta}{\partial t})$ for the three scenarios respectively. Dry zones at ebb are	
832		blanked.	53
833	14	Spatial distribution of (a;b) maximum flood current differences and (c;d) maximum ebb	
834		current differences between the three modeled scenarios. The reference scenario is C2 (see	
835		Table 5). Positive (negative) current differences mean flow acceleration (deceleration). . . .	54
836	15	Spatial distribution of velocity skewness ratio between (a) C1 and C2 scenarios and (b)	
837		C3 and C2 scenarios. The reference scenario is C2 (see Table 5). If velocity skewness	
838		ratio is negative, both C1 and C3 scenarios switch the flood (ebb) dominance to ebb (flood)	
839		dominance. The flood dominance is amplified (decreased) for both C1 and C3 scenarios when	
840		the velocity skewness ratio is larger than one (between zero and one). The ebb dominance	
841		is amplified (decreased) for both C1 and C3 scenarios when the velocity skewness ratio is	
842		between zero and one (larger than one).	55

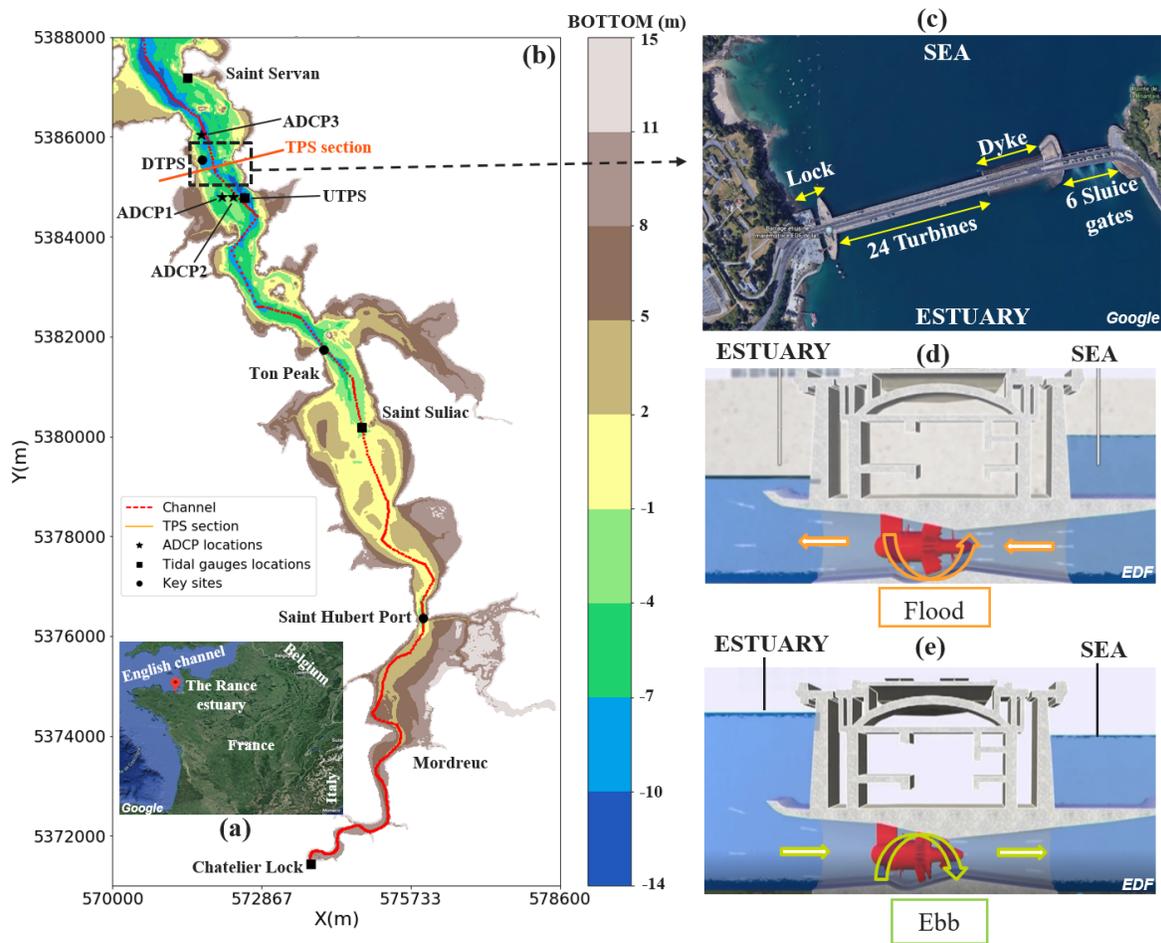


Fig. 1. The Rance estuary: (a) location map, (b) zoom on the estuary with filled contours of 2018 bathymetry, (c) zoom on the tidal power station (TPS). Vertical plan view of the turbine generators during (d) flood and (e) ebb. Sketches (d) and (e) © EDF (modified).

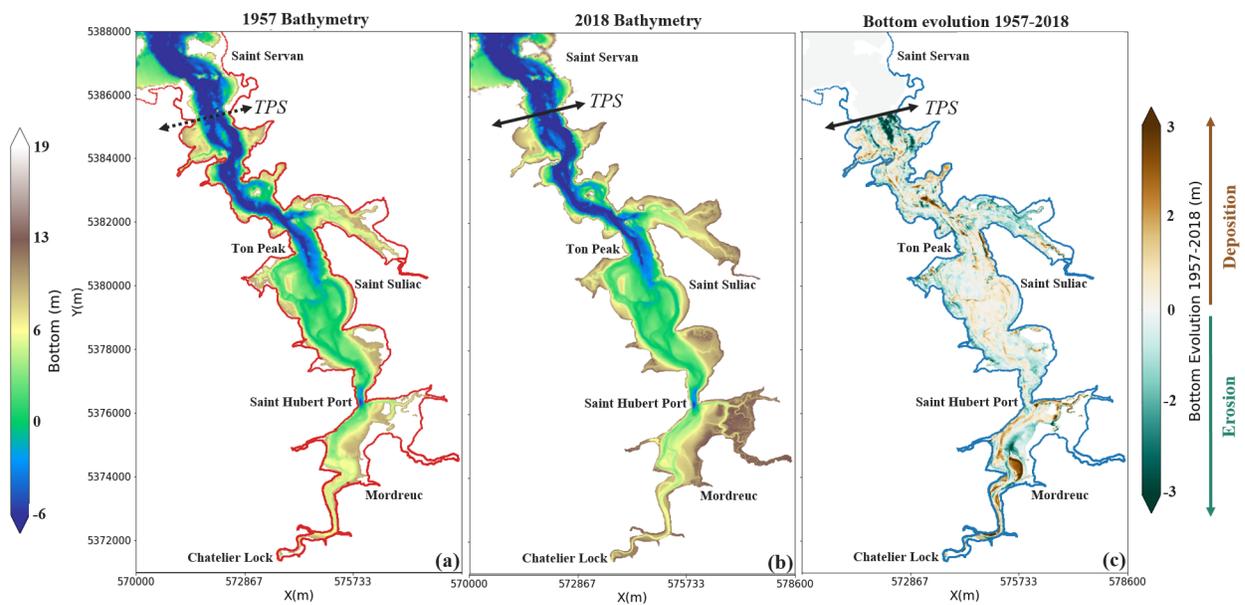


Fig. 2. (a) Bathymetry of 1957 (before the construction of the tidal power station). Blank area represents the zones where the bathymetry is less reliable. (b) Bathymetry of 2018. Bathymetry evolution between 1957 and 2018.

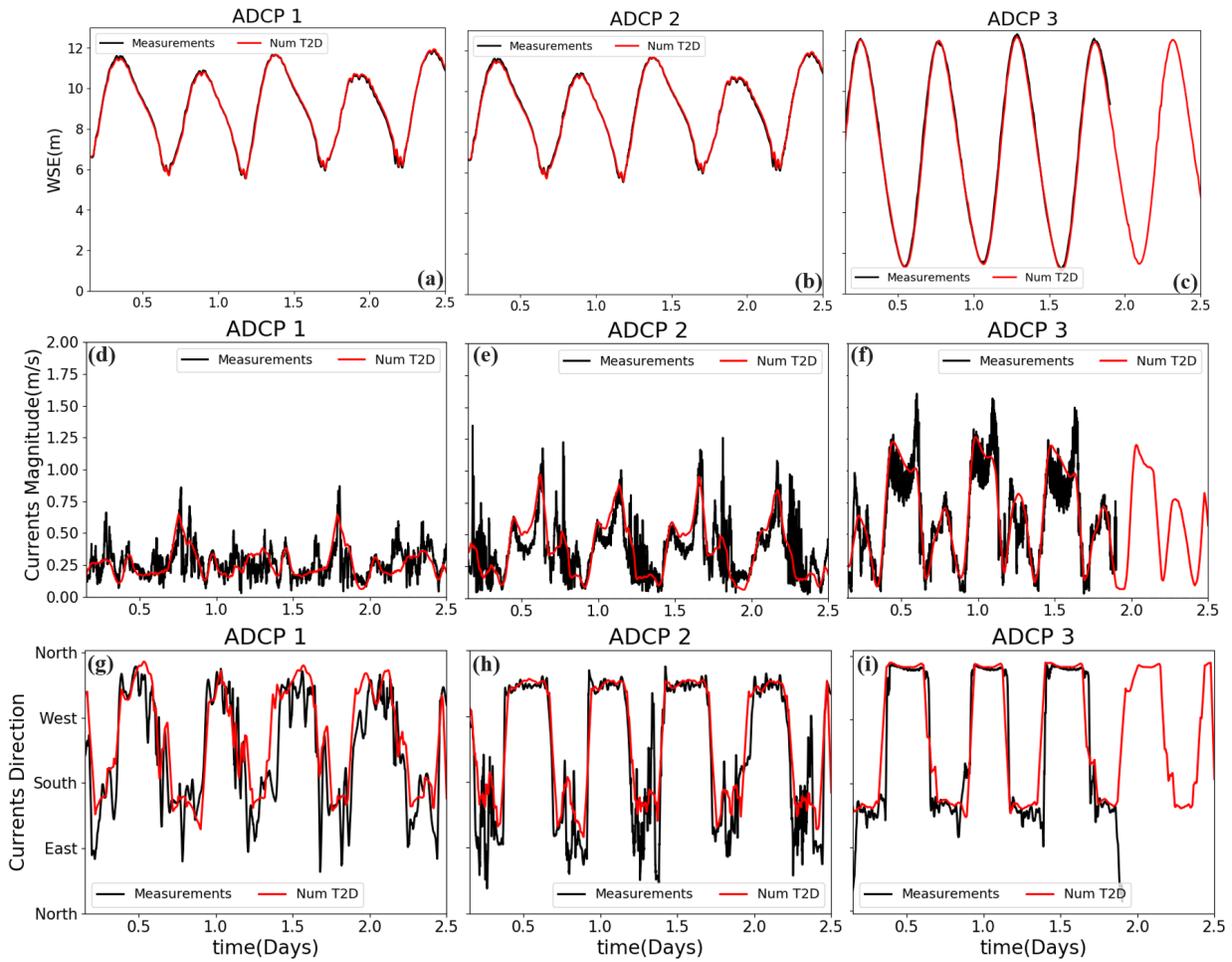


Fig. 3. Comparison of numerical results and measured data from data set of 2012: water surface elevation, current magnitude and current direction respectively at positions (a;d;g) ADCP 1 upstream of the turbines, (b;e;h) ADCP 2 upstream of the sluice gates and (c;f;i) ADCP 3 downstream of the tidal power station (see locations in Figure 1).

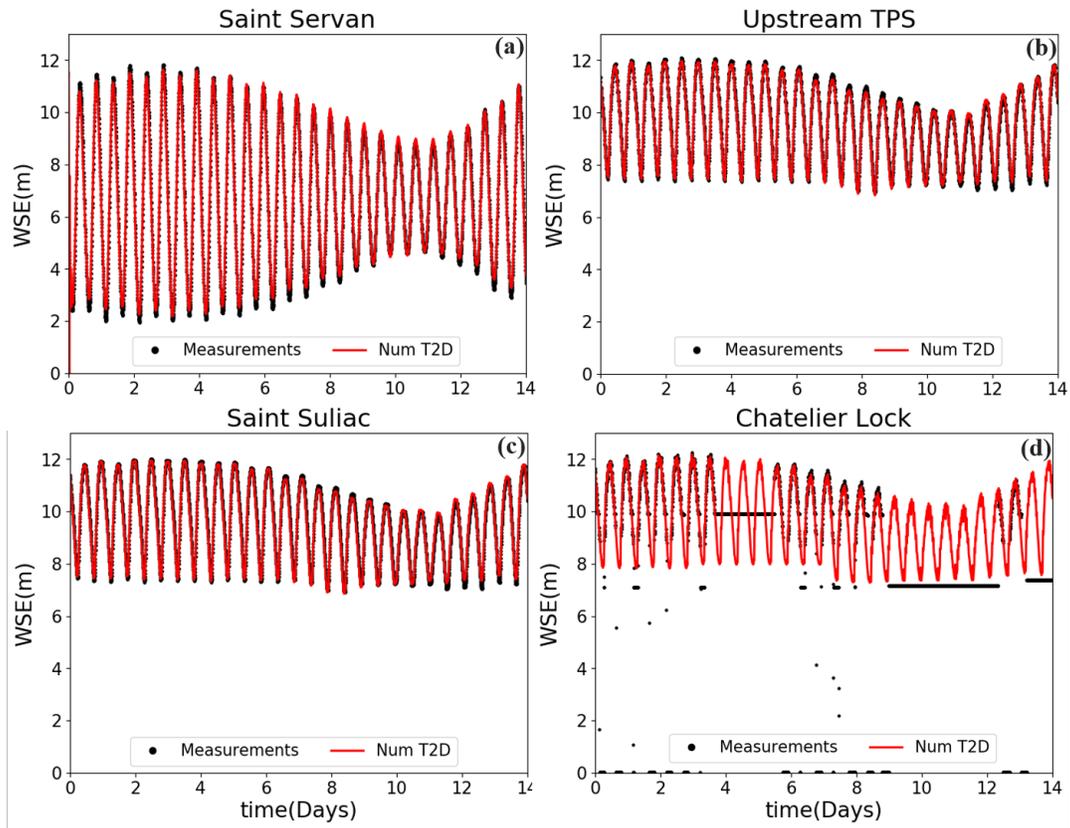


Fig. 4. Comparison of water surface elevation between numerical and measured data, over a period of a fortnight from August 15 to 28 2019, at (a) Saint Servan, (b) upstream of tidal power station, (c) Saint Suliac and (d) Chatelier lock (see locations in Figure 1). Red lines and black dots indicate respectively numerical results and measured data. The measurements are not reliable at low tide at Chatelier Lock station because of technical difficulties of the gauge.

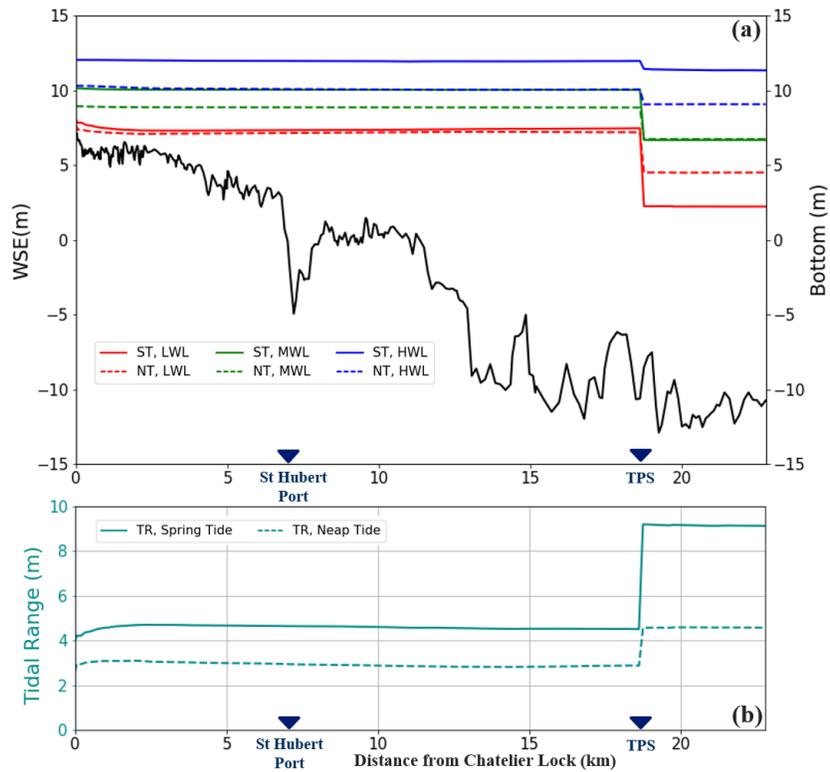


Fig. 5. Comparison of (a) low, mean, high water levels and (b) tidal range at neap and spring tide along the estuary channel (see Figure 1 for channel position). The black line indicates bed elevation.

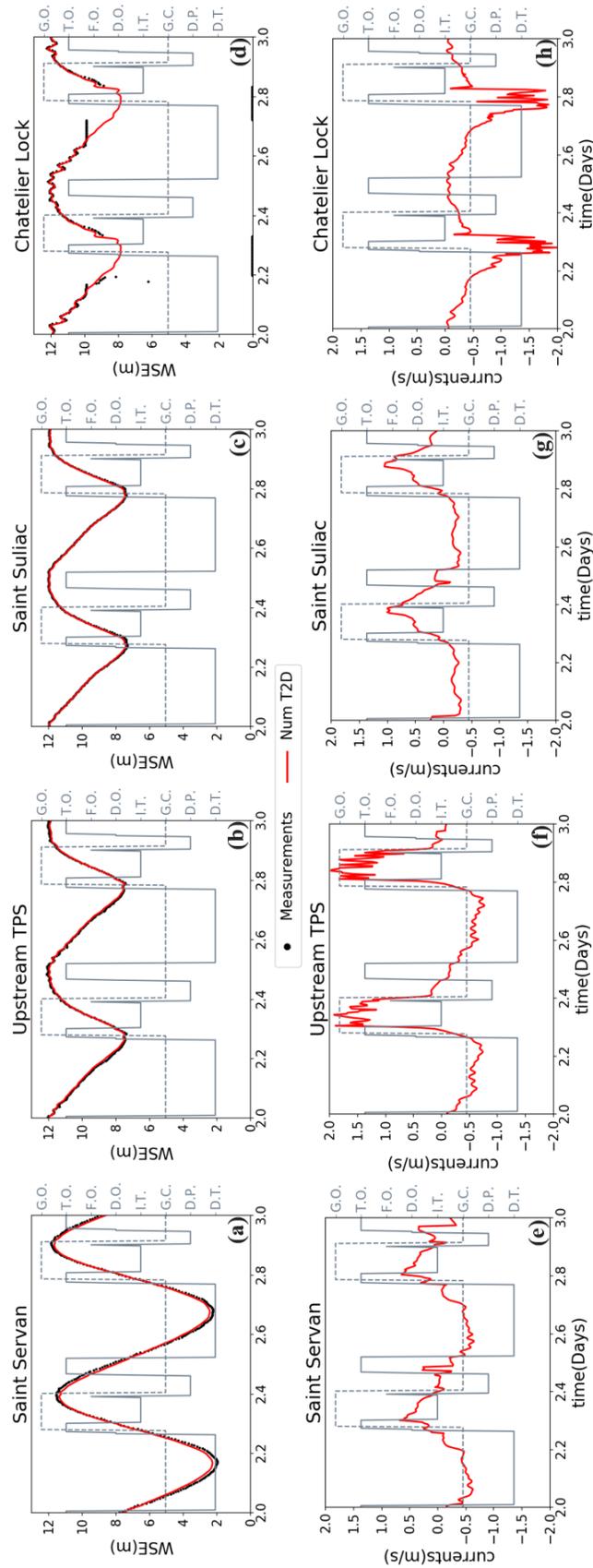


Fig. 6. Hydrodynamic variables during spring tidal period: water surface elevation and currents respectively at locations (a,e) Saint Servan, (b,f) upstream of TPS, (c,g) Saint Suliac and (d,h) Chatelier Lock. Black dots and red lines indicate respectively measurements and numerical simulation. Gray solid- and dashed-lines represent operating modes of the TPS (see Table 1).

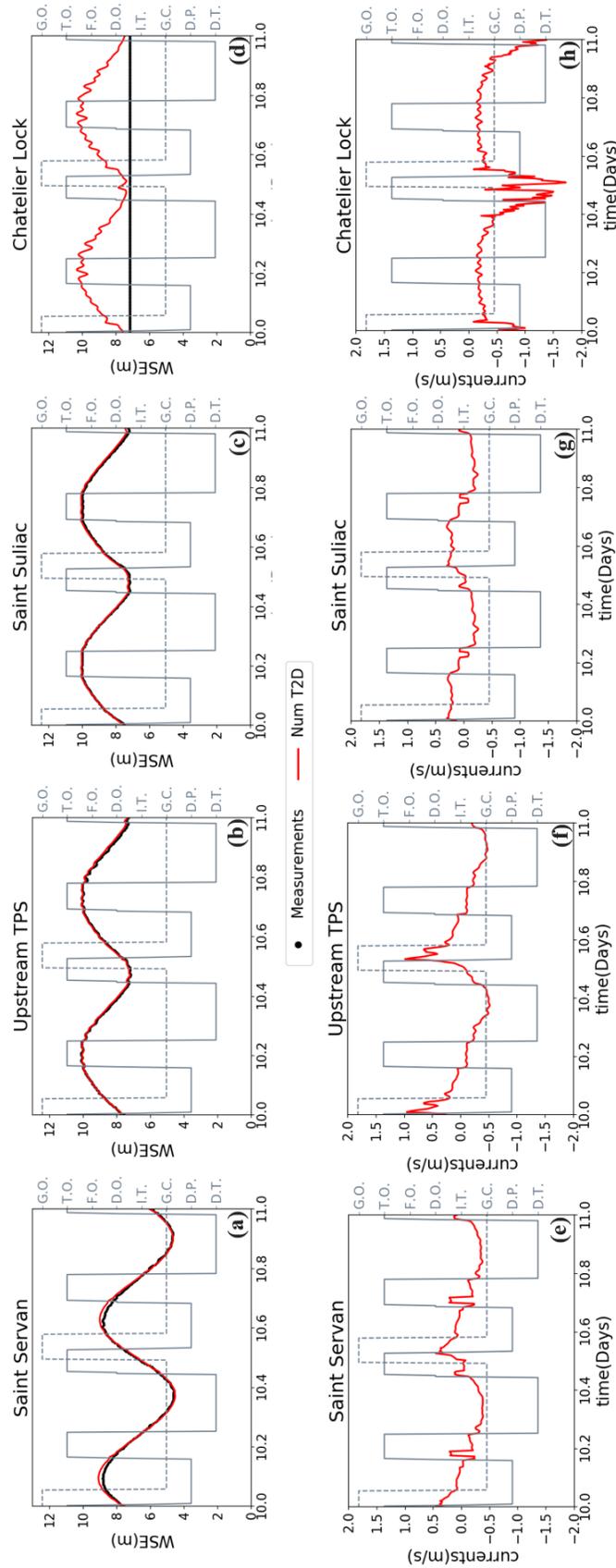


Fig. 7. Hydrodynamic variables during neap tidal period: water surface elevation and currents respectively at locations (a,e) Saint Servan, (b,f) upstream of TPS, (c,g) Saint Suliac and (d,h) Chatelier Lock. Black dots and red lines indicate respectively measurements and numerical simulation. Gray solid- and dashed-lines represent operating modes of the TPS (see Table 1).

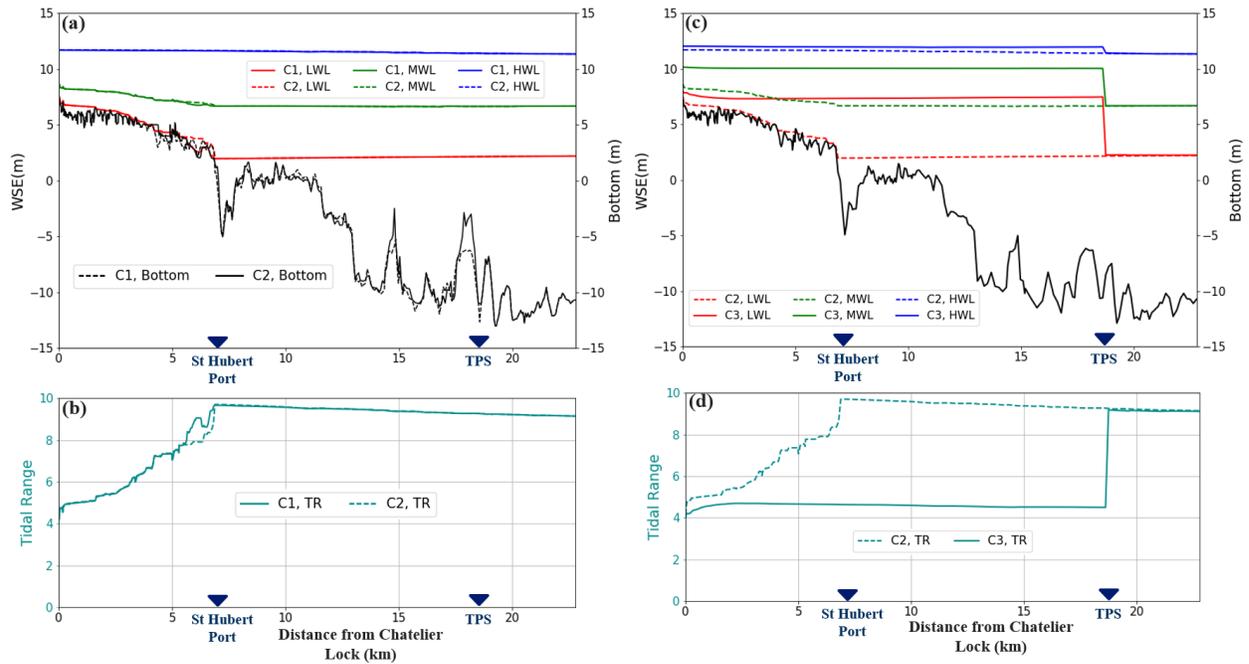


Fig. 8. Spatial comparison of hydrodynamic parameters between configurations C1, C2 and C3 along the estuary channel at spring tide (see Figure 1 for channel location). (a);b) For low, mean, high water levels and tidal range respectively between configurations C1 and C2. (c);d) For low, mean, high water levels and tidal range respectively between configurations C2 and C3. Black dashed- and solid-lines indicate bed elevation in 1957 and 2018 respectively.

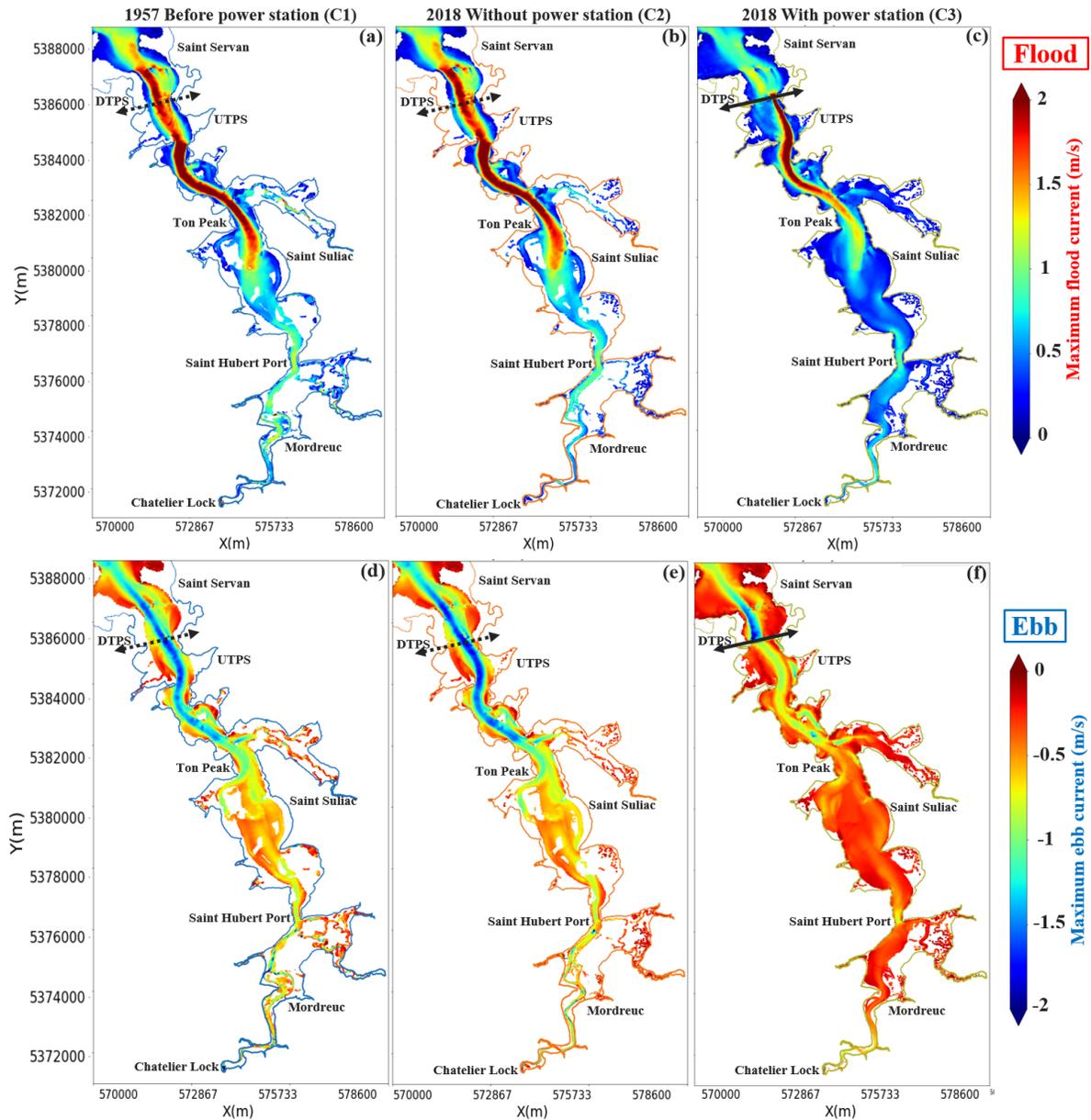


Fig. 9. Spatial distribution of (a;b;c) maximum flood currents and (d;e;f) maximum ebb currents for the three studied scenarios respectively. Dry zones at ebb are blanked.

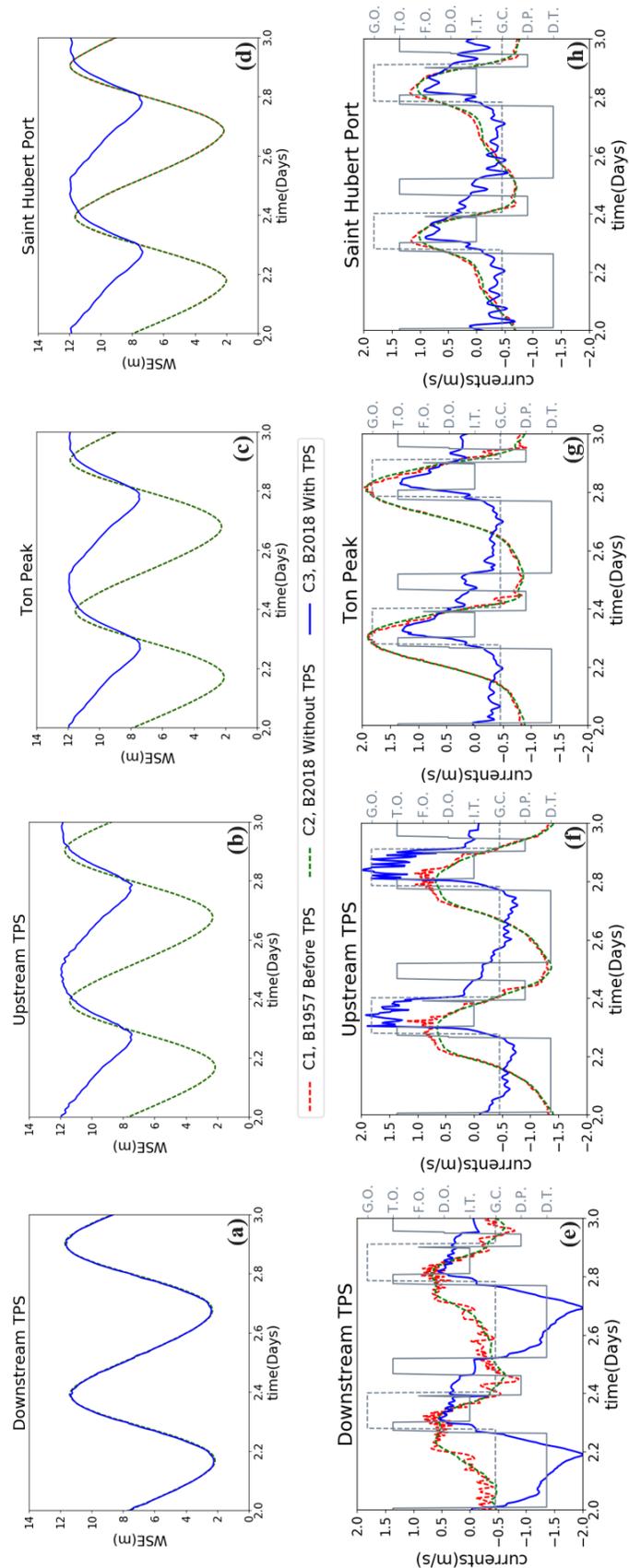


Fig. 10. Hydrodynamic variables of the three scenarios during spring tidal period: water surface elevation and currents respectively at locations (a;e) downstream of TPS, (b;f) upstream of TPS, (c;g) Ton Peak and (d;h) Saint Hubert Port. Gray solid- and dashed-lines represent operating modes of the TPS (see Table 1).

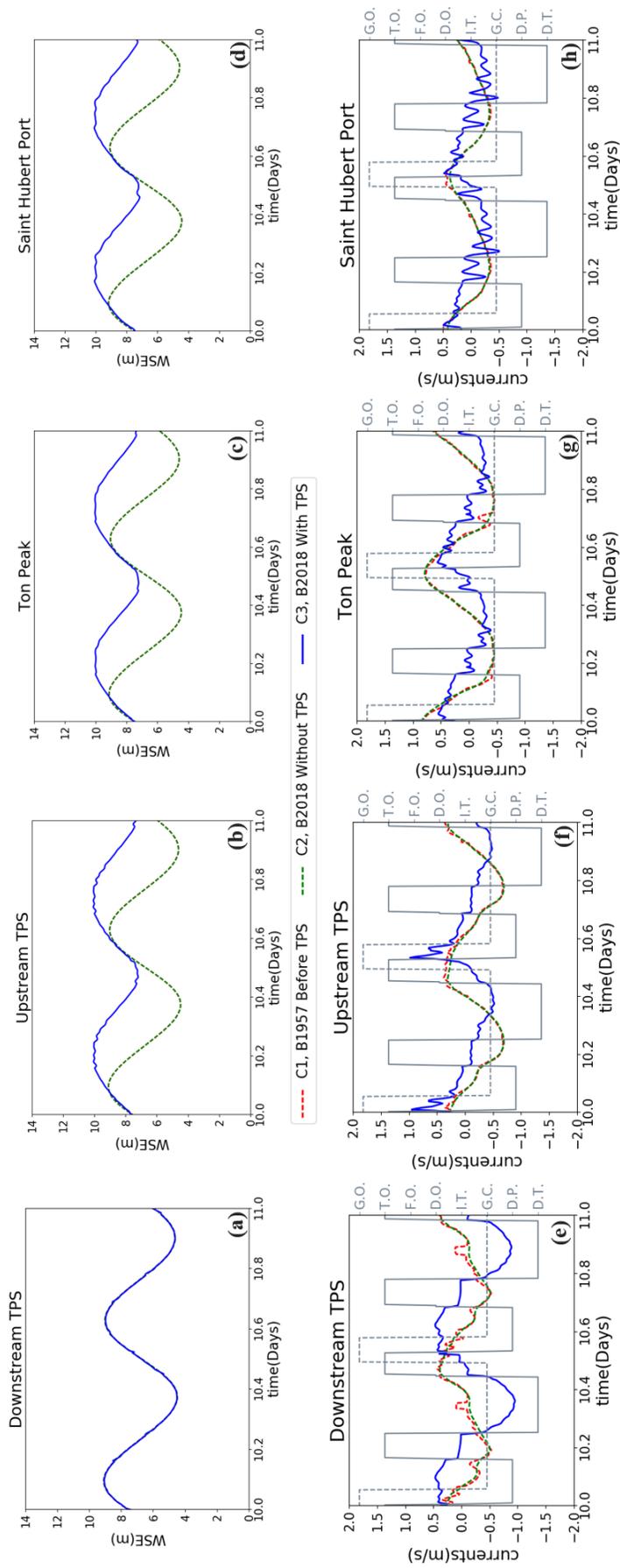


Fig. 11. Hydrodynamic variables of the three scenarios during near tidal period: water surface elevation and currents respectively at locations (a,e) downstream of TPS, (b,f) upstream of TPS, (c,g) Ton Peak and (d,h) Saint Hubert Port. Gray solid- and dashed-lines represent operating modes of the TPS (see Table 1).

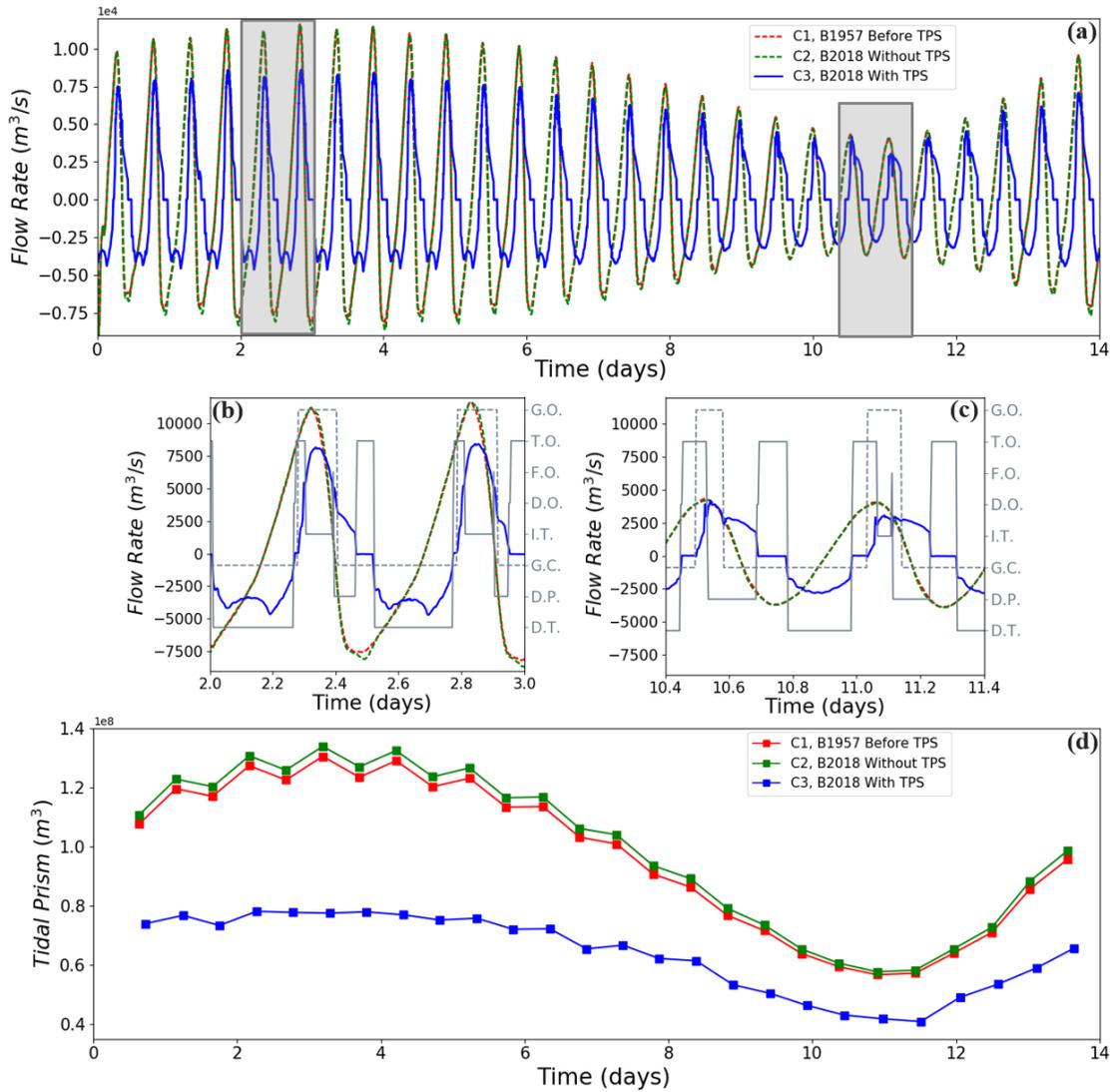


Fig. 12. Temporal evolution at TPS section of (a) flowrate during a fortnight period, (b) zoom on flowrate during spring tide (two-way generation mode), (c) zoom on flowrate during neap tide (one-way generation mode) and (d) tidal prism for the three scenarios. (see Figure 1 for section location).

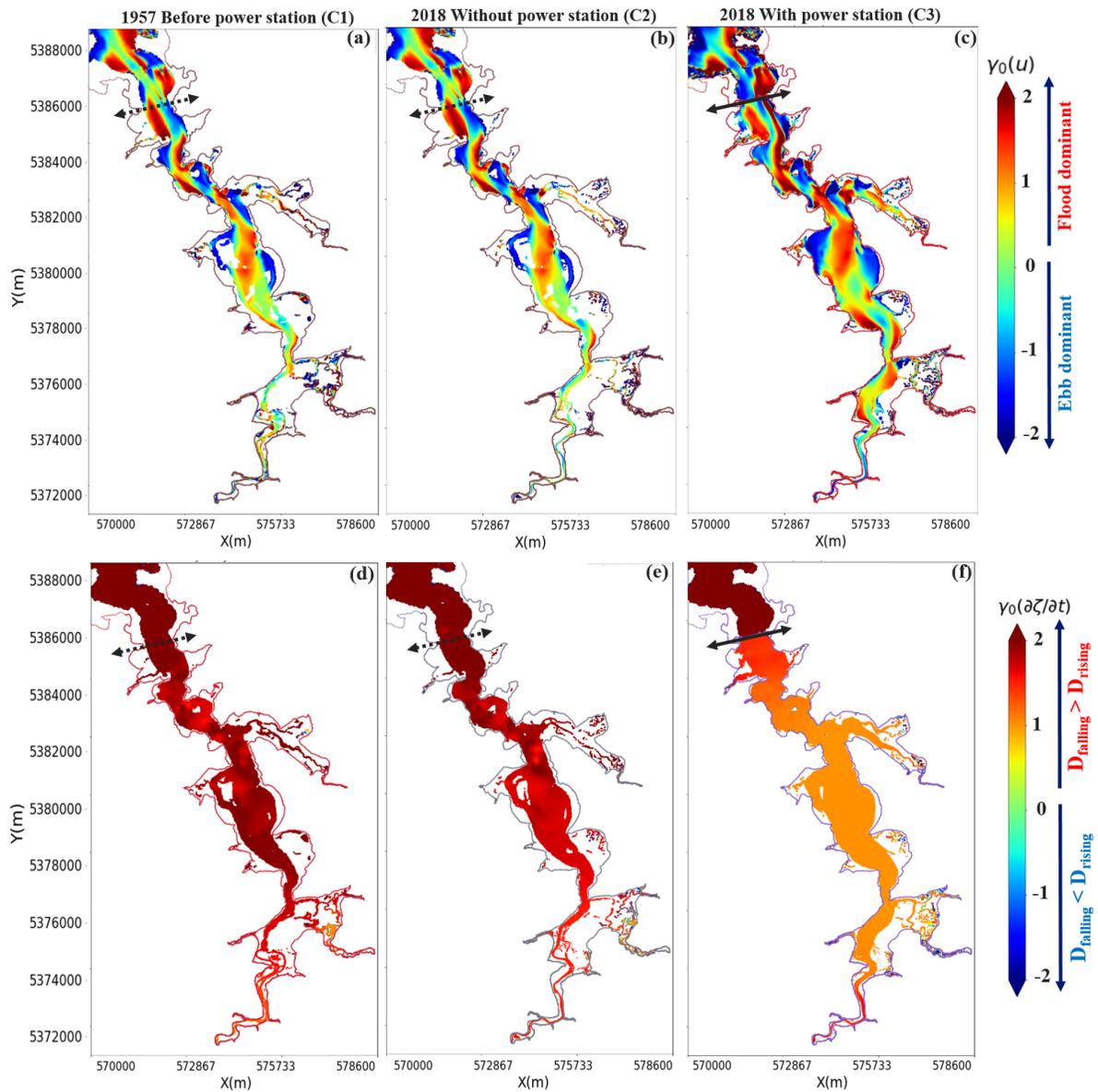


Fig. 13. Spatial distribution of (a;b;c) velocity skewness parameter $\gamma_0(u)$ and (d;e;f) tidal duration asymmetry parameter $\gamma_0(\frac{\partial \zeta}{\partial t})$ for the three scenarios respectively. Dry zones at ebb are blanked.

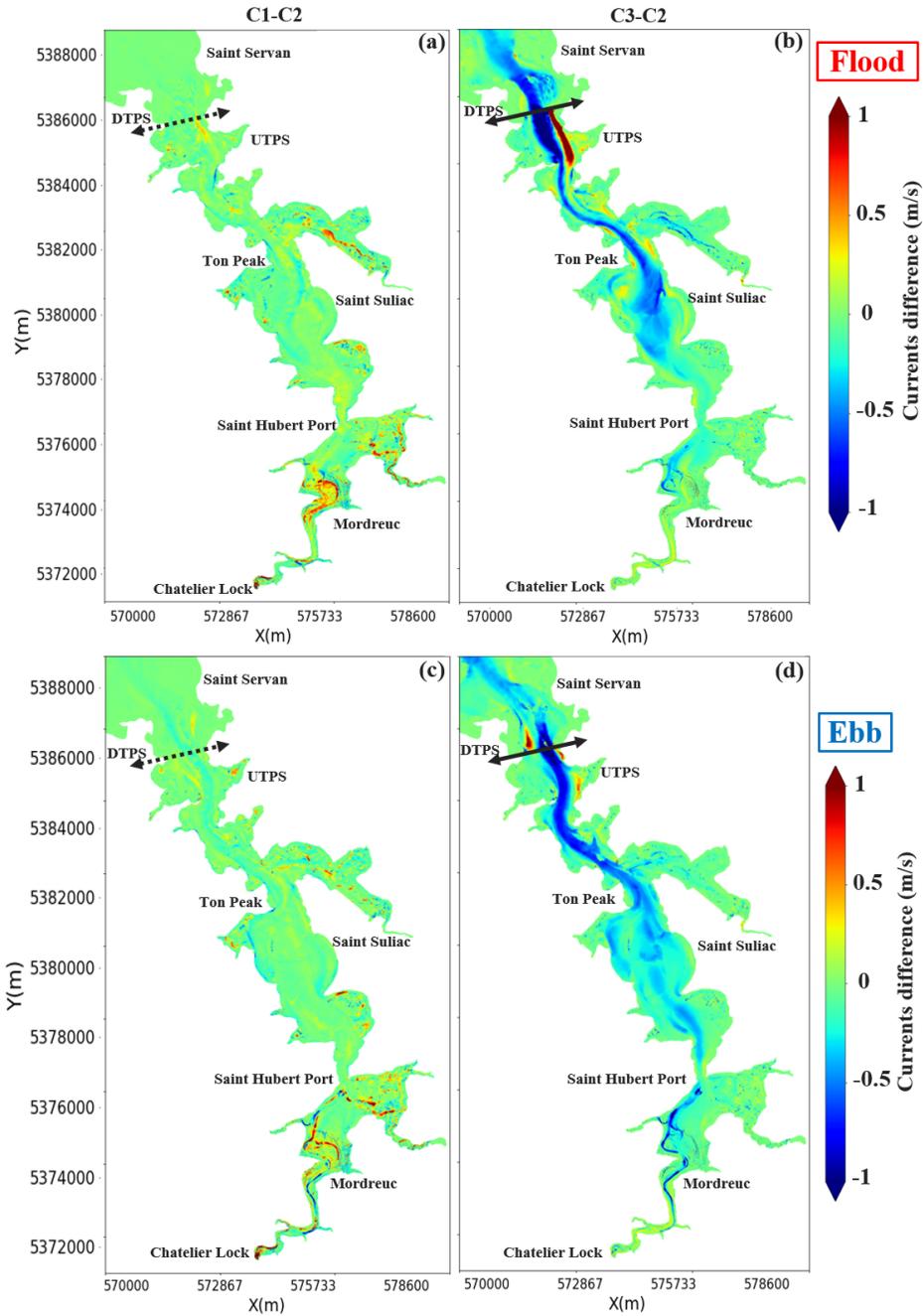


Fig. 14. Spatial distribution of (a;b) maximum flood current differences and (c;d) maximum ebb current differences between the three modeled scenarios. The reference scenario is C2 (see Table 5). Positive (negative) current differences mean flow acceleration (deceleration).

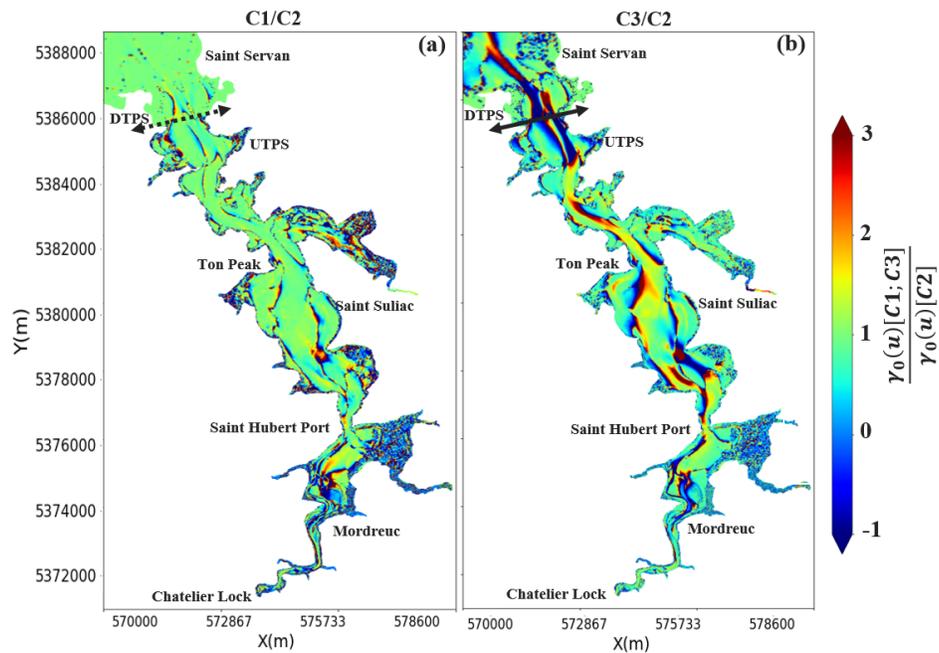


Fig. 15. Spatial distribution of velocity skewness ratio between (a) C1 and C2 scenarios and (b) C3 and C2 scenarios. The reference scenario is C2 (see Table 5). If velocity skewness ratio is negative, both C1 and C3 scenarios switch the flood (ebb) dominance to ebb (flood) dominance. The flood dominance is amplified (decreased) for both C1 and C3 scenarios when the velocity skewness ratio is larger than one (between zero and one). The ebb dominance is amplified (decreased) for both C1 and C3 scenarios when the velocity skewness ratio is between zero and one (larger than one).