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Monitoring discharge in a tidal river using water level observations: application to the Saigon River, Vietnam

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1 Abstract

2 The hydrological dynamics of the Saigon River is ruled by a complex com-
3 bination of factors, which need to be disentangled to prevent and limit risks
4 of flooding and salt intrusion. In particular, the Saigon water discharge is
5 highly influenced by tidal cycles with a relatively low net discharge. This
6 study proposes a low-cost technique to estimate river discharge at high fre-
7 quency (every 10 minutes in this study). It is based on a stage-fall-discharge
8 (SFD) rating curve adapted from the general Manning Strickler law, and cal-
9 ibrated thanks to two ADCP campaigns. Two pressure sensors were placed
10 at different locations of the river in September 2016: one at the centre of
11 Ho Chi Minh City and one in Phu Cuong, 40 km upstream approximately.
12 The instantaneous water discharge data were used to evaluate the net resid-
13 ual discharge and to highlight seasonal and inter-annual trends. Both water
14 level and water discharge show a seasonal behaviour. Rainfall, including
15 during the Usagi typhoon that hit the megalopolis in November 2018, has
16 no clear and direct impact on water level and water discharge due to the
17 delta flat morphology and complex response between main channel and side
18 channel network and ground water in this estuarine system under tidal in-
19 fluence. However, we found some evidences of interactions between precip-

20 itation, groundwater, the river network and possibly coastal waters. This
21 paper can be seen as a proof of concept to (1) present a low-cost discharge
22 method that can be applied to other tidal rivers, and (2) demonstrate how
23 the high-frequency discharge data obtained with this method can be used to
24 evaluate discharge dynamics in tidal river systems.

25 ***Keywords***

26 Saigon River, water level, water discharge, tidal river, flood, stage-fall-discharge
27 rating curve.

28 **1 Introduction**

29 A good understanding of the hydrological cycle, and discharge in particular,
30 in tidal rivers enables reliable forecasting and decision making by researchers
31 and policy makers. Some priorities are generally put on the protections
32 against floods, saline intrusion and the dynamics of pollutants because of the
33 social, economic and political stakes they are linked to. Hydrological cycles in
34 Low Elevation Coastal (and deltaic) Zone (LECZ, 0-10 masl) differ a lot from
35 their upstream environments due to the tidal influence ([van Driel et al., 2015](#)).
36 Although this is a strategic zone at the interface between land and ocean,
37 physical and environmental data collected in this environment remain sparse
38 because of inherent logistical difficulties due to the unsteadiness of the flow
39 ([Taniguchi et al., 2013](#)). On one hand, the river water discharge is influenced
40 by tidal dynamics, which modulate hydrodynamics at high and low frequency
41 and can reshape the geomorphology, with feedback loops on hydrodynamics
42 ([Mao et al., 2004](#)). On the other hand, estuarine and deltaic zones are highly
43 influenced by peak fresh water discharges, which are themselves modulated
44 by tidal asymmetry ([Sassi and Hoitink, 2013](#)).

45 In the floodplain of the Saigon River, which is part of the LECZ of the
46 south of Vietnam, vulnerability could be assessed according to four factors
47 ([McGranahan et al., 2007](#); [van Driel et al., 2015](#)) : (i) Relative Sea Level Rise
48 (RSLR) due to climate change and natural and anthropogenic subsidence;
49 (ii) Wetland ecological threat; (iii) Population pressure: and (iv) Delta gov-
50 ernance (adaptivity, participation, fragmentation). The Saigon River flows
51 through Ho Chi Minh City (HCMC), a highly populated area, where popu-
52 lation density can reach up to 30,000 inhabitants/km² ([Nguyen et al., 2019](#)).
53 The unprecedented growth of HCMC induces pressure on the environment
54 and especially water resources ([Van Leeuwen et al., 2016](#)).

55 A major issue in such regions is to measure the instantaneous discharge

56 for a tidal river and to evaluate the residual discharge of the tide-affected
57 river. Indeed, a simple stage-discharge relationship cannot be used because
58 of the downstream influence of the tide. Stage-fall-discharge (SFD) rating
59 curves are traditionally and successfully used to compute discharge at sites
60 where variable backwater effects could affect a classical stage-discharge re-
61 lationship (Rantz, 1982). Such methods have recently improved thanks to
62 Bayesian methods (Petersen-Overleir and Reitan, 2009; Mansanarez et al.,
63 2016). However, the relation between stage, slope, and discharge has gener-
64 ally been considered too complex in tidal rivers to attempt to obtaining
65 accurate discharges. Rantz (1963) proposed a graphical method using mul-
66 tiple correlation, which remains difficult to apply, especially when the tidal
67 influence leads to discharge fluctuations as large as the residual discharge.
68 That is the reason why there exists nearly no hydrometric stations world-
69 wide in such rivers. Recently, acoustic sensing techniques (through HADCP,
70 Horizontal Acoustic Doppler Current Profiler) have been implemented suc-
71 cessfully in some tidal rivers such as the Sacramento River, California (Ruhl
72 and DeRose, 2004) or in the rivers Berau and Mahakam in East Kaliman-
73 tan, Indonesia (Hoitink et al., 2009; Sassi et al., 2011). Such techniques
74 generally correspond to a velocity index method. Similar method using an
75 ADP (Acoustic Doppler Profiler) current meter was deployed on the Tan-
76 shui River, Taiwan (Chen et al., 2012b) or fixed ADCPs (Acoustic Doppler
77 Current Profiler) on the Yangtze River at Xuliujing, China (Zhao et al.,
78 2016; Mei et al., 2019). These methods remain however expensive (around
79 30k€excluding structural works and maintenance) and difficult to display in
80 an urban place due to risk of vandalism.

81 In a recent work, Camenen et al. (2017) proposed to apply a stage-fall-
82 discharge rating curve to estimate instantaneous discharges in tidal rivers.
83 Such simple model can be calibrated using intense discharge campaigns achieved
84 over a full tide cycle, which are easily available nowadays thanks to the ADCP
85 technology. The first application of the method was based on field measure-
86 ments made on the Saigon River in September 2016 and was particularly
87 successful (Camenen et al., 2017). It presented some limitations for a very
88 asymmetric tidal wave (close to a tidal bore), which is not the case for the
89 Saigon River.

90 In this paper, this simple low-cost water level-based discharge monitoring
91 is applied the Saigon River for a two-year period. A calibration and validation
92 of the method are first presented. The monitoring of two hydrological seasons
93 from January 2017 to Dec 2019 is then discussed. Results obtained allow for
94 examining and discussing two specific aspects : first, what is the hydrological
95 pattern of the Saigon River at different time scales, from the event scale to
96 years, and how is it influenced by the sea level ; second, how much the rainfall

97 regime is directly influencing the Saigon River dynamics, in particular, how
98 does the river react to extreme events?

99 **2 Material and methods**

100 **2.1 Study site**

101 The Saigon River is located in the South of Vietnam, in a low elevation
102 coastal zone, i.e. between 0 and 10 m above mean sea level (MSL, Figure
103 1). The Saigon River takes its source in Cambodia and is 225 km long.
104 Its catchment area has a surface of 4717 km² (Nguyen et al., 2019). The
105 Saigon River is actually a complex river system, subject to several human
106 and environmental interactions, including many canals while it crosses Ho
107 Chi Minh City (HCMC) megalopolis, before flowing into the Dong Nai River
108 and the coastal waters. Upstream the megalopolis, the river is regulated by
109 the Dau Tieng dam, which was built during the 1980's, in order to mitigate
110 saline intrusion and secure the fresh water supply uptake station of HCMC.
111 The situation of HCMC is all the more critical as 65% of the city is located
112 at an altitude of 1.5 m above MSL (Scussolini et al., 2017; Vachaud et al.,
113 2019).

114 The flow of the Saigon River is predominantly driven by tidal currents,
115 which affects both the water level and water discharge, with regular exfil-
116 tration of water in some urban districts during high spring tides. Over the
117 year, precipitation follow two contrasted seasons: the dry season, usually ex-
118 tending from November to April and the wet season from May to October,
119 which gathers about 80% of the total rain (Nguyen et al., 2019). Rain event
120 can be severe and precipitation record can locally exceed 300 mm/day, even
121 400 mm/day. In this paper, we focus on one of the most severe rainy events
122 that experienced the city. It occurred in November 2018, when Usagi typhoon
123 hit HCMC. During this event, there was an increase of more than 300 mm
124 in rainfall which caused flooding, material and human damages reported in
125 several newspapers.

126 **2.2 Water discharge estimation**

127 The instantaneous water discharge was estimated by applying a stage-fall-
128 discharge (SFD) rating curve adapted from the general Manning-Strickler
129 law, previously tested and validated by Camenen et al. (2017). This model
130 is based on the assumption of a pseudo-uniform flow and a prismatic sec-
131 tion, which is valid for a low slope river with slowly varying water depth.

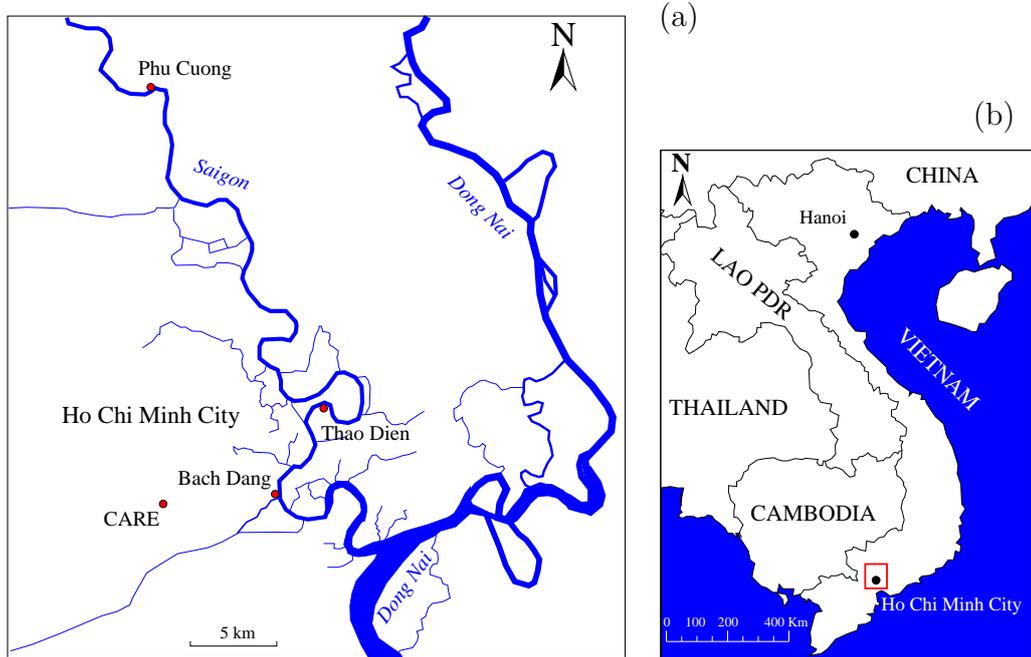


Figure 1: Location of the study site: the low elevation coastal zone of the Saigon River system, including the Saigon and Dong Nai rivers and Ho Chi Minh City (red points correspond to the position of pressure gauges).

132 Considering an almost constant flow between two water level measures, the
 133 Manning-Strickler equation can be applied :

$$Q = K A_w R_h^{2/3} \sqrt{S} \quad (1)$$

134 with Q the water discharge [m^3/s], K the Manning-Strickler coefficient [$\text{m}^{1/3}/\text{s}$],
 135 $R_h = A_w/P_w$ the hydraulic radius [m], A_w the wet section [m^2], P_w the wet
 136 perimeter [m], and S the energy slope [-] assumed equal to the water slope.
 137 Another assumption made here is that the river section and reach are stable
 138 with no significant bed changes. It was verified by comparing the different
 139 bathymetries from both ADCP campaigns.

140 Two hydrological stations are needed to evaluate the hydraulic slope of
 141 the river: the water level z_{up} and z_{dn} were measured at Phu Cuong (upstream
 142 station) and Bach Dang then Thao Dien stations (downstream stations),
 143 which are named “PC”, “BD”, and “TD” hereafter (see Fig. 1a). Distance
 144 between stations is around $L = 42$ km (PC-BD) and $L = 35$ km (PC-TD),
 145 which is sufficient to have a significant difference in altitude and to estimate
 146 slope with a good resolution for this low slope system. Due to tides and

147 flow oscillation, the slope oscillates between positive and negative values.
 148 Also, the slope in Equation (1) ($S = (z_{up} - z_{dn})/L$) does not correspond to
 149 the local slope at the point in which the discharge is evaluated, i.e. at Phu
 150 Cuong (PC). Indeed, because of the distance between the two stations, the
 151 flow discharge is slightly different at the two stations. However, this spatial
 152 offset can be translated as a lag time Δt . As a consequence, the discharge
 153 estimation at PC can be written :

$$Q(t) = K A_w(z_{up}(t)) R_h(z_{up}(t))^{2/3} \sqrt{|S(t + \Delta t)|} \frac{S(t + \Delta t)}{|S(t + \Delta t)|} \quad (2)$$

154 By specifying the river cross-section at PC (assuming it is relevant for the
 155 whole reach), one can easily evaluate A_w and R_h as a function of the water
 156 level z_{up} . In Equation (2), two parameters need to be calibrated :

- 157 - K , the Strickler coefficient of the river reach supposed homogeneous
- 158 between PC and BD,
- 159 - Δt , a priori negative since the tide progresses from downstream to
- 160 upstream.

161 The Strickler coefficient could vary depending on the discharge due to addi-
 162 tional head losses at low flows (emergence of sills) or at high flows (flood-plain
 163 interaction). Nevertheless, such cases were not observed for the specific case
 164 of the Saigon River.

165 2.3 Water level measurement

166 To apply Equation (2), CTD DIVER sensors were installed at PC and BD
 167 stations in September 2016, as reported in Figure 1. They measure pressure,
 168 conductivity and temperature every 10 minutes. Conductivity and temper-
 169 ature were considered as interesting proxy to interpret data series and were
 170 used to operate the post processing, but were not used directly in this study.
 171 PC sensor was immersed in the river bank of the Saigon River, close to Phu
 172 Cuong city, TD sensor was immersed in the heart of the megalopolis of Ho
 173 Chi Minh City, in Thao Dien district. Both sensors were downloaded at a
 174 bimonthly basis. Due to logistical constraints, significant risks of theft and
 175 of mechanical deterioration, TD station was displaced twice with a corre-
 176 sponding adjustment of parameters in Equation (2) (L and Δt). The sensor
 177 was initially installed in Bach Dang, in the city centre in September 2016. It
 178 was moved to Boat House (BH), 8.5 km upstream of the Bach Dang point,
 179 from January 2017 to the 8th of March 2017. Then, since 15th March 2017,
 180 the sensor is located in Thao Dien Village (TD). Distance between those

181 two last sites is only 0.9 km. To compensate water level measurements from
 182 atmospheric pressure fluctuations, a barometer was installed at the CARE
 183 center (Ho Chi Minh University of Technology, see Figure 1).

184 Some drifts of the water level measurements were observed due to fine
 185 deposit accumulation leading to over-pressure. Water levels at PC and TD
 186 were thus corrected based on monthly campaigns made by Sub Institute
 187 of Hydrometeorology and Climate Change (SIHYMECC, also named CEM
 188 hereafter for Center of Environmental Monitoring) of Ho Chi Minh City.
 189 During these campaigns, water levels were measured every hour for three
 190 days at the staff gauge. In Figure 2, one can observed a very good agreement
 191 between CTD DIVER data and SIHYMECC data (the water level H cor-
 192 responds the the difference between the water surface level and a reference
 193 level of the station).

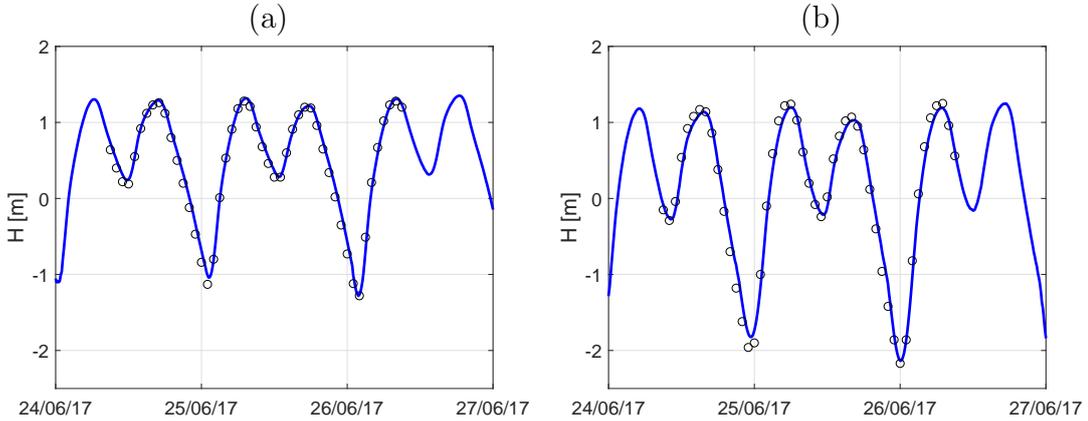


Figure 2: Comparison between water levels H measured at PC (a) and TD (b) stations and water levels measured by the SIHYMECC at the staff gauges for the selected period between 24th to 27th of June 2017.

194 2.4 Residual discharge

195 In order to study the net water discharge in the Saigon River and evalu-
 196 ate the hydrological cycle, the instantaneous water discharge needs to be
 197 averaged over four tide periods ($T_{tide} = 12.4$ hours) to filter the 1st order
 198 semi-diurnal tidal signal from the data-series. As a consequence, $Q_n(t_0) =$
 199 $\int_{t_0-2T_{tide}}^{t_0+2T_{tide}} Q(t)dt$. In the same way, the tidal averaged water level can be ob-
 200 tained such as $z_{ta}(t_0) = \int_{t_0-2T_{tide}}^{t_0+2T_{tide}} z(t)dt$. The acquisition of data at high
 201 frequency (every 10 minutes) and over a longer period (two hydrological sea-
 202 sons) is a prerequisite to such evaluation.

203 **3 Calibration and validation of the SFD rat-** 204 **ing curve**

205 **3.1 Calibration of the model using ADCP campaigns**

206 Two Acoustic Doppler Current Profiler (ADCP) campaigns have been led
207 in September 2016 and March 2017 with a Rio Grande 600 kHz (Dinehart
208 and Bureau, 2005). During 24 hours and for every hour, one gauging, i.e.
209 three transects, was realized at PC with a boat and a georeferenced ADCP
210 mounted on it. ADCP campaigns were used to calibrate the water discharge
211 estimation, calculated with Equation (2) (Camenen et al., 2017). K and
212 Δt were calibrated such as the modelled discharge fit to observed data (see
213 also appendix A.1). Also, since it is very difficult to evaluate the exact
214 vertical reference level of each station, these campaigns were used to optimize
215 the measured difference $z_{up} - z_{dn}$ using an additional parameter Δz (i.e.
216 $z_{up} - z_{dn} = (z_{up} - z_{dn})_{measured} + \Delta z$)

217 To ensure the robustness of the hydraulic model, calibration were real-
218 ized during both wet (September 2016) and dry (March 2017) seasons. These
219 ADCP campaigns were also used to determine the river cross-section char-
220 acteristics, to calculate A_w and R_h as a function of water level. Error in
221 ADCP measurements were evaluated at 10% using a minimum error value
222 of 100 m³/s since the conditions were adverse (Le Coz et al., 2016). We
223 found the best results using a Manning-Strickler coefficient $K = 26$ m^{1/3}/s
224 and $\Delta t = -2.0$ hours (see Appendix A.1). Results are presented in Fig. 3.
225 Very good results can be observed for the September 2016 campaign. Some
226 slight error may be observed at the end of the first flow peak (Fig. 3a, at
227 around 21 h, local time) but it is due to a pressure gauge outside water. For
228 the 2017 campaign, results are not as accurate but still in good agreement
229 with data. The clear asymmetric semi-diurnal tidal signal for this specific
230 day may explain some of the differences (Camenen et al., 2017).

231 **3.2 Validation of the model using other discharge es-** 232 **timations**

233 The monthly campaigns made by SIHYMECC also include some discharge
234 estimation every hour for 48 h. They applied the velocity index method
235 by measuring the water level and the depth-averaged velocity $\overline{u_{index}}$ at one
236 location y_{index} (Chen et al., 2012b) :

$$Q = \alpha_{index} \overline{u_{index}} A_w \quad (3)$$

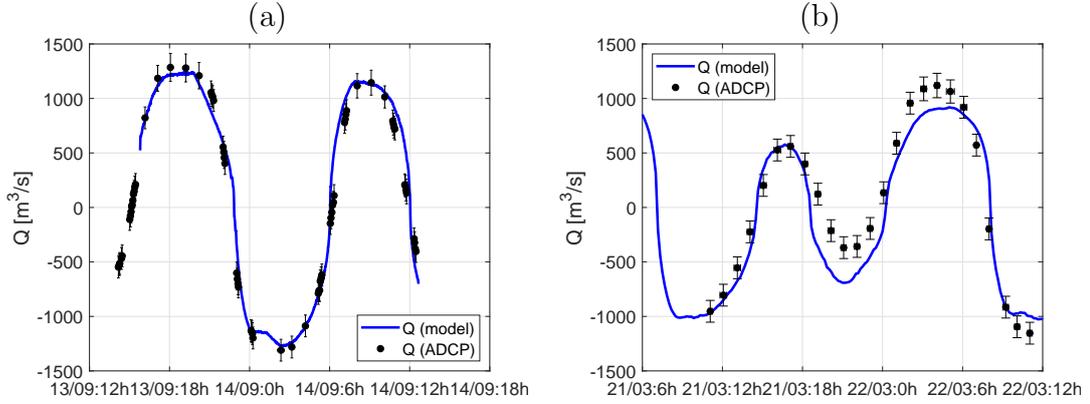


Figure 3: Water discharge Q comparison between model results and ADCP measurement campaigns in September 2016 (a) and March 2017 (b).

237 with $\alpha_{index} = 0.8$ a calibration coefficient, $\alpha_{index} = U/\overline{u_{index}}$ where $U = Q/A_w$
 238 the section-averaged velocity. Again, since conditions are adverse, we roughly
 239 estimated the error from this method equal to 15% plus a minimum error of
 240 $150 \text{ m}^3/\text{s}$ based on [Ruhl and Simpson \(2006\)](#).

241 The corresponding water discharge estimated from Equation (2) are in
 242 good agreement with data from SIHYMECC (Fig. 4). The model tends to
 243 yield smaller peak values for the inward discharge (negative), even if this
 244 trend is not observed for all tidal cycles. This tendency is more pronounced
 245 for the 2018 data (Fig. 4b). This could be the consequence of either a
 246 varying flow repartition throughout the river section during the ebb and flow
 247 not caught by the index velocity method or a bias on the slope estimation
 248 by the proposed model based on a slope downstream of the station.

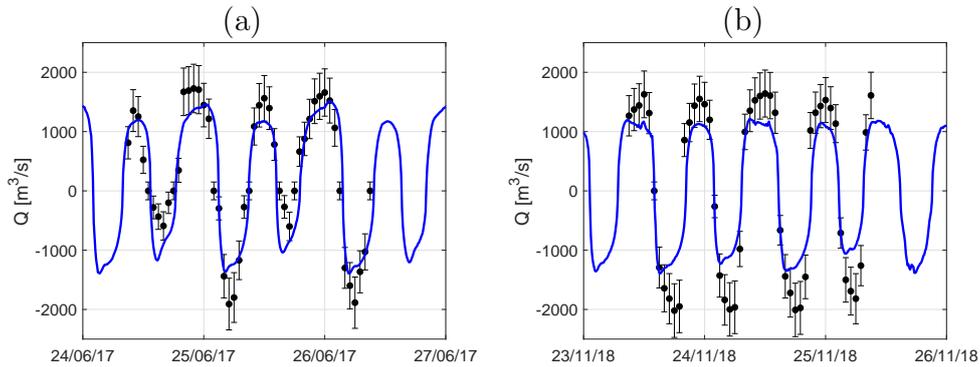


Figure 4: Water discharge Q estimated at PC (blue line) in comparison to SIHYMECC data for two contrasting hydrological periods in June 2017 (a) and in November 2018 (b).

249 4 A two-year monitoring of the Saigon River

250 4.1 Water levels

251 The water level time series, which covers two hydrological years, from January
252 2017 to December 2018 are reported in Figure 5a. For both stations, the
253 reference level is the one of the staff gauge, which explains the existence of
254 some negative values.

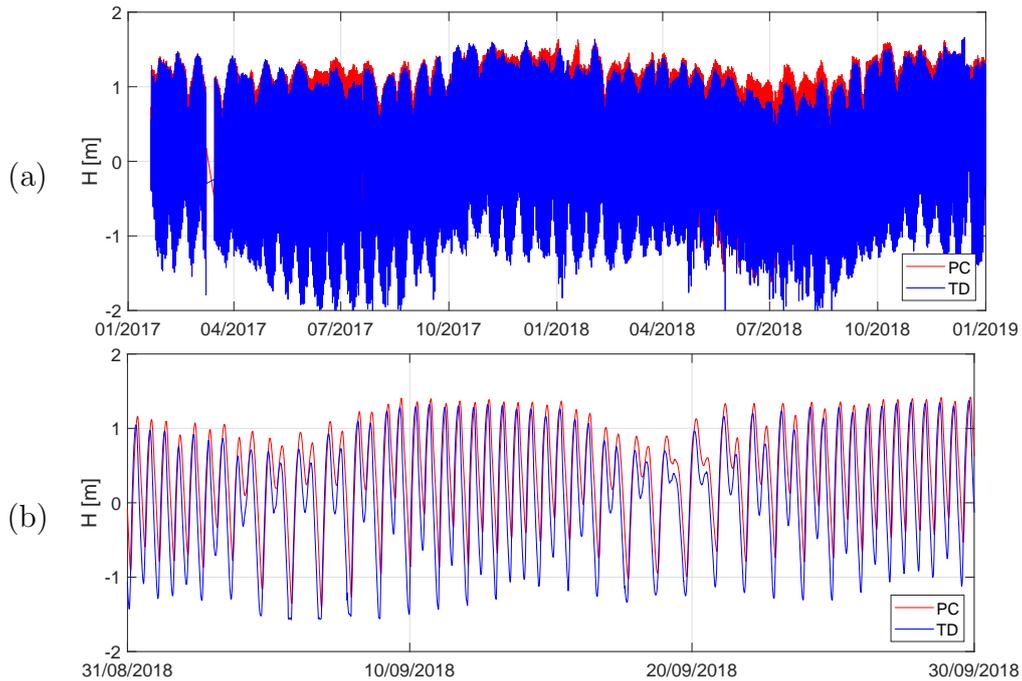


Figure 5: Two-year water level time series measured at PC and TD (a) with a zoom in September 2018 (b).

255 In each panel, one can see that the tidal signal clearly predominates with
256 a strong semi-diurnal harmonic. The cyclicity is particularly emphasized
257 through the examination of a zoomed period in September 2018 (Figure
258 5b). The cyclicity is evidenced on both PC and TD stations, who present
259 synchronous fluctuations, with a time laps of about 1 hour and 10 minutes,
260 which corresponds to the duration of tide wave propagation between the two
261 stations. The tidal magnitude is smaller at PC station (by 17%) than at TD
262 station, which is physically consistent with quadratic friction dissipation: the
263 further upstream the station is, the less it is influenced by tidal waves. Tidal
264 range was measured to oscillate between -2.00 m and 1.50 m at both TD and
265 PC stations.

266 A first glimpse of seasonality can be observed in the two-year time-series.
 267 One can observe lower water levels in the rainy season (May to September)
 268 and higher values in the dry season (November to March). Semi-diurnal tidal
 269 forcing clearly prevails on the Saigon River. As illustrated in Figures 2 and 5,
 270 the 14-days cycle presented both symmetric and asymmetric tides; a pattern
 271 which is particularly well developed in the estuaries located in the south of
 272 Vietnam (Chen et al., 2012b).

273 4.2 Continuous discharge estimation

274 By applying Equation (2), one can easily calculate the discharge at PC using
 275 water levels from both PC and TD stations. Water discharge is dominated
 276 by tidal semi-diurnal harmonics, as for water level data-series (Figure 6).
 277 Instantaneous discharge ranged from -2000 to 2000 m³/s. The oscillation of
 278 the magnitude of tides, between spring and neap tides, is also well-identified
 279 (Figure 6b). Maxima appears at every syzygy between the sun, the moon and
 280 the earth. Overall, the analysis of instantaneous water discharge highlighted
 281 the predominant forcing of tides on any other forcing, despite contrasted and
 282 well-marked dry and rainy seasons.

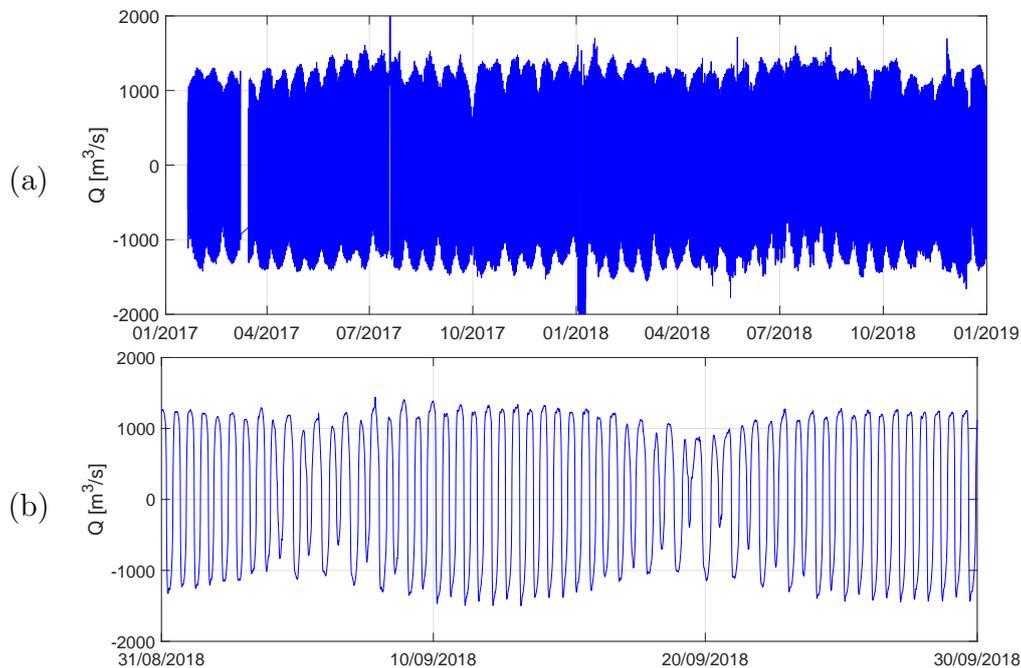


Figure 6: Two-year water discharge time-series (a) with a zoom in September 2018 (b) at Phu Cuong (PC).

283 4.3 Residual discharge

284 All data from the SIHYMECC field campaigns (which correspond to a 48 h
285 experiment $\approx 4T_{tide}$) were compared to the proposed model (Figure 7a). As
286 expected, since the model yields smaller amplitudes (see Figure 4), one gen-
287 erally finds a good correlation but with few outliers, predominantly above the
288 1:1 line for negative discharge and below the 1:1 line for positive discharge
289 (i.e. $|Q_{model}|/|sim|Q(CEM)|$). One should note also the many zero values for
290 the SIHYMECC (CEM) data, which may be the consequence of a human bias
291 (while reading the staff gauge) and partly explains uncertainties in experi-
292 mental data and some of the scatter in the model response. A comparison of
293 the net water discharge measured by the SIHYMECC and modelled by our
294 group is reported in Figure 7b for the 18 SIHYMECC campaigns available.
295 One can realize the order of magnitude of difference between maximum in-
296 stantaneous discharges and net discharges, which corresponds to the red box
297 in Figure 7a. Despite the existence of few outliers, modelled points for net
298 water discharge are well correlated with the estimation from measured data.
299 As expected, since the model yields smaller amplitudes, the net discharge
300 estimations are generally smaller. The existence of outliers is not surprising
301 looking at the sensitivity of such calculation while net discharge is one order
302 of magnitude smaller than peak values (positive and negative). But surpris-
303 ingly, while SIHYMECC estimations of the net discharge are always positive,
304 the proposed model leads sometimes to negative values. Although difficult to
305 explain, these negative values may result from a combination of factors, such
306 as the asymmetrical tides and complex exchanges with groundwater and with
307 the canal network. The regular occurrence of salt intrusions up to HCMC
308 does confirm the possible occurrence of a net negative water discharge. Also,
309 as discussed above, the model is very sensitive to a possible error in water
310 level estimation at PC and BD, TD stations. Hence, for the net discharge,
311 we evaluated the error equal to 20 m³/s per cm of error in the vertical axis
312 (See Appendix A.3).

313 The net discharge time series over this two-year experiment is presented in
314 Figure 8. Compared to monthly SIHYMECC campaigns, we observe more
315 variability in the net discharge time-series. Some spikes are however not
316 realistic and result from data gaps (January 2018, December 2019).

317 The seasonality of precipitation in this tropical humid low lying area
318 is expectedly a main driver of the annual hydrological cycle, but as shown
319 previously, this driver is masked by the tidal forcing (Figure 8). The wet
320 season is expectedly linked with a higher water discharge and a refill of
321 the groundwater. At the opposite, the dry season is expectedly linked with
322 a decrease of the net water discharge. This general pattern was broadly

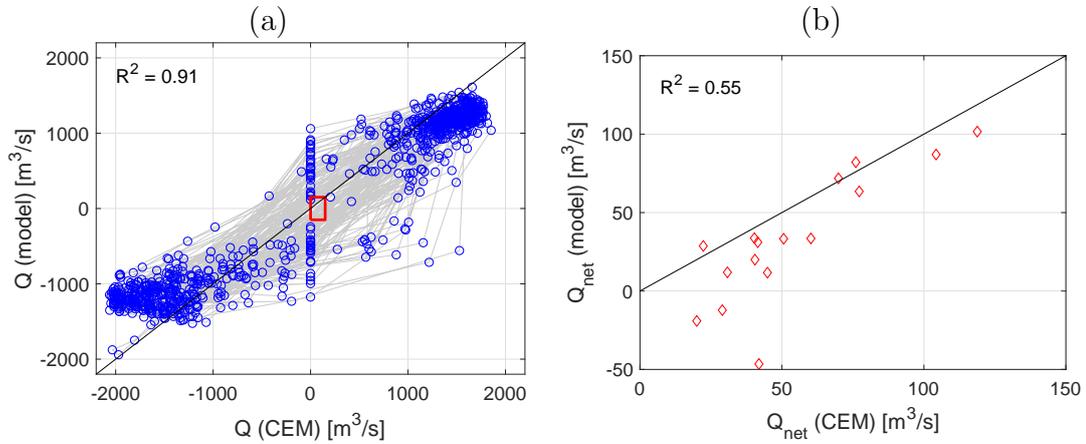


Figure 7: Comparison of the instantaneous (a) and net (b) discharges obtained by the SIHYMECC (CEM) and the proposed model for all 2017 and 2018 SIHYMECC campaigns.

323 described by [Nguyen et al. \(2019\)](#), but needs to be detailed and should be
 324 understood on a physically based characterization of the main drivers. One
 325 can clearly observe the seasonality of net discharge with peak values during
 326 the wet season in [Figure 8](#). In 2017, the peak net discharge reached $300 \text{ m}^3/\text{s}$
 327 and lasted only for two months in the beginning of June and the end of
 328 July. In 2018, net discharges exceeded $200 \text{ m}^3/\text{s}$ from June to August with
 329 maximum values up to $400 \text{ m}^3/\text{s}$. It then decreased before a second peak
 330 was reached in early October. Flood extended for more than four months,
 331 leading to one of the most humid year of the decade ([Fig. 8](#) and [Fig. 10](#)).

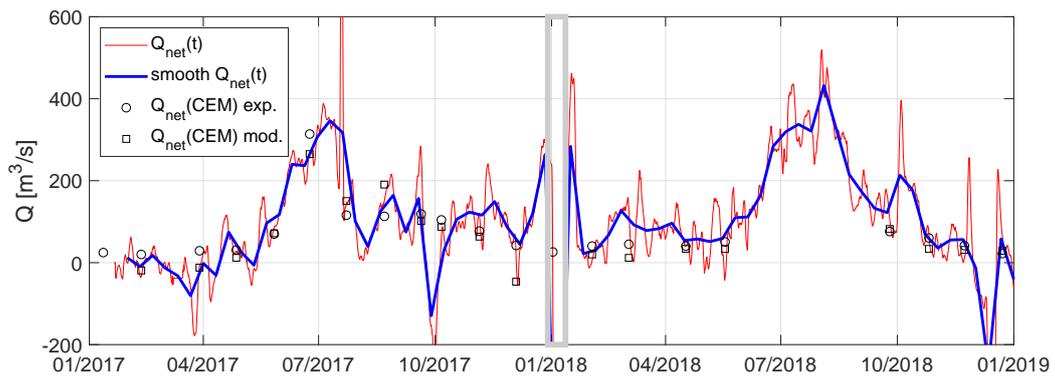


Figure 8: Net discharge Q_{net} estimate for the January 2017 - December 2019 period (full lines correspond to the model results while symbols correspond to values for the SIHYMECC campaigns using their own estimations -exp.- or using the model -mod.-; the grey line delimits a period of missing data at PC).

332 Monthly cumulated precipitation, tide-averaged water level along the
333 Saigon and Dong Nai rivers and monthly averaged net-discharge are pre-
334 sented in Figure 9 for the 2017 and 2018 periods. 2017 and 2018 rainy
335 seasons are well-marked, with an increase in precipitation from June to Oc-
336 tober. In 2018, precipitations are particularly high and extended in October
337 and November. The tide-averaged water level follows the rain pattern for
338 both increasing and decreasing phases, with a shift of two to three months.
339 Concerning the averaged water discharge, it was measured to fluctuate be-
340 tween -100 to 500 m³/s (no value is given for January 2018 since there was a
341 too long gap in data), with a magnitude that was quite different for both hy-
342 drological years. In 2017, one can noticed that there exists an expected time
343 lag between rain (first) and river discharge (few weeks later) but there is also
344 some delayed and complex interactions with groundwater and/or water level.
345 The rainy season, which started in May, was followed by a rise in the net
346 water discharge only one month later (June) and then, by an increase of the
347 tide-averaged water level few weeks later (July, August). Also, one observed
348 a drop in net discharge in August and September, while precipitation remains
349 high followed by a rise in net discharge while precipitation dropped. It seems
350 there are strong exchanges of water with groundwater and/or floodplain with
351 a possible recharge from the groundwater and/or floodplain in May, August
352 and September and a restitution to the river in November and December.
353 However, [Van and Koontanakulvong \(2018\)](#) estimated possible exchanges of
354 water between the aquifer and the Saigon River of approximately 0.02 m³/s
355 per km, which appears negligible. Effects of the large drainage and canal
356 system around the Saigon River (i.e. of the Saigon floodplain) may prevail
357 here. Also, anthropogenic influences such as Dau Tieng dam management
358 or water supply pumping may significantly affect the net Saigon river water
359 discharge. In 2018, cumulated rain also led to an increase of the net water
360 discharge, but the rise of the Saigon River discharge was much faster and
361 almost correlated to precipitation, which lets presume that soil saturation
362 was higher and led to a direct response of the river to precipitation. Even
363 if rain initiated late in the season, as compared with year 2017 (May and
364 June in 2018 instead of April and May in 2017), the shape and cumulative
365 rain during the rainy season was quite comparable to 2017. The net water
366 discharge responded similarly to 2017 in June 2018. However, in 2018 the
367 response to precipitation is stronger with a monthly averaged net discharge
368 above 400 m³/s in July and August. Surprisingly, in October and November,
369 while precipitation is particularly high in fall and superimposed with the ex-
370 treme typhoon event in late November, one can observe a decrease of the net
371 discharge. Significant floods have been observed during this period; a large
372 part of the water volume from precipitation may have been spread over the

373 flood plain.

374 Looking at the tide-averaged water level (Figure 9b) measured at Phu
375 Cuong (PC), Thao Dien (TD) or Phu An (PA), but also at Vam Sat (station
376 located downstream on the Dong Nai River at approximately 20 km from
377 the sea shore), a clear annual fluctuation can be observed with high water
378 levels from October to April. Such high values yield an averaged negative
379 slope leading some counter-effects on the net discharge (see Appendix A.3).
380 Interestingly, these fluctuations are not correlated to precipitations and could
381 partially explain the deficit in net water discharge compared to precipitation.
382 We suspect these fluctuations to be a consequence of the peak flow season of
383 the Mekong River, which occurs in October in coastal floodplain and could
384 influence sea water levels next to its river mouth (Chen et al., 2012a; Ho
385 et al., 2014; Thi Ha et al., 2018).

386 4.4 Effects of long-term precipitation

387 To get further in the analysis of the interaction between the Saigon River
388 discharge and its surrounding floodplain, we examined a pluriannual monthly
389 rainfall series (Figure 10). This series was associated with the severe Niño
390 event in 2015-2016 (Thirumalai et al., 2017; Thi Ha et al., 2018). In Figure
391 10, one can observed a regular decrease of annual precipitation from 2009
392 to 2012, a minimum from 2013 to 2015 and an increase until 2019. The
393 2013-2015 period thus corresponded to a deficit of rain, which was evidenced
394 by socio-political impacts described in newspapers, particularly during the
395 dry season 2015-2016. This dry season was reported as the worst drought
396 ever reported in 98 years of monitoring in the floodplains of Mekong and
397 Saigon-Dong Nai hydrosystems.

398 The 2017-2018 and 2018-2019 hydrological seasons that are reported in
399 Figure 9 support the hypothesis of a phase of recovery after these pluri-annual
400 droughts. The 2017 wet season showed a priori an atypical hydrological
401 response, with a normal rainy season from May to October, that is not in
402 correlation with water discharge due to strong exchanges with groundwater.
403 There is indeed a shift between the discharge increase and the precipitation
404 increase. This may result of years of deficit in the groundwater.

405 In 2018, the precipitation-river interaction was noticeably different. It
406 seems the groundwater recovered from the drought leading to a more typical
407 response of the river to precipitation. We may hypothesize that regional
408 recovery of rain during the last wet seasons (2016-2018) led to a recharge
409 of the groundwater table, and further of the river, presumably because the
410 floodplain had fully recovered from the pluri-annual drought that hit the
411 region from 2013 to 2016.

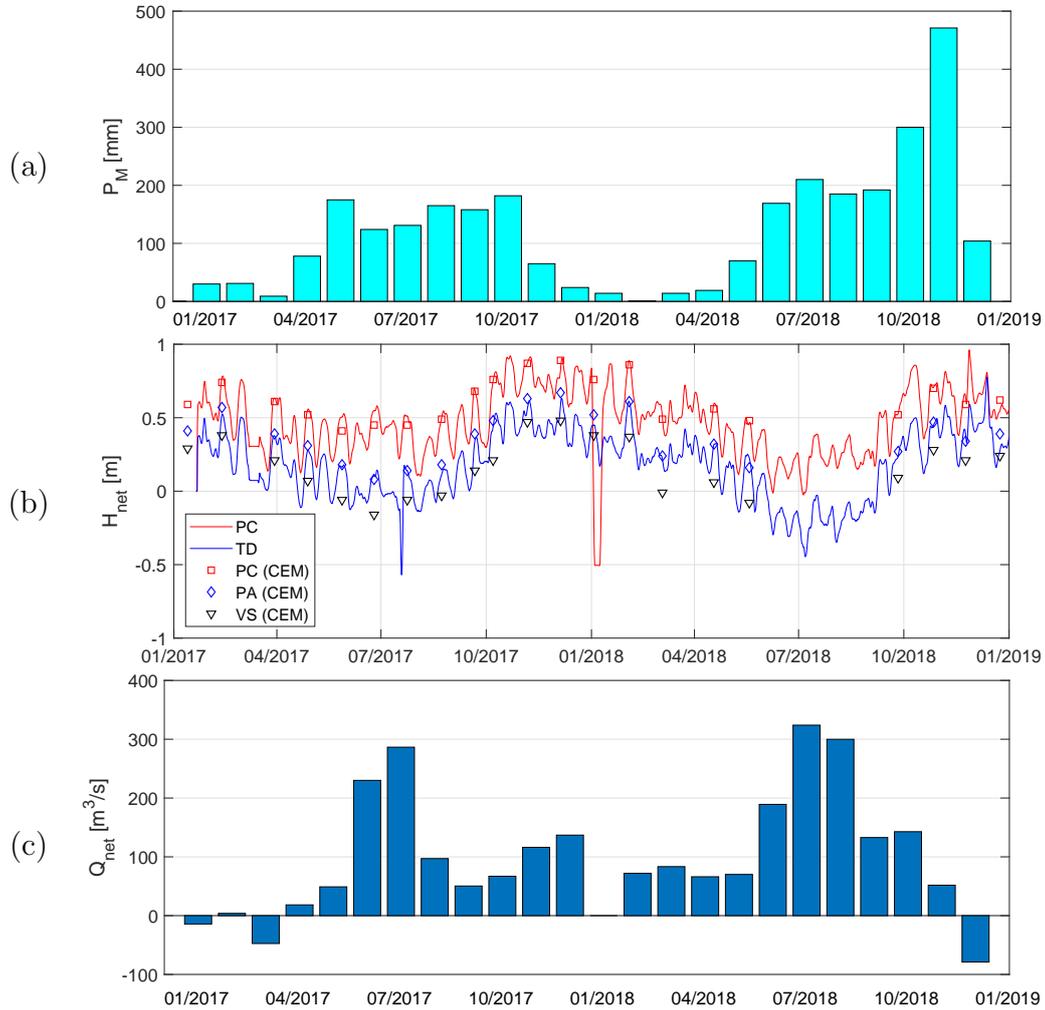


Figure 9: Monthly rainfall P_M (a), tide-averaged water levels H_{net} (b) and monthly net discharge $Q_{M,net}$ (c) for the January 2017 - December 2019 period.

412 4.5 Effects of an extreme event : the Usagi typhoon

413 On November 25th 2018, HCMC was hit by Usagi typhoon. Arriving from
 414 the East-south east, it reached the coast, at 50 km of Ho Chi Minh City
 415 (Ba Ria-Vung Tau Province) in the morning. It continued moving North-
 416 west ward inland over HCMC area as a tropical depression. According to the
 417 forecast department of the Southern Centre for Hydro-Meteorological Fore-
 418 casting (SCHMF), this was the highest ever recorded rainfall in a 24-hours
 419 period in the megalopolis. Districts of HCMC recorder cumulated daily rain
 420 between 293 to 408 mm for independent stations of measurements. While
 421 there is no debate concerning the intensity of Usagi event and the severity

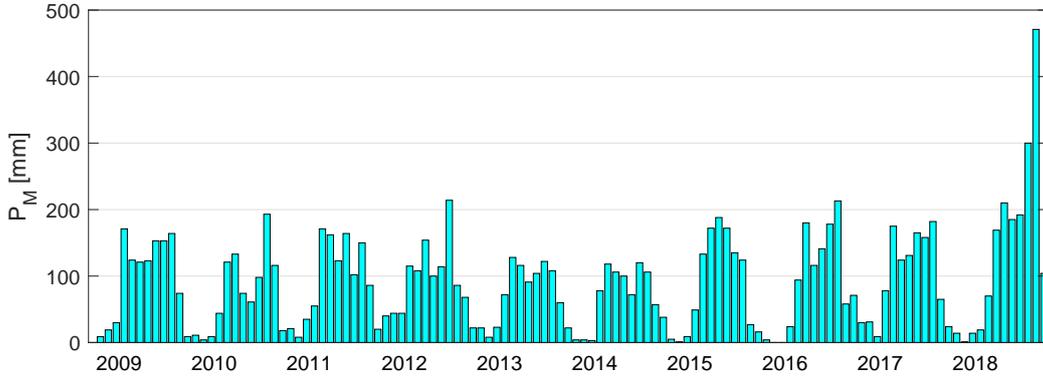


Figure 10: Monthly rainfall P_M at HCMC from 2009 to 2019.

422 of damages, there is a clear interest in understanding how the hydrosystem
 423 physically behaved during and just after those exceptional rains. The para-
 424 doxical result is the lack of direct response of the Saigon River to the extreme
 425 precipitations. As shown in Figure 5, none of the two hydrological stations
 426 recorded any consistent rise of the water level during the typhoon, neither
 427 any flash rise of the river discharge (Figure 6). The only noticeable impact
 428 recorded by our CTD sensors was a slight reduction of the conductivity at
 429 the PC station, which dropped of a few percent when Usagi typhoon hit the
 430 region (not shown in this paper). Could we conclude that the typhoon had
 431 no effects on the river dynamics? Has the Dau Tieng dam totally regulated
 432 the flow?

433 By comparing data from November 2017 and November 2018, one can
 434 observe that despite a rise of rainfall by a factor six, mean water level and
 435 net discharge reduced during this period by 15% (0.77 m in Nov. 2017 and
 436 0.66 m in Nov. 2018) and 50% ($65 \text{ m}^3/\text{s}$ in Nov. 2017 and $30 \text{ m}^3/\text{s}$ in Nov.
 437 2018), respectively. It clearly shows that floods observed in some districts of
 438 the city during the event were not directly driven by the overflow of water
 439 from the river, but certainly by intense run off over impervious streets. Also,
 440 we should not underestimate the potential impact of the Dau Tieng dam
 441 management; large amount of water may have been retained during the flood
 442 and slowly reinjected in the river during the following weeks. Finally, since
 443 tide-average water levels in the Saigon River are relatively higher in late fall
 444 (Fig. 9), and because of the storm surge, evacuation of water may have been
 445 more difficult. This can be explained by the morphology of the delta, which
 446 is very flat and close to the sea shore. Results from Scussolini et al. (2017)
 447 showed the influence of the sea level on HCMC flood risk. Ho et al. (2014)
 448 argued that main hydrological explanations for the flood risk on HCMC area
 449 are the upstream floods including those of the Dong Nai and Mekong delta,

450 local rainfall, land subsidence, and sea level rise. Our results indicate that
451 local rainfall and sea water level may be the most impacting factors.

452 **5 Conclusion**

453 Tidal rivers and their floodplains are environments that are hardly monitored
454 although they concentrate most of the human activities and form habitats
455 for rich ecosystems. Flood risk is a particular issue for such environment
456 and requires a good monitoring and a good understanding of its hydrological
457 functioning.

458 Here, we applied a stage-fall-discharge rating curve adapted from the gen-
459 eral Manning-Strickler law (Camenen et al., 2017) to assess the instantaneous
460 water discharge on the Saigon River. For the first time, the Saigon River dy-
461 namics was recorded at high frequency over two hydrological years, including
462 the heaviest rain event ever recorded. Such tool appears to be a very effi-
463 cient and low cost system for estimating discharge in tidal rivers as soon as
464 the tidal wave is not too asymmetric and the river bed is stable (no general
465 erosion nor aggradation). One issue remains the estimation of the slope since
466 the model is sensitive to possible errors in water level measurements. This is
467 particularly true for the Saigon River, which is tide dominated.

468 The analysis of the data-series highlights the driving role of tides on water
469 mixing and water dynamics at hourly to monthly timescales. Once filtered
470 from tidal effects, the averaged water level and water discharge points out a
471 rather small contribution of run-off and a potential significant impact of flood
472 plain and anthropogenic structures (Dau Tieng dam, canals, water pumping,
473 etc.) to the hydrosystem response. The study of river response during Usagi
474 typhoon illustrated how much the floodplain can attenuate the direct impact
475 of intense precipitations and how critical is the sea water level to evacuate
476 the flood. Also, the seasonal variability of the tidal-averaged water levels
477 showed a possible influence of the nearby Mekong high flows that reduces
478 the slope and limits the net discharge.

479 This study remains a preliminary study, which needs to be completed with
480 some further studies on groundwater and flood plain dynamics, including
481 the complex canal network in HCMC to get an accurate evaluation of the
482 vulnerability of the megalopolis to flooding during extreme events and how
483 this vulnerability will evolve during coming decades under a worrying context
484 of subsidence and sea level rise.

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A Sensitivity analysis

A.1 Error calculation on experimental data

A first sensitivity analysis was made to optimize main model parameters (Strickler coefficient K and the time shift Δt) to experimental data. For both ADCP campaigns in September 2016 and March 2017 (see Figure 3), the estimation of the error was made using the mean square error :

$$E(Q) = \sqrt{\frac{1}{n} \sum_{i=1}^n [Q_{mod.}(t_i) - Q_{meas.}(t_i)]^2} \quad (4)$$

where n is the number of gauging data, $Q_{mod.}$ the modelled discharge and $Q_{meas.}$ the measured discharge, and t_i the time of each of these gauging. As can be observed in Fig. 11, errors are significantly smaller for the first campaign for which the tide was more symmetrical. Indeed, $E(Q) \approx 200 \text{ m}^3/\text{s}$ for the September 2016 campaign whereas $E(Q) \approx 350 \text{ m}^3/\text{s}$ for the March 2017 campaign. From this sensitivity analysis, one would choose $K = 25 \text{ m}^{1/3}/\text{s}$ and $\Delta t = -2.04 \text{ h}$.

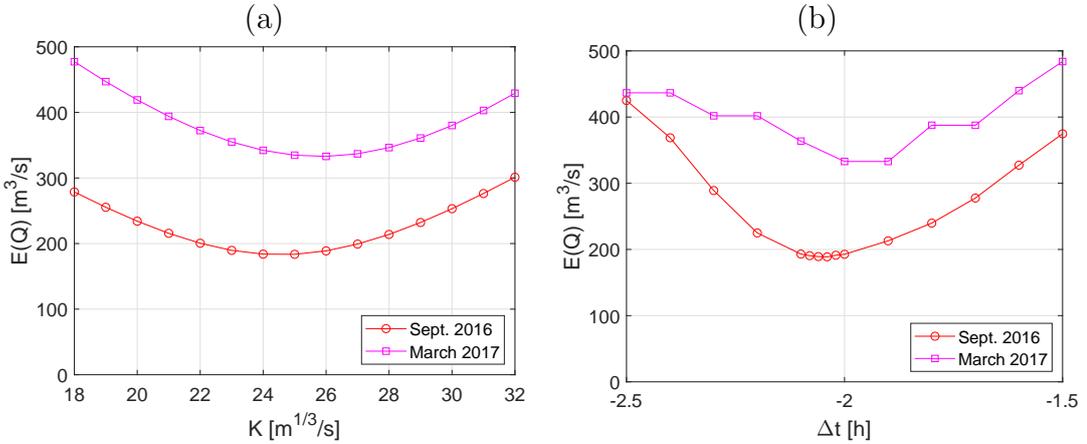


Figure 11: Sensitivity of the Strickler coefficient K (a) and time shift Δt (b) on the error calculation compared to ADCP campaigns.

However, as can be seen in Figure 12a, using $K = 25 \text{ m}^{1/3}/\text{s}$ would lead to some underestimation of the peak discharge values. Indeed, the error calculation is biased by the more numerous data points around the zero discharge value, which are slightly better predicted using a smaller value of the Strickler coefficient (see also Figure 3). Also, the effect of Δt appears not as sensitive. It is also important to realize that water level data present a frequency of 10 min (1 min in September 2016), which does not allow to

fit Δt in such detail. Moreover, the position of the Thao Dien station (used for the 2017-2018 period) being a few km upstream of Bach Dang (used during the September 2016 experiment, see Figure reffig:Saigon), the time shift should be smaller. As a consequence, we eventually chose $K = 26 \text{ m}^{1/3}/\text{s}$ and $\Delta t = -2.0 \text{ h}$.

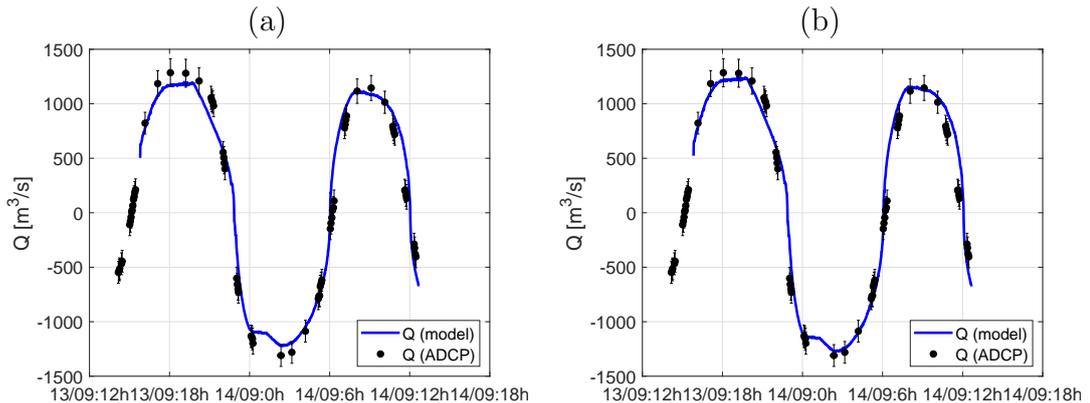


Figure 12: Comparison between the model and discharge measurement campaigns in September 2016 using $K = 25 \text{ m}^{1/3}/\text{s}$ and $\Delta t = -2.00 \text{ h}$ (a) and $K = 26 \text{ m}^{1/3}/\text{s}$ and $\Delta t = -2.04 \text{ h}$ (b).

A.2 Sensitivity analysis on main parameters

Equation (2) was calibrated by fitting two parameters: the Strickler coefficient K and the time shift Δt . As can be observed in Figure 13, the Strickler coefficient has a linear effect on both instantaneous and net discharge. It is quite obvious since $Q \propto K$. An error of approximately 8% in K would yield an error of 8% as well for both instantaneous and net discharge.

Since the coefficient Δt leads to a time shift of the curves, it induces large errors around the flow reverse (Figure 14). However, the effect on the net discharge is very low; a shift of 12 min leads to an error of $\pm 5 \text{ m}^3/\text{s}$ approximately.

A.3 Sensitivity analysis on input

The only input data of the model (Equation (2)) are the water levels measured at the downstream and upstream stations. The water level measured downstream will only affect the slope estimation whereas the water level upstream (at the reference station PC) will also affect the estimation of the wet section and hydraulic radius.

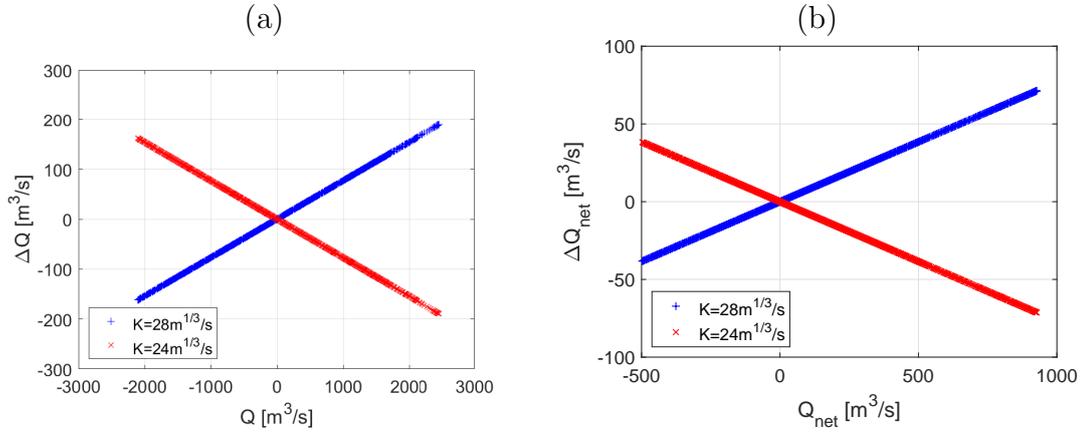


Figure 13: Sensitivity of the Strickler coefficient K on the instantaneous (a) and net (b) discharge.

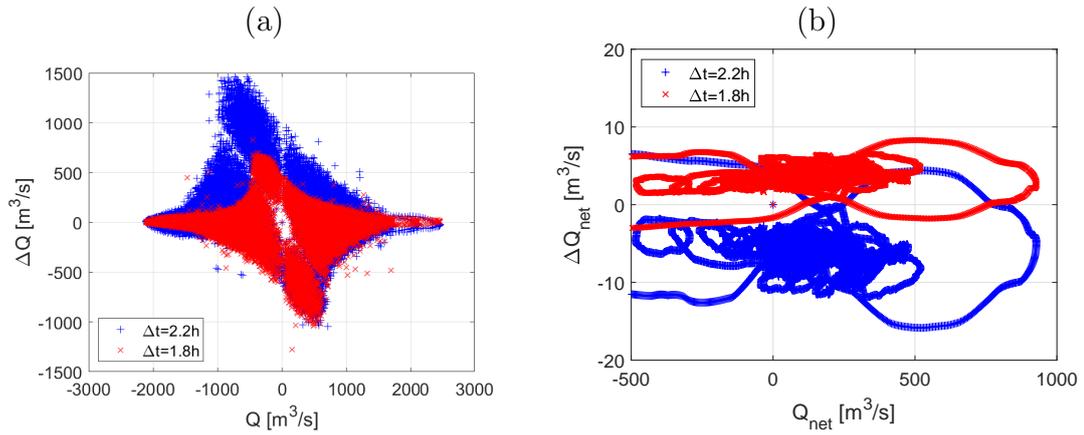


Figure 14: Sensitivity of the time shift Δt on the instantaneous (a) and net (b) discharge.

In Figure 15 is tested an error of 1 cm in the downstream water level on the estimated discharge. The effect is inversely proportional to the discharge and errors can reach $300 \text{ m}^3/\text{s}$ for $Q(t) \approx 0$ assuming an error of 1 cm. The asymmetrical shape of the figure is due to the time shift on the slope. On the other hand, error on the net discharge is quite limited but not negligible with an error of $\pm 20 \text{ m}^3/\text{s}$ approximately.

In Figure 16 is presented the errors in discharge estimations for an error of 1 cm in the upstream water level. Surprisingly, effects are very similar (opposite) to the error in the downstream water level. Indeed, the sensitivity on the water slope is much higher than the sensitivity on the hydraulic radius or wet section.

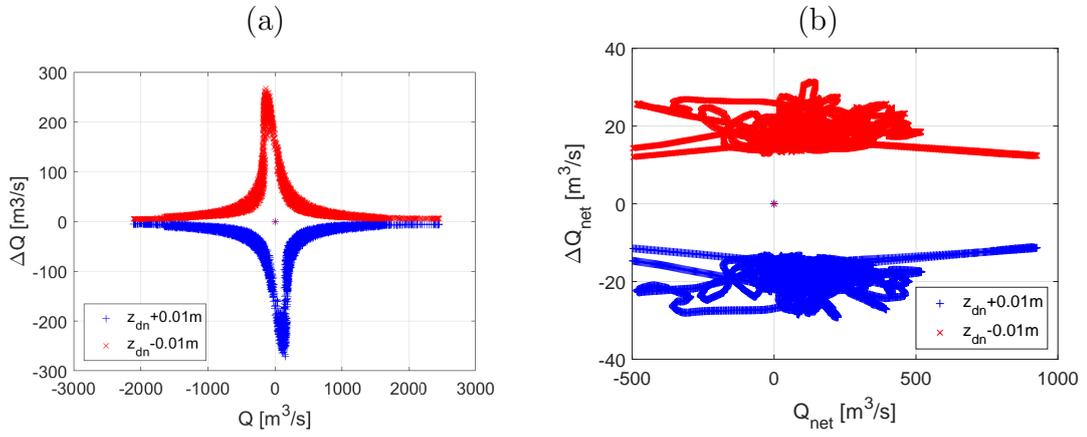


Figure 15: Sensitivity of the water level measured downstream on the instantaneous (a) and net (b) discharge.

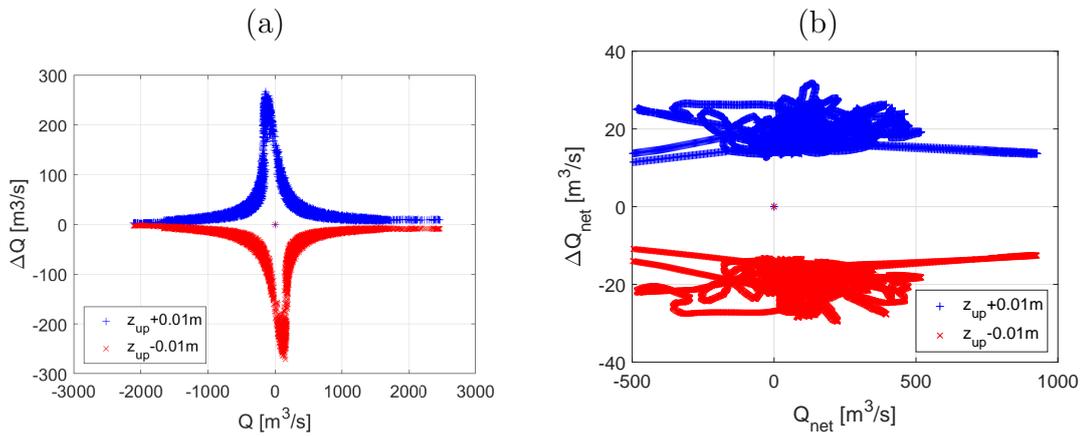


Figure 16: Sensitivity of the water level measured upstream on the instantaneous (a) and net (b) discharge.