The effect of hydrographs shape on river deltas salinization

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Key Points:

- The shape of annual hydrographs influences the level of salinity in river deltas and can contribute to a more sustainable water management.
- The peak flow magnitude and hydrographs tails determine freshwater areas, residence and renewal times and stratification.
- Salinity responds slower to flow decreases than increases and decreases faster with higher hydrographs slopes.

Abstract

Excessive salinity can harm ecosystems and compromise the various anthropogenic activities that take place in river deltas. The issue of salinization is expected to exacerbate due to natural and/or anthropogenic climate change. Water regulations are required to secure a sufficient water supply in conditions of limited water volume availability. Research is ongoing in seek of the optimum flow distribution establishing longer-lasting and fresher conditions in deltas. In this study a three–dimensional (3D) numerical model was used to unravel the influence of hydrographs shape on the deltas salinity. Our results show that it is possible to improve the freshwater conditions in deltas without seeking for additional water resources but by modifying the water distribution. The peak flow magnitude and timing and the tails of a hydrograph were found to be important parameters affecting stratification, freshwater residence and renewal times. Hydrographs having lighter tails and smaller range were the most successful in keeping the delta and its river inlet fresher for longer periods. Salinity distributions showed a slower response to decreasing rather than increasing river discharges. An increase in the flow rate can achieve a desired salinity standard in much shorter time. Hydrographs with heavier tails can push the salt intrusion limit further away and are more efficient in mixing the water column. However, they present low freshwater residence and high water renewal times. These results have implications for coastal scientists and stakeholders dealing with the management of freshwater resources in river deltas across the world.

Plain Language Summary

High salt concentration is detrimental for the anthropogenic activities taking place in river deltas. Natural or anthropogenic climate change can increase the salt water threatening the deltas sustainability. Limited freshwater availability demands the design of new water management policy to secure a sufficient water supply. It is speculated that the problem can be solved with friendlier environmental instead of technical solutions. This study investigates the effect of different annual freshwater flow distributions on the deltas salinity. By implementing numerical modelling for an idealized river delta, it was discovered that it is possible to establish longer-lasting freshwater conditions. Attributes of a hydrograph such as the peak flow magnitude, timing and its tails were found to be important parameters. Hydrographs with light tails can keep the delta fresh for longer times while higher peak flows can result in freshwater covering larger areas and decrease stratification. For equal flow ranges, the salinity was found to decrease faster than increasing. Higher flow rates can decrease salinity to a desired standard in shorter time. These results have implications for coastal scientists and stakeholders dealing with the management of freshwater resources in river deltas across the world.

1 Introduction

Rising sea level and decreasing streamflow threaten water resourcing and freshwater availability by exacerbating salt intrusion in low lying areas such as deltas (Zhou *et al.*, 2017). Salt intrusion (SI) is a serious problem that affects households, agriculture, irrigation and industry (Allison, 1964; Smedema and Shiati, 2002; Zhang *et al.*, 2011) because rivers and aquifers contaminated by high salinity decrease freshwater storage and water quality (Gornitz, 1991). In addition, SI reduces soil fertility resulting in low crops yield (Bhuiyan and Dutta, 2012), threatens vegetation and marine species with limited salinity tolerance (Visser *et al.*, 2012; White *et al.*, 2019), increases plants mortality (Kaplan *et al.*, 2010; Bhuiyan and Dutta, 2012) and affects human health (Sarwar, 2005; Rahman *et al.*, 2019).

Many deltas face already the consequences of salt intrusion including the Mekong in Vietnam (Nguyen and Savenije, 2006; Trieu and Phong, 2015; Eslami *et al.*, 2019) the Ganges-Brahmaputra in Bangladesh (Nobi and Das Gupta, 1997; Bhuiyan and Dutta, 2012; Rahman, 2015; Yang *et al.*, 2015; Bricheno, Wolf and Islam, 2016; Sherin *et al.*, 2020; Bricheno, Wolf and Sun, 2021), the Mississippi in the Gulf of Mexico (Holm and Sasser, 2001; Day *et al.*, 2005; Das *et al.*, 2012) , the Yangtze in China (Chen *et al.*, 2001; Hu and Ding, 2009; Dai *et al.*, 2011; Qiu and Zhu, 2015), the Pearl River (Liu *et al.*, 2019; Hong *et al.*, 2020) and the Nile Delta (Frihy, 2003). Unfortunately, limitations in water supply come along with an increase in water demand because of population growth, economic development and land use change (Phan *et al.*, 2018).

Sustainable water management and enhanced water conservation practices are necessary for the available water supply to meet with the future demand (Dawadi and Ahmad, 2013). These practices often rely on the scientific consensus that salt intrusion reduces as river discharge increases (Garvine et al. 1992; Gong and Shen, 2011). In the absence of tides or other driving mechanisms (i.e. atmospheric or oceanic forcing) the river discharge dominates the salinity distribution (Valle-Levinson and Wilson, 1994; Wong, 1995; Monismith *et al.*, 2002). During the 20th century, water management relied on technical and engineering solutions (Ha *et al.*, 2018). The so called 'hard-path' approach consisted of dams, aqueducts, pipelines and complex treatment plants (Gleick, 2003). However, this type of solutions often comes with a cost. For example, tens of millions of people have been displaced by their homes due to water related projects (Adams 2000) while the flows reaching many deltas are not adequate anymore and this has several consequences for the local environment and population (Gleick, 2003). Recently, the need for more adaptive management to sustain freshwater resources has been identified (Ha *et al.*, 2018; Zevenbergen *et al.*, 2018). A 'soft-path' approach for water is now promoted that would include regulatory policies for better use of existing water resources than seeking for additional ones (Gleick, 2002). In this context, an efficient water usage is preferred with equitable distribution and sustainable system operation over time while local communities should be also included in water management decisions (Gleick 2002; Wolff and Gleick 2002; Gleick 2003). Within this concept, the problem of salt intrusion in deltas could probably be mitigated by an efficient water management of a catchment's freshwater availability instead of resorting to technical solutions. This could be achieved for example by storing a certain amount of water that is available during a wet season and supply it during the next dry season when the demand for freshwater is higher. Coastal reservoirs -water storage structures constructed at a river estuary or other coastal area to store fresh water and control water resources- have already been constructed in China, South Korea, Hong Kong and Singapore (Tabarestani and Fuladfar 2021; Yuan and Wu, 2020). Independent of a hard or soft path, the main management strategy is to affect river discharge, which is likely to cause changes to the annual hydrograph. Even though salinity response to changes in river discharges has been studied extensively in estuaries (Garvine et al.1992; Wong, 1995; Uncles and Stephens, 1996; MacCready, 1999; Chen et al. 2000; Monismith *et al.*, 2002; Bowen & Geyer 2003; Banas *et al.*, 2004; Chen, 2004; Hetland and Geyer, 2004; Brockway *et al.*, 2006; Liu *et al.*, 2007; Lerczak et al.2009; Gong and Shen, 2011; Wei et al. 2016) it is still unclear if and how this changes in the presence of a channelized network.

The present study investigates the effect of various annual flow distributions of equal water volume on the salt intrusion. The paper tries to answer questions such as: 1) how does salinity respond to flow changes, 2) what is the impact on salinity from hydrographs shape changes depending on the cause of change, 3) which is the most appropriate flow distribution to minimize stratification and 4) which hydrograph ensures high water quality (i.e. low salinity) and for how long.

The answer to the last question derives from measuring flushing and residence times that are useful tools to assess the efficacy and adequacy of a certain flow distribution for averting the salt intrusion (Choi and Lee, 2004; Sámano *et al.*, 2012). Flushing time (FT) is defined as the time required for the cumulative freshwater inflow to equal the amount of freshwater originally present in the region (Dyer 1973; Sheldon and Alber, 2002). The simplest and most common method for the FT calculation is the freshwater fraction in which the freshwater volume is divided by the freshwater input (Lauff 1967; Dyer 1973; Fischer et al. 1979; Williams, 1986). A difficulty on the determination of the freshwater volume and input arises in the case of unsteady flow and tidal conditions. Many researchers implemented the method by taking averages over a certain period (Pilson 1985;Christian et al.1991;Asselin & Spaulding 1993;Balls, 1994; Lebo et al. 1994; Swanson & Mendelson 1996;Eyre and Twigg, 1997;Chan Hilton et al. 1998; Alber and Sheldon, 1999; Hagy, Boynton and Sanford, 2000; Huang and Spaulding, 2002; Sheldon and Alber, 2002; Huang, 2007). Alber and Sheldon (1999) proposed a specific technique to determine the appropriate averaging period of the river discharge by assuming that this should be equal or very close to the flushing time itself. They tested their method in Georgia Estuaries. Whereas the FT is a unique value representative of an entire water body, the residence time (RT) is a measure of spatial variation (Choi and Lee, 2004; Sámano *et al.*, 2012). It is defined as the remaining time that a particle will spend in a defined region after first arriving at some starting location (Zimmerman, 1976; Sheldon and Alber, 2002). Therefore, the RT is applied within a restricted geographical area such as an estuary, a water basin or a box model (Hagy et al. 2000; Sheldon and Alber, 2002; Sámano *et al.*, 2012).The knowledge of a particle's RT is important because pollutants exert most of their effects only if their biochemical scales are smaller than that (Wang et al. 2004; Yuan et al. 2007). In the case of freshwater, RT would mean the time between entering and leaving a domain and therefore might also be called as the transit time (Sheldon and Alber, 2002).

A freshwater RT would normally correspond to a certain salinity threshold. The acceptable salinity levels can vary depending on the various aforementioned activities. For irrigation and agriculture, some studies accept salinity of up to 4 PSU (Clarke *et al.*, 2015) but others suggest values below 2.5 PSU (Đạt et al.2011). Some marine (e.g. phytoplankton, larvae fish, shrimps, smelt etc.) and vegetation (e.g. Sagittaria Latifolia, Sagittaria Lancifolia, phragmites australis) species do not survive in environments with more than 2 PSU salinity (Jassby *et al.*, 1995; Visser *et al.*, 2012; Hutton *et al.*, 2016; White *et al.*, 2019; Wang *et al.*, 2020). Salinity in drinking water must be less than 1 PSU to avoid the development of germs related to water borne diseases like cholera (Ahmed & Rahmad;Sarwar, 2005; Dasgupta *et al.*, 2015). Overall, a critical threshold of 2 PSU appears to satisfy most of these requirements and thus the bottom 2 PSU isohaline (commonly denoted in the literature as X2) is often used as an indicator for salt intrusion (Schubel, 1992; Monismith *et* *al.*,1996,2002; Herbold and Vendlinkski, 2012; Andrews et al. 2017). Therefore, the freshwater RT in this study is defined as the time that the salinity remains below 2 PSU.

For the purposes of this study, a 3D numerical model for an idealized delta configuration is built in Delft3D and five simulations with different flow distributions are carried out. The implemented hydrographs follow typical distributions that can be often found in real deltas. The paper aspires to provide answers through the idealized modelling for a more sustainable use of freshwater resources in deltaic systems.

2 Methods

2.1 Model setup

The present work uses a 3D model with an idealized delta configuration that can be seen in Figure 1F. The model that was built in Delft3D (Deltares, 2014) encompasses a larger area with dimensions 20 km x 22 km but the area of interest for this research contains only the delta configuration with its channels and interdistributary areas (Figure 1f). Results outside of the delta and throughout the deeper offshore area are not presented as they are out of this paper's scope. The model's bathymetry remains constant during the simulations and there is no sediment input. Bed level changes are not considered so that the impact of flow distributions on the salinity is isolated from any morphological effects. The vertical resolution consists of eight sigma layers. The default Delft3D values for horizontal diffusion and viscosity are introduced in the model equal to 10 m^2/s and 1 m^2/s respectively. A spatially constant Chezy coefficient (45 $m^{1/2}$ / s^{-1}) is implemented to account for bed roughness. A cyclic implicit numerical scheme is used and the time step is 30 seconds being the optimum value for both model stability and computational time. Further details on the model's grid resolution and the process of bathymetry development can be found in the Supplementary Material (S1).

2.2 Hydrodynamic forcing

The model is forced with an annual river flow distribution. Five simulations are setup with hydrographs of equal water volume but different shape each time. A real flow distribution with data from the Po Delta for 2009 (Montanari, 2012) is used to construct the hydrographs. The data are converted first into a cumulative distribution where each daily flow has a probability of occurrence once in 365 days. A beta distribution is then built using the following equation (Yue *et al.*, 2002):

$$B\ (\alpha, \beta) = \int_0^1 x^{\alpha-1}\ (1-x)^{\beta-1} dx \qquad (1)$$

$$0<x<1\ ;\ \alpha, \beta > 0$$

Where x is the variable and the shape of the hydrograph is determined by the shape parameters α and β. The normalized probability distribution is then converted to a flow distribution by multiplying by the annual water volume of the real hydrograph (Po Delta in 2009). However, the data need to be scaled down to fit the model's dimensions and ensure its stability. The scaling is done based on the river cross-sections' ratio between the real (Po Delta) and the idealized delta. The produced hydrographs can be seen in panels a-e of Figure 1. Table 1 presents the basic statistic parameters for each beta distribution. Equal shape parameters result into symmetric hydrographs (Figure 1 a,b,c) and the higher their value the higher the peak is. When α is smaller than β a positively skewed hydrograph occurs (Figure 1d). The hydrograph exhibits negative skewness when b is smaller than a (Figure 1e).

The five hydrographs in Figure 1 can be qualitatively classified based on their shape and the tails of each distribution as: 1) Platykurtic (light tails and low peak), 2) Mesokurtic (relatively light tails and medium peak), 3) Leptokurtic (heavy tails and high peak), 4) Positively skewed (long tail on the right) and 5) Negatively skewed (long tail on the left). All of them correspond to seasonal regimes with a pronounced wet season (Hansford et al. 2020). The distinction between heavy and light tails in this paper is defined as follows: heavy tails indicate distributions with larger probability of getting an outlier (e.g. leptokurtic) and light tails indicate distributions that go to zero faster than the exponential distribution (e.g. platykurtic) (Bryson 1974;Glen 2016).

Annual flow distributions with shapes close to the hydrographs of Figure 1 are recorded often in many real deltas. For example, right skewed hydrographs (Figure 1d) were reported in deltas located at the Gulf of Mexico including the Wax Lake Delta in the years between 2006 and 2010 (Shaw et al. 2013) and the Mississippi Delta between 1993 and 2012 (Kolker et al. 2018). Based on large data records from internet data bases and national agencies, Latrubesse et al. (2005) showed that the Mekong and the Ganges-Brahmaputra river catchments develop usually left skewed annual hydrographs (Figure 1e). The Yangtze delta sees its peak flow often in the middle of the year at some time during the wet season that occurs between May and September (Birkinshaw *et al.*, 2017). Such flow distributions are similar to that of Figure 1c and have been reported in the years between 1996 and 2005 (Lai *et al.*, 2014; Birkinshaw *et al.*, 2017) in the Yangtze Delta. In addition, when Hansford et al. (2020) averaged daily flow data for one year between 1978-2009 in the Parana Delta (Argentina), they detected an annual flow hydrograph very similar to a platykurtic distribution (Figure 1a). Finally, mesokurtic hydrographs as the one in Figure 1b have been observed in the Colorado and Nile deltas. Averaged annual hydrographs for the 1950-1993 period in the Colorado (Pitlick and Cress ;2000) and flow distributions at several stations in the Nile (Eldardiry and Hossain, 2019) confirm this. The averaged over the years 1984-1996 annual hydrograph in the Niger Delta also exhibited a mesokurtic hydrograph shape (Lienou *et al.*, 2010).

Table 1 Statistical Parameters for each hydrograph type

Scenario	Shape parameters	Kurtosis	Qmax (m^3/s)	Qmean (m^3/s)
Platykurtic	a =b = 2	2.14	140	93
Mesokurtic	a =b = 4	2.45	204	93
Leptokurtic	a = b =8	2.68	293	93
PosSkewed	a = 2 b= 4	2.62	197	93
NegSkewed	a = 4 b= 2	2.62	197	93

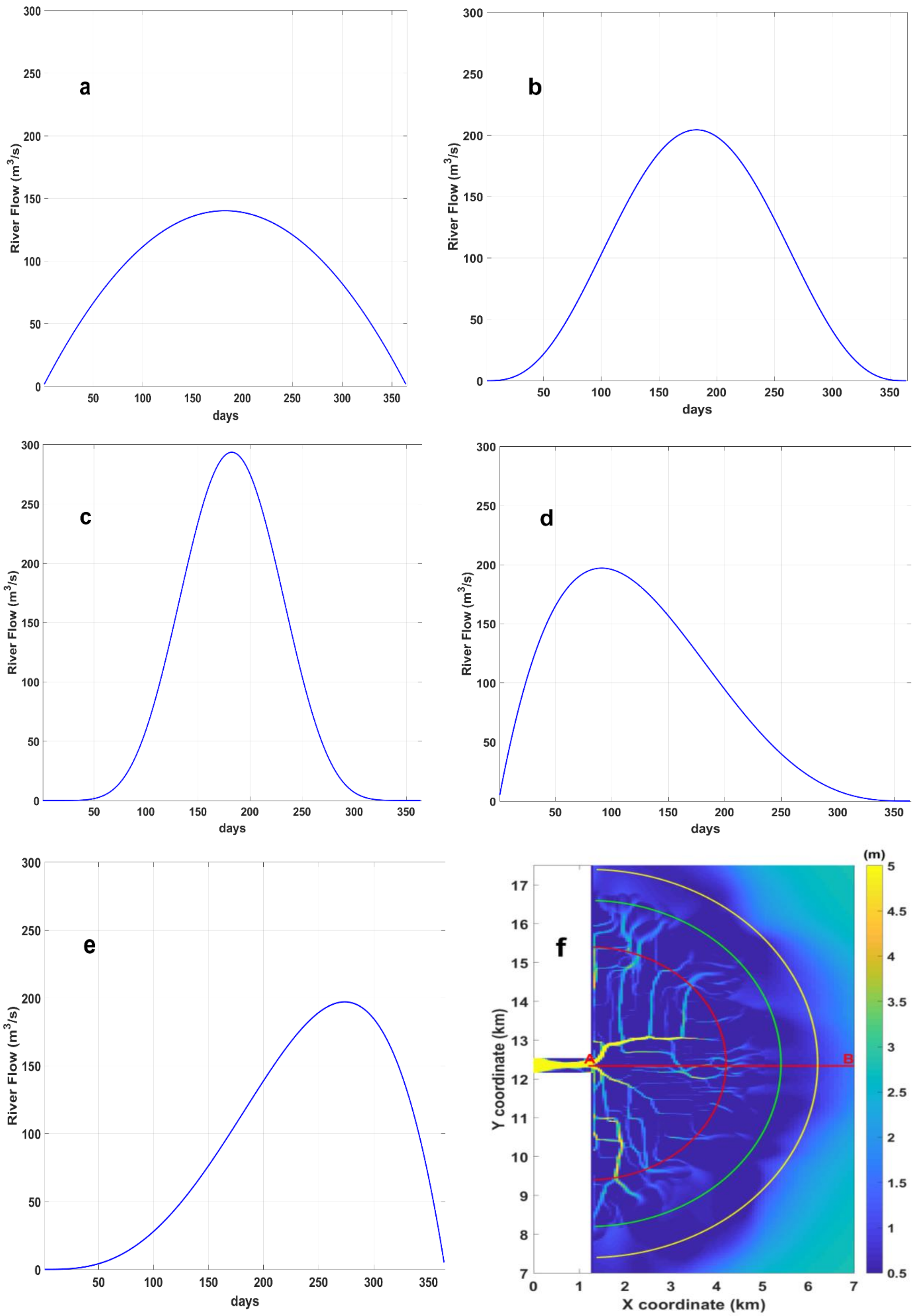
a
b
c
d
e
f
River Flow (m3/s)
days
Y coordinate (km)
X coordinate (km)
(m)
A
B

Figure 1 The hydrographs implemented in the model: a) Platykurtic b)Mesokurtic c) Leptokurtic d) Left Skewed and e) Right Skewed flow distribution for one year. f) The delta bathymetry. The red line AB measures the 6km distance from the river mouth (point A) corresponding to the length of the salt intrusion curve displayed in Figure 5b. The coloured semicircles with their centre at point A and radius 3km (red), 4.2km (green) and 5km (yellow) visualize the cross sections over which salinity is averaged for the result analysis in sections 3.1, 3.2 and 3.4.

2.2 Boundary Conditions

The effects of tides and the Coriolis force are neglected in order to isolate the influence on salinity from the various flow distributions. A zero water level is implemented at the offshore boundary while the Riemann condition (in the form of a zero velocity variant) applies in the lateral boundaries. Fresh water is assumed at the upstream river boundary and seawater salinity (30PSU) at the offshore and lateral boundaries.

2.3 Initial Conditions

A spin-up simulation precedes each time to get a dynamic equilibrium for salinity to be introduced as initial conditions. A uniform salinity equal to 30 PSU is implemented in the model except for the river upstream boundary where zero salinity is imposed. It is decided to spin-up the model with the initial flow of each hydrograph in Figure 1. These are very small but non-zero values and this reduces the time required to reach a dynamic equilibrium. In this way, the simulations will start from dry season (low flows) conditions. The river flow in the spin-up model is constant and the simulation is stopped after 30 days when steady state conditions are reached in all cases.

3 Results

3.1 Salinity response to river discharge changes

Previous studies detected a hysteresis on the salinity's temporal response to flow changes in estuaries (Hetland and Geyer 2004; Savenije 2005; Chen 2015). The salinity responds slower to flow decreases than increases. An investigation follows on the existence or not of this hysteresis in the idealized delta for the symmetric and skewed hydrographs in separate. To do this, the salinity is first averaged over depth and over a radial cross-section of 3 km distance from the mouth. Then, this is plotted either in time and/or against the river discharge. The decision to show results for this particular radial section (3 km) for both symmetric and skewed distributions is taken with the consideration that it is probably safer to assess the salinity response in a location with medium influence of the river discharge where the water does not become completely fresh. This is a somewhat arbitrary decision but it does not affect much the conclusions. The same analysis but for a section closer to the river (1 km) (available in the Supplementary Material, section S2, Figure S3 and Figure S4) shows similar results.

3.1.1 Symmetric Hydrographs

Figure 2a displays the mean over depth daily salinity averaged over a radial cross-section of 3 km distance (red semicircle in Figure 1f) from the mouth at every date for the three symmetric distributions. The bottom axis shows the dates of the 1st semester and the corresponding salinity for each day denoted by dotted lines. During the 1st semester the salinity decreases monotonously. The top axis shows the dates of the 2nd semester in reverse order starting from right to the left and the corresponding salinity for each day is denoted by circled lines. During the 2nd semester the salinity increases monotonously. The unique daily values of the river discharge from each one of the three symmetric hydrographs are also added in the plot displayed as continuous lines and with its scale being on the right axis. Due to the symmetry, the dates on the top are projections of the dates on the bottom axis of equal river discharges. Therefore, the points of intersection of a vertical line drawn in Figure 2a with the dotted and circled lines give us the salinity level at days of equal flow.

Figure 2a shows that initially, the order between the three symmetric distributions is as follows: $S_{leptokurtic} > S_{mesokurtic} > S_{platykurtic}$ because the relationship between the river discharge (Q) magnitude of the three symmetric distributions follows the opposite order $Q_{platykurtic} > Q_{mesokurtic} > Q_{leptokurtic}$. The order between the river discharges changes as the flow increases in the 1st semester and so does that of the salinity. $S_{leptokurtic}$ falls below $S_{platykurti}$c at first and $S_{mesokurtic}$ a few days later. The dates of the intersection between the salinity curves correspond to the dates of intersection between the flow curves in each case which means that the salinity becomes lower in one simulation when its flow becomes higher than the flow of another simulation.

The opposite procedure takes place at the 2nd semester and as long as the flow decreases. The salinity of the leptokurtic hydrograph becomes higher than the mesokurtic and then than the platykurtic salinity.

Figure 2a indicates that there is a hysteresis on the salinity's response between increasing and decreasing flows. For example, the leptokurtic salinity falls below the platykurtic one in the 1st semester on the 5th of May. This means that the change occurs only 55 days before the peak flow day on the 1st of July. On the contrary, the leptokurtic salinity becomes higher than the platykurtic one in the 2nd semester on the 10th of September. This is 72 days far from the 1st of July (peak flow day) which shows a delay in comparison to the interchange in the 1st semester between the two simulations. Similar conclusions can be drawn when comparing between any couple of simulations.

In addition, it can be seen that there is a time frame in each simulation when the salinity in the 2nd semester is always lower compared to its corresponding date of equal flow in the 1st semester. This indicates that the salinity might not be equal at dates of equal flow depending on whether the flow is increasing or decreasing and whether the peak flow has occurred already or not. However, this effect is not present for very low flows (at the start of the simulation) or very high ones while getting closer to the peak flow day. In this case, the salinity is equal for equal flows independent of increasing or decreasing river discharge.

To get a clearer image of this salinity asymmetry between 1st and 2nd semester, the salinity differences of more than 0.5 PSU between the two semesters are plotted in Figure 2b for each day and each simulation separately. The maximum salinity difference increases with the peak flow magnitude but the duration of salinity differences decreases with it. For example, differences in salinity between the two semesters can reach 10 PSU in the leptokurtic case but they are present only for approximately 1.5 months. On the contrary, the maximum salinity difference in the platykurtic case is 8PSU but differences are present for 2.5 months instead.

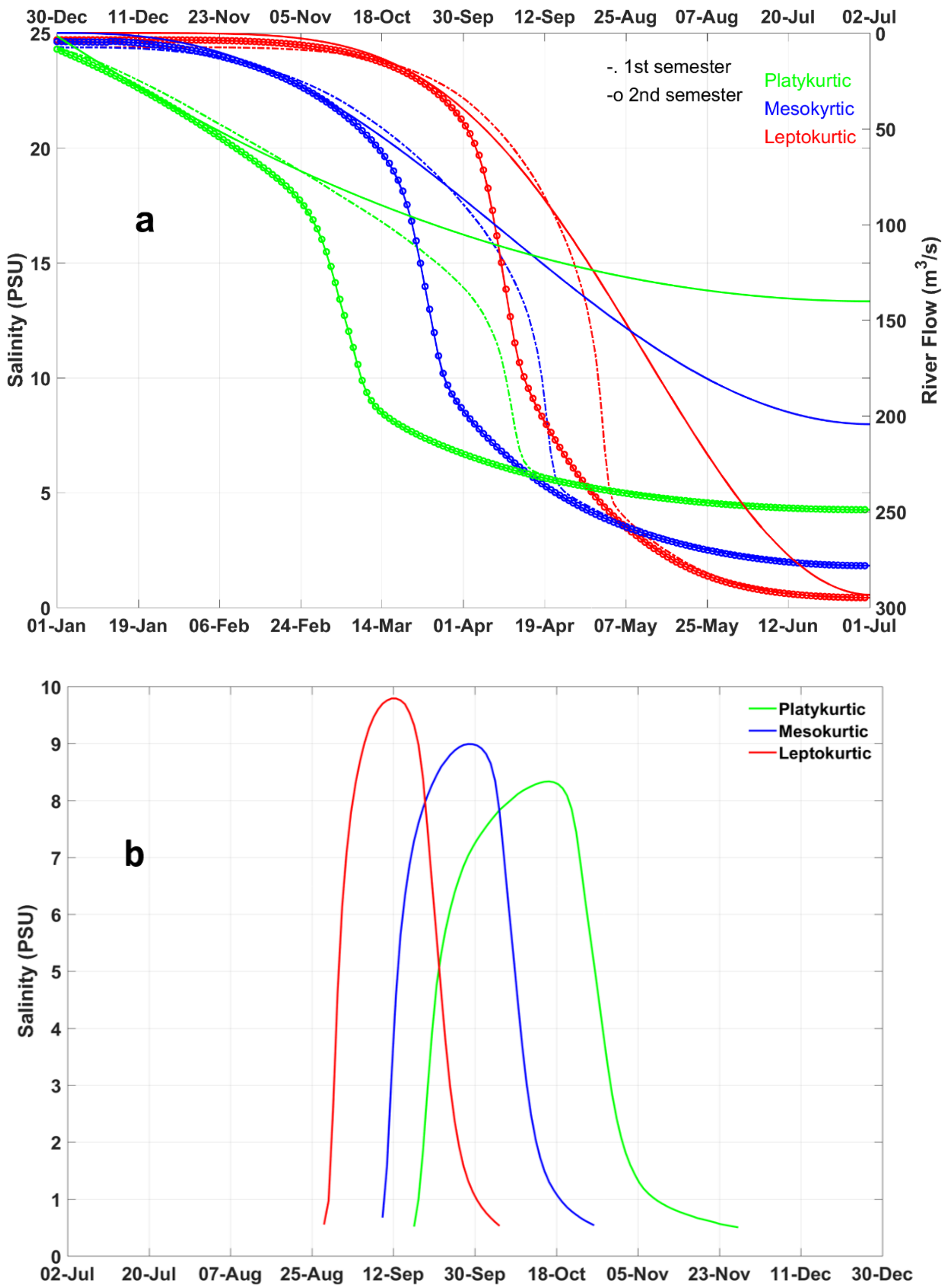

Figure 2 a) A comparison of the mean over depth salinity averaged over a distance of 3km from the river mouth between the three symmetric distributions. Bottom axis shows the dates of the 1st semester. The dotted lines denote salinity in the 1st semester. Top *axis shows the dates of the 2nd semester moving from right to the left. Circled lines denote salinity in the 2nd semester increasing from right to the left. The river discharge of each symmetric distribution is added with continuous lines and with its scale on the right axis. The flow increases from 1st of January until 1st of July following the bottom axis and decreases from 2nd of July until 31 of December following the top axis. b) A timeline of the salinity differences above 0.5 PSU between the 1st and 2nd semester for each symmetric distribution.*

3.1.2 Skewed hydrographs

The analysis for the two skewed hydrographs is presented in a different manner since the flow range remains the same in both cases. Figure 3 displays the salinity averaged over depth and over the radial cross section 3 km far from the mouth against the river discharge. The positive skewed case shows almost equal salinity between the start and the end of the simulation. The long tail covers a period of 9 months with decreasing flows that allows the salinity to recover and return to its initial state. In contrast, the salinity for the negative skewed hydrograph is about 1 PSU lower at the end of the simulation compared to its initial value. In this case, the simulation ends with the short tail that covers a period of only 3 months with a very sharp flow decrease that does not allow the salinity to recover.

There are indications of a hysteresis in salinity's response to flow changes in Figure 3 as well. Both simulations exhibit a time frame with lower salinity during the decreasing flow periods compared to equal discharges at increasing flow periods. The salinity is lower in the short tail for the negative skewed and in the long tail for the positive skewed case.

Similarly to what is observed in Figure 2a for the symmetric hydrographs, there is a flow range with equal salinity. This occurs during high flow periods. When the flow is between 120 m^3/s and 200 m^3/s the salinity is equal between the two skewed hydrograph simulations. This means that for very high flows, the salinity's response is independent of skewness and of increasing or decreasing flows.

The flow range in the short and long tails is equal in both simulations and varies between very low discharges and the peak flow that is close to 200 m^3/s. The short and long tail seem to cause the same level of salinity variation as this fluctuates between 0 PSU and 24 PSU. This indicates that by increasing the flow rate a salinity standard could be achieved in much shorter time.

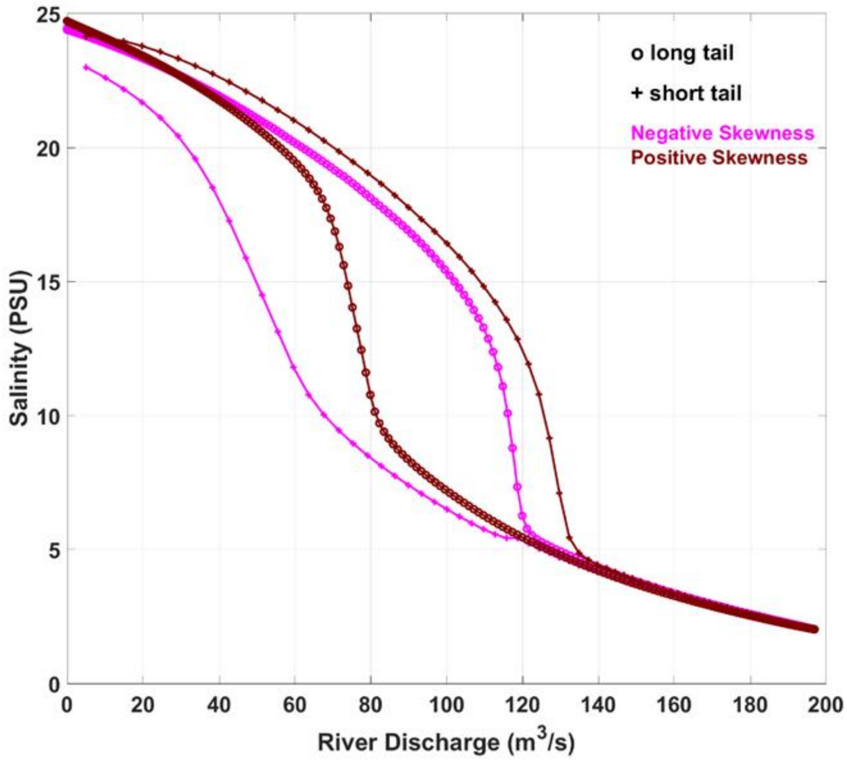

Figure 3 The mean over depth salinity averaged over a distance of 3 km far from the river mouth against the river discharge for the two skewed hydrographs. The circles correspond to the dates of the long tail and the crosses to those of the short tail.

3.2 Stratification

Changes in the river discharge affect the stratification. Increases in the river discharge usually result in stronger stratification (Monismith *et al.*, 2002; MacCready, 2004; Ralston, Geyer and Lerczak, 2008; Lerczak, Geyer and Ralston, 2009; Wei et al. 2016) with high top to bottom density differences. Therefore, the influence of the flow distribution on the stratification is measured in this section by taking the difference of the top to bottom layer salinity. To visualize the results, the top to bottom salinity differences are averaged over radial cross-sections like it was done in section 3.1. The averaging is done over points in a distance of 3 km and 5 km from the river mouth (red and yellow semicircles in Figure 1f) to compare results between shallow locations in the delta front (i.e. area including delta channels) and deeper ones at the pro-delta (i.e. delta area beyond the channels ends) (Hori & Saito 2007). The evolution in time of the stratification is presented for both symmetric and skewed flow distributions and for both radial sections in Figure 4.

The shape of the hydrograph does not seem to affect the range of stratification which remains similar between the five cases in each section (3km and 5km). This range is relatively small at the 3 km section (Figure 4a and b) which is the shallower one where mixing occurs under the influence of stronger bottom friction. The three symmetric hydrographs (Figure 4a) show a stratification level that increases initially following the hydrographs shape. For example, the leptokurtic curve demonstrates heavier tails and almost constant stratification for the period that the hydrograph has also heavier tails. At the same time, the platykurtic curve demonstrates light tails with a sharp increase of stratification in accordance with the sharp flow increase in Figure 1a. As the river discharge increases continuously, it crosses a threshold above which it manages to mix the water column despite the absence of other contributors (e.g. tide-induced mixing). This is most probably accompanied by a seaward shift of the salt intrusion length. The level of mixing depends on the level of the peak flow. The higher the peak the lower the stratification is. In that sense, the leptokurtic is the more efficient hydrograph against stratification while the decrease of stratification in the platykurtic is not substantial. The skewed hydrographs (Figure 4b) present similar results. Initially, the stratification increases following the flow increase but it drops when the river discharge is high enough to mix the waters. This occurs earlier in the positively skewed case, 40 days after the start of the simulation and during the short tail. It occurs later in the negatively skewed simulation, 170 days after the start and during the long tail. In both cases, the stratification starts to increase again when the river discharge drops below a threshold value when it cannot mix the water anymore. After this point and till the end of the simulation, the top to bottom salinity differences follow the flow distribution.

In the deeper waters (5 km radial section, Figure 4c and d), the stratification follows the flow distribution and increases/decreases when the river discharge does increase/decrease too irrespective of the hydrograph shape. Its value reaches its maximum at the time of the peak flow. Accordingly, the higher the peak flow the higher the stratification can become and this is why the leptokurtic shows the maximum top to bottom salinity difference (17 PSU) and the platykurtic the minimum one (13 PSU). In the same concept, the two skewed simulations (Figure 4d) show an equal maximum stratification occurring though at different time moments following the difference in the position of their peak on the hydrograph.

Changes in the spatial salinity distribution are reflected in Figure 4c and d as spikes, one before and another one after the peak flow. As the flow increases, the freshwater spreads radially in wider areas resulting in more symmetric spatial distributions. An example of a change in the spatial salinity distribution for the platykurtic hydrograph is given in the Supplementary Material (section 7.3). At the moment this change occurs, the rate of stratification increase/decrease in the 1st/ 2nd semester also changes. The time period between the spike and the peak flow is longer in the 2nd semester when the flow decreases as a result of the slower salinity's response to decreasing than increasing flows.

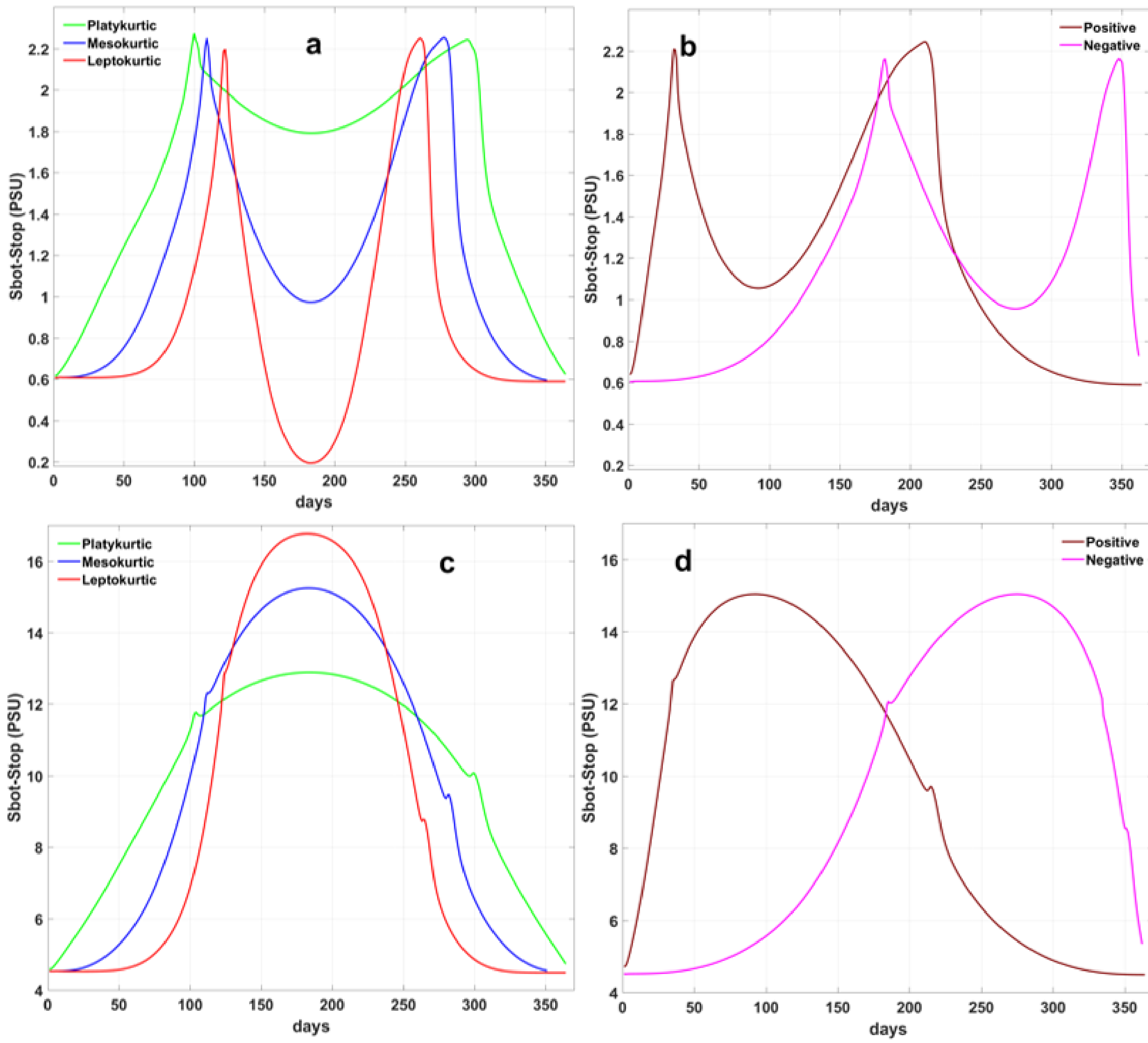

Figure 4 a), b) The evolution in time of the top to bottom layer difference of the radially averaged salinity in a distance 3 km from the mouth in the symmetric and skewed flow distributions respectively. c), d) The evolution in time of the top to bottom layer difference of the radially averaged salinity in a distance 5 km from the mouth in the symmetric and skewed flow distributions respectively.

3.3 Salt intrusion in the inlet

Sustained drought periods may result in salt intrusion inside the river mouth. This is often defined by the location of the 2 PSU bottom isohaline (Schubel, 1992; Monismith *et al.*,1996,2002; Herbold and Vendlinkski, 2012; Andrews et al. 2017). The time that the salinity at the bottom of the river mouth remains below 2 PSU is measured for each simulation with the intention to detect the flow distribution that keeps the river mouth fresh for the most time. Figure 5a shows the level of the bottom salinity at the river mouth (point A in Figure 1f) for the whole simulation period in each case. The five simulations start from a dry season state with very high salinity at the bottom of the mouth meaning that there is salt intrusion in the inlet. The intrusion is averted when the river flows become higher during the wet season. It is identified from Figure 5 that the river discharge at the time the salinity falls below 2 PSU is approximately 100 m^3/s in each case. The rate at which the flow rises in each hydrograph until it reaches this threshold determines the moment that the inlet's salt intrusion disappears first. The earliest this can happen is for the positive skewed and the latest for the negative skewed hydrograph. The time period that the inlet remains fresh is determined by the hydrographs' tails and the peak flow position. Table 2 displays the total number of days and the days after the peak flow that the bottom salinity at the mouth is less than 2 PSU. The symmetric distributions indicate that the lighter the tails (platykurtic) the longer the inlet is fresh (210 days). The positive skewed case, which also shows light tails but for shorter time, exhibits the second longer period (189 days). Being antisymmetric to the positive, the negative skewed hydrograph keeps the inlet fresh for a long period as well (179 days). However, the fact that its peak occurs much later in time seems to have an effect by cutting out 10 days making it equal to the mesokurtic hydrograph. The minimum duration of all (147 days) corresponds to the leptokurtic as it has the heavier tails. The results are a bit different when the time is measured after the peak flow. In this case, the positive skewed hydrograph exhibits the longer duration (126 days) with the platykurtic being second now (119 days). This indicates that it might be better to force a peak flow to occur early in the year in order to establish a fresh water system for longer periods. This is further supported by the fact that the negative skewed hydrograph manages to keep the bottom salinity at the mouth below 2PSU only for 80 days, even 2 days less than in the leptokurtic hydrograph.

Table 2 The total duration and the time after the peak flow that the bottom salinity is less than 2 PSU at the river mouth

Case	Total Duration (days)	Duration after the Peak (days)
Platykurtic	210	119
Mesokurtic	179	100
Leptokurtic	147	82
PosSkewed	189	126
NegSkewed	179	80

3.4 Salinity longitudinal distribution

Possible effects of the hydrographs shape on the salinity longitudinal distribution are investigated in this section. In Figure 5b, the mean over depth and annual averages of salinity in the delta are averaged over radial cross sections every 300 m along a distance of 6 km from the river mouth (see cross-section AB in Figure 1f). This technique follows the concept of the salt intrusion curves, often used in other studies to measure cross-sectional salinity averages from the estuary mouth's to its head (Savenije, 1993; Nguyen and Savenije, 2006; Nguyen et al., 2008; Zhang et al., 2011). The annual salinity average at the river mouth is above the 2 PSU threshold in every case. This is probably caused by the long periods of heavy tails (meaning very low flows) at all hydrographs except for the platykurtic one. Having the lightest tails of all, the platykutic case presents the lowest salinity value and closest to the 2 PSU threshold at the river mouth. The spatial salinity distribution in the delta increases gradually downstream. The rate of salinity increase between two successive sections is not constant because in contrast to their length, the depth of the radial cross-sections does not increase monotonously downstream. The shape of the five curves in Figure 5b is very similar and does not seem to be affected by the shape of the hydrograph. A border exists 4.2 km far from the river mouth where downstream of it the salinity is equal between the platykurtic, mesokurtic and the two skewed hydrographs. The green semi-circle in Figure 1f denotes the radial section of 4.2 km. This is located at the border between the delta front and the pro-delta. Upstream of this border, hydrographs with lighter tails (platykurtic) provide a salt intrusion curve of the lowest salinity. Hydrographs with similar peaks and flow ranges, such as the positive skewed and the mesokurtic provide exactly the same spatial salinity distribution in the delta. The salinity in the negative skewed is slightly higher than them. This indicates a negative effect of moving the peak closer to the end instead of the start of the hydrograph as it causes an increase of salinity. Downstream of the green semicircle, in the absence of complex bathymetry and in deeper waters (pro-delta), the salt intrusion curve is the same for all cases with the exception of the leptokurtic hydrograph that still shows the highest salinity. It appears then that the salinity in deep areas is less affected by changes in a hydrograph shape.

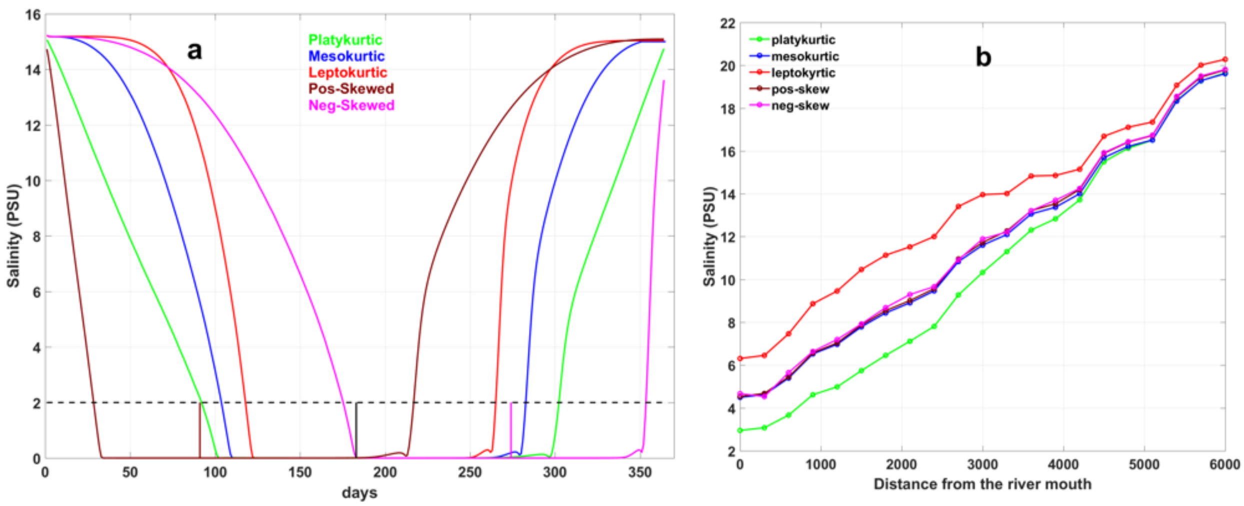

Figure 5 a) Time series of the bottom salinity at the river mouth (point A in Figure 1f). Each colour represents results for a simulation with a different hydrograph. The dashed black line draws the 2PSU threshold. The short brown, magenta and black vertical lines indicate the time moment of the peak flow on the horizontal axis for the positive skewed, negative skewed and symmetric distributions equal to 91,274 and 183 days respectively. b) Annual averages of the mean over depth salinity when averaged radially every 300 m along a distance of 6km from the river mouth.

3.5 Freshwater residence time

Considering the water to be fresh as long as its salinity remains below 2 PSU, its residence (or transit) time is calculated to determine how long the delta remains fresh in each simulation and to what extent. Figure 6 includes maps of the delta for each simulation displaying the total time in days that the depth averaged salinity remains below 2 PSU. The delta channels borders are delineated in the background (in black colour) to visualise the size of the area that becomes fresh in each case. The cyan colour in these maps represents areas that never become fresh (freshwater RT is zero). In every case, the tendency is that the time salinity remains below 2 PSU decreases downstream in long distances from the river mouth. The peak flow seems to be the determinant factor for the extent that becomes fresh. This is almost the same for the mesokurtic (Figure 6b) and the two skewed cases (Figure 6d,e) because their maximum flows are very close (204 m^3/s in the mesokurtic and 197 m^3/s in the skewed hydrographs).

In the symmetric distributions, the delta area that becomes fresh increases with increasing peak flow. Hence, every delta channel becomes fresh when the leptokurtic hydrograph is implemented - with the exception of the two most distant ones at the top left and bottom left corner of the map. On the contrary, a more limited delta area becomes fresh with the platykurtic hydrograph (Figure 6a) compared to the other hydrograph cases. Interestingly though, this case provides the longest fresh water conditions period. The delta is fresh in relatively small or medium distances from the mouth for almost 7 months. The duration of a freshwater period for a symmetric distribution decreases as the tails of the hydrograph become heavier. This is why the maximum time that salinity can be below 2 PSU with the leptokurtic hydrograph is only 5 months (Figure 6c). In the case of the skewed hydrographs the positive one (Figure 6d) keeps the delta fresh for more time than the negative (Figure 6e) highlighting the importance of its hydrograph slope that shows a rapid flow rise in the 1st semester and an early in time peak discharge. The hydrograph's slope is identified as another crucial factor because the two cases exhibiting the faster rate of flow rise in the 1st semester (platykurtic and right skewed) provided the longer fresh water conditions in the delta.

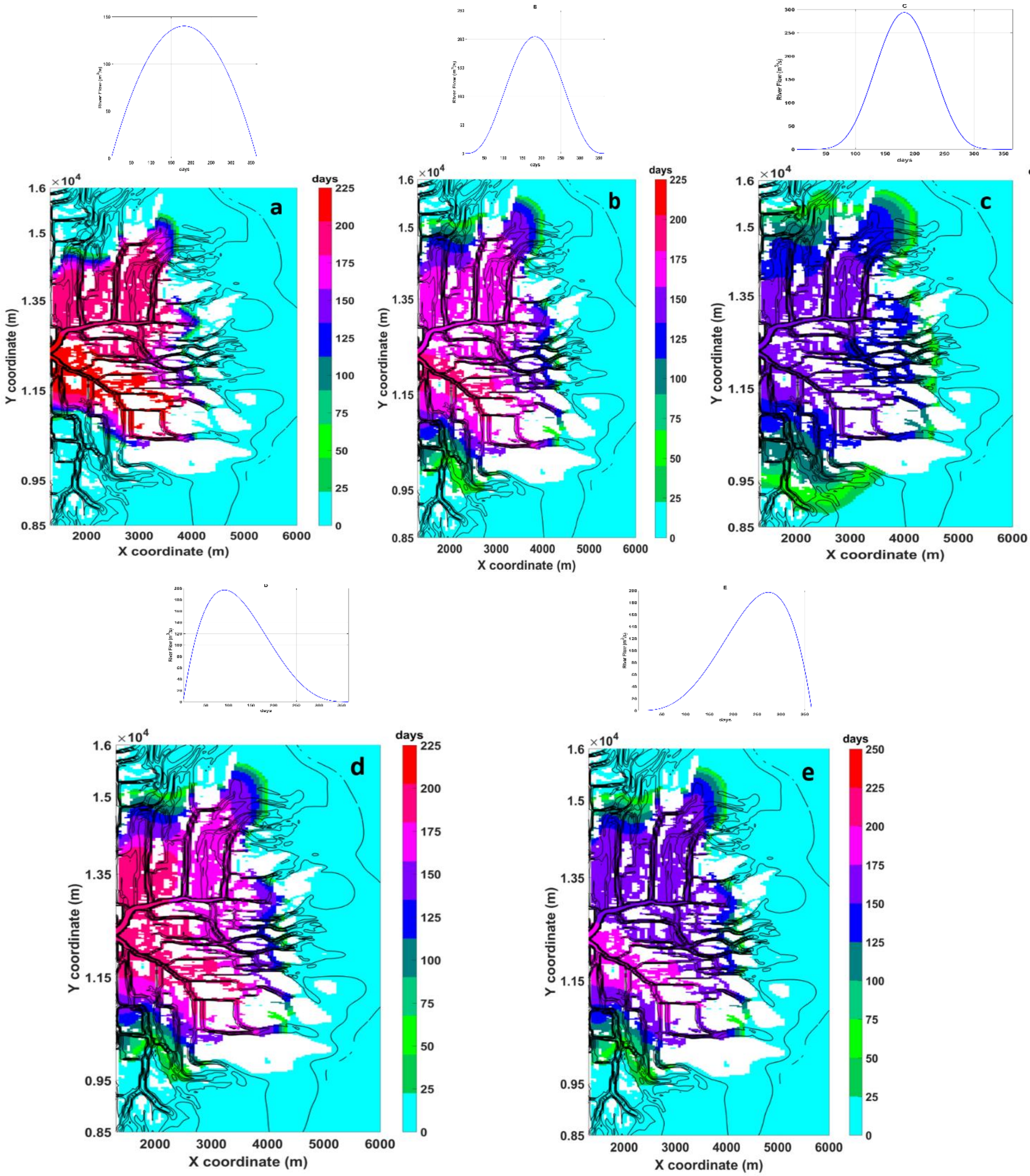

Figure 6 The time in days that salinity is less than 2 PSU in the delta for the a)Platykurtic b)Mesokurtic c)Leptokurtic d)Positive and e) Negative skewed hydrograph cases. The hydrograph corresponding to each plot is added on top of it as a miniature. The

black lines in the background delineate the delta channels. White coloured spaces denote dry areas. The river inlet has been taken out from the maps and the abscissa is set to start at the river mouth. Cyan coloured areas never become fresh.

In the map plots, differences in the duration within certain areas of the delta indicate bathymetry effects. There seems to be a difference of 25 days in the duration between the right and left sides of the inlet (looking seaward) (Figure 6a,b,d). The latter is deeper and thus the higher bottom salinity reduces the duration in comparison to the shallower areas right of the inlet. This difference is more pronounced in the negative skewed case (Figure 6e) when the dry season is prolonged and the low fresh water flows do not manage to decrease the salinity in the deeper areas. On the other hand, this separation between deep and shallow areas is not present in the leptokurtic case (Figure 6c) because the peak flow is very high and distributes symmetrically the fresh water throughout the delta.

3.6 Flushing times

The flushing time (FT) in each of the five simulations is calculated by the following equation (Dyer 1973; Alber and Sheldon, 1999):

$$FT = \frac{\sum_i^n \left(\frac{S_{SW} - S_i}{S_{SW}}\right) V_i}{Q_F} \tag{2}$$

For a total number n of grid cells i , V_i and S_i are its volume and salinity respectively. S_{SW} is the sea water salinity (in this case equal to 30PSU) and Q_F an averaged over a time frame river discharge. The determination of the appropriate period of averaging for the calculation of Q_F can be a complex issue. In this paper, the Date Specific Method (DSM) is used as introduced by Alber and Sheldon (1999). The method assumes that the averaging period must be equal to the FT. By selecting an observation day as a starting point, the FT is calculated through an iterative process working backwards and stops when its value equals the period over which the river discharge is averaged.

The FT was measured twice after determining the averaging period first by setting the start at the day of the maximum flow and second at the last day of the simulation. Figure 7a displays the FT for both starting days. The five simulations show comparable results when the maximum flow day is considered the starting point. In this case, the averaging period is only one day because the river flow is so high that replaces immediately the salt with fresh water and so Q_F in equation 2 is also Q_{max}. Consequently, the FTs are about 1 day and the differences between the five simulations are in the order of a few hours. The order of the FT between the five hydrographs follows the order of their peaks and the higher the flow the lower the FT is.

If the last day of the simulation is taken as the observation day to determine the averaging period, the differences in the FT between each hydrograph are more significant. The negative skewed hydrograph exhibits the lowest FT (4 days) because it contains the highest flows at its end. The symmetric distributions show a progressive decrease of the FT as the hydrographs tails become lighter. As a result, the leptokurtic hydrograph requires the most time for water renewal (17 days) with the positive skewed one demonstrating similar values since its heavy long tail occurs at the end of the simulation.

However, since most of the hydrographs contain very low river discharges at the end of their simulation, it is possible that the average discharge Q_{end} introduced in equation 2 might lead to an underestimation of the FT when the starting date is the last one. For this reason, the calculation of the FT is repeated for this specific case by introducing the median discharge over the averaging period instead of its mean value. Figure 7b provides a comparison between the FTs measured with the median and the average discharge. The outcome is very interesting because even though the relationship of the FTs between the various hydrographs remains the same, the values in some cases are quite different. In the leptokurtic case, the median FT is more than 120 days (4 months) while the average one was just 17 days. Clearly, the average discharge leads to an underestimation for a hydrograph with very heavy tails. Similarly, the positive skewed hydrograph that also exhibits heavy tails at the end of the simulation gave a higher median FT (30 days) than its average one (17 days). In addition, the median FT uncovers a significant difference of the time required for water renewal between the leptokurtic and the positive skewed hydrograph which was not detected when the average discharge was used. The positive skewed hydrograph exchanges water 3 months faster than the leptokurtic according to the median FT calculation.

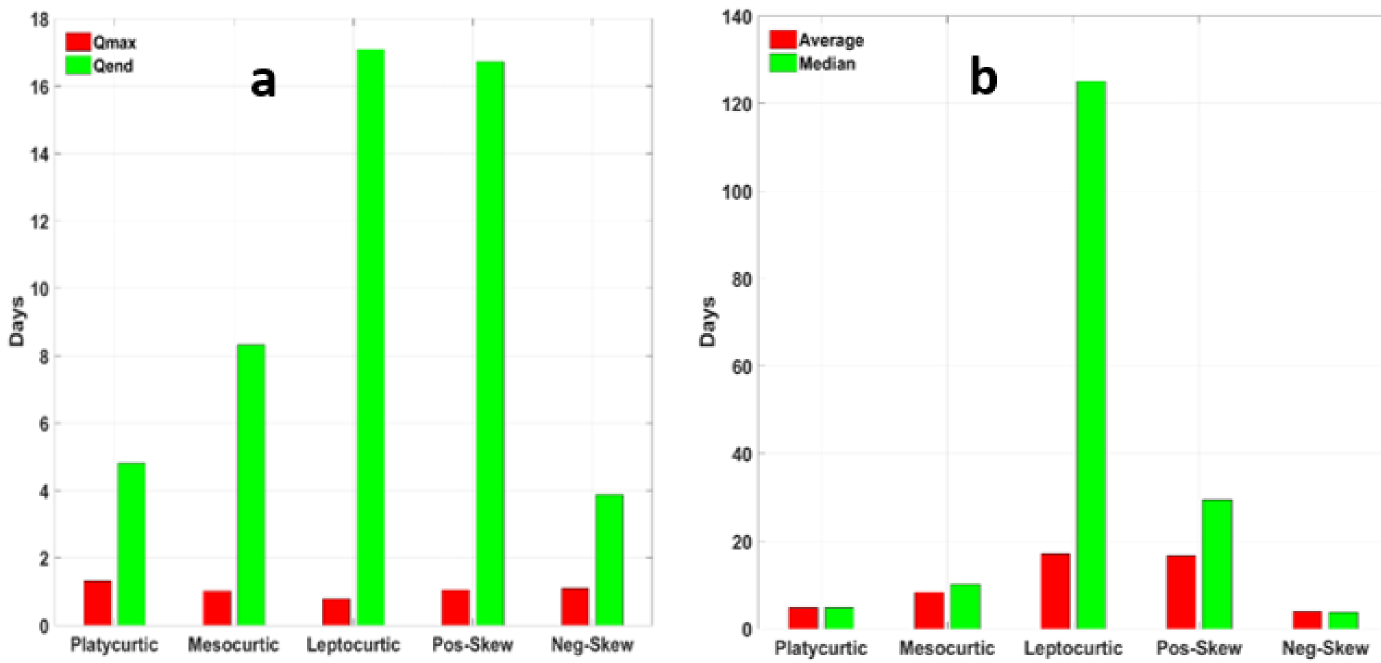

Figure 7 The flushing time for each simulation calculated using the Date Specific Method (DSM) to determine the river discharge averaging period. a) Comparison of the flushing time measured with the average river discharge over a period with the starting date at the day of the maximum flow (Qmax, red bars) and the last day of the simulation (Qend, green bars).b) Comparison of the

flushing time measured with the average (red bars) and the median (green bars) river discharge over a period with a starting date at the last day of the simulation

4. Discussion

4.1 Salinity response to river discharges

Results in section 3.1 indicate the existence of an asymmetry in the salinity response to flow changes. The salinity responds slower to decreasing than increasing flow independent of the hydrographs shape. This asymmetry has been identified in several estuarine studies as well (Blanton et al. 2001; Hetland & Geyer, 2004; Savenije 2005;MacCready, 2007; Uddin and Haque, 2010; Chen, 2015). Savenije (2005) simply states that the replacement of fresh with salt water takes more time. Hetland & Geyer (2004) attributed the asymmetry in the estuarine response to the increase of the bottom drag when the flow decreases. The idealized delta presents a complex and asymmetric bathymetry so that it would be reasonable to assume an effect of the bottom drag to the salinity response. For example, Figure 6 shows higher freshwater RT in the shallower parts of the delta for some simulations. However, Figure 2a shows that this asymmetry does not concern periods with very high or very low flows. At these times, the salinity is equal for equal flows between the two semesters irrespective of whether the flow increases or decreases. The peak flow magnitude seems to have a strong influence. The higher the peak the shorter the asymmetry period is and the higher the salinity decrease is too (Figure 2b). This could be similar to the shorter adjustment times to large peaks in estuaries that Chen (2015) reported. In contrast to Hetland and Geyer (2004), Chen (2015) claims that the asymmetry is caused by two other factors: non-linearity of the salt flux and large variations in the river forcing. The results in section 3.1 present a direct dependence of the salinity response timescale to the flow. Monismith (2017) states that this is true only in systems close to steady state although the relationship is not linear. This is most probably true for the present case since the hydrographs of Figure 1 assume slow flow changes and this justifies the direct dependence of salinity response to river discharge observed in the results. In addition, Monismith (2017) examined if it is possible to take advantage of this asymmetry and achieve a specific salinity standard with flow variations of lower freshwater volumes compared to a constant flow for the same time frame. The outcome was that the flow needed to obtain a certain salinity value (e.g. 2 PSU) increases as the period of flow variation increases. Similarly, Figure 6c indicates that to sustain the 2 PSU salinity threshold in its most distance position, higher flow would be required to vary for a longer period. However, this would result in an increase of the freshwater volume compared to the other hydrographs.

The response asymmetry of salinity to flow changes can be well detected in the skewed hydrographs too (Figure 3). The effect of high flow periods when the salinity does not vary between increasing or decreasing flows is also present. Most importantly though, the conclusion is that for a given flow range a standard salinity decrease could be achieved in much shorter time if the flow rate is increased or in other words if the hydrographs tails become sharper.

The latter outcome could be extremely useful in terms of water management as it seems that for a given flow range, the increase of its rate can decrease faster the salinity and remarkably improve the conditions in the delta. The faster rate of flow change (lighter tails) is also what probably makes the platykurtic hydrograph a preferable option compared to the leptokurtic one since it sustains freshwater conditions in the delta for longer periods. This would prolong the period that the various anthropogenic activities could take place safely in the delta even though the leptokurtic hydrograph could achieve larger salinity decrease but for a limited time.

4.2 Drivers of hydrographs shape change and its impact on salinity

Deltas can be found at all latitudes and climatic zones (Roberts, Weimer and Slatt, 2012). Although not absolute, a hydrograph's shape could be indicative of certain climate zones. Climate change will affect hydrological regimes in the future which can reflect as changes in hydrographs shape. Riverine flow changes result from either natural climate variability (NCV) (Deser *et al.*, 2012) or anthropogenic climate change (ACC) (Zhang and Delworth, 2018). NCV influences riverine floods magnitude and timing (Merz *et al.*, 2014; François *et al.*, 2019). Atmospheric processes such as intensified precipitation (Viglione et al. 2016) can increase riverine flood peak discharges (Hall *et al.*, 2014; Zhang *et al.*, 2015). Such increases may result in hydrographs like the leptokurtic in Figure 1c that presents a sharp peak. This type of hydrograph with large differences between maximum and minimum flows is often found in monsoonal climates (Hansford et al. 2020). The results analysis in section 3 indicates that peak flow increases could result in an offshore displacement of the salt intrusion length, freshening of a larger area in the delta, mixing of the water column with freshwater and fast renewal times during this period. However, this positive effect would be only temporary if it is not accompanied by an increase of the streamflow throughout the year and the delta's salinity will shortly recover to its pre-peak flow state. A platykurtic hydrograph that has lower peak but smaller differences between maximum and minimum flows is more successful in retaining the delta fresh for longer periods. Increases of peak flows magnitude with thus similar effects may arise by ACC as well as for example urbanization and land use changes that decrease soil infiltration and weaken the natural buffering effect (Vogel et al.2011; Prosdocimi et al. 2015; François *et al.*, 2019).

Warmer temperatures have led to earlier spring discharges in rivers affected by snowmelt (IPCC 2007;Matti *et al.*, 2017;Bloschl et al. 2017). The positively skewed hydrograph's peak is of similar magnitude to the mesokurtic and the negative skewed one but occurs earlier in time. An earlier occurrence of the same magnitude peak flow shows to have an advantage in terms of keeping the delta and its river mouth fresh for longer periods compared to the two other cases. Despite this, the annual and spatial averaged salinity remains the same between these three cases. Moreover, the earlier spring peak discharge shifts the river runoff away from the summer and the autumn which are the months with the highest water demand and so special consideration should be taken in these conditions (IPCC 2007). On the other hand, polar warming has caused a delay of winter floods in the North Sea and some sectors in the Meditteranean Coast (Bloschl et al. 2017). In the hydrographs of Figure 1, when the peak flow is positioned late in time (negative skewed) the freshwater residence time is much lower compared to other cases of equal peak flow. However, the winter's water renewal time may become faster in this case because of the higher flows during this period.

Rises of temperature, increases of evaporation and warming of the oceans in recent years has intensified droughts that have also become more frequent (IPCC 2007). In addition, reduction of runoff in many regions is assumed to be the result of a poleward expansion of the subtropical dry zone due to anthropogenic climate warming (Lu et al.2007; Milly *et al.*, 2008). Conversion of delta regions to arid zones due to sustained drought periods could modify their annual hydrographs into a mesokurtic shape which is the hydrograph type usually met in these zones (Hansford et al. 2020) as is the case for the Colorado and Nile deltas (Day *et al.*, 2021). The effect on salinity would depend mainly on the peak flow change. If the peak flow increases then an offshore displacement of the salt intrusion zone should be expected, a decrease of stratification and freshwater residence times together with a delay in water renewal times. The reverse effects should be expected if the peak flow decreases.

4.3 Effects of flow distributions on stratification

The evolution of stratification in time with flow changes depends a lot on bathymetry. In deep waters, it follows the hydrographs shape consistent with what is reported in many estuarine studies (Monismith et al., 2002; MacCready, 2004, 2007; Ralston et al.2008; Lerczak et al.2009; Wei et al. 2016). The level of stratification increases with the flow increase so that the leptokurtic hydrograph exhibits the maximum and the leptokurtic the minimum top to bottom salinity differences. In shallow waters, the link between the stratification and the hydrograph shape breaks when the river discharge is sufficient to mix completely the water column. This is expected to happen in areas closer to the river mouth where the depth is shallower and the river discharge's influence stronger. This difference of stratification between deep and shallow areas is not surprising and has been reported earlier. For example, Sridevi et al. (2015) observed something similar in the Godavari estuary where the top to bottom salinity differences varied along the estuary due to bathymetric differences. Stratification was higher in deeper stations and lower in the shallow ones. Several conclusions can be drawn considering this result.

If the interest regarding stratification is focused inside the delta and in areas closer to the river mouth, a flow distribution that follows the leptokurtic hydrograph shows several advantages. It presents longer periods with either mixed waters or very low vertical salinity differences compared to the other hydrographs. It should be noted though that during low flow periods, the salinity can be high despite low vertical differences Special consideration should be taken then concerning the salinity thresholds of different activities taking place in the delta. The two skewed and the mesokurtic hydrographs demonstrate a very similar stratification range in accordance with their flow range. This is an indication that the level of stratification is more sensitive to the peak flow magnitude than its position in the hydrograph.

The range of stratification is much higher in the deeper areas (Figure 4c and d) and that can be explained by the weakening of the bottom friction that leads to stronger stratification (Monismith et al., 1996; Shaha et al., 2012). This can have several environmental consequences even though deeper areas are located downstream and closer to the sea where the activities taking place in the delta may not be so much affected. Stratification may cause anoxic conditions at the bottom layers and low oxygen can have environmental consequences to the aquatic life (Chant, 2012). For example, riverine waters are responsible for recurrent summertime hypoxia at the bottom waters of the river dominated Mississippi Delta (Schiller et al., 2011).

4.4 Hydrograph shape effects on water renewal and freshwater residence times

The results of sections 3.5 and 3.6 indicate that each hydrograph type has certain advantages and disadvantages. Therefore, the decision on the selection of an optimum hydrograph in regard to water quality should be per case and according to water management demands. The peak flow magnitude and the tails of each hydrograph are important parameters affecting freshwater RT and water renewal time. An incremental increase of the peak flow results in a seaward salt intrusion limit displacement due to the negative correlation between river discharge and salinity (Garvine et al. 1992; Wong, 1995; Liu et al., 2001, 2007; Monismith et al., 2002; Becker et al. 2010). This is reflected in the panels of Figure 6 as an increase of the freshwater area with the peak flow increase. The freshwater area and RT follow an opposite trend. A peak flow increase results in a freshwater area increase but RT decrease. This is a consequence of the heavier tails that the higher peak flows hydrographs exhibit. For example, the leptokurtic hydrograph shows the lowest RT because of its sharp peak and the uneven flow distribution throughout the year. For the same reason, the leptokurtic dry season FT is also the maximum one since the freshwater cannot be fast enough replenished in such low flow conditions. The effect of heavy tails causes also the leptokurtic hydrograph to present the maximum annual and space averaged salinity while the platykurtic shows the minimum.

Hydrographs of similar flow range and peak flows (e.g. skewed and mesokurtic) make fresh almost equal areas (Figure 6). However, the RT may vary between them because of bathymetry or the time of the peak flow in the hydrograph. For example, the positive skewed hydrograph shows higher RT which indicates positive effect of an early peak river discharge. In contrast, when the peak flow is positioned at the end of the year (negative skewed) the RT decreases significantly. In the last case, bathymetric effects are more pronounced because the difference in the RT between shallow and deeper areas is much higher than the two other cases.

FT is known to vary a lot with seasonality (Ensign et al. 2004) and this results in different order of FTs between the five hydrographs during wet and dry season. FT gets shorter values during wet and higher during dry seasons. The critical parameters for the FT are the peak flow in the wet and the hydrographs tails in the dry season. However, the effect of the tails in the second case is much stronger than that of the peak discharges in the first case. The hydrographs shape does not influence significantly the FT during wet seasons. Although the FT decreases with the peak flow increase the difference is only within the range of hours. On the contrary, the FT increases by days as the tails become heavier. The selection of the statistical river discharge value to be introduced in the freshwater fraction method equation is very important in the case of heavy tails such as those of the leptokurtic and positively skewed hydrographs. The use of an average over a period of very low discharges such as those included in hydrographs with heavy tails can decrease the FT and provide an unrealistic estimation of the renewal time (Alber & Sheldon, 1999). The use of the median discharge is proposed instead.

5. Conclusions

This study investigated the influence of different shape but equal volume flow distributions on the salinity in deltaic systems. A 3D numerical model built in Delft3D for an idealized delta configuration was used. A series of five simulations was carried out with three hydrographs of symmetric distributions but of different peak flow magnitude and two skewed ones (positive and negative). The results showed a hysteresis between increasing and decreasing river discharge for every distribution. The salinity response is slower to river discharge decreases than increases similar to what is observed in estuaries. This asymmetry is mitigated in periods of very high or very low flows. In addition, an increase of the flow rate could result in a salinity standard in much shorter time.

Natural climate variability and anthropogenic climate change modify the hydrological regimes of many deltas causing changes to their annual hydrograph shapes. Modifications in the shape of the annual hydrographs can have positive or negative effects on the stratification, freshwater conditions, water renewal and residence times.

The relationship between stratification and hydrographs is much affected by bathymetry. There are two different responses of stratification to flow changes observed. The top to bottom salinity differences in deeper water areas follow exactly the hydrographs shape. This means that leptokurtic hydrographs cause higher stratification. This outcome is though reversed when the focus is in shallower areas. In this case, the river discharge manages to mix the vertical column with freshwater so that stratification decreases with the increase of the river discharge making the leptokurtic hydrograph the most efficient case for mixing. The stratification is more sensitive to peak flow magnitude than position in the hydrograph because flow distributions of similar flow range present a similar range of stratification levels.

Freshwater areas, renewal and residence times depend on a hydrograph's peak flow magnitude and tails. The time with freshwater in the delta increases when the hydrograph's tails are light and the maximum to minimum flow differences become smaller to allow a more even distribution of the water volume throughout the year. The bathymetry can affect the residence time because shallow areas remain fresh for longer time. Freshwater areas and residence times follow an opposite trend. The latter increases with the decrease of the peak and the former decreases.

The flushing time does not vary significantly during wet seasons between the different types of hydrographs. It does vary though in the range of days or months during dry season. In low flow periods, the flushing time increases as the hydrograph's tails become heavier. For the water renewal time calculation in heavy tails hydrographs (e.g. leptokurtic and positively skewed), the use of the median instead of the average discharge is suggested to avoid an underestimation of the flushing time by mitigating the effect of very low flows.

The work in this paper aspires to contribute in the efforts for a more sustainable water management in river deltas under the challenges of climate change and water demand increase. The results indicate that it is possible to mitigate salt intrusion issues by water supply regulations. Each type of the annual flow distribution investigated in the present work demonstrates its own advantages and disadvantages. The selection of the most appropriate one probably can depend on many parameters. For example, the choice might be different if the goal is just to reduce the salinity in the delta than cause further mixing or push fresh water further away from the river. Nevertheless, the present study focused on river flow forcing only and so further research might be needed to determine the influence of other parameters such as for example tide-induced mixing.

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