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River mouths along sandy coastlines are influenced by alongshore transport of littoral sands and the interaction of hydrodynamics processes at the river mouth. These interaction are responsible for opening/closure of river outlets and subsequent episodes of sand bypassing by spitbreaching. Here, we study these mechanisms of alongshore sediment bypassing at a river mouth along the French Mediterranean coast. Over the last 6 years, bypassing processes were found to be associated with spit elongation and spit breaching. Hydrodynamics measurements were implemented in order to assess the respective role of river jet and wave conditions on these opening/breaching episodes. Results tends to point on one major mechanism: spit overtoping that induces breaching. For the floods events analysed, the river jet has apparently only a very low contribution to this opening.

INTRODUCTION

Intermittently open/closed estuaries (IOCE, McSweeney *et al*., 2017) are dynamic coastal areas where morphology and by-passing mechanisms are driven mainly by waves and fluvial processes. As for tidal inlets, several bypassing processes can be observed (spit breaching, bar bypassing, channel rotation, Fitzgerald at al., 2001, Fitzgerald *et al*., 2002, Balouin and Howa, 2002, Nienhuis *et al*., 2015). In wave dominated river outlets, interaction between the river discharge and the coastal dynamics generates complex hydrodynamic processes interacting with morphological features. Spit growing can partialy or fully close the river mouth during the dry season but also generates abrupt opening during floods, storm surge or concimittance of these events. In these environments, such behaviours are key parameters in the definition of coastal hazards. Indeed, the spit disturbes the river jet inducing an increase of the water level on the river side, while limiting the impact of waves and marine surge in the river. When conditions are met to breach the spit, it allows river jet flushing and penetration of waves in the outlet. This breaching is also the main mechanism for sand bypassing the oulet. Here, we study the mechanisms by which the interaction between the flash flood and storm surge controls the openings of the river entrance and sediment bypassing at the Têt river mouth in SE France.

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Fieldsite

Têt river's mouth is located in the Roussillon coast, along the French Mediterranean coast. This is a small mountaineous river draining a catchment around 1400 km². Hydrological regime is typical of Mediterranean area. The rainfall pattern is characterized by long dry periods interrupted by short mediterranean events leading to flash floods.

The mean water discharge at Perpignan station is around 11m^3/s but can reach 1800 m^3/s during major floods (Bourrin *et al*., 2008). The river mouth tend to a seasonal closure during the summer period and re-opening during the winter period.

The Roussillon coast is a microtidal, wave dominated sandy coast. The tidal range is very low (< 0.30 m at mean spring tides). Nevertheless, large variations in water level can occur in response to wind forcing and atmospheric pressure fluctuations. Maxium water level can exceed 1 to 1.5 m near the shore (Certain, 2002) under the combined action of storm surge and waves. These events are able to overtop sand spit that has an elevation ranging from 1.2 to 2 m above mean sea level.At the coast, significant wave heights (H_s) are generally low (H_s < 0.3 m for 75% of the time and H_s < 1.5 m for 94%) but can reach more 3 m during each winter storms. The residual longshore drift is northward and is estimated to be around 200 000 m3/y (Kulling, 2017).

Two wind orientations prevail in the study area: NW offshore winds (60% of the time with velocities pouvant atteindre 100 km/h) inducing short-period waves directed southwards and E to SE onshore winds (30% of the time) during marine storm event.

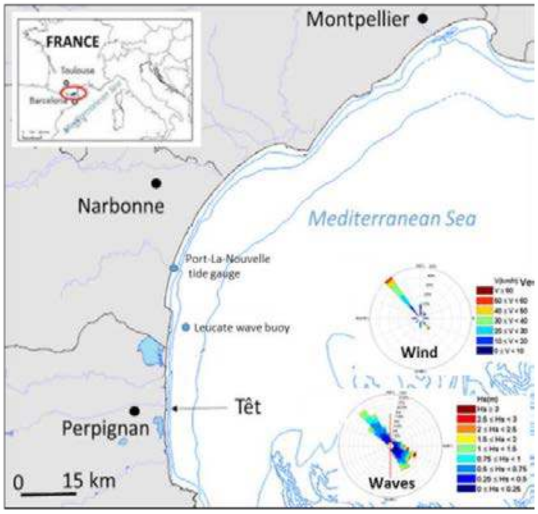

Figure 1. Localisation of the fieldsite along the French Mediterranean coast.

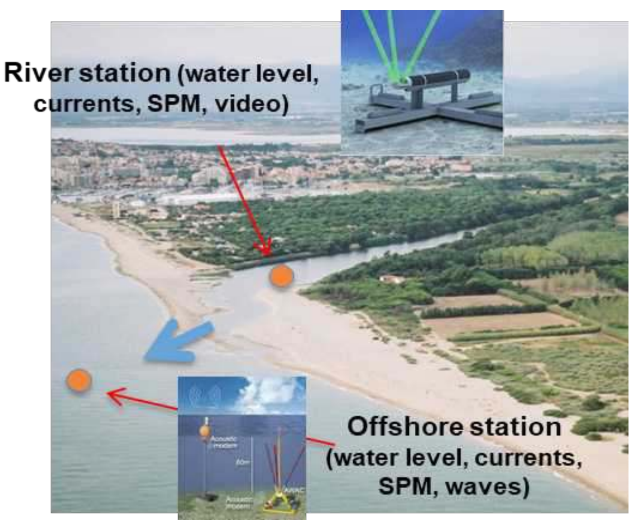

Figure 2. Measurement of hydrodynamics offshore and in the Têt river mouth.

METHODS

Morphology Monitoring

The Roussillon coast is monitored since summer 2013 within the Coastal Observatory of the sandy catalan coast (http://obscat.fr). A particular attention was paid to river mouths (Balouin *et al*., 2019) where topo-bathymetry, UAV photogrammetric surveys are done by ®Ecoceanodrone every 6 months before and after the most energetic winter period. Both Aerial and marine UAV permit to obtain an accurate topography survey (grid 2*2 cm, Dz~5 cm) of the river mouth.

Additional information is provided by Sentinel-2 satellite images obtained using the Coastsat algorithm (Vos *et al*., 2019, 2019b). After filtering images having a too large cloud cover, the spacing between 2 images varies between 5 and 15 days (235

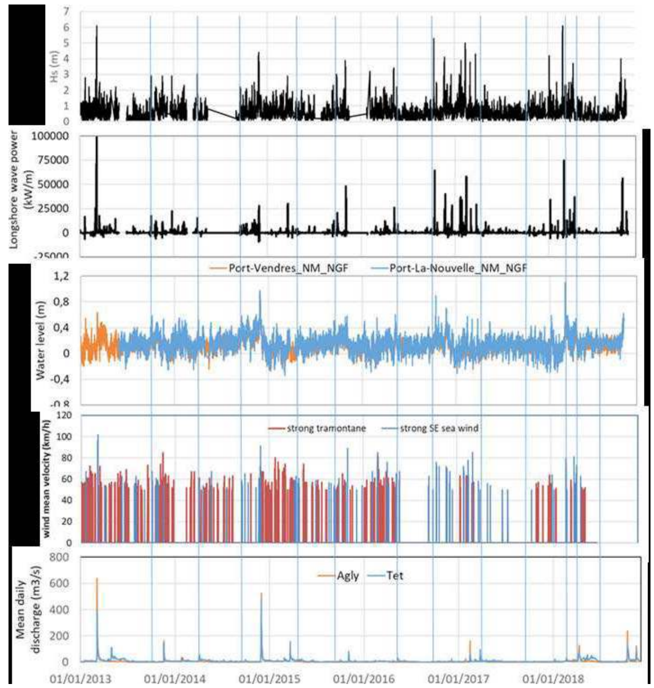

Figure 3. Hydrodynamic conditions during the monitoring period: from top to bottom: Hs (m), Longshore wave power (kW/m), water level (m); strong winds (km/h) and daily-averaged discharge (m3/s). Vertical blue lines indicate the field surveys.

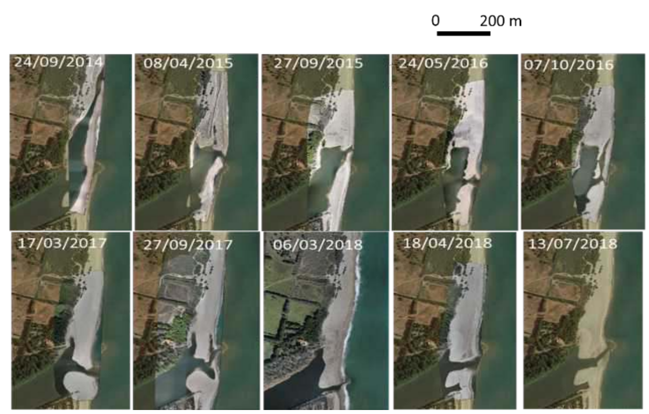

Figure 4. UAV aerial photos and DTM undertaken at the Tet river mouth between 2014 and 2018.

images from 2016 to 2019). These images were used to describe opening events of the river mouth, as well as spit morphology and outl*et al*ongshore migration.

Hydrodynamics

Offshore waves are recorded by the regional authority (DREAL Occitanie) at the Leucate wave buoy (around 10 km northward from the site), water levels at Port-La-Nouvelle (Refmar) and water discharge at Perpignan station (Banque Hydro) (Figure 1).

To better assess the interactions between river jet and waves, two stations (Figure 2) were implemented since June 2018 within the Dem'Eau project: one offshore of the site (10 m depth) with a ©Nortek AWAC current profiler coupled with an Optical backscatter sensor (OBS), the other one in the river mouth with a ©Nortek Aquadopp profiler and an OBS. Datasets used in this study include water level offshore and in the river mouth (every 10 min), current profiles (0.1 m cells in the river mouth and 1 m cells offshore) and wave measurement every 30 min (20 min bursts at 2 Hz).

RESULTS

Hydrodynamic and Wind Conditions

During the monitoring period (2013-2019), offshore wave climate (Figure 3) was typical from the area with at least two storm events per year over 4 m in Hs. Winter 2016-2017 was more energetic with 6 successive events. The most important storm waves were March 2013, Nov 2014, Oct 2016 and March 2018. These events were associated with high water levels due to an important storm surge. Half of the storm events are associated with flash floods. Main flash floods occurred during the winter periods and are always combined with SE storm waves (except 30/04/2013). The most important river discharges were recorded in March 2013 and Nov 2014, with daily-averaged discharges reaching more than 600 m^3/s. Important NW offshore winds were observed, particularly at the beginning of 2014 and 2015. They can play an important role on sediment transport inducing a reverse drift along the Roussillon coast.

Mid-term Morphological Evolution of the River Mouth

Figure 4 present the UAV aerial photos of the Têt river mouth between 2014 and 2018. Morphology evolution is characterized by a cycle involving spit elongation and spit breaching. At the beginning of the survey (2013-2014), the narrow spit was elongated northwards more than 500 m, inducing a strong meandering of the river mouth. The marine storm/flash flood event of Nov 2014 opened a new outlet to the south, that immediately began to migrate northwards. Successive marine storm/flash flood events of Nov 2015 and Feb 2017 opened a new river outlet, and the closure of the previous one. In March 2018, a major marine storm was observed, that almost closed the river mouth.. In such conditions, the marine storm/flash flood event of April 2018 induced the only northwards relocation observed during the survey of the outlet. Impact of strong NW offshore winds is observed (*e.g.*, April 2015, Oct 2016 or sept 2017) and induced a local reverse drift southwards, able to generate small southwards spits. Nevertheless this outlet behavior appears to be limited even if temporary favouring temporairement spit growth and its vertical accretion.

Morphological Response during Marine Storm/Flash Flood Events

The role of spit growing under the prevailing northwards longshore drift is evident, but the mechanisms involved in spit breaching and subsequent sand bypassing remain unclear. The available dataset indicates several key processes: regular breaching, dominant effect of concomitant marine storm/flash flood events, spit growth closing the entrance under prevailing SE waves or NW offshore winds. To document these mechanisms, 4 opening events (14-17/10/2018, 17-20/11/2018, 21-24/04/2019 and 22-24/10/2019) were analysed. As shown on Figure 5, all

Figure 5. Têt river discharge (m3/s) at Perpignan station.

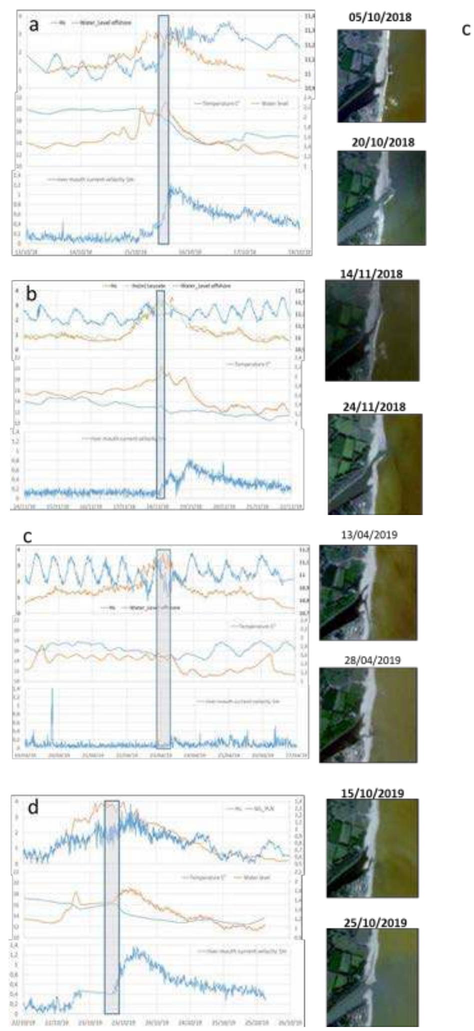

Figure 6. Hydrodynamics during the most important events: for each event: top: wave and sea water level (m), middle: river level and temperature; bottom current velocity at mean water column (m/s); right: sentinel-2 images before and after the event.Urban monitoring system. The shadow area represents the time of breaching estimated to be correlated with the sudden increase in flushing current velocity.

these events were characterized by an important river discharge, except for the one of april 2019.

During the first event (Oct 14-17th 2018, Figure 6a), storm waves and high river discharge were recorded. At the beginning of the event, the spit was elongated northward and the river outlet

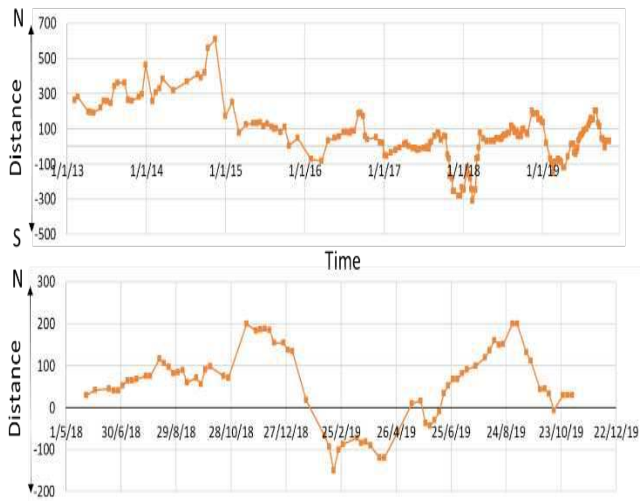

Figure 7. Migration of the river entrance: North-South distance of the entrance from the main river axis. Top: position of the river mouth since 2013; bottom: zoom on the position from mid 2018 to 2019.

mostly closed. An increase in wave high and river water level was firt observed until Oct 15th. Then, an important increase of the sea water level (storm surge) was observed. In the river mouth, current velocities were very low. When water level offshore reaches its maximum, spit breahing occurred, probably resulting from wave overtopping the narrow spit. A rapid decrease of river mouth water level and an increase of the river jet was measured, confirming the opening of the river mouth that allowed the river jet to flush seaward. Water temperature decrease also indicates the rapid mixing of river and sea water masses.

During the second event (Figure 6b), the same mechanisms was observed, but the river current velocities remained low and the opening was observed north from the main axis of the river. During this event, wave highs were mostly the same (around 4 m in Hs), but the storm surge was very low.

The fourth event presents the same characteristics than the first one, the opening, based on the sudden increase in flushing current velocity, being observed at the storm peak (in wave and surge elevation).

The third event is quite different. There was no flash flood during this event, and thus only marine conditions are supposed to be involved in the opening. The river mouth presented a large meander southward, but a very narrow sand spit. Before the storm peak, a narrow opening was artificially done in the northern part of the river entrance. At the pic of the storm, the opening in the southern extremity of the river mouth was observed, yielding a decrease in the river mouth water level. Given the very low discharge during this event, the river water leverl is supposed to be mostly due to wave beaking and wave setup at the river mouth. The artificial opening in the northern part does not seem to have had any effect as this narrow channel was closed during the event, and the main chanel opened more than 150 m southward.

Bypassing Mechanisms

The outer part of the Tet river mouth is not stabilized and the most important morphological evolution is the spit development during the summer period and spit breaching when concomittant marine storm/flash flood events exceeding 100 m3/s water discharge are observed. The outer river delta is very limited (only a few meters offshore) with low or inexistent bar by-pass on the small shoals. More offshore bar by-pass can be deduced from the bathymetry surveys, but data indicates that this sediment volume stays in the nearshore and does not reach the downdrift coast, at least not in the first hundred meters.

As shown on Figure 7, the position of the river mouth can be more than 200 m from the river axis in both northward and southward direction according to the wave climate (it can even exceed 700 m northwards during the longer monitoring period). This indicates that opening of the river outlet during storm not always indicate the prevailing northwards sand bypassing. After long northern conditions (dec 2018 as an example), a very long southward elongation can be observed and in this situation, opening will not induce any sand bypassing to the downdrift north coast.

DISCUSSION

Concomittance between marine storm and flash floods appears to be the main factor influencing the river entrance opening by spit breaching. These events can generate an important amount of sediment from the spit to the downdrift coast. As an example, more than 30 000 m^3 were transferred to the northern coast during the event of winter 2014-2015 when a new entrance was opened 400 m southward (Figure 7). The residual longshore drift is estimated to be around 200 000 m^3/y (Kulling, 2017), suggesting than most of the sediment transfer from the updrift to the downdrift coast is done while the river entrance is closed.

Despite a very dynamic evolution (development and closure during fair weather conditions, abrupt opening and relocation during more energetic conditions), the river entrance is quite stable at a pluri-annual timescale. This is obvisouly due to the fact that the internal river is stabilized, but also derives from the high frequency of opening/closure of the outlet that prevent spit growth and formation of dunes.

CONCLUSIONS

Sand bypassing at the Tet river mouth has been monitored since 2013. The main processes observed are associated with spit elongation under the prevailing northward longshore drift, and spit breaching during the most energetic events. To analyse these energetic events yielding to the opening of the river outlet, hydrodynamic measurements were performed on the nearshore and in the river mouth. Most of the time, flash floods are associated with storm waves, and the main mechanisms explaining the breaching remained unclear. Our results suggest that the river jet itself has a very low contribution to the opening of the river outlet and the subsequent sand bypassing. Four energetic events were analysed and each time, the breaching occurs when the significant wave high exceed 3 m in the nearshore, and when the water level offshore is increased by the storm surge and wave setup. Despite no visual observation are available during these events, it is evidenced that breaching is dur to wave overtopping the spit, putting in relation sea and river waters masses. The river jet is then fushed out of the outlet with a strong increase of current velocities observed.

Monitoring os going and further instrumentation (video monitoring) should be deployed in the next months to better document the timing and kinetics of these breaching episodes.

ACKNOWLEDGEMENTS

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