



It is well known that the coastal areas and urban areas located along the coastline, especially in the case of particularly low lying areas, are subjected to episodes which originate both from rainfall and from the sea.

5 The episodes of flooding from the sea are mainly due to storm surge (sea rise due to waves and wind). These flooding scenarios together with the high human pressure *through* of uses of the coastal areas, lead to coastal hazards in coastal areas *are* which may be particularly high *involve*

10 Wave transformations in the area close to the shoreline *are* are very complex processes, but of fundamental importance for the hydrodynamic and morphodynamic modelling of the land – sea interface. Levels reached by the sea on the shoreline during a storm are the sum of different contributions, basically summarized in: astronomical tide, storm surge, wave set-up. The first is *obviously* easily forecasted. The second is caused primarily by high winds pushing on the sea surface: the wind causes the water to pile up higher than the ordinary sea level. The third occurs in the area between the breaker zone and the shore and reaches values far from negligible. Various empirical *modelling* and numerical formulations are available in the scientific literature for the wave set-up *careful modelling of* modelling, which often rely on simplified assumptions regarding the shape and type of seabed.

20 Moreover, the presence of coastal defence structures changes the dynamics in the coastal zone, requiring *to carefully model* to carefully model the wave set-up, due to an accumulation of water during storms between the parallel structures and the beach (known as piling up, Cappiotti et al., 2007), which often leads to a wave reduction, but an increase in local sea water levels. *can lead*

25 Combined waves and storm surge is the cause of wave overtopping which leads to flooding, of which the disastrous consequences are well known, but extreme overtopping events throw water over the crest with considerable velocities imposing serious hazards to both people and infrastructure. *close to the coast*

Difficult decisions are therefore required to those who have responsibility for managing coastal areas and to choose the types of intervention for their protection. Coastal *of*

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3 flood defences *work* can mitigate inundation risk, by reducing sea and storm surge energy by enlarging the beaches (nourishments) or dissipating energy by hard structures *groynes* (groin, detached breakwaters, barriers), or the combination of the two (Archetti, 2009; Kroon et al., 2007). Moreover, even if the flooding risk from *the* sea can be controlled or reduced, when the sea is the receiving water body of an urban drainage system or, in general, when its level acts as the downstream boundary condition, the drainage system's hydraulics may be significantly affected, leading to critical states even under apparently not exceptional conditions (if considered individually).

10 Recent developments in computational technology allowed for deepening the aspects of flooding in the traditional codes for the simulation of urban drainage networks. They can be used in order to predict the most critical points of the network, either in terms of flooding event magnitude, or accounting for the importance and vulnerability of a certain specific point.

15 Some of the widely adopted numerical simulation tools for urban drainage networks, like MOUSE (Danish Hydraulic Institute), InfoWorks CS (Wallingford Software Ltd.) and SWMM (Huber and Dickinson, 1988), directly or indirectly allow for establishing a relationship between rainfall and flooding.

20 Urban flooding in coastal urban areas may be caused by more than one single climatic source. We can highlight "sea sources" (sea levels and storm surges), "inland sources" (rainfall and rainfall-runoff processes) and in case the urban site lies close to a river (river mouth) there could be also "river sources" (river level). All these sources and their effects are often treated separately, so coastal protection experts and maritime hydraulics focus on the probability that the sea will reach certain levels (jointly considering the two variables sea level and storm surge), while those dealing with urban drainage networks, in order to define an outfall boundary condition *will* will probably consider a certain representative sea level, so to cautiously analyze possible backwater effects and relative flooding problems.

25 Since each of the previously mentioned sources exhibits its own significant variability, it appears essential to tackle the problem by carrying out an integrated analysis of the

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contemporary phenomena that may cause flooding in urban coastal areas. This is ~~related~~ related to the joint probability of the two phenomena, i.e. the probability that two or more conditions occur at the same time (Tawn and Vass, 1990; Hawkes et al., 2002, 2008; Hawkes, 2008). *Lie*

The purpose of this paper is to show an approach that can be followed in the joint study of rainfall and sea conditions. Basing on a real case study, the way the combination of variables "rain-sea level" lead to flooding effects in a coastal urban area, is hereinafter presented by defining charts representing the combined degree of risk sea-rainfall.

## 2 The case study

The site chosen as the case study is a portion of the drainage network serving the northern area of the Municipality of Rimini (Italy), along the Adriatic coast (Fig. 1). The drained catchment has a total area of approximately 540 ha and consists of two distinct parts: a band close to the urbanized coast, where the drained area is approximately 60 ha and a remaining part, considerably less urbanized, which ~~goes for~~ *extends* about 6 km inland.

The urban part could be further divided into two different zones: a densely urbanized area, about 250 m wide, lying between the railway line Rimini-Ravenna and the coastline and some lower-density housing immediately upstream of the railway (Fig. 2). Both of these urban areas are almost completely flat (negligible slope) and their ground elevation ~~never higher than~~ *is* 3 m a.s.l. The upstream portion of the basin is instead almost entirely made up of natural terrain, with average slopes close to 0.5% (Fig. 3). *What is "a.s.l."*

The drainage network in the upstream part consists mostly of a network of natural ditches and drains, including short stretches of closed conduits. The main drain (called Sortie), once ~~enters~~ *it enters* the urbanized area (about 300 m upstream of the railway) flows in a closed rectangular box conduit, whose dimensions are 355 × 150 cm, with an almost zero slope (Fig. 4). Due to some sparse household connections in the upstream part,

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Sortie acts as a combined sewer, while the urbanized area is served by a separate sewer network, where Sortie is the trunk main for the storm separate network. Close to the outfall, Sortie exhibits invert levels slightly lower (-0.19 m) than mean sea level, and since (for the small amount of wastewater coming from upstream) it is a combined sewer conduit, ~~the presence of~~ *maybe explain, e.g. "(rainfall and sewage)"* a sluice gate avoiding sewage spill into the sea and a pumping station (flow approx. equal to 50 l s<sup>-1</sup>) are required.

The gate is operated remotely via remote control system and its opening is regulated by an automatic control based on water level on the upstream side. When this level exceeds a preset threshold, the gate is open (duration of operation: approximately 2–3 min) ~~actually~~ *a* putting the drainage system in communication with the sea. *Assessment* The assess of the influence that the sea level has on the operation of the network during rainfall is of fundamental interest.

### 2.1 General characteristics of the climate nearby the case study site

*For* The descriptions of sea state and wave climate here reported, refer to the measures recorded by the wavegauges at the AGIP (Petrol and Gas company) offshore platform, by the wavebuoy RON (Rete Ondametrica Nazionale, Italian Wavegauge network, [www.telemisura.it](http://www.telemisura.it)) located offshore the city of Ancona and to recent wave data recorded by the wavebuoy placed offshore the town of Cesenatico (ARPA ISCM – Regional Agency for the Environmental Protection, <http://www.arpa.emr.it/sim/?mare/boa>). The latter, as a result of a spectral analysis performed on the sea level variable of signal level, returns the significant wave height value, the average period, the peak period and the wave direction with an hourly frequency from 1 July 2007. *(wave gauge) (wave buoy)*

The wave climate off the coast of Rimini is mainly characterized by events from the NE (Bora) and SE (Scirocco). While the ~~first~~ *former* are more intense (Cesini et al., 2004; Martucci et al., 2010), critical conditions often leading to high sea levels on the coast are caused by ~~second~~ *the latter*. During the events of Bora, average peak periods are normally in the range of 6 s, while during the storms of Scirocco, the wave peak periods ~~is~~ *are* on average higher. This is due to the longer fetch length in the Northern Adriatic for winds

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rainfall intensity has been separately classified according to the two different critical durations, previously identified.

This procedure has led to the definition of Fig. 10, where each rainfall event occurred in the year 2009 is represented by a point, whose different marker highlights whether the numerical model detects flooding or not. For the four events where flooding occurred the percentages of flooded nodes is indicated in brackets.

The results therefore show that the lines generated by interpolating the simulations results based on fixed rainfall and sea conditions (Figs. 7 and 8), can satisfactorily predict the effects produced by a long time real data series.

Just a slight underestimation case appears for one of the real events that resulted in 5% of nodes flooded, when classified according to the two-hour duration.

## 5 Conclusions

The work has analyzed the behaviour of a portion of the drainage network of a city located on the sea, Rimini, considering not just the effects due to rainfall events, but also to the different conditions of sea water level at network outfall.

The analysis has been carried out by means of numerical hydraulic simulations of the drainage system, which allowed to identify the percentage of network nodes that may experience flooding as a function of given rainfall and sea conditions. Isolines representing equal severity in terms of urban flooding have been created from the interpolation of the simulations results, showing a combined (rainfall-sea) risk for the sewer system under consideration. The presented approach is therefore an attempt to identify the critical hydraulic states of a sewer system, not only in terms of possible rainfall events, but also jointly considering the conditions of the receiving water body.

This simplified methodology appears both effective and interesting, especially in urban areas, where the deterministic analysis of flood events should rely on a 2-D surface model, whose applicability requires a highly detailed ground model. The method can

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be extended and applied to similar drainage systems in coastal areas, and may turn useful during both the design and the operation and management phases.

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