STREAM Guidelines for modelling for pilot sites in order to create a flood forecasting system

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1 INTRODUCTION

The STREAM project deals with territorial challenges connected to flooding in the Adriatic region. In this context, numerical modelling has become a fundamental tool for describing the dynamics of terrestrial and marine environments, investigating the impact of severe weather events and promoting flood forecasting services and early warning systems (EWS). Early warning is a major element of flood risk management and disaster risk reduction. It can prevent loss of life and reduce the economic and material impacts of hazardous events including disasters. To be effective, early warning systems need to actively involve the people and communities at risk from a range of hazards, facilitate public education and awareness of risks, disseminate messages and warnings efficiently and ensure that there is a constant state of preparedness and that early action is enabled (Valentini et al., 2019).

Areas of the potentially significant risk of flooding can have very different characteristics, therefore requiring different modelling systems. The STREAM pilot sites involved in the modelling and forecasting activities greatly differ for morphological characteristics, potential flood hazards and vulnerabilities. They have been grouped according to the following flood types:

- coastal flood: Emilia-Romagna coast (Italy), Lagoon of Venice and its city (Italy), Peschici and Manfredonia towns (Apulia Region, Italy), Lecce and Torchiarolo wetlands (Apulia Region, Italy);
- fluvial flood: Chienti and Foglia watersheds (Marche Region, Italy);
- urban pluvial flood: City of Zadar (Croatia);
- compound flood site: Po Delta (Italy) and Ofanto river-sea system (Apulia Region, Italy).

The location of the considered pilot sites is presented in Fig. 1, with the colours representing the different flood types.

This document presents the guidelines for modelling floods in the different pilot areas of the STREAM project, in order to facilitate the creation of site-specific flood forecasting systems. In section 2, we provide an overview of the general prerequisites for flood modelling and forecasting, mostly related to meteorological modelling on which all ocean, fluvial and urban models rely. The document is organized distinguishing coastal (Section 3), fluvial (Section 4) and urban pluvial (Section 5) flood modelling. Section 6 provides a brief description of the modelling guidelines in case of compound flooding events. Conclusions and general recommendations are presented in section 7.

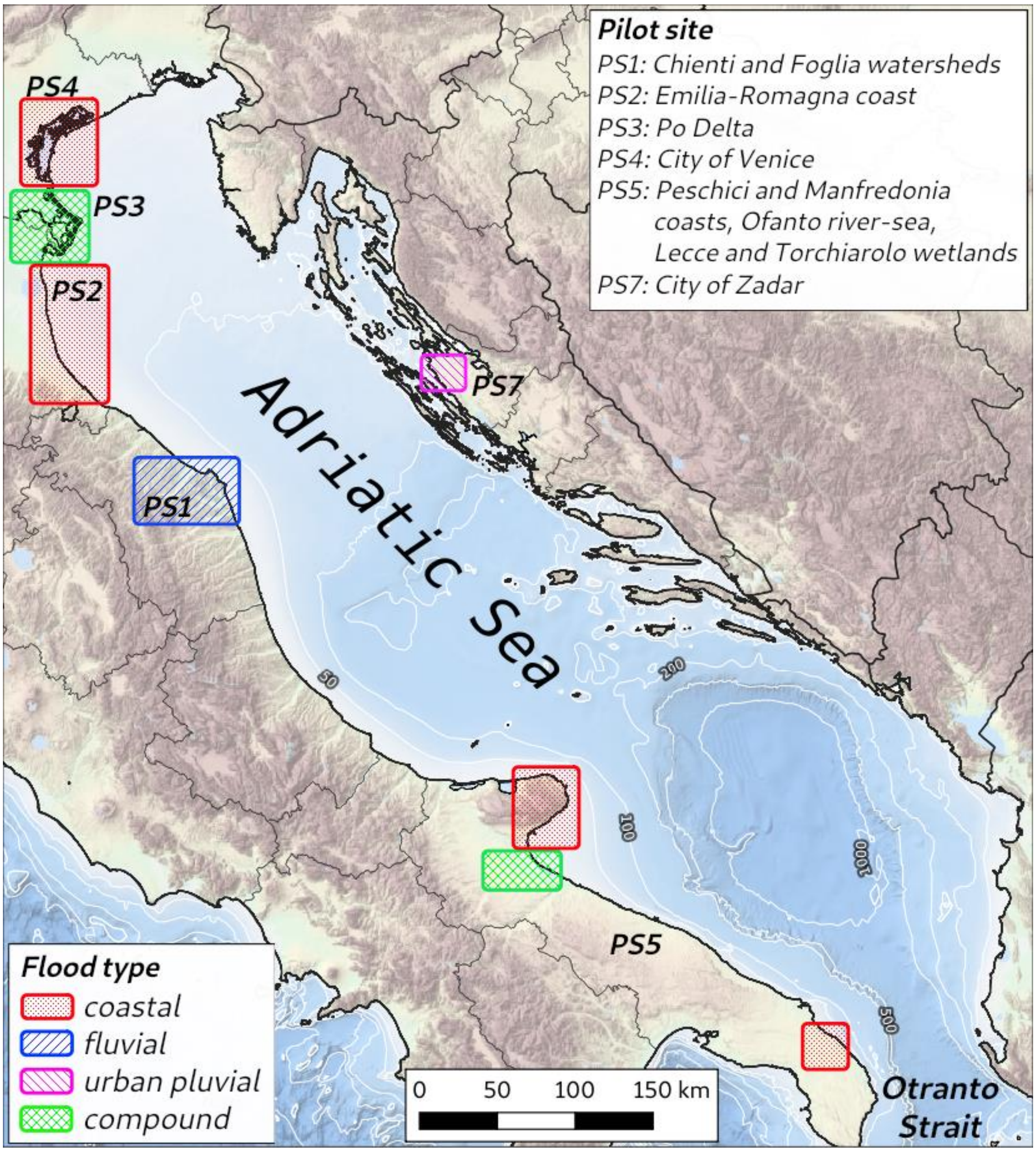

Figure 1: Location of the STREAM pilot sites involved in the forecasting activities.

2 GENERAL FLOOD MODELLING REQUIREMENTS

Although flood risks cannot be completely eliminated, flood modelling, as an important and integral part of an early warning service, is crucial for the improvement and efficiency of interventions in the case of flood risk. Reliability of forecasts has increased in the recent years due to the integration of meteorological, hydrodynamic and hydrological modelling capabilities, improvements in data collection through satellite observations, and advancements in knowledge and algorithms for analysis and communication of uncertainties. Successful flood warning systems must predict flood hazard (e.g. rainfall, high river flows, sea storms) accurately and with enough lead time to take action. It is worth mentioning that all ocean, fluvial and urban models are just an approximation of reality, despite their continuous development and improvements.

Simulation of flooding events and of the principal physical processes affecting the pilot areas requires the use of numerical models at high spatial resolution capable of representing complex natural morphological features as well as several anthropogenic constructions (dikes, riverbanks, buildings, piers, harbours, breakwaters, jetties, etc.) present at the coast, along a river and within an urban area. This goal can be achieved through the implementation of numerical models based on a unique unstructured grid able to describe processes at different spatial scales, or through the nesting of models (structured and unstructured) at different resolutions.

Generally, most of the uncertainty associated with the reproduction of a flooding event resides in the atmospheric components, mostly wind and mean sea level pressure for sea storms and rain for fluvial and urban floods. The interactions between the atmosphere and both the terrestrial and ocean environments are not fully understood, resulting in larger uncertainties in the predictions of flooding (Zou et al., 2013). This is mainly due to the chaotic nature of the atmosphere and the complexity of the air-sea and air-land interactions across scales over several orders of magnitude (Schevenhoven and Selten, 2017).

Therefore, a certain degree of uncertainty in the forecasts is unavoidable. It can be reduced using high-resolution meteorological models able to capture the temporal and spatial inhomogeneity of the atmospheric conditions, in particular under extreme conditions. The capability of reproducing the development of small scale meteorological features, like the one observed in the northern Adriatic Sea during the November 12th 2019 coastal flood event (Cavaleri et al., 2020), therefore requires model resolution of the order of one km, to correctly describe the convective activity and local processes such as air-sea exchanges and interaction with the local orography, which play a key role. In the case of pluvial events, finely-gridded precipitation data are required. It is, therefore, necessary to apply convection-permitting models, possibly nested into mesoscale models. In this context, data assimilation and ensemble forecasting techniques should be considered, even if they are still at their beginnings for high-resolution convection-permitting modelling systems (Finn et al., 2020).

In any case, however, dealing with small-scale non-linear phenomena implies a faster error amplification deriving from the growth of uncertainties of the initial state and the boundary conditions (Lorenz, 1963). The error then propagates in the modelling chain affecting also the prediction of flood extent and duration. The awareness of the prediction uncertainties and errors has led many operational and research flood forecasting systems around the world to move toward numerical forecasts based on a probabilistic concept: the ensemble technique (Cloke and Pappenberger, 2009). This usually involves using an ensemble of meteorological prediction systems (EPS) as input to an ocean, hydrological or hydraulic model to produce coastal, fluvial or urban predictions. EPS is based on the perturbation of initial conditions, forcing and parameters of a single model. An alternative is constituted by a multi-model ensemble system which combines different forecasting models that are used as members of the ensemble (Ferrarin et al., 2020).

Probability forecasts are generally provided in terms of the ensemble mean and standard deviation. The spread (i.e. standard deviation) among the operational simulations is expected to represent a measure of the uncertainty of prediction and should be linked to the forecast error so that cases with the largest spread are those with the highest uncertainty and where a large error of the ensemble mean (and also of the deterministic forecast) is more likely (Flowerdew et al., 2010).

3 MODELLING COASTAL FLOODS

Coastal flood modelling requires the correct reproduction of the sea conditions (in terms of wave characteristics and sea level) during severe meteo-marine events as well as the detailed description of the morphological characteristics and swash processes at the specific coastal site.

3.1 Modelling sea conditions

Within the framework of the Interreg I-STORMS project, a sea conditions probabilistic forecasting system was developed to combine the outcomes of the existing ocean and wave modelling systems for providing flooding alerts over the entire Adriatic-Ionian macro-region (Ferrarin et al., 2019). According to Di Liberto et al. (2011), operational forecast benefits from the combination of different ocean models by considering different physical parameterization, numerical schemes, model resolution and forcing. Several operational ocean forecasting models are currently available for the Adriatic Sea. We mapped 17 forecasting systems, with 10 predicting sea level height (either storm surge or total water level) and 9 predicting wave characteristics. The general characteristics of the forecasting systems are summarised in Tables 1 and 2 of Ferrarin et al. (2020) for sea level and wave, respectively.

The different operational models are forced at the surface boundary by several meteorological models (ECMWF, BOLAM, MOLOCH, COSMO, WFR and ALADIN) with horizontal resolution ranging from 16 to 1.4 km. The length of the ocean forecast is mostly related to the length of the meteorological forecast and varies from 1.5 to 10 days. There is a large variability in the model's set-up in terms of spatial resolution, temporal frequency, spatial domain (Mediterranean Sea, Adriatic Sea, northern Adriatic Sea), grid arrangement (e.g. structured or unstructured) and data format (NetCDF, GRIB). Only two of the considered systems (Kassandra and Adriac) account for the current-wave coupling and two forecasting systems perform data assimilation of tide gauge observations in the operational chain (SIMMb and SIMMe).

An example of the multi-model ensemble system (MMES) in the Adriatic Sea is provided in Ferrarin et al. (2020) for the sea storm event of October 29th, 2018. Here we report in Fig. 2 the sea storm ensemble modelling results in terms of the ensemble mean and standard deviation for both the sea level height (panels a and b) and the significant wave height (panels c and d). Storm surge during the 29 October event affected mostly the northern Adriatic Sea, while severe sea conditions occurred over most of the Adriatic Sea with the higher waves impacting the Croatian coast.

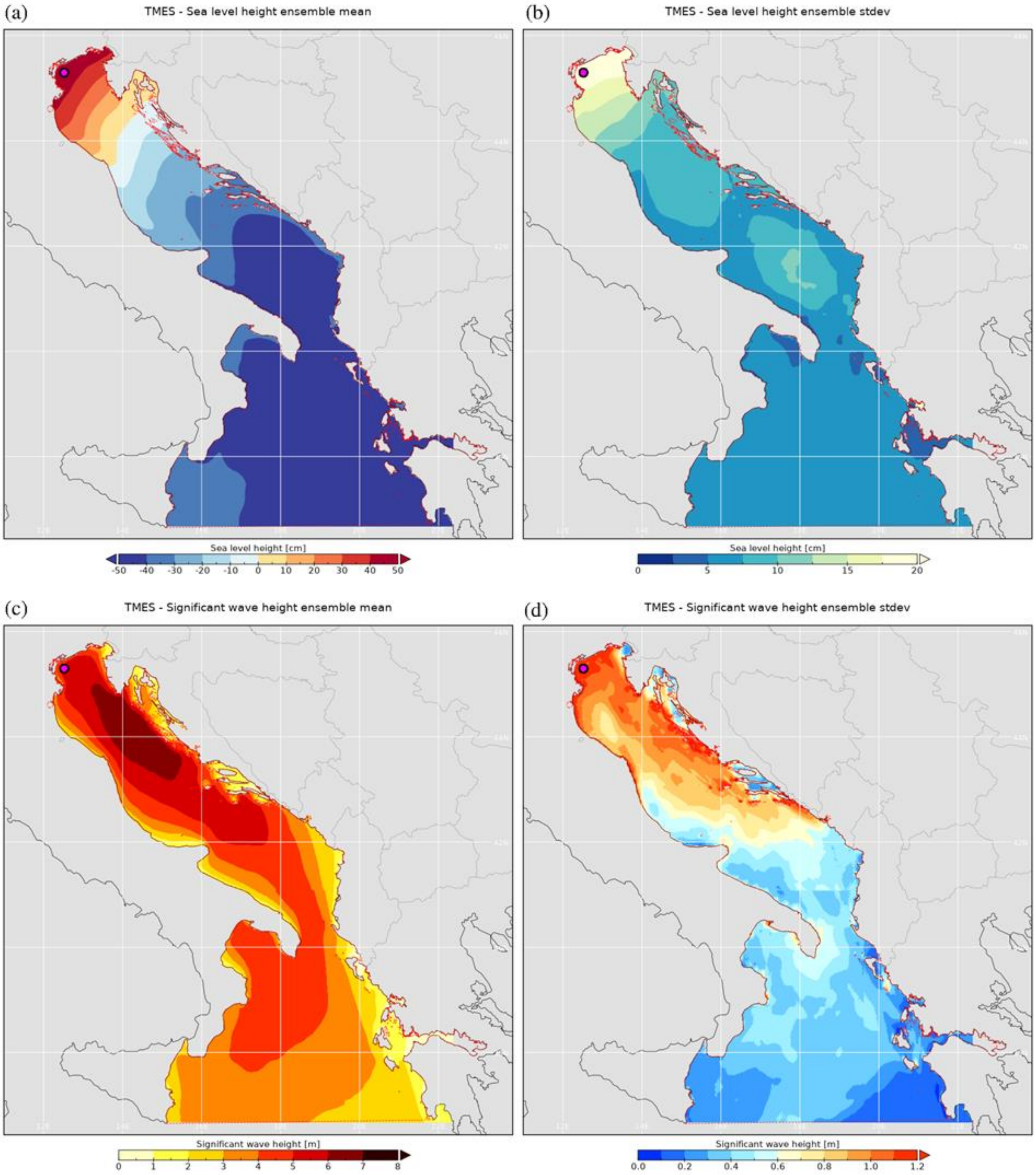

Figure 2: October 29th 2018 results of the multi-model ensemble in terms of the ensemble mean (a, c) and ensemble standard deviation (b, d) for sea level height at 13 UTC (a, b) and significant wave height at 19 UTC (c, d), respectively.

The multi-model ensemble is implemented as an internal processing engine which interacts directly with the resources to access the datasets and to produce the processing results (ensemble mean and standard deviation). Forecast results are collected by the system every day in the morning: the program contacts each provider of the list, checks if an updated model exists, downloads it and stores it on a local filesystem using one folder for each node with current and historical data. If the updated forecast is not present in the node, the system will pass to the next node and retry later.

Once all forecasts available are downloaded, the multi-model builder prepares the data harmonizing all different forecasts. All numerical model results are interpolated, through a distance-weighted average remapping of the nearest neighbours, on a common regular lat-lon grid covering the Adriatic Sea with a resolution of 0.02 deg. For coastal flooding hazard purposes, the total sea level height must be forecasted. Therefore, the astronomical tidal level values obtained by a specific SHYFEM application over the Mediterranean Sea (Ferrarin et al., 2018) are added to the residual sea level simulated by the operational systems not accounting for the tide (SHYMED, ISSOS, SIMMb, SIMMe and MFS). The obtained sea level height simulated by the different models are all referred to the geoid. Sea conditions obtained by the multi-model ensemble are used as boundary conditions for modelling and forecasting coastal flooding in the different pilot areas.

Actually, only a few forecasting systems are operationally used in the existing version of the multi-model ensemble system. In the framework of the STREAM project, we will continue developing the multi-model ensemble by integrating more forecasting models into the operational chain.

One of these will be the upgraded SANIFS operational forecasting system, developed at CMCC for providing short term forecasts of sea level, currents and active tracers (Federico et al., 2017). The operational system is based on the SHYFEM model which consists of a 3-D finite element fully-baroclinic hydrodynamic model, solving the Navier–Stokes equations by applying hydrostatic and Boussinesq approximations. Actually, the SANIFS configuration (Fig. 3) covers the entire Southern Adriatic and Northern Ionian Sea, with a resolution ranging from 3 km in open-sea to 100 m in the Italian coastal waters to 20 m in some hotspot (e.g. the coastal-harbour areas of Taranto, Brindisi and Bari). The forecasting system provides 3 days of hourly forecasts on daily bases (http://sanifs.cmcc.it/).

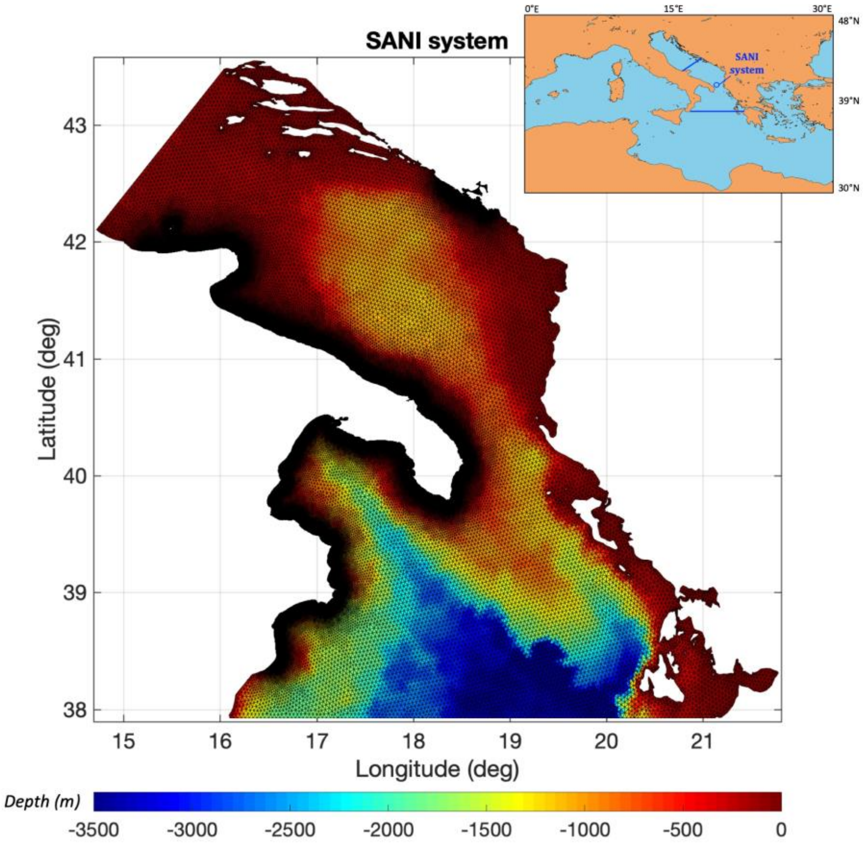

Figure 3: Horizontal grid with bathymetry overlapped of the SANIFS forecasting system.

Starting from the experience of the SANIFS system CMCC will apply the similar methodology to extend the modelling capabilities of SANIFS enlarging the geographical coverage of the domain and including other physical processes necessary for storm surge (e.g. waves). Two new implementations based respectively on SHYFEM and WW3 will be developed on the same spatial grid for the entire Adriatic Sea and Northern Ionian Sea. A single open boundary will be imposed in the southern part of the domain at the same position of LOBC of SANIFS. The grid will be refined overall on the coast, both eastern and western side. The horizontal resolution at the coast will be approximately 300 m. The hydrodynamic modelling set-up will be enhanced including all the rivers discharge values for the area by climatology or fluvial models or near-real time, where possible. The downscaling will be performed from hydrodynamic and wave regional models of Copernicus Marine Service - CMEMS (http://marine.copernicus.eu/).

3.2 Coastal modelling

Downscaling techniques are needed in order to transfer the sea conditions of the multi-model ensemble system to the coast and to adequately reproduce the mass exchange between the open sea and the coastal area. It is important to simulate the storm propagation towards the coast (from offshore to the shore) with an appropriate spatial and temporal resolution. The use of an unstructured grid gives the advantage of using higher resolution at the coast while applying more modest resolution towards the open sea, an approach that has proved to be accurate for many coastal systems in the Adriatic Sea.

Coastal flooding is induced by extreme sea levels, determined by the increase in sea level caused by strong winds and low atmospheric pressure (storm surge), often in combination with high tides. Under such extreme meteorological conditions, the coast could be also vulnerable to stormy waves with potential damage to infrastructure and erosion. Moreover, when waves reach the coast they interact with the bathymetry and drive an additional increase in water levels through wave set-up (Longuet-Higgins and Steward, 1963), and they travel up and down the beach before being reflected seaward (swash processes). The maximum vertical excursion of wave uprush on a beach or structure above the still water level is called the wave run-up. The total water level (TWL) used for estimating the flood area is computed by combining the sea level height, wave set-up and wave run-up.

The vulnerability to sea storms of a particular coastal area depends on a wide number of variables not only related to the magnitude of the storm but also including the land characteristics and the social and economic activities that distinguish that area. Therefore, generally, the coast is subdivided into segments of variable length as a function of morphology (vertical land movement, coastal slope, coastal material), human settlements and administrative boundaries. Several methodologies have been developed and applied at the basin and local scales for estimating hazard maps for coastal flooding (Wolff et al., 2016; Ferreira et al., 2017; Armaroli and Duo, 2018; Postacchini et al. 2019). One of the most diffuse approaches for coastal segments characterised by sandy beaches is to compute the TWL combining the sea level height and wave characteristics with the coastal characteristics (coast material and slope) according to the parametric Stockdon's formula (R2, the 2% exceedance level of runup maxima; Stockdon et al., 2006). In the case of steep coasts (reflective conditions), the use of an alongshore-averaged beach slope in practical applications of the run-up parametrization may result in large run-up error (Stockdon et al., 2006). For gravel beaches and rocky cliffs, other parametric methodologies should be used for estimating wave run-up (Poate et al., 2016; Dodet et al., 2018). The inundation intensity and extent along the coast can be estimated combining the obtained TWL with a digital elevation model (DEM).

Alternatively, the estimation of the total water level and of the maximum beach inundation can be determined by applying more complex model chain methodologies. Numerical models, based on physical conservation laws, are also used to simulate the propagation of the waves towards the coast and the runup on the emerged beach. Postacchini et al. (2019) estimate the maximum beach inundation through a model chain methodology where the final part, i.e. the beach-inundation prediction, is undertaken through a model based on Non-linear Shallow Water Equations, obtained from depth integration of the Reynolds equations, hence properly describing the main shallow-water processes, like the wave runup.

In the following subsections, we briefly present the state of the art of the modelling and forecasting activities existing in the STREAM coastal pilot sites, as well as the expected future developments within the framework of the project.

Emilia-Romagna coast (Italy)

One of the most advanced coastal flood forecasting systems in the Adriatic Sea is implemented by Arpae for the Emilia-Romagna coast (northern Italy). The Emilia-Romagna coastline is particularly vulnerable to sea storms due to its low-lying nature and high coastal urbanization (Armaroli and Duo, 2018) with the water levels often exceeding those of the dune crest and building foundations during major storm events (Harley et al., 2016).

The existing Coastal Early Warning System (Harley et al., 2016) is based on the 1D cross-shore implementation of the XBeach morphodynamic model (Roelvink et al., 2009), a 2DH (depth-averaged) process-based model that solves intra-wave flow and surface elevation variations for waves in intermediate and shallow waters. XBeach is used to forecast wave run-up and total water levels during storm events. For the Emilia-Romagna region, the coastal hazard is estimated by this approach in terms of two storm impact indicators (SIIs, Fig. 4):

- Safe Corridor Width (SCW), a measure of the amount of dry beach available between the dune foot and waterline for safe passage by beach users,
- Building Waterline Distance (BWD), a measure of the amount of dry beach available between the seaward edge of a building and the model-derived waterline.

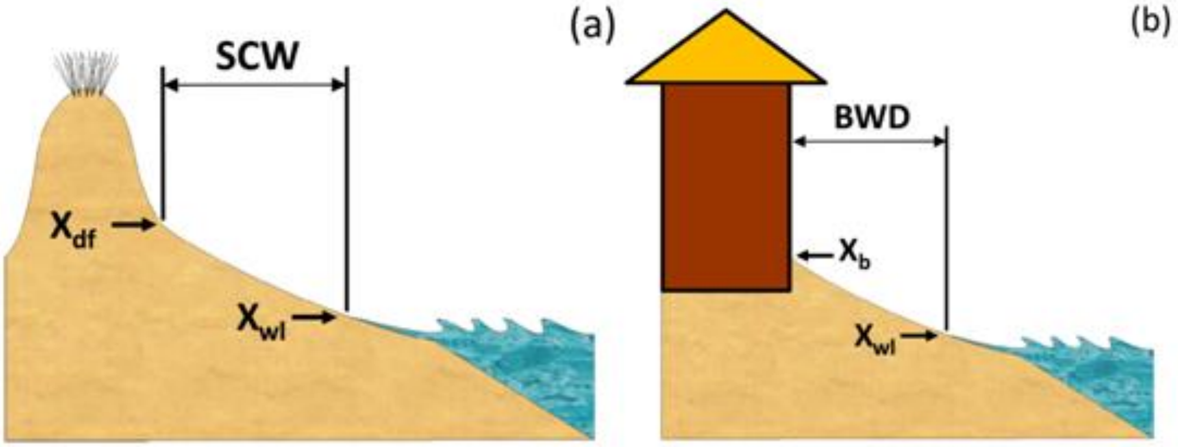

Figure 4: Schematic representation of the SCW (a) and the BWD (b). Xdf stands for the dune-foot position, while Xwl and Xb represent the model derived water line and the reference building positions, respectively. Modified from Harley et al. (2016).

Currently, the implemented deterministic coastal EWS uses SWAN- (Valentini et al., 2007) and ROMS-based (Chiggiato and Oddo, 2008) wave and sea-level forecasts, respectively, as boundary conditions to XBeach covering 12 sites (16 cross-shore profiles) along the region's coast. Summarized resolution and implementation methodology details for both sea state and hydrodynamic models can be found in Russo et al. (2013).

In the context of the STREAM project, the development and operational implementation of a probabilistic XBeach-based coastal EWS involves the recent developments provided by the aforementioned multi-model ensemble system (MMES). Currently, MMES provides daily 48h forecasts in terms of mean and standard deviation values calculated combining five wave and six sea level forecasting systems for the Adriatic Sea. Initially, the probabilistic approach will combine the MMES outputs and use them as forcing to XBeach instead of SWAN and AdriaROMS outputs. This approach intends to cover a higher number of scenarios as means to assess initial condition uncertainties and to provide additional information to the forecasters/modellers and the decision makers.

City of Venice (Italy)

The City of Venice pilot site focuses on the urban floods affecting the historical centre and the littoral area. The elevation of these islands is extremely low, subjecting them to flooding during storm tides (resulting from the combination of storm surge and the astronomical tide). In the city of Venice, a bulletin of forecasted sea level up to 3 days is emitted three times per day (at 09:00, 13:00 and 17:00 UTC) by the Tide Forecast and Early Warning Center (CPSM) of the City of Venice municipality. The forecast is based on a combination of statistical and deterministic models as well as an evaluation of the synoptic meteorological conditions.

In the STREAM project, the multi-model ensemble forecasting systems of the Adriatic Sea will provide the condition to be used for determining dynamic maps of flooding of the urban surface. Since Venice is protected from the sea by barrier islands (separated by three inlets), storm waves do not affect significantly - through set-up and run-up - the sea level height inside the lagoon (Roland et al., 2009). For those reasons, sea level height forecasts are used instead of TWL predictions in the operational system. To propagate the sea level from the inlets to the inner lagoon, nearshore values of sea level height (referred to the local sea level reference datum of Punta della Salute, called ZMPS) and used as open-sea boundary conditions in the SHYFEM finite element hydrodynamic model of the lagoon of Venice (Umgiesser et al., 2014). Such a model adequately reproduces the complex geometry and bathymetry of the lagoon of Venice using an unstructured numerical mesh composed of triangular elements of variable form and size (down to a few metres in the tidal channels; Fig. 5). The model has been used in several hydrodynamic and storm surge studies of the Lagoon of Venice.

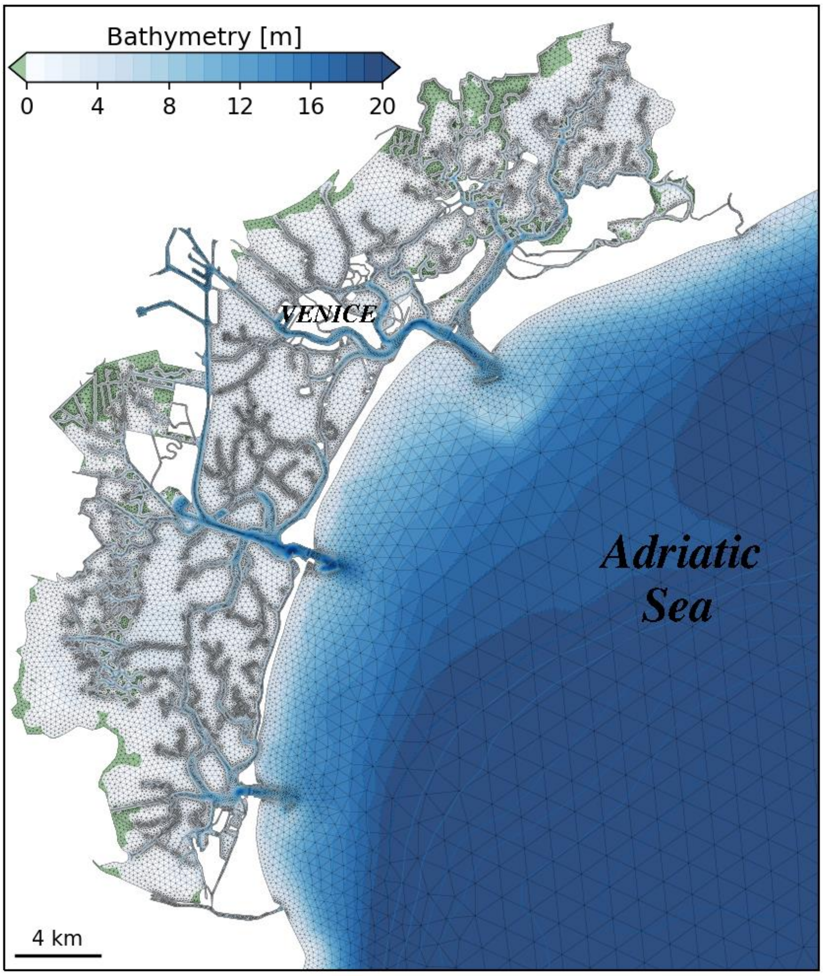

Figure 5: Numerical mesh of the hydrodynamic model for the Lagoon of Venice.

Flooding maps of the city floor will be produced by imposing the sea level height observed and predicted at Punta della Salute (at intervals of 5 cm) to a centimetre-accurate digital terrain model of the city (http://www.ramses.it). As an example, we report in Fig. 6 the static flooding map of the City of Venice for the water level of 160 cm.

Figure 6: Flooding map of the city of Venice according to the predicted sea level height of 160 cm. Light blue colour indicates the canals.

Apulia coasts (Italy): Peschici-Manfredonia and Lecce-Torchiarolo Pilots

The Apulia region is one of the Italian regions with the largest coastal extension (~985 km). The three main categories of the coastal morphology are: (i) rocky coasts (about 31%), such as in the Gargano area; (ii) cliffs called "*falesie*" (about 22%) which are very steep escarpment due to the strong and continuative erosive action of the sea on the rocky coast with sheer walls; (iii) sandy coasts (about 29%), located in some spots over the entire region, with the largest extension in the southern part of Apulia (e.g. in Gulf of Taranto).

Coastal modelling for the Apulia region in the STREAM project is mainly focused on the following pilots:

1. **Peschici-Manfredonia Pilot**. Here, the coastal ocean and the inland waters (rivers, mainly small and intermittent) interact one each other, causing surge and inundation events. The Peschici area is mainly characterized by the high and rocky coast, while the Manfredonia zone extending for about 20 km is mainly sandy. A vulnerable area is represented by Siponto (Fig. 7), due to the presence of forest and wetland area at the interface with the ocean. This

pilot area was strongly impacted by the meteo-marine extreme events that occurred on 6th September 2014 in Apulia region, causing coastal flooding and inundation (Fig. 7) mainly driven by the two rivers of Ulso and Chianara (having a hydrographic extension of about 11 and 30 km^2 respectively).

2. **Lecce-Torchiarolo Pilot**. The coastline length of Lecce town is about 21 km. It consists both in natural (beach, dunes and marshes behind the dunes) and human-impacted (man-made settlements, roads and artificial channels) features. Strong surges cause flooding in several areas, from the sea into the marshland areas. The coast of Torchiarolo is characterized by the presence of a continuous beach, with a width ranging from a few meters to a few tens of meters. Cliff coasts are also present in several hotspots with a height ranging between 8m and 13m. Both beaches and cliffs are affected by coastal erosion. Examples of dunes in strong erosion are shown in Fig. 8.

Figure 7: Siponto in Peschici-Manfredonia Pilot. Sandy coast, marshland and forest of Siponto (left panel). Coastal flooding and inundation during the meteo-marine extreme events occurred on 6th September 2014 (right panel).

Figure 8: Lecce-Torchiarolo Pilot: example of dunes in strong erosion.

The coastal modelling developments planned in STREAM for Apulian test cases are based on a two-stages strategy: (i) the first is oriented to create a storm surge modelling platform for the sub-regional and coastal scale, (ii) the second is addressed to the nearshore scale of the Pilots with the aim of modelling the flooding events in terms of inundation.

Two limited-area nearshore implementations (both for hydrodynamics and waves) will be built for the Apulian coastal Pilots. The resolution of these new implementations will be of the order of meters. The wetting-and-drying of the SHYFEM-WW3 model will be tested. The configurations will be tested both nested into CMEMS products and in the sub-regional coastal scale model developed in the project.

4 MODELLING FLUVIAL FLOODS

The important effect, in terms of human losses and economic damages, of flash flood and flood on small-to medium size watersheds along the Adriatic coast, suggests the need to optimize Early Warning System, real-time hydrologic and hydraulic modelling and nowcasting, and to relate predicted flooding area scenarios to damage estimation. The ability of Flood EWS to mitigate flood risks and impacts on communities is widely acknowledged (Basher, 2006; Cools, 2016; Pappenberger, 2015; Thielen-del Pozo, 2015; WMO, 2013) even if early warnings do not always translate into an emergency response from all individuals at risk (Perera, 2020).

Forecasting floods is one of the aspects of an EWS. Rainfall-runoff (RR) models play a central role for a real-time flood forecasting system in small to medium catchments (200–5000 km^2), characterized by a different level of complexity and data requirement. Research on watershed hydrological models is generally concerned with the basic scientific questions of hydrology, which are how to improve accuracy and how to better simulate and predict what happens to the rain (Rui et. al, 2013). A comprehensive compendium and comparison of catchment models can be found in Singh and Woolhiser (2002) and Kampf and Burges (2007).

Methodology for comparing ensemble streamflow simulations from hydrologic models with high- and low-spatial resolution under uncertainty in both precipitation input and model parameters have been investigated in order to improve operational forecast (Carpenter et al., 2006). Probabilistic forecasts are receiving growing attention and enable rational decision making quantifying the predictive uncertainty (Krzysztofowicz, 2001; Chen, 2007), such as forecast stress indexes with the aim to highlight river segments where a flood is expected to occur.

The increased severe precipitation events and draft periods, forced by climate change, push the need to improve the reliability of disaster management systems related to river and coastal floods, shallow landslide and water exploitation. The physical variable that links together all these aspects is the soil moisture. Recently researchers proved the importance of its estimation or modelling, enhancing the capability to forecast extreme events and managing the water cycle (Brocca et al., 2017). These data are still not fully assimilated or modelled by the main operative early warning system, evaluated in irrigation planning or combined with satellite remote sensing in operative services.

For a complete comprehension of the potential consequences of future floods, the possible role in flow peak reduction of existing man-made infrastructures as dams (Shrestha and Kawasaki, 2020), even of small-medium dimension, must be taken into account. Assessment for the lamination effect of the reservoirs is still in progress and needs to be improved (European Working Group on Dams and Floods, 2010). Moreover, integration with sea conditions is a challenge to be investigated also in small-medium basins of the Adriatic coast, in which coastal areas are highly urbanized and vulnerable.

In the following subsections, we briefly present the state of the art of the modelling and forecasting activities existing in the STREAM fluvial pilot sites, as well as their future developments that will be expected within the framework of the project.

Chienti and Foglia watersheds (Marche Region, Italy)

In the Marche region, main watersheds Flood-Proofs system (Delogu et al, 2020) is currently operative in order to support decision makers during the operational phases of flood forecast and monitoring. The Flood-PROOFS system ingests data and manages the model workflow needed for the hydro-meteorological forecast: LAMI and ECMWF meteorological models, quantitative precipitation forecasts issued by regional center experts, real-time meteorological stations data, meteo-radar maps merged with rain gauges data, data of the operation of regulating hydraulic structures and snow cover satellite data. It provides a quantitative evaluation of discharge and peak flow and evaluates the probability to exceed critical thresholds in critical outlet sections of the catchments (Fig. 9). The hydrological model used in Continuum (Silvestro et al. 2013, 2015) that is a continuous distributed physically-based hydrological model. The outputs produced consist of a deterministic and probabilistic discharge prediction in 97 outlet sections, soil moisture, land surface temperature, evapotranspiration and snow depth regional maps.

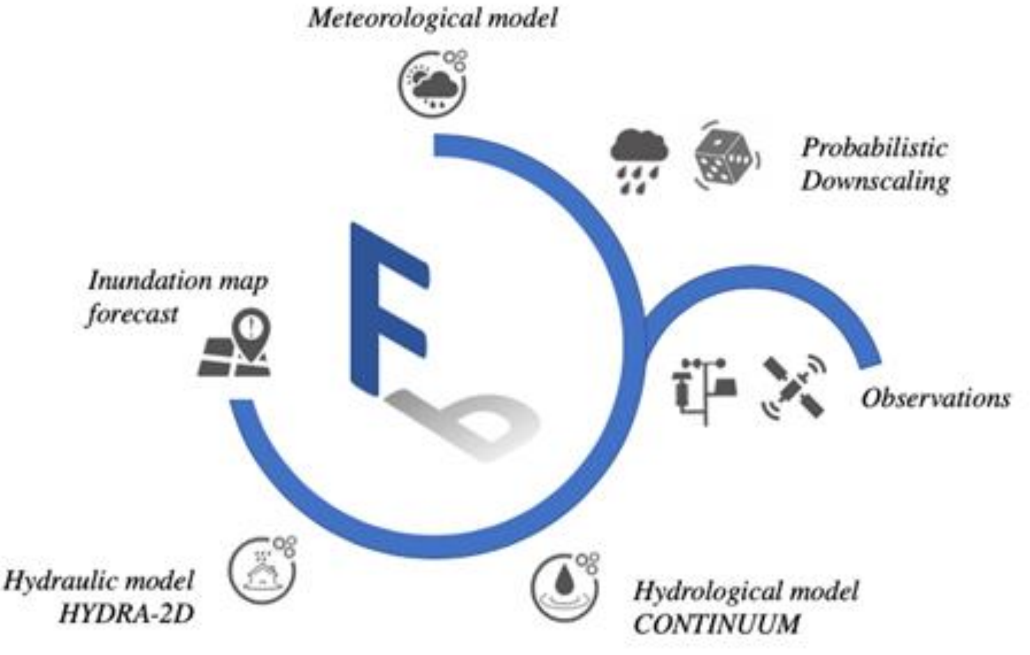

Figure 9: The Flood-PROOFS forecasting chain.

The open-source algorithms developed by CIMA and used for the flood forecasting system implementation are freely available at the Flood-PROOFS GitHub repository (https://github.com/c-hydro). Outputs are published and visualized on MyDewetra, a web GIS platform already used and capitalized by other EU projects such as IPA AdriaRadNet and CapRadNet (Fig. 10).

Figure 10: The Flood-PROOFS outlet sections visualised by MyDewetra platform, with pilot basins location.

The STREAM project will update the model calibration with new years of available data and model code to speed up output generation and to improve the description of natural processes. The flood forecasting chain, for the two pilot watersheds, is going to be extended to include a 2D hydraulic model (HYDRA 2D) and inundation scenarios through abacus for predicted flows. Moreover, a new dams tool will be added in order to include the real-time data of the operation of regulating hydraulic structures and evaluate the dynamic role of hydraulic manoeuvres in flow peak mitigation. Continuum flow output will be provided to coastal modelling in order to investigate river influences.

The estimation of accurate soil moisture, groundwater and superficial water balance is becoming essential for different fields such as crop irrigation, forest fire susceptibility, landslide and flood protection, water supply, hydropower production. Soil moisture sensors networks are rare and without relevant territories coverage. The project idea is to implement and test about 20 soil moisture sensors and to evaluate the integration with satellite data, and comparison with the modelled soil moisture by the operative hydrogeological forecast chain, in order to evaluate future assimilation.

New video cameras implemented close to the most relevant water level station will help to validate model performances and sensor data and to monitor river bed changes.

On Marche territory, the CETEMPS Hydrological Model CHyM model (Sohoroshan et al., 2008, Colaiuda et al., 2020) is also implemented. It is a grid-distributed, physical-based hydrological model, through which two stress indices have been developed in order to identify river segments at flood risk. The first one is the “Best Discharge Detection” (BBD) index, which is calculated as the ratio between the simulated discharge values simulated over each grid-point of a river and the corresponding squared hydraulic radius, the latter being a function of the upstream drained area. The second hydrological stress index is the CAI (CHyM Alarm Index), calculated for each grid-point of the spatial domain, as the ratio between the total precipitation drained by the cell, in a time interval corresponding to the mean concentration time, and the drained area upstream. Namely, it represents the average precipitation drained by a cell during a time interval corresponding to the runoff time. An example of stress indices maps for a relevant past event in the Marche Region is shown in Fig. 11.

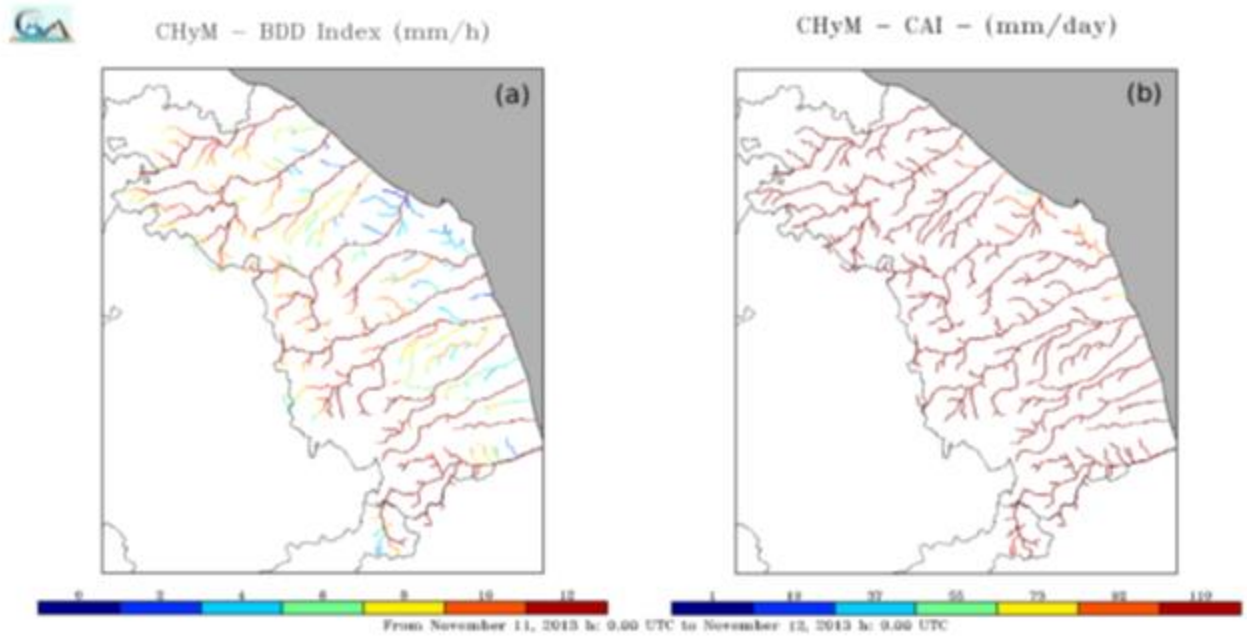

Figure 11: BDD and CAI stress index obtained for November 11th 2013, by forcing the CHyM model with observed rainfall data.

STREAMS activities will allow to upgrade the model code and improve the model operational performances with ECMWF meteorological forcing and Cingoli meteo-radar new products. Moreover, in order to investigate sea influence, CHyM will be updated to a new version, containing the calculation scheme to simulate the barrier effect of the sea in case of storm surge, capitalizing AdriaMORE project. The implemented parameterization will be adapted and calibrated over the regional target watersheds on a case study-basis. In this new module, the measured (or simulated) sea level at the river mouth grid-point will be assimilated, in order to give a Manning's coefficient correction to increment the friction and reduce the flow velocity at the estuary. On case studies, the Landslide Activation Index (LAI) will be also tested on regional territories to evaluate model performances in shallow landslide prediction.

Activities will be performed in collaboration with the Competence Centres of the Italian Civil Protection System, respectively for FloodProofs system by CIMA Foundation and for CHYM model by CETEMPS, as models developers.

5 MODELLING URBAN PLUVIAL FLOODS

Floods have become serious natural threats that significantly affect the economy and human lives, especially in urban areas (Natarajan and Radhakrishnan 2019; Bulti et al. 2019; Bulti and Abebe, 2020). Flooding of urban areas is associated with coastal (Adelekan, 2010; Tanim and Goharian, 2020), fluvial (Apel et al., 2016; Verol et al. 2019) and pluvial floods (Rosenzweig et al. 2018; Meng et al. 2019).

In recent years, pluvial floods have been considered as a major threat for many cities (Rangari et al. 2018; Bulti and Abebe, 2020). Urban pluvial floods usually occur when rainfall exceeds the capacity of the stormwater drainage system (Bulti and Abebe, 2020), which usually occurs when an extremely large amount of precipitation occurs in a relatively short period of time. For example, the coastal part of Croatia recorded rainfall events with more than 200 litres of rain per square meter in less than 24 hours, while at the same time the rainfall amount and intensity were lower in continental part (Holjević, 2016).

There are numerous different approaches for modelling urban pluvial floods (Fritsch et al. 2016; Bulti and Abebe, 2020). In the past few years, advanced 2D mathematical simulations have been developed focusing on the flood simulation, runoff velocity and intensity within the urban environments (Glenis et al., 2018; Rangari et al. 2018; Natarajan and Radhakrishnan 2019; Bulti et al. 2019; Meng et al. 2019;). High-quality data is necessary to create high-resolution models of urban pluvial floods. By increasing the spatial resolution of input data it is possible to obtain precise flood maps (Fritsch et al. 2016; Glenis et al., 2018; Meng et al., 2019; Bulti and Abebe, 2020).

Zadar pilot area (Croatia)

The City of Zadar is located in the middle of the eastern Adriatic coast. It consists of 37 local committees of which 12 are located on the islands[1]. Research of urban pluvial floods will be carried out in the mainland area of the Zadar City, that is the settlement of Zadar. The coastal area of Zadar is exposed to storm surges due to low relief while the rest of the city is vulnerable to frequent pluvial floods caused by a large catchment area, a high percentage of impermeable surfaces and poor drainage system. Additionally, the frequency and intensity of rainfall is expected to increase in the future as a result of climate change (van Dijk et al., 2014; Jiang et al., 2018). The most significant

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[1] https://www.grad-zadar.hr/mjesni-odbori-81/

flood event in the past few decades occurred on September 11, 2017, when about 285 mm of rain fell on the city area within 24 hours. A thunderstorm resulted in torrential floods and caused significant material damage (Fig. 12). Earlier, a similar event was recorded on the same date in 1986, when 352.2 mm of rainfall was recorded in the 24-hour period (CMHS, 2017; Oskoruš et al., 2017).

Figure 12: Consequences of the catastrophic flood event in Zadar of November 9th, 2017[2].

The Zadar pilot area is divided into three levels of research: **macro**, **meso** and **micro** (Fig. 13).

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[2] https://www.jutarnji.hr/vijesti/hrvatska/otkrivaju-se-razmjeri-katastrofe-nakon-poplava-u-zadru-stete-ce-biti-vece-od-milijardu-kuna-popularni-trgovacki-centar-ostat-ce-zatvoren-mjesecima-6561636

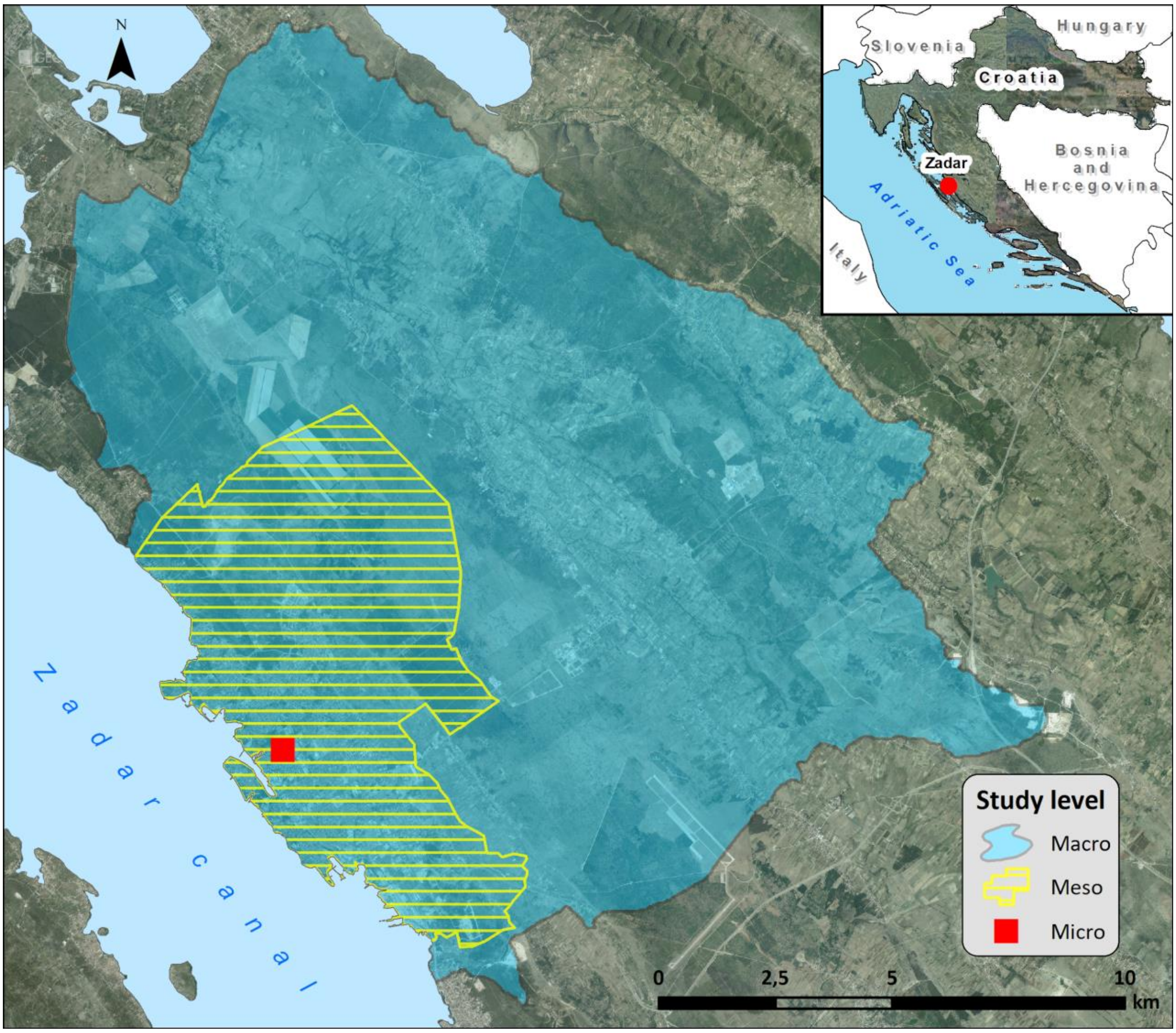

Figure 13: Study levels of Zadar pilot area.

The **macro level of research** includes the catchment area of the Zadar settlement (blue area in Fig. 13). At this level of research, surface elevation data (height points and lines) collected by photogrammetric restitution (by State Geodetic Administration – SGA) will be used to create a digital terrain model (DTM). The most suitable interpolation method will be selected by evaluating various geostatistic and deterministic interpolation methods (Šiljeg et al., 2015; Šiljeg et al., 2018). Spatial resolution will be determined considering a number of samples and size of the research area (Hengl, 2006; Šiljeg et al., 2019). Furthermore, satellite imagery (Sentinel 2) with a spatial resolution of 10 m will be used to create a land cover model (LCM) using GEOBIA (Geographic Object-Based

Image Analysis) methodology (Hay and Castilla, 2008; Blaschke, 2010; Chen et al., 2018; Maxwell et al., 2019). Segmentation parameters and optimal classifier will be determined by assessing the classification accuracy of several most used classifiers (Maxwell et al., 2015; Li et al., 2016; Jozdani et al., 2019). LCM and derived parameters from DTM will be used for more accurate modelling of surface flows considering absorption characteristics of different soil types. Furthermore, data from the Central Register of Spatial Units (CRSU) (roads and facilities) as well as the updated data from the meso level of research will be used for generating flood sensitivity, vulnerability, hazard and risk maps. The aim of this research level is to obtain information about the general hydrological characteristics (slope, imperviousness, infiltration, roughness, etc.) of the Zadar catchment area (Fig. 14A).

The **meso level of research** includes the administrative border of the Zadar settlement (yellow area in Fig. 13). At this level, aerial photogrammetric data (RGB + infrared (IR)) from the State Geodetic Administration (DGU) will be used to create a digital surface model (DSM), DTM and LCM with a spatial resolution <1 m. Segmentation parameters and optimal classifier for creating LCM will be determined using the same scientific methods as at the macro-level of research. Furthermore, CRSU data (roads and facilities) will be updated with detailed facility and population data acquired from different sources (open-source data, field survey, Croatian Bureau of Statistics (CBS) etc.). The modified dataset will be used for assessing the flood sensitivity and vulnerability maps, as well as the flood hazard and flood risk maps. Communal infrastructure data (manholes, pipe flows, drainage systems, wastewater plants, etc.) will be collected from the local municipalities, public utility companies and field surveys in order to develop a high-quality input data and support pluvial flood modelling. These data will be used on all three study levels. The goals of this research are to: (1) obtain information on a detailed hydrological characteristic within the catchment - settlement of Zadar; (2) define the most flood-prone (vulnerable) location to pluvial floods, using GIS-MCDA (Multi-criteria Decision Analysis). The latter will be studied in more details at the micro level of this research (Fig. 14B).

The **micro level of the research** will cover a small pilot area within the Zadar settlement with a total area up to 5 ha (an urban block sub-catchment) (red square in Fig. 13). Within the defined test area, aerial photogrammetric (RGB and multispectral images (MS)), Terrestrial Laser System (TLS) and Aero Laser System (ALS) data all with a spatial resolution <5 cm will be conducted. These high-resolution data will be used to create DSM, 3D city model and LCM. Within the GEOBIA process, segmentation parameters and optimal classifier for LCM will be determined using advanced scientific methods. Updated CRSU data from meso level as well as underground and aboveground communal infrastructure data will also be used. The stormwater drainage system data will be updated and precisely located using Ground-penetrating radar (GPR) technology. Furthermore, specialized radars for the detection and quantification of stream floods will be installed on specific locations. Also, advanced pan-tilt-zoom (PTZ) cameras will be mounted along the roads to count people and different vehicle types. Within the selected test area, at several specific locations, Physio-chemical analysis of the stormwater's quality will be examined using a multiparameter sonde. The sonde will provide information on the pH value, turbidity, nutrients and heavy metals of the stormwater. The aim of this research is to determine which amount of runoff is affected by wastewater and other pollutants. Research goals at the micro-level are to perform detailed analysis and obtain very-high quality information of the hydrological processes within the most flood-prone location within Zadar and to propose "smart" solutions (such as Sustainable Urban Drainage Systems – SUDS) to mitigate pluvial floods and reduce its negative effects on the environment. Depending on the study area location and analysed flood type, a multibeam echosounder (MBES), thermal camera and non-contact water level sensors will potentially be used to collect additional data (depth, temperature, sea-level fluctuations, etc.) to generate even higher quality models. If possible, a 3D scanner will also be used to scan the morphology of roads and shafts to get a better insight into the runoff at the sub-micro level (Fig. 14C).

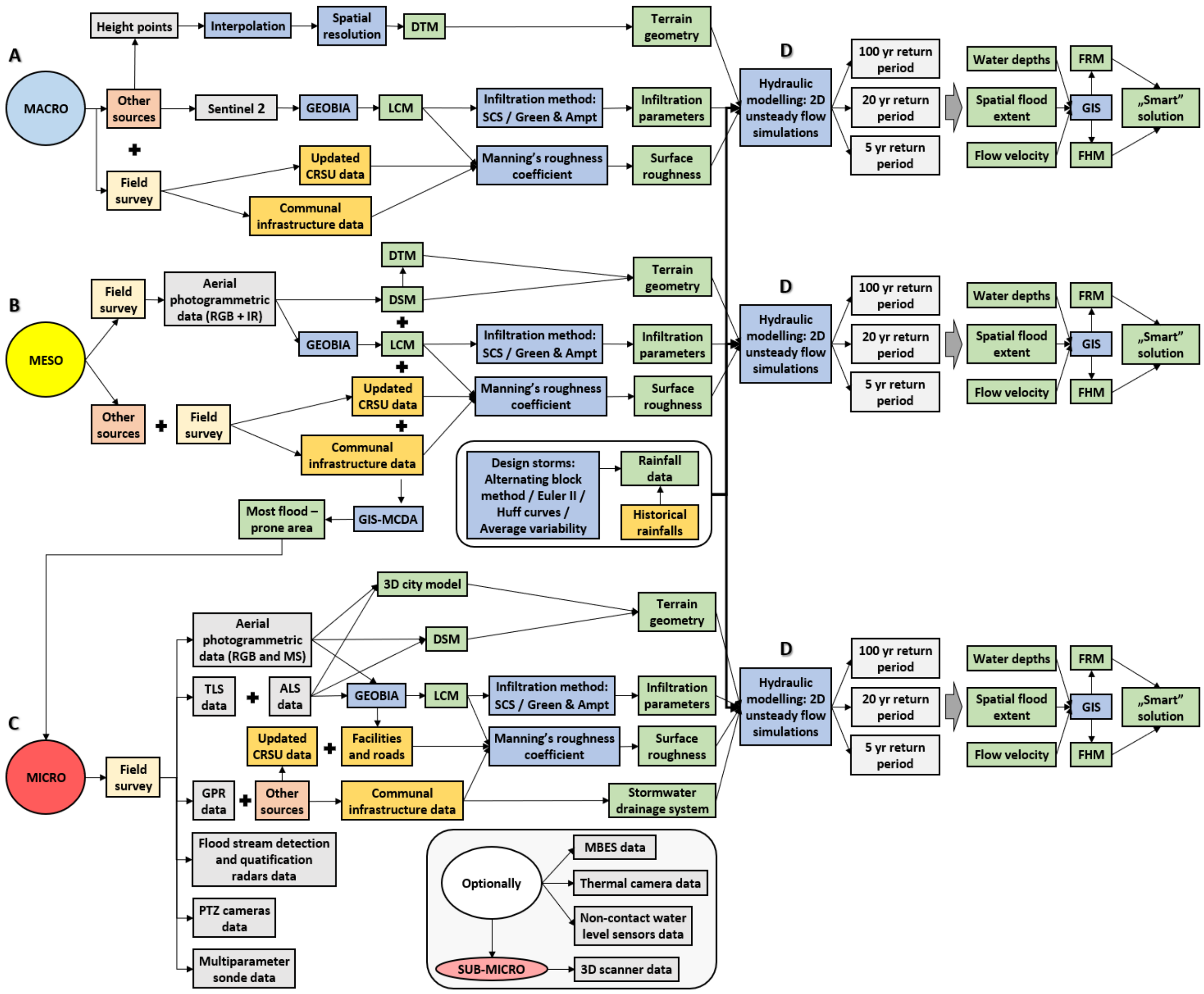

Figure 14: Methodological framework for modelling urban pluvial floods.

The main purpose of pluvial flood modelling in urban areas is to obtain results for the preparation of flood hazard maps, which will be further used to prepare flood risk maps. Flood hazard maps will be derived for three scenarios, as defined by the EU Directive on the assessment and management of flood risks (2007/60/EC, i.e., the Flood Directive):

- floods with a low probability, or extreme event scenarios (100yr return period),
- floods with a medium probability (20yr return period),
- floods with a high probability (5yr return period).

For each scenario referred to above, the following elements will be computed and illustrated on a flood hazard map:

- the spatial flood extent,
- water depths or water surface elevation,
- flow velocity or the relevant water flow.

Pluvial floods in urban areas will be simulated by a 2D hydraulic model at all tree levels – macro, meso and micro. To accurately capture all relevant physical processes of pluvial flood flows in an urban environment, the hydraulic model should be robust and based on full shallow water equations. Additionally, the simulations should be based on 2D unsteady flow. The hydraulic model should have a sub grid bathymetry to include irregular bathymetry at each computational cell. In this way, a high-resolution DSM can be incorporated in a computational model while using a larger cell size to keep reasonable computational times. Furthermore, the hydraulic model should have the option to account for spatially and temporally variable rainfall and spatially variable infiltration. For the reasons stated above, the pluvial flood modelling will be performed by the HEC-RAS 6.0 model, which has all the required characteristics.

Considering that pluvial floods are generated by extreme rainfalls, special attention will be placed on the selection of appropriately designed storms to describe a synthetic hyetograph (Krvavica & Rubinić, 2020). For this purpose, several approaches will be considered at the pilot site, including alternating block method, Euler type II, Huff curves and the average variability method. All four design approaches will be compared to historical rainfalls and the most suitable one will be selected for flood hazard analysis. Furthermore, in addition to synthetic hyetographs, several historical rainstorms will be considered for validation purposes.

The modelling domain will be defined by DSM and spatial distribution of impervious surfaces, where pervious surfaces will have infiltration capability defined by SCS method or the Green and Ampt method. Furthermore, based on the land cover and infrastructure data, spatial distribution of surface roughness will be defined by the Manning's roughness coefficient.

Once all the simulations and scenarios are completed, the hydraulic results (spatial extent, water depths, water velocities) will be exported to a GIS environment to prepare flood hazard and flood risk maps (Fig. 14D).

6 MODELLING COMPOUND FLOODS

Compound flooding is an extreme impact event resulting from the interaction of multiple physical and anthropogenic drivers (Zscheischler et al. 2018). Floods often arise through the joint occurrence of different source mechanisms. As mentioned in the above sections, this can include oceanographic drivers such as tides, storm surges, or waves, as well as hydrologic drivers such as rainfall-runoff (pluvial) or river discharge (fluvial). Often, two or more of these flood drivers affect the same region and are correlated with each other (e.g. storm surge and high river discharge), which needs to be accounted for in flood modelling and forecasting.

Low-lying coastal areas, like the ones present in the northern Adriatic Sea, are particularly vulnerable to compound floods as they are exposed to different sources of flooding driven by the interaction of oceanographic, hydrological and meteorological processes.

In the following subsections, we briefly present the state of the art of the modelling and forecasting activities existing in the STREAM compound pilot sites, as well as their future developments that will be expected within the framework of the project.

Po Delta

The Po is the largest Italian river which originates in the western Alps and drains a large basin encompassed by the mountain ranges of the central and western Alps and the northern Apennines. The lower Po River creates a complex delta, with five main branches (Po di Maistra, Po di Pila, Po di Tolle, Po di Gnocca and Po di Goro), some secondary branches and a system of seven coastal lagoons (Caleri, Marinetta, Basson, Barbamarco, Canarin, Scardovari and Goro).

The Po Delta is a heavily anthropized system with artificially stabilized river embankment and many urban settlements. Agriculture is a key activity in the delta, carried out over tens of thousands of hectares of formerly marshes, drained and turned into cultivable land and currently lying below the mean sea level. The phenomenon of the coastal flood is particularly pertinent to the delta of the Po river where it strongly affects farming and daily activities of the local people. STREAM activity in this pilot site will focus on the development of a forecasting system for simulating hydrodynamic conditions and flooding in the whole Po Delta region.

The hydrodynamic model SHYFEM has been already applied to the Po Delta for investigating hydrodynamics in the whole river-sea system (Maicu et al. 2018); to understand the interaction between inland chemical fluxes and lagoon processes in controlling Manila clam responses (Stefani et al. 2018), and to study coastal mixing off the multiple river mouths (Bellafiore et al. 2019). The model was applied to a numerical domain which comprises all Po river branches starting from the Pontelagoscuro cross-section (90 km upstream), all delta lagoons, and an area of the coastal sea. The use of triangles of different form and size is necessary to represent in detail all river branches (with the floodplain) and the seven shallow coastal lagoons (Fig. 15).

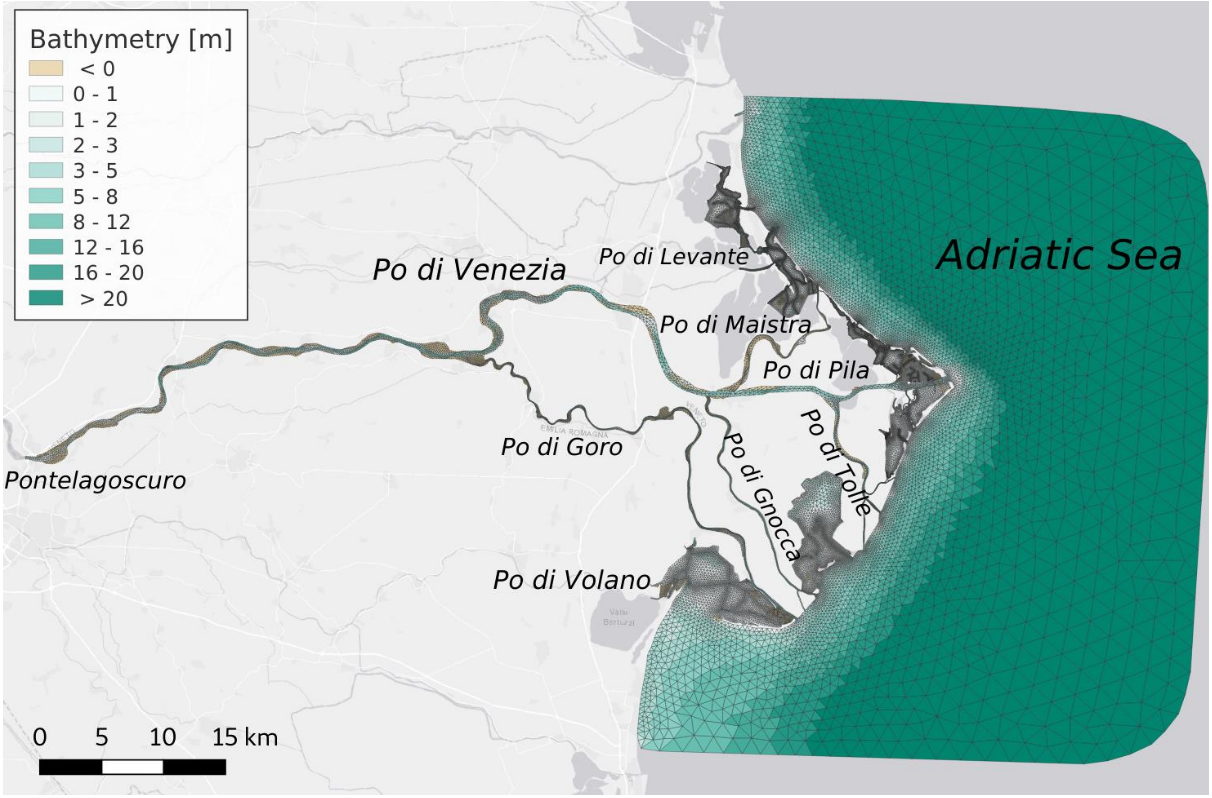

Figure 15: Unstructured numerical mesh of the Po Delta pilot site.

The investigated system is characterized by the presence of sheltered environments in the upper coastal intertidal zone (mashes) and river floodplains which are periodically flooded during the tidal cycle and during bigger floods. Thus, an accurate representation of wetting-drying processes in tidal marshes, coastal areas and floodplains is a crucial issue for hydrodynamic models, which has been the subject of many studies and still represents a numerical challenge (Medeiros and Hagen, 2013; Le et al., 2020). The wetting-drying involves a delicate balance of computational efficiency (both processing demand and memory allocation), numerical stability (convergence, spurious oscillations), and scientific accuracy. The SHYFEM model includes a wetting and drying algorithm, which will be further tested in the project.

In STREAM, the existing numerical grid will be extended to consider other areas subjected to flooding. The system will be coupled with the probabilistic forecasting system of the Adriatic-Ionian region and with the operational forecasting system of the Po River watershed managed by Arpae in order to be able to simulate floods due to high river discharge, stormy sea conditions and the combination of both.

Ofanto river-sea system

The Ofanto River is one of the most important rivers and watersheds in Southern Italy. The basin (Fig. 16) extends for about 3060 km^2, affecting the territory of three Italian regions (Campania, Basilicata and Puglia), with an average altitude of about 425 m above the mean sea level. The length of the main branch is about 180 km, making it the second-longest river in Southern Italy. The hydraulic regime is torrential, characterized by prolonged periods of lean, which are associated with short but intense flood events, especially in Autumn - Winter time. The mean annual discharge at the outlet is around 15 m^3s^{-1}; minimum monthly climatology is 2.27 m^3s^{-1} in August and reaches its monthly peak, 35 m^3s^{-1}, in January. The inundation events in the Ofanto river-shelf-coastal area is mainly caused by the interaction of three factors: extreme inland river discharges, obstructions in riverbed due to sediment deposition and sea level extremes from the Adriatic Sea.
Here we have an overview of the existing modelling system for the river scale of Ofanto, with the meteo-hydrological modelling system for the reconstruction river runoff based on WRFHydro.

The Ofanto catchment is challenging in terms of both meteorological and hydrological modelling purposes. With regard to the hydrological modelling, this is a medium-sized catchment with a “rain-runoff” response time which varies from several days up to a few hours, which makes the streamflow prediction highly demanding. Concerning meteorological modelling, the basin is located in Southern Italy, where several heavy rainfalls and flash flood events have occurred in the last decades, triggered by lee cyclogenesis and convective instability.

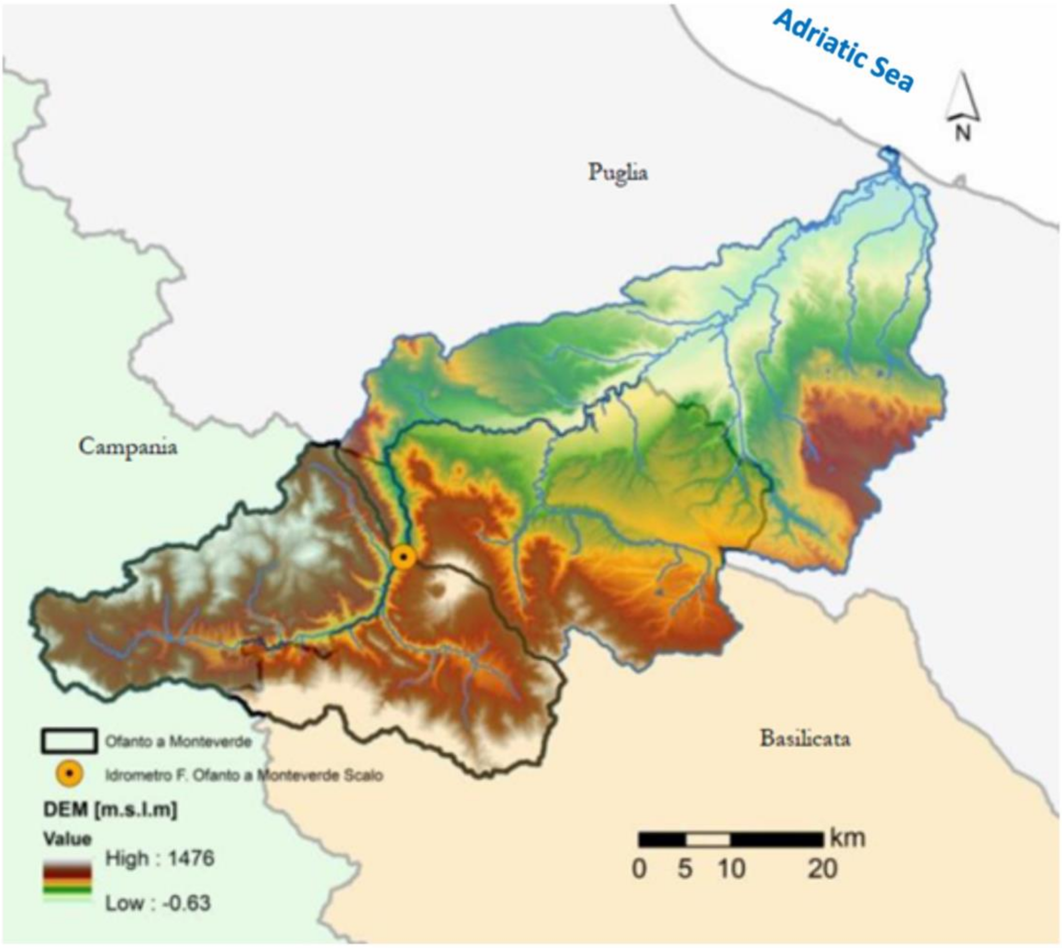

Figure 16: Ofanto Pilot: hydrographic basin and Digital Terrain Model (DTM).

Several sensitivity tests were performed in this basin along with an assessment of which tunable parameters, numerical choices and forcing data most impact on the modelling performance. The WRF precipitation was validated by comparison with rain gauges in the Ofanto basin. The WRF model is found to be sensitive to the initialization time and a spin-up of about 1.5 days is needed before the start of the major rainfall events in order to improve the accuracy of the reconstruction. Moreover, an optimal interpolation method has been developed to correct the precipitation simulation. It is based on an objective analysis (OA) and the least square (LS) melding scheme, collectively named OA+LS. The validation of the river streamflow has shown promising statistical indices. Fig. 18 shows the observed and modelled hydrograph of the Ofanto river during peak events in February and March 2011. Overall the final set-up of our meteo-hydrological modelling system is capable of realistically reconstructing the local rainfall and the Ofanto hydrograph (Verri et al 2017).

More research is required to establish better groundwater modelling that at the moment considers seasonally dependent, ad hoc values of both the soil infiltration and the aquifer water storage. Different parameterisations of the aquifer recharge/discharge could be evaluated.

Moreover, the hydrology models are able to represent the terrestrial waters only. There are no open boundaries with marine waters at the surface (estuary) neither at the subsurface (groundwater runoff). Thus an integrated modelling approach is required to provide a reasonable flood forecasting system.

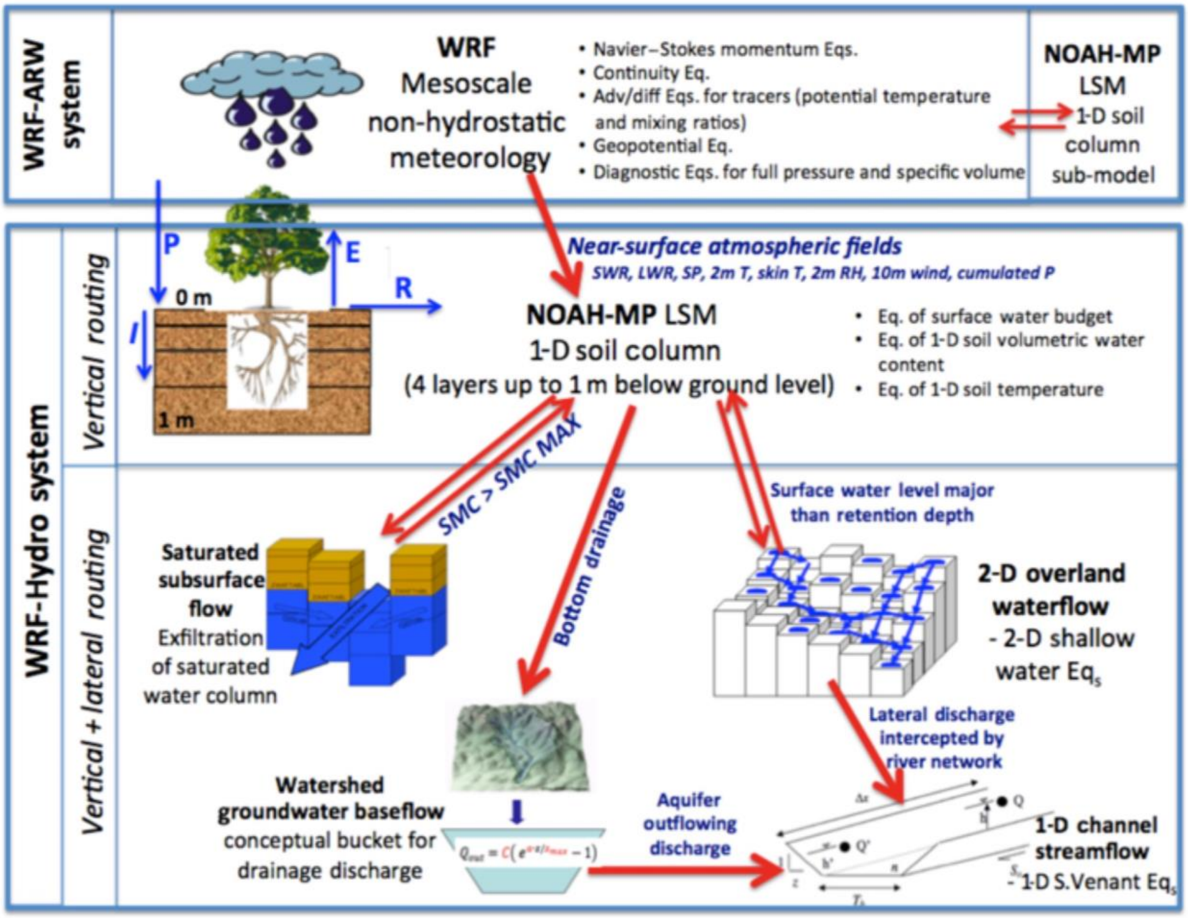

Figure 17: The meteo-hydrological modelling chain of the Ofanto river.

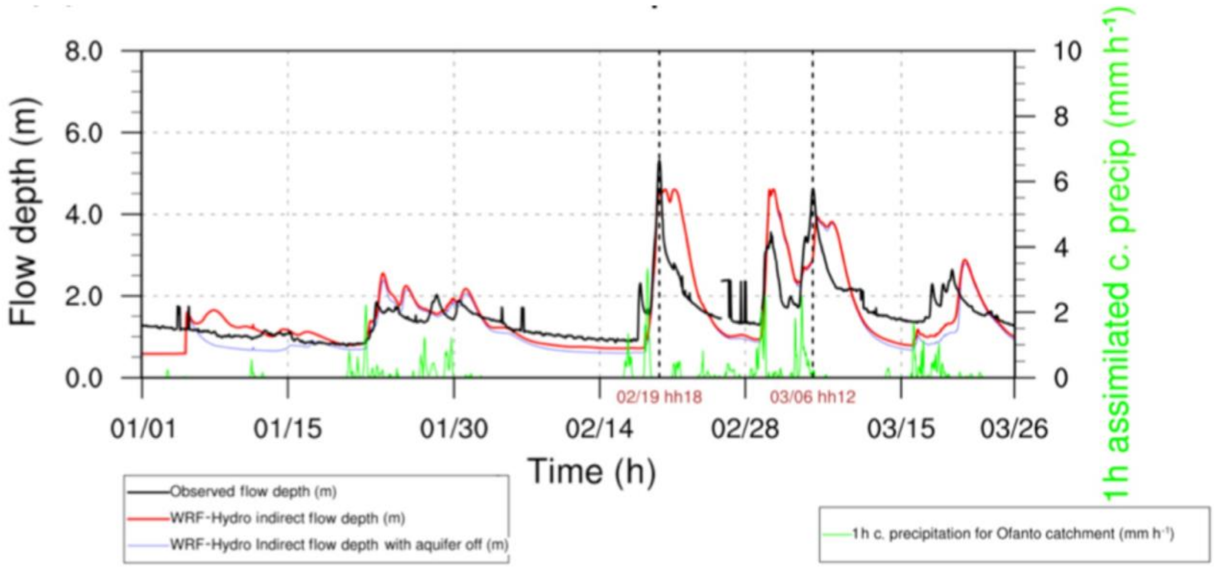

Figure 18: Validation of the Ofanto water level ("indirect flow depth" means water level derived by the directly modelled runoff) at the Cafiero station (20 km upstream of the river outlet).

In particular, the Ofanto Pilot will be a testbed for river-sea continuum representation, testing the capability of the model to reproduce flooding events due to compounding effects from river and sea.

The compounding effects of pluvial flooding, fluvial flooding and coastal inundations in the downstream part of the Ofanto catchment could be investigated with an integrated modelling approach. All types of surface waters, from the river catchment to the shelf and open sea will be represented in a seamless way by avoiding nesting techniques near the coast and/or coupling at the land-sea interface and by exploiting the multi-scale and cross-scale capabilities of the SHYFEM model. The SHYFEM model is intended to cover the downstream part of the Ofanto catchment which is exposed to compound flood events while the WRFHydro model is expected to provide the river runoff as a lateral open boundary quite upstream the river network, i.e. where salinity is equal to zero. The WRFHydro capability to represent the link between surface and subsurface waters will be included in the SHYFEM code.

7 FINAL REMARKS

Modeling coastal flood, fluvial, urban pluvial and compound floods poses many site specific challenges. Therefore, we could not define general modelling recommendations, except for the fact that probabilistic forecasting systems should be preferred in all pilot sites.

For coastal and compound floods is it important to improve the representation of the land-sea interactions at the coast - especially near river deltas, estuaries, lagoons, bays, marshes, headlands - through:

- a seamless and variable resolution horizontal mesh for representing the morphology of the land-coast-sea transition;
- an adequate vertical coordinate system for describing the vertical processes and gradients at the river-sea and air-sea interfaces;
- the coupling with watershed models for considering the correct and often underestimated flux of fresh water into the sea.
- coupling of storm surge, tide and wave components.

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