CoastFLOOD: fine-resolution modelling of flood inundation due to storm surges in the coastal zone

C.V. Makris[1*], Z.C. Mallios[1], Y.S. Androulidakis[1], Y.N. Krestenitis[1]

[1]Division of Hydraulics and Environmental Engineering, School of Civil Engineering, Aristotle University of Thessaloniki, Thessaloniki, Central Macedonia, 54124, Greece
[*]Corresponding author: cmakris@civil.auth.gr

Abstract

In this paper, we present the CoastFLOOD numerical model for coastal inundation induced by sea level elevation due to storm surges enhanced by astronomical tides and mean sea level rise. CoastFLOOD is a high-resolution, O(*dx*)=1, raster-based, storage-cell model for mass balance floodwater flow by decoupled 2-D Manning-type equations. It may be applied on geophysical local-scale, O(*x*)=20km, lowland coastal areas with natural floodplains and urban settings. It can be forced by either output of regional-scale storm surge simulations or field data (i.e., satellite altimetry for sea level anomaly or *in situ* tide-gauge measurements for sea surface height). We present selected results from high resolution (2–5m) model simulations for Greek case studies at low-lying coastal sites of the Ionian Sea (east-central Mediterranean basin). New features of the model are tested concerning the detailed inclusion of terrain Manning roughness (bottom friction), incorporation of boundary conditions for coastal currents, and treatment flood front propagation over steeply varying topography. Verification of the model is performed by comparisons against satellite data of estimated flooded areas by the Normalized Difference Water Index and estimations of a “bathtub” inundation approach with hydraulic connectivity.

Keywords Coastal flooding, Littoral inundation, Storm surge, Numerical model.

1 INTRODUCTION

Storm surges threaten lowland littoral areas by increasing the risk of seawater inundation of coastal floodplains and low-lying urban environments. This threat intensifies when high seas due to storm surge (meteorological residual of sea level elevation) are combined with high astronomical tides (storm tides), leading to events of extended flood inundation over the inland part of the coastal zone. Coastal inundation is the most significant natural hazard induced by episodic maxima of Sea Surface Height (SSH) or long-term Mean Sea Level Rise (MSLR), mainly responsible for land loss, soil erosion, damages on onshore infrastructures and properties, environmental degradation of coastal aquatic ecosystems, saltwater intrusion in coastal aquifers, and occasionally human casualties, etc. For the simulation of such phenomena, a robust model, which can produce realistic inundation hazard maps is crucial in terms of coastal management and risk studies in order to enhance flood hazard mitigation and first-level response to disaster.

In this paper, we present the most recent version of a numerical modelling suite (CoastFLOOD; Makris et al., 2023a) for coastal inundation on littoral floodplains induced by storm surge and enhanced by tidal effects (and probable MSLR). The inundation model can be forced by Sea Level Anomaly (SLA) observations (*in situ* recordings from tide-gauges and satellite altimetry data) or SSH model output of storm surge simulations (Androulidakis et al., 2023). The High-Resolution Storm Surge (HiReSS; Makris et al., 2019) model has been used in operational forecast mode for short-term marine weather (sea level and currents) predictions (e.g., Makris et al., 2021), providing boundary conditions to CoastFLOOD simulations along the Greek coastal zone (Makris et al., 2022). Furthermore, it can be fed by outputs of the Mediterranean Climatic Storm Surge (MeCSS; Makris et al., 2023b) model that can implement long-term hindcasts or future projections of storm surge patterns in the Mediterranean Sea for climatic-scale studies. Herein, we attempt to verify the CoastFLOOD model’s ability to simulate the coastal inundation extents due to storm tides in operational forecast mode by comparing its results against estimations of flooded areas based on either an index for “wet area” identification by satellite ocean colour observations (Sentinel-2 images) or an enhanced "bathtub" approach for coastal flooding with hydraulic connectivity (Williams and Lück-Vogel, 2020).

2 METHODS AND DATA

2.1 Numerical Model

CoastFLOOD performs detailed modelling of the shallow and rather slow process of seawater uprush and flood routing due to episodic, mid-term, and large-scale, sea level elevation, i.e., induced by storm surges/tides. It is a fine resolution, raster-based, 2-D horizontal, mass balance flood model for coastal inland areas, following the simplified concept of a reduced complexity form of the Shallow Water Equations (SWEs) solved on an ortho-regular grid (Figure 1, representing the GIS study domain) by the storage-cell concept (Bates et al., 2010; Hunter et al., 2007). Only the large-scale low-frequency phenomena of coastal inundation due to storm surges and tides are simulated, not considering the high-frequency undulating processes of coastal flooding due to wave action. The storm-induced SLA or SSH on the coastline feeds the seawater surge on the littoral floodplain via a set of 2-D decoupled Manning-type flow equations. The simplified form of the 2-D equations for conservation of mass (continuity) and momentum describes the floodwater flow between adjacent cells, which is driven by the hydraulic head created from the inter-cell difference of water surface height in all four cardinal directions of the horizon during a typical timestep of the numerical solution. The set of equations is written as:

$$h_{i,j}^{t'} = h_{i,j}^{t} + dt \cdot \frac{Q_{x_{i-1/2,j}}^{t} - Q_{x_{i+1/2,j}}^{t} + Q_{y_{i,j-1/2}}^{t} - Q_{y_{i,j+1/2}}^{t}}{dx \cdot dy} \quad (1)$$

$$Q_{x_{i-1/2,j}}^{t} = \frac{h_{flow_{x_{i-1/2,j}}}^{t\ 5/3}}{n} \cdot \left(\frac{h_{i-1,j}^{t} - h_{i,j}^{t}}{dx}\right)^{1/2} \cdot dy,\quad Q_{x_{i+1/2,j}}^{t} = \frac{h_{flow_{x_{i+1/2,j}}}^{t\ 5/3}}{n} \cdot \left(\frac{h_{i,j}^{t} - h_{i+1,j}^{t}}{dx}\right)^{1/2} \cdot dy \quad (2)$$

$$Q_{y_{i,j-1/2}}^{t} = \frac{h_{flow_{y_{i,j-1/2}}}^{t\ 5/3}}{n} \cdot \left(\frac{h_{i,j-1}^{t} - h_{i,j}^{t}}{dy}\right)^{1/2} \cdot dx,\quad Q_{y_{i,j+1/2}}^{t} = \frac{h_{flow_{y_{i,j+1/2}}}^{t\ 5/3}}{n} \cdot \left(\frac{h_{i,j}^{t} - h_{i,j+1}^{t}}{dy}\right)^{1/2} \cdot dx \quad (3)$$

$$h_{flow_{x_{i-1/2,j}}} = \left(max\{H_{i-1,j}, H_{i,j}\} - max\{z_{i-1,j}, z_{i,j}\}\right) \quad (4)$$

where, i and j are the cell (i,j) centered indices in x- and y-directions of the Cartesian grid (for scalar parameters); +1/2 in indexing denotes the intercell positioning of vectorial flow parameters; t is the time and dt the timestep of temporal discretization ($t'=t+dt$ the following timestep in the solution scheme); Q_x and Q_y are the volumetric flow rates between adjacent floodplain cells in the zonal x- and meridional y-directions of the Cartesian grid, respectively; h is the local floodwater height above each grid cell's land elevation, z; dx and dy are the cell dimensions; H is the local floodwater height above MSL. The model can be applied at very high spatial resolutions (e.g., dx=1-5m) for geophysical-scale flows (e.g., O(Dx)=1-20km).

2.2 Available datasets

Bottom friction is the main parameterization feature of reduced complexity flood inundation models. As the typical model cell's dimensions and depth are assumed to be uniform for each grid element, an effective Manning's bottom roughness coefficient, n, at grid unit scale can be determined as a calibration parameter. By integrating all relevant literature, we have created a detailed collective ensemble of proposed n values discretized at 36 increments (Makris et al., 2023a). These listings are fitted to the Corine Land Cover CLC-2018 (https://land.copernicus.eu/pan-european/corine-land-cover/clc2018) codes that refer to data of natural and manmade land cover types. Terrain heterogeneities on the sub-grid level can cause discrepancies in the representation of land cover texture, thus Manning's n is commonly used as a determinative calibration parameter rather than a physical factor of actual field friction. Land elevation grids are derived by post-processing of available geospatial datasets from the Digital Elevation/Surface Model (DEM/DSM) of Hellenic Cadastre (https://www.ktimatologio.gr/en) on a GGRS87 projection. The operational forecast model validation is performed with the use of satellite observations (Sentinel-2 images) producing the Normalized Difference Water Index (NDWI; Androulidakis et al., 2023; Makris et al., 2022).

2.3 Case Studies

The CoastFLOOD model has been tested at 10 selected case study areas of the western Greek coastal zone, which are rather frequently inundated by storm surges of the Ionian Sea (e.g., due to Ianos Medicane; Androulidakis et al., 2023; Makris et al., 2022), including Manolada-Lechaina (Area 1), Vassiliki bay (Area on Lefkada Island, Preveza coast (Area 3), Igoumenitsa port (Area 4); Livadi coastal area (Area5) in Cephalonia Island; Kalamata (Area 6); Argostoli (Cephalonia Island, Area 7); Kyparissia (Area 8); Laganas (Zakynthos Island, Area 9); Patra city (Area 10).

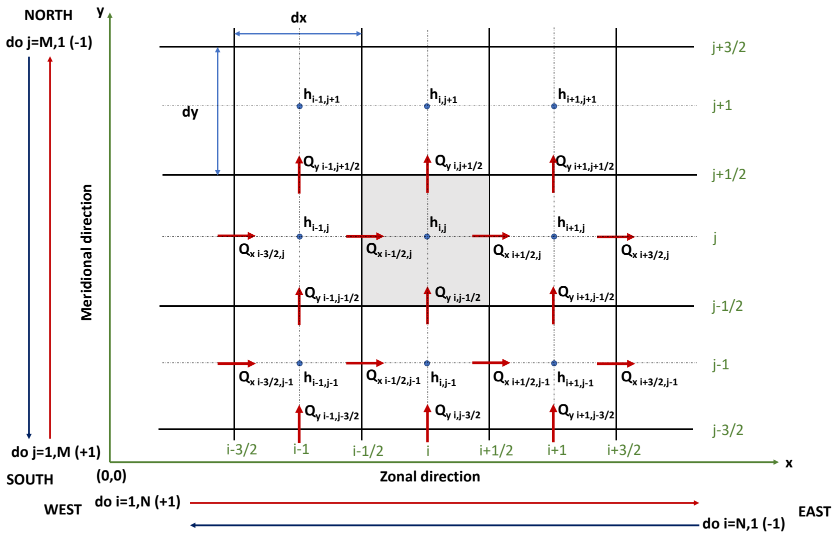

Figure 1 Prototype raster-based staggered grid of CoastFLOOD model with *dx*-*dy* cell discretization over *i*-*j* coordinate system on Cartesian *x*- and *y*-directions (zonal and meridional directions of the horizon); notation of scalar parameters (floodwater height *h*) at the grid cell center and of decoupled vectorial parameters (volumetric flow rate, Q_x and Q_y) transversal to the grid cell interface; arrows' positive direction represents flows from upstream to downstream areas

3 RESULTS

3.1 Model Validation

Two areas and events are used for qualitative verification of the coastal flooding model's performance against satellite data due to lack of *in situ* observations. Figure 2 depictions present flood maps of model simulations overlaid by satellite-tracked wet regions. The CoastFLOOD results are driven on the coastal boundary of Areas 1 and 5 by recorded SLA values on 14/12/2021 and HiReSS-modelled SSH from operational forecasts by the WaveForUs system on 17/09/2020, respectively. The maps depict the overlap of NDWI-identified wet areas by satellite images above flood inundation model output focusing on the mainly affected parts of both study areas. In general, the CoastFLOOD simulations reproduce the coastal flooding mechanism in areas that are more-or-less influenced by storm surge driving seawater onshore uprush during the timeframe of analysis. Furthermore, model results maybe overpredict the momentary depiction of flood extents as derived by the NDWI method based on the recorded images. However, there is no guarantee that the satellite data represent the actual situation of floodwater extents during the storm-induced high seas due to unavailability of data during the storm passage (e.g., no satellite track in the area or cloud contamination). Discrepancies may also stem from the fact that the NDWI depicted areas usually act as drainage bilges that are usually flooded with water originating from local intense rainfall and/or stormwater surface runoff from surrounding higher grounds. An extreme case scenario of Total Water Level, *TWL*=1m, typical for a possible cumulative sea level increase due to the combined effects of surges and waves, is also provided (yellow patches) for comparison of the flood-prone littorals against the actually impacted touristic coastal areas.

3.2 Operational Output

Figure 3 presents the simulated test case of Area 7 (left graph); CoastFLOOD model results agree well with Bathtub-HC ones for an extreme *TWL*=1m scenario as a driver of coastal inundation. As expected, the former ones are slightly underestimated compared to the latter, yet therefore, CoastFLOOD shows a more realistic perspective of littoral inundation, given the error of the DEM topography. The unmatched inland flood-prone areas identified through the Bathtub-HC approach are obviously located on inclined higher elevation ground, in areas where the bottom friction considered by CoastFLOOD plays a crucial role to the modelling of floodwater extents. The proposed model achieves similar performance in both the natural and urban settings. Figure 3 (right graph) presents operational forecasts and scenario-based model outputs for Vassiliki bay (Area 2; Lefkada Island). The natural coastal sites and the surrounding touristic residencies on its northern part seem to be more likely to be impacted by extreme seawater floods, rather than the small harbour in the north-eastern part of the bay.

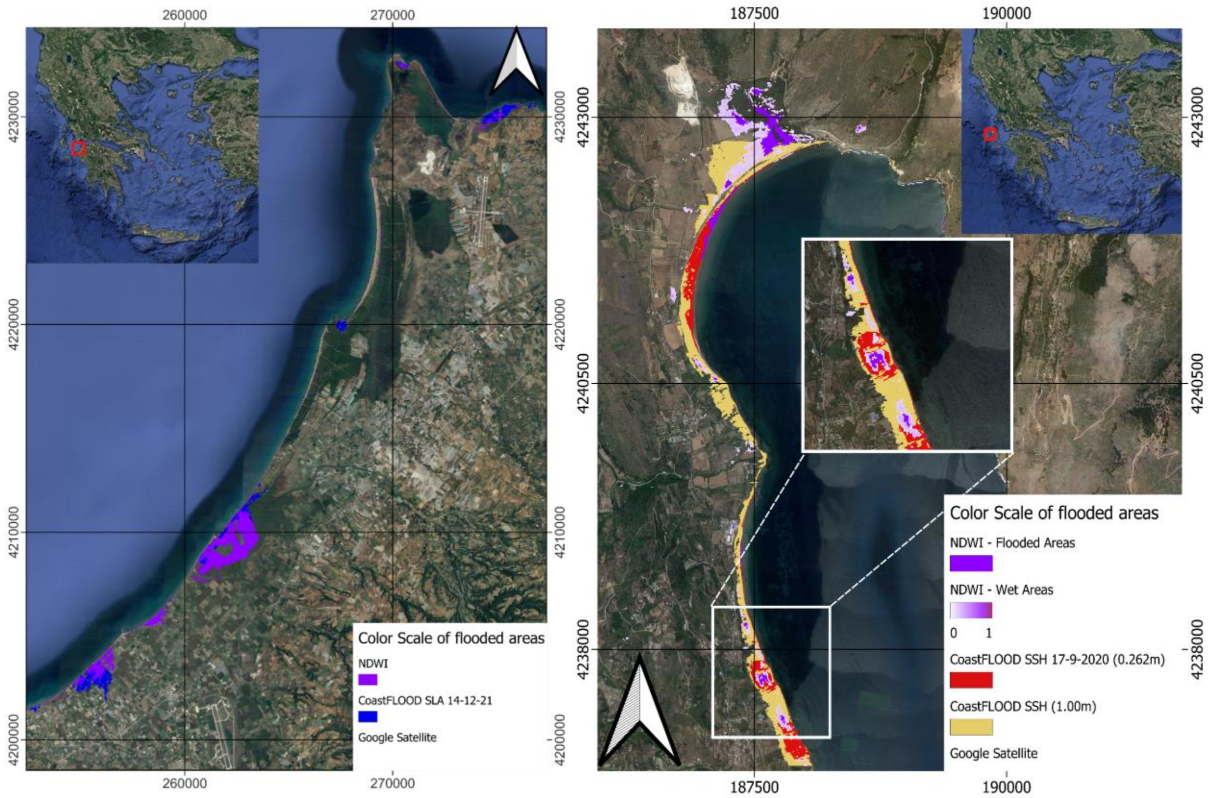

Figure 2 Left graph: Map of estimated flooded areas by NDWI satellite data (purple colour) overlaid on CoastFLOOD simulation results driven by recorded SLA on 14/12/2021 (blue colour) for Manolada-Lechaina study area; Right graph: modelled SSH (red colour) at Livadi (right) after Ianos Medicane's passage together with an extreme *TWL*=1m also provided with yellow colour; Insert map presents zoom-in depiction of impact

4 CONCLUSIONS

We presented a robust, easy-to-use, numerical tool for coastal inundation due to storm surge/tide flooding, under the reduced complexity notion, imperatively needed for operational forecasts of storm impacts on littoral areas. Comparisons against satellite datasets of NDWI are quite satisfactory; any discrepancy in the validation of modelled flood extents in the coastal zone probably also hinges on the uncertainty of field data concerning the actually occurred flood rates. The verification of the proposed model's efficiency to reproduce the highest possible flood extent in coastal plains has also tested well against an efficient Bathtub-HC estimation approach. Therefore, the CoastFLOOD model can be a useful tool for both operational forecast applications and projected climatic studies of coastal inundation under extreme scenarios (Makris et al., 2020) to help coastal zone managers, policymakers, and involved stakeholders to better estimate the characteristics of coastal (or compound) flooding under the condition of possible environmental changes.

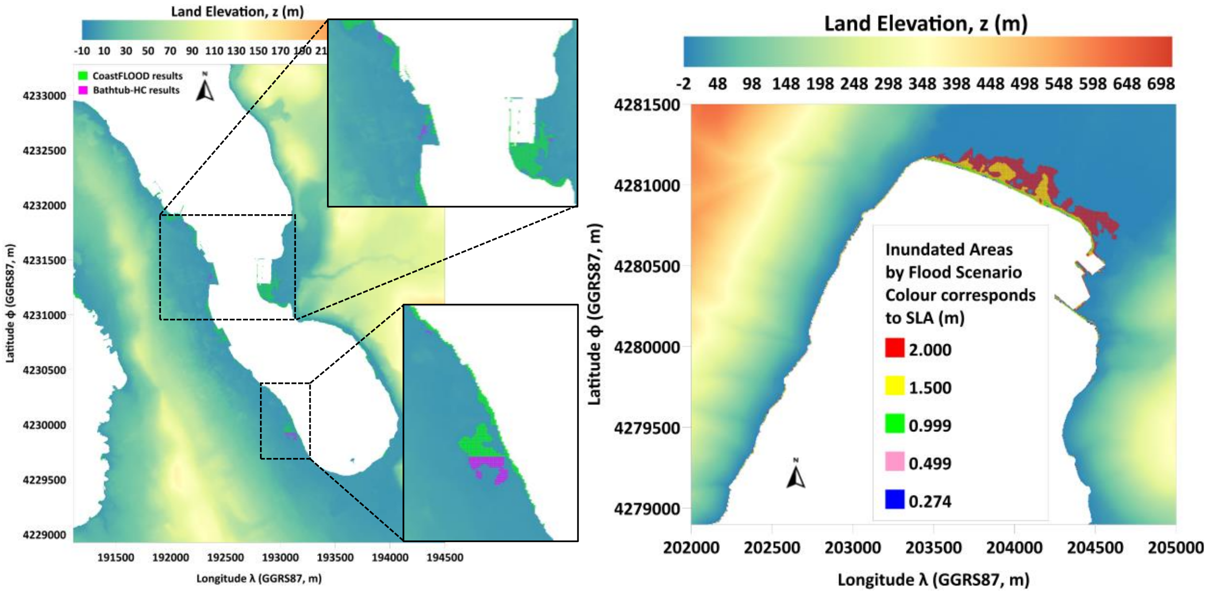

Figure 3 Left graph: Map of estimated flooded areas by Bathtub-HC approach (purple colour) and CoastFLOOD simulations (green colour), for *TWL*=1m in Argostoli coastal inlet (Area 7; Cephalonia Island) with Goodness-of-Fit=0.96; Right graph: Map of estimated flooded areas by operational CoastFLOOD simulations, driven by *in situ* recorded SLA=0.274m and 4 extreme cases of *TWL*=0.5-2.0m in Vassiliki bay (Area 2; SW Lefkada Island)

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