OceanPredict
Advancing the science of ocean prediction

COSS-TT International Coordination Meeting (9)

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CoastFLOOD

a reduced complexity high-resolution flood model for coastal inundation due to storm surges

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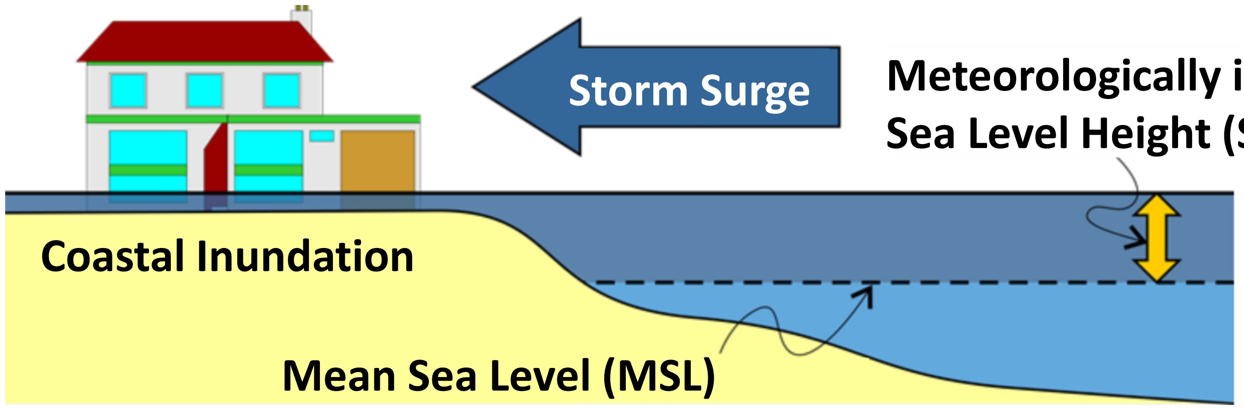
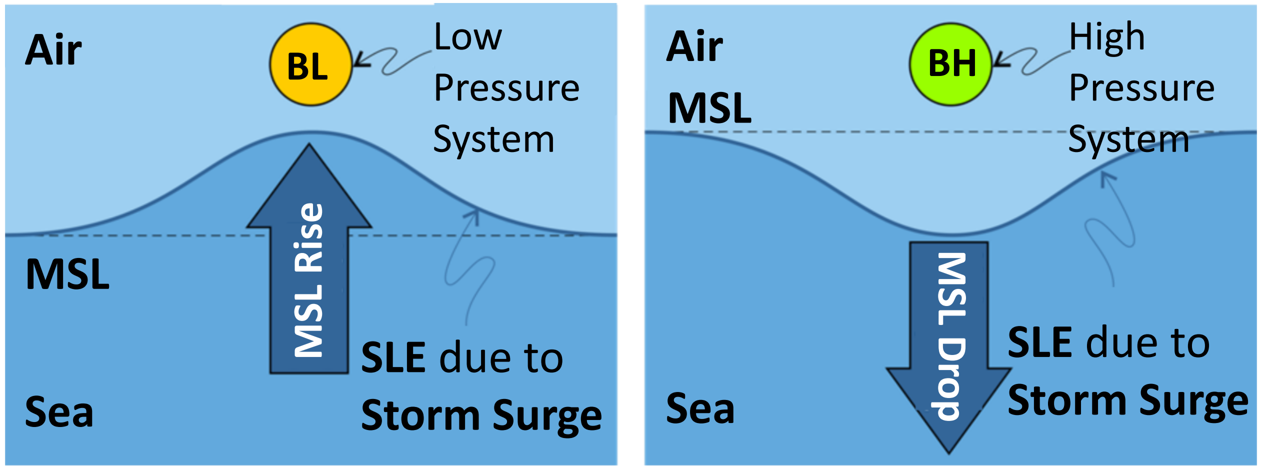
Mechanism for Coastal Inundation

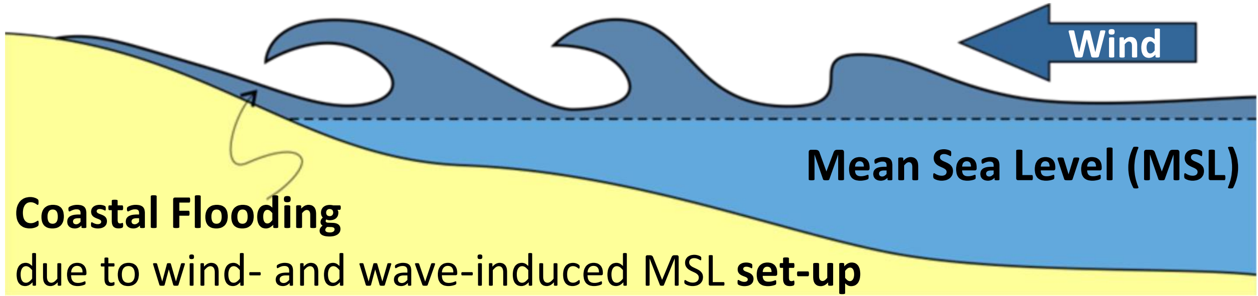


Barometric Systems and **Storm Surges**



Case 1: storm surge (± tides)
[+ SLR for long-term projections]

Case 2: TWL = combined storm surge + wave runup (only steady-state approximation in the surf zone + on the coast) **± tides** [+ SLR for long-term projections]



Methodology Coastal Inundation Modules **3 Approaches**

Coastal Flooding models include 3 approaches for coastal inundation due to Sea Level Rise

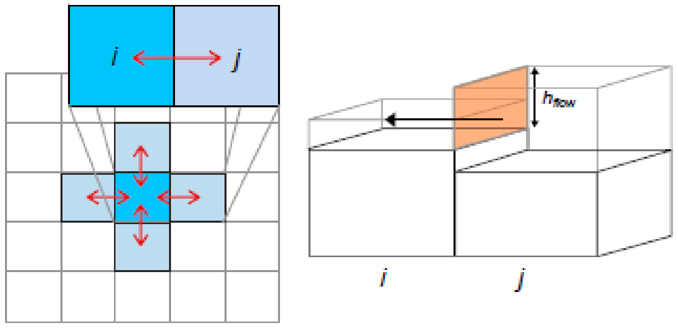
1. A **static-level** inundation module operating in **bathtub** mode
   - traces and marks flood-prone low-land cells with ground elevation z<predefined threshold (e.g., storm surge extreme) on the computational raster grid
   - too simplistic → may lead to unphysical overestimations of coastal flood extents

2. An **enhanced bathtub** approach **with hydraulic connectivity** (Bathtub HC)
   - allows water flow in adjacent cardinal and diagonal directions by the **eight-side rule**
   - constricts implausible overestimation of possibly inundated areas by seawater masses
   - **Neglects bottom friction** due to floodplain terrain roughness and permeability, **time integration** for the duration of the storm surge event, **water flow height** and **velocity** that affect the overland flood extension from the coastline
   - Performs **better** than the **simple bathtub approach →** provides more conservative inundation results with no unrealistically detached flooded areas

3. CoastFLOOD-type of **hydraulic flow** modules with proper spatial- and time-stepping algorithm

Model Conceptual Approach CoastFLOOD

Numerical Model	Reduced complexity 2-D mass-balance floodplain flow
Hydrodynamics:	Decomposed Manning-type hydraulic flow
Mechanics:	SSH difference between neighboring cells
Concept:	Raster-based wet/dry storage cell module
Boundaries:	**SSH on the seafront** by HiReSS model *or* SLA (satellite altimetry) *or* tide-gauge observations
Simulation Period:	hours to days
Cases:	**Ianos Medicane** storm surge events **Projected or historical** SSH/SLA **maxima**
Scales:	**10-20km × 10-20km** inundation areas



Grid formulation: treatment of water height over uneven bed elevation cells

Coastal zone

Discretization: **dx = 2-5m** RAM limit: **15x10⁶ cells**

Hellenic Cadastre https://www.ktimatologio.gr/

Outputs

1. Coverage percentage of inundated areas (by number of wet cells) numerically estimated by flood model
2. Comparisons to potentially flooded areas of the raster grid
3. Accounts for most significant topographic details on coastal land

Model Hydraulic Flow Equations CoastFLOOD

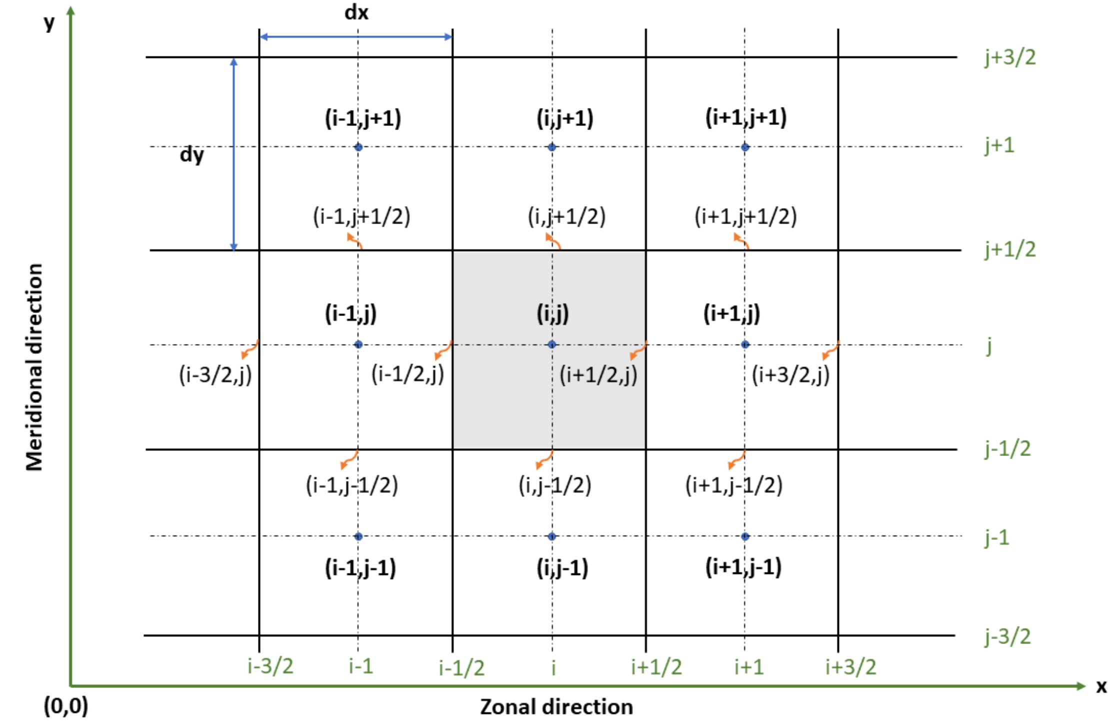
Continuity Equation (mass conservation law)

$$\frac{\partial V}{\partial t} = Q_x^{in} - Q_x^{out} + Q_y^{in} - Q_y^{out}$$

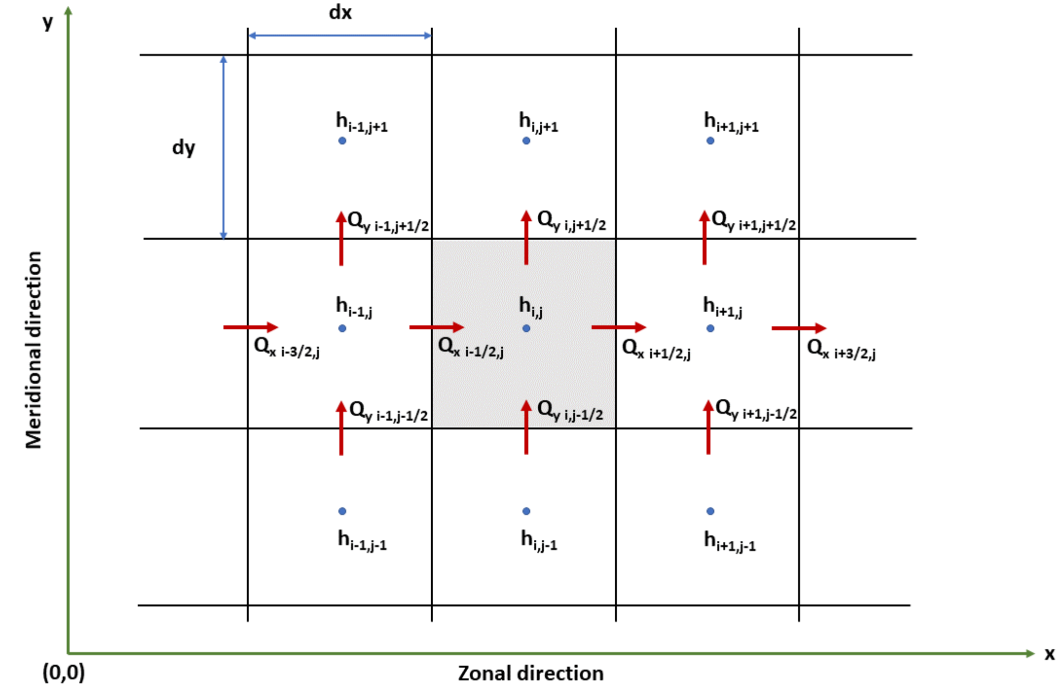
$$\frac{\partial h_{i,j}}{\partial t} = \frac{Q_{x_{i-1/2,j}} - Q_{x_{i+1/2,j}} + Q_{y_{i,j-1/2}} - Q_{y_{i,j+1/2}}}{\partial x \cdot \partial y}$$

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

a



b



Motion Equation (flow rate conservation law)

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

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

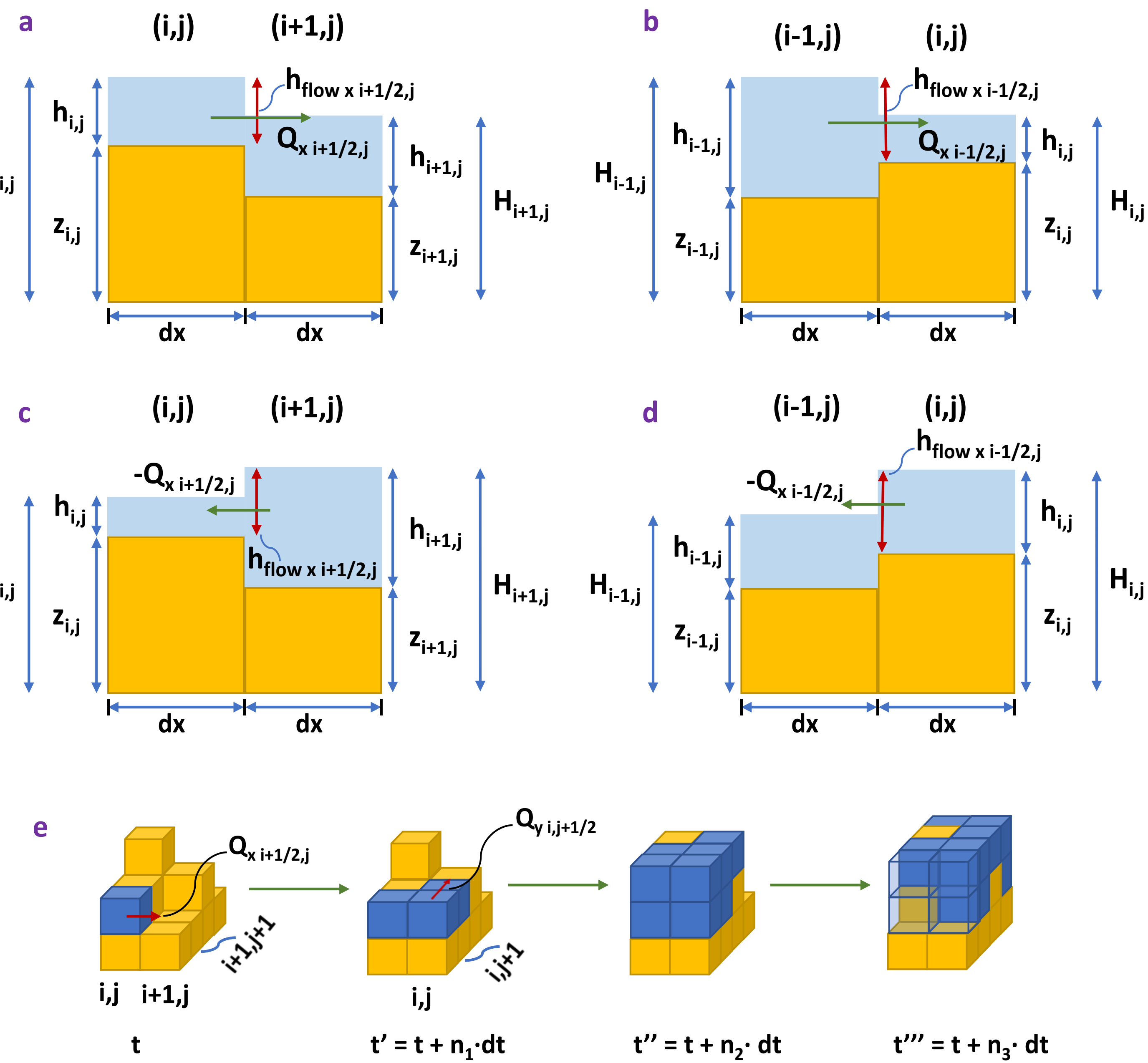
Definition of floodwater exchange flow height

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

Depiction of floodwater front propagation over typical grid cells in CoastFLOOD model

- 2-D x-z plane (a - d)
- wet/dry cell expansion in pseudo-3D projection (d)

Schematic representation of Q_x and h_{flow} (flow depth between two adjacent cells) = difference of the highest floodwater surface elevation from MSL, H, minus the maximum bed elevation, z, between two neighboring cells



Numerical schemes

Forward-Time and Centered-Space (**FTCS**) finite difference

implicit (θ<1) Backward-Time and Centered-Space (**BTCS**) algorithm

Courant-Friedrichs-Lewy (CFL) criterion

$$C = u_x dt/dx < 1$$

Limits to ensure numerical stability

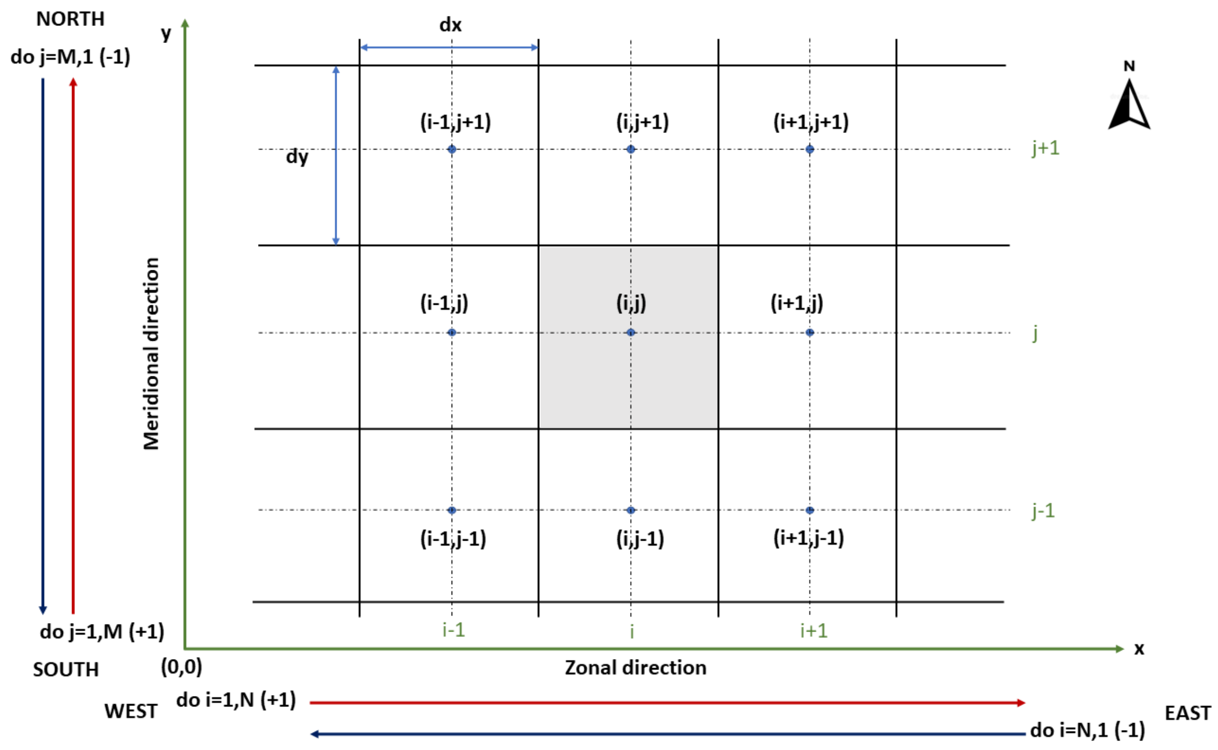
$$dt_{max} = a \cdot dx/\sqrt{gh_{ij}} < 1, \qquad a = 0.3 - 0.7$$

Adaptive timestep based on the Von Neumann condition especially for the diffusive wave case

$$dt \leq \frac{dx^2}{4(1-\theta)} \;=>\; dt = \frac{dx^2}{4} min\left(\frac{2n}{h_{flow_x}^{5/3}}\left|\frac{\partial h}{\partial x}\right|^{1/2}, \frac{2n}{h_{flow_y}^{5/3}}\left|\frac{\partial h}{\partial y}\right|^{1/2}\right)$$

Flow limiter (Q_{min} threshold) prevents instabilities in adjacent cells of very large differences in floodwater depth

$$Q_{x_{i-1/2,j}} = min\left\{calculated\ Q_{x_{i-1/2,j}}, \frac{dxdy\left(h_{i,j}^t - h_{i-1,j}^t\right)}{8dt}\right\}$$



Cross-type scanning process of the numerical grid in CoastFLOOD

Red and blue arrows represent the direction of numerical scan of the grid cells on zonal and meridional, x- and y-axis

Basic assumptions of CoastFLOOD

- Steady state forcing of the flood flow on the coastal boundary (smoothly varying sea level maxima)
- Non-treatment of the floodwater ebbing phenomenon (model considers spatiotemporally local wetting/drying of individual cells, yet computations cease when floodwater reaches the farthest area from the coastline or the waterfront)
- IF coastline SSH > MSL then h(t) ≡ SSH(t) on the seaside boundary (ghost) cell used to calculate the initial volume flux to all adjacent shoreland cells and then onto the floodplain cells
- Dirichlet-type boundary condition h=SSH−z
- To include barotropic current's effect on the momentum flux of the first land cell adjacent to the seawater cell we added an impromptu $Q_{xs}=U_{cx}\cdot d_y\cdot h_{flow,x}$ (U_c: storm surge-induced current)

Model New Features CoastFLOOD

Table 2. CoastFLOOD 2-D modified floodplain Manning coefficient list.

A/A	n	Description of Areas' Characteristics
1	0.001	open water
2	0.0115	concrete surfaces
3	0.010	rural driveways (dirt road and granules)
4	0.012	urban land uses (asphalt mixtures and other urban surface features: artificial stones, paving blocks, lightweight aggregate concrete), concrete rooftop, playground, yard, barren land
5	0.013	main asphalt roads (national, regional highway networks, autobahns, etc.)
6	0.015	brick terrain, unidentified high and low development urban environment, inland open waters (reservoirs, lakes, ponds, lagoons, estuaries)
7	0.017	city streets (asphalt, concrete, etc.)
8	0.018	unidentified/unclassified urban terrain
9	0.020	clean to gravelly earth pathways (pebbles with a small portion of cobbles), muddy/sandy open waters and sandy terrains, sea bottom (saturated wet sand or silt-sand) and channel beds
10	0.030	bare unidentified/unclassified soil
11	0.022	bare land, stone paved road and ceramic sett, or paving sett pathways
12	0.029	stony cobble lands, pastures, and farmlands
13	0.025	manmade structures, gravel beds and pathways (pebbles with nominal diameter: d_{n50} = 4–64 mm, cobbles: d_{n50} = 64–256 mm)
14	0.0375	cultivated fields and pasture, grassland (including prairies, steppes, plains)
15	0.0425	isolated sand/gravel(mixed) pits, estuary channels, and uneven urban areas
16	0.029	emerged sloping sandy beaches, sand dunes
17	0.030	managed grasslands
18	0.0115	unclassified/unidentified rural areas
19	0.033	grass surfaces
20	0.035	short stiff grass areas
21	0.0575	weeds with or without structure
22	0.0555	heavy brush floodplains
23	0.040	arable land plains, heavy/coarse gravel (boulders: d_{n50} >= 256 mm) areas, unclassified grassland, and shrubs (including savannah, meadow, veldt, pampa, tundra)
24	0.050	unclassified trees, open development areas (containing parks, streets of rural character)
25	0.055	herbaceous wetlands
26	0.067	emerged barriers
27	0.140	hardwood woodland and cultivated woodland
28	0.086	unclassified wetlands (including watersheds, salt/fresh marshes, bottomland hardwood, swamps, mangrove swamps, seagrass flats, forest swamps)
29	0.100	forest land and unidentified forest trees evergreen forest, pasture, hay, crop, vegetation
30	0.120	deciduous forest, natural grassland, herbaceous lands
31	0.150	mixed forest, shrubs, scrub, emergent herbaceous wetlands
32	0.240	cultivated vegetation
33	0.300	unidentified densely built urbanized zones (uncharacterized structures)
34	0.320	very dense tall (long trunk) trees forest (jungles, etc.)
35	0.368	very dense and/or stiff grasslands (reedy bamboo, etc.)
36	0.400	very dense small forest trees and thick shrubs

CLC uses a minimum mapping unit of 25 ha for areal phenomena and a minimum width of 100 m for linear phenomena

CLC is mainly produced on a country/state-level by visual interpretation of fine-resolution satellite imagery from Sentinel-2 and Landsat-8 (for gap filling) products

CORINE Land Cover (CLC) inventory

provides a robust record of land cover in 44 classes for Europe

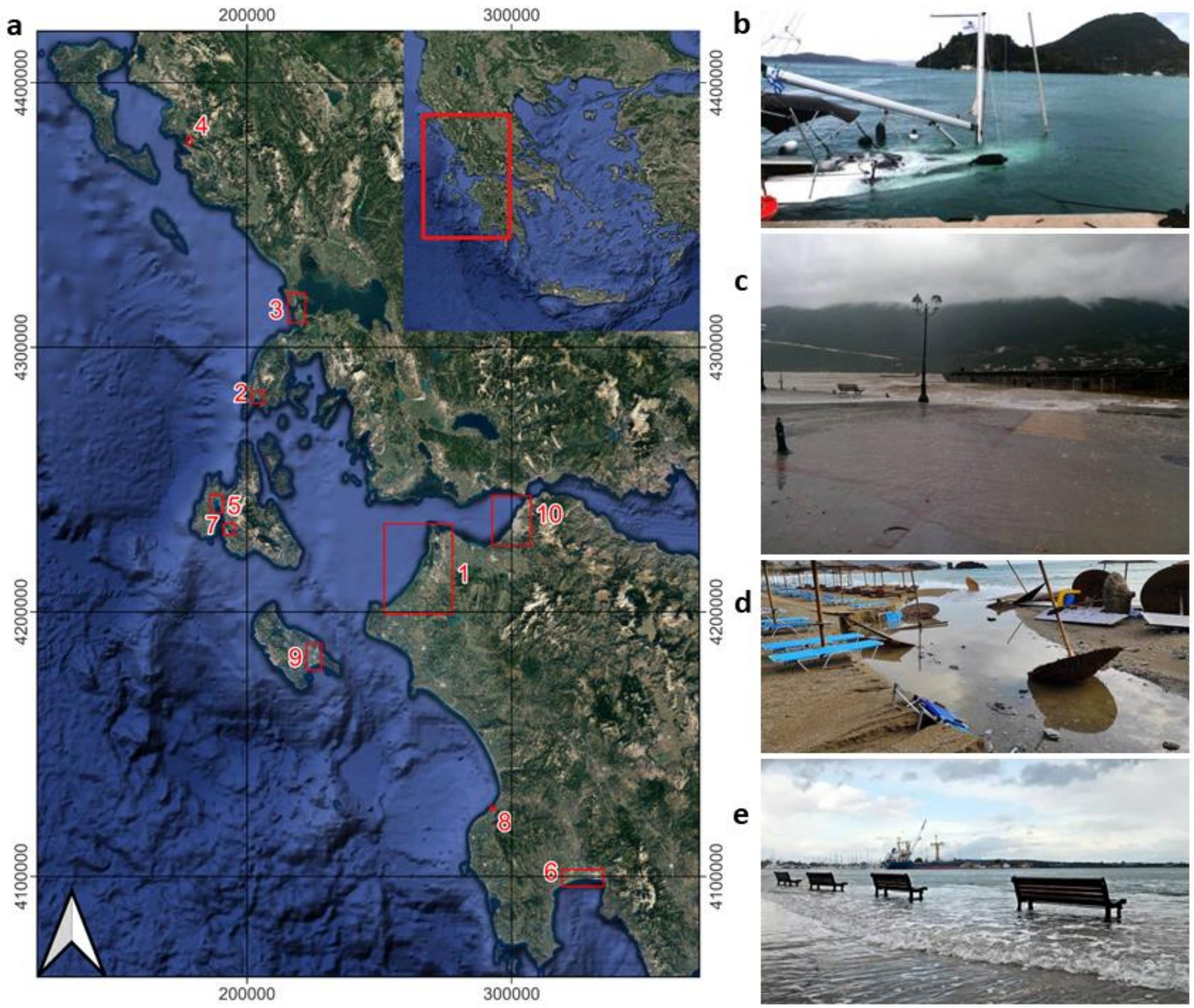
time consistency referring to 2017–2018

Copernicus Land Monitoring Service. Available online:

https://land.copernicus.eu/pan-european/corine-land-cover

(accessed on 20 April 2023)

Case Studies   Mediterranean Sea   Greek coastal zone



a) Map of selected study areas to apply the CoastFLOOD model areas

1: Manolada-Lechaina

2: Vassiliki bay

3: Preveza coastal area

4: Igoumenitsa port

5: Livadi bay

6: Kalamata

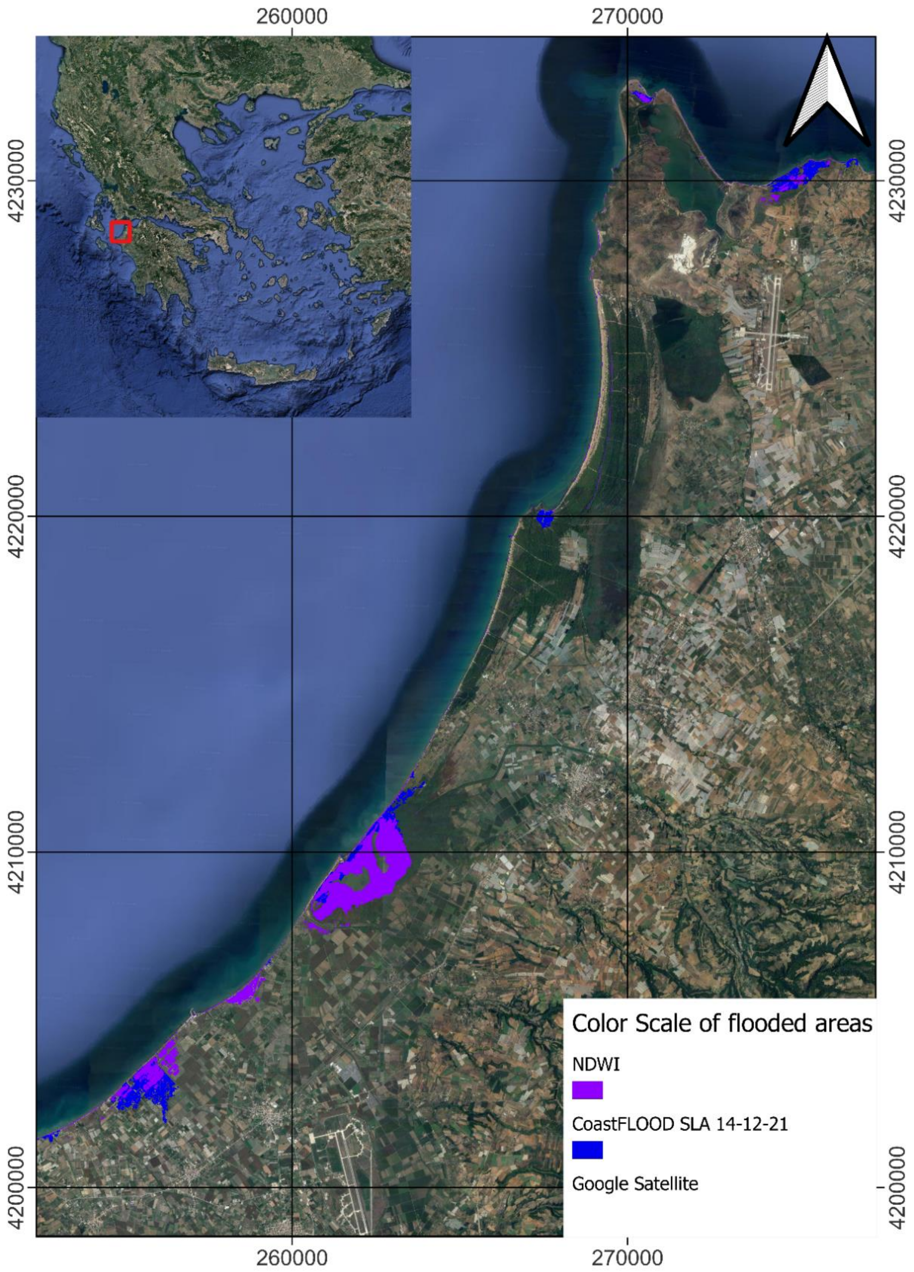
7: Argostoli

8: Kyparissia

9: Laganas

10: Patra city

b-e) Depiction of coastal inundation damages due to “Ianos” Medicane (September 2020) “Ballos” storm (October 2021)



Map of estimated flooded areas as depicted by

- NDWI satellite data (purple color)

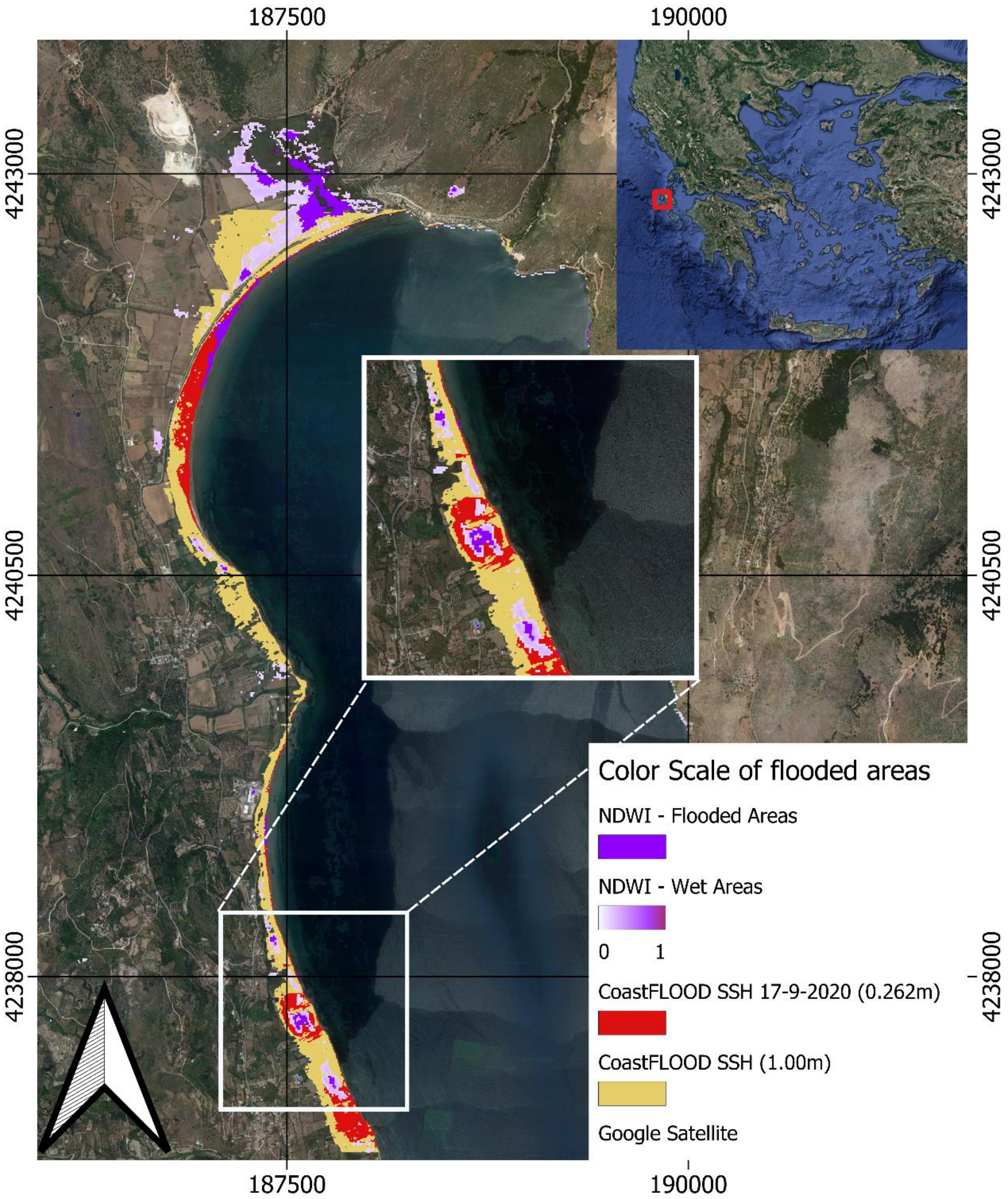
overlaid on

- CoastFLOOD simulation results (blue color)

driven by recorded SLA values on 14 December 2021

for the Manolada-Lechaina study area (NW Peloponnese)

Flooded areas’ extents over background of recent GoogleEarth satellite images



Map of estimated flooded and wet areas as depicted by

- NDWI differences by satellite data before and after Ianos Medicane passage from the study area (white-to-purple color shift corresponding to 0–1 of NDWI values

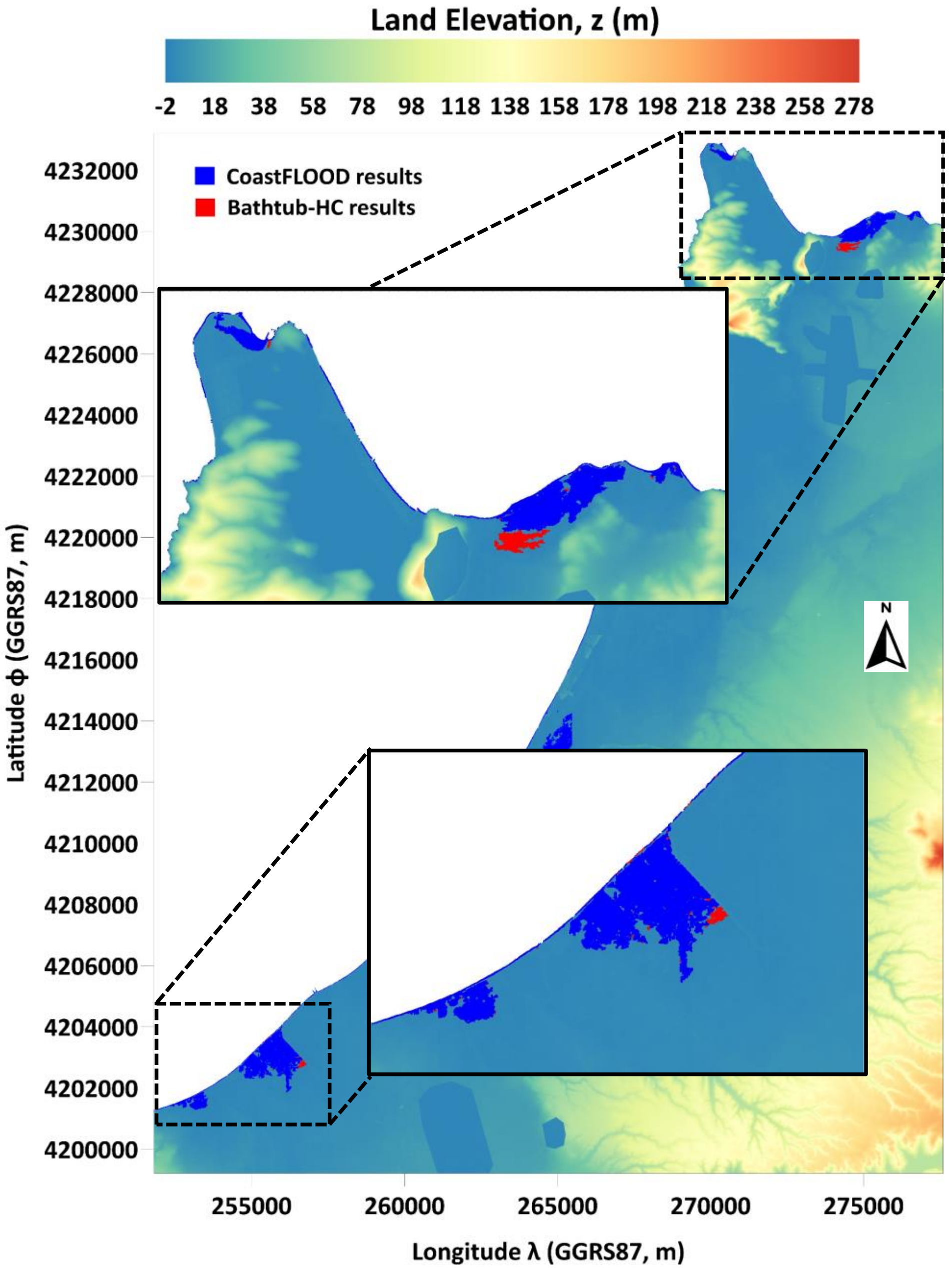
overlaid on

- CoastFLOOD simulation results driven by HiReSS-modelled SSH from operational forecasts by the WaveForUs system during Ianos Medicane landfall on 17 September 2020 (red color)

for the Livadi study area, on Cephalonia Island, in the Ionian Sea

Modelled flood area extents for extreme case scenario of TWL = 1 m is also provided in yellow color

Results   Model Validation   CoastFLOOD vs Bathtub-HC



Model performance metric

Goodness-of-Fit

> 0.95

$$GoF = \frac{FA_{mod_{CF}} \cap FA_{est_{BHC}}}{FA_{mod_{CF}} \cup FA_{est_{BHC}}}$$

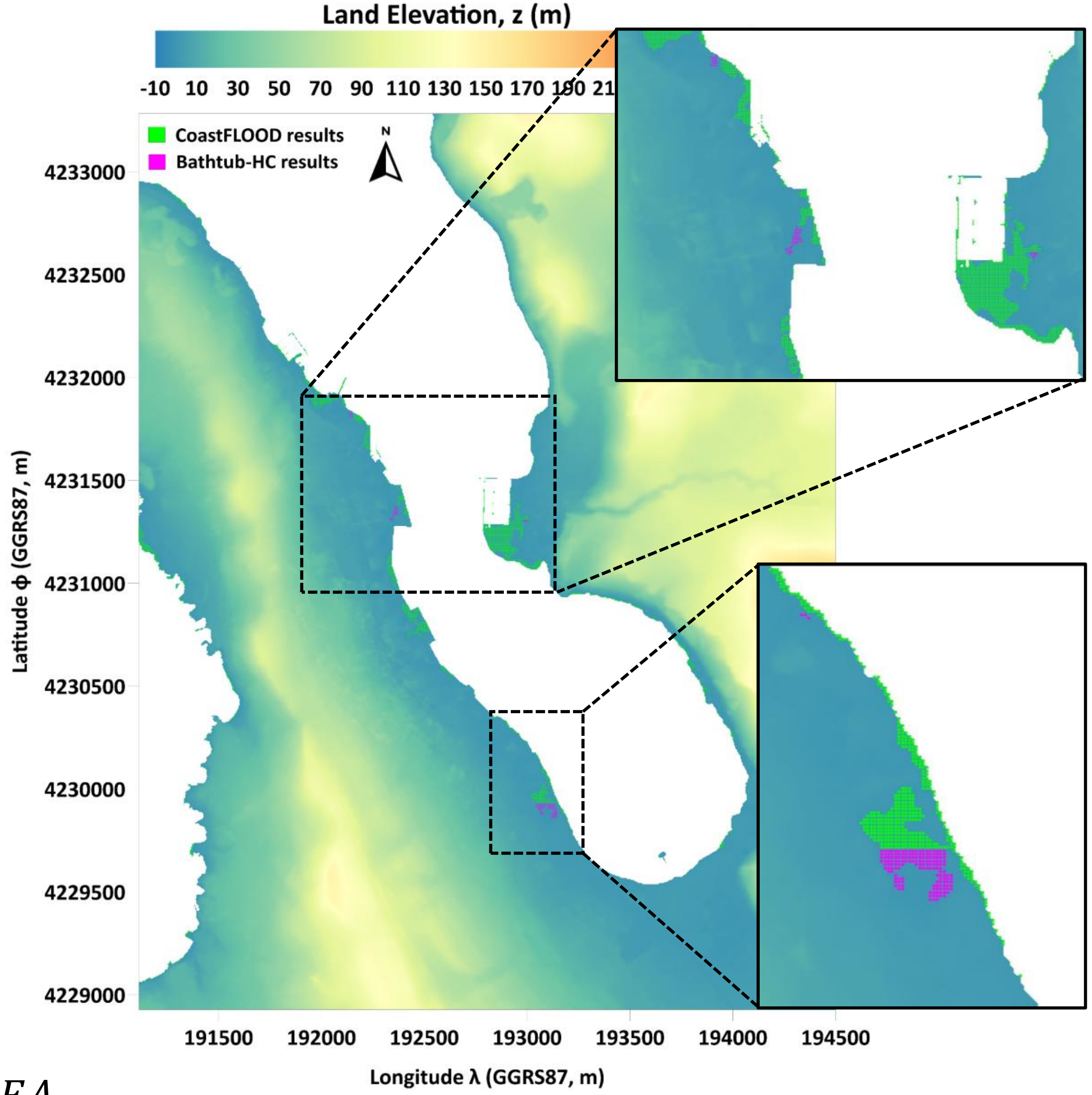


Table 4. Timeframe for Maximum Flood Inundation Reach, t_{MIR}.

SLA (m)	0.2–0.3	0.5	1	1.5	2
Study Area			t_{MIR} (hrs)		
Laganas	4.25	3.61	4.45	6.40	8.87
Kyparissia	0.82	0.72	1.12	1.98	2.21
Kalamata	3.96	5.13	25.76	28.59	32.79
Patra	14.46	15.93	50.12	77.39	81.97
Vassiliki	0.18	0.45	1.11	4.21	8.90
Livadi	0.22	0.49	5.33	19.87	38.43
Igoumenitsa	0.20	0.32	0.93	3.76	5.28
Argostoli	0.67	1.57	6.97	9.23	10.18

* *The two highlighted rows correspond to exceptional cases of counterintuitively higher values of t_{MIR} for lower values of SLA = 0.2–0.3 m.*

Interesting feature: formulation of timeframe for maximum flood inundation reach $\mathbf{t_{MIR}}$ in some study cases

The pattern of tMIR is similar and, in general, increasing for the ascending values of SLA_{max}=0.2–2m

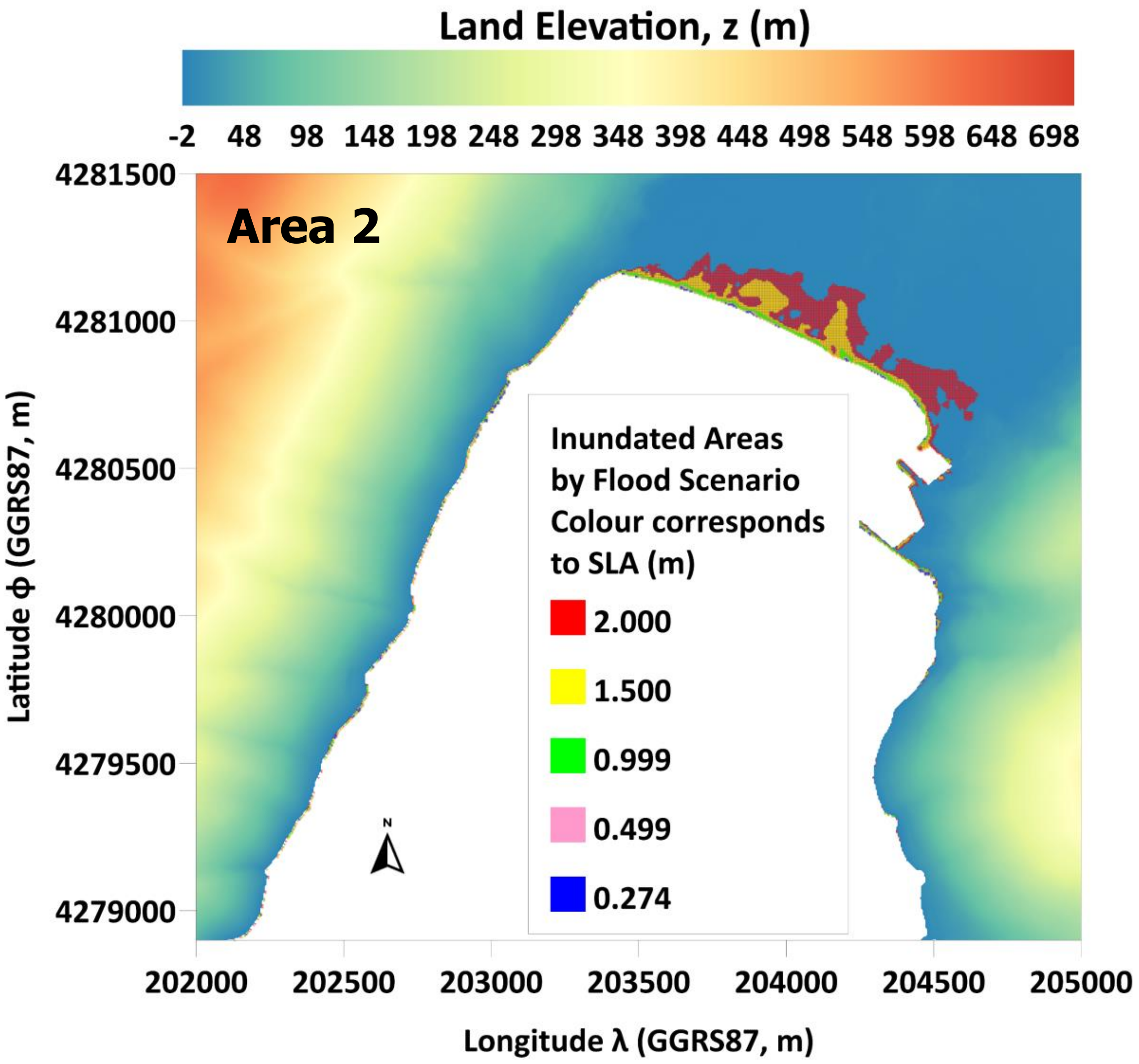
except from Laganas and Kyparissia case studies

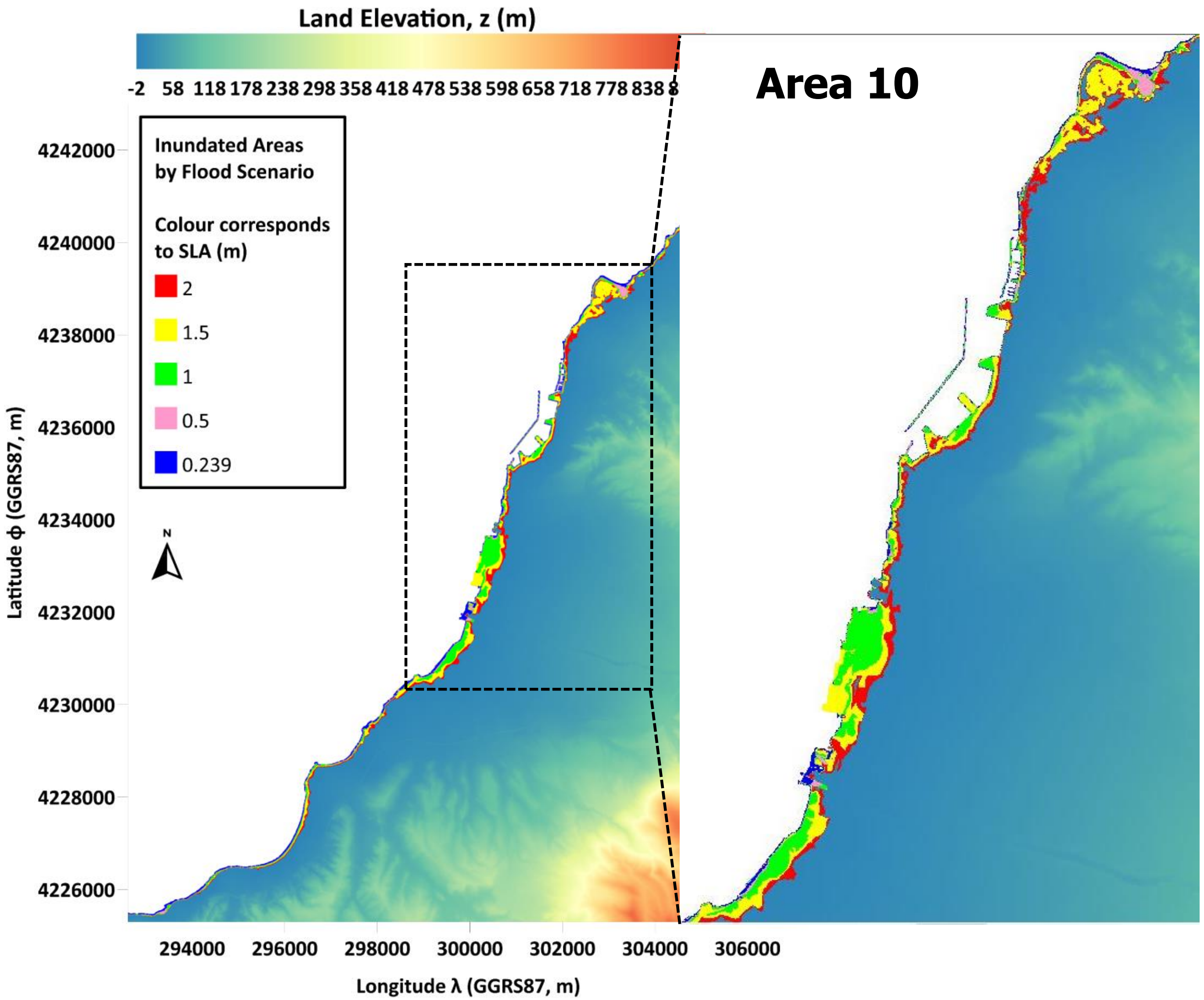
where for lower values of recorded SLA_{max}=0.2–0.3m

t_{MIR} is counterintuitively quite high > t_{MIR} of larger SLAs and consequent inundation extents

Probably reasonable because lower SLA values on the coastline drive **much slower inundation flows** than larger storm surge levels, since shoreline SLA/SSH acts as the main formulation factor of the hydraulic head of the flood front propagation

1. **Flood hazard maps (inundated areas extents)**
2. **Impacted areas of the raster grid**





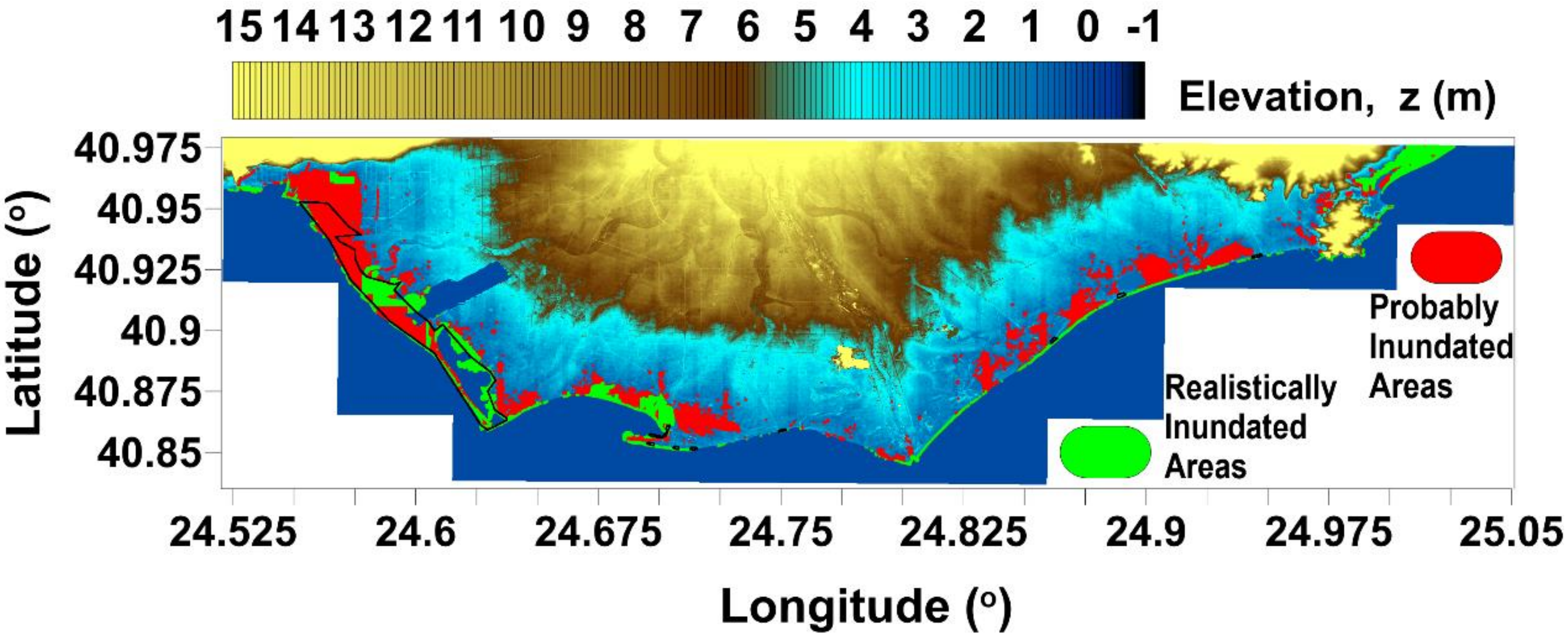


Illustration of the simulated results of storm surge inundation in low-land areas coastal for a theoretical extreme value of SSH = 1 m, in Nestos river delta. Red color refers to probably inundated low-land areas; green color refers to actually inundated areas by realistic CoastFLOOD simulations

black closed lines refer to possibly affected areas (lagoons; urban, port and touristic areas).

MeCSS-driven CoastFLOOD (M-CF) model results

A) Flooded Area FA (ha)

Study Case		A			B			C		
Scenario	Period	CMCC M-CF *FA* (ha)	CNRM M-CF *FA* (ha)	GUF M-CF *FA* (ha)	CMCC M-CF *Diff* (%)	CNRM M-CF *Diff* (%)	GUF M-CF *Diff* (%)	CMCC-CNRM M-CF *Diff* (%)	CNRM-GUF M-CF *Diff* (%)	GUF-CMCC M-CF *Diff* (%)
Historical	RP	380.897	354.832	452.257	0	0	0	7.09	-24.14	17.13
RCP4.5	STF	381.420	358.847	447.705	0.14	1.13	-1.01	6.10	-22.03	15.99
RCP4.5	LTF	352.045	356.615	382.425	-7.57	0.50	-15.44	-1.29	-6.98	8.27
RCP8.5	STF	365.465	377.780	359.442	-4.05	6.47	-20.52	-3.31	4.97	-1.66
RCP8.5	LTF	359.477	365.055	383.352	-5.62	2.88	-15.24	-1.54	-4.89	6.43

A) Flooded Probability FP (%)

Study Case		A			B			C		
Scenario	Period	CMCC M-CF *FP* (%)	CNRM M-CF *FP* (%)	GUF M-CF *FP* (%)	CMCC M-CF *Diff* (%)	CNRM M-CF *Diff* (%)	GUF M-CF *Diff* (%)	CMCC-CNRM M-CF *Diff* (%)	CNRM-GUF M-CF *Diff* (%)	GUF-CMCC M-CF *Diff* (%)
Historical	RP	0.15	0.09	0.35	0	0	0	44.90	-115.18	80.72
RCP4.5	STF	0.09	0.01	0.35	-38.66	-91.58	0.86	168.00	-191.21	117.86
RCP4.5	LTF	0.08	0.03	0.25	-42.34	-65.32	-27.67	89.66	-154.29	98.79
RCP8.5	STF	0.10	0.10	0.23	-33.99	8.43	-32.01	-3.96	-79.88	83.19
RCP8.5	LTF	0.04	0.05	0.15	-73.23	-46.90	-57.42	-22.72	-99.49	115.67

B) respective differences Diff (%)

between climatic scenario runs

C) Diff (%) by different forcing input

as CMCC-, CNRM-, GUF-forced MeCSS

Impact Risk Assessment CoastFLOOD

Risk = Probability × Consequence

Risk matrix for **CFRI** (Coastal Flood Risk Index) *refers to large scale coastal inundation by extreme storm surge events, defined by the seawater flooded area and the corresponding flood probability derived with the coupled MeCSS-CoastFLOOD model*

PERIOD	RP: 1971-2000
RCM \ WCS	REF
CMCC	2
CNRM	1
GUF	5

SCENARIO \ PERIOD		STF: 2021-2050			LTF: 2071-2100		
RCP	RCM \ WCS	REF	CC	EXT	REF	CC	EXT
4.5	CMCC	1	1	1	1	1	1
	CNRM	1	1	1	1	1	1
	GUF	5	5	5	3	3	3
8.5	CMCC	2	2	2	1	1	1
	CNRM	2	2	2	1	1	1
	GUF	3	3	3	2	2	2

CFRI COLOR SCALE		
RANK	VALUE	COLOR
VERY LOW	1	
LOW	2	
MODERATE	3	
HIGH	4	
VERY HIGH	5	

$$R = H \times V$$

R is risk

H is hazard

V is vulnerability

$$V = \frac{E \times S}{C}$$

E is exposure

S is sensitivity

C is adaptive capacity

Discussion

- Storm-induced sea level conditions should last for at least a few hours and up to 3 days, given that it does not abruptly change in time but follows the slow smooth variation of e.g. the tidal component
- Approach ideal for scenarios of long-term MSLR or Total Water Level (TWL) on the coastline
- Approach actually ignores the momentum exchange effects between neighboring cells in the floodplain, therefore introduces a restricted physical interpretation of the flow characteristics
- Can capture all the dominant features of the shallow seawater onshore flow which leads to the rather slow propagation process (thus, seawater flux may be neglected) of coastal inundation
- Inclusion of coastal currents does not seem to drastically influence the inland flood inundation extent but it is a step towards improvement of the physical representation of onshore seawater flow
- Main disadvantage of reduced complexity flood models is the oversight of sub-grid scale features of the flow e.g. cavitation, recirculation, aeration, debris advection, and viscosity effects
- Does not include 1-D urban flood flow yet, i.e. fine-scale spatial features (drainage systems, sewers, conduits, bridge culverts, pools, and drillings)
- Neglects percolative interaction with porous bed and downward infiltration to aquifers (however, these flows are usually very slow processes compared to the hydraulic propagation of flood fronts, cannot significantly influence the hydrodynamics of inundation)
- Need for integration with fluvial and pluvial (surface runoff) inundation for a proper compound flooding estimation

Conclusions

- New code (CoastFLOOD) in FORTRAN-95 for classic modelling approach of 2-D hydraulic flood flow in coastal areas
- Concept: reduced complexity, high-resolution, storage-cell, mass balance flood inundation for coastal lowlands; simplified Manning-type flow equation running on a fine-scale GIS raster-based domain
- CoastFLOOD relies on computational efficiency and delivery of stable simulations with robust results
- Model performance evaluated for predicted and observed storm surges affected by tidal components of sea level elevation (storm tides)
- Model applied in operational forecast applications and long-term climatic or short-term extreme scenarios of TWL (also considering an estimative mean condition for wave runup)
- Model results slightly overpredict recorded flood extents because the satellite data are not totally accurate to represent the actual situation of floodwater extents during the storm surge (due to cloud contamination, not representative of the maximum flood reach)
- Predicted flood extents on the southern coastal zone of Cephalonia Island (Area 5) overlap and include the wet areas traced by remote sensing (on the safe side in terms of engineering and coastal management)
- Validation of CoastFLOOD vs. Bathtub-HC approach: agreement quite high GoF scores >0.95
- Vey detailed depiction of bottom roughness connected to official land cover data
- No availability of benchmark tests for geophysical scale flows
- Uncertainties of field data stem from the additional sources of floodwater inundation, except from storm tides, e.g., wind waves and swell, surface runoff, precipitation, etc.