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Floodplain mapping via 1D and quasi-2D numerical models in the valley of Thessaly, Greece

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1. Abstract

The European Union Floods Directive defines a flood as ‘a covering by water of land not normally covered by water’. Human activities, such as agriculture, urban development, industry and tourism, contribute to an increase in the likelihood and adverse impacts of flood events. The study of the hydraulic behaviour of a river is important in flood risk management. Here, we investigate the behaviour of three hydraulic models, with different theoretical frameworks, in a real case scenario. The area is located in the Penios river basin, in the plain of Thessaly (Greece). The three models used are the one-dimensional HEC-RAS and the quasi two-dimensional LISFLOOD-FP and FLO-2D which are compared to each other, in terms of simulated maximum water depth as well as maximum flow velocity, and to a real flood event. Moreover, a sensitivity analysis is performed to determine how each simulation is affected by the river and floodplain roughness coefficient, in terms of flood inundation.

2. Introduction

The 2007/60/EC Directive implementation by Member States requires flood hazard and flood risk maps for low, medium (likely return period ≥100 years) and high flood probability. In this context, hydraulic models are widely used for simulating flood events and mapping the resulting flooded areas. Comparing such models leads to conclusions about their performance under specific scenarios and their particularities . In this study three models are used: one 1D (HEC-RAS) and two quasi-2D (LISFLOOD-FP and FLO-2D). The study area is located at Thessaly, in central Greece (Figure 1) and extended to a length of 40 km, from the Ali Efenti (upstream) to Amygdalia (downstream) locations at the western basin of Penios river. The area of the basin is over 6300 km^2, with an average annual rainfall of 779 mm.

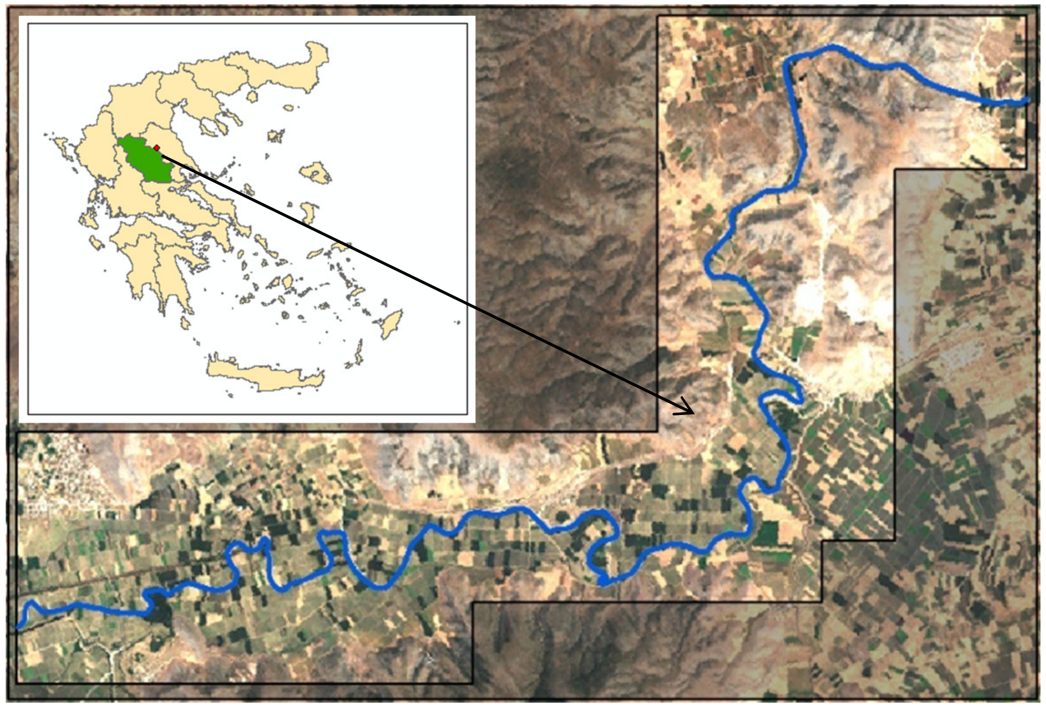


Figure 1: study area

All three models are calibrated based on a recorded Landsat image flood event (figure 3), on 28/1/2003. The calibration parameters are the river and floodplain Manning’s coefficients as well as the river discharge. The flood event occurred on 21-28 January 2003.

3. Elevation and satellite data

Elevation data are critical for hydraulic simulation. A 5 m × 5 m Digital Elevation Model (DEM) with a 2 m vertical accuracy is available (Figure 2). To increase the accuracy of the DEM, editing of the raw dataset is necessary. This is accomplished in a way that the main river line coincides with the edge of the slope change and the deepest line of flow.

Due to the size of the study area and the cell size limitations imposed by one of the models, a coarser DEM is produced with 50 m × 50 m analysis.

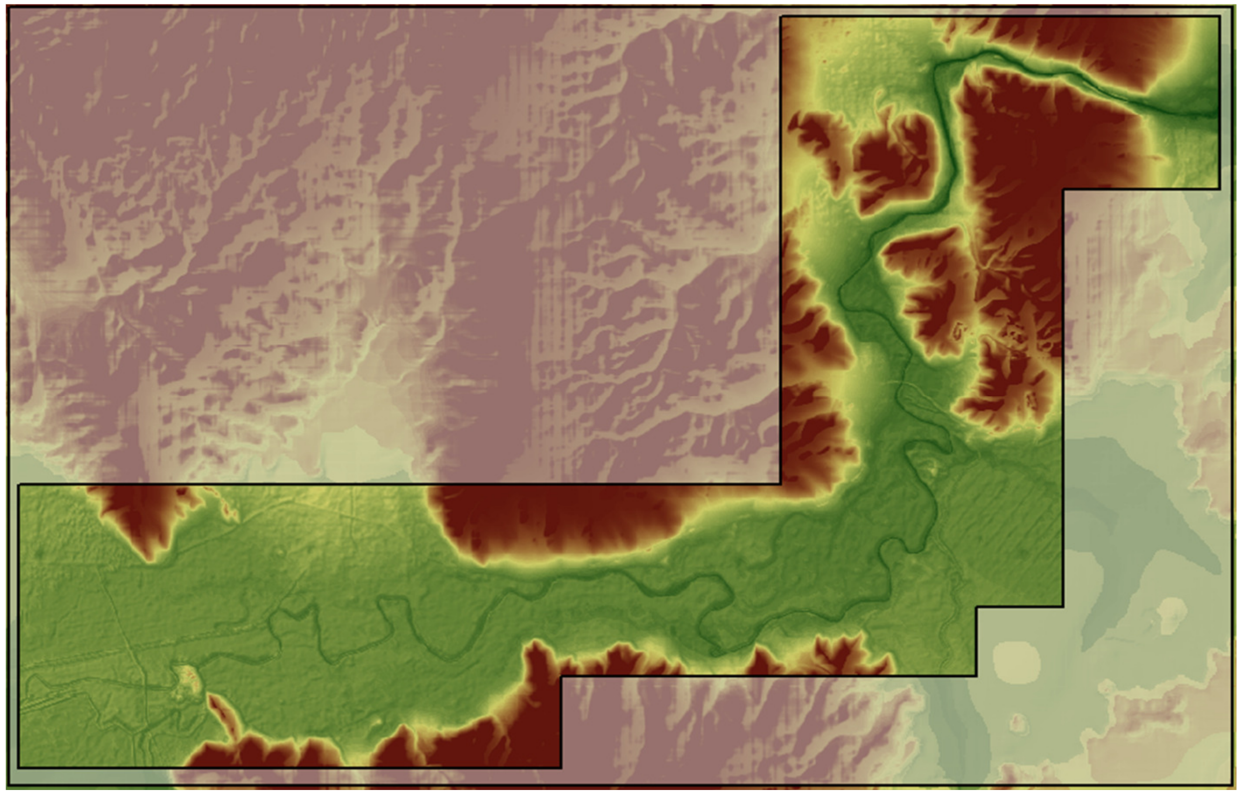


Figure 2: Study area DEM

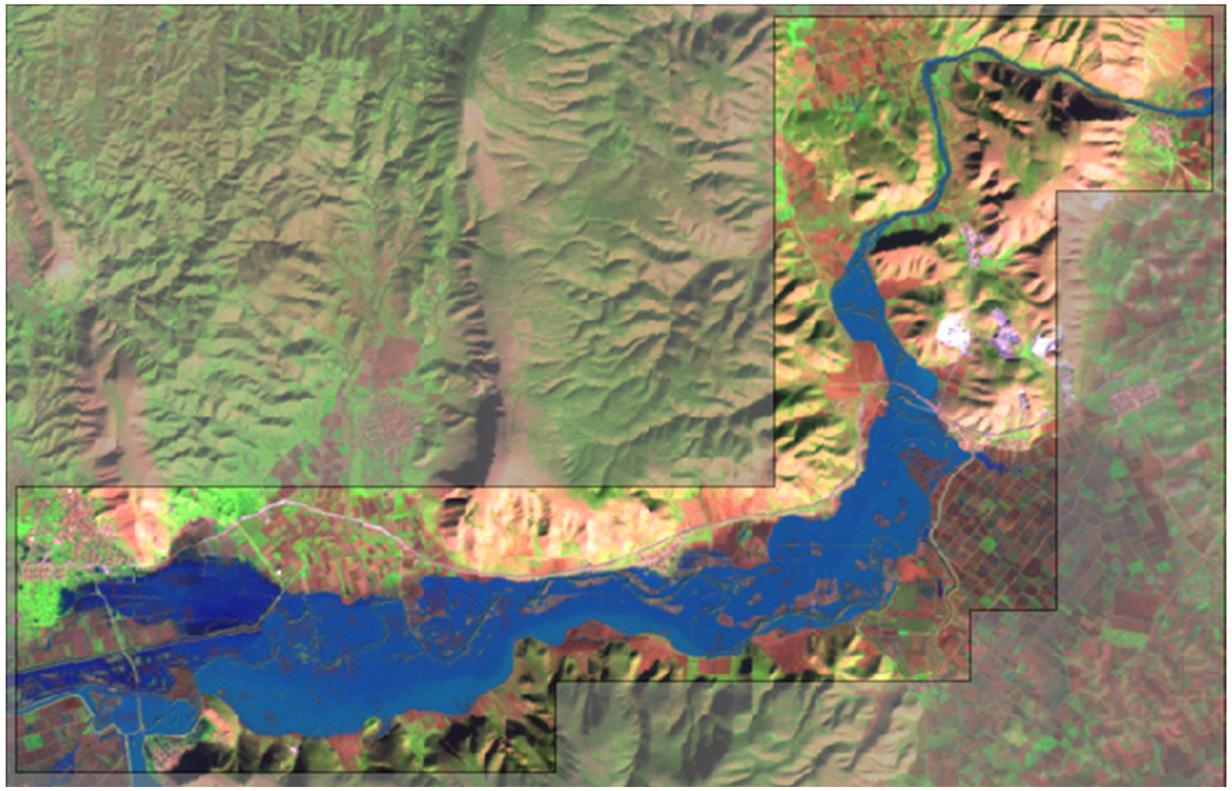


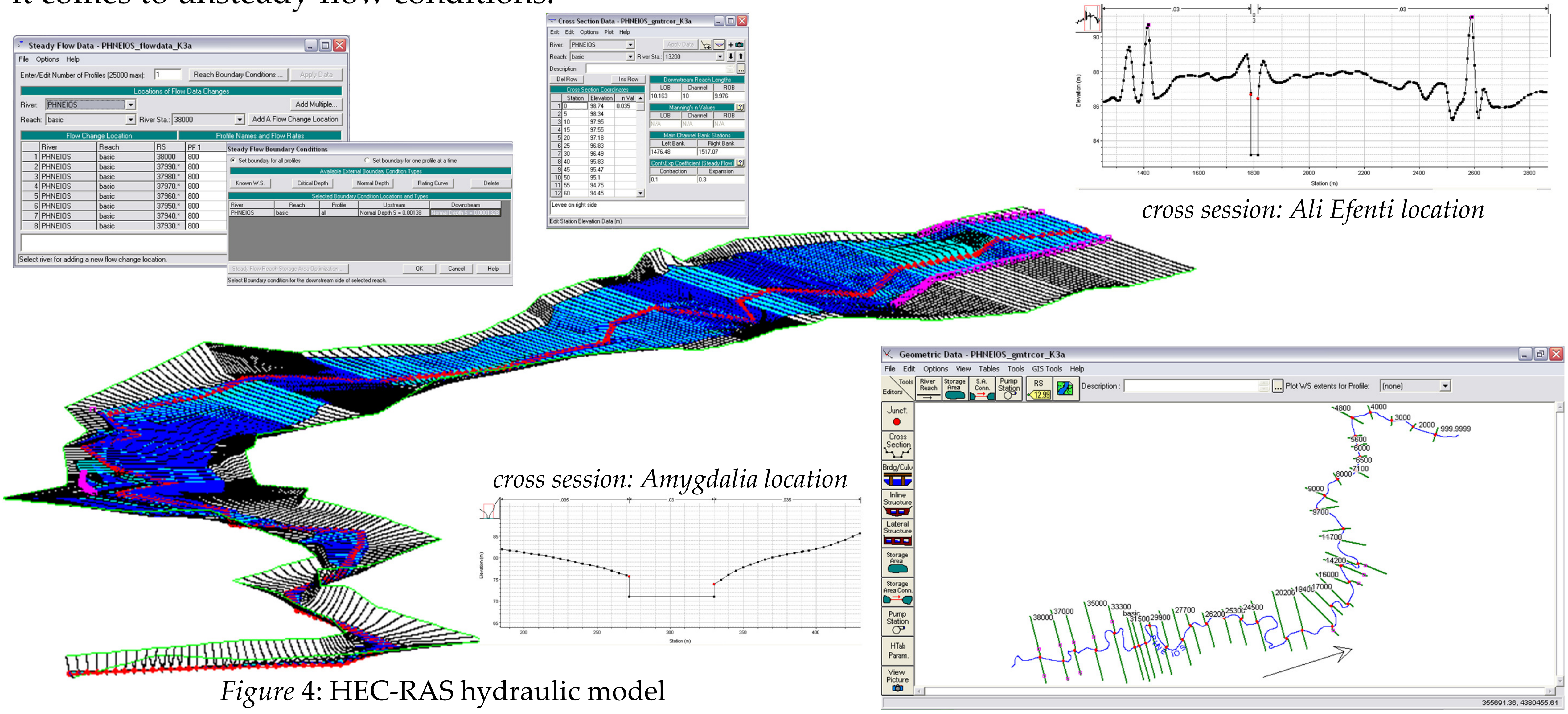
Figure 3: Landsat-7 satellite image (flooded area)

Still, the original finer analysis of 5 m × 5 m is used to compare two of the models (see section 9).

The extent of the flood is estimated with a semi-automated methodology to distinguish stagnant water from soil, using an averaged image of the infrared channel 5 of the Landsat ETM+ system (http://landsat.usgs.gov/). Note that the visibility limit of the image is 30 m (on the soil).

4. HEC-RAS

HEC-RAS (http://www.hec.usace.army.mil/software/hec-ras/) is a freeware 1D hydraulic model, which estimates the flow characteristics (e.g. free surface elevation, mean velocity) in a cross section, under steady and non-steady flow conditions. It solves the 1D dynamic wave equation using an implicit finite difference method. The required initial data are the geometry of the cross section, the Manning coefficient along the cross section, the inflow discharge and hydraulic boundary conditions (Bruner, 2010). It is noted that, based on research experience, it provides adequate results in cases of steep and narrow channels but it deviates from reality in cases of floodplains with small gradients. Also, it experiences difficulties when it comes to unsteady flow conditions.



Steady Flow Data - PHNEIOS_flowdata_K3a

Enter/Edit Number of Profiles (25000 max): 1

Locations of Flow Data Changes

River: PHNEIOS

Reach: basic   River Sta.: 38000

	Flow Change Location			Profile Names and Flow Rates
	River	Reach	RS	PF 1
1	PHNEIOS	basic	38000	800
2	PHNEIOS	basic	37990.*	800
3	PHNEIOS	basic	37980.*	800
4	PHNEIOS	basic	37970.*	800
5	PHNEIOS	basic	37960.*	800
6	PHNEIOS	basic	37950.*	800
7	PHNEIOS	basic	37940.*	800
8	PHNEIOS	basic	37930.*	800

Select river for adding a new flow change location.

Steady Flow Boundary Conditions

● Set boundary for all profiles   ○ Set boundary for one profile at a time

Available External Boundary Condtion Types

Selected Boundary Condition Locations and Types

River	Reach	Profile	Upstream	Downstream
PHNEIOS	basic	all	Normal Depth S = 0.00138	Normal Depth S = 0.0001328

Select Boundary condition for the downstream side of selected reach.

Cross Section Data - PHNEIOS_gmtrcor_K3a

River: PHNEIOS

Reach: basic   River Sta.: 13200

Description:

Cross Section Coordinates

	Station	Elevation	n Val
1	0	98.74	0.035
2	5	98.34	
3	10	97.95	
4	15	97.55	
5	20	97.18	
6	25	96.83	
7	30	96.49	
8	40	95.83	
9	45	95.47	
10	50	95.1	
11	55	94.75	
12	60	94.45	

Downstream Reach Lengths

LOB	Channel	ROB
10.163	10	9.976

Manning's n Values

LOB	Channel	ROB
N/A	N/A	N/A

Main Channel Bank Stations

Left Bank	Right Bank
1476.48	1517.07

Cont\Exp Coefficient (Steady Flow)

Contraction	Expansion
0.1	0.3

Levee on right side

Edit Station Elevation Data (m)

Geometric Data - PHNEIOS_gmtrcor_K3a

Description:

Plot WS extents for Profile: (none)

355691.36, 4380455.61

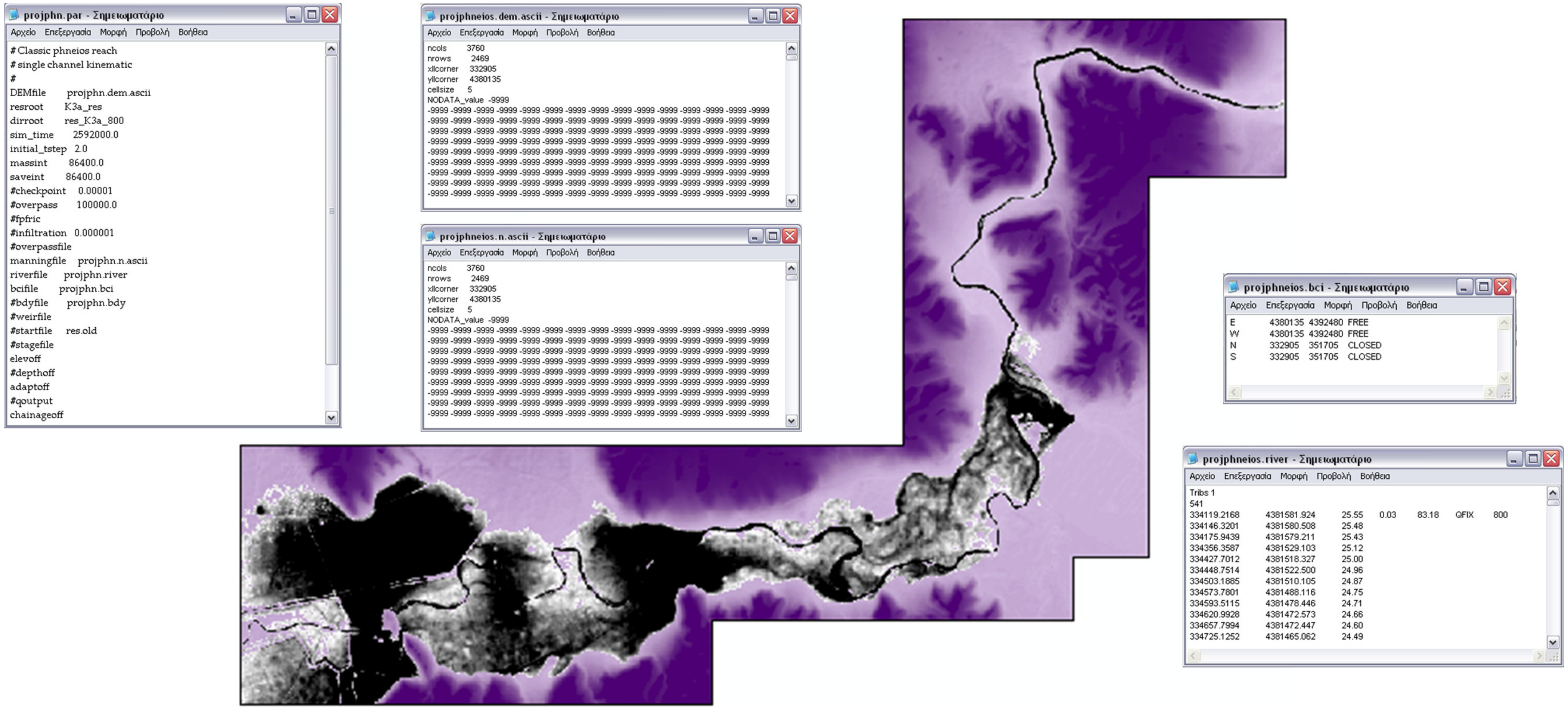
cross session: Ali Efenti location

cross session: Amygdalia location

Figure 4: HEC-RAS hydraulic model

5. LISFLOOD-FP

LISFLOOD-FP (http://www.bris.ac.uk/geography/research/hydrology/models/lisflood) is a freeware quasi-2D hydraulic model, which estimates only the flow depth across the grid elements, under steady and non-steady flow conditions. It uses the Manning equation along the river and the 1D kinematic wave equation for lateral flow expansion. The required initial data are a DEM, the river location and its mean depth and width (the model assumes a rectangular cross section), the inflow discharge and some simple hydraulic boundary conditions (Bates et al., 2005). It is noted that, based on research experience, it provides adequate results for large basins with narrow rivers, up to 10^6 grid cells of any realistic size can be used and is convenient for applying probabilistic approaches based on multiple runs.



```
# Classic phneios reach
# single channel kinematic
#
DEMfile      projphn.dem.ascii
resroot      K3a_res
dirroot      res_K3a_800
sim_time      2592000.0
initial_tstep  2.0
massint      86400.0
saveint      86400.0
#checkpoint   0.00001
#overpass     100000.0
#fpfric
#infiltration  0.000001
#overpassfile
manningfile   projphn.n.ascii
riverfile    projphn.river
bcifile     projphn.bci
#bdyfile     projphn.bdy
#weirfile
#startfile    res.old
#stagefile
elevoff
#depthoff
adaptoff
#qoutput
chainageoff
```

```
ncols       3760
nrows        2469
xllcorner    332905
yllcorner    4380135
cellsize     5
NODATA_value  -9999
-9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999
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nrows        2469
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yllcorner    4380135
cellsize     5
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```

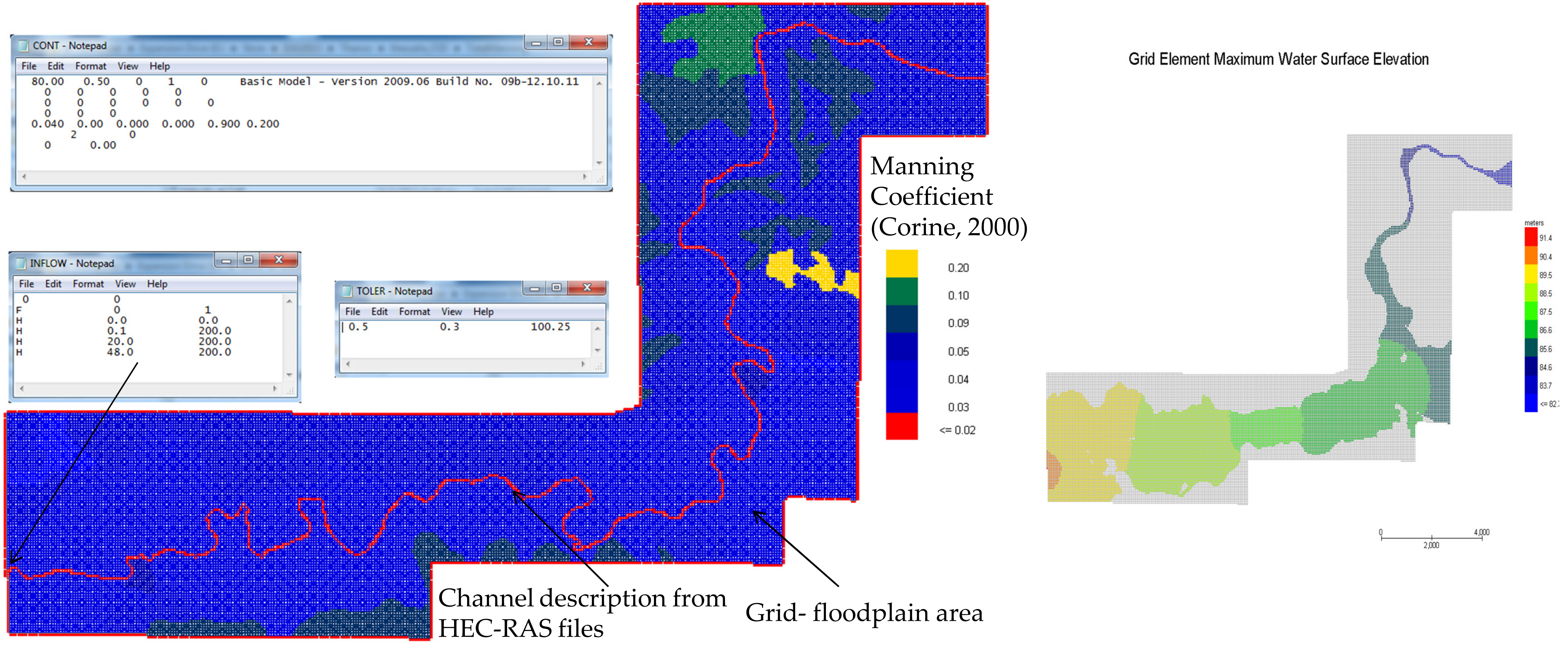
```
E         4380135  4392480  FREE
W         4380135  4392480  FREE
N         332905   351705   CLOSED
S         332905   351705   CLOSED
```

```
Tribs 1
541
334119.2168       4381581.924       25.55     0.03      83.18     QFIX      800
334146.3201       4381580.508       25.48
334175.9439       4381579.211       25.43
334356.3587       4381529.103       25.12
334427.7012       4381518.327       25.00
334448.7514       4381522.500       24.96
334503.1885       4381510.105       24.87
334573.7801       4381488.116       24.75
334593.5115       4381478.446       24.71
334620.9928       4381472.573       24.66
334657.7994       4381472.447       24.60
334725.1252       4381465.062       24.49
```

Figure 5: LISFLOOD-FP hydraulic model

6. FLO-2D

FLO-2D (http://www.flo-2d.com/) is a freeware quasi-2D hydraulic model, which estimates the maximum flow depth across the grid elements, under steady and non-steady flow conditions. It uses the 1D dynamic wave equation for the main and lateral flow direction. It is noted that, based on research experience, it provides adequate results for any type of topography but it experiences difficulties when it comes to small grid size. In this study, input data are a DEM, the inflow discharge and some simple hydraulic boundary conditions. Also, channel geometry, being time consuming, is left out and only river location is considered.



CONT - Notepad

```
 80.00   0.50    0    1    0      Basic Model - Version 2009.06 Build No. 09b-12.10.11
    0     0     0     0     0
    0     0     0     0     0     0
    0     0     0
 0.040  0.00  0.000  0.000  0.900 0.200
       2          0
    0      0.00
```

INFLOW - Notepad

```
 0                0
F                 0                1
H                0.0              0.0
H                0.1              200.0
H                20.0             200.0
H                48.0             200.0
```

TOLER - Notepad

```
| 0.5             0.3              100.25
```

Figure 6: FLO-2D hydrodynamic model

7. Model comparison (common scenario)

For a direct model comparison the chosen scenario assumes 800 m^3/s steady flow and common roughness coefficient in both channel and floodplain equal to 0.03 $m^{-1/3}$ s. As can be observed from figure 7, flood inundation is extended more in the case of LISFLOOD-FP and FLO-2D rather than in HEC-RAS. Also, it can be seen that according to HEC-RAS, flood does not cover entirely the upstream small basin (shown in red circle). This is due to HEC-RAS prevention of multiple flow directions within a single cross section.

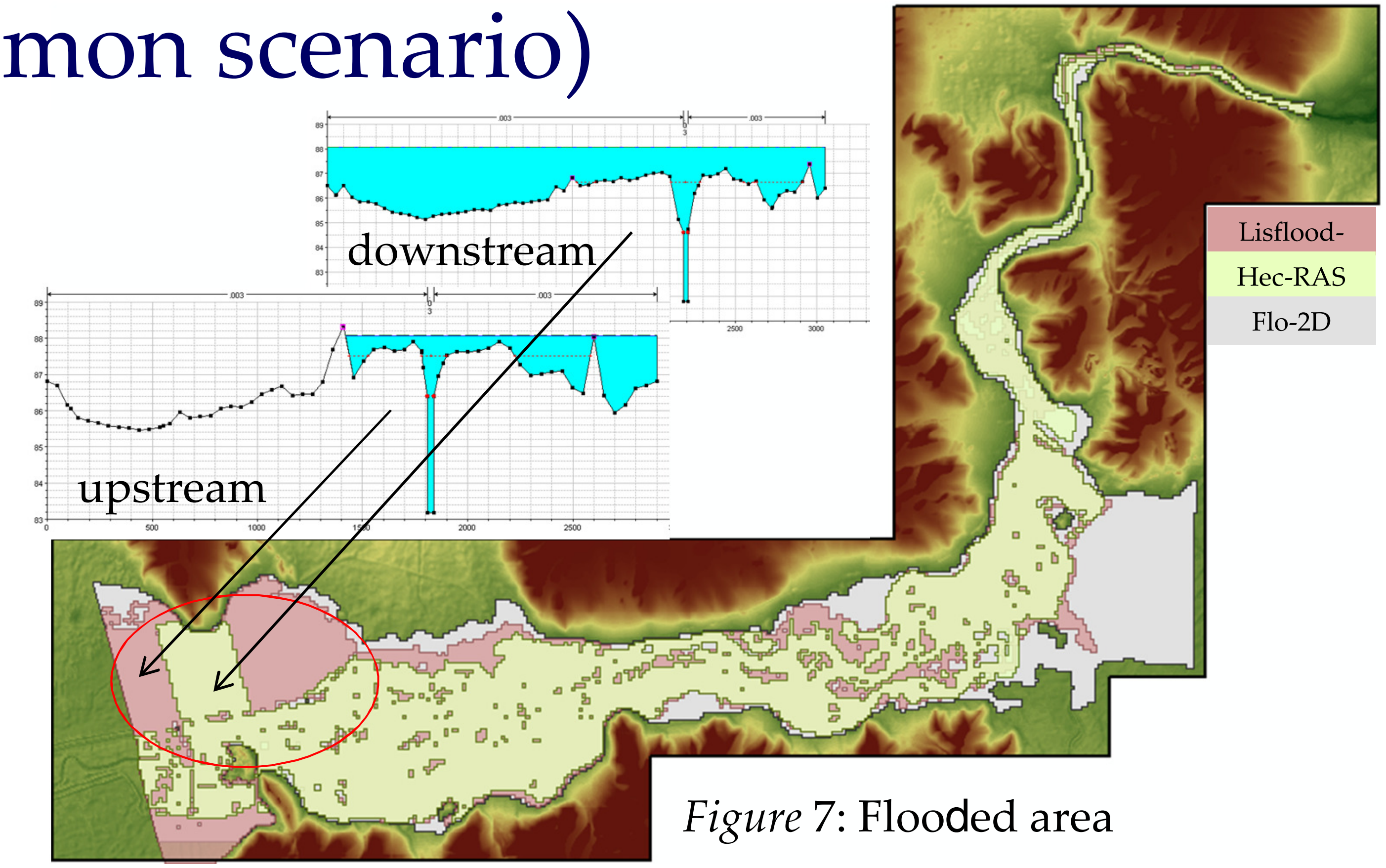


Figure 7: Flooded area

water depth (m)			floodplain *n* ($m^{-1/3}$s)		
			0.003	**0.03**	**0.3**
Lisflood-FP	**channel n ($m^{-1/3}$s)**	**0.003**	2.23	2.23	2.23
		0.03	5.65	5.78	6.36
		0.3	6.90	7.17	8.31
Hec-RAS		**0.003**	1.64	1.64	1.62
		0.03	6.05	7.9	8.83
		0.3	6.79	11.29	19.47
Flo-2D		**0.003**	11	10.11	5.74
		0.03	9.41	10.12	6.39
		0.3	11.37	11.57	10.17

Table 1: Water depth at the outflow point

To introduce a probabilistic view of the flood mapping necessary when simulating floods (di Baldassare et al. 2010), a sensitivity analysis is made based on the channel and floodplains Manning's coefficients. Three values of the coefficient are being tested, the dominant value in the study area of 0.03 $m^{-1/3}$ s (used for permanently irrigated land) and two extreme (and unrealistic) values of 0.3 and 0.003 $m^{-1/3}$ s; and the water depth at the river's outflow location is recorded (table 1 and figures 7, 8, 9 and 10).

It can be observed that the models are very sensitive concerning the channel's roughness coefficient opposing to the floodplains' one. Also, it can be seen that the FLO-2D results are very different than in the other models due to the absence of channel simulation.

8. Model comparison (common scenario; contd.)

In the figures below, it can be noted that in the cases of LISFLOOD-FP and FLO-2D simulations, the resulted flood is more uniformly distributed in contrast to the HEC-RAS one, which evaluates the flood routing from cross-section to cross-section, creating in certain cases abnormal discontinuities.

Moreover, it can be seen that the flow has spread more in the FLO-2D simulation rather than in the other two models showing also the lack of sensitivity for the Manning coefficient in the channel as well as in the floodplain areas.

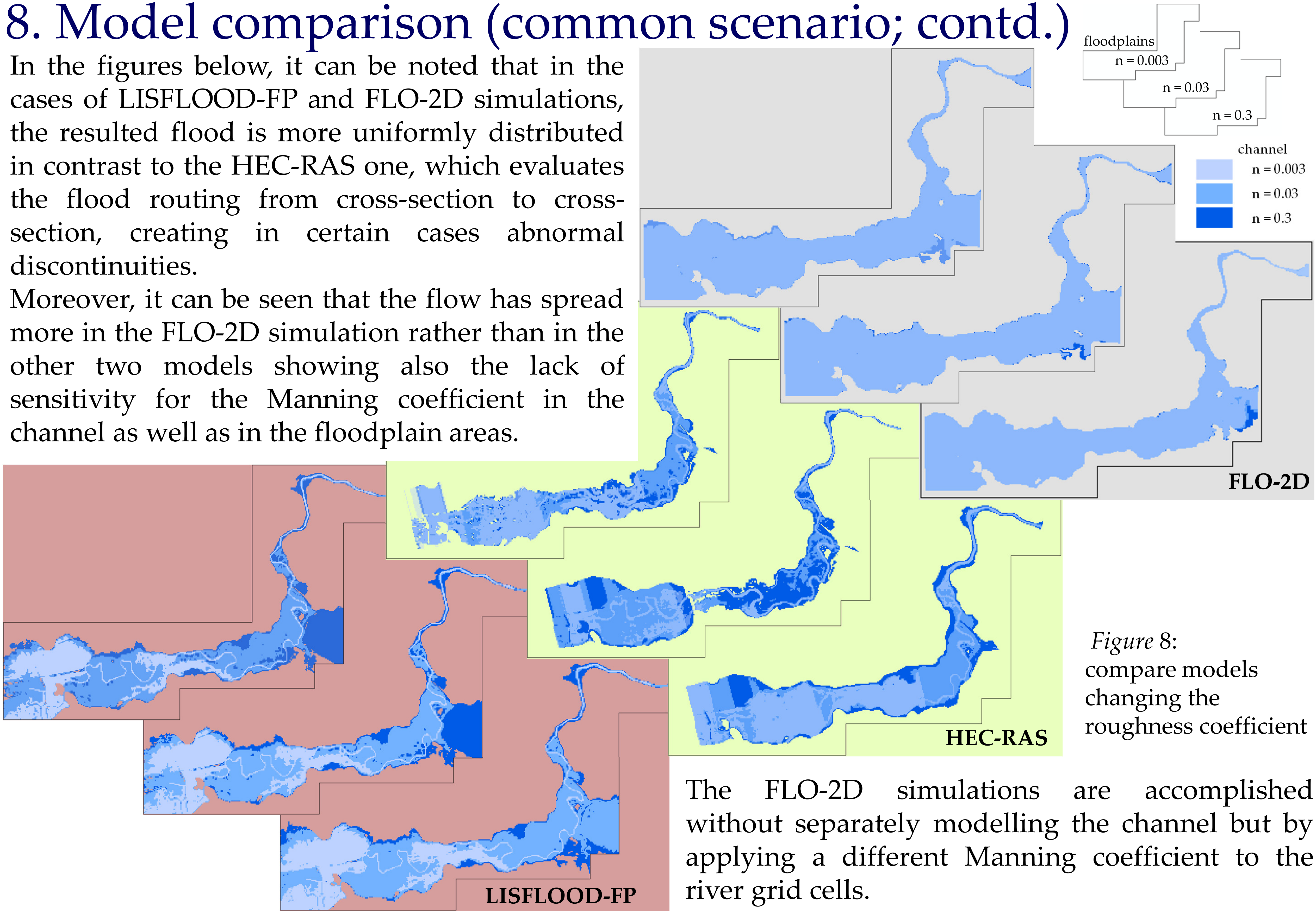


Figure 8:
compare models changing the roughness coefficient

The FLO-2D simulations are accomplished without separately modelling the channel but by applying a different Manning coefficient to the river grid cells.

9. Model comparison (common scenario; contd.)

The figures below, demonstrate the change in flooded area and water depth at the river outflow point with the channel's and floodplain's Manning coefficient. One can observe that, as mentioned before, the FLO-2D is not much sensitive to the roughness coefficient change, probably due to the absence of channel representation. Moreover, HEC-RAS curves underestimate in general the flooded area. Also, they exhibit a large sensitivity to the channel's and floodplain's roughness coefficients. Finally, LISFLOOD-FP curves exhibit a large sensitivity to the channel's roughness coefficient and a small sensitivity to floodplain's roughness. Note that each simulation lasts approximately 3 h for the LISFLOOD-FP, 2 h for the FLO-2D and 10 min for the HEC-RAS.

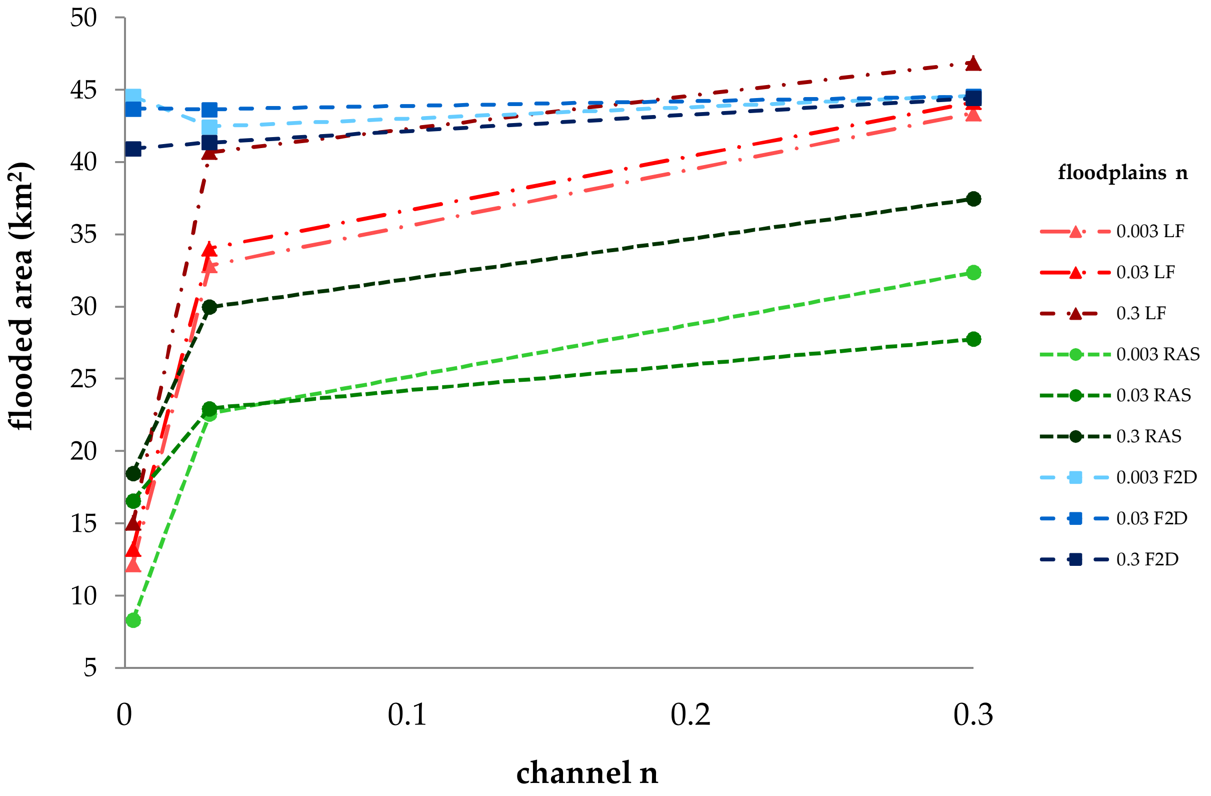


Figure 9: Flooded area

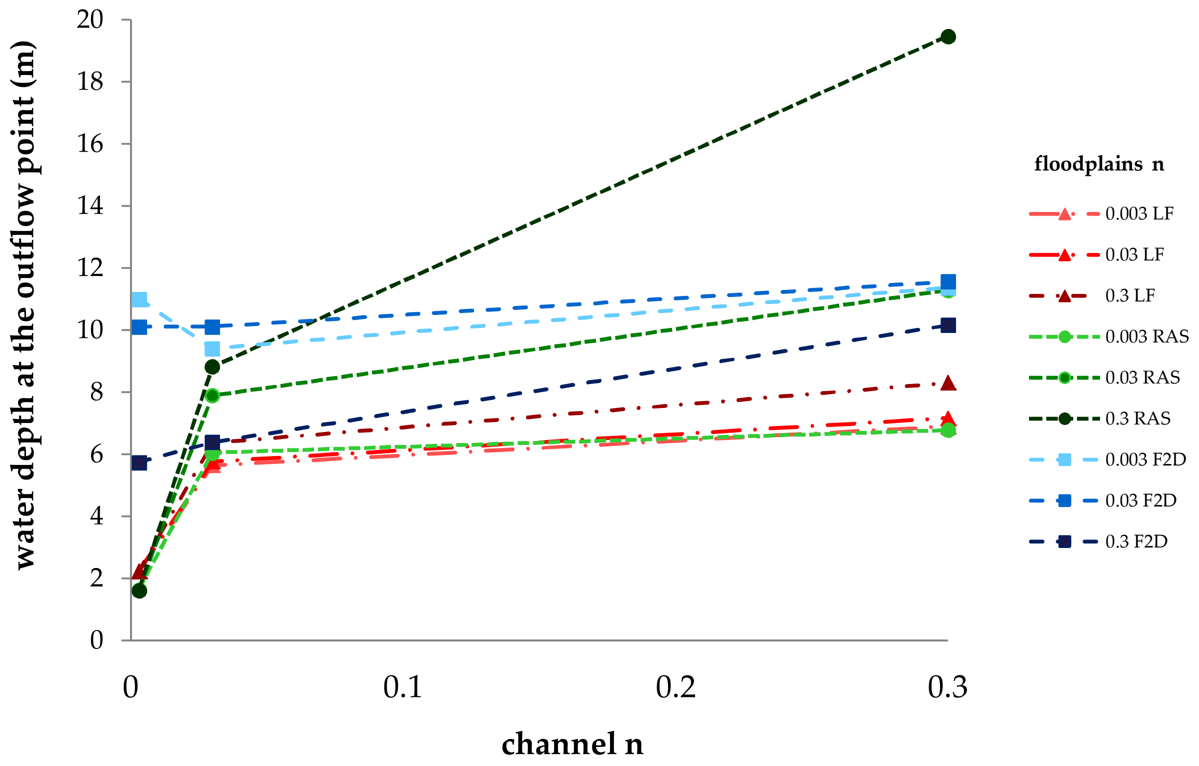
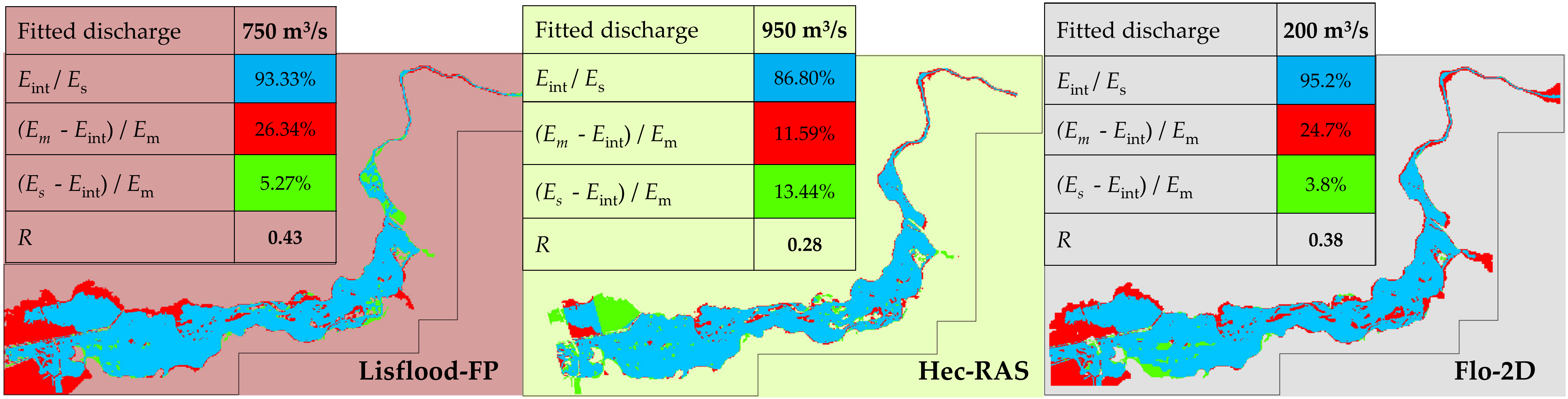


Figure 10: Water depth at the outflow point

10. Model comparison (50 m × 50 m DEM)

In this section, the ‘ideal’ steady flow is estimated based on the minimization of an evaluation coefficient (as described in equation 1) which compares the satellite observed footprint of the flooded area with the simulated one. The roughness coefficients are now based on the land cover of the study area as documented in the EU Corine project in 2000 (Yan Huang, 2005). Again, the topographic data of the study area are derived from the 50 m × 50 m DTM.



Fitted discharge	**750 m³/s**
E_{int} / E_s	93.33%
$(E_m - E_{int}) / E_m$	26.34%
$(E_s - E_{int}) / E_m$	5.27%
R	**0.43**

Fitted discharge	**950 m³/s**
E_{int} / E_s	86.80%
$(E_m - E_{int}) / E_m$	11.59%
$(E_s - E_{int}) / E_m$	13.44%
R	**0.28**

Fitted discharge	**200 m³/s**
E_{int} / E_s	95.2%
$(E_m - E_{int}) / E_m$	24.7%
$(E_s - E_{int}) / E_m$	3.8%
R	**0.38**

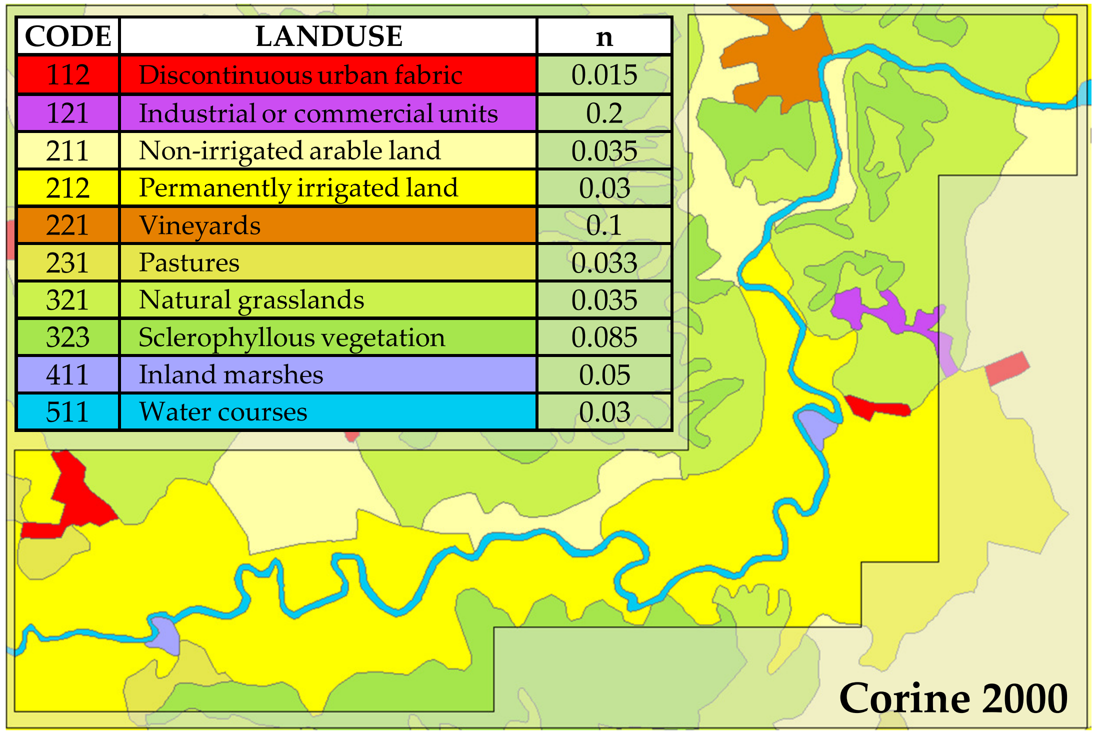
Figure 11: Best fit of the observed flooded area for each model

$$R = \frac{E_s + E_m}{E_{int}} - 2 \qquad (1)$$

where, E_s the flooded area observed by the satellite,
E_m the flooded area simulated by the model, and
E_{int} the intersection of the observed flooded area and the flooded area simulated by the model.

Based on previous studies (cf. Mimikou & Koutsoyiannis, 1995), the observed discharge cannot be as large as HEC-RAS indicates and not as small as shown by the FLO-2D simulation. It will be useful to run the FLO-2D scenarios (in future studies) by adding the channel geometry and banks, so as to compare with the ones without the channel and derive more robust conclusions concerning the FLO-2D best fit simulation.

11. Model comparison (5 m × 5 m DEM)



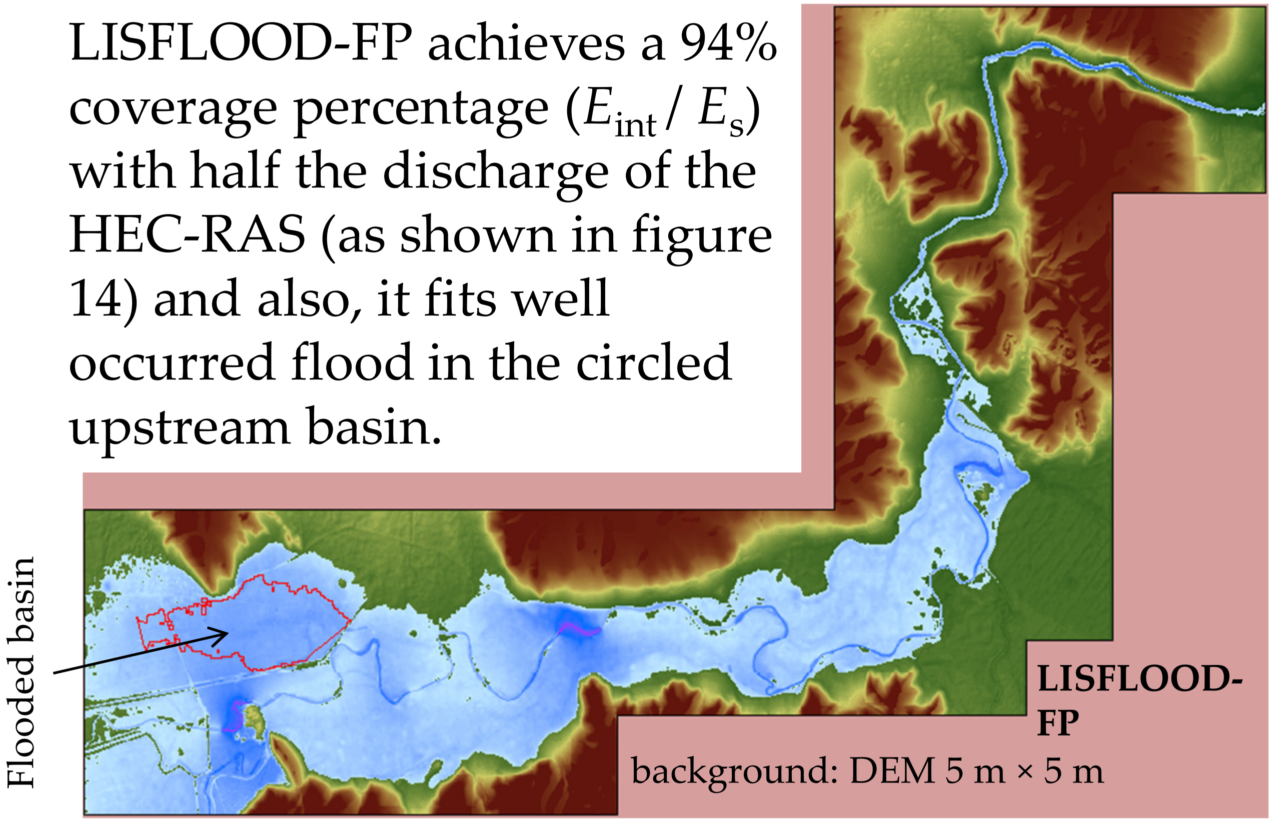
CODE	LANDUSE	n
112	Discontinuous urban fabric	0.015
121	Industrial or commercial units	0.2
211	Non-irrigated arable land	0.035
212	Permanently irrigated land	0.03
221	Vineyards	0.1
231	Pastures	0.033
321	Natural grasslands	0.035
323	Sclerophyllous vegetation	0.085
411	Inland marshes	0.05
511	Water courses	0.03

Figure 12: Land use data (Corine, 2000)

Here, the more fine DEM of 5 m × 5 m analysis is used, in steady flow conditions, for the LISFLOOD-FP and HEC-RAS models. Again, the roughness coefficient is based on the land cover data of the Corine project. Following the previous section's analysis, the best fitted discharge is estimated at the rate of 850 m³/s (with 8.59 m water depth at the outflow point) for the HEC-RAS and at 400 m³/s (with 5.96 m water depth at the outflow point) for the LISFLOOD-FP. The FLO-2D experiences difficulties when it comes to large extent and small grid size. Note that each simulation lasts approximately 60 h for the LISFLOOD-FP and only 10 min for the HEC-RAS.

LISFLOOD-FP achieves a 94% coverage percentage ($E_{\text{int}} / E_{\text{s}}$) with half the discharge of the HEC-RAS (as shown in figure 14) and also, it fits well occurred flood in the circled upstream basin.

HEC-RAS achieves an $E_{\text{int}} / E_{\text{s}} = 83.5\%$. Although the downstream section's embankment is overrun by the flood, opening a north-west path for the water to penetrate the small upstream basin, the flow does not even reach that area.



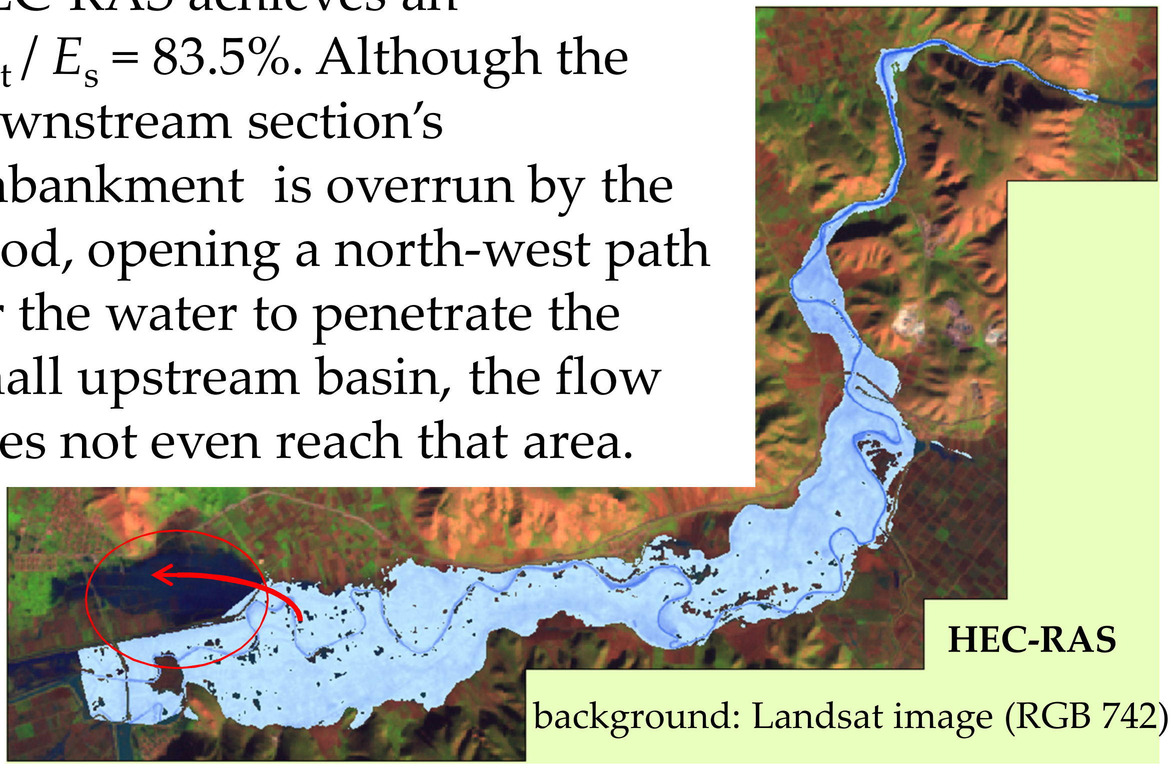
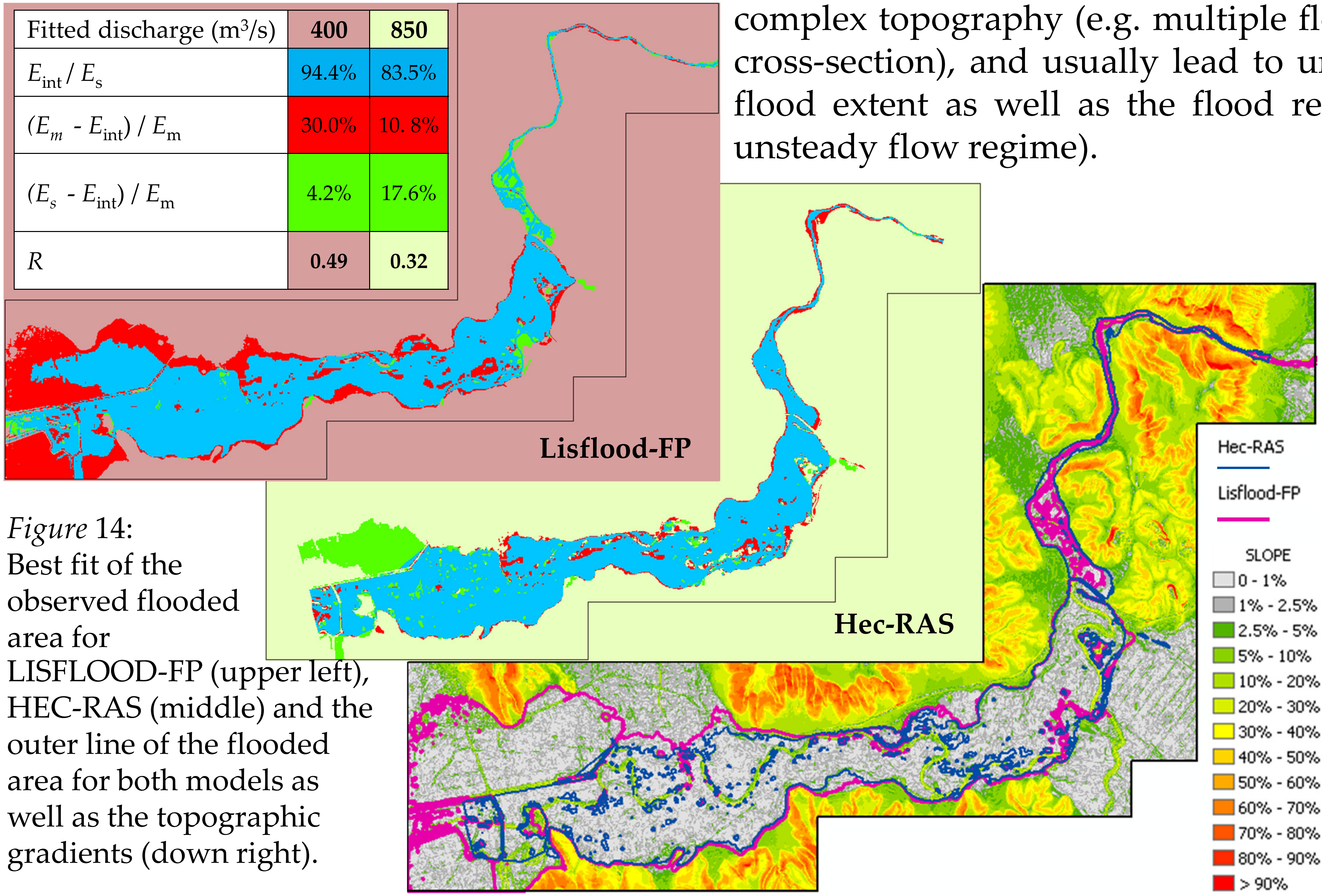


Figure 13: Flooded area (using the 5 m × 5 m analysis DEM)

12. Model comparison (5 m × 5 m DEM; contd.)

Here, the resulted best fit simulation is presented for LISFLOOD-FP and HEC-RAS. Moreover, the outer line of the simulated flood for both models is shown in addition with the topographic gradients of the area. As can be observed, the topographic gradients on both plains of the river are smaller than 2.5%. Thus, as already mentioned in section 4, the problematic behaviour of HEC-RAS is maybe due to the 1D nature of the model. 1D models have difficulties to simulate flood routing in areas with small gradients, complex topography (e.g. multiple flow directions within a cross-section), and usually lead to underestimations of the flood extent as well as the flood residence times (for the unsteady flow regime).

Thus, using a 1D model in a such cases could be misleading and could lead in wrong conclusions about the location and geometric characteristics (height, width) of the embankment structures.



Fitted discharge (m^3/s)	**400**	**850**
E_{int} / E_s	94.4%	83.5%
$(E_m - E_{int}) / E_m$	30.0%	10. 8%
$(E_s - E_{int}) / E_m$	4.2%	17.6%
R	**0.49**	**0.32**

Figure 14: Best fit of the observed flooded area for LISFLOOD-FP (upper left), HEC-RAS (middle) and the outer line of the flooded area for both models as well as the topographic gradients (down right).

13. Conclusions

- Overall, the case study illustrates the large uncertainties in modelling flow in inundated floodplains.
- In cases of a complex topography (like the one in this study) where multiple directions of the flow is possible within a cross section, 1D models often fail to correctly simulate the flood in contrast to quasi-2D models with grid-based numerical schemes.
- In cases of small gradients, the simulated discharge of the quasi-2D LISFLOOD-FP is much closer to the expected value in comparison to the underestimated one of HEC-RAS (especially in the case of fine grid) and the overestimated one of FLO-2D (note that for the FLO-2D the channel is not modelled separately as in LISFLOOD-FP).
- In cases where a fine grid is applied, LISFLOOD-FP has no difficulties with the small cell size in contrast to FLO-2D. Moreover, the HEC-RAS numerical scheme is not grid-based and thus, increasing the resolution of the grid only affects the number of cross-sections.
- LISFLOOD-FP seems to be in a better agreement with the general conclusion that there is a much greater sensitivity of the flood extent to the channel's Manning coefficient rather than the floodplain's one (similar conclusions have been derived by Cunge et al., 1980 and Hunter et al., 2005).

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