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Safer_RAIN: a DEM-based hierarchical filling-&-spilling algorithm for pluvial flood hazard assessment in urban areas

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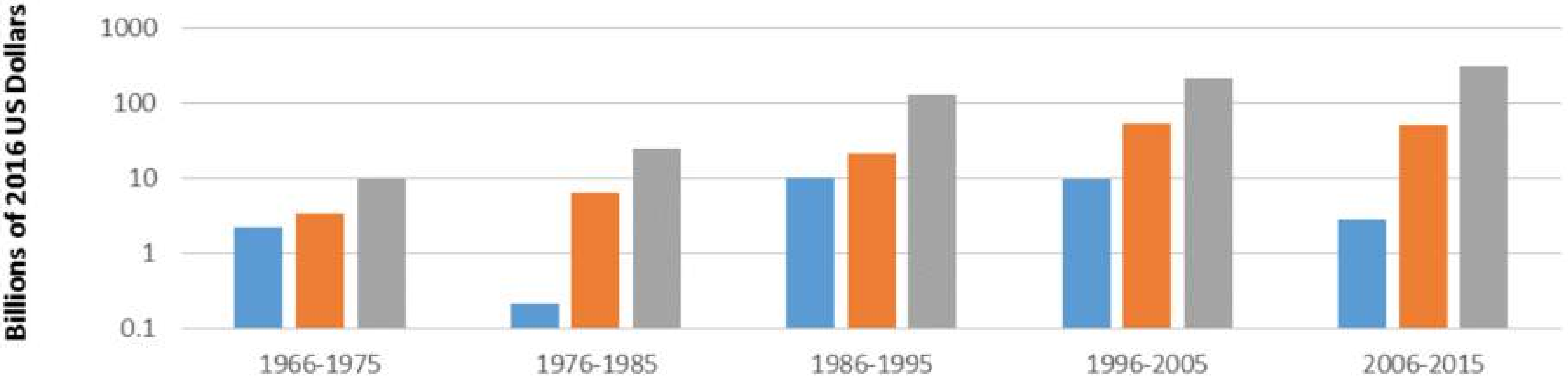
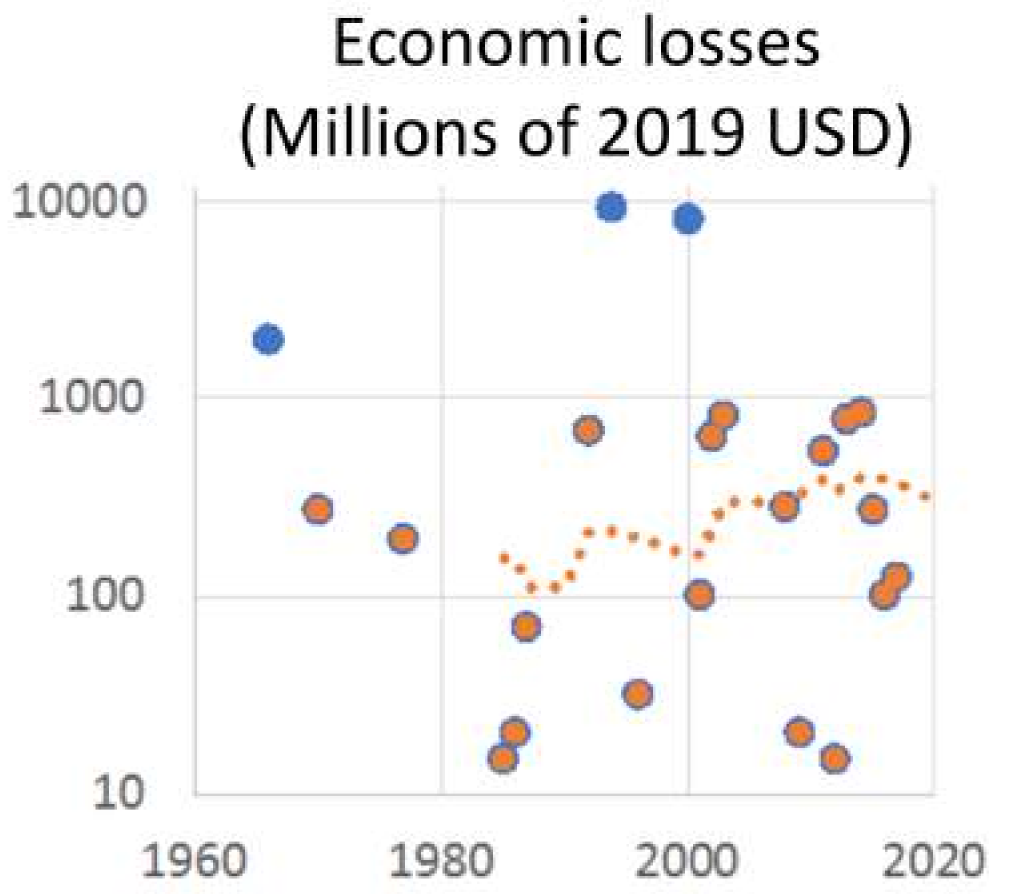
Presenting author: Attilio Castellarin

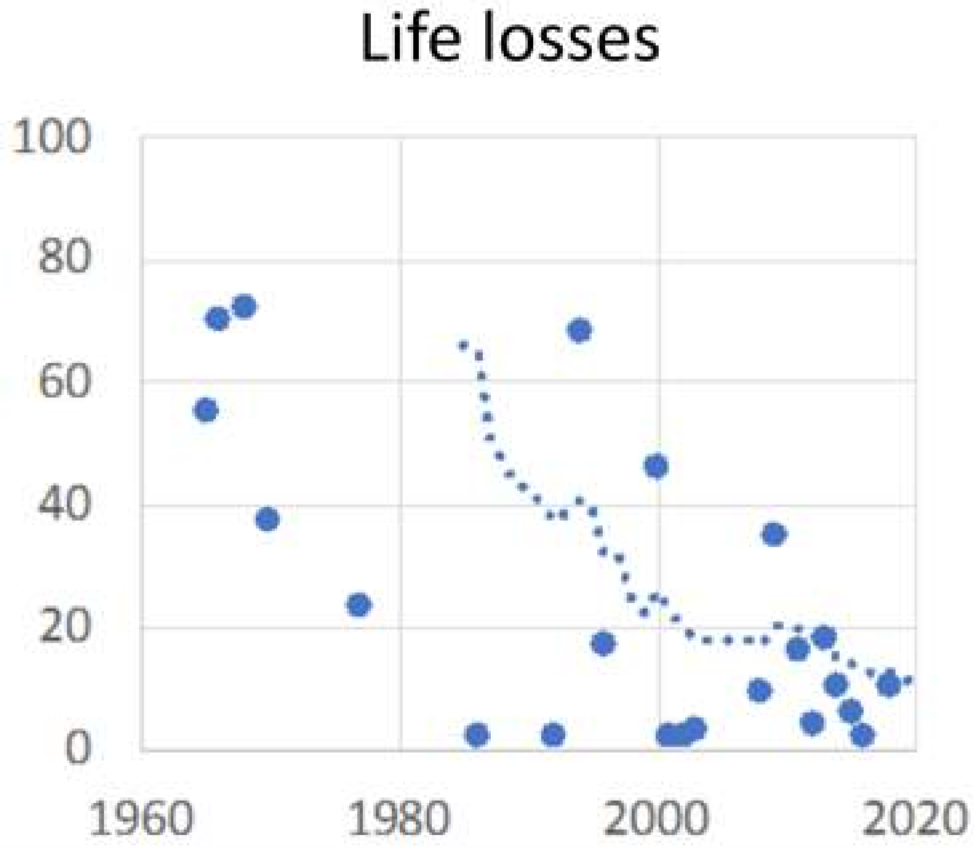
Flood Losses: Italian, European and Global Scale



Data source: http://www.emdat.be/

Italy: flood losses and victims





Data source: http://www.emdat.be/

'Floods Directive' – Directive 2007/60/CE
D.Lgs. N. 49 del 23/2/2010

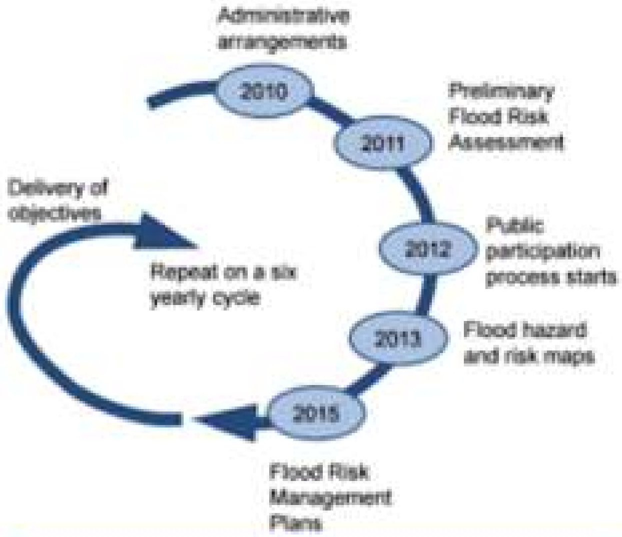
Directive 2007/60/CE or «Floods Directive» aims at harmonizing flood hazard and risk assessment and management across European Member States.

Objective:
Its aim is to reduce and manage the risks that floods pose to human health, the environment, cultural heritage and economic activity.

The Directive requires Member States to **carry out a preliminary assessment, to identify the river basins and associated coastal areas at risk of flooding**. For such zones they would then need to **draw up flood risk maps** and **establish flood risk management plans focused on prevention, protection and preparedness**. The Directive applies to **inland waters as well as all coastal waters** across the whole territory of the EU.

http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:288:0027:0034:IT:PDF
http://www.isprambiente.gov.it/pre_meteo/file/DLGS_49_2010_agg2014.pdf

Directive 2007/60/CE: Planning Cycle



Chapter VIII: reviews, reports and final provisions

'Floods Directive' – Directive 2007/60/CE
D.Lgs. N. 49 del 23/2/2010

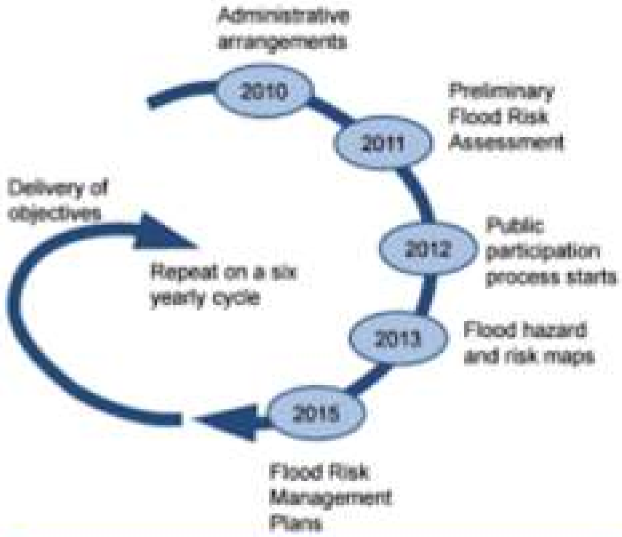
(Research) Challenges from the Floods Directive

1. Large Scale Assessment (Nation-wide, pan-European)
2. Holistic Approach (Solidarity principle)
3. Objective and Quantitative (Risk quantification)
4. Dynamic Interpretation (6-year review cycle)

Systems approach to flood risk assessment and mitigation

Floods Directive poses science questions that need to be addressed by ad-hoc research activities

Directive 2007/60/CE: Planning Cycle



Chapter VIII: reviews, reports and final provisions

(see e.g. Vorogushyn et al. (2018): Evolutionary leap in large-scale flood risk assessment needed)

Numerical modelling and Flood Hazard and Risk Assessment

Numerical two-dimensional inundation models:

- Wealth of hydraulic information
- Resource intensive & Scale of the application is limited by the resolution of the output

Hydro_AS-2D - Two-dimensional rainfall-runoff and hydrodynamic model

TELEMAC-2D - Two-dimensional hydrodynamic model
http://www.opentelemac.org (Free and Open Source SW)

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SAFERPLACES

Climate-KIC

Improved assessment of pluvial, fluvial and coastal flood hazards and risks in European cities as a means for building safer and more resilient communities

SAFERPLACES' CONSORTIUM

Research Centers

GFZ Helmholtz Centre Potsdam

cmcc Centro Euro-Mediterraneo sui Cambiamenti Climatici

Universities

Alma Mater Studiorum Università di Bologna

Politécnica

SME's

MEEO Meteorological Environmental Earth Observation

geco

IBH

Climate-Kic Flagship Initiative

oasis HUB

SAFERPLACES

Improved assessment of pluvial, fluvial and coastal flood hazards and risks in European cities as a means for building safer and more resilient communities

SAFERPLACES' MAIN OBJECTIVE CONCERNING FLOOD HAZARD CHARACTERIZATION:

To assess the potential of **fast-processing DEM-based algorithms** for **consistent flood hazard characterization** at local scale, and their viability for upscaling and generalizing the assessment to larger areas (e.g. large floodplains, large metropolitan areas and regional assessments)

Considered hazard sources: **Fluvial, Pluvial, Coastal Flooding**

Today's focus:

Fluvial-flooding across large floodplains

Pluvial-flooding in urban areas

Follow us!

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Hashtag: #SAFERPLACES_CKIC

Why Pluvial Flooding in Urban Areas?

Particularly severe storms, with limited duration and highly localized can trigger «*urban flash-floods*»

Italian press launched the term ***«water bomb»*** to identify a classical phenomenon in Italy: «nubifragio», «*cloudburst*» in English, a violent and short rainstorm resulting in a cumulated rainfall depth **in excess of 30mm in 1 hour**.

Livorno, Sept. 9-10, 2017
Rainfall depth at Valle Benedetta: 235 mm in 3 hrs.

Lignano (Udine), Sept. 10-12 2017
Rainfall depth: 280 mm, of which 120 mm in 4 hrs., 55 mm in 1 hr.

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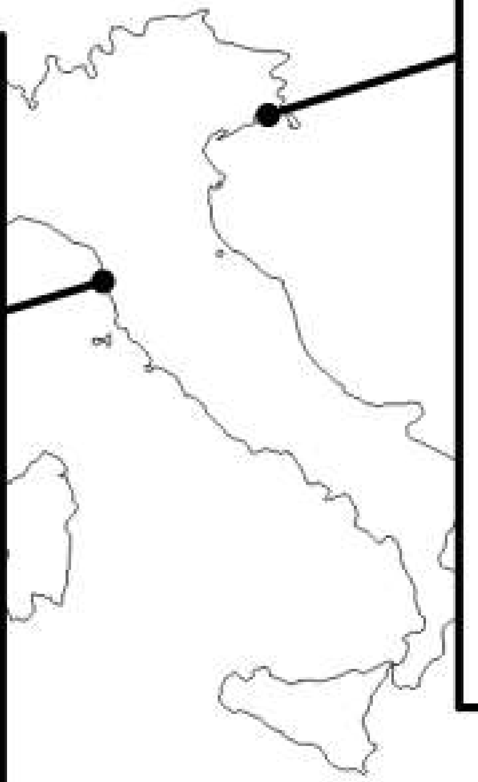


Relative to fluvial flooding:
- Localized damages, yet
- Higher frequency

Non-negligible
Expected yearly losses

Li… 17
Rainfall depth: 280 mm, of which 120 mm in 4 hrs., 55 mm in 1 hr.

1^{st} part: Fluvial Flooding

SAFERPLACES research goal:
Developing a **fast-processing DEM-based GIS algorithms** for characterizing fluvial-flooding hazard across large floodplain areas

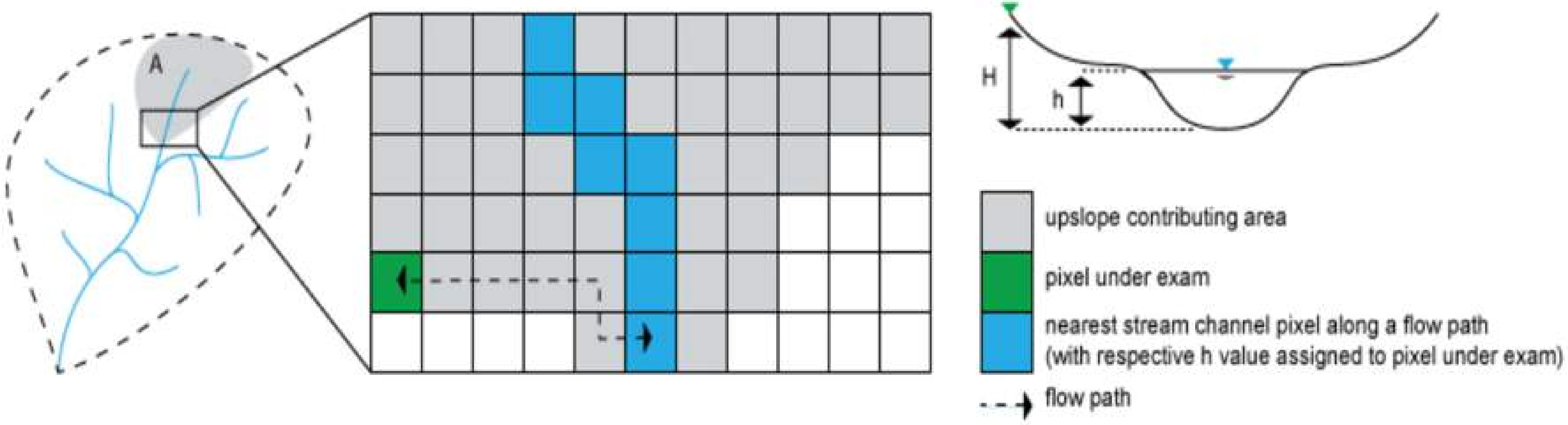
Motivations:

- Need for a consistent flood hazard characterization across large floodplains
- Heterogeneities and gaps in current flood hazard and risk mapping at national scale
- Traditional approaches are still resource inntensive

DEM-based flood-hazard characterization: Geomorphic Flood Index (GFI)

$$GFI^1 = ln\left(\frac{h}{H}\right)$$

- $h = bA^n$, empirical power law $[m]$
- H, elevation difference[2] $[m]$
- A, upslope contributing area $[km^2]$



[1] Samela et al., Adv. Water. Resour., 2017
[2] Nobre et al., Hydrol. Proc., 2016

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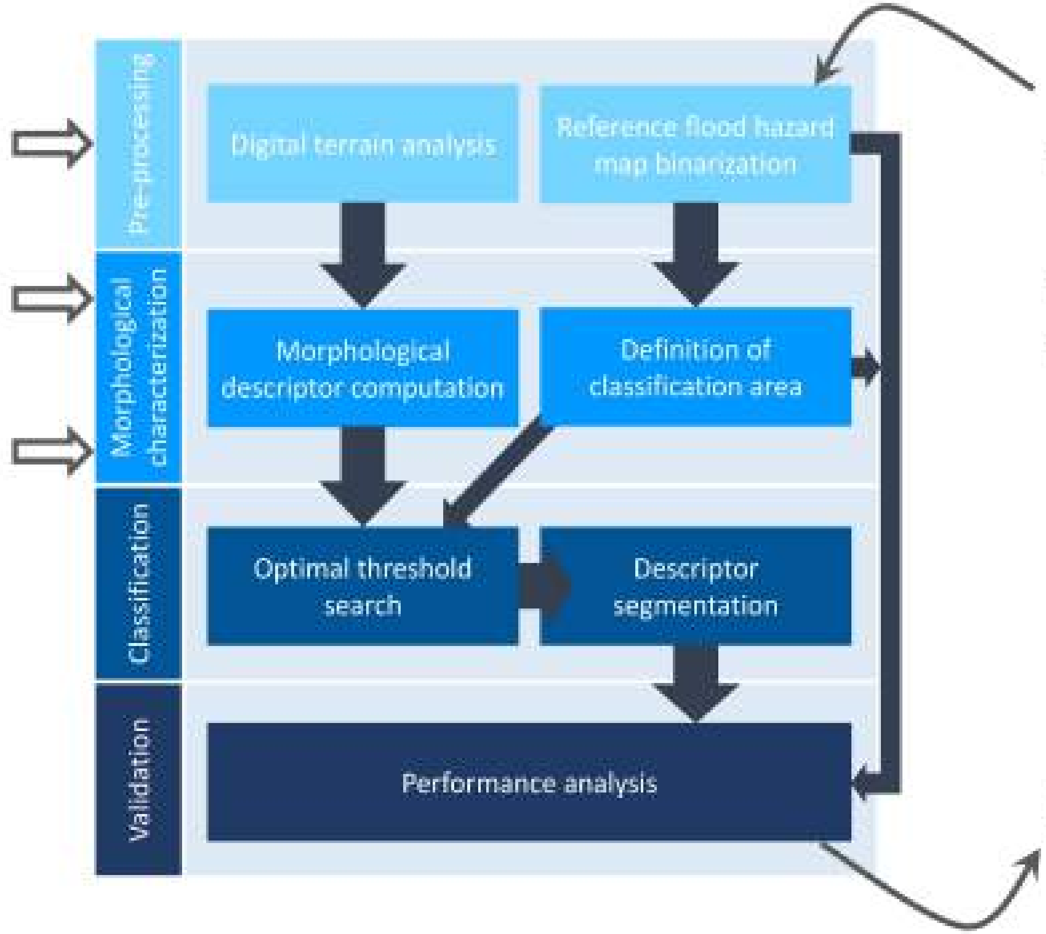
GFI computation and use: Workflow[1]

Digital Elevation Model

Channel initiation

Hydrologic scaling

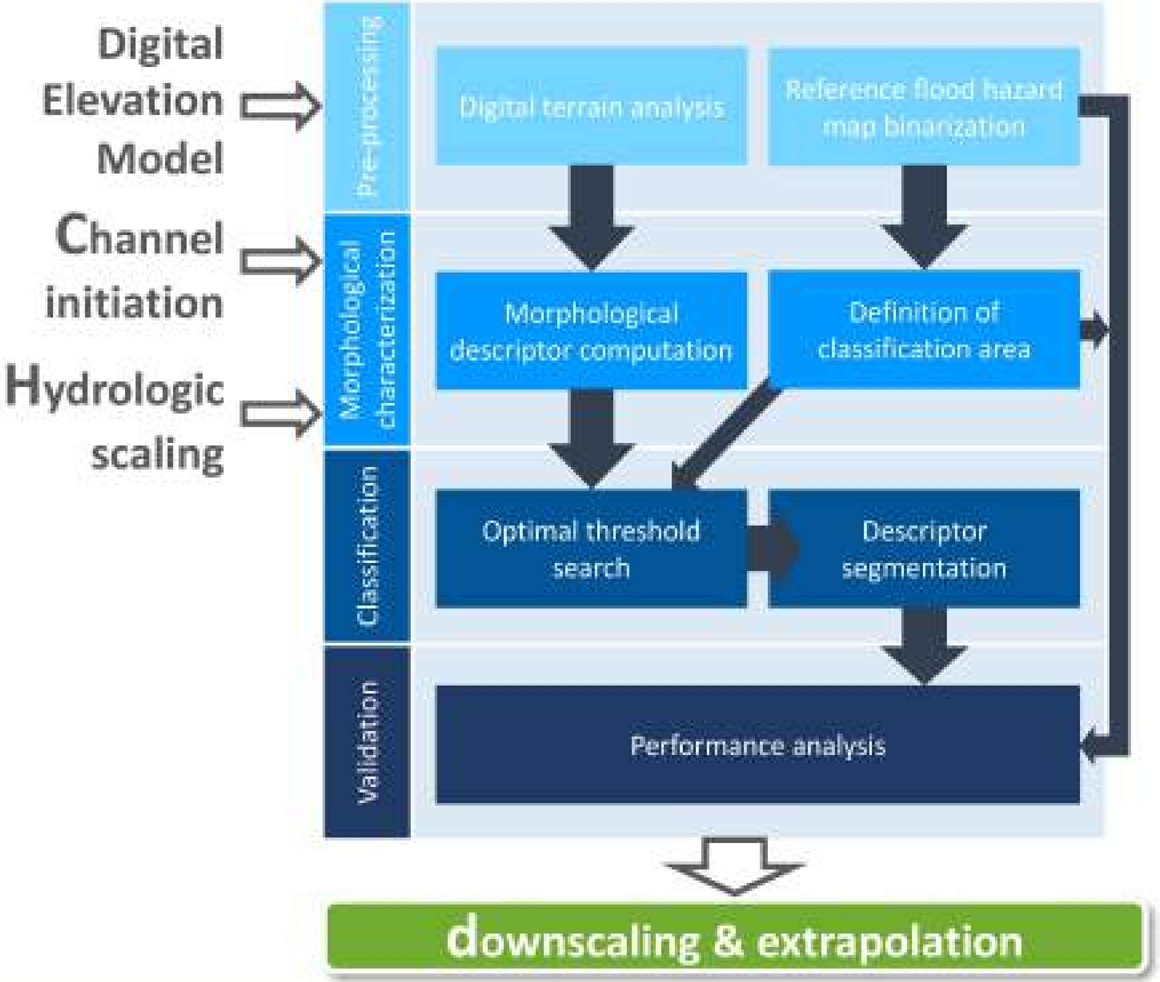


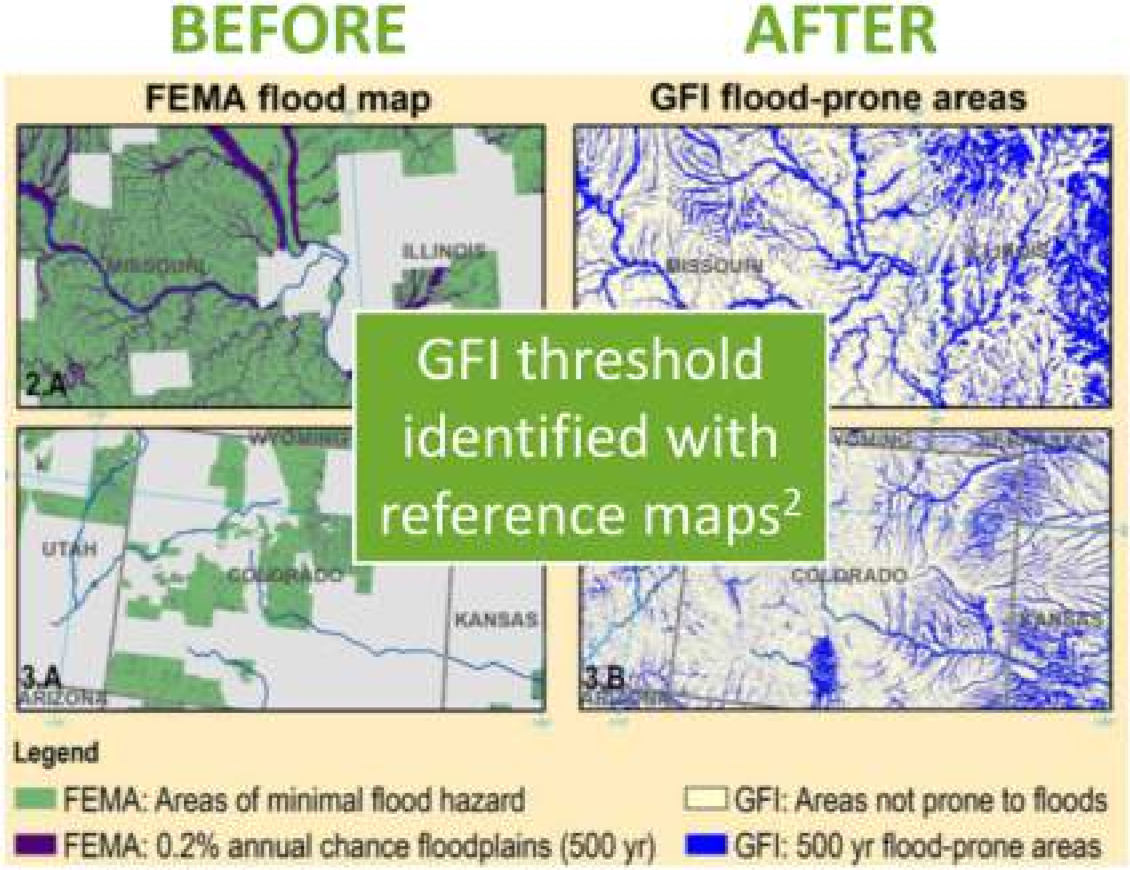
- flood extent from modelling results
- flood extent from remote sensing
- flood extent from field surveys

hydrogeomorphic flood extents

[1] Tavares da Costa et al., Env. Software & Mod., 2019

GFI computation and use: Workflow[1]





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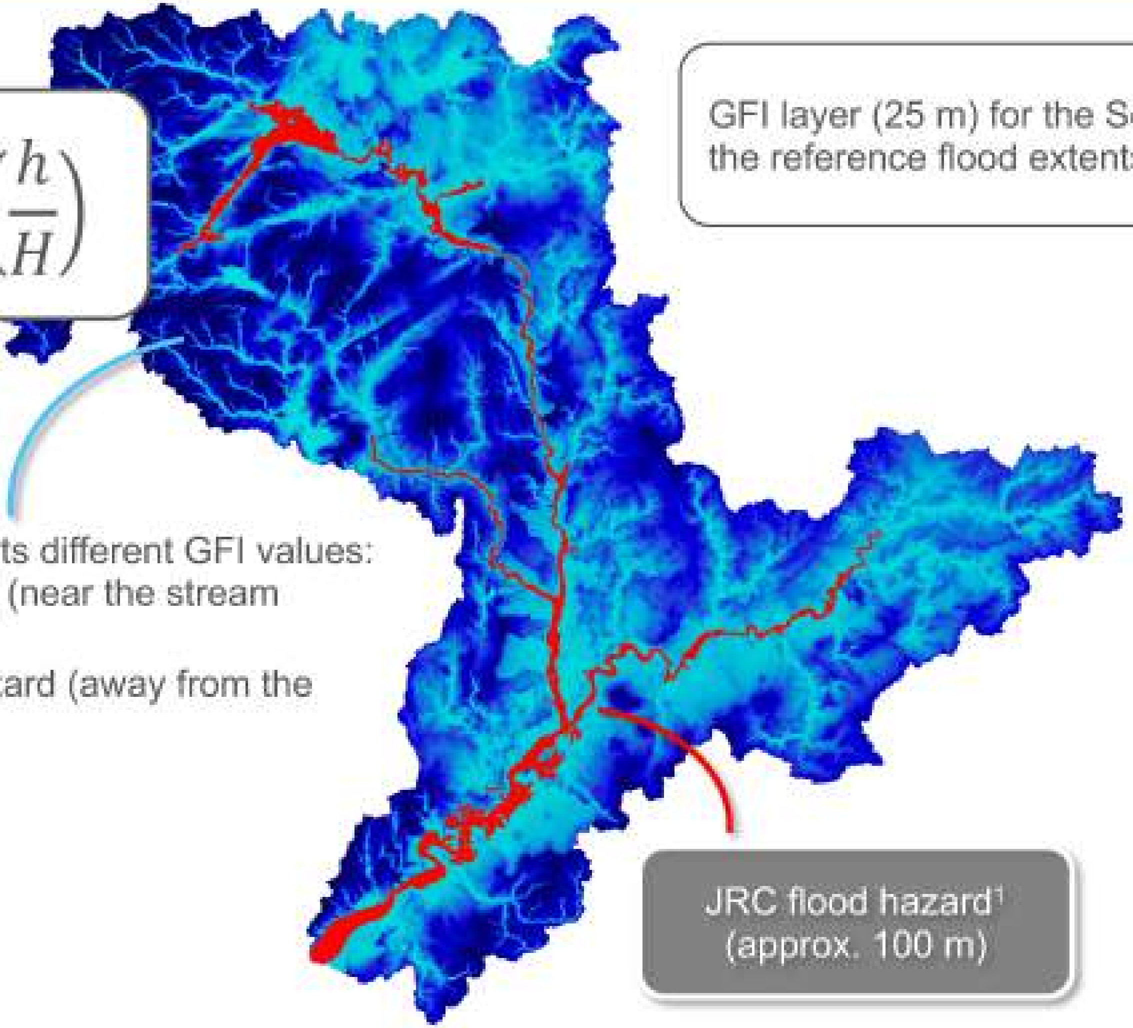
[1] Tavares da Costa et al., Env. Software & Mod., 2019
[2] Samela et al., Adv. Water. Resour., 2017

GFI Classification

$$GFI = ln\left(\frac{h}{H}\right)$$

GFI layer (25 m) for the Severn river basin (UK) ready to reproduce the reference flood extents from a detailed flood study

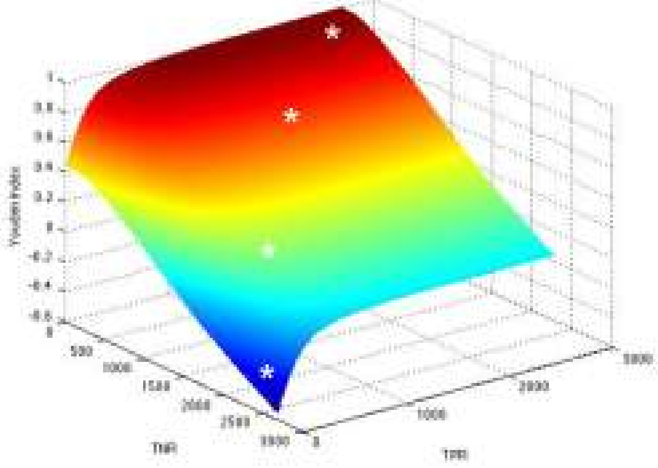


colour gradient represents different GFI values:

- 1 (cyan) high hazard (near the stream channel)
- 0 (dark blue) low hazard (away from the stream channel)

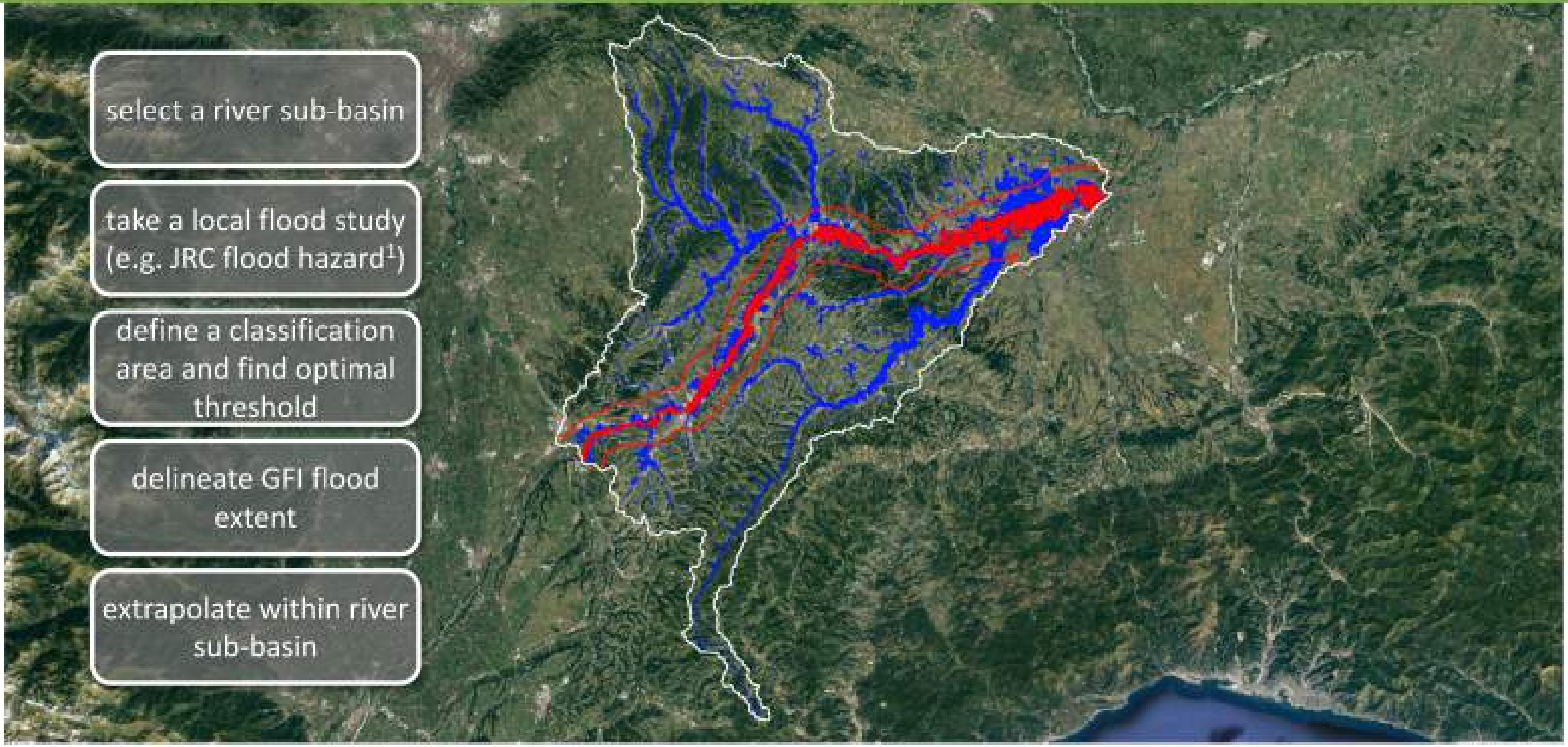
JRC flood hazard[1] (approx. 100 m)

Objective function max($J = tpr + tnr - 1$)



[1] Dottori et al., European Commission, Joint Research Centre, 2016

GFI Delineation: example



[1] Dottori et al., European Commission, Joint Research Centre, 2016

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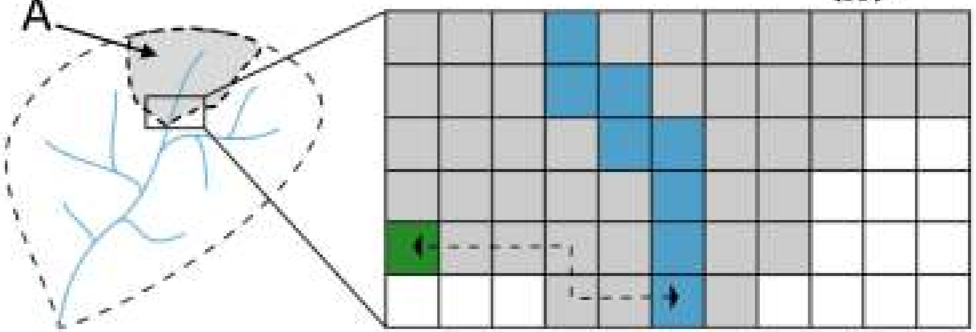
2^{nd} part: Pluvial Flooding

SAFERPLACES research goal:
Developing a **fast-processing GIS algorithm** for characterizing pluvial-flooding hazard on the basis of high-resolution Digital Elevation Models (DEMs) of (large) urban areas

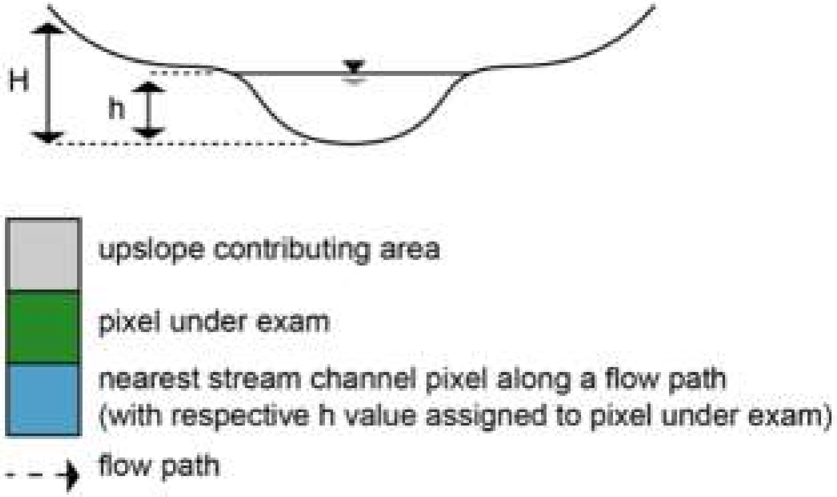
Motivations:
- Availability of LiDAR high resolution DEMs (≈1m) is steadily increasing
- Hazard hotspots localization is needed across large or very large urbanized areas (urban sprawls)

An alternative approach: DEM-based Hierarchical Filling-&-Spilling

Geomorphic Flood Index: $GFI = ln\left(\frac{h}{H}\right)$



with $h = bA^n$, where A is the upslope contributing area, and H is the elevation difference



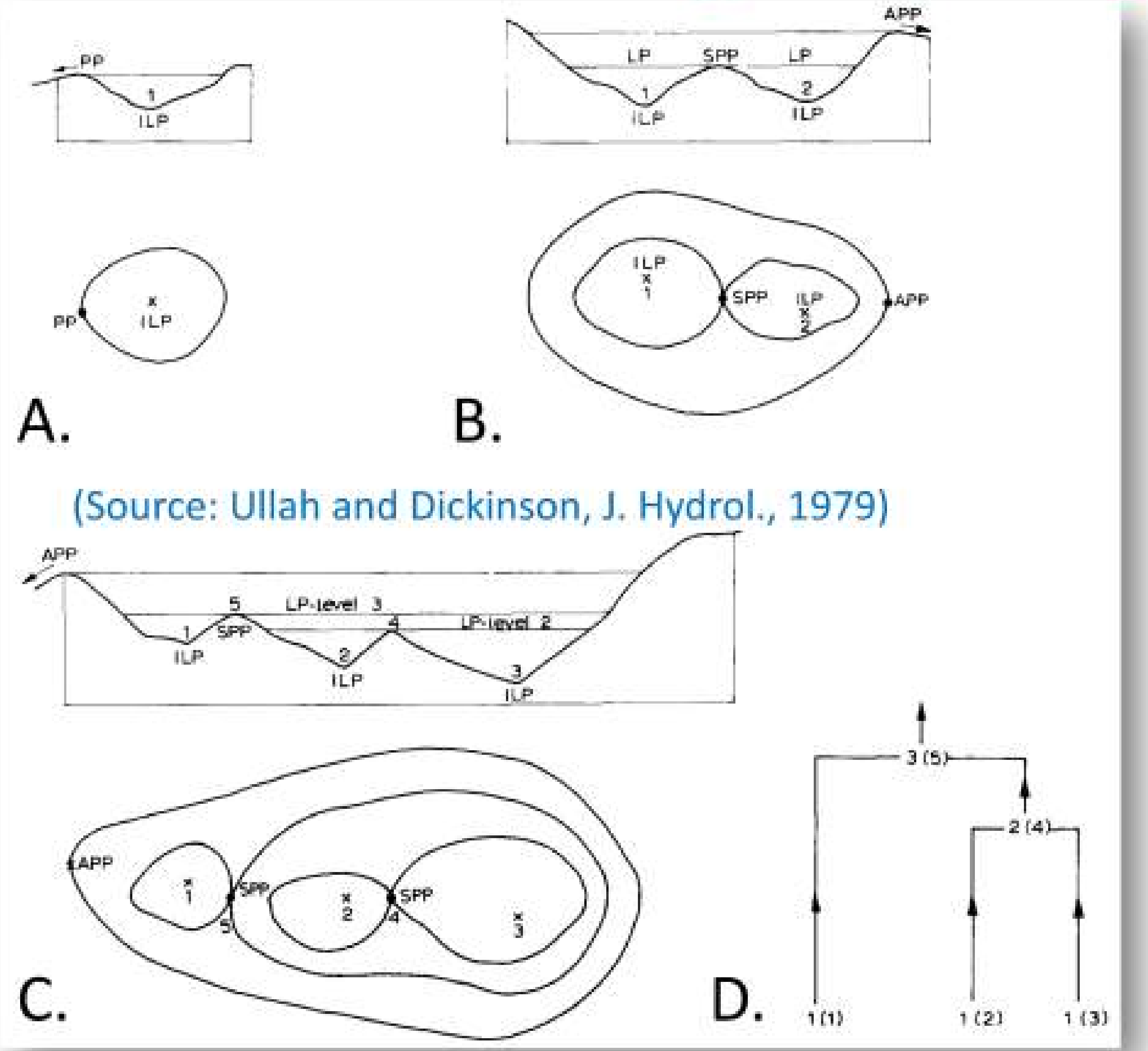
Q: Is GFI suitable for characterizing pluvial-flooding hazard in urbanized areas?

A: NO, according to preliminary tests on high-resolution DEM.

Main reasons:

- Topographical surfaces are deeply altered (anthropogenic impact)
- Abundance of flat and sub-horizontal areas
- Diffuse presence of sinks and pits
- Extent of flooded areas are largely controlled by rainfall spatial distribution and volume

An alternative approach: DEM-based Hierarchical Filling-&-Spilling



(Source: Ullah and Dickinson, J. Hydrol., 1979)

Journal of Hydrology, 42(1979) 63—75 63
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[1]

QUANTITATIVE DESCRIPTION OF DEPRESSION STORAGE USING A DIGITAL SURFACE MODEL
I. Determination of Depression Storage

W. ULLAH* and W.T. DICKINSON

E.g. Ullah and Dickinson (J. Hydrol., 1979), illustrate a 4-direction DEM-based algorithm.

A. Simple depression (first-order basin)
B. Complex depression (second-order basin)
C. Complex depression (third-order basin)
D. Link and order list: order(basin no.)

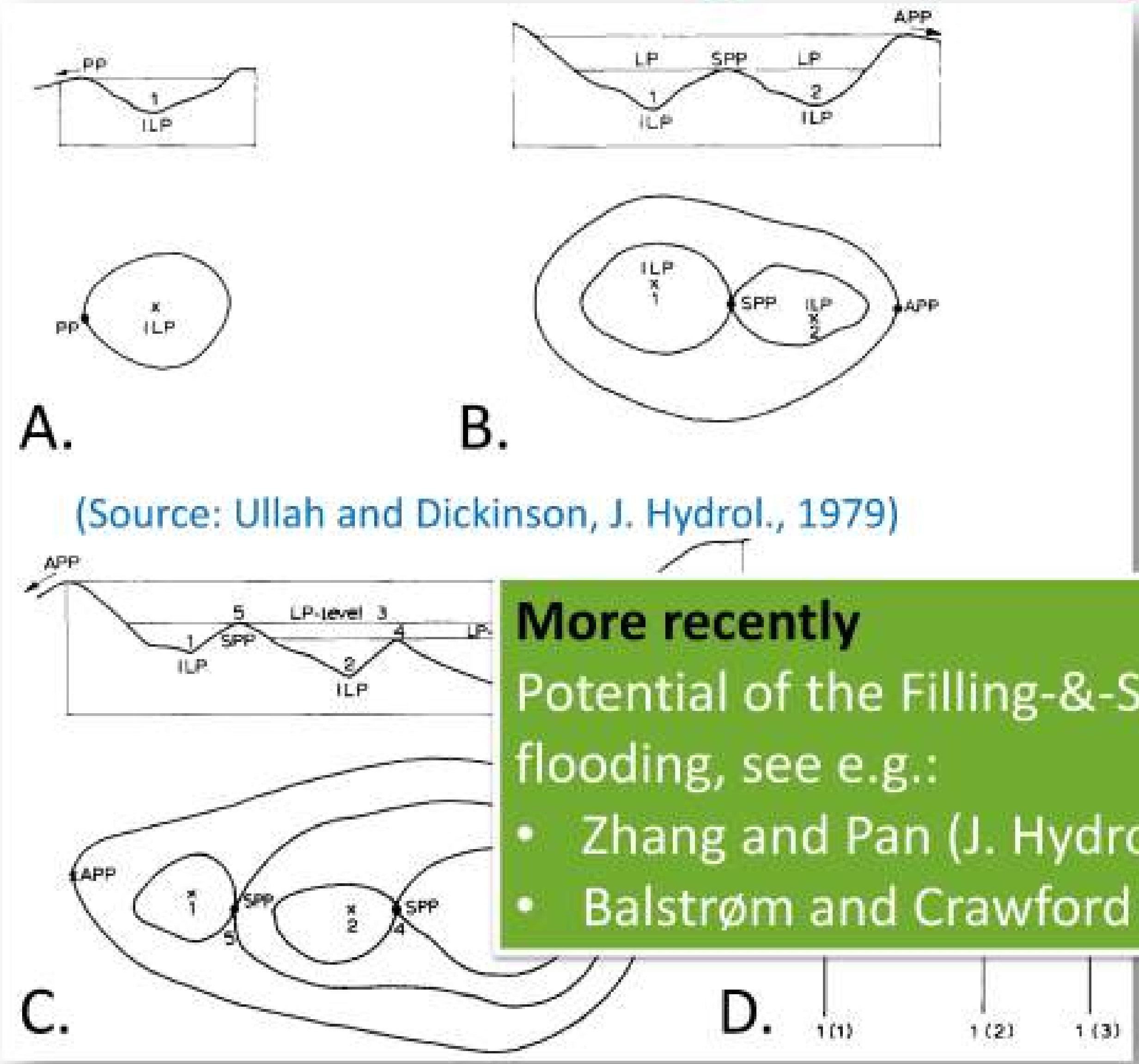
Notation

ILP: initial low point

SPP: shared pour point

APP: active pour point

An alternative approach: DEM-based Hierarchical Filling-&-Spilling



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A. Simple depression (first-order basin)
B. Complex depression (second-order basin)
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rder(basin no.)

More recently

Potential of the Filling-&-Spilling tested for pluvial flooding, see e.g.:

- Zhang and Pan (J. Hydrol., 2014)
- Balstrøm and Crawford (Comp. Geosci., 2018)

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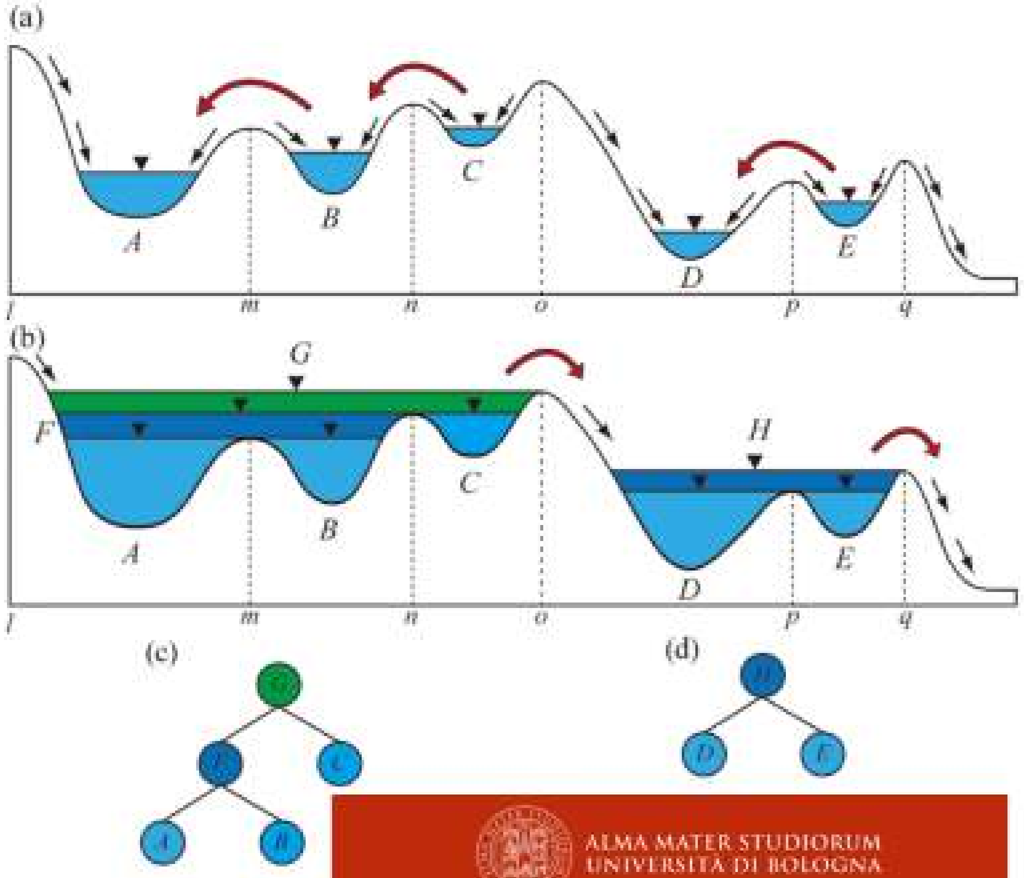
DEM-based pluvial-flooding hazard characterization:

Proposed approach

(Source: Wu and Lane, HESS, 2017)

Main simplifying assumptions

- Dynamics is neglected, rainfall water volume flows downstream instantaneously
- Water flows according to the “D8” method (see e.g. O’Callaghan and Mark, Comp. Vision. Graph. & Image Proc., 1984).
- The terrain is an impermeable surface (relaxed).
- The spatial distribution of rainfall is uniform (relaxed)



DEM-based pluvial-flooding hazard characterization:

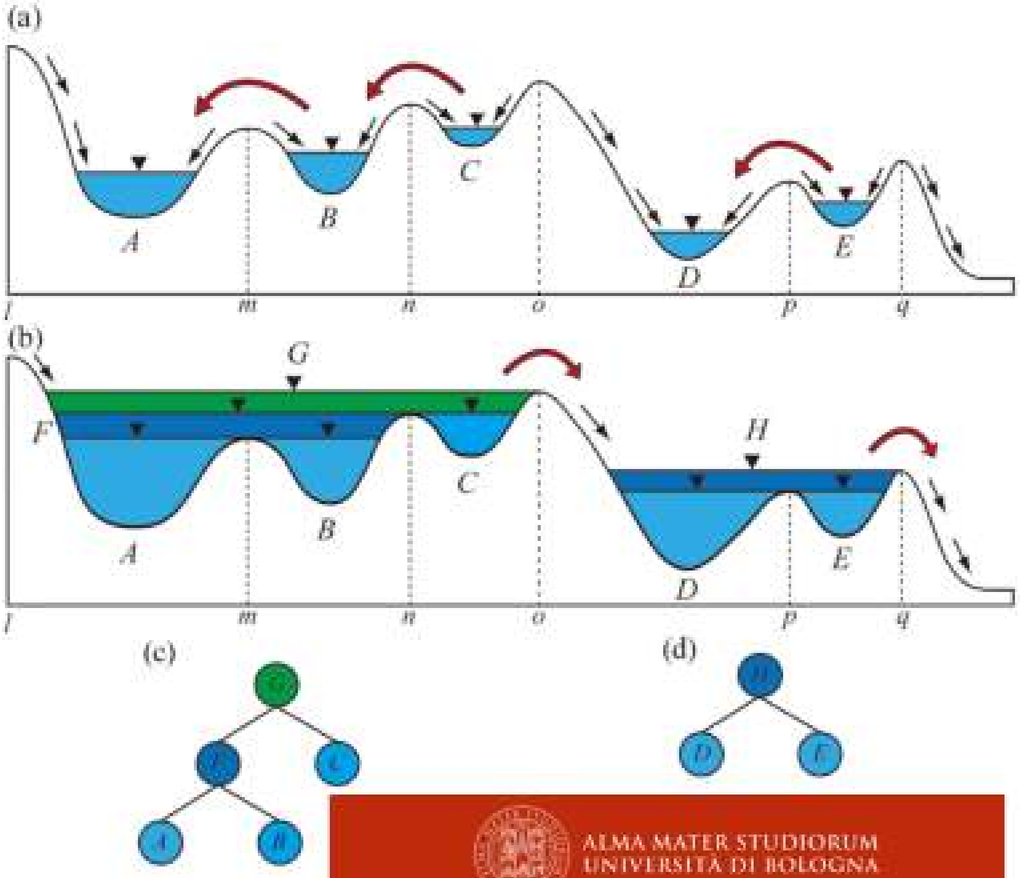
Proposed approach

(Source: Wu and Lane, HESS, 2017)

DEM pre-processing

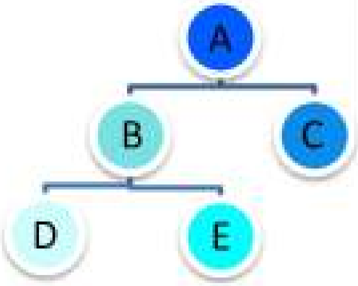
Algorithm main steps

1) Definition of **horizontal hydrological hierarchy**: identification of blue-spots (first-level depressions, G and H in the figure) through **DEM pit-filling**, and corresponding pour-point and contributing watersheds;
2) Definition of **vertical hierarchical structure within each blue-spot**, the higher level depressions (A, B, C, D, E, and F in the figure)their hierarchical relationship and water-level / volume relationship through **Top-down level-set method**, Wu et al., JAWRA, 2018)
3) Identification of **flooded areas for a given rainfall volume, partial filling** is addressed through a **Bottom-up level-set method**



DEM-based pluvial-flooding hazard characterization:

Proposed approach



STEP 2)

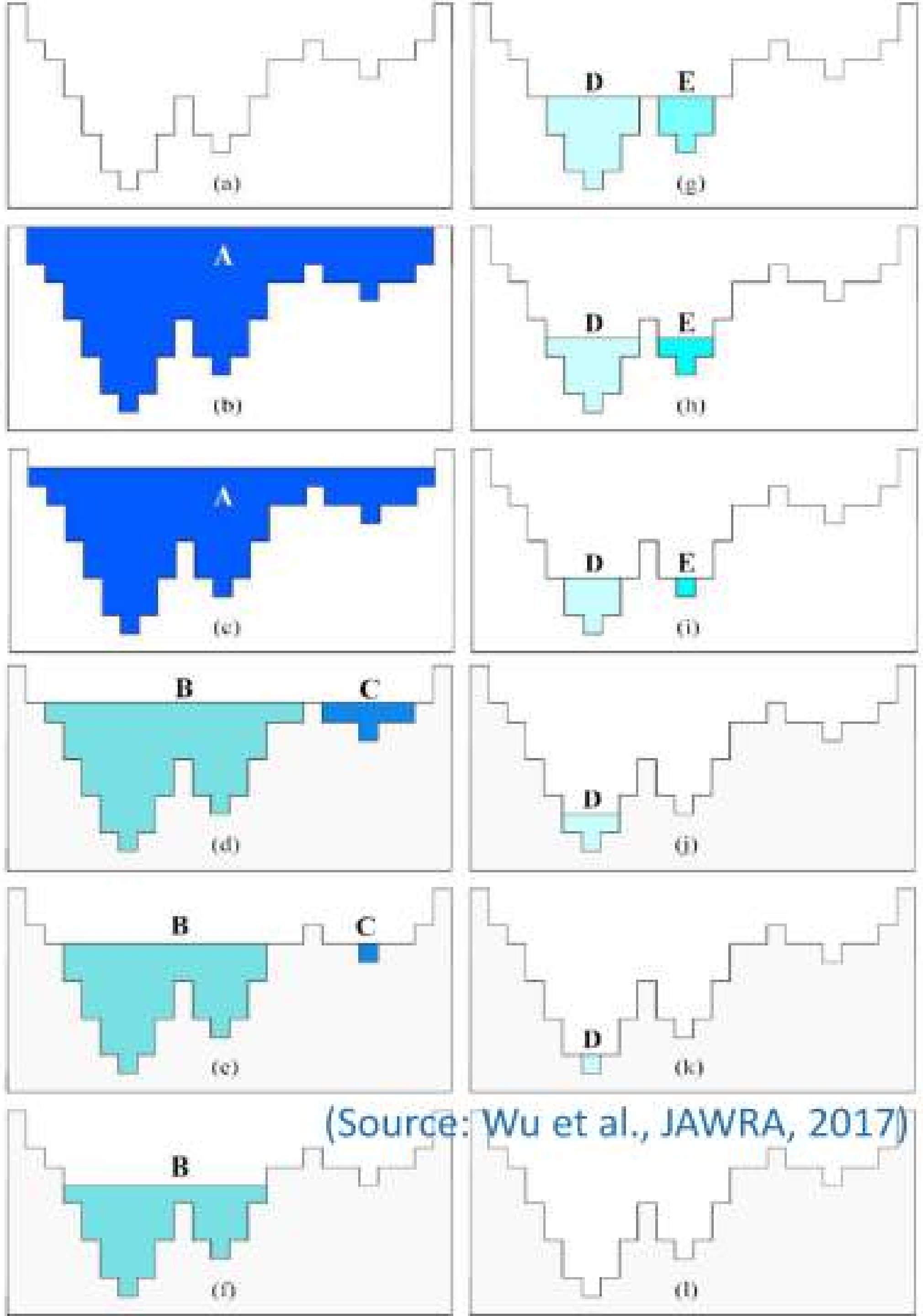
Top-down level-set method is presented in:

"Efficient delineation of nested depression hierarchy in digital elevation models for hydrological analysis using level-set methods"

Wu et al. (JAWRA, 2018)

From (a) to (l):

1. it starts form a **filled condition** (the blue-spot **A** is full)
2. the **level decreases gradually**, characterizing the water-level/volume relationship
3. the 2nd (**B** and **C**) and 3rd (**D** and **E**) level depressions are **gradually identified**
4. nested depression hierarchy and water-level/volume relationships are fully characterized



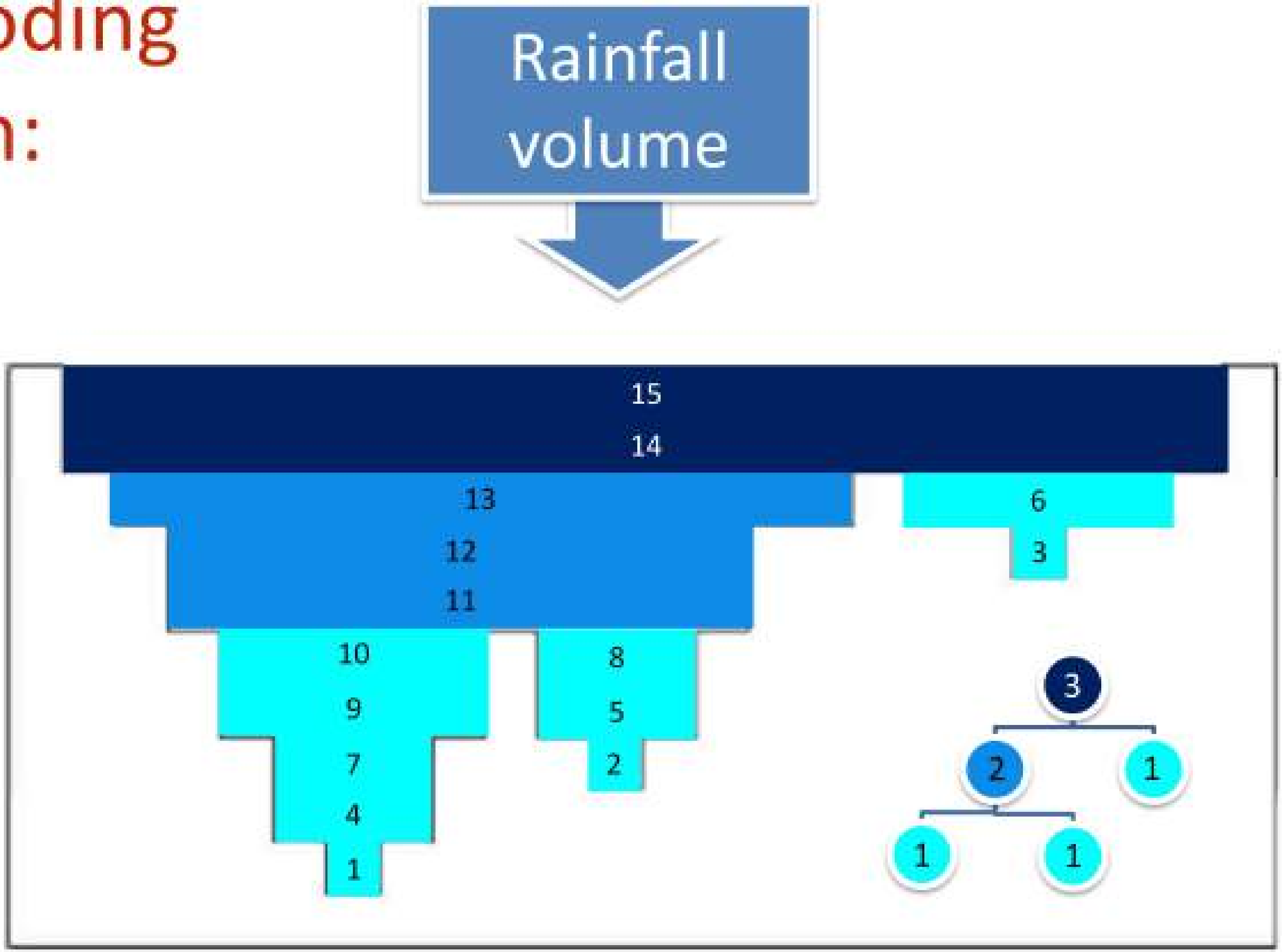
(Source: Wu et al., JAWRA, 2017)

DEM-based pluvial-flooding hazard characterization:

Proposed approach

STEP 3)
Bottom-up level-set method is used for quantifying **partial filling** in nested higher-level depressions:

1. it starts form an **empty condition** (the blue-spot A is empty)
2. according to their vertical hierarchy, **nested depressions are gradually filled** through bottom-up a level-set method
3. gradual filling is performed step-by-step, **rotating depressions** with same hierarchical order



Samela et al. (2020)

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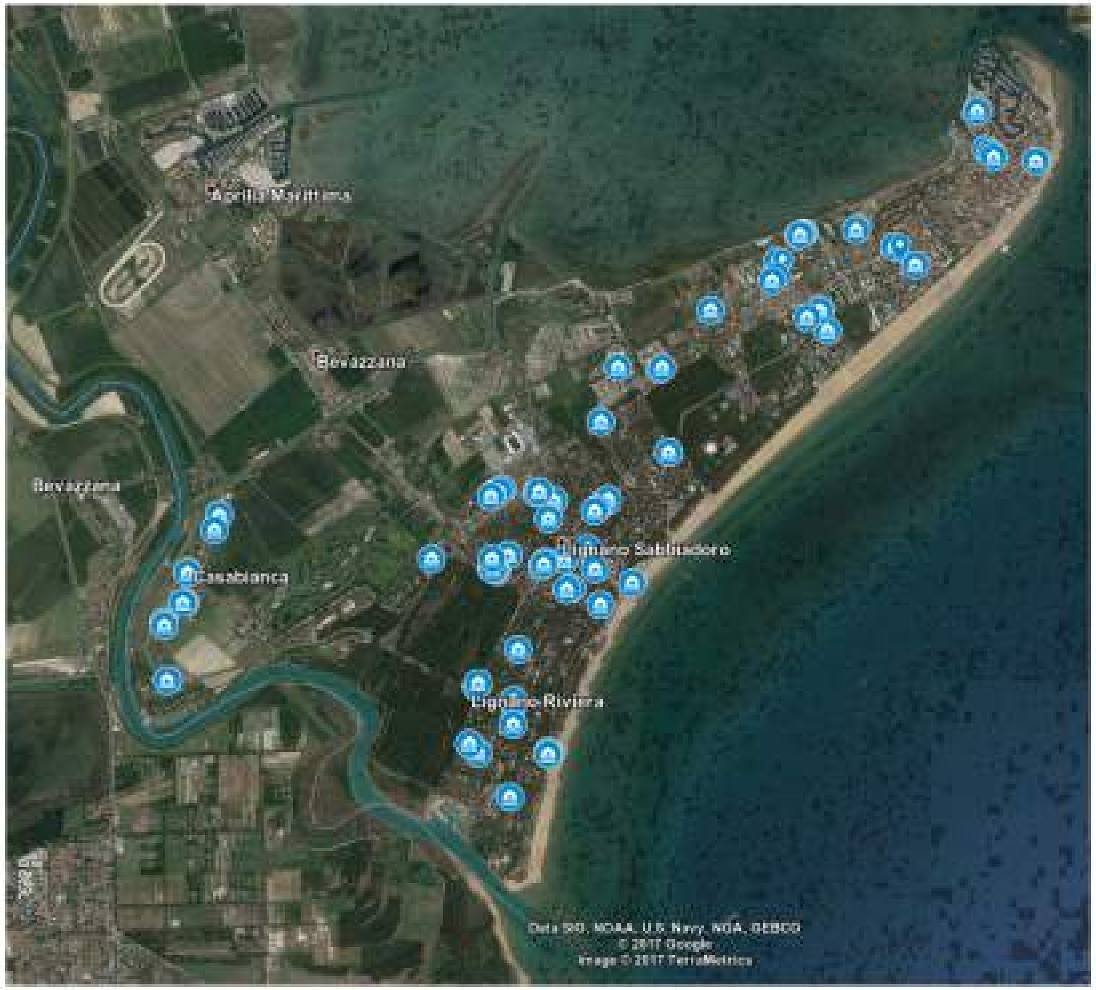
Lignano: pluvial flooding

Rainstorm, 10-12 September 2017

Large Pluvial Flooding
Resulting from two intense rainstorms



Flooded locations
Map of recorded emergency calls

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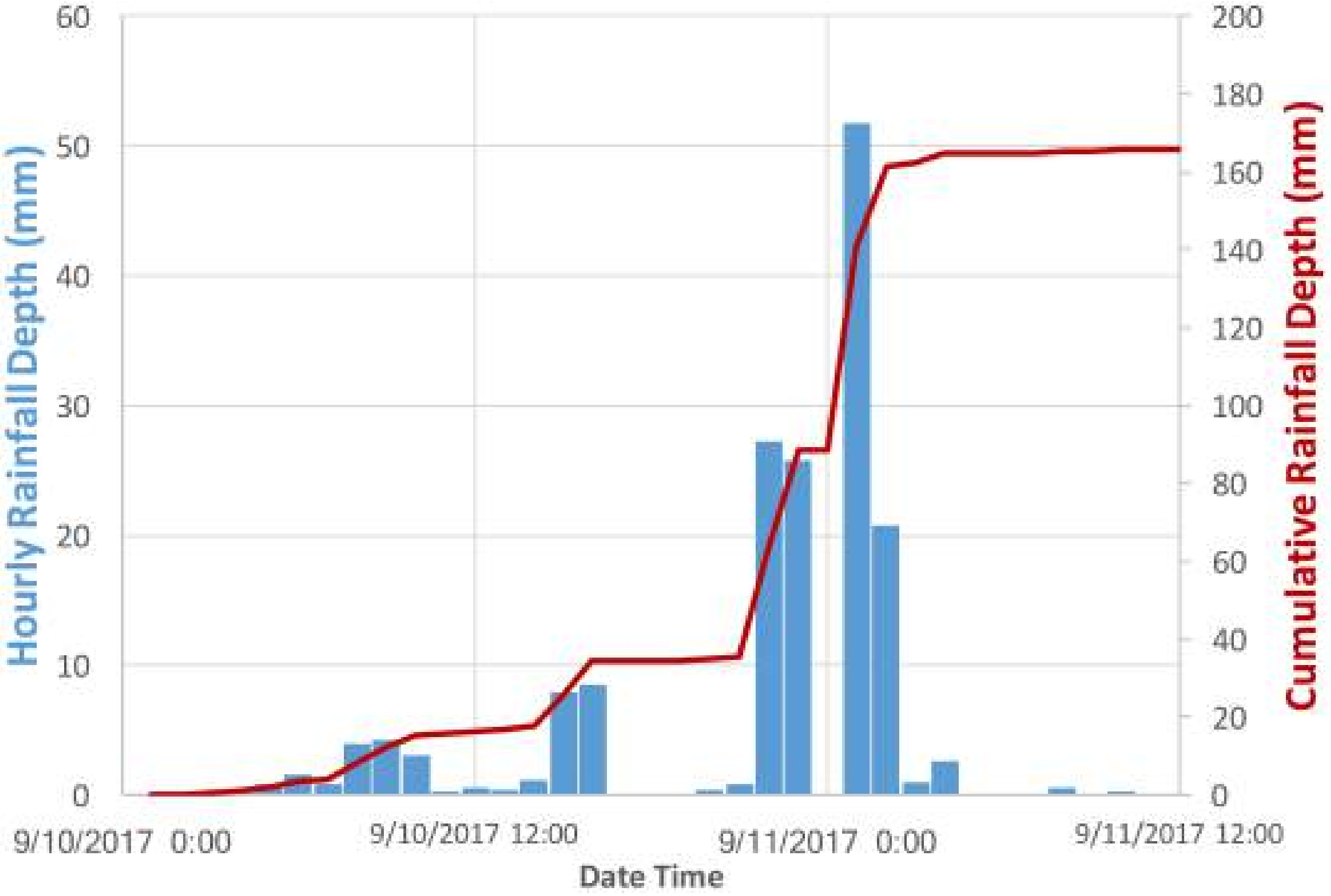
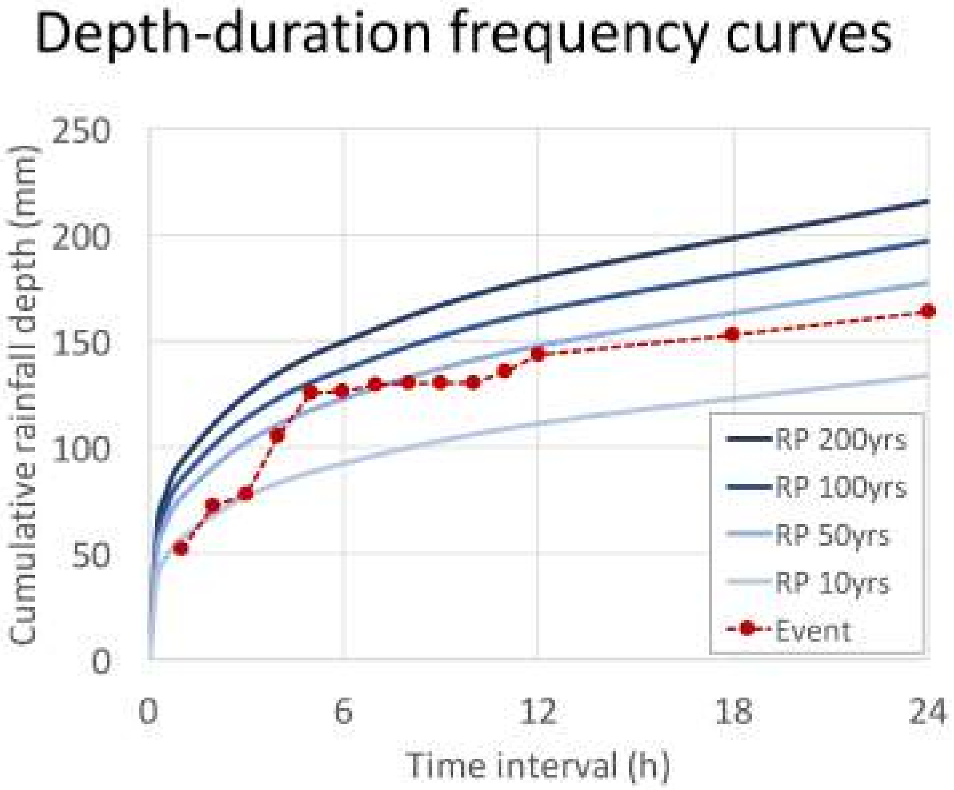
Lignano: pluvial flooding

Rainstorm, 10-12 September 2017





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Lignano: pluvial flooding

Land-use dynamics:
Touristic vocation resulted in
intense urban development in the last 30 years
(source: Google Earth)

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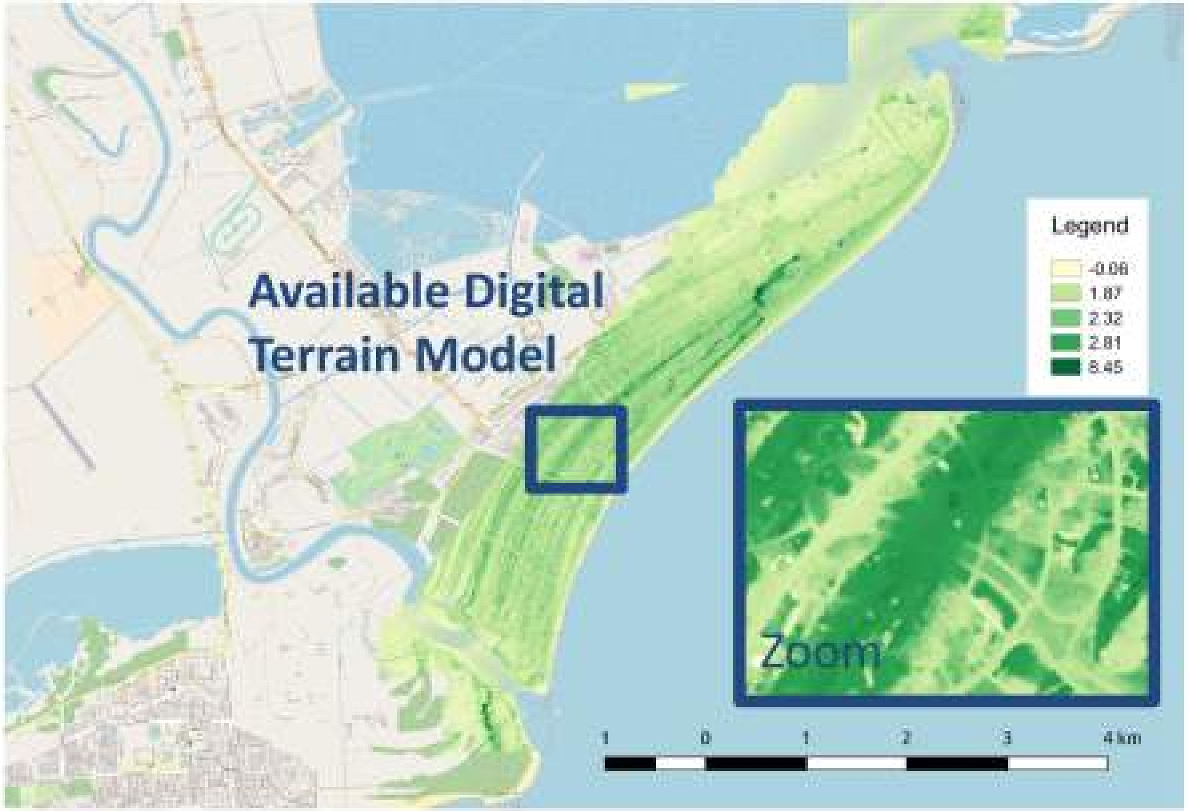
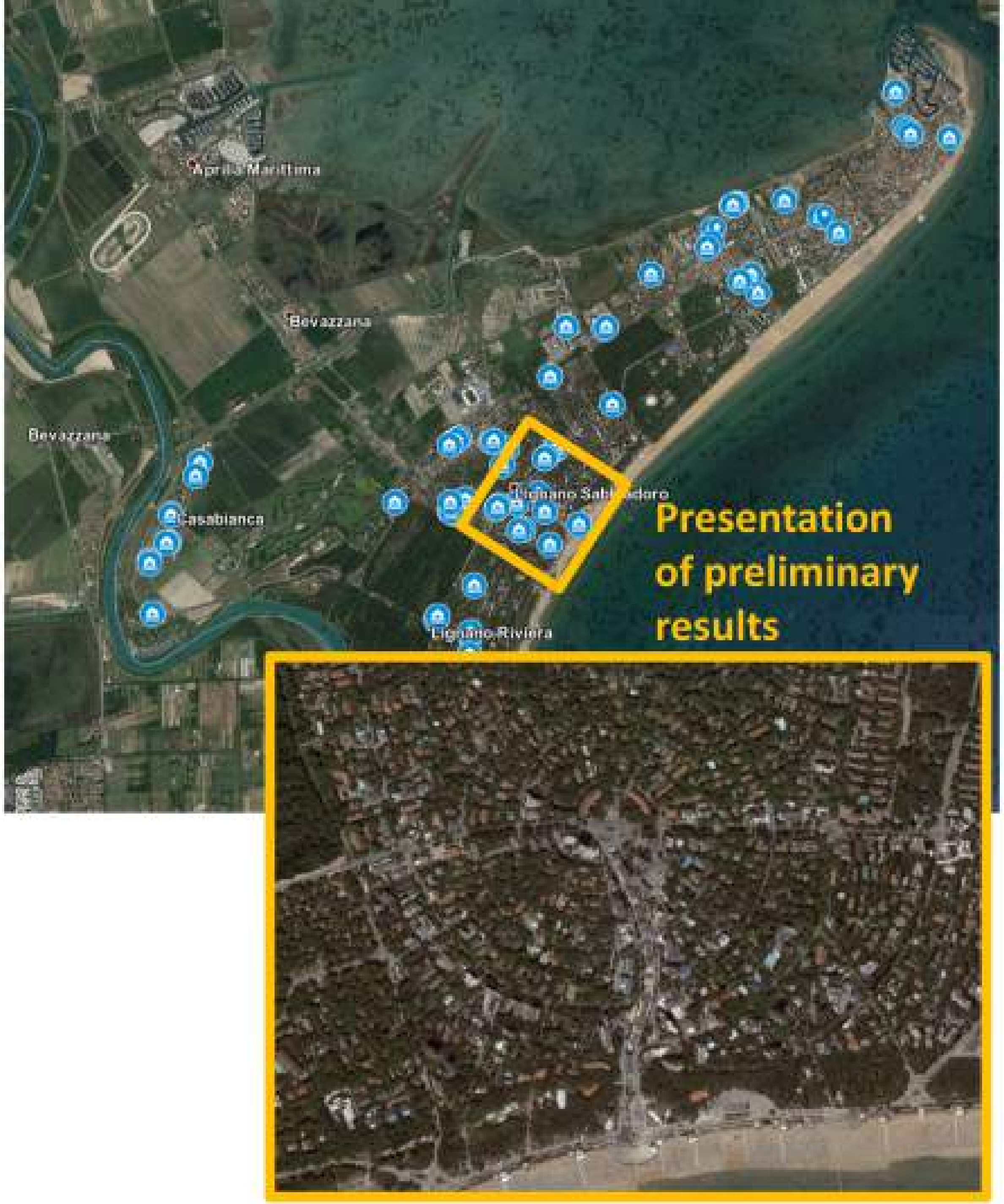
Available DEM and area of interest

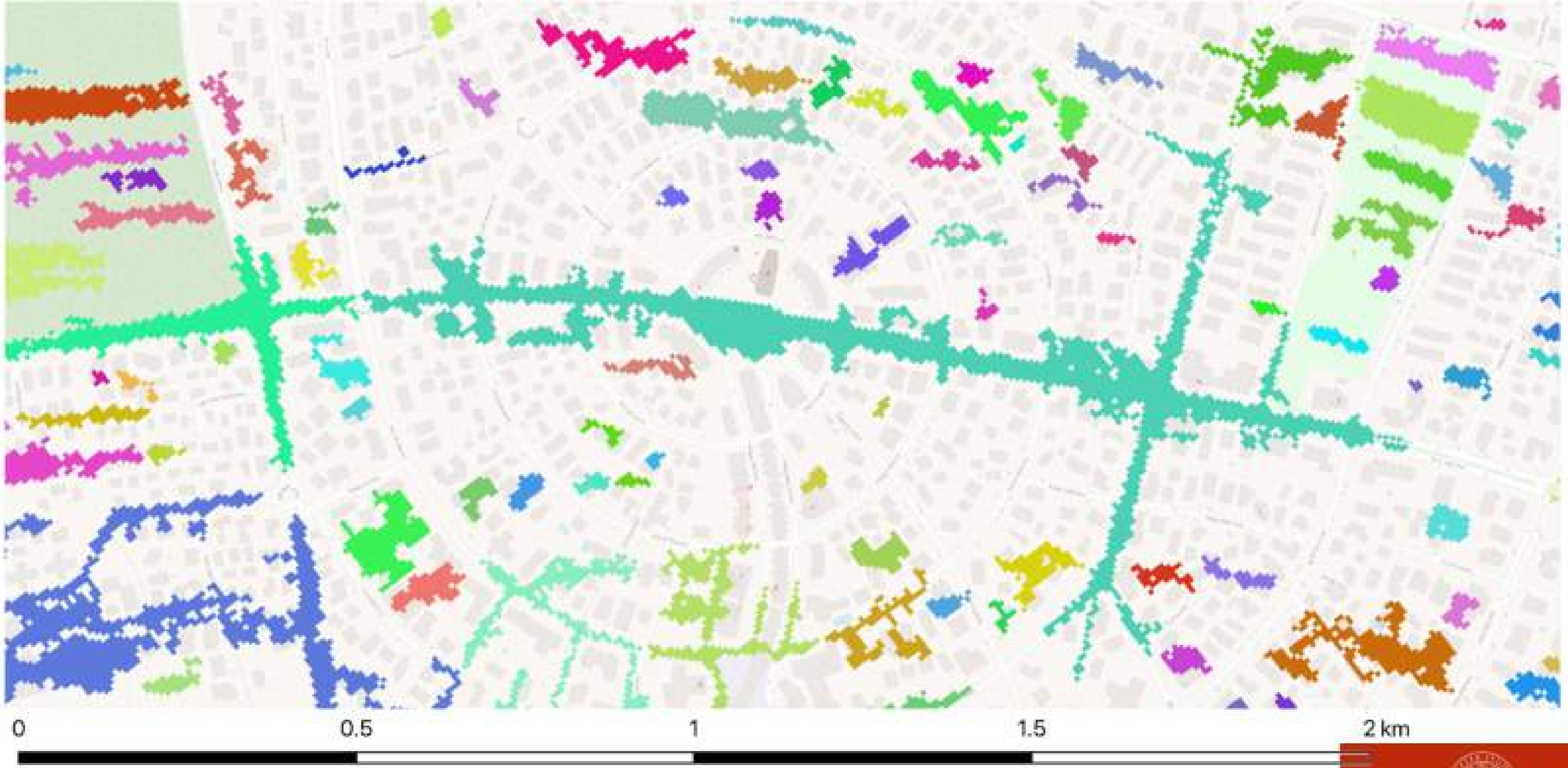


LiDAR DTM
Ministero dell'Ambiente e della Tutela del Territorio e del Mare
(Creation 2009-06-01, resolution 2m)



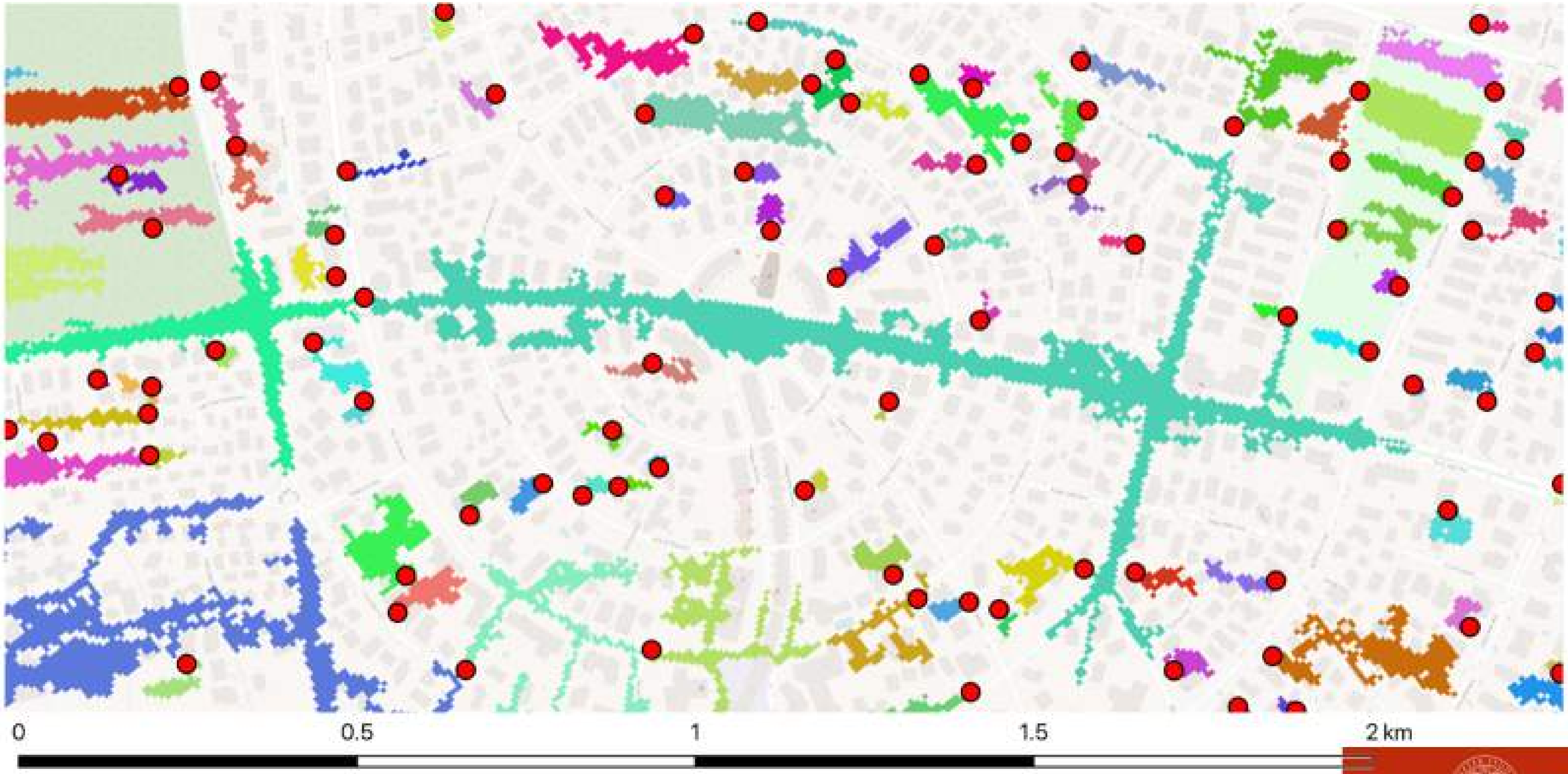
DEM pre-processing: application

Identification of: (a) blue-spots (binary maps, each blue-spots has a unique ID)



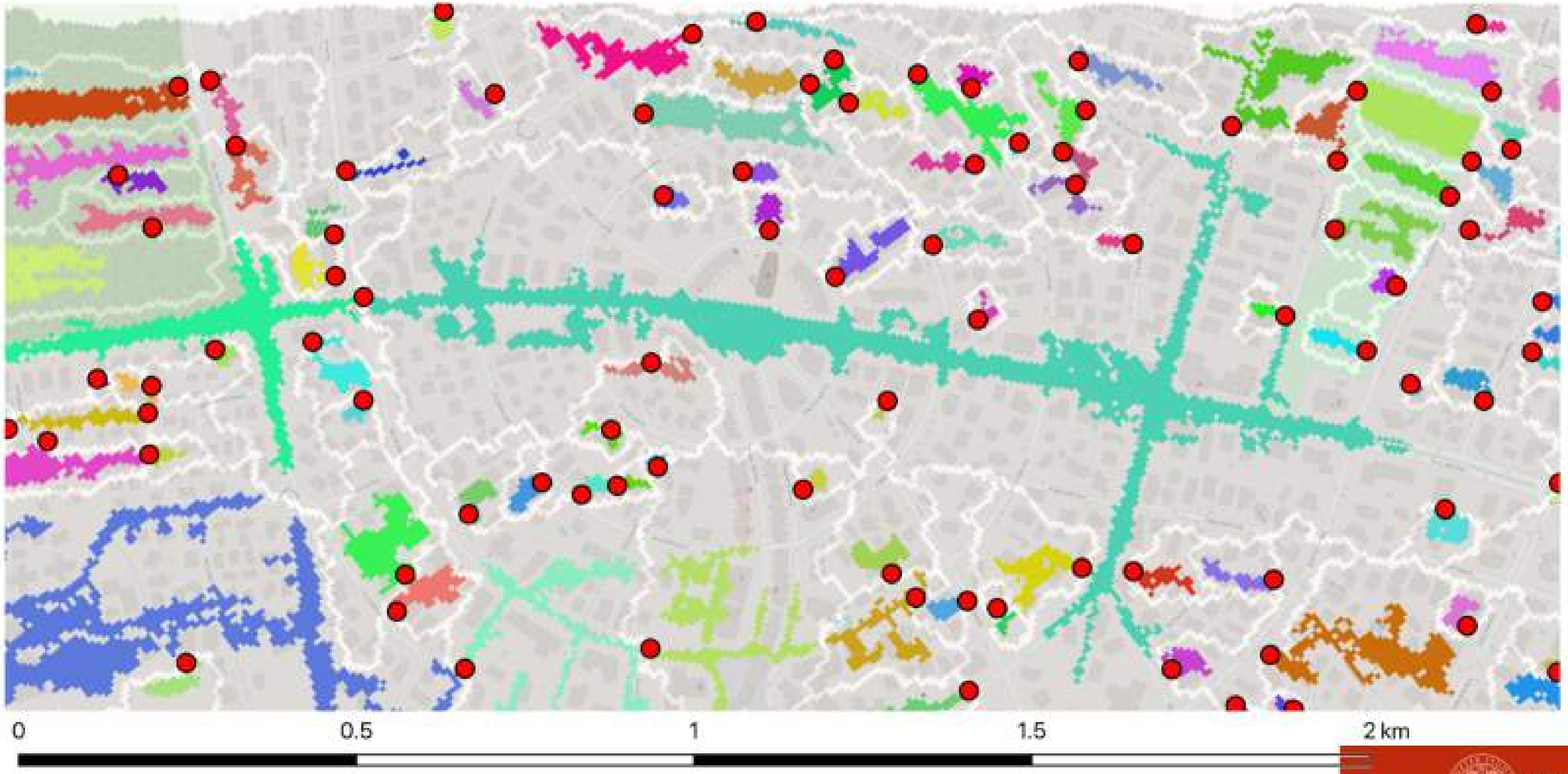
DEM pre-processing: application

Identification of: (a) blue-spots (binary maps, each blue-spots has a unique ID), (b) spilling points



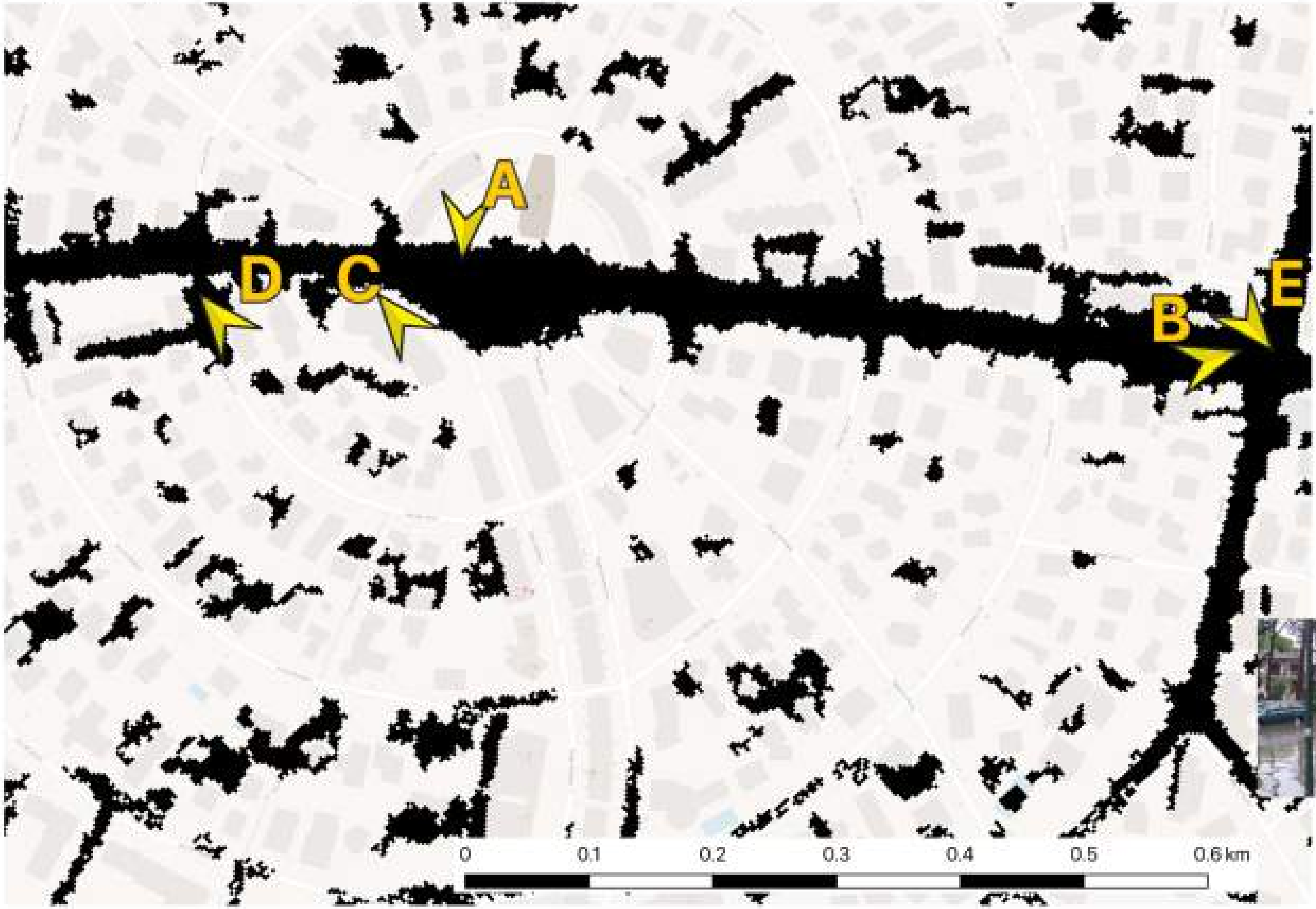
DEM pre-processing: application

Identification of: (a) blue-spots (binary maps, each blue-spots has a unique ID), (b) spilling points, and (c) watersheds



Results: ground evidence on flooded areas

Sept. 11, 2017 event, cumulated rainfall depth ≈125 mm (5-hour time interval)



(source: local TV-news footage, TRG Friuli-Venezia-Giulia)

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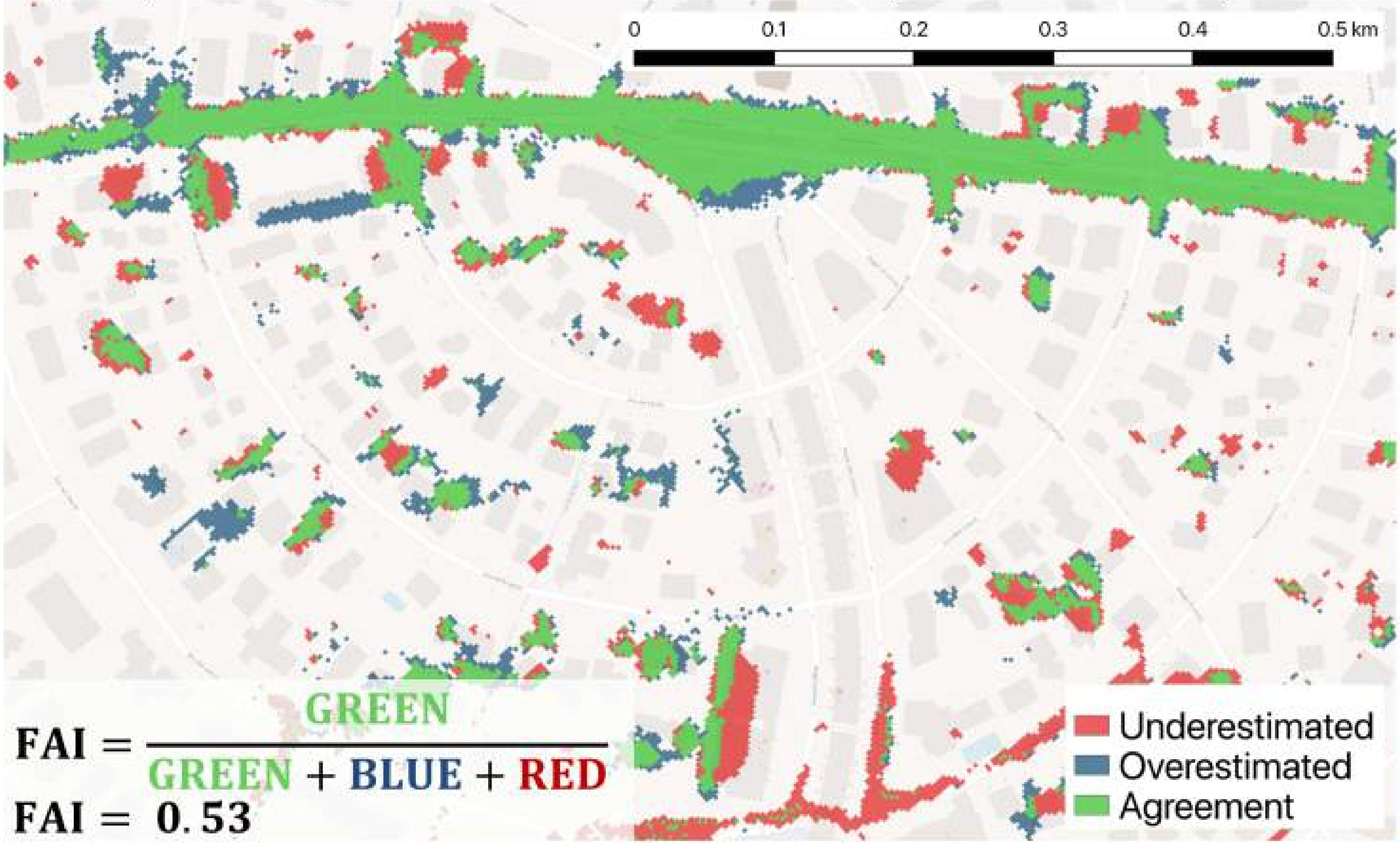
Results: comparison with a hydrodynamic model output

Sept. 11, 2017 event, cumulated rainfall depth ≈125 mm (time interval 5 hours)



$$\mathbf{FAI} = \frac{\mathbf{GREEN}}{\mathbf{GREEN} + \mathbf{BLUE} + \mathbf{RED}}$$

$$\mathbf{FAI} = \mathbf{0.53}$$

Flooded areas

- DEM-based algorithm
- Maximum water level simulated through a fully-2D hydrological-hydrodynamic model solving the shallow water equations (benchmark model, developed by IBH, https://ib-humer.at)

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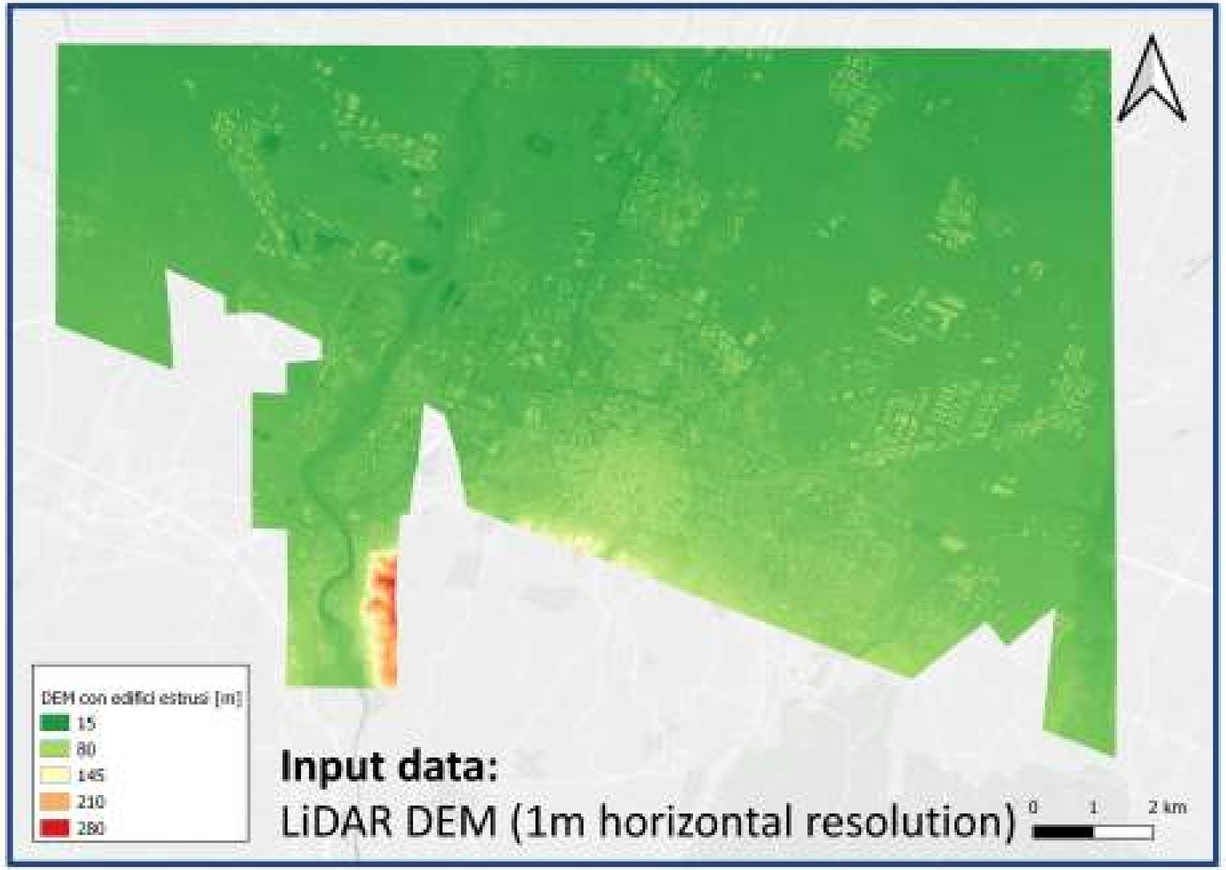
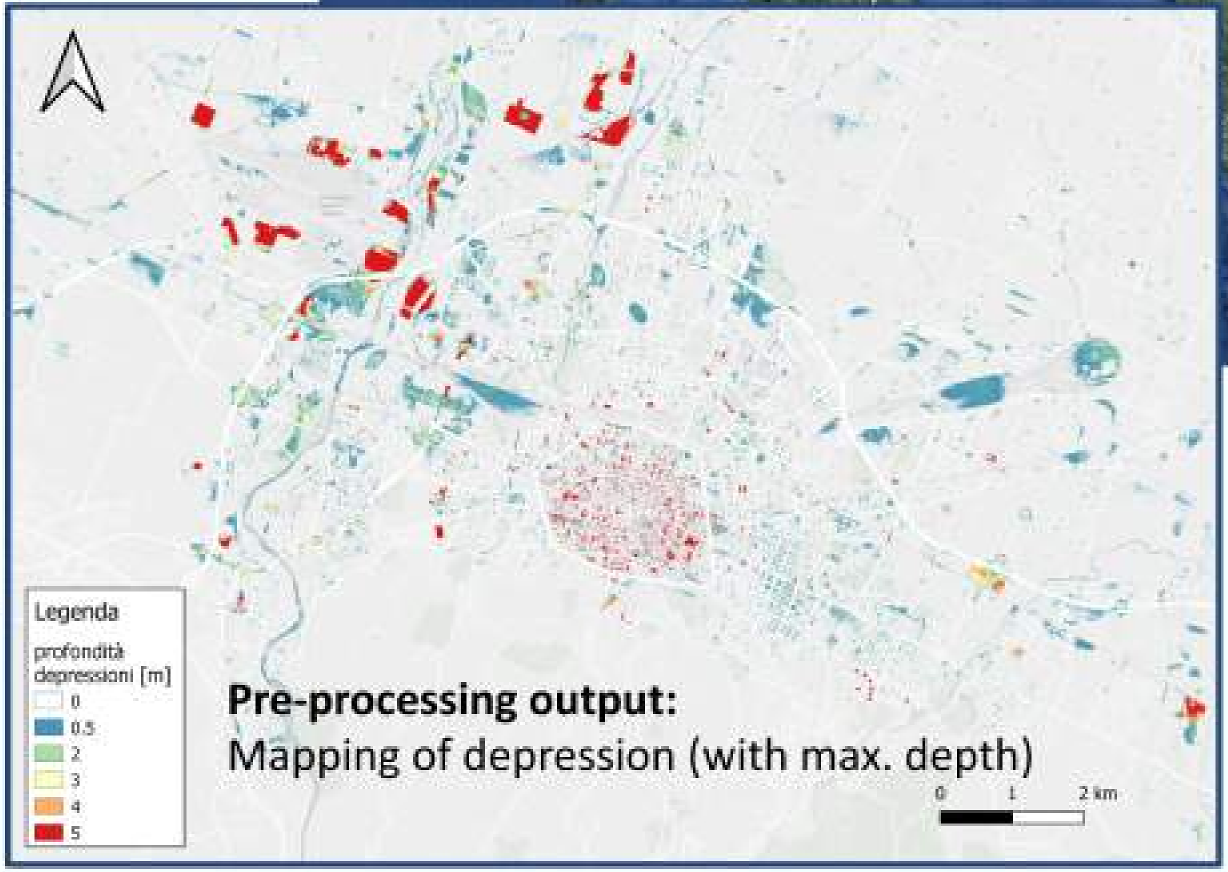
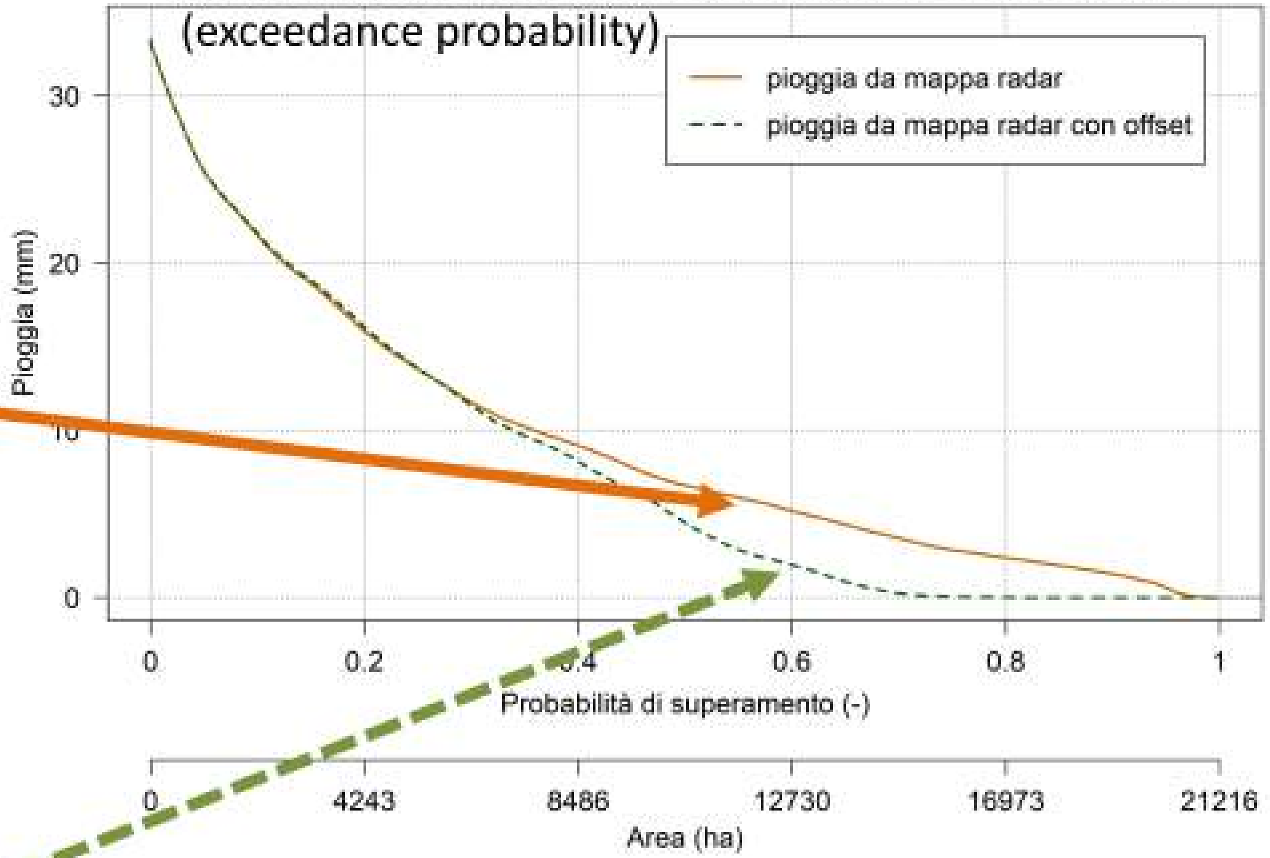
Bologna: spatially distributed rainfall data (weather radar)





Bologna: Spatially distributed rainfall data (weather radar)

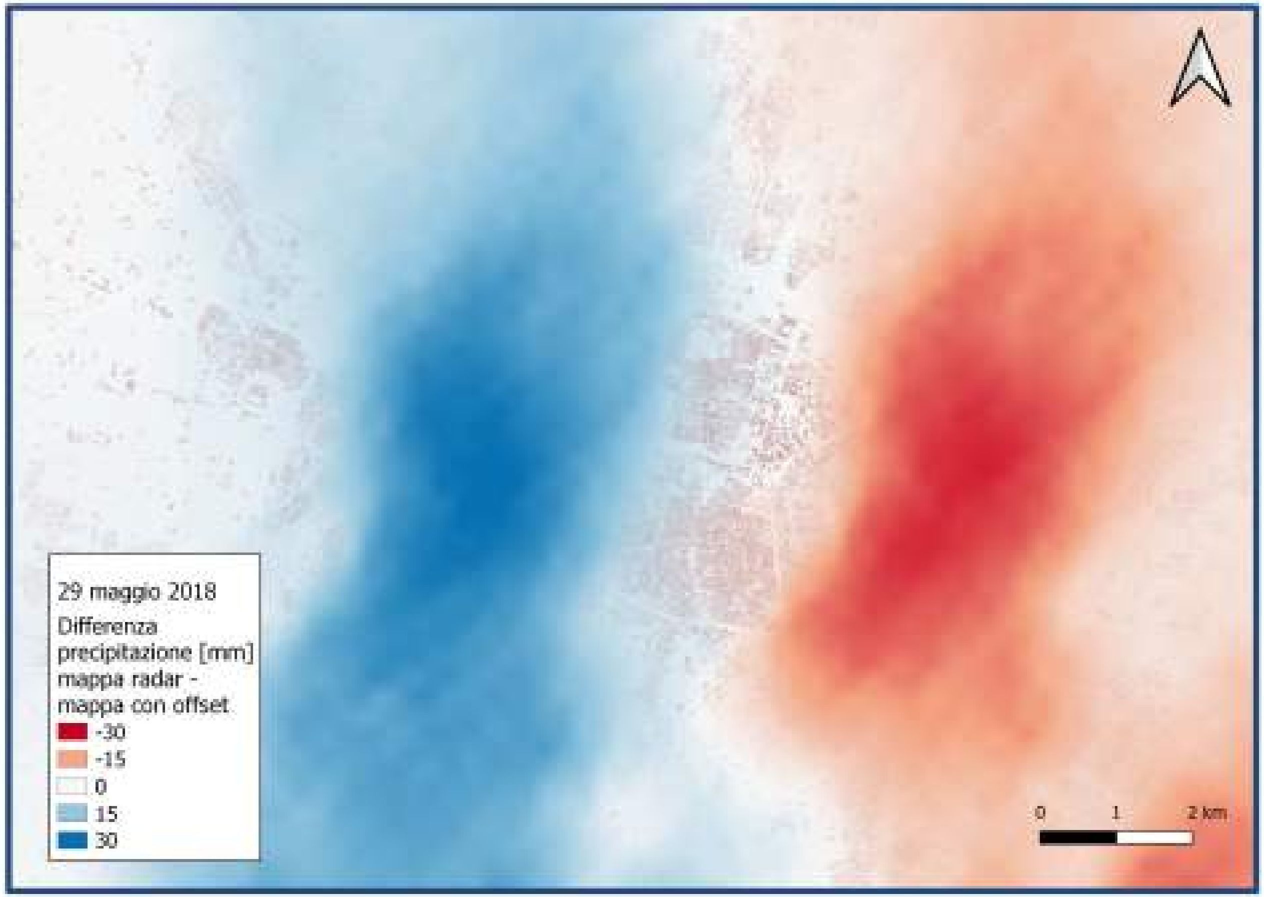
Spatial distribution of 1h cumulated rainfal depths
(exceedance probability)



Bologna: Spatially distributed rainfall data (weather radar)

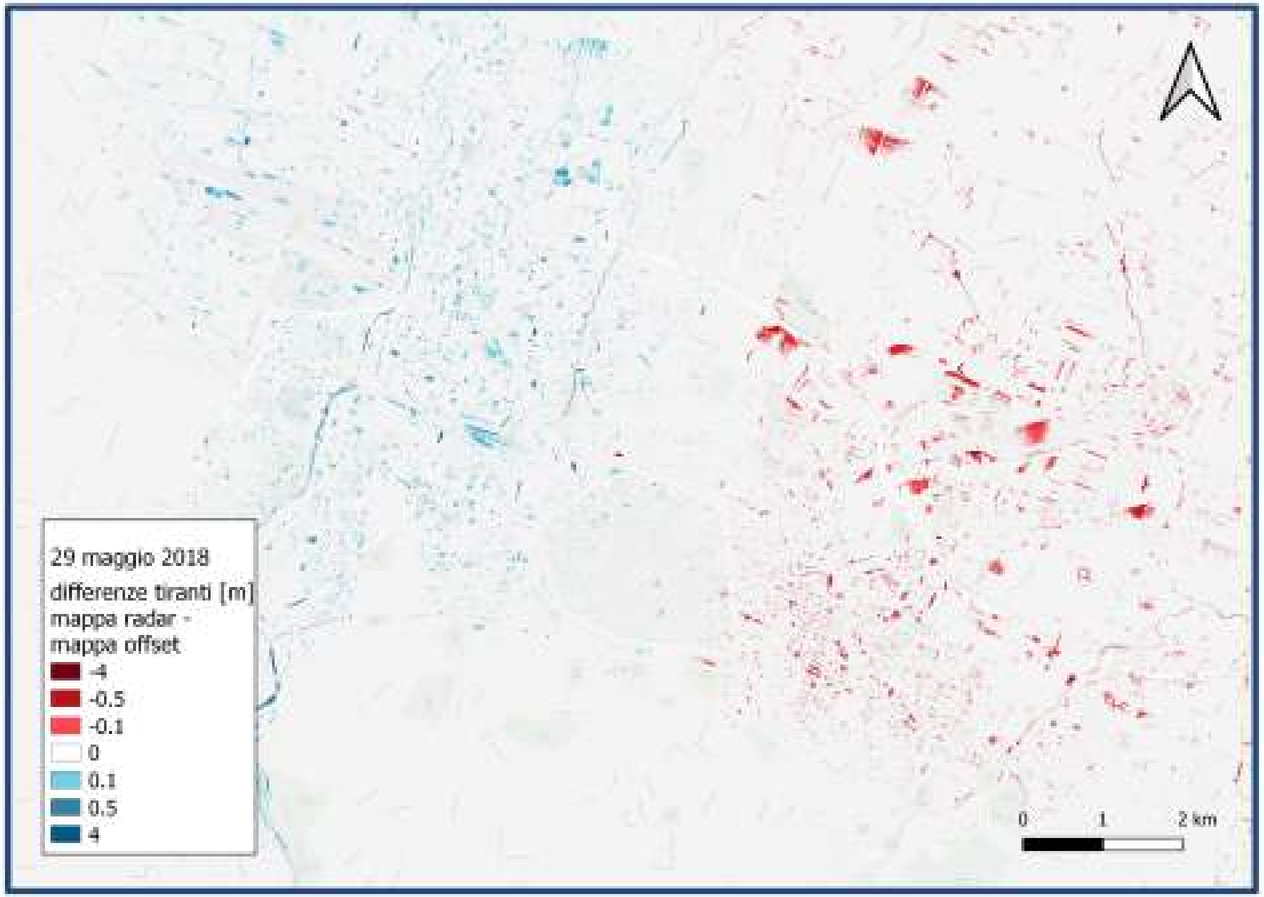
Real vs. synthetic event

Difference in terms of cumulative 1h rainfall depth (real – synthetic)

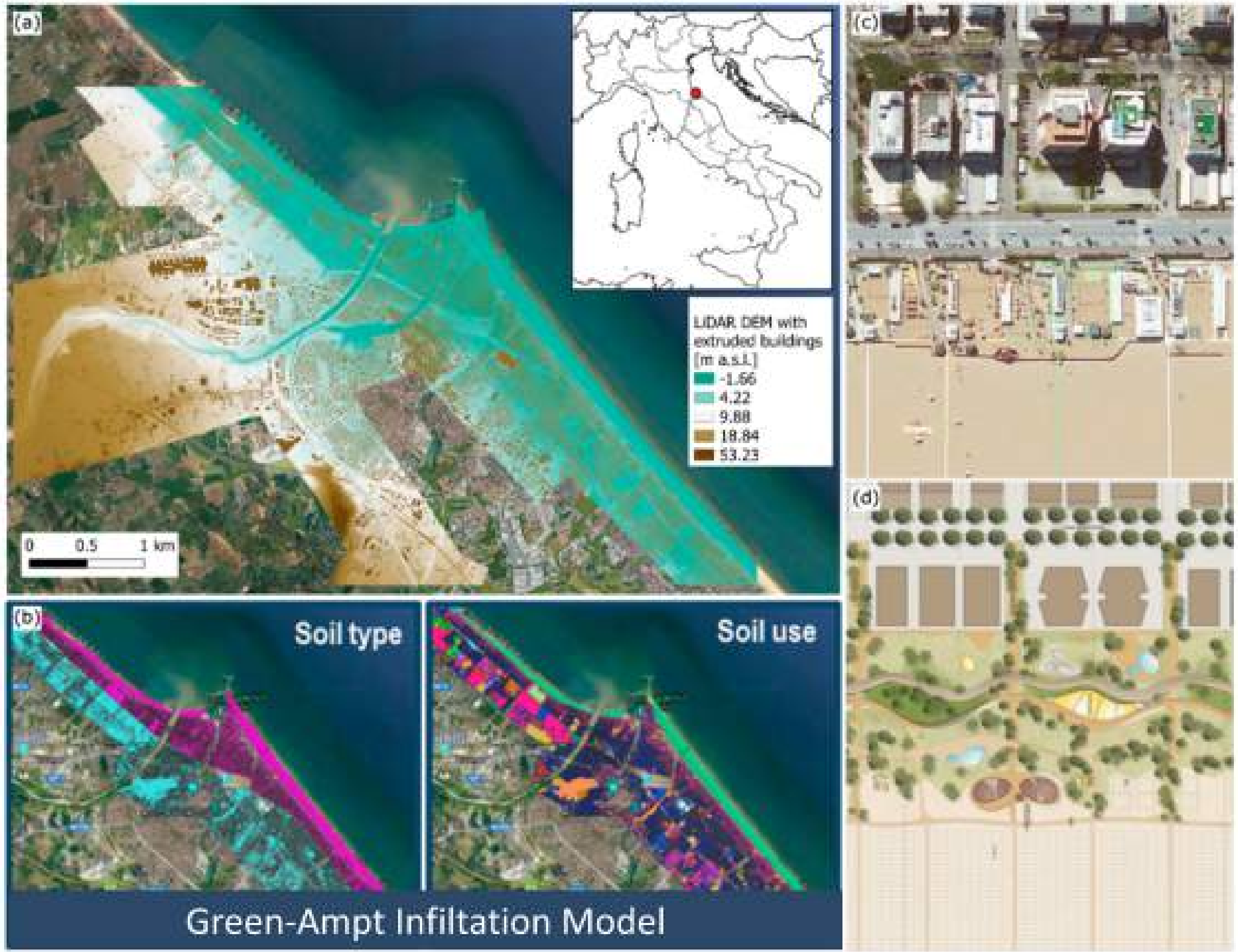


Flooded areas

Difference between maximum water depths simulated for the real and synthetic events

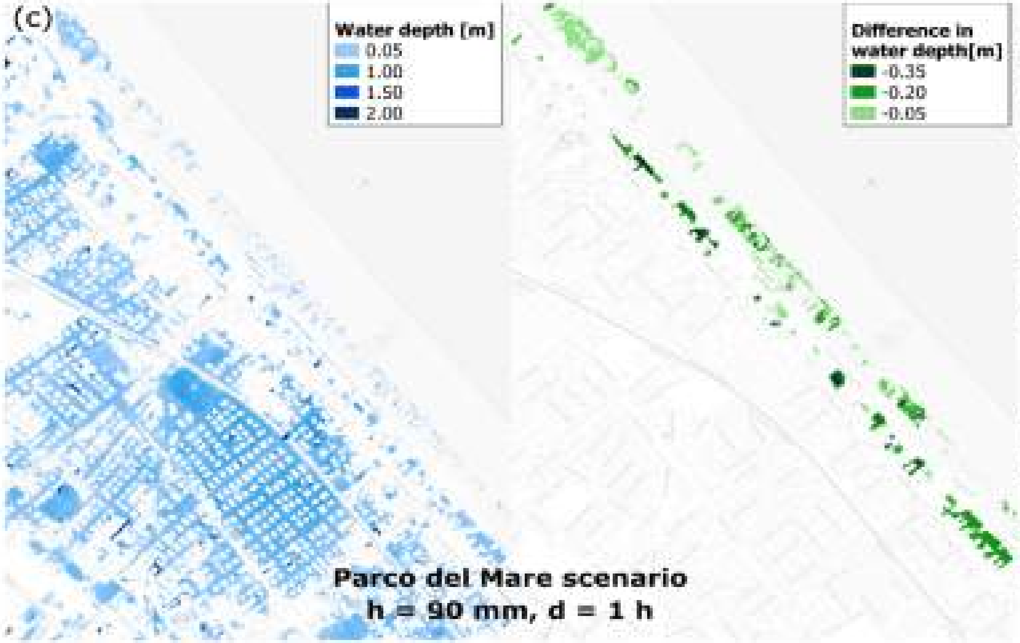


Rimini: pluvial flooding scenarios



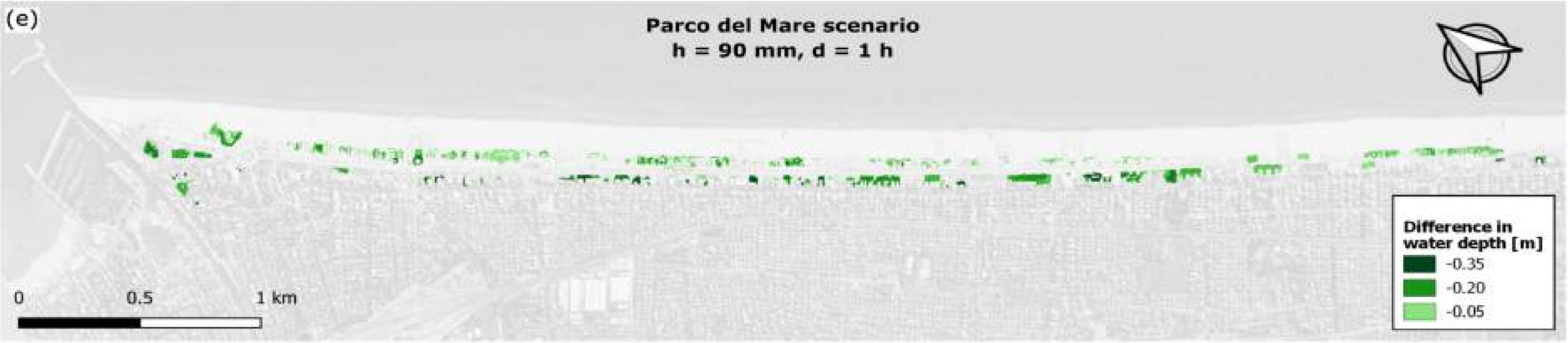
(a) location of the case study and 1 m LiDAR Digital Elevation Model (DEM)
(b) soil-type and land-use maps for the study area
(c) and **(d)** current layout of the seafront (satellite image) and **future green infrastructure according to the rehabilitation and renovation project *Parco del Mare***

Rimini: pluvial flooding scenarios

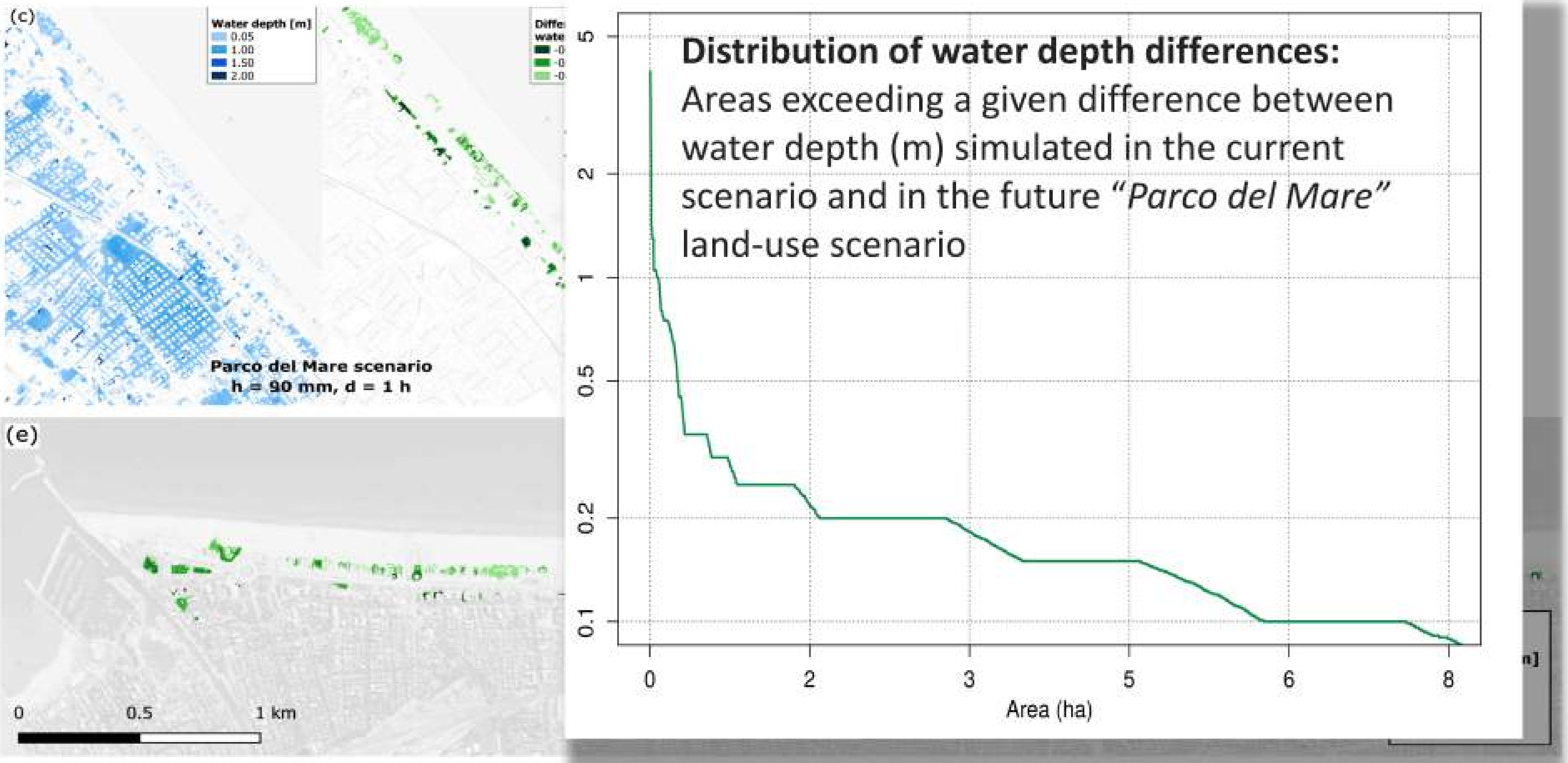


90 mm 1-h rainfall event:
(c) water depth for the 1h rainfall event **and the *Parco del Mare* land-use scenario** (urban green-infrastructure, left) and differences in water depth compared to the current layout (right);

(e) water depth for the *Parco del Mare* urban green infrastructure **minus** the simulated water depth for the current land-use scenario



Rimini: pluvial flooding scenarios



https://saferplaces.co/

SaferPlaces: web-based climate service

The beta version of the SaferPlaces Platform, a cloud web-service for cost-effective mapping of flood hazard and risk in urban areas, is now accessible online for everyone. You can test it directly at this link: platform.saferplaces.co

Video tutorial: https://youtu.be/xvqjLTHJc5A

Discussion and Outlook

Main Limitations

- Flooding dynamics is not modelled: underestimation of maximum water levels, no indication on timing, **nor velocity**

Main advantages and ideal applications

- Terrain pre-processing is run once and it fully characterizes the hierarchy for filling and spilling processes (**very fast computation of flooded areas**)
- Straightforward application to spatially variable precipitation and infiltration losses
- Identification of pluvial-hazard hotspots
- Optimal location of detention tanks/ponds
- Pluvial flooding scenarios for e.g. evacuation plans

Recent features

- Spatially variable precipitation (e.g. **weather radar**)
- Spatially variable losses (capacity of storm water drainage systems, variable land-cover and infiltration rates)

Example for a 982 by 1068 grid on a 2 CPU's, Intel(R) Xeon(R) CPU @ 2.30GHz, cache: 46080 KB

Preprocessing ti

Computation of

- **10.9s** for a cu
- **9.2s** for a cur

Lignano, Sept. 11, 2017 rainstorm
Cumulative rainfall depth 280 mm,
120 mm in 4 hours, 55 mm in 1 hour

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