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Mathematical Modelling in Civil Engineering
Vol. 18-No. 1: 38-50-2023
10.2478/mmce-2023-0004

IDENTIFICATION OF THE AREAS AT HIGH PLUVIAL FLOOD RISK BASED ON URBAN HYDRAULIC MODELLING. CASE STUDY FOR TULCEA MUNICIPALITY

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Abstract: Pluvial floods are frequent phenomena in Romania occurring during torrential rainfall, causing significant damage. Pluvial floods occur due to extreme rainfall when the natural infiltration of excess water into the ground is artificially reduced and when runoff into urban areas exceeds the capacity of existing drainage systems. In urban areas, pluvial flooding is more frequent due to extended impermeable areas, buildings, and undersized drainage systems. Tulcea municipality is characterized by periodic rainfall flooding events with consequences on properties and communities, infrastructure, and on the economic activities. In the second cycle of implementation of the Floods Directive 2007/60/EC, 17 Areas of Potential Significant Flood Risk (APFSR) pluvial source areas were identified, covering 19 municipalities and towns, for which pluvial hydraulic models were carried out. Tulcea municipality was one of the cities designated as having areas of potential significant pluvial flood risk. Hydraulic modelling results have been used for the construction of pluvial flood hazard and risk maps, these being the first pluvial maps reported by Romania to the European Commission. Based on these maps, critical drainage areas have been identified at the level of Tulcea Municipality and some potential flood risk reduction measures have been recommended.

Keywords: urban floods, hydraulic modelling, pluvial hazard and risk, Tulcea

Introduction

Pluvial flooding in urban areas occurs due to extreme rainfall when infiltration into the ground is reduced due to land use change or when rainwater cannot be collected and drained by the sewage system. Ponding occurs in low elevated and depressional topographic areas characterized by deep concavity. Potential pluvial flooding depends on the local land topography which implicitly define the runoff directions, on the land use and land cover (degree of impermeability) and on the transport capacity and performance of the urban stormwater systems [1] [2].

Similar to fluvial floods, hazard and risk maps are the primary and mandatory tools for identifying the areas affected and exposed to pluvial floods and also necessary for developing strategies and action plans to manage and reduce risk. This is, in fact, the very essence of Directive 2007/60/EC (known as the Floods Directive), which came into force in 2007 [3]. For the implementation of the second planning cycle of the Floods Directive, in the framework of the RO-FLOODS application (Strengthening the capacity of the central public authority in the water field in order to implement the 2nd and 3rd stages of the 2nd Cycle of the Floods Directive, SIPOCA code 734), the main beneficiary - the Ministry of Environment, Water and Forests has signed with the World Bank, a Reimbursable Technical Assistance Agreement for the elaboration of Flood Risk Management Plans for Romania.

Subsequently to this contract, following a competitive tender, the World Bank awarded the consortium led by JBA Consulting (UK / Ireland / Romania) - project leader, together with partners HKV (Netherlands), DHI (Denmark / Romania) and Aquaproiect (Romania), the consultancy contract entitled "Consultancy services for the preparation of hazard and flood risk maps and Flood Risk Management Plans for Romania". This contract was carried out over a period of approximately 24 months and was recently completed in June this year.

As part of the afore mentioned consulting contract, JBA produced the first national-scale flood hazard and risk maps for the pluvial source for 17 Areas with Potential Significant Flood Risk (APFSR). The 17 pluvial APFSRs (covering 19 municipalities and cities) reported to the European Commission in 2019 are Reşiţa, Caransebeş, Oţelu Roşu, Timişoara, Petroşani, Caracal, Piteşti, Ploieşti, Cernavoda, Corbu, Tulcea, Constanta (including Eforie and Costineşti), Cluj-Napoca, Zalău, Roman, Suceava, Gura Humorului (Figure 1).

To obtain the hazard maps, JBA built 19 HEC-RAS 2D hydraulic models for which very high accuracy data were used: 0.5m resolution DTM, Intensity-Duration-Frequency curves updated at the time of the project, assumptions on the sewer networks in order to integrate them into the models, database of recorded historical floods for model validation, which finally led in the end to high confidence results and hazard maps. Based on the hazard maps, pluvial risk maps were built for the same 17 APFSRs, which are also the first hazard and risk maps of this type produced on a national scale and reported to the European Commission for Romania.

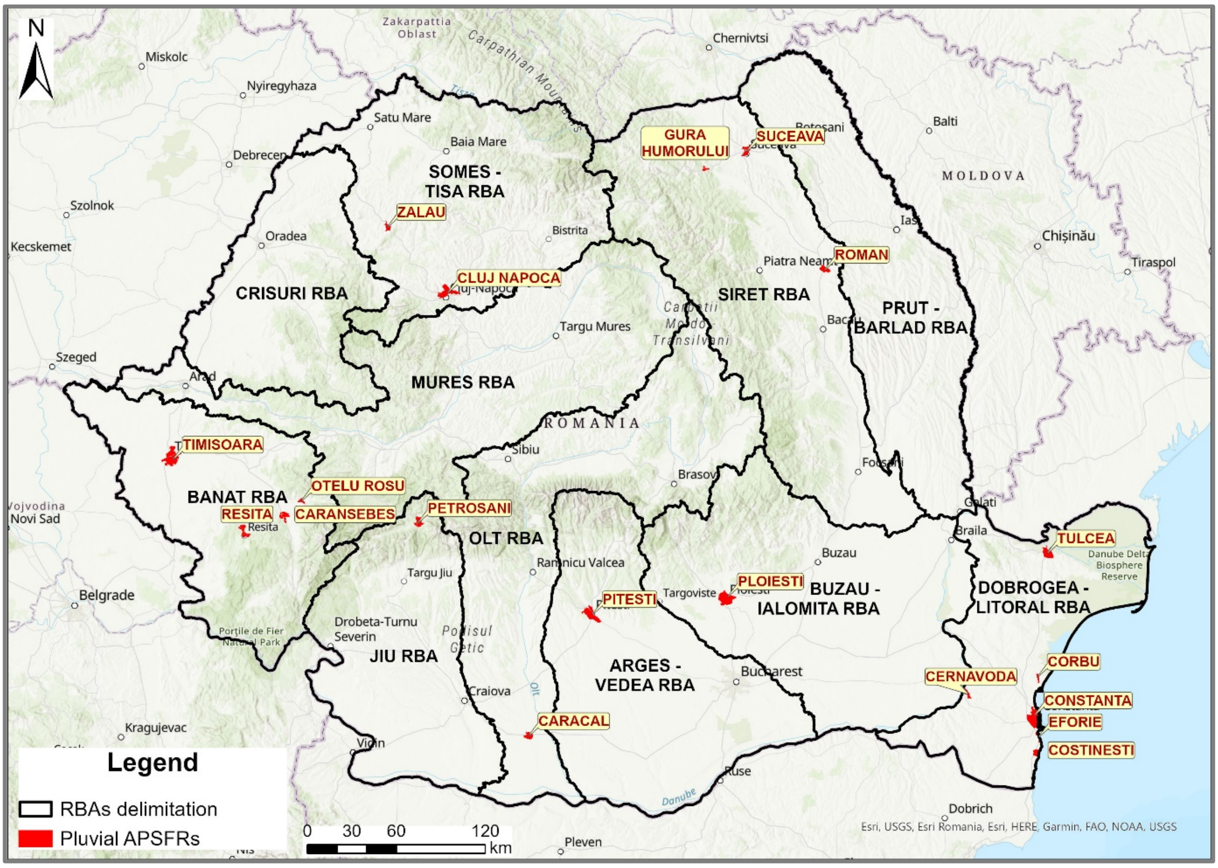

Fig. 1 - Areas with Potential Significant Flood Risk (pluvial APFSRs) identified in Romania and reported toward to the European Commission in 2019.

Tulcea Municipality is the administrative center of the county of the same name, located in the south-eastern part of Romania on the right bank of the Sfântu Gheorghe branch of the Danube, at the entrance into the Danube Delta. On the right bank of the Sfântu Gheorghe branch there is an existing defense dike designed for 1% annual exceedance probability, Tulcea being protected against the fluvial floods.

Tulcea is frequently exposed to urban flooding caused by intense rainfall, due to the steep slopes of the surrounding hillsides, which have short concentration time, generating torrential surface runoff and flows which exceed the transport capacity of the stormwater network. The water collected from the catchment is drained along the slopes directly into the central low-lying areas of the city around the bend of the Sfântu Gheorghe branch, affecting important buildings and completely disrupting the traffic [1].

According to the information provided by the General Inspectorate for Emergency Situations (IGSU), in the period between 2016-2020, 65 locations were affected by pluvial floods in the Tulcea generating significant damage (Figure 2), the average frequency of occurrence being 2 times a year.

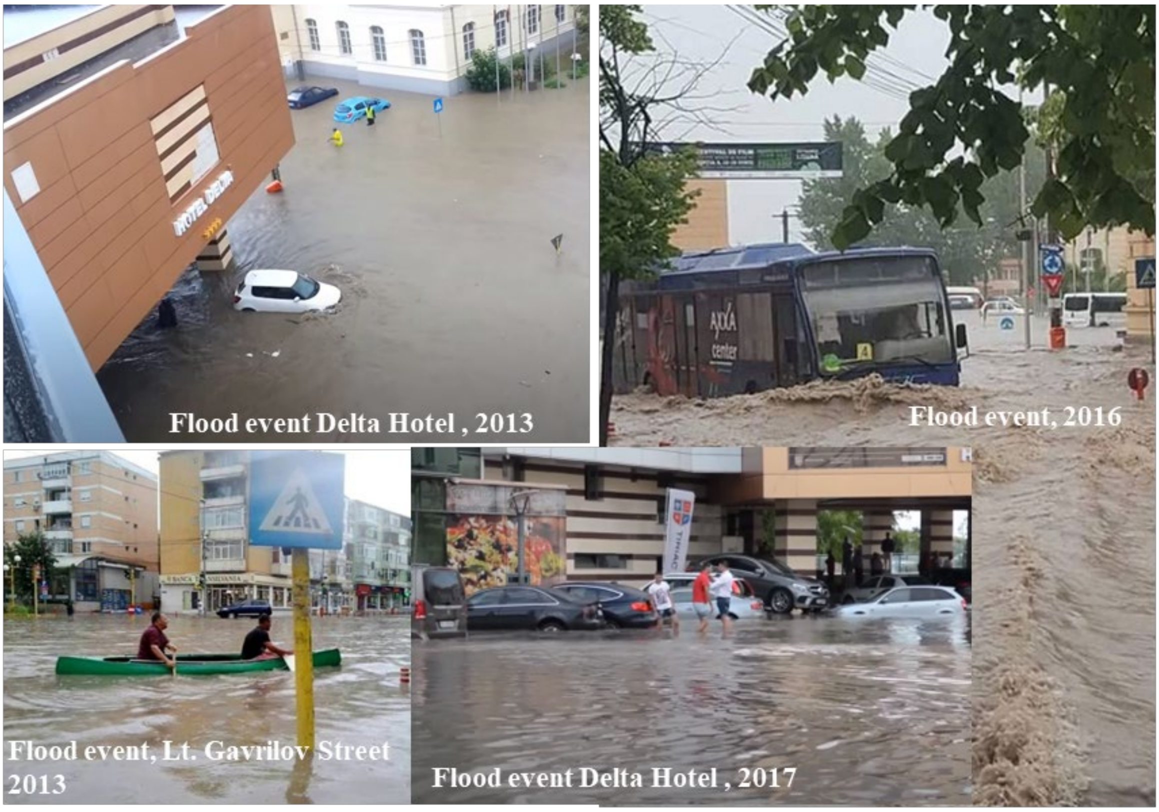

Fig. 2- Pluvial floods affecting Tulcea (online sources).

The infrastructure for stormwater drainage in Tulcea consists of a pluvial sewage system and 5 pumping stations having the purpose to evacuate the water accumulated behind the dikes. When the Danube water level is below the inverts of the outlet pipes of the sewage system the discharge happens gravitationally, but when the level of the Danube is high, the accumulated water is drained behind the dikes by pumping. According to the information provided by R.B.A. Dobrogea - Litoral, the drainage network is predominantly represented by a combined system (mixed collection of stormwater and wastewater), with only few separative sectors in newly developed areas where the stormwater is collected and transported separately.

The urban sewage system in Tulcea is designed for rainfall having the frequency of 1 in 2 yr. During heavy rainfall exceeding the capacity of the sewage system, the network overflows mixed waters generating flooding which can reach the local water courses, having the potential of causing water quality and environmental issues.

Material ad methods

Tulcea is highly exposed to pluvial flooding due to the steep slopes of the hills which border the urban area generating surface runoff along existing valleys and along the streets, the water being diverted towards the city center. To assess the urban pluvial flooding for the study area, a 2D hydraulic model was developed using the HEC-RAS software. The 2D model used a flexible computational mesh with cell size of 10m and using 5m and 2m discretization in the detail regions where key infrastructure was identified. The mesh around existing infrastructure (dikes, roads, streets) was discretized using breakline elements to accurately capture any rapid elevation variations and the crests of structural elements. Shallow Water Equation were used for simulations, these complex equations including the Coriolis acceleration and forces and accounting all flow directions [4] [5].

The computational domain of the 2D model included all the surrounding slopes and hillsides to integrate the entire catchment which contributes to the surface runoff and the flows accumulation reaching the urban area of Tulcea.

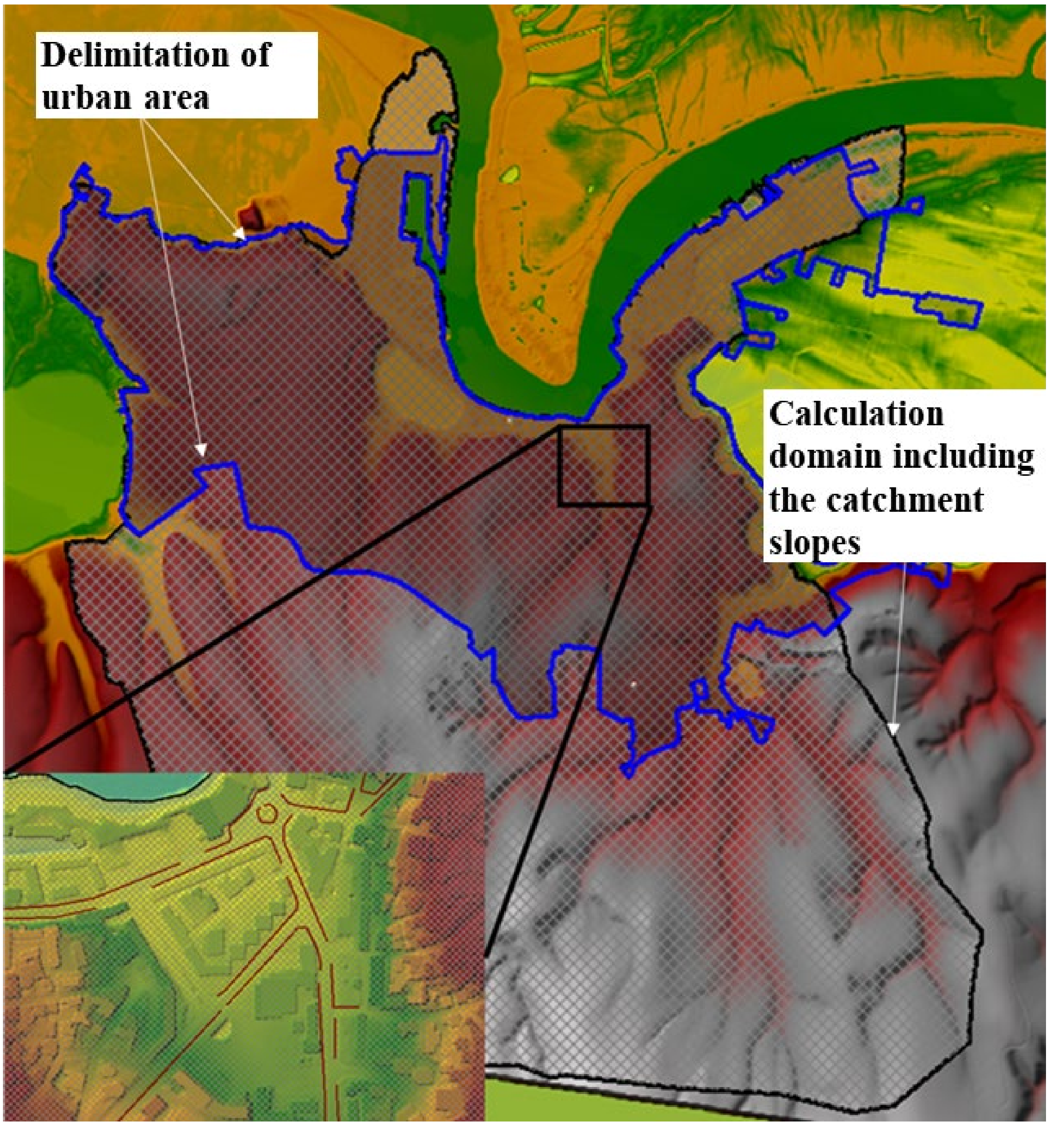

Fig. 3 - Calculation domain of the urban pluvial model.

Digital terrain model (DTM)

The digital terrain model is essential for pluvial flood modelling as it provides information about the terrain slope, elevation classes, existence of concavities which are ultimately instrumental in determining runoff flows and directions. The Tulcea rain-on grid model benefited from a high-quality Lidar, measured within the RO-FLOODS project, with a very high resolution of 0.5m. The building footprint was lifted by 30cm and integrated into the Lidar, based on exposure data.

Model boundary conditions - rainfall hyetographs

The upstream boundary conditions for the rain-on-grid models are represented in general by the rainfall hyetographs for different annual exceedance probabilities. For Tulcea municipality a wide range of probabilities were assessed, such as of the 33%, 10%, 1%, 0.5%, 0.1% and the climate change scenario.

The hyetographs were built based on of the Intensity-Duration-Frequency curves (IDF curves) provided by the National Meteorological Administration at the Tulcea weather station. The alternating blocks method was used for the development of the hyetographs (Figure 4)[6] [7].

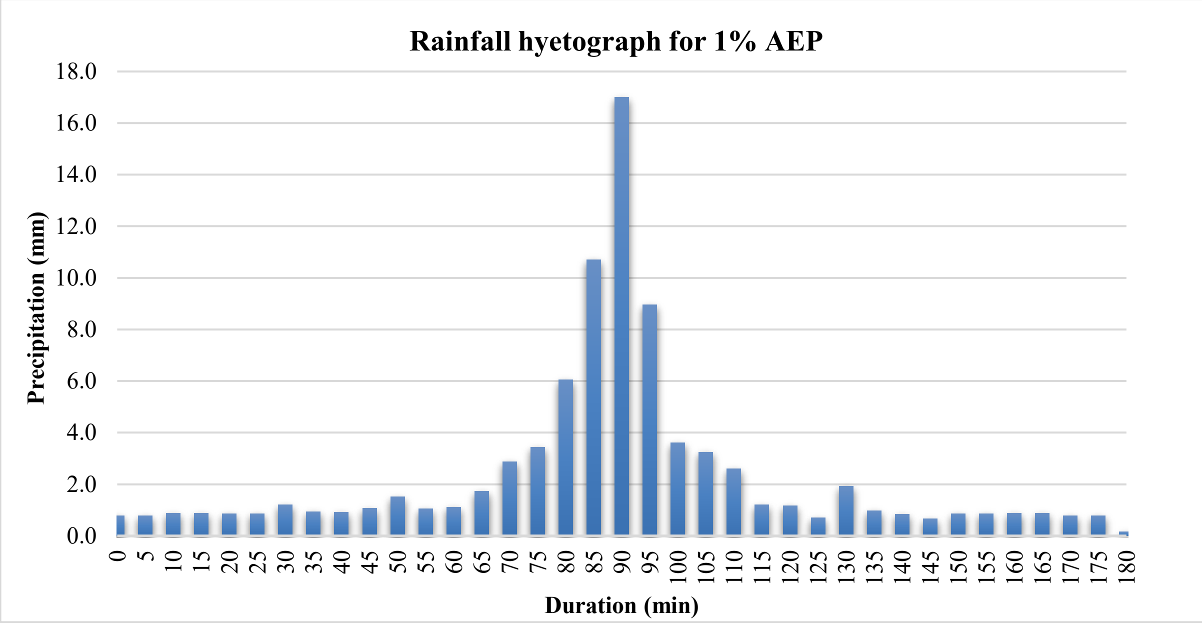

Fig. 4 - Rainfall hyetographs corresponding to the 1% annual exceedance probability, Tulcea weather station.

Land use data

The runoff and the amount of rainfall accumulated on the terrain surface, leading to urban flooding, are directly dependent on the land roughness and the soil infiltration layer, both being influenced by two other components: land cover and soil type.

Land cover data determines the spatial distribution of the Manning's roughness coefficient n but also the delineation of permeable or impermeable areas in the modelled domain. Land cover controls the percentage of rainfall that either infiltrates or becomes surface runoff.

The model for Tulcea used GIS layers Copernicus Corine Land Cover and Urban Atlas (source https://land.copernicus.eu) to define land use classes within the urbanized area and outside of the urban area [8]. These layers have been improved by integrating building footprints and for each land use category, roughness coefficients were associated according to the literature [9].

Soils data

Soil type data are very important for the quality of rain-on-grid model predictions, because together with the land cover component they determine what portion of rainfall becomes runoff in urban areas. Soil infiltration was estimated using the SCS Curve Number (CN) method. The SCS Curve Number method is an empirical method for assessing surface runoff developed by the US Department of Agriculture's (USDA) Natural Resources Conservation Service (NRCS). The CN coefficient is assigned to a land cover class based on the permeability of the underlying soils. The CN coefficient can have values ranging from 0-100, with 0 meaning a highly permeable soil and 100 meaning an impermeable soil [4] [10] [11] [12].

To determine the CN coefficients corresponding to our computational domain, the Soil Map of Romania (Scale 1:1000000) was used and the soils were grouped into 4 central groups (groups A, B, C, D) based on the criteria presented in Figure 5 [4].

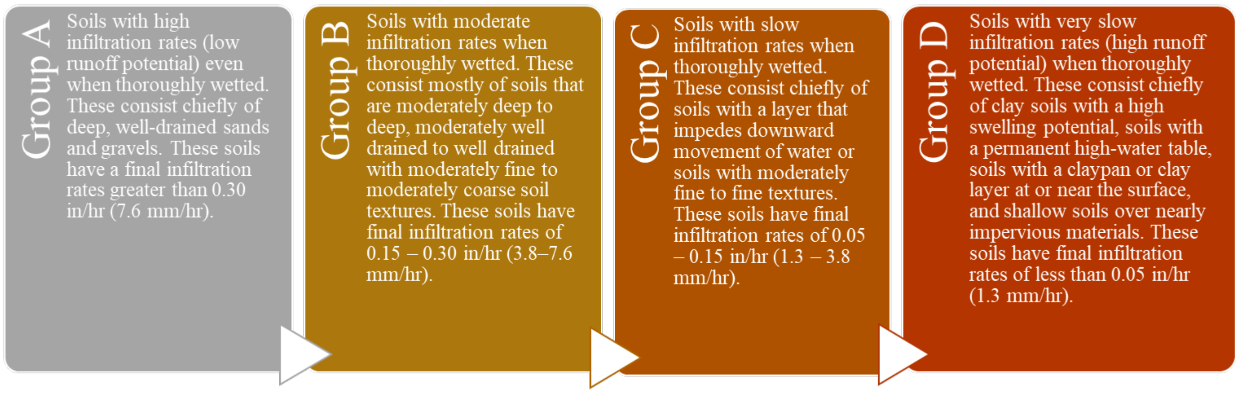

Fig. 5 – Soil groups corresponding to the SCS Curve Number method

The distribution of the reclassified soils into these groups has been intersected with the land cover map resulting in unique combinations to which CN coefficients with values between 30 and 100 were assigned to reflect the percentage of imperviousness and related infiltration capacity of the soil for each distinct area in the calculation domain.

Data on the stormwater drainage network

The Romanian standard SR 1846/2-2007 establishes the design rainfall frequency (a way of expressing the rainfall annual exceedance probability) for sewage networks in urban or rural areas in Romania [13]. As there is no precise information available on the design rainfall used for the designing of the current sewage network in Tulcea, the Romanian standard was used, based on which the design rainfall frequency was assigned according to the number of inhabitants. With a population of about 74.000 people, the sewage system was considered dimensioned for the frequency 1:2yr. Therefore, the urban sewage system was integrated in the hydraulic model as having the capacity to store the water volume produced by the rainfall event similar to the 1:2 yr and for this it was associated an average rainfall intensity of 15.73 mm/hour. The rain intensity was extracted from the Intensity - Duration - Frequency curves for the considered event.

The model is conceived for pluvial hazard assessment and does not include coupling with the real sewage network that would involve the integration of the sewage pipes. However, to represent the capacity of the sewage system in the model, it was assumed that additionally to the soil infiltration, an infiltration loss equivalent to the design rainfall intensity used for the network designing (15.73 mm/hour) is added [14]. This loss was applied as a constant value on the actual network route and not on the whole computational domain of the model.

The data and assumptions used for the sewage system are critical for the model predictions, as they can influence the runoff or water accumulation on the terrain surface and hence the mechanisms of flooding.

Model validation

Historical flood records are important to validate the predictions provided by hydraulic models. The hazard maps resulted from the rain-on-grid model were checked against historical urban flood records from 2006 to 2020, based on the dataset provided by the (General Inspectorate for Emergency Situations) IGSU. Most of the recorded historical events, especially those in the area of Isaccei, Păcii, Babadag and Unirii streets, were reproduced through the simulations carried out (including simulations performed for low events such as 33% and 10% probabilities), which validates and proves a good accuracy of the model.

Results

The hazard maps resulting from the hydraulic simulations indicate areas affected by severe flooding on the territory of Tulcea municipality for events with 10%AEP and 1%AEP (annual exceedance probabilities) and the climate change scenario (but also for events with lower AEPs such as 0.5%, 0.1%). The model clearly predicts the main runoff paths along the city. For the 33% exceedance probability there is only one main affected area in the central part of the city at Delta Hotel.

According to the modelling results produced by JBA, the main affected areas in Tulcea municipality, as illustrated within the pluvial hazard map shown in Figure 6, are:

- At the south-east of Tulcea, around the properties on Elizeului Street and Mahmudiei Street there are ponding areas, with water depths up to 0.5 m for the 10% AEP and 1 m for the 1% AEP. The runoff originates from the steep eastern slopes of Bididia Hill and the Bididia Quarry, collecting flows of $17m^3/s$ for 10% AEP and $56m^3/s$ for 1% AEP.
- To the north of Lake Ciuperca, the model predicts an extensive stormwater ponding on Constructorilor Street at the intersection with Isaccei Street, but also near Primary School No. 10 on Victoriei Street. The water depth estimates are 0.5 m for a 10% AEP and 0.7 m for a 1% AEP. Floodwater originates from slopes at Victoria Park.
- In the city central area, the flooding affects a large area formed by 7 main streets: Isaccei Street, Gării Street, Păcii Street, Babadag Street, Unirii Street, Gloriei Street, Grigore Antipa Street. Important receptors such as the Museum of Art, Delta Hotel, and a high density of secondary commercial units are found in the flooded area. The water depth can reach up to 1m for the 10% AEP and 1.7m for the 1% AEP, the greatest water depths being marked at the Delta Hotel and the adjacent roundabout, as well as along the entire length of Gării Street. Floodwaters originate from the steeper slopes to the east, with Păcii Street being the main runoff collector.
- Sporadic ponding areas having up to 30cm water depth (for 1% AEP) are also observed in two industrial zones, one located west of Ciuperca Lake and the other in the northeastern side of the city.

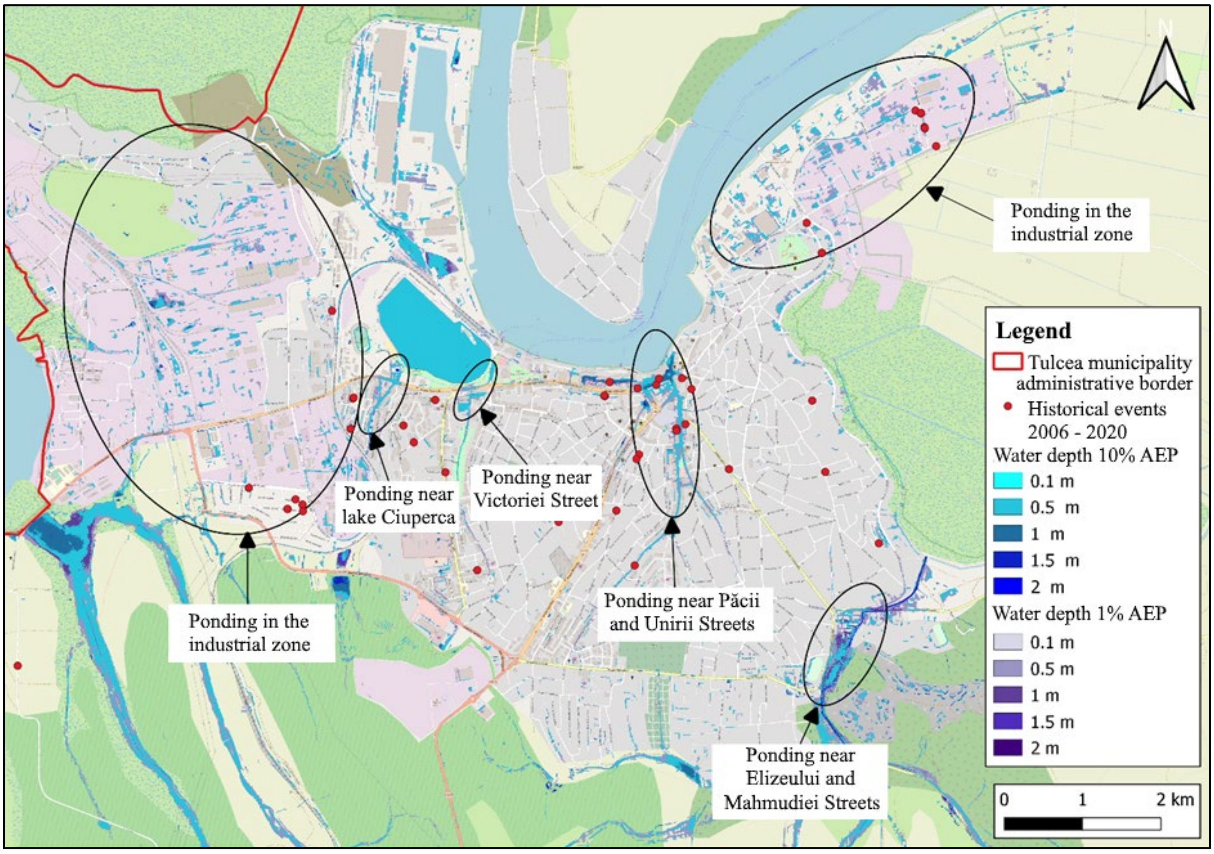

Fig. 6 - Schematic map of Tulcea municipality with the main areas exposed to pluvial floods (10% AEP and 1% AEP)

Figure 7 presents in more detail three of the most affected areas listed above. Stormwater ponding at the intersection of Constructorilor Street and Isaccei Street floods a commercial area adjacent to the pumping station (SP1). Another ponding area originates from the existing drainage channel near Victoria Park (north-south direction) having the capacity exceeded and generating flooding of the school at the north of the Victoriei Street.

Where Isaccei Street, Păcii Street, Babadag Street and Unirii Street join all together, there are important flood-affected receptors, as well as heritage buildings, tourist attractions and administrative buildings, with water depths of more than 1m around them. This area is close to pumping station SP3. Also, on Strada Gării multiple houses and buildings are affected, the street being completely flooded and inaccessible. The hazard maps indicate 1.6 km of Păcii Street being flooded, south of Strada Isaccei. This joins with another significant runoff path from Corneliu Gavrilov Street which continues to flow downstream for another 1.6 km. At north of Cornelius Gavrilov Street, flooding of existing buildings is observed.

Flood water accumulates also at east of the residential areas on Orizontului Street, Flamingo Street and Meteor Street. In the southeast, ponding occurs on Elizeului Street affecting commercial establishments.

Worth to mention that the flood hazard and risk maps, which were presented in the current article, are also available for public access on the online platform developed under the RO-FLOODS project using the webpage inundatii.ro.

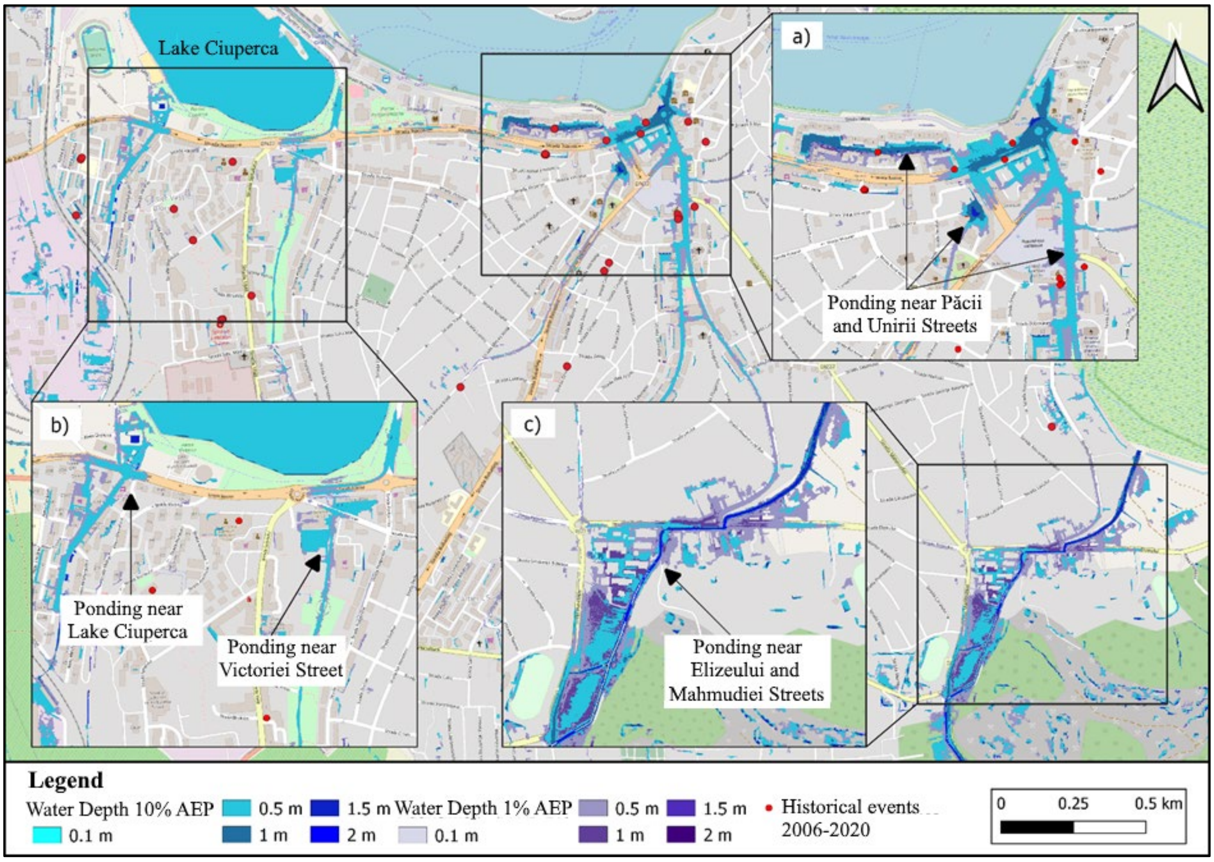

Fig. 7 - Detailed map for the main areas exposed to pluvial flooding in Tulcea: a) Intersection of Isaccei Street, Păcii, Babadag Street and Unirii Street b) Intersection of Constructorilor Street with Isaccei Street and Victoriei Street c) Elizeului Street.

Figure 8 presents the area most known as intensely affected by frequent pluvial flood events in Tulcea which is represented by the city center at the junction of Isaccei Street, Gării Street, Păcii street, Babadag Street, Unirii Steet, Gloriei Street, Grigore Antipa Street. Major floods like the events occurred in 2013, 2016, 2017 have led to complete flooding of streets, disruption of transportation, flooding of buildings, displacement of cars, causing countable damages almost each year. The 2D hydraulic model also confirms and highlights this area as being at highest hazard. In general, in Romania, the data available for calibration of rain-on-grid models is limited but according to the water level marks recorded during the events and to the visual estimates, water depths reach up to 1.5m which is also validated by the predictions of the HEC-RAS model developed by JBA.

In this area flagged as highest hazard, the main runoff is formed on the Păcii Street and Corneliu Gavrilov Street, both of which are flooded for about 1.6km, resulting in maximum flows of about $16m^3/s$ corresponding to a 1% AEP. This runoff flows down to the roundabout at the Delta Hotel, from here splitting in multiple directions on Grigore Antipa Street and Isaccei Street towards to Gării Street where the water accumulates creating a storage having 1.5m in depth.

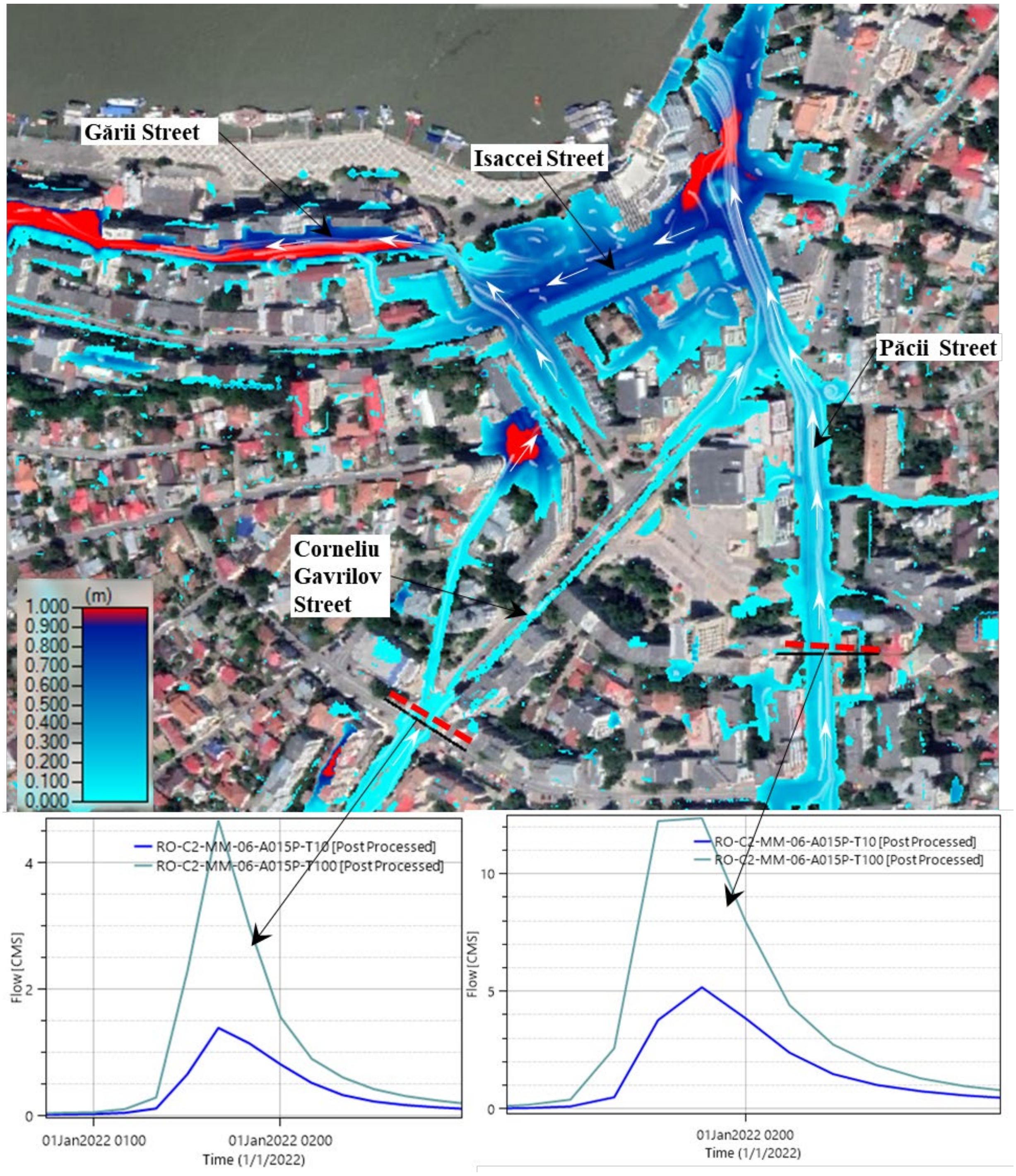

Fig. 8 - Runoff directions and flows generated at the junction of Gării Street, Isaccei Street, Păcii Street for 1%AEP event

Figure 9 shows the longitudinal profiles on the above-mentioned streets, highlighting the ponding effect on the Gării Street, Isaccei Street and adjacent to the Delta Hotel. Having low lying terrain, the area effectively becomes a storage area where water accumulates and cannot drain.

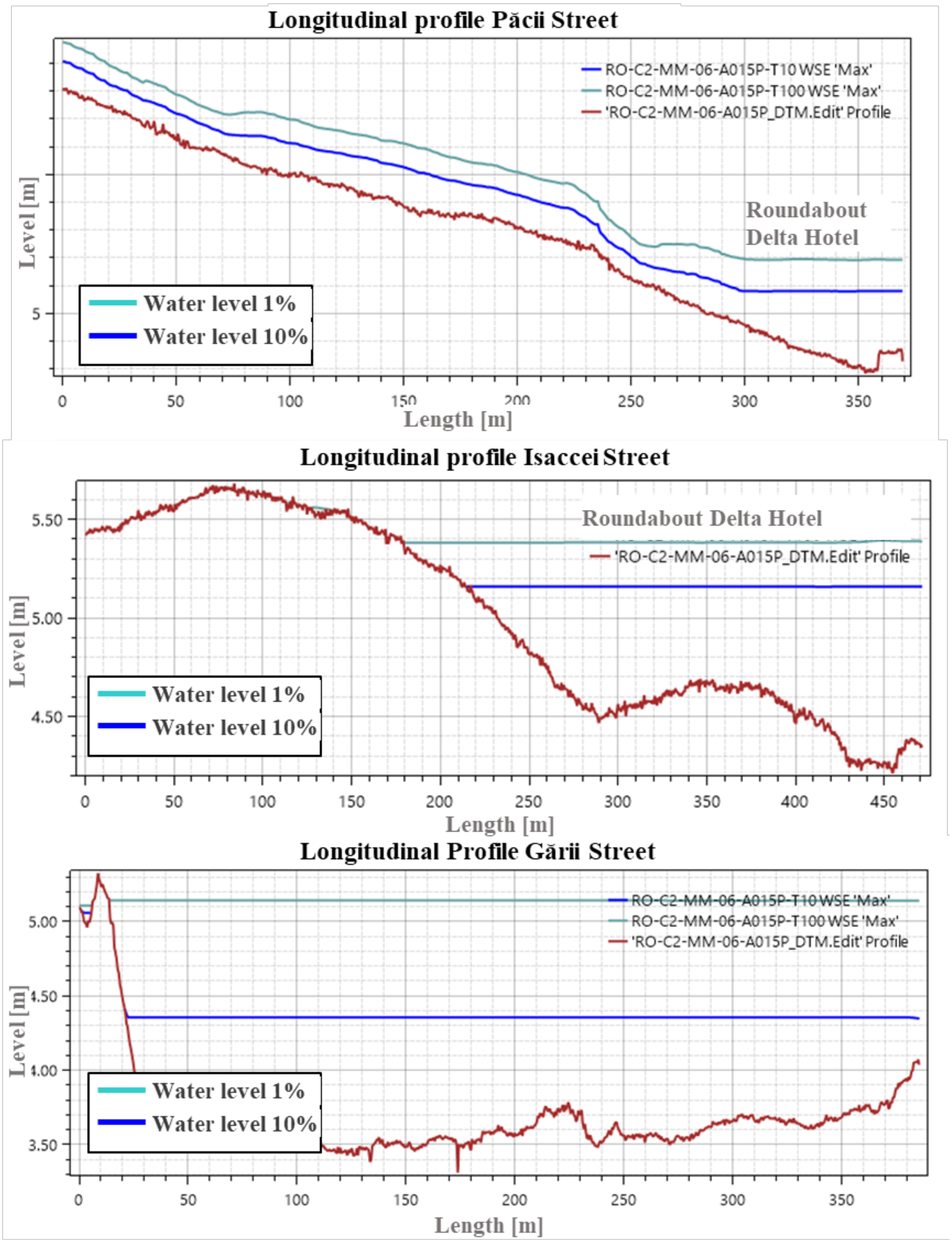

Fig. 9 - Longitudinal profiles on Isaccei Street, Păcii Street, Gării Street representing the maximum water levels for 10%AEP and 1%AEP events

Discussions

Nature-based solutions (NBS) imply green measures such revegetation and landscaping for valleys and slopes to retain and attenuate flows close to the source as much as possible [15[[16] [17]. The NBS maps, produced by JBA for Romania in the framework of the above-mentioned consultancy project, identify areas with green potential at south of Tulcea [18] [19]. However, the hills bordering the urban area of Tulcea city along the south, south-east and south-west borders have short concentration times, and such green solutions may prove insufficient. Therefore, measures such as Sustainable Urban Drainage Systems (SuDS) in the urban area are a necessity for Tulcea.

As a result of our hazard maps analysis, it was concluded that the urban area in Tulcea presents opportunities to adopt SuDS measures such as: connecting wetlands or creating natural storage areas, creating retention and infiltration ponds, or temporary water storages to attenuate flows corresponding to 33% AEP, 10% AEP, and 1% AEP events. In addition, paved roads with tiles for gradual and permanent water drainage can be a benefic technical solution for rod network.

There are two distinct problems in Tulcea that require different technical solutions for flood management. The steep streets such as Păcii Street and Corneliu Gavrilov Street which are running along the slopes require measures to attenuate surface runoff as the current impermeable-sealed layer accentuates the velocity regime and accelerates the water conveyance towards the central low-lying area. On the other hand, in the central low-lying where most of the flood water is collected (Delta Hotel Square and Gării Street), significant new storage volumes are required, supplemented by increasing of the pumping capacities as the water cannot be gravitationally evacuated when Danube levels are high.

Therefore, the feasible solution for Tulcea municipality involves a mix of traditional structural measures, SuDS measures and nature-based solutions, maximizing the effect of green measures, storage potential (natural or through underground storage tanks) but also the optimization of the existing 5 pumping stations [19].

The implementation of a Surface Water Management Plan is a necessity for the urban area of Tulcea Municipality, this city experiencing annual flood events which cause significant damages. Based on the hydraulic model already developed by JBA for Tulcea, refined with additional information on the stormwater drainage infrastructure, it is possible to propose an optimal combination of flood risk management measures to reduce surface runoff in the upper catchment, to efficiently collect and convey stormwater flows through the sewer network and to determine the appropriate solution for water retention and/or water drainage from the depressional areas.

Measures such as land use zoning and urban development control measures are prerequisites and crucial for the implementation of any flood risk management scheme [19].

Conclusions

Tulcea city is at high pluvial flood risk due to the steep topography of the hills bordering the urban area, which accelerates the surface runoff diverting the water directly to the city center through the streets running along the existing valleys toward to the Sfântu Gheorghe branch. Thus, the stormwater accumulates in the low-elevated urban areas with incisive concavity, but also on impermeable surfaces where waterproofing layers such as bitumen-sealed layers are used or where the transport capacity of sewage systems is insufficient or finally where there is no sewage or surface drainage network exist at all.

To produce hazard maps for Tulcea municipality (one of the pluvial APSFRs from Romania), JBA built a rain-on grid hydraulic model, using HECRAS 2D. The rainfall input data used for developing the model was based on Intensity-Duration-Frequency (IDF) curves being updated with the most recent events and records, until 2020, at Tulcea station. Hyetographs were produced for each simulated event including climate change scenario, using the alternating blocks method.

The capacity of the existing stormwater system was represented in the model, using an extra infiltration rate, expressed in mm/hour, applied in addition to soil infiltration losses. This "infiltration rate" was applied only to land cover classes identified as impermeable in urban areas (such as streets and roads), which are likely to be controlled and drained by the existing stormwater system. This approach significantly increases the predictability of the model by not ignoring the storage capacity of the stormwater system, but uncertainty related to the real capacity of the system remains.

Although flood impacts are assessed only within the APSFR (administrative boundary), the model domain has been extended to include all the adjacent hills that border the catchment that contributes to the runoff.

A set of historic storm floods, recorded between 2006 and 2020, was used to validate the model, for which properties, roads and locations affected by the floods are known. Most of the flood events were replicated by our simulations even for the high probability events such as 10% AEP, which validates and proves the good predictability of the model.

The overall quality level of the hydraulic model is very high due to the accuracy of the input data used, the complexity of the model and its validation. There is, however, a degree of uncertainty over the results provided by the model due to limited information on the design event of the sewage system, the complexity and current functionality of system, as well as on existing structures acting as obstacles to stormwater runoff. We recommend evaluating in detail these uncertainties in the close future within the elaboration of the Surface Water Management Plans for the main urban area of Tulcea.

To implement the proposed measures and recommendations, it is necessary to develop a Surface Water Management Plan for Tulcea Municipality [8]. The model built by JBA for the Dobrogea-Litoral Riber Basin usage is a very complex and useful instrument which can be explored for any future projects and Plans.

Due to the planned upgrades and extensions of the sewage network in Tulcea, it is also essential to revisit the sewage discharge capacity used in the model (15.73 mm/hour) to reflect any new infrastructure improvements, which in the end will result in updates of the model and hazard maps implicitly.

By developing and implementing a Surface Water Management Plan we estimate a series of benefits such as:

- Reducing flood risk in urban areas
- Water pollution management and compliance with environmental legislation
- Improving and creating additional urban green spaces
- Increasing the social value resulting from citizens involvement in risk reduction
- Creating detailed pluvial flood hazard maps, to be published for consultation and to inform territorial planning and urban development control
- Increasing resilience to climate change in the local community
- Understanding the requirements for future investments.

Acknowledgments

We present our gratitude for World Bank support, for the Ministry of Environment, Waters and Forests and the National Romanian Water Administration for the constructive contribution offered to JBA within the project "Consultancy services for the development of flood hazard and risk maps and the Flood Risk Management Plans for Romania" - contract no. 8006777 signed by the World Bank with the consortium led by JBA Consulting (2021 – 2023).

We mention that the JBA's deliverables within ROFLODS project are also based on the efficient contribution of the experts' team from the Dobrogea - Coastal River Basin Administration.

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