WDSA CCWI 2022

2nd International Joint Conference on Water Distribution
Systems Analysis & Computing and Control in the Water Industry

Valencia (Spain), 18-22 July 2022
doi: https://doi.org/10.4995/WDSA-CCWI2022.2022.14144

GIS-INTEGRATED PLUVIAL FLOOD RISK ASSESSMENT METHODOLOGY FOR URBAN AREAS

Murel Truu[1], **Ivar Annus**[2] **and Nils Kändler**[3]

[1,2,3] *Department of Civil Engineering and Architecture, Tallinn University of Technology, Tallinn, Estonia*
[1] *murel.truu@taltech.ee,* [2] *ivar.annus@taltech.ee,* [3] *nils.kandler@taltech.ee*

Abstract

To different extents, most urban areas in Europe are exposed to pluvial flood hazards. The local communities, as well as city governments have to find measures either to cope with the consequences or look for solutions to prevent the possible damage of the floods. Moreover, in most cases cities cannot be transformed to be flood resilient with single isolated interventions, but need an adaptive approach for flood-conscious governance and management. For this, cities require up-to-date information on the flood risk, to make data-based decisions on how to avoid disastrous events, plan for flood resilient high-quality living environment, and where relevant, design and implement transformative interventions. The conventional definition of disaster risk combines the likelihood of potential hazard, exposure magnitude, and the level of vulnerability. However, when considering the multifaceted challenge of assessing the susceptibility and damage potential of urban pluvial flooding, this three-dimensional risk assessment methodology is not yet widely implemented. Additionally, a standardized risk management framework proposes an iterative risk assessment procedure, which could be well-suited for an adaptive governance approach. However, until now, the pluvial flood risk assessment has not been fitted to this framework. In the paper, we present a tiered pluvial flood risk assessment methodology, which can be applied to any urban area. The proposed solution couples the disaster risk function with the standardized iterative risk assessment procedure. This allows cities in various entry-level preparedness to improve their understanding of the city-wide pluvial flood susceptibility and identify the flood-prone urban watersheds in which more specific risk analyses are required. The methodology includes coupling a digital twin of an urban drainage system (UDS) and a geographical information system (GIS). By integrating the pluvial flood risk assessment procedure in the city GIS the cities can automatically determine the potential hazard and coping capacity of exposed areas, and analyse the concurrent vulnerabilities. The methodology has been tested in a small, but densely populated urban area in Estonia, Rakvere town.

Keywords
Pluvial flooding, risk assessment, flood modelling, GIS analysis, urban resilience.

1 INTRODUCTION

Cities need to consider the pluvial flood hazard in various governance decisions, both for routine everyday decision making as well as for far-sighted strategic planning. Examples of strategies in which municipalities need to have adequate up-to-date information on pluvial flood risk include city-level comprehensive spatial plans, sewer management plans, sustainable energy and climate plans, and various strategic investment plans. Moreover, also the routine permitting of various infrastructure and building projects as well as the drafting of related policies, should be based on informed decisions on floods. Therefore, risk-based management of the pluvial floods has become more relevant for the urban areas.

Pluvial flood-conscious cities assess urban flooding risk using a variety of methods, whereas many of them are based only on historical floods and community knowledge of such events [1], [2], [3]. With changing climate as well as transforming cityscapes, such methods fail in projecting future risks [4]. Only a limited number of studies (Table 1) responding to "pluvial flood" & "risk assessment" inquiry in the Web of Science platform apply the United Nations Disaster Risk Reduction Office (UNDRR) disaster risk framework. Whereas, the ones that do, fail in consistency in terms of interpreting the different risk parameters in the function. Moreover, the methods are developed and tested for cities of various sizes and complexities, some proposing solutions for only small towns [5],[6] while others are applied for large metropolitan regions [7],[8]. Data sources and methods, which are used to analyse the different risk parameters, vary significantly. However, most of the investigated solutions exploit the capacity of digital elevation/terrain models (DEM/DTM) and different public datasets available for the analysed area. None of the identified methods consider the hydraulic capacity of the urban drainage system (UDS) in case of extreme weather events. While more general approaches exist for assessing the effect of the coping capacity for the flood risk [9] and the adaptive iterative approach to flood management is supported in policy [10], then the adaptability of existing city-based risk assessment methods is limited.

Table 1 Studies presenting pluvial flood risk assessment methods that correspond with UNDRR risk function

Method	Case study area	Hazard	Exposure	Vulnerability
Othmer et al. 2020 [5]	53 km^2 area with a densely built urban centre covering ~17% of the territory (Olfen, Germany)	Flow path and sink analysis (DEM) combined with 2D surface runoff calculation	x	Potential damage to buildings weighed with the vulnerability of residents (age dependant)
Szewrański et al. 2018 [6]	5 km^2 village with a densely built urban centre covering ~16% of the territory (Dobrzykowice, Poland)	Precipitation forecast data combined with surface runoff estimation and sink evaluation (DEM)	Water level in lowpoint areas	Damage to buildings
Di Salvo et al. 2018 [7]	1285 km^2 metropolitan area of the city (Rome, Italy)	Flood susceptibility-combining observed floods with flood prediction based on DTM	x	Potential impact - damage to buildings, commercial activities, critical urban elements, potential pollution sources, heritage objects
Sperotto et al. 2016 [8]	416 km^2 densely populated urban area (Venice, Italy)	Intensity of future precipitation combined with maximum pluvial emergency thresholds	Exposed buildings and infrastructures	Vulnerability factors: slope, permeability, historically flooded areas

As seen from the selection of the available methods described above, concern about pluvial flood risk is universal to large metropolitan regions and small urban villages. While it is well understood that the pluvial flood damage to urban assets varies significantly depending on the size and complexity of the city, small rural towns can also face events with such disastrous impacts for which the risks have to be assessed and thereby addressed.

2 MATERIALS AND METHODS

2.1 Fitting the pluvial flood risk assessment into the standardized disaster risk assessment framework

In simple terms, the risk is understood as the potential for damage from unwanted events. As such, the term is broadly applied to quite a range of phenomena, covering both the causes and the effects of the unwanted event in focus. While risk perception can be subjective, risk governance should be standardized and, therefore, also framed by clear methods. The international standard ISO 31000 for Risk Management Principles [11] provides a comprehensive framework, principles, and a process description for risk management. The given framework places risk assessment into a holistic iterative cycle, where the risk assessment is only one step in a sequence of many (Figure 1).

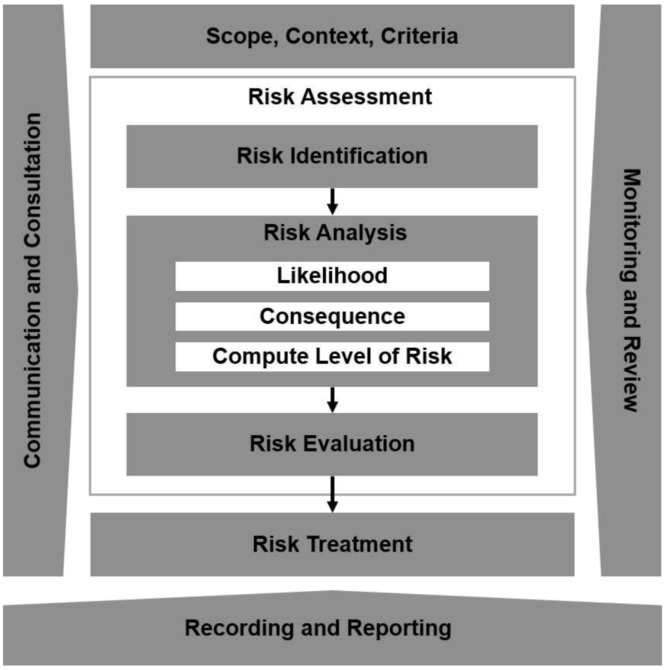

Figure 1 Risk management framework according to ISO 31000 [11]

The risk management principles listed in the standard foresee that the risk assessment is carried out using the state of the art methods and the best available data. Although for fluvial floods the EC Flood Directive [12] offers a widely applied and thus well-known methodology, the situation is much different in terms of the assessment of urban pluvial floods. In normal circumstances, the pluvial floods are considered minor to medium level inconveniences in the city. However, in case of extreme events, the damage from pluvial floods can be as disastrous. Therefore, when looking for methods for understanding the risks, clear interlinkages should be made with the risk definition provided by UNDRR. While in broad terms risk is understood as a two-parameter index combining the likelihood of non-anticipated events and their potential damages, then in the context of environmental disasters UNDRR describes risk [1] as a function of hazard, exposure, and vulnerability (1).

$$Risk \ = \ Hazard \ x \ \text{Exposure} \ x \ Vulnerability \tag{1}$$

This function describes well the external risks of various disasters for which mitigative measures are not applicable. This, however does not stand for pluvial flood risks that are greatly affected by the urban development, in most cases planned long in advance. Furthermore, when placing the risk assessment in the iterative risk management framework, the risk reduction capacity is crucial for assessing the treatment alternatives. And when projecting the future risks it is necessary to analyse not only the positive coping capacity that would reduce the risks, but also the various negative development scenarios. The risk index function that considers coping capacity is well presented by Imamura, 2022 [9], developed for the generic country-scale flood risk assessment.

Previous studies that have applied the UNDRR function for the assessment of pluvial flood risk are inconsistent in interpreting the various risk parameters as presented in Table 1. However, the Intergovernmental Panel on Climate Change (IPCC) [14] and several review papers on the challenges of pluvial flood risk assessment [4], [15] have a common understanding. This allows to define risk parameters for any type of flooding as follows: 1) hazard is the likelihood of occurrence of a driving event; 2) exposure is the amount of people and assets that would be directly impacted (flooded zone), and; 3) vulnerability is understood as the severity of impacts.

2.2 Tiered pluvial flood risk assessment framework

The current paper presents a tiered pluvial flood risk assessment procedure (Figure 2), which combines the ISO 31000 risk management standard procedure with the UNDRR disaster risk function and integrates it into city GIS to institutionalize the further automatic iterations of the risk assessment. The iterative tiered pluvial flood risk assessment method developed in our research proposes a procedure on how to combine risk identification on a large metropolitan scale and application of detailed methods for small catchment-level risk analysis and unify the interpretation of the risk parameters. In the proposed procedure risk assessment is carried out in 3 tiers (Figure 3), whereas the various predefined scenarios allow us to carry out comparative iterations of the assessment or renew the assessment as baseline data changes.

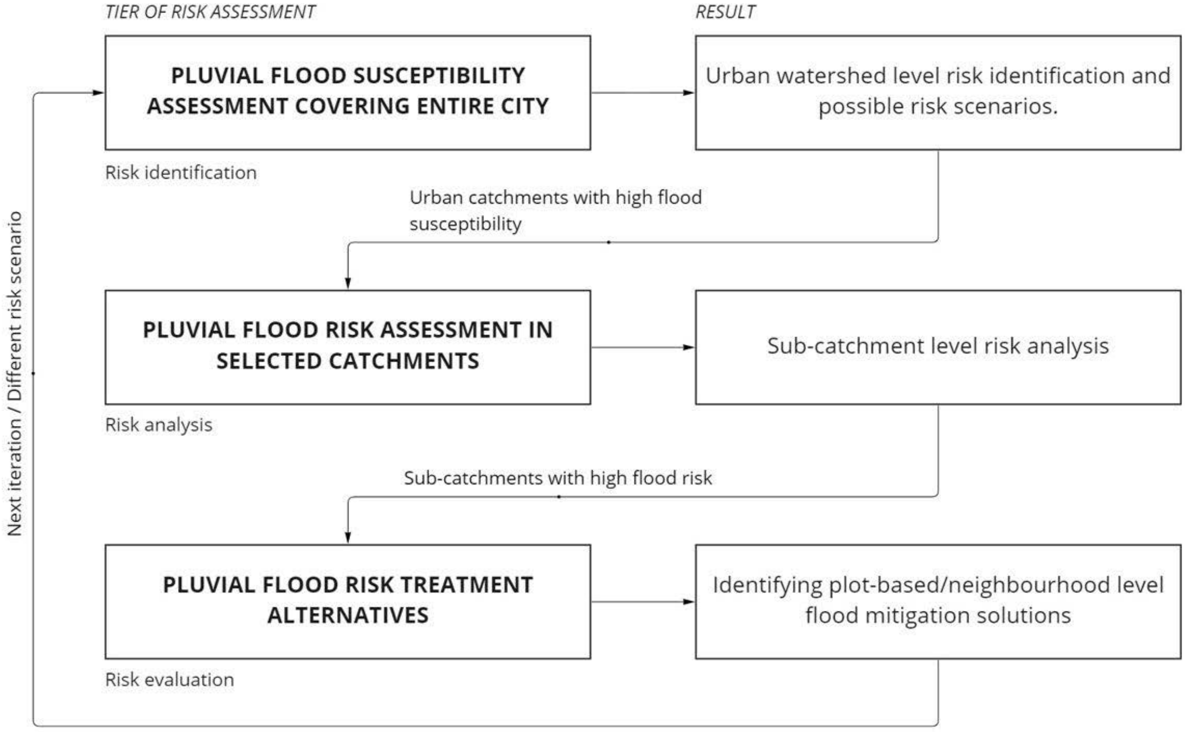

Figure 2 Overview of the proposed tiered procedure to assess the risks of pluvial floods

Risk identification on tier 1 stands from the mapping pluvial flood susceptibility. Risk identification is carried out using widely accessible data and GIS methods. The overall objective of this step is to compare the flood susceptibility of different urban watersheds and identify areas where further analysis is needed. The identification procedure allows determining the specific factors that need to be considered in a detailed risk analysis carried out in Tier 2 and what methods to use for this. The main output of the risk identification stage of the assessment is a comparative flood susceptibility index of urban watersheds, which allows identifying of districts in the city where detailed risk analysis is required. The risk identification tier, if carried out with no further investigations, does not provide adequate answers about the potential consequences of the extreme events.

The risk analysis on tier 2 covers detailed risk assessment in catchments with higher pluvial flood susceptibility. This step of the analysis must consider the character of the catchment, due to which the resulting risk levels can be adequately compared only within the urban watershed being analysed, not on the city level. Different modelling methods can be applied for analysing the hydrodynamic features causing the urban flood risk in pipe-based systems or in peri-urban open-channel catchments. The main outputs of the risk analysis stage are the comparative risk index of sub-catchments and sub-catchment level estimates of potential damage.

Risk evaluation on tier 3 consists of weighing the alternatives of treating the pluvial flood risk. This step goes beyond the pluvial flood hazard, exposure, vulnerability, and predefined capacity to cope with consequences and investigates the level of acceptance of flood risk and thus weighs solutions to mitigate the flood risk in comparison with potential losses. This step also allows considering the residual risk and plan for measures for coping with this. In the evaluation stage, various thematic maps can be generated to visualize the impact on vulnerable urban features, as well as investigate possibilities to transform the city space with additional measures. If such solutions for risk treatment are found, new risk scenarios can be developed and assessed. The main outputs of the risk evaluation stage are decisive risk levels for high-risk sub-catchments/plots, determining whether risks are acceptable, need to be treated, or should be considered as residual risks that cannot be treated. The risk evaluation stage can be coupled with GIS-based decision support to localize the various flood mitigation solutions. Also, the risk evaluation stage provides suitable baseline data to monetize possible damage and assess alternative costs for not taking further action to treat the risks.

When handling the risk parameters, it is necessary to understand their connectivity (Figure 4) and to either consider the interdependencies or abandon the linkages decided based on the sensitivity of the analysis. Disassembling the risk factors also allows constructing of various risk scenarios based on the likelihood of the hazard or manifestation of concurrent hazards, with considerations of different development scenarios or governance decisions prioritizing critical urban vulnerabilities.

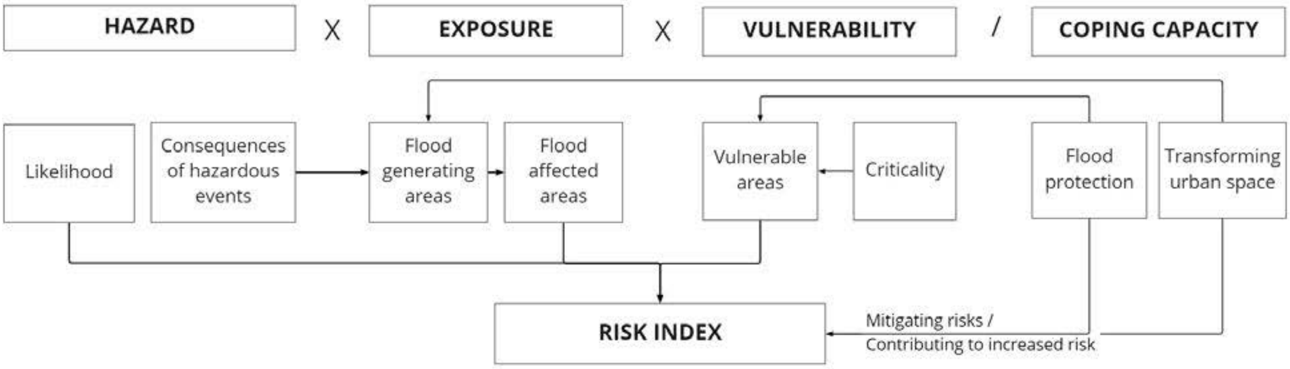

Figure 3 Simplified presentation of the interconnectivity of different risk factors

The risk scenarios to be assessed depending on hazard likelihood as well as preparedness to cope/mitigate the consequences, thus the risk scenarios are selected as combinations of manifested hazards (either independent extreme precipitation or concurrently manifesting hazards of fluvial floods, technical failures, etc.) and the planned/discussed interventions for dealing with the consequences.

In the current paper, the risk index is calculated using an expanded UNDRR function (2-3), which allows to separately weighing each sub-indicator to determine the risk parameters in the equation. For the baseline scenario to compare the risk indexes against, the coping capacity factor is abandoned. Weighing factors for the risk indicators are to be decided by an expert decision and can vary depending on the city. The indicators used in the function need to be normalized to a range of 0-1. Weighing factors of the risk sub-indicators - a_i, b_j, c_k, d_m. Risk sub-indicators for hazard (H), exposure (E) and vulnerability (V), coping capacity (CC) - H_i, E_j, V_k, CC_m. Modelled exposure indicator considering hazard magnitude and proposed coping measures as defined in analysed Scenario - $\frac{E_{H,j}}{CC_j}$;

$$Risk_{Tier\ 1} = \frac{\sum(a_i \cdot H_i)\ x \sum(b_j \cdot E_j)\ x\ \sum(c_k \cdot V_k)}{\sum(d_m \cdot CC_m)} \qquad (2)$$

$$Risk_{Tier\ 2} = \sum\ (a_i \cdot H_i)\ x\ \sum\ (b_j \cdot \frac{E_{H,j}}{CC_j})\ x \sum\ (c_k \cdot V_k) \qquad (3)$$

In tier 3 the decisions, whether the resulting risk level is to be considered as A - acceptable; T - treatable; or R – residual, are based on public risk perception and local governance decisions.

2.3 Materials and methods to understand the hydrodynamic nature of pluvial floods

The occurrence mechanism of the pluvial flood is a complex and dynamic problem. Not only are the pluvial floods dependant on hardly predictable extreme and very local downpours, but the floods are as much affected by the fine-scale character of the city-scape. As both the climate and the cities are subject to changes, historical evidence and present-day design standards are in many cases inadequate in solving the challenge. While calculating the risk levels, it is relevant to also consider future hazard scenarios as well as urban development projections to assess vulnerability, the key challenge in understanding the future risks lies in modelling of the pluvial flood exposure.

Model selection for the risk assessment depends on the risk assessment stage. Flood identification can be carried out using simplified methods such as topographic wetness index (TWI) [16] or rapid flood spreading models (RFS) [17]. Flood-prone district identification for city-level strategic planning can be less precise, as the simpler models are favoured also due to data availability as well as processing speed (run-time) while covering large territories. For a more comprehensive understanding of the complexity of the consequences as well as possible damages, more detailed models coupling overland flow and hydraulic capacity of the systems are required [18]. As the detailed models also demand precise baseline data, it would take decades to map, model, and calibrate all urban drainage systems in adequate quality to be used for comprehensive modelling for cities in need of flood inundation mapping. Identification of flood-prone areas should be carried out based on existing data in public registries and city GIS and only for the high-risk districts more specific studies are to be carried out.

Coupling pluvial flood modelling with geographic information systems (GIS) will add substantial value to risk assessment allowing fast and efficient adaptation of the risk calculation to the ever-changing urban environment and supporting risk communication to the stakeholders and citizens. The state-of-the-art GIS-based methods for pluvial flood risk assessment can interpret publicly available datasets such as digital elevation models, various state registries (environmental, heritage, building, etc.), and municipal datasets (population density, public transport). Large scale calculations can be carried out for translating vector data into raster layers for which multi-criteria ranking can be performed using user-defined weighs and site-specific concurring factors contributing to the risk. In such a manner the risk assessment has high automation potential.

3 CASE STUDY AREA

Rakvere is a small town (~11 km^2) located in northern Estonia with a population of approximately 15 000 people. Two small streams, the Soolikaoja creek, and the main Tobia ditch flow through the city and the recreational forest covers approximately 15 % of the city's territory. The majority of the city is situated in the large watershed of Soolikaoja creek however, due to the urban drainage system and urban-space characteristics the town is better described by smaller catchments. In our work, these catchments have been generated in GIS based on 5x5m resolution DEM and modified according to the UDS (Figure 5). The waterbodies in the city are not prone to fluvial flooding. However, the flow rates in the streams affect significantly the capacity and performance of the UDS [19].

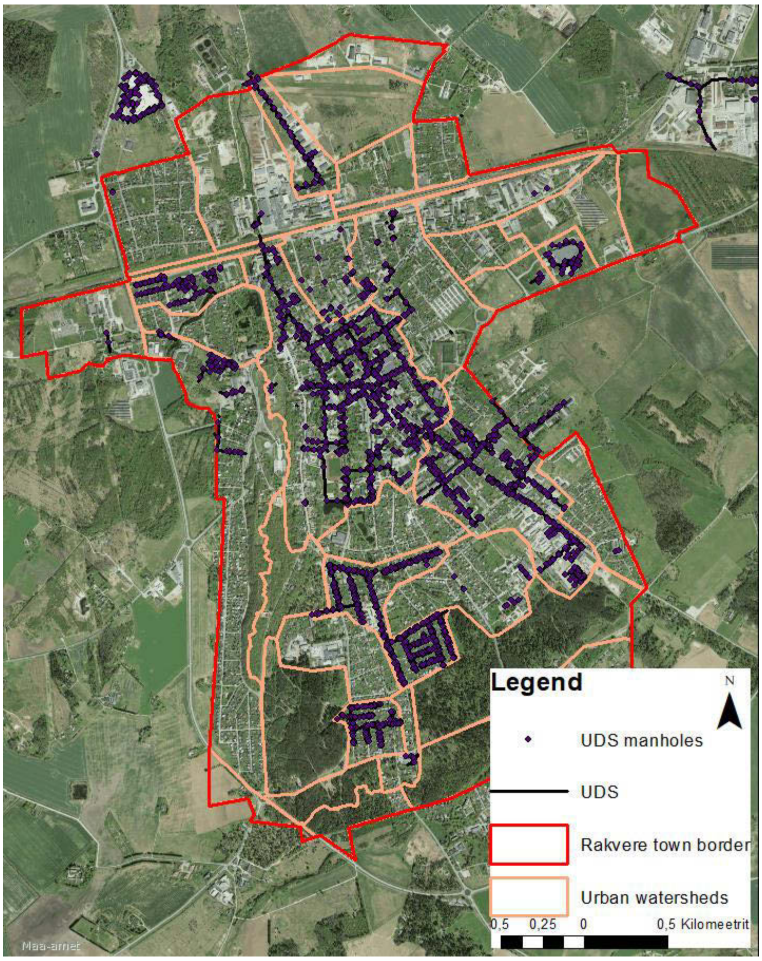

Figure 4 Rakvere city and the catchments generated with ArcMap Spatial Analyst tools based on 5x5m DEM and character of UDS.

Approximately half of the territory of the towns is covered with stormwater drainage system, while a large part of the town still deals with the stormwater runoff with combined sewage, open ditches and undirected infiltration areas (random and not specially designed permeable areas). The areas in the town with separate stormwater systems perform either as pipe-based systems or utilize open ditches, streams, and ponds.

4 RESULTS & DISCUSSION

The proposed methodology and procedure have been applied in the Rakvere case study area, using data available from public registries and the local municipal datasets (Table 2). In the current paper, we present the overall framework and demonstrate the potential of tier 1 and tier 2 assessments with a limited number of scenario iterations. Tier 3 evaluation is presented only as a concept and will be demonstrated in further papers.

4.1 Tier 1: Identifying pluvial flood susceptible districts/watersheds

Tier 1, identification of flood susceptible urban watersheds, can be carried out by urban planners or environmental consultants, with no comprehensive background in pluvial flood modelling. The procedure requires adequate DEM, land-cover data, pluvial flood design thresholds, and city-level understanding on urban flood vulnerabilities. Rapid analysis as described here can easily be set up and automated in GIS to be applied for various strategic planning documents, where such generic flood inundation mapping is required. For the iterative application of the flood identification stage, the different parameters can be updated as baseline data is updated or upgraded.

Table 2 Pluvial flood susceptibility parameters and the data used for the baseline scenario in Rakvere case study.

Risk factor	Concept
Hazard	Likelihood of occurrence for extreme precipitation/Variable intensity according to the cityscape. Baseline applied in case study: national design standard [20]
	Concurrent hazards: to be considered in case the pluvial flood is magnified by other natural or manmade hazards (e.g. fluvial floods, system failures)
Exposure	Topographic susceptibility of flood: DEM based surface flow modelling results (TWI, RFS or other) Baseline applied in case study: TWI based on 1x1m DEM [21]
	Infiltration capacity: Landcover based infiltration capacity estimate. Baseline applied in case study: national 1:10 000 base map landcover data [22] combined with national design standard surface runoff rate [20]
Vulnerability	City based estimate. According to the EC Flood Directive the flood risk needs to be assessed against economic, social, environmental and cultural vulnerability [12] Baseline applied in case study (weighing factor): density and value factor of built-up area (1), population density (1), UDS character (0.5), overlay of heritage monuments (0.5)
Coping capacity	Scenario based estimate. Indicators need to show the direction of the impact of the coping measures. Current paper demonstrates the impact of green factor policy to city level flood susceptibility.

The flood risk index is calculated using equation 3 and simple GIS raster calculation through various raster layers (figure 5) representing the indicators representing the risk parameters described in Table 2.

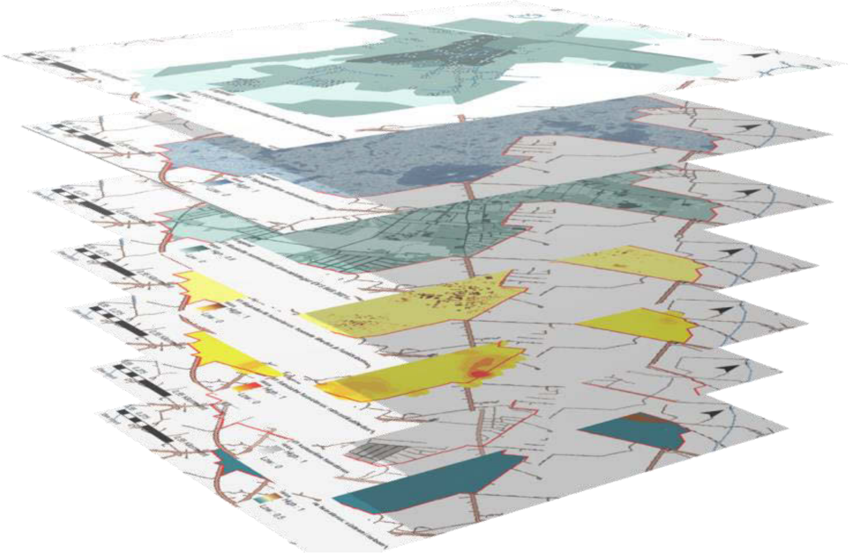

Figure 5 Risk index is calculated in GIS through various raster layers consisting of normalized flood risk indicators describing the specific parameters. If any of the baselines is updated, the risk level can be recalculated.

As a first step, the baseline scenario against what the further alternatives are to be analysed was defined. In Rakvere case study, the baseline scenario was set up as a current hazard in the current urban space, which meant that the indicator rasters were set up by national design standard, current land-use and current socio-economic and cultural-environmental characteristics of the town (Table 2). It must not be forgotten that the risk level in tier 1 is only applicable as comparative index. As the tier 1 is meant to identify the flood prone urban watersheds, then the risk levels have to be calculated for predefined watersheds or system units (Figure 6).

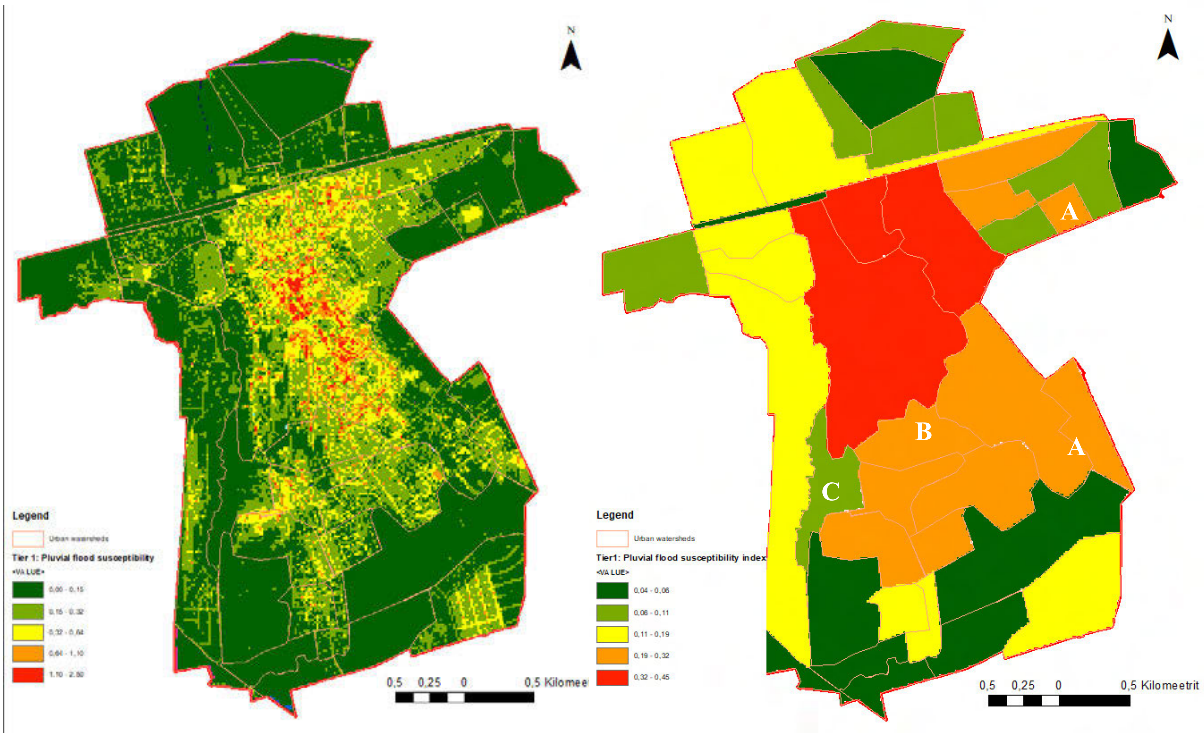

Figure 6 Tier 1 pluvial flood risk index raster (Left) and mean risk index of urban catchment (Right) for the baseline scenario. For avoiding misinterpretations only the urban watershed level risks should be used for decision-making.

The identified risk index allows to either contrast different sewer-sheds or compare different coping scenarios. When the mean risk index of the catchment is classified using natural breaks distribution then only 3 watersheds belong to the highest risk category (red). These are the most densely built and populated areas. 9 catchments belong to the no risk (dark green) category, whereas 8 catchments fall to the low risk level (light green). In most cases these are existing green areas in the city, recreational forests or yet undeveloped green spaces. Almost half of the territory of the city can be categorized as moderate (yellow) or significant (orange) risk levels. A large part of the moderate risk level areas is residential zones with private gardens. The reasons why watersheds fall in the significant risk levels however differ: in some cases the higher risk is caused by densely built-up area being situated in lowpoint areas (A, figure 6). In other cases the higher risk is a cause of higher vulnerability, which in the current case is the density of milieu-valuable wooden buildings and higher population density (B, figure 6). However, when comparing the latter another high vulnerability watershed (C, figure 6) with a relatively densely built up heritage protection area, the flood risk level there is lower as the topography does not favour floods.

The analysis of coping scenarios in Tier 1 can be carried out in a generic level. Various coping measures, which contribute to the reduction of any of the risk factors, can be assessed in such a manner. However, it must be acknowledged that in the risk function, the coping capacity indicators can only show the direction of how coping measures affect the risk level, not their absolute effect on flood reduction.

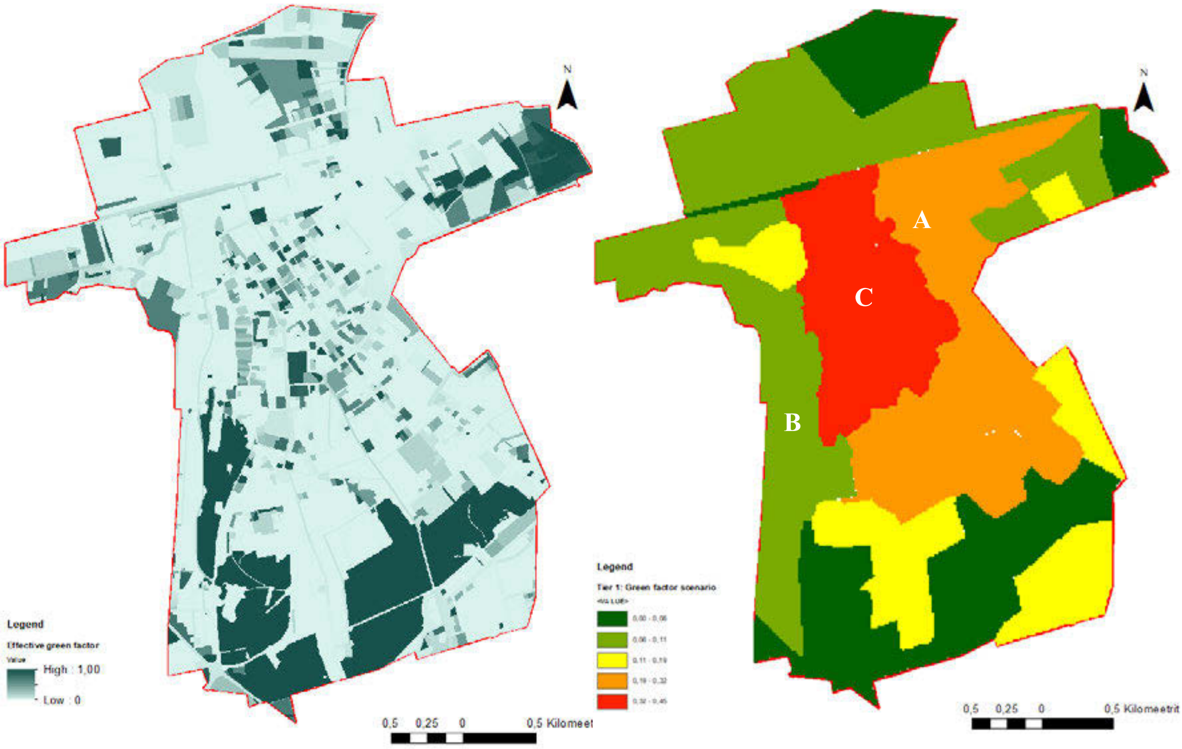

Figure 7 Effective green factor of property plots (Left). The risk level of catchments as policy would be enforced (Right).

This solution is useful for large territories in assessing city-wide policy effects or strategic planning decisions. To demonstrate the potential of the solution, a green factor scenario was prepared for the case study area. Several cities in the world have implemented a requirement of the green factor as a flood resilient measure for spatial planning of cities [23]. Until now, Rakvere town has not implemented a complete green factor requirement however, we analysed the current ratio of effective green areas in the city (recreational forests, greenfields, parks and gardens) and developed a raster layer representing the ratio of existing green area within a property plot (figure 7, left). Based on that an indicator raster layer was prepared, showing the gap between the current green factor and the potential policy requirement (30%). This allowed to analyse the coping capacity potential of the town if all plots in the city would fulfil the green factor requirement. The resulting map (figure 7, right), shows that such a policy would have flood risk mitigation potential in the eastern part of the central town (figure 7, A) as well as some residential zones (figure 7, B). However the increase of green areas reduces the absolute pluvial flood susceptibility risk in the central town, then the risk still remains high as in the baseline scenario (figure 7, C).

As described above, risk identification serves the role of identifying the hotspots that need more attention and in-depth modelling. Tier 1 helps to identify also the main causes why catchments fall into different risk classes allows to prepare for the next tier or of the assessment. In the current paper, we demonstrate the tier 2 analysis in the central part of the town, which fell into the highest risk class both in the baseline scenario as well as the green factor scenario. To advance with tier 2 analysis, a modelling method needs to be selected to refine the understanding of the causes and consequences of the pluvial floods. Many existing pluvial flood risk decision support tools do not consider the performance of the urban drainage system and expect it to fail in extreme weather events that exceed the design thresholds. While in many cases this is an adequate simplification, the malfunctions of urban drainage systems can significantly affect the consequences of extreme weather events [4].

4.2 Tier 2: Pluvial flood risk analysis in pipe-based urban catchments

The risk identification carried out in Tier 1 allowed several simplifications, for example, all the risk parameters were handled as separate indicator raster layers and potential feedback loops were abandoned. As the tier 2 analysis aims to establish an understanding of the damage potential of pluvial floods, not only the susceptibility of them, then more attention is given to the interconnectivity of the risk factors. As both the hazard magnitude and implemented coping measures define the exposed areas, then for every analysed risk scenario, a separate modelling simulation is required. In our study the modelling was carried out using EPA SWMM 5.1 modelling software [24], the sub-catchments for which the detailed analysis was carried out, were automatically generated using the GISto SWMM module [25]. A more detailed description of the used method is given by Truu et al. 2021 [18].

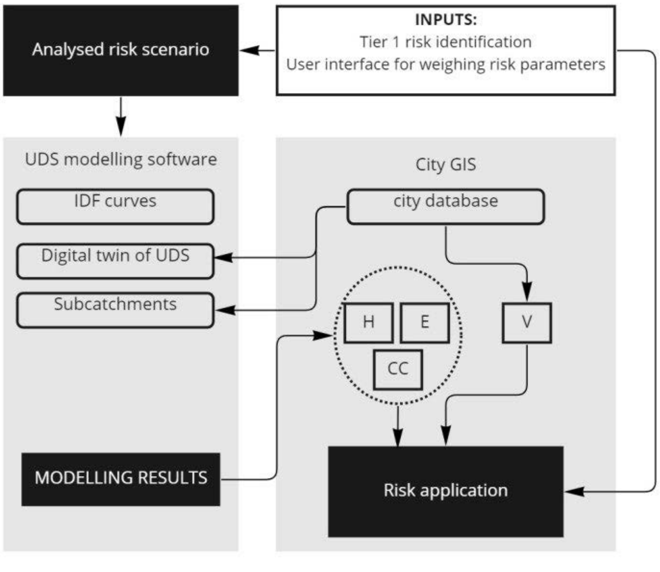

Figure 8 Concept for the risk analysis step for tier 2

Truu et al. 2021 [18] presented the flood risk on three levels (low, moderate and high), however did not assess the different vulnerability of the cityscape for the various flooding events. In the current paper, the modelling is carried out to define the sub-catchment level indicators that show the combined effect of the magnitude of the hazard, applied countermeasures or implemented development scenarios to the pluvial flood exposure (figure 8). In Rakvere, flood volume and flood duration sub-indicators were calculated and converted to raster analysis. In such manner, these modelled features serve as combi-indicators that presents the scenario-based effect to the hazard-exposure and coping capacity. With an expanded analysis modelling can result additional sub-indicators as water-quality, ponding depth or other, relevant to different urban vulnerabilities.

The resulting sub-catchment level risk map is applicable for fine scale analysis that interlinks the hazard occurrence probability with its damage potential. Pluvial flood modelling results indicator against the resulting risk map. Modelling allows to determine the consequences of the extreme weather event and the coupled GIS analysis finalizes the analysis by determining the damage potential. In the example visualized in figure 9, it is shown that while flood volume in catchment A is classified as high, then as it occurs on a parking lot (figure 8, A), it is less relevant than the flood in catchment B, where similar flood volume affects several buildings (figure 8, B).

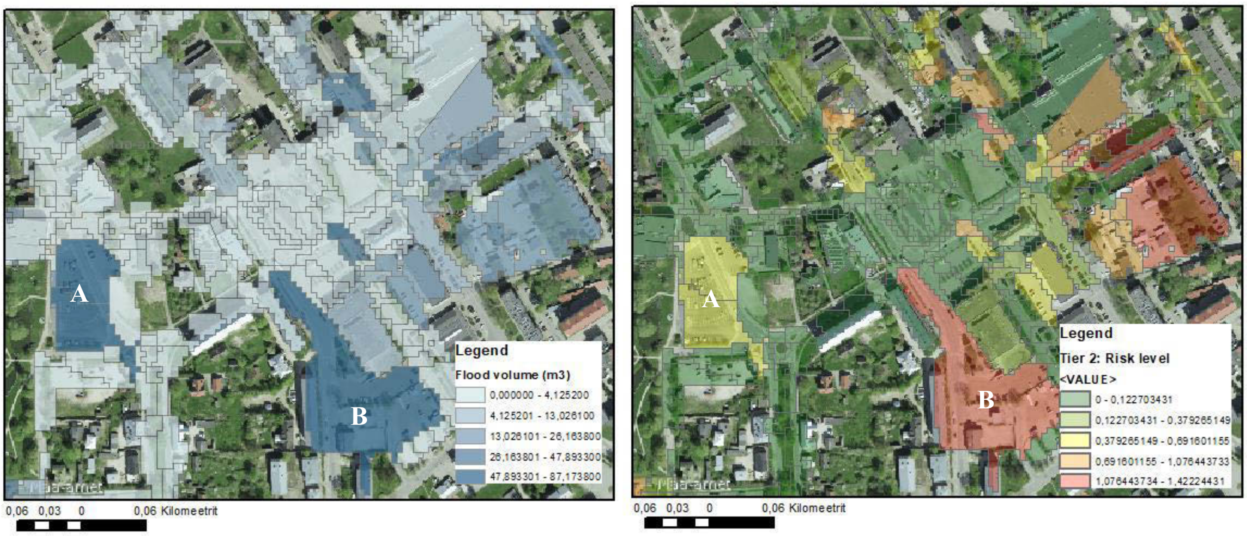

Figure 9 Fragment of pluvial flood combi-indicator raster showing the modelling results of flood volume in catchments in the baseline scenario (m^3) (left) and the risk level assessed based on vulnerability.

Additionally, the automation of the Tier 2 risk assessment tool in city GIS was piloted in Rakvere. The pilot tool combines drainage modelling software and a GIS database. All the input and output data is automatically exchanged between these two modules and necessary additional information like street objects and borders of the properties are acquired from the public databases.

EPA SWMM [24] modelling software engine with Python-based package PySWMM [26] was used for the analysis of the drainage system. ArcMap GIS software with built-in Python package ArcPy [27] was utilized to script data links between the modules. The stormwater catchments and drainage pipelines with manholes - compulsory data to model the runoff in SWMM - are kept in the GIS system which facilitates keeping this data up-to-date. Before each simulation, the information about the model elements and catchments can be automatically imported from GIS to the SWMM input file. User has to choose the pre-defined climate scenario (precipitation intensities) and after simulation the results, flood prone manholes are automatically imported back to the GIS with the data about the flood duration, depth, and volume. The results can be integrated into the risk function to allow also non-professional modellers to precept the risks in urban districts. The automated risk assessment module has also an interlinkage with public web map services (WMS) that allows the automatic update of spatial data (property borders, street names, etc.).

5 CONCLUSIONS

Cities need to consider the pluvial flood risk for different regular and routine governance decisions. While the development of the strategic documents requires a holistic understanding of the pluvial flood risk, then the routine land use decisions and various investments in the cityscape require a much more detailed understanding of the consequences of the floods. As the pluvial flood is a dynamic problem, then static risk assessments expire fast. The cityscape is not the only parameter subject to constant change, also other data (vulnerability parameters), climate scenarios, and design thresholds are regularly revised and if relevant also changed. All this requires an adaptive management approach, a concept which is mainstreamed also in the generic EU climate adaptation policy framework Climate-Adapt [10]. Moreover, the pluvial flood risk is a growing interest not only for Water Engineering field, but also for the disciplines of Social Sciences and Humanities. This means the baseline methods to determine the different risk parameters are constantly advancing [4], [15].

The GIS integrated risk assessment methodology proposed herein, fits well to the adaptive management framework. The proposed risk assessment solution couples ISO standard of risk management with UNDRR conceptual risk function. In a practical sense, it provides a set of risk parameters that are calculated based on information in public datasets already synchronized with city GIS and sets up a procedure how to calculate the risk index. The proposed procedure allows to deliver new risk assessments at request or as data updates.

The novelty of the described methodology lies in its iterative and dynamic nature allowing it to automatically calculate the summary risk for all land parcels in the analysed area. Any change in land use, UDS configuration, and vulnerabilities can be instantly referred to in a change in the risk levels. This allows municipal officers to deliver up-to-date risk assessment iterations with only minor effort and evaluate future risk scenarios with the same system to understand the effect of various urban development plans or also flood mitigation measures, i.e. increase of the permeable areas, planning detention facilities and improving the operation of UDS. Moreover, the iterative risk assessment method allows to upgrade the risk assessment by replacing any of the sub-indicators with new and improved understanding. Also, the results of risk assessment tiers can feed into plans, strategies and decisions of different level as not all governance decisions require supportive baseline data in same precision.

6 REFERENCES

[1] J. Chen, W. Chen, and G. Huang, “Assessing urban pluvial flood resilience based on a novel grid-based quantification method that considers human risk perceptions,” Journal of Hydrology, vol. 601, p. 126601, Oct. 2021, doi: 10.1016/j.jhydrol.2021.126601.

[2] V. Norén, B. Hedelin, L. Nyberg, and K. Bishop, “Flood risk assessment – Practices in flood prone Swedish municipalities,” International Journal of Disaster Risk Reduction, vol. 18, pp. 206–217, Sep. 2016, doi: 10.1016/j.ijdrr.2016.07.003.

[3] “Member States’ examples of Flood Hazard and Flood Risk Maps,” 2014. Accessed: Apr. 25, 2022. [Online]. Available: https://ec.europa.eu/environment/water/flood_risk/pdf/MS%20examples.pdf

[4] L. Cea and P. Costabile, “Flood Risk in Urban Areas: Modelling, Management and Adaptation to Climate Change. A Review,” Hydrology, vol. 9, no. 3, Art. no. 3, Mar. 2022, doi: 10.3390/hydrology9030050.

[5] F. J. Othmer, D. Becker, L. M. Schulte, and S. Greiving, “A Methodological Approach to Municipal Pluvial Flood Risk Assessment Based on a Small City Case Study,” Sustainability, vol. 12, no. 24, Art. no. 24, Jan. 2020, doi: 10.3390/su122410487.

[6] S. Szewrański, J. Chruściński, J. Kazak, M. Świąder, K. Tokarczyk-Dorociak, and R. Żmuda, “Pluvial Flood Risk Assessment Tool (PFRA) for Rainwater Management and Adaptation to Climate Change in Newly Urbanised Areas,” Water, vol. 10, no. 4, Art. no. 4, Apr. 2018, doi: 10.3390/w10040386.

[7] C. Di Salvo, F. Pennica, G. Ciotoli, and G. P. Cavinato, “A GIS-based procedure for preliminary mapping of pluvial flood risk at metropolitan scale,” Environmental Modelling & Software, vol. 107, pp. 64–84, Sep. 2018, doi: 10.1016/j.envsoft.2018.05.020.

[8] A. Sperotto, S. Torresan, V. Gallina, E. Coppola, A. Critto, and A. Marcomini, “A multi-disciplinary approach to evaluate pluvial floods risk under changing climate: The case study of the municipality of Venice (Italy),” Science of The Total Environment, vol. 562, pp. 1031–1043, Aug. 2016, doi: 10.1016/j.scitotenv.2016.03.150.

[9] Y. Imamura, “Development of a Method for Assessing Country-Based Flood Risk at the Global Scale,” Int J Disaster Risk Sci, vol. 13, no. 1, pp. 87–99, Feb. 2022, doi: 10.1007/s13753-021-00388-w.

[10] “Home — Climate-ADAPT.” https://climate-adapt.eea.europa.eu/ (accessed Sep. 24, 2021).

[11] “ISO 31000:2018 - Risk management - A practical guide,” EVS. https://www.evs.ee/et/iso-31000-2018-risk-management-a-practical-guide (accessed Apr. 18, 2022).

[12] Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks (Text with EEA relevance), vol. OJ L. 2007. Accessed: Sep. 01, 2021. [Online]. Available: http://data.europa.eu/eli/dir/2007/60/oj/eng

[13] “UNDRR Understanding Risk,” UNDRR Understanding Risk. https://www.undrr.org/building-risk-knowledge/understanding-risk (accessed Mar. 12, 2022).

[14] “IPCC, 2022: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,” IPCC, 2022. Accessed: Apr. 12, 2022. [Online]. Available: https://report.ipcc.ch/ar6wg2/pdf/IPCC_AR6_WGII_FinalDraft_FullReport.pdf

[15] B. R. Rosenzweig et al., “Pluvial flood risk and opportunities for resilience - Rosenzweig - 2018 - WIREs Water - Wiley Online Library.” https://wires.onlinelibrary.wiley.com/doi/10.1002/wat2.1302 (accessed Mar. 12, 2022).

[16] C. Kelleher and L. McPhillips, “Exploring the application of topographic indices in urban areas as indicators of pluvial flooding locations,” Hydrological Processes, vol. 34, no. 3, pp. 780–794, 2020, doi: 10.1002/hyp.13628.

[17] “A rapid flood inundation model for hazard mapping based on least squares support vector machine regression”, doi: 10.1111/jfr3.12522.

[18] M. Truu, I. Annus, J. Roosimägi, N. Kändler, A. Vassiljev, and K. Kaur, “Integrated Decision Support System for Pluvial Flood-Resilient Spatial Planning in Urban Areas,” Water, vol. 13, no. 23, Art. no. 23, Jan. 2021, doi: 10.3390/w13233340.

[19] N. Kändler, I. Annus, and A. Vassiljev, “Controlling peak runoff from plots by coupling street storage with distributed real time control,” Urban Water Journal, vol. 19, no. 1, pp. 97–108, Jan. 2022, doi: 10.1080/1573062X.2021.1958235.

[20] “EVS 848:2021,” EVS. https://www.evs.ee/et/evs-848-2013 (accessed Sep. 01, 2021).

[21] Maa-amet, “Laadi kõrgusandmed alla.” https://geoportaal.maaamet.ee/est/Ruumiandmed/Korgusandmed/index.php?lang_id=1&page_id=614 (accessed May 05, 2022).

[22] Maa-amet, “Eesti põhikaart 1:10 000.” https://geoportaal.maaamet.ee/est/Ruumiandmed/Topokaardid-ja-aluskaardid/index.php?lang_id=1&page_id=30 (accessed May 05, 2022).

[23] S. Juhola, “Planning for a green city: The Green Factor tool,” Urban Forestry & Urban Greening, vol. 34, pp. 254–258, Aug. 2018, doi: 10.1016/j.ufug.2018.07.019.

[24] “SWMM-Docs: Open Water Analytics Stormwater Management Model.” http://wateranalytics.org/Stormwater-Management-Model/index.html (accessed Mar. 16, 2021).

[25] L. Warsta et al., “Development and application of an automated subcatchment generator for SWMM using open data,” Urban Water J., vol. 14, no. 9, pp. 954–963, 2017, doi: 10.1080/1573062X.2017.1325496.

[26] O. US EPA, "Storm Water Management Model (SWMM)," May 21, 2014. https://www.epa.gov/water-research/storm-water-management-model-swmm (accessed Sep. 01, 2021).

[26] PySWMM documentation, https://pyswmm.readthedocs.io/en/latest/overview.html, May 2022.

[27] ArcPy https://github.com/pmacMaps/ArcPy, May 2022.

7 ACKNOWLEDGEMENTS

The research was supported by the Estonian Research Council grant PRG667.