Selecting a flood mitigation measure for Matera, Italy, and determining its effectiveness in reducing physical flood characteristics

Report Bachelor Thesis Civil Engineering
30 June 2021

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McGill UNIVERSITY

UNIVERSITA' DEGLI STUDI DELLA BASILICATA 1982

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Colophon

This report contains the findings of the Bachelor thesis project of Lieke van Haastregt for completion of the Bachelor Civil Engineering at the University of Twente.

Title	*Choosing a flood mitigation measure for Matera, Italy, and determining its effectiveness in reducing certain physical flood characteristics*
Version	*Final*
Report size	*82 pages*
Location	*Montréal*
Date	*30 June 2021*
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Preface

This report presents the findings of my Bachelor thesis '*Selecting a flood mitigation measure in Matera, Italy, and determining its effectiveness in reducing physical flood characteristics*'. This thesis forms the concluding research assignment of a three-year Civil Engineering Bachelor programme at the University of Twente. The aim of the research was to find a flood mitigation measure that is suitable for implementation in Matera, that could potentially reduce the nuisance that is caused by pluvial floods in Matera. This aim has been achieved by conducting a multi-criteria analysis taking into account various flood mitigation measures, of which the best performing measure has been evaluated with regards to its performance in reducing certain physical flood characteristics, using the FLORA-2D software in QGIS.

The research has been conducted at McGill University, in close cooperation with the University of Basilicata, from April 12th 2021 to June 30th 2021. Due to COVID-19 regulations and physical distance, most of the preparation and supervisory sessions have been held online, but I experienced it as a great opportunity to work together with like-minded people from different locations. I would like to thank everyone that has been involved in this research project for offering helpful advices and for making the research project possible.

Especially, I would like to express my gratitude to Raffaele Albano and Leonardo Mancusi, for being patient and helping me with the simulation and modelling aspects of the research. Also, I would like to thank Reza Alizadeh, for his feedback on the largest part of the research and also for his enthusiasm on the topic. It encouraged me to be decisive on some difficult parts and move on to the next steps in the project. Lastly, I would like to thank Jan Adamowski and Martijn Booij, for facilitating the set-up of the entire research project and for providing feedback.

Finally, I hope you enjoy reading this report and find it informative. If there are any comments, questions or further interests regarding this report or the thesis subject in general, I invite you to contact me.

Lieke van Haastregt
30 June 2021, Montréal

Summary

This report explains the set-up and findings of a research project that is focussed on the selection of a flood mitigation measure for Matera, a city in Italy, as well as the differences the implementation of this measure causes in the study area in terms of physical flood characteristics. The research project has been conducted with the support of McGill University, the University of Basilicata, and the University of Twente.

In Matera, an increasing amount of nuisance is experienced due to an increase in the severity and frequency of pluvial flooding. With the ancient city centre of Matera, the Sassi, enlisted by UNESCO as a world heritage site, it is necessary to intervene in the area with the aim to reduce flood events. Therefore, this research project focussed on (i) the selection of a flood mitigation measure that is suitable for Matera, and (ii) the evaluation of the implementation of this flood mitigation measure in terms of changes in each cell in maximum inundation depth, maximum flow velocity, and the maximum value of the product of the inundation depth and flow velocity (hereafter called DV) in the study area.

For the first part of the research, a multi-criteria analysis was set up in which the alternatives were flood mitigation measures that were taken from literature, and in which the criteria and their weights were formulated and calculated based on a stakeholder analysis. Like the alternatives themselves, their performance has been assessed based on literature, resulting in a ranking of seven different flood mitigation measures. After a sensitivity analysis was done for the weights of the criteria and performance assessment, the measure that ranked highest was taken for the second part of the research.

The second part of the research consisted of a comparison of the three mentioned flood characteristics and the pedestrian hazard in the current situation (no measure in place) and the new situation (highest ranked measure in place). This comparison was based on simulation results from a two-dimensional hydrodynamic model developed at the University of Basilicata, called FLORA-2D, for which an urban basin characterization, data from a historic rainfall event, and an urban context assessment in the form of identification of critical points in the study area were used as boundary conditions. FLORA-2D is a model that does not simulate interaction with any kind of drainage system, but the choice was still made to use the model because the rainfall event that was simulated was too large for the existing sewerage system to drain all the runoff.

It is found that flood prevention, easy maintenance, enhancement of the living area, various aspects regarding construction of the measure, and sustainability are the main factors that determine the suitability of flood mitigation measures for Matera. Scoring well on all these aspects, a bio-retention system comes out highest in the ranking, followed closely by urban wetlands. Also performing relatively well are rain barrels and detention tanks and on ranking lowest are green roofs, retention ponds, and permeable pavement.

Simulation of the rainfall event shows for both the current and the new situation that the locations with the highest maximum inundation depth, flow velocity, and DV are the Via Vincenzo Cappelluti, which connects the intersection of the main roads to the entry of the Sassi, the beginning of the Via Fiorentini, which is the entry of the Sassi, and the north-eastern part of the study area. Even though the maximum value of each characteristic decreased outside of the Sassi, the highest values are still found at the same locations after implementation of bio-retention systems as before implementation of the systems. At the entry of the Sassi, the maximum values even increase, which is the case as well for the pedestrian hazard. Thus, the flood reduction effectivity of bio-retention systems with the placement that was used for the simulation, was found to be mixed.

Unfortunately, the research was bound to a limited time schedule. Because of this, some assumptions had to be made and literature had to be used in many steps instead of actual real-life information or input. Because the performance of flood mitigation measures is very context specific, and because the input of stakeholders has a large impact on the set-up of criteria and weights, this might have reduced the accuracy of the multi-criteria analysis and subsequently the ranking of alternatives.

Even though FLORA-2D was useful for simulation of the flood event, its use also limited the flood mitigation measures that were used as alternatives to measures that do not affect drainage systems, since the impact of measures that do affect the drainage systems could not be simulated by the model. Also regarding the simulation, some assumptions had to be made because the urban basin characterization was not complete, since for some areas the sources that were used did not give a clear image of the surface type. The characterisation was also not very detailed, since only three permeability factors were taken into account for the surface types to reduce the amount of work. A last limitation for the second part of the research, is that the resolution of the grid that was used for the urban basin characterization was at some points too low for easy use. This made the implementation of the bio-retention systems less accurate, and it also made the output of the simulations more difficult to interpret.

Some recommendations for future research are done. For the first part of the research, it is first of all recommended to look into flood mitigation measures that can mitigate urban pluvial floods via the drainage system as well. If there are promising measures, it might be useful to combine an alternative model (one that takes into account the effect of drainage systems on the flow dynamics) with FLORA-2D to evaluate their flood reduction effectivity. Secondly, the multi-criteria analysis could be more accurate if stakeholders can give input into the matter, and if literature is used that describes measures' performances in conditions that are more similar to the conditions of the study area.

For the second part of the research, firstly it is recommended to visit the study area to make the urban basin characterization more accurate. Secondly, it is recommended to look into the effect that the permeability factor has on the runoff in the study area. If this is a large effect, it is recommended to specify the surface type into more than three categories. Thirdly, it is suggested to simulate more rainfall events and different set-ups of implementation of bio-retention systems (or another measure), since the placement of the measure most likely affects its flood reduction effectivity.

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1. Introduction

Due to climatic changes and human interference in southern Italy, the frequency of severe flood events in the Basilicata region has increased (Bentivenga et al., 2020). This is also the case for Matera, a city in Basilicata that was the European Capital of Culture in 2019 because of an architectural highlight called the Sassi, also known as the cities historical centre (European Commission, 2021). The Sassi and the Park of the Rupestrian Churches of Matera are UNESCO World Heritage of Humanity, because of their architectural history and integration in the surrounding terrain and ecosystem. To preserve this special place, departments have been established that manage maintenance activities and adherence to building regulations that should protect the area (UNESCO, 2021). Because of the protected status of the Sassi, attention for the increased frequency of flood events increased after multiple floods ruined premises in Matera in 2019, by overloading them with murky water (Speak, 2019). Since the floods lead to nuisance and damage in Matera and in particular the Sassi, intervention is necessary to preserve the unique site. Unfortunately, no information about current flood mitigation projects in the area could be found.

1.1. Study area

In Figure 1, the study area is outlined in red. It is limited to the south-eastern part of the city, including the northern part of the Sassi. For this area, a digital elevation model (DEM) is available that has been used for simulation of current flood problems in the area before (Sole et al., 2019), which can be seen in Figure 2. In the DEM also the elevation of buildings is included. The figure shows that the Sassi, in the right corner, is the lowest part of the area. Since runoff will always flow to areas with a lower elevation, it can be explained that the Sassi experiences the highest nuisance due to the floods.

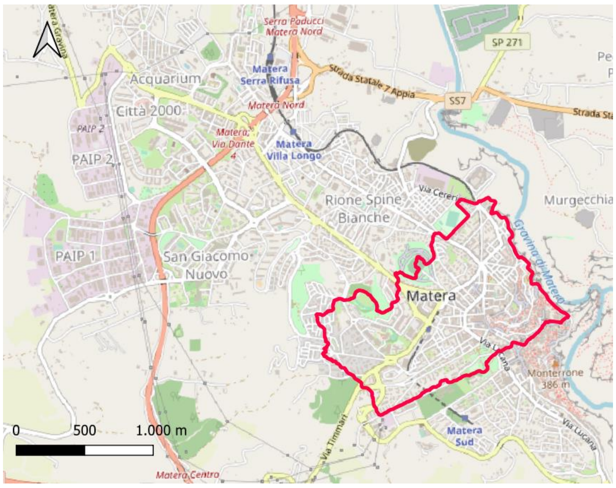


Figure 1 - Matera, study area outlined in red

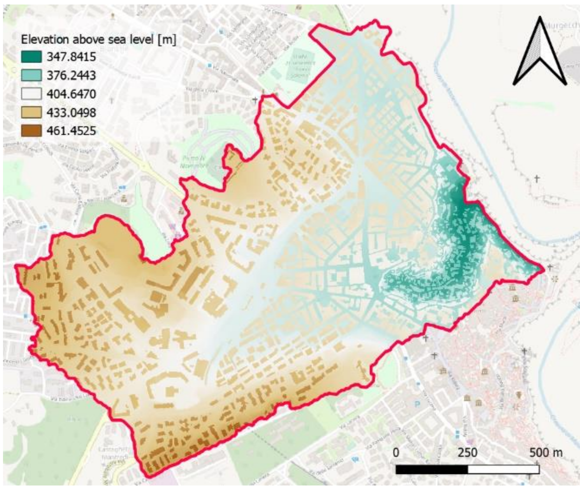


Figure 2 - Digital Elevation Model (DEM) of the study area

At an altitude of around 400 meters above sea level, the city Matera lies in the Bradano catchment, which has an average precipitation ranging spatially from 300 to 700 mm per year (Canora et al., 2015). The Bradano River lies just outside of the research area, on the eastern side, but it is located in a valley. Therefore, river floods are no issue for the city centre. The climate in the city Matera is moderate, with an average precipitation of almost 600 mm per year and a mean temperature of 15.4 °C (Climate-data.org, n.d.).

1.2. Cause of the problem

The problem that is occurring in Matera, which is increased nuisance by flood events, may be explained by an increase of the frequency of severe pluvial floods and increased impact in the area. The first is affected by both climatic changes and human interference. It can be seen in observational records from the last hundred years that, especially in the last two decades, there is a positive trend in the amount of extreme rainfall (Bentivenga et al., 2020). On top of that, an increasing amount of land is covered by impermeable surfaces, due to urbanization (Bentivenga et al., 2020), see Figure 3. Since the precipitation cannot infiltrate into the subsurface at areas that were permeable previously, runoff is directed into the city. Increased impact in the area is also the result of increased urbanization, since flood events result in more damage in urbanized areas.

Figure 3 – Orthophotos showing the urbanization of Matera in 1994 (left), and 2017 (right) (RSDI Basilicata, 2021)

To solve the problem of increased nuisance by flood events, which is caused by the underlying problems of increased flood frequency and severe impacts, the main causes of these underlying problems (which are increased rainfall and urbanization) should be tackled or mitigated.

1.3. State of the art

1.3.1. Flood inundation modelling

Flood inundation modelling is an extensive area of research that continues to develop each day. In general, a distinction can be made between three different types of methods for this type of modelling, which are empirical methods, hydrodynamic models, and simplified (non-physics-based) methods (Teng et al., 2017). For pluvial flood inundation modelling, 2D hydrodynamic models are often used, which are mathematical models. These models are combined with a DEM of the study area and data of local rainfall events to calculate physical flood characteristics in the area (Guerreiro et al., 2017), often using GIS software.

Examples of 2D hydrodynamic models are TELEMAC 2D, LISFLOOD and HEC-RAS 2D (Teng et al., 2017). These models are comparable to FLORA-2D, another model that has been used more often for the Basilicata region for both pluvial and river flood modelling (Scarpino et al., 2018; Cantisani et al., 2014). FLORA-2D is also a two-dimensional hydrodynamic model, based on the shallow water equations, that focuses specifically on the flow resistance that is caused by vegetation and soil roughness, and it evaluates the surface runoff for paved and unpaved surfaces, the inundation depth, and the discharge in each cell (Cantisani et al., 2014). It does not simulate the effect of the sewerage system. Even though the FLORA-2D model has been used previously in the Basilicata region, there is no notion of it being used to do research involving the evaluation of flood mitigation measures. More information about the working and set-up of the model is presented in Appendix A.

In conclusion, much research about flood events in the Basilicata region has been done so far (a.o. (Cantisani et al., 2014; Sole et al., 2007; Manfreda & Samela, 2019; Bentivenga et al., 2020)). However, there seems to be little research into measures that might decrease the severity of flood events in the region.

1.3.2. Evaluation of flood mitigation measures

It appears that there is not one leading framework for doing a systematic evaluation of an implemented measure in terms of flood risk reduction. Flood risk is calculated by multiplying the (a) probability of a flood event happening with the (b) impact of that flood event, and when quantifying the impact, damage that is the consequence of the event is often given a monetary value. Casualties are often not included in flood risk assessments, because it is difficult to give a monetary value to a human life, compared to things such as damage to buildings and infrastructure (Pellicani et al., 2018). Factors such as sustainability or social impact are often also not included, for the same reason.

When evaluating the impact of flood mitigation measures on the more physical characteristics of floods, factors that are often taken into account include the geographic coverage of the flood event, the exposure to the flood event of humans, property, and infrastructure, but also the vulnerability of these three to the event and its impact (Armenakis & Nirupama, 2013). These factors indicate that the land use of the flooded area contributes largely to the degree in which floods are perceived as a nuisance. When evaluating the effect of implementing a flood mitigation measure, it is therefore important not only that the flood decreases (either in flood extent, inundation depth, duration of the flood or flow velocity), but also that the decrease occurs at a location that is experiencing a lot of nuisance due to the flood. For example, a flood reduction in a park might reduce the perceived nuisance less than the same flood reduction on the intersection of the main roads in the area.

1.4. Research objective and research questions

The problem in Matera is that people and property experience large nuisance due to an increased frequency in (severe) flood events. To support the problem solving process, the research objective is formulated as follows:

Determine a suitable flood mitigation measure for Matera, and determine how it affects physical flood characteristics in Matera by (i) qualitatively comparing flood mitigation measures and (ii) evaluating the flood reduction effectivity of the most promising measure with the help of the FLORA-2D model by comparing simulation results of the current and the new situation.

To achieve this objective, it has been posed in the form of the main research question:

What is a suitable flood mitigation measure for Matera and how effective is it in reducing physical flood characteristics in Matera?

To answer this question, six sub-questions have been defined as follows:

1. What are possible flood mitigation measures?
2. Which criteria are important for selecting a flood mitigation measure for Matera?
3. Which flood mitigation measure is most desired in Matera?
4. What is the flood risk in Matera in the current situation (no flood mitigation measure in place) in terms of physical flood characteristics?
5. What is the flood risk in Matera in the new situation (implemented flood mitigation measure) in terms of physical flood characteristics?
6. What are the differences in physical flood characteristics in Matera in the new situation compared to the current situation?

The answers to these questions support the formulation a complete answer to the main research question and, eventually, help to achieve the research objective.

1.5. Scope

Since the research had to be carried out in a limited time period and with limited means, the scope of the research project was limited. The effects of this are explained in this section.

1.5.1. Possible flood mitigation measures

In this research, the FLORA-2D model will be used. Even though the model does not take into account the effect of the sewerage system on the flow dynamics, it was still decided to use the model. This is based on the choice to neglect the effect of the drainage system, since the rainfall events that cause the floods are too large to be drained by the system. Because of this, however, flood mitigation measures that are taken into account for this research are limited to measures that do not affect the drainage system, unless their effect can be imitated with a work-around. Besides that, flood mitigation measures are only taken into account for this research if they function as pluvial flood mitigation measures. River or coastal flood mitigation measures are out of the scope of this research, since their function as flood mitigation measure is not effective for pluvial flooding.

1.5.2. Assessment of flood risk

As is explained in section 1.3.2., the assessment of actual flood risk is quite complicated and difficult to do for all aspects that contribute to the total flood risk. Therefore this research will focus only on the changes in the maximum inundation depth, the maximum flow velocity, and the maximum value for the product of the inundation depth and flow velocity (further called 'DV'). In this case, the maximum value is for each cell in the study area the highest value that is measured for the entire simulation period. The decision is made to use these characteristics because they are given as output by FLORA-2D, and because they show the physical state of the flood event well.

1.5.3. Simulation of flooding

Due to the limited time that is available for this research project, simulations will be done for only one (historic) rainfall event. Also, no calibration or comparison with real life data will be done to assess the reliability of the simulation output due to lack of data availability and limited time. However, it is assumed that the model gives reliable results since it has been used for research on the study area before (Sole et al., 2019).

1.6. Reading guide

This report consists of five main chapters. The current chapter, chapter 1, includes an introduction to the context of the research. Chapter 2 describes the methods that have been used to carry out the research, whereas chapter 3 presents the results. Chapter 4 includes a discussion of the results. Chapter 5, lastly, provides conclusions for the research questions and recommendations for further research.

2. Methods

The basic set-up of the research consists of two parts, which are (i) determining which flood mitigation measure is most suitable for reducing floods at Matera and (ii) evaluating the effectiveness of the measure in reducing physical flood characteristics. The first part is done by conducting a multi-criteria analysis (MCA), whereas the second part is done by simulating the implementation of the most suitable measure in FLORA-2D via QGIS and comparing output of the model for the current and the new situation. This chapter explains the methodology that has been used to get to an answer to the research (sub-)questions, of which the first three help to achieve the first part of the research, and the last three contribute to the achievement of the second part of the research.

2.1. Schematic overview of research approach

In Figure 4, a schematic overview of the research approach is given, based on the theory described by (Verschuren & Doorewaard, 2010). In the figure, the blue box indicates the objective. The orange boxes indicate simulation results, the white boxes indicate technical preparation and model settings, and the red boxes indicate theoretical and non-technical aspects. The text between the white boxes is an indication of the various types of data that were needed to set up the model for the study area. The double-sided arrows indicate that there was an interaction between two boxes, the single-sided arrows indicate that one object was necessary before the other object could be achieved.

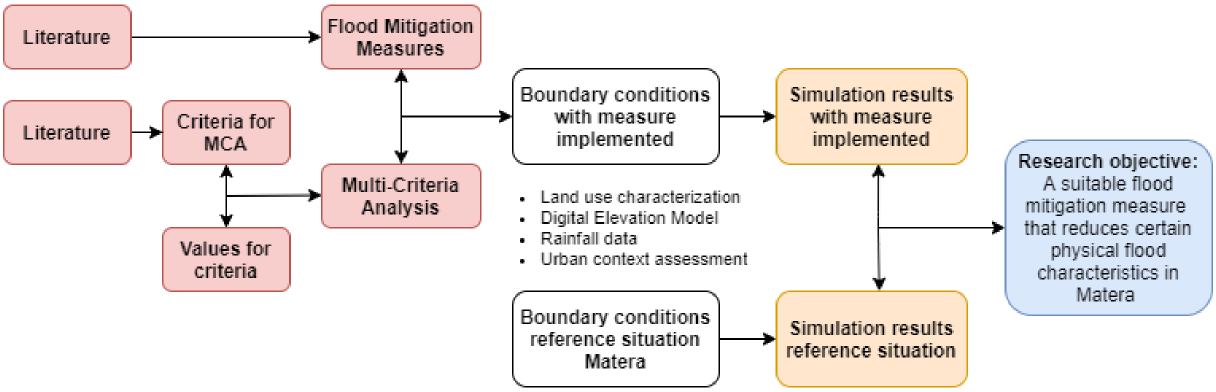


Figure 4 - Schematic overview of research approach

In words, Figure 4 can be explained as follows: at the start of the research project mostly literature review was done, which formed the basis for both the criteria of the MCA and information about flood mitigation measures. The products of the literature review, which were the set-up of an MCA and input of the MCA in the form of flood mitigation measures and their performance on the criteria of the MCA, were combined. After this step, the focus shifted towards modelling of the study area. Both a reference situation (the current situation) and the new situation have been simulated, in which the new situation included the (simulated) implementation of a flood mitigation measure that scored best in the MCA. As a last step the simulation results of both scenarios were compared to formulate a conclusion that achieves the research objective.

2.2. Set-up MCA – Alternatives (Q1)

This section describes the methodology that was followed to formulate an answer to the question '*what are possible flood mitigation measures*'. The measures that are given as an answer to this question served as alternatives for the MCA that was conducted to formulate an answer to research sub-question 3.

When creating an overview of the flood mitigation measures, firstly literature review was done on flood mitigation measures by searching in Google Scholar for general terms such as 'flood mitigation measure', 'pluvial flooding mitigation', 'urban flooding mitigation'. Publications that were retrieved by these terms were scanned for relevance in the title, abstract, and key words. After this, more specific searches were done with terms such as 'Nature Based Solution', 'flood reduction effectivity', and the name of specific measures that seemed promising in other publications. Eventually, 23 publications were used to construct a general overview of measures for pluvial flood mitigation, with for each measure: general information about its workings, its performance in runoff and peak flow reduction, general advantages and disadvantages, and a suggestion for how to simulate implementation of the measure in the model. This information and references to the publications are given in Appendix B. Later, this general overview was expanded with the performance of each measure on the criteria of the MCA. The methodology for this is explained in section 2.4.

2.3. Set-up MCA – Criteria (Q2)

This section describes the methodology that was followed to formulate an answer to the question '*which criteria are important for choosing a flood mitigation measure for Matera*'.

A flood mitigation measure that is suitable for Matera, must comply with the interests of all the parties that are affected by construction and/or implementation of the measure. Criteria that specify these interests are therefore necessary, and they should be as comprehensive and carefully weighted as possible.

2.3.1. Stakeholder analysis

To get a list of criteria, first a stakeholder analysis was done to get an overview of the parties that are involved, as well as their interests and power position (i.e. their influence in the decision process). An extensive stakeholder analysis about crisis management (regarding flood events) in Matera has been done for ongoing research (R. Albano, personal communication, April 29, 2021). This stakeholder analysis was taken as a start for the stakeholder analysis of this research project. Because the stakeholders play a role in assessing weights to the criteria, they were categorised in groups with similar interests and power positions. The groups made the process more insightful and easier to manage. To each group a score was given, based on its interests and power position. The interests of each group were given a score similar to the common score of the group. This was used in a later step to calculate the relative weights of the criteria. The left part of Figure 5 shows a flowchart of these steps, including an example of a stakeholder (residents).

To assign a score to the stakeholder groups, a power-interest grid was made. This power-interest grid was made by placing the different categories of stakeholders on a position in the grid according to their level of interest and their level of power. This helped in getting insight into how important it is to take the interests of the various groups into account. The four quarters of the grid can be categorised as subjects (low power & high interest), players (high power & high interest), crowd (low power & low interest), and context setters (high power and low interest). The players are the most important group, their interests should be taken into account at all times and they should be closely involved in the process. The subjects should be kept informed at all times, but are slightly less important to satisfy. The context setters are important to satisfy as well, but their interests in the project are lower than for subjects and players. Lastly, the crowd plays a minor role because of their low interest and low power. They should be informed from time to time, and if their interests are complied to that is good, but not ultimately necessary. If it is assumed that there are no conflicting interests, the order of importance in satisfying stakeholders is (i) players, (ii) subjects, (iii) context setters, (iv) crowd.

2.3.2. Value tree hierarchies

Taking the interests of all stakeholder groups together, value tree hierarchies were set up (van de Poel, 2013). Value tree hierarchies consist of three levels that are made more context specific on each level (values → norms → design requirements), which makes it possible to get a clear overview of the relation between the interests of all stakeholders. The lowest level, design requirements, are assessable, which means they can be measured in some way. Similar design requirements can contribute to the achievement of multiple (different) norms, and even to the achievement of multiple values (van de Poel, 2013). Not all stakeholder interests were directly formulated as design requirement, but the structure of value tree hierarchies facilitated that also interests that were formulated as values or norms were specified into design requirements. This ensured that, eventually, the criteria would be a representation of all of the stakeholder interests.

The design requirements formed the basis of the criteria, so a score was given to them which was eventually used for the calculation of the weights of the criteria. This score was based on the scores that were assigned to the interests of the stakeholders in the previous step. Because interests could be either formulated as a value, norm, or design requirement, this was a complicated task. If an interest was formulated as a design requirement, that design requirement got the score of that stakeholder interest added to its total score. If an interest was formulated as a norm, all the design requirements that contributed to achievement of that norm got the score of that interest added to their total score. If an interest was formulated as a value, similarly all the design requirements that contributed to achievement of that value (through the norms) got the score of the interest added to their total score. The middle part of Figure 5 shows a flowchart of these steps, including an example about the design requirements that were linked to one of the interests of a stakeholder (residents).

2.3.3. Criteria

The design requirements that were set up in the previous step were formulated in a way that they formed a criterion. Criteria that were very similar were taken together as one new criterion, formulated in a way that it linked to all the design requirements that corresponded to the previous similar criteria. After this initial set-up of criteria, they were assessed on completeness, redundancy, operationality, mutual independence of preference, double counting, and impacts that occur over time (Department for Communities and Local Government, 2009). If necessary, the criteria were reformulated to perform better on these aspects. After that, the criteria were categorised in groups, based on overarching themes in the criteria.

As a final step, weights were assessed to the criteria. For this, the scores of the design requirements were used in combination with the analytical hierarchy process (AHP). The AHP is based on a comparison between all criteria, which eventually gave them a value relative to each other (Department for Communities and Local Government, 2009). Before the AHP could be applied, the scores of the design requirements were linked to the criteria. This was done by adding the scores of all design requirements that were represented by a criterion. These added scores formed the total (absolute) score of that criterion.

Once all criteria had an absolute score, the AHP was applied by setting up a matrix for each group of criteria. This matrix included the absolute score of each criterion in the group relative to the scores of the other criteria in the group. The average of each row was calculated and divided by the sum of the row averages of the criteria in the group. These values were the weights of each criterion relative to the weights of the other criteria in the group. The groups of criteria were assigned a weight in the same way. The absolute score of a group was the sum of the absolute scores of all the criteria in that group. By using this method, all the criteria were assigned a weight relative to each other.

The right part of Figure 5 shows a flowchart of these last steps of setting up the criteria.

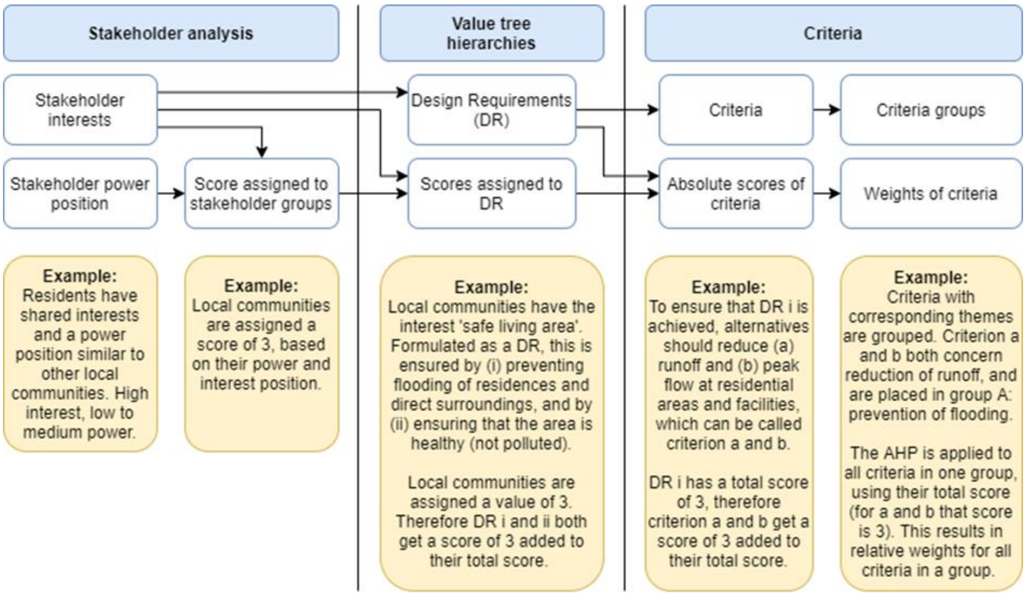


Figure 5 - Flowchart of the process of establishing weighted criteria

2.4. Conducting MCA (Q3)

This section describes the methodology that was followed to formulate an answer to the question '*which flood mitigation measure is most desired in Matera*'.

2.4.1. Calculation of ranking

To conduct the MCA, the performance of all the alternative measures were assessed on each criterion. This assessment was based on literature that was found for the first question, combined with other sources and assumptions. The sources that were added, were found by googling targeted key words (e.g. '[flood mitigation measure]', 'maintenance', 'construction costs', 'water quality', etc.). They include papers, reports, news-sites, informational sites (of companies), blogs, and various other types of websites. The information that was taken from these publications and references to them are presented in Appendix B. The performance assessment was needed to calculate the actual performance scores of the alternatives.

The performance scores depend on the type of MCA that is used. For this research, the decision was made to use an MCA based on the AHP, since it gives a little more room for uncertainties and allows for relative comparison of the performances (Department for Communities and Local Government, 2009). Based on the literature that was found, an assessment score was given to the performance of each alternative on each criterion. This score could be a value that came directly from literature, or it could be based on a verbal classification. After a score was given for each criterion and each measure, the AHP was applied in the same way as described in the previous section, only the relative score of the performance of an alternative for a group was not the sum of the absolute performance scores of the criteria in that group, but the sum of the weighted performance scores in that group.

2.4.2. Sensitivity analysis

After the ranking was calculated, a sensitivity analysis was done to determine how much uncertainties in the performance assessment and the stakeholder weight allocation affected the ranking.

The sensitivity analysis of the stakeholder weight allocation was done by changing the scores that were given to the interests of the stakeholder groups to different ratios, to see if this affected the ranking of the alternatives. The different score ratios were 5 scenarios, where one was the scenario that was actually used for the rest of the research, while the other scenarios were a value of 10 for one of the stakeholder groups and a value of 1 for all the other stakeholder groups (e.g. 10:1:1:1).

The sensitivity analysis of the performance assessment was done by creating a pessimistic and an optimistic scenario and checking how much these scenarios changed the final alternative scores. The pessimistic scenario was created by subtracting 10% from the assessment scores that were most uncertain (no literature available), subtracting 7.5% from the assessment scores that were based on an assumption which was based on 1 source, and by subtracting 5% from the assessment scores that were based on just 1 source (no assumption made). The optimistic scenario was created by adding the same percentages in the same cases, instead of subtracting them. For each alternative, the pessimistic and optimistic scenario were applied, after which the alternative scores for all alternatives were calculated. Only one scenario was applied at a time, giving 14 different alternative scores. In this way, for all alternatives the average, minimum, and maximum score could be found, as well as a standard deviation from the average score.

2.5. Evaluating current situation (Q4)

This section describes the methodology that was followed to formulate an answer to the question '*what is the flood risk in Matera in the current situation (no flood mitigation measure in place) in terms of physical flood characteristics*'. To set up the model for the study area, an urban basin characterization and rainfall data were needed. More information about FLORA-2D is given in Appendix A.

2.5.1. Urban basin characterization

The urban basin characterization was made by categorising the surface of cells in the study area as paved areas, buildings, semi-permeable areas, or green areas, creating a QGIS shapefile. This categorisation was based on data from RSDI (Regional Spatial Data Infrastructure) Basilicata, which provided QGIS shapefiles of different types of land-use (RSDI Basilicata, 2021), and visual assessment of the area via Google Street View and Google Maps. Besides this shapefile, a DEM was used. The DEM that was used for this research project has a resolution of 2x2 meters, and it was already available from previous research, as explained in section 1.1. A value for the Manning's roughness coefficient was given to each surface type, being 0.055 for paved areas and buildings, 0.06 for semi-permeable areas, and 0.07 for green areas (R. Albano & L. Mancusi, personal communication, 2021).

In the study area, there were certain locations that were of more interest than other locations. These locations are called critical points. They could be important infrastructure, buildings with a high social or cultural importance (e.g. a hospital or the Sassi), or points with an expected high inundation depth. The critical points that are presented in Table 1 were pinpointed in the map of the study area as HTEM (H-temporal) points, which means that for these locations output was given in the form of graphs showing inundation depth, flow velocity, and the DV over time.

Table 1 – Critical points in Matera

Street	Location	Interest
1. Viale Aldo Moro	Intersection main roads	Important infrastructure
2. Viale Aldo Moro	Entryway hospital	Important infrastructure
3. Via Lucana	Bus station and intersection near Sassi	Important infrastructure
4. Via Giuseppe Gattini	Police station	Important infrastructure
5. Piazza della Visitazione	Parking lot central station/court	Expected high inundation
6. Piazza Vittorio Veneto	Largest entryway Sassi	Expected high inundation
7. Via D'Addozio	Northern outlet of Sassi	Expected high inundation
8. Via Madonna delle Virtù	Southern outlet of Sassi	Expected high inundation
9. Via Fiorentini	Main road of Sassi	High cultural value

2.5.2. Rainfall data

A hyetograph of a 4:15 hour rainfall event that caused a large flood in 2019 was available from previous research (Sole et al., 2019). The rainfall in the hyetograph was used as rainfall for each cell in the study area, and linked to the surface type that was given in the shapefile, for which the process is explained in Appendix A. Since permeability of the soil is not simulated by FLORA-2D, its effect was taken into account by subtraction of the rainfall that can infiltrate the surface type, which means that only the effective rainfall is used as input for the model. To calculate the effective rainfall, the paved areas and buildings were set to have similar permeability, with a runoff curve number (CN) of 98. The semi-permeable areas were set to have a CN of 86, and the green areas were set to have a CN of 75. These curve numbers are the same as for previous research in the study area, since the surface types also remained unchanged (Sole et al., 2019). Based on these curve numbers, the effective rainfall was calculated with the SCS curve number method to be used as input for the model. This resulted in the effective rainfall for each surface type as presented in the hyetographs in Figure 6.

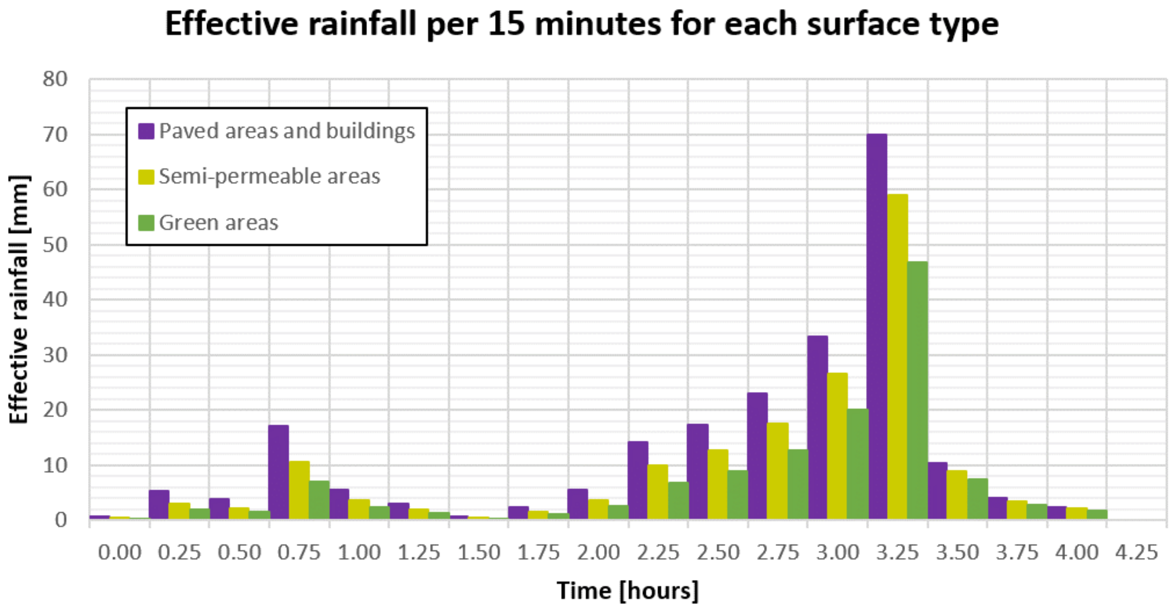


Figure 6 - Hyetographs of effective rainfall for each surface type

2.5.3. Model output

As output of the simulation, three maps were created that present for each cell in the study area for the entire simulation period the maximum inundation depth, the maximum flow velocity, and the maximum DV. Also, for each critical point graphs were created that present the inundation depth, flow velocity, and DV over time. The maps and graphs together were used to interpret the flood risk in the study area.

2.6. Evaluating new situation with implemented measure (Q5)

This section describes the methodology that was followed to formulate an answer to the question '*what is the flood risk in Matera in the new situation (implemented flood mitigation measure) in terms of physical flood characteristics*'. To adjust the model so that implementation of a flood mitigation measure was simulated, an updated urban basin characterization and updated rainfall data were needed.

2.6.1. Urban basin characterization

The difference between the new situation and the current situation was that in the current situation no flood mitigation measure was present or simulated, while in the new situation the implementation of a flood mitigation measure was simulated. For this, the urban basin characterization needed to be adjusted. Since the adjustments depended on the flood mitigation measure that was selected, the method for adjusting the urban basin characterization is described for each measure in Appendix B.

2.6.2. Rainfall data

For the rainfall data, the effective rainfall remained unchanged for the four surface types that were used in the current situation. For the areas that were covered by the bio-retention systems, it was altered. Since this alteration depended on the flood mitigation measure that was selected, the method for altering the rainfall data is described for each measure in Appendix B.

2.6.3. Model output

The same method has been used to read the output of the model as for the current situation, which is described in section 2.5.3.

2.7. Comparison of new situation with reference situation (Q6)

This section describes the methodology that was followed to formulate an answer to the question '*what are the differences in physical flood characteristics in Matera in the new situation compared to the current situation*'.

To get a clear view of the changes that occured in the new situation compared to the old situation, maps were created in QGIS that present for each cell the change in the maximum inundation depth and the maximum flow velocity in the new situation with regards to the current situation. The change in the maximum DV is also presented in a map by calculating the hydraulic invariance for each cell, using Equation 1. The hydraulic invariance is a means of checking whether a characteristic has changed by showing the relative differences between the current situation and the new situation (Pappalardo et al., 2017).

$$Hydraulic\ invariance = \frac{DV_{new}}{DV_{current}} - 1 \qquad \text{Eq. 1}$$

The decision was made to show the hydraulic invariance of the maximum DV, since the DV is a characteristic that can be used to estimate pedestrian hazard (Russo et al., 2013).

For urban floods, a DV of 1.51 m/s can be categorised as a low hazard for pedestrians, whereas a DV of 1.56 m/s can already be categorised as a medium hazard. A DV of 1.88 m/s or higher can be categorised as a high hazard. In this, a low hazard is understood as an event in which the flow conditions cause anxiety for pedestrians, or another form of feeling unsafe. A medium hazard occurs when the flow conditions make a pedestrian lose stability significantly (moving unsteadily), and a high hazard occurred when the flow conditions make pedestrians lose stability to the degree where they can no longer be stable in a standing or walking position (Russo, Gómez, & Macchione, 2013). It must be noted that the values that are mentioned are averages, since they are affected by the length and weight of an individual. To get an image of the pedestrian hazard in the study area, maps were created that show the hazard level in each cell as well, both for the current and the new situation.

All maps, as well as the graphs that were created for the critical points in both situations, were visually inspected to interpret the differences in flood risk for both situations.

3. Results

Based on the methodology as described in chapter 2, results were retrieved that substantiate answers to the research sub-questions. In the following sections, these results are presented.

3.1. *Possible flood mitigation measures in Matera (Q1)*

The cause of increased urban flooding in many cities is an increase in the frequency and severity of rainfall, in combination with an increase in impermeable area. Since it is not a feasible option to reduce the rainfall intensity while dealing with this issue, there are two options for reducing floods.

The first option focusses on quick drainage of runoff, which is done by using grey infrastructure, such as storm sewers, gutters, and conventional drainage systems (Huang et al., 2020; Lashford et al., 2019). The second option focusses on going back to pre-development conditions in the area, or in other words: increasing permeability of the surface. This can be done by using so-called nature-based solutions (NBS), that aim to improve water related issues by working with features that are present naturally in ecosystems while at the same time enhancing environmental, economic and social aspects (Oral et al., 2020).

Because grey infrastructure does not seem to mitigate urban floods sufficiently, an increasing amount of research is done on NBS (Huang et al., 2020). Examples of NBS are green roofs, bio-retention systems (also called rain gardens), permeable pavement, and water storage or retention ponds. In the field of NBS, different terminology is used. Terms like Low Impact Development (LID), Best Management Practice (BMP), Water Sensitive Urban Design (WSUD), Sustainable Urban Drainage System (SUDS), Green Infrastructure (GI), and Sponge Cities are used often to refer to NBS (Huang et al., 2020). For most NBS it is the case that an increased implementation area results in a higher decrease in runoff.

Since most grey infrastructure measures cannot be implemented in FLORA2D or QGIS, the measures that are used as alternatives in the MCA will be mostly NBS. In this section, the characteristics of the selected measures are shortly described. In Appendix B, a more detailed elaboration of each measure is given, as well as their performance on the criteria of the MCA. The measures that have been looked into are: (1) green roofs, (2) permeable pavement, (3) bio-retention systems, (4) retention ponds, (5) rain barrels, (6) urban wetlands, and (7) detention tanks.

3.1.1. Green roofs

A green roof is a system that covers flat roofs with a few layers that together form a rainwater absorption system, to decrease the runoff from impermeable surfaces on buildings. The layers are roughly a roof deck layer, a medium layer that drains and filters the water, and a vegetation layer.

3.1.2. Permeable pavement

Permeable pavement is pavement that lets rainfall infiltrate in the surface. Generally, pavement is part of the large impermeable surface area that is a factor in the cause of increased pluvial flooding in urban environments. Permeable pavement might thus help to reduce runoff and flood peak flow (Zhu et al., 2019). There are different types of permeable pavement, with various degrees of permeability (Hu et al., 2018; Zhu et al., 2019). It is also widely applicable, for example it can be used for sidewalks, roads that are not used by heavy traffic, or for parking spaces (Costa et al., 2021; Zhu et al., 2019).

3.1.3. Bio-retention systems

A bio-retention system, also called rain garden, is a vegetated landscaped depression, that collects runoff from impervious areas around it. It consists of several layers, among which are a weir to prevent overflow, a vegetation layer, filter layer, transition layer, and a drainage layer. Generally, bio-retention systems are relatively small (smaller than 2 ha) (Shafique, 2016). A bio-retention system lets rainfall infiltrate on the spot, and additionally allows runoff from rainfall in nearby areas to infiltrate. Also evapotranspiration plays a role in reducing total runoff and peak flow.

3.1.4. Retention ponds

A retention pond is a basin that receives runoff from surrounding areas during rainfall events, which is eventually drained via multiple outlets. Retention ponds are designed to reduce peak flow, or provide lag time to prevent peak flows in streams that drain the runoff eventually (Hancock et al., 2010).

3.1.5. Rain barrels

Rain barrels are a means of rainwater harvesting. They are installed so that they harvest the runoff from roofs (Akter et al., 2020). When rain barrels are full and the water is not used, they release the water, which is then drained through the conventional drainage system (Freni & Liuzzo, 2019).

3.1.6. Urban wetlands

An urban wetland is a piece of land that is often low-lying and characterised by a very humid environment. This means that it consists of hydric soils, hydrophytic vegetation and water (Palta et al., 2017). As a flood mitigation measure, an urban wetland is comparable to a combination of a bio-retention system and a retention pond.

3.1.7. Detention tanks

A detention tank is a large underground tank that stores water when the conventional drainage system is over-occupied with draining the runoff from large rainfall events. To be effective, tanks can have a volume as large as 2800 m^3 (Li et al., 2019).

3.2. Set-up of criteria and valuation of criteria (Q2)

In this section, the results are divided into two parts: the stakeholder analysis, which consists of a stakeholder (interest) overview and a power-interest grid, and the criteria and their weights.

3.2.1. Stakeholder analysis

The stakeholders that have been taken into account have been divided into four groups, based on shared interests and the role the stakeholders have in the process of choosing a flood mitigation measure. Figure 7 shows the stakeholders divided into local authorities, local communities, businesses, and civil societies, based on the stakeholder analysis that is mentioned in section 2.3.1., together with their interests. In the overview of stakeholders, the national authorities have been left out. This was done because they generally leave projects such as the implementation of local flood mitigation measures to the local authorities. The groups include all stakeholders that play a significant role in the decision-making process. The numbers in the bottom boxes of Figure 7 correspond with the numbers in the power-interest grid in Figure 8.

In Figure 8, the power-interest grid is presented for the flood mitigation project in Matera. The four quartiles have been coloured to represent which group of stakeholders represents the quartiles most (e.g. the upper right quartile is only represented by local authority stakeholders, so that quartile is given the same colour as the stakeholder group in Figure 7). Based on this division and the theory that is described in section 2.3.1., the order of prioritising the interests of the stakeholder groups should be (i) local authorities, (ii) local communities/businesses, (iii) civil societies. The local authorities are assigned a score of 4, the local communities and businesses are assigned a score of 3, and the civil societies are assigned a score of 2, to represent the difference in importance of the stakeholder group interests. This means that the score ratio is 4:3:3:2.

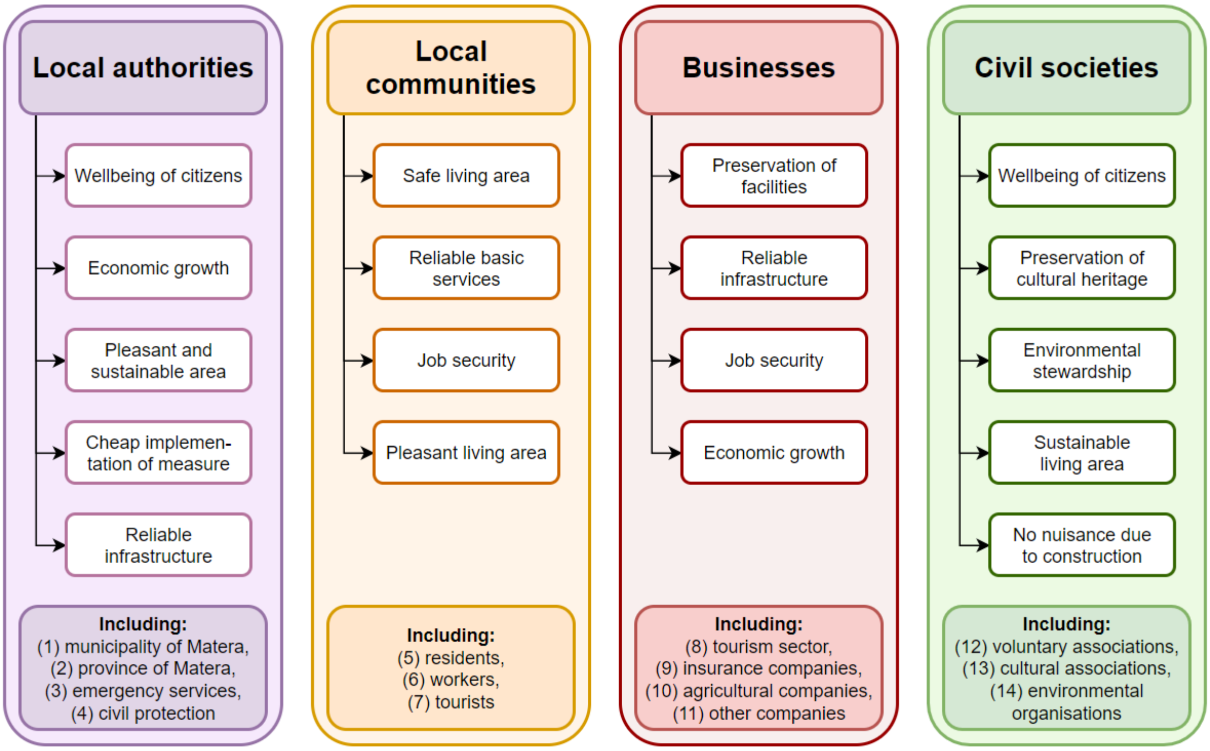


Figure 7 - Stakeholders and their interests, grouped

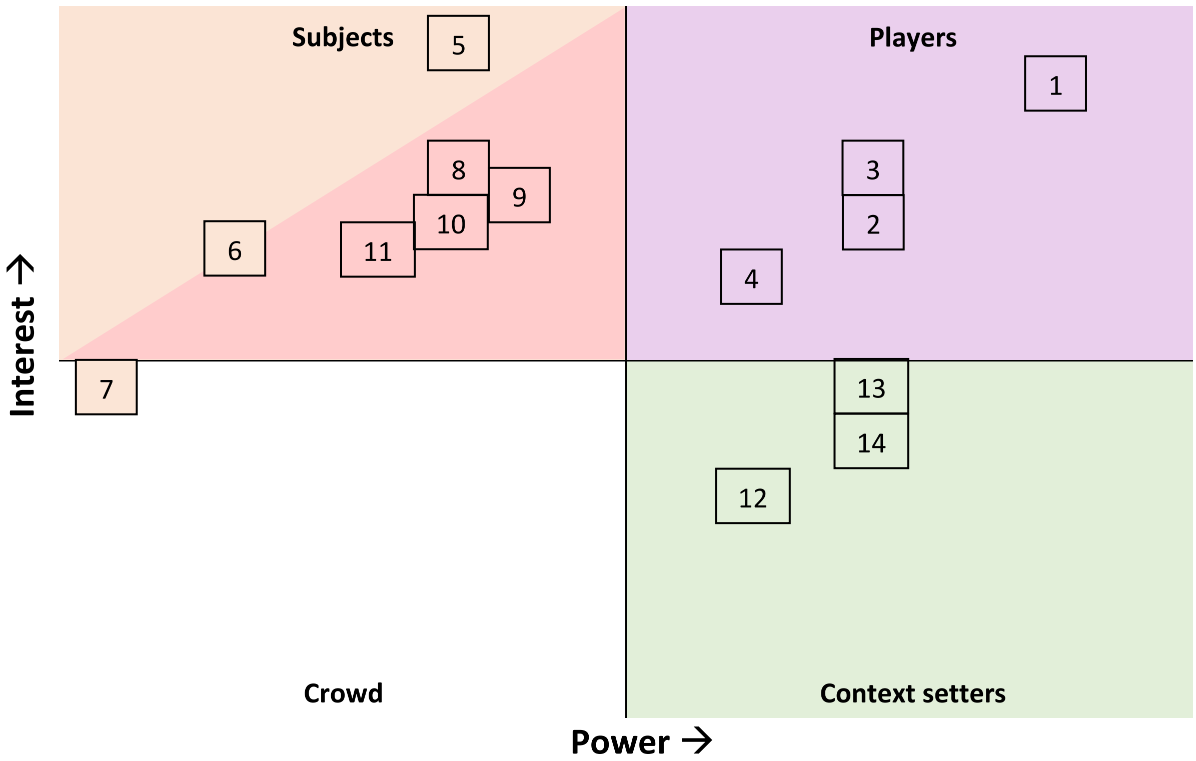


Figure 8 - Power-interest grid of stakeholders in the flood mitigation project in Matera

3.2.2. Criteria and weights

The stakeholder interests have been transformed into three value tree hierarchies, with on top the values ‘human wellbeing’, ‘economic prosperity’, and ‘environmental stewardship’. The value tree hierarchies form the base of the criteria for the MCA, but since they are only an intermediate step in the process of forming criteria, they are presented in Appendix C, together with the process that links them to the criteria. Appendix C also includes a visual explanation of the weight allocation and calculation, which is done according to the method that is described in section 2.3.

The criteria and their weights are shown in Table 2, grouped into five categories, which are prevention of flooding, maintenance of the area, enhancement of living area, construction of the measure, and sustainability of the measure. To ensure that the criteria are qualitatively good, they have been checked for completeness, redundancy, operationality, mutual independence of preference, double counting, and time span, as described in section 2.3.3.

Table 2 - Criteria for choosing a flood mitigation measure in Matera

#	Criterion	Weight
Group A: Prevention of flooding		**0.37**
1.a	Measure reduces total runoff for rainfall events with a return period of 30 years: At infrastructure	0.19
1.b	Measure reduces total runoff for rainfall events with a return period of 30 years: At residential areas & facilities	0.14
1.c	Measure reduces total runoff for rainfall events with a return period of 30 years: At the Sassi	0.17
2.a	Measure reduces peak flow for rainfall events with a return period of 30 years: At infrastructure	0.19
2.b	Measure reduces peak flow for rainfall events with a return period of 30 years: At residential areas & facilities	0.14
2.c	Measure reduces peak flow for rainfall events with a return period of 30 years: At the Sassi	0.17
Group B: Maintenance of area		**0.35**
3.a	Measure does not complicate maintenance of infrastructure	0.41
3.b	Measure does not complicate maintenance of residential areas & facilities	0.22
3.c	Measure does not complicate maintenance of the Sassi	0.34
4.	Measure has long lifespan	0.03
Group C: Enhancement of living area		**0.09**
5.	Measure adds blue and/or green area	0.41
6.	Measure adds place for recreation	0.33
7.	Measure reduces pollution of water	0.26
Group D: Construction of measure		**0.14**
8.	Construction of measure has low impact on its surroundings (during construction)	0.70
9.	Construction of measure has a short duration	0.15
10.	Costs of construction materials of measure are low	0.15
Group E: Sustainability		**0.04**
11.	Measure can be constructed with circular materials	0.33
12.	Measure requires little energy to function	0.33
13.	Measure enhances the existing ecosystem, or keeps it intact at least	0.33

3.3. Preferred flood mitigation measure in Matera (Q3)

In this section, firstly a ranking is presented that results from the MCA. Secondly, a sensitivity analysis is shown that has been conducted taking into account two factors. These factors are the values that have been allocated to the stakeholder groups in the stakeholder analysis phase, and the performance assessment of the alternatives for all criteria.

3.3.1. Final ranking

Based on the results as described in section 3.1. and 3.2., the measures have been ranked on suitability for implementation as flood mitigation measure in Matera. Their performance scores on the criteria have been multiplied with the corresponding weights, which has resulted in the ranking as shown in Table 3. A table with the performance scores per criterion can be seen in Table 4 on the next page.

Table 3 - Ranking of alternatives

Rank	Alternative	Score
1.	Bio-retention systems	71
2.	Urban wetlands	70
3.	Rain barrels	60
4.	Detention tanks	55
5.	Green roofs	43
6.	Retention ponds	36
7.	Permeable pavement	35

It can be seen that bio-retention systems are the most suitable flood mitigation measure for Matera. This is mostly because bio-retention systems perform well on flood prevention and sustainability, and because their characteristics are performing above average on maintenance, enhancement of the living area, and construction, compared to the other alternatives.

Another promising measure is an urban wetland, which performs almost as well as bio-retention systems. Other measures that are relatively suitable for Matera are rain barrels and detention tanks. Green roofs, retention ponds, and permeable pavement score lowest, mostly because of their limited performance on flood prevention. Besides that, a disadvantage of green roofs and permeable pavement is that they need to be implemented on a large scale, which takes a longer construction time, often leads to higher construction costs, and generally requires increased maintenance.

3.3.2. Sensitivity analysis - stakeholder group values

The sensitivity of the scores of the alternatives is presented in Figure 9. The alternative scores are plotted, dependent on the ratios that have been described in section 2.4.2. The ratio does not seem to have a big effect on the ranking, since for all scenarios, only two changes were noticed in the ranking. When the interests of local communities were valued most, permeable pavement (Alt 2) moved up one place (to #6), and when the interests of businesses were valued most, permeable pavement moved up two places (to #5).

3.3.3. Sensitivity analysis - performance assessment

The average, minimum and maximum score for each alternative are shown in Figure 10. In Table 5 the standard deviation of each alternative is presented, which is calculated based on the scores of a pessimistic and an optimistic scenario for the reliability of the performance assessment for all alternatives. These are 14 scores in total, as explained in section 2.4.2.

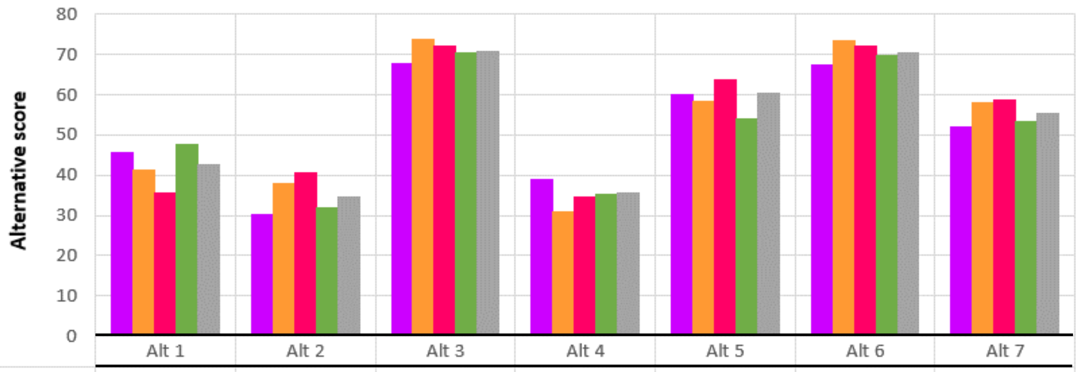
In almost all uncertainty scenarios the ranking stays the same. The only two exceptions are for alternative 3 and 6, and for alternative 2 and 4. The scores of alternative 3 and 6 are very close, and they can switch place in the ranking in the most pessimistic scenario for alternative 3, and for the most

Table 4 – MCA and criteria scores for alternatives

	Alternative 1		Alternative 2		Alternative 3		Alternative 4		Alternative 5		Alternative 6		Alternative 7	
	Green roofs		Permeable pavement		Bioretention systems		Retention ponds		Rain barrels		Urban wetlands		Detention tanks	
Criteria	Perfor.	Weigh.	Perfor.	Weigh.	Perfor.	Weigh.	Perfor.	Weigh.	Perfor.	Weigh.	Perfor.	Weigh.	Perfor.	Weigh.
A: Prevention of flooding	**5.3**	**2.0**	**47.3**	**17.5**	**98.7**	**36.5**	**0.9**	**0.3**	**60.2**	**22.2**	**98.2**	**36.3**	**77.5**	**28.6**
1a – Runoff reduction infrastructure	0	0.0	79	15.1	97	18.5	3	0.5	82	15.6	100	19.0	95	18.0
1b – Runoff reduction residential areas	18	2.6	34	4.7	97	13.5	0	0.0	82	11.3	100	13.9	95	13.2
1c – Runoff reduction Sassi	0	0.0	36	6.1	97	16.7	3	0.4	82	14.1	100	17.1	95	16.3
2a – Peak flow reduction infrastructure	3	0.7	59	11.2	100	19.0	0	0.0	38	7.3	96	18.3	60	11.4
2b – Peak flow reduction residential areas	11	1.5	32	4.5	100	13.9	0	0.0	38	5.3	96	13.4	60	8.4
2c – Peak flow reduction Sassi	3	0.6	32	5.6	100	17.1	0	0.0	38	6.6	96	16.5	60	10.3
B: Maintenance of area	**65.0**	**23.0**	**39.5**	**14.0**	**60.8**	**21.5**	**60.3**	**21.3**	**69.1**	**24.5**	**60.3**	**21.3**	**61.1**	**21.6**
3a – Added maintenance infrastructure	100	S41.2	0	0.0	100	41.2	100	41.2	100	41.2	100	41.2	100	41.2
3b – Added maintenance residential areas	20	4.4	100	22.1	10	2.2	10	2.2	50	11.1	10	2.2	0	0.0
3c – Added maintenance Sassi	50	16.8	50	16.8	50	16.8	50	16.8	50	16.8	50	16.8	50	16.8
4 – Life span measure	82	2.5	18	0.5	18	0.5	0	0.0	0	0.0	0	0.0	100	3.0
C: Enhancement of living area	**87.5**	**7.9**	**17.7**	**1.6**	**47.9**	**4.3**	**30.0**	**2.7**	**0.0**	**0.0**	**49.8**	**4.5**	**12.9**	**1.2**
5 – Added green/blue area	100	41.0	12	4.8	10	4.1	17	7.1	0	0.0	10	4.1	0	0.0
6 – Added recreational area	100	33.3	0	0.0	60	20.0	35	11.6	0	0.0	60	20.0	0	0.0
7 – Water pollution reduction	51	13.2	50	12.9	93	23.8	44	11.3	0	0.0	100	25.7	50	12.9
D: Construction of measure	**50.1**	**7.2**	**1.4**	**0.2**	**34.1**	**4.9**	**55.0**	**7.9**	**80.2**	**11.5**	**32.0**	**4.6**	**20.5**	**2.9**
8 – Impact of construction on surroundings	71	50.0	0	0.0	43	30.0	36	25.0	100	70.0	36	25.0	29	20.0
9 – Duration of construction	0	0.0	7	1.1	19	2.9	100	15.0	5	0.7	31	4.6	3	0.5
10 – Costs of construction materials	0	0.0	2	0.3	8	1.2	100	15.0	63	9.5	15	2.3	0	0.0
E: Sustainability	**59.5**	**2.6**	**31.0**	**1.4**	**78.6**	**3.4**	**78.6**	**3.4**	**50.0**	**2.2**	**83.3**	**3.6**	**21.4**	**0.9**
11 – Circularity of construction materials	64	21.4	29	9.5	100	33.3	100	33.3	100	33.3	100	33.3	0	0.0
12 – Energy required by measure	50	16.7	50	16.7	50	16.7	50	16.7	50	16.7	50	16.7	50	16.7
13 – Enhancement of ecosystem	64	21.4	14	4.8	86	28.6	86	28.6	0	0.0	100	33.3	14	4.8
Total score	**42.6**		**34.6**		**70.6**		**35.7**		**60.3**		**70.3**		**55.3**	

optimistic scenario for alternative 6. The scores of alternative 2 and 4 are very close as well. However, they do not switch place in the ranking, since the scenarios with a low score for alternative 4 give a score for alternative 2 that is even lower, and the scenarios with a high score for alternative 2 give a score for alternative 4 that is higher.

Sensitivity of alternative scores to stakeholder group value

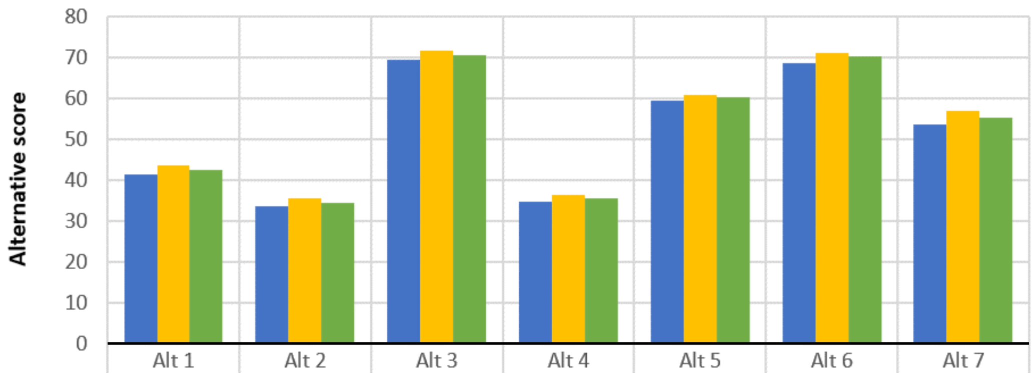


	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Alt 7
Local authorities	45.5	30.3	67.7	39.0	59.9	67.4	52.1
Local communities	41.4	38.0	73.7	30.9	58.2	73.4	57.9
Businesses	35.6	40.5	72.2	34.5	63.8	72.2	58.8
Civil societies	47.5	32.0	70.4	35.2	54.1	69.7	53.2
Ratio used	42.6	34.6	70.6	35.7	60.4	70.4	55.3

Alternatives and their exact score per ratio

Figure 9 - Sensitivity of alternative scores to stakeholder group value ratio

Minimum, maximum and average alternative score for varying uncertainty factors



	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Alt 7
Minimum score	41.5	33.7	69.3	34.8	59.3	68.6	53.6
Maximum score	43.7	35.5	71.7	36.4	60.8	71.2	56.8
Average score	42.6	34.5	70.5	35.7	60.3	70.2	55.2

Alternatives and their exact score

Figure 10 - Minimum, maximum, and average alternative score for varying uncertainty factors

Table 5 – The standard deviation of the average score of all alternatives for varying uncertainty factors

Alternative	Standard deviation
1	0.45
2	0.41
3	0.62
4	0.36
5	0.37
6	0.55
7	0.71

3.4. Flood risk in Matera without measure implemented (Q4)

This section presents the urban basin characterization for the current situation, as well as the output of the model for the current situation.

3.4.1. Urban basin characterization current situation

As explained in section 2.5., first an urban basin characterization was made. The urban basin characterization includes a classification of homogeneous surface areas (see Figure 11), a DEM, and an identification of the critical points in the study area (also presented in Figure 11). In Figure 11, semi-permeable areas are understood to be areas that are not paved, but are also not covered fully by vegetation. Green areas are understood to be areas that are fully covered by vegetation.

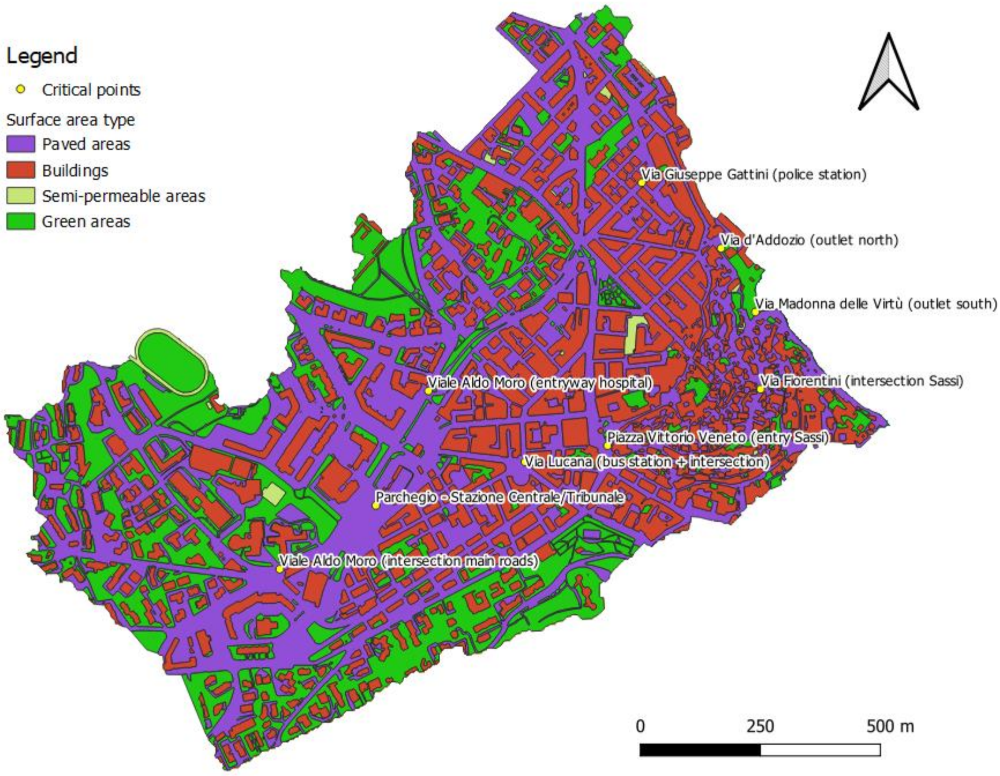


Figure 11 - Map with surface area types in the study area in the current situation

3.4.2. Maximum inundation depth, flow velocity, and DV current situation

Figure 12, 13, and 14 show, for the entire study area in the current situation, the maximum inundation depth, flow velocity, and DV for the entire simulation period (4:15 hours, as long as rainfall occurs in the event). The right side of each figure shows a close-up of the Sassi. The inundation depth, flow velocity, and DV in the current situation over time at all critical points are presented in Appendix D, since they do not show an overview of the area as clear as the maps.

The figures show that the Via Fiorentini (main road in the Sassi) and the Via Vincenzo Cappelluti (connecting road between the intersection of the main roads of Matera and the entrance of the Sassi) experience the highest flow velocity and DV. Those same roads, as well as the north-eastern section of the study area, experience the highest inundation depth.

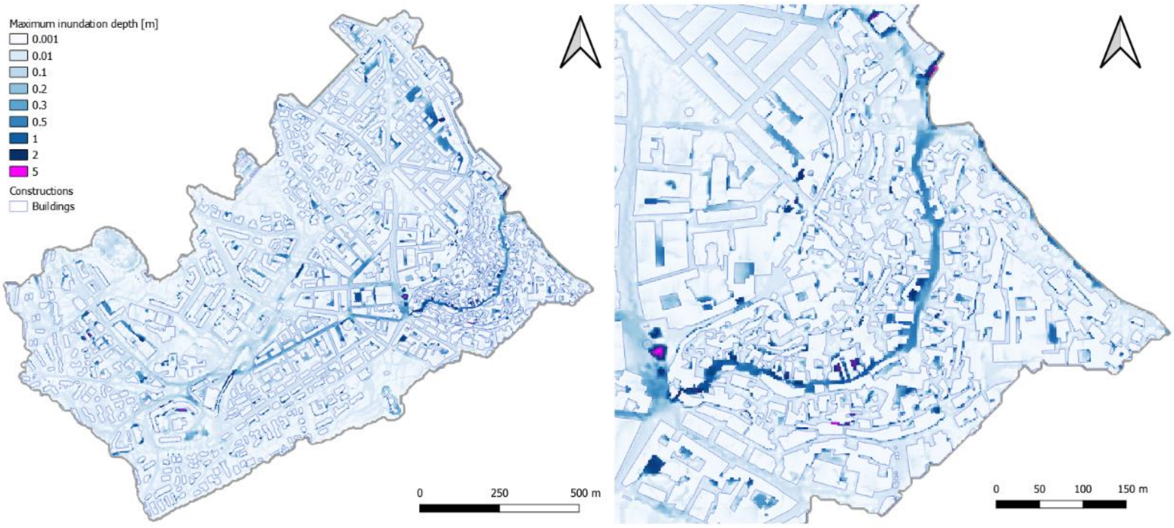


Figure 12 - Maximum inundation depth for the current situation in the complete study area, and close up in the Sassi

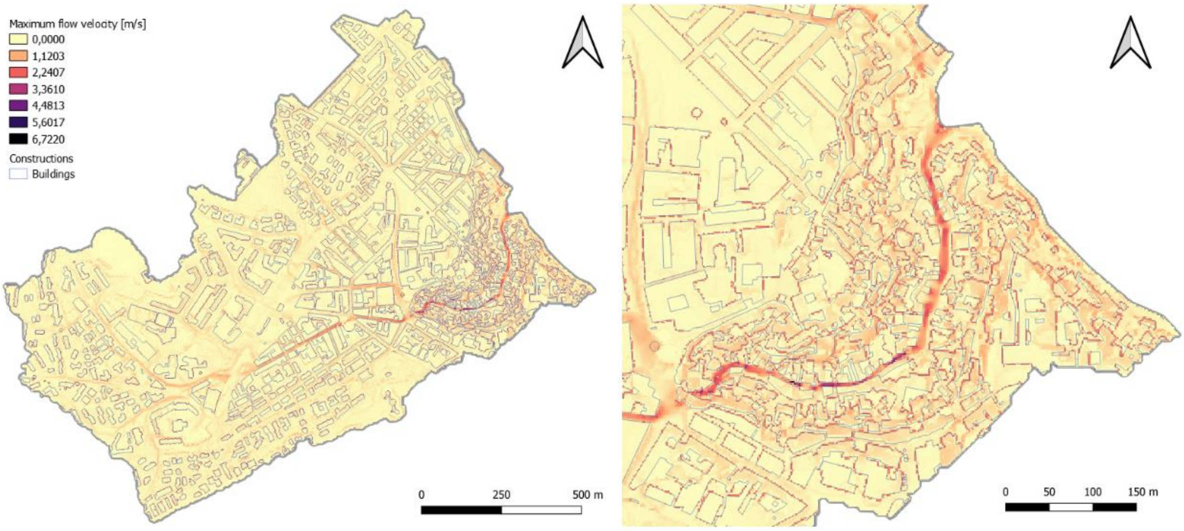


Figure 13 - Maximum flow velocity for the current situation in the complete study area, and close up in the Sassi

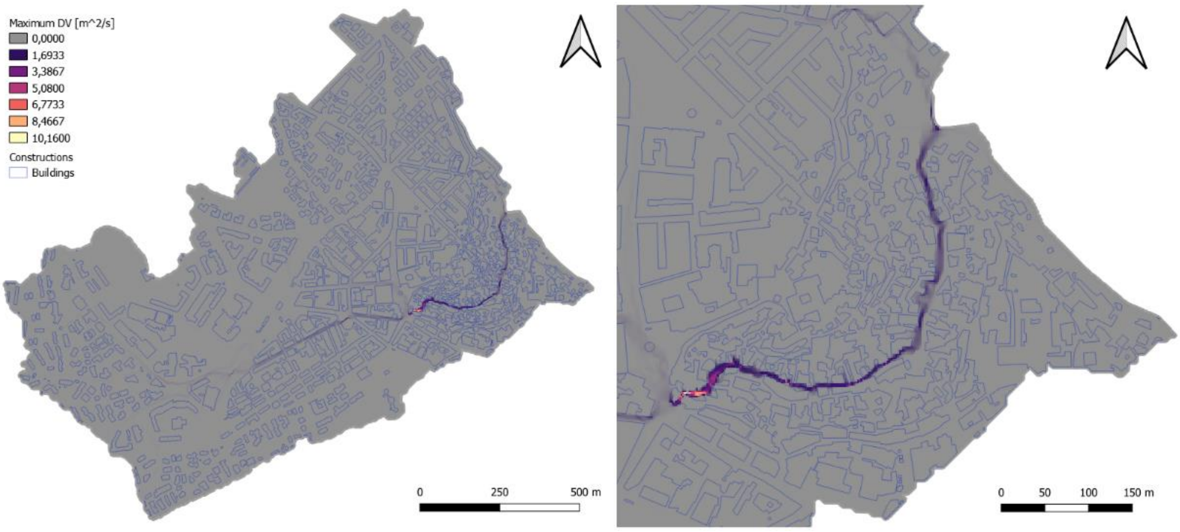


Figure 14 - Maximum DV for the current situation in the complete study area, and close up in the Sassi

3.5. Flood risk in Matera with measure implemented (Q5)

This section presents the urban basin characterization for the new situation, as well as the output of the model for the new situation.

3.5.1. Urban basin characterization for new situation

For the urban basin characterization of the new situation, alterations have been made to the homogeneous areas shapefile and to the DEM according to the method as described in Appendix B. Since the bio-retention systems were the best scoring alternative, suitable locations for the implementation of the systems have been appointed based on visual inspection of the homogeneous areas shapefile, the DEM, Google Street View, and Google Maps. The most ideal locations for bio-retention systems have an undeveloped surface area with a low elevation and a soft soil (Shafique, 2016). Based on mostly the first two, this has resulted in the locations as indicated on the updated map of homogeneous areas, which can be seen in Figure 15. The DEM has been altered by -0.5 meter at all cells that are covered by a bio-retention system, so that the system can receive runoff of surrounding areas, as explained in Appendix B, Table 8. The elevation of the system located at the intersection of the Via Lucana (critical point 3) has been altered by -1.5 meter, since the surface of that area is a meter higher than the surrounding area in the current situation. The Manning's coefficient for the new surface type was set at 0.07, similar to that of green areas.

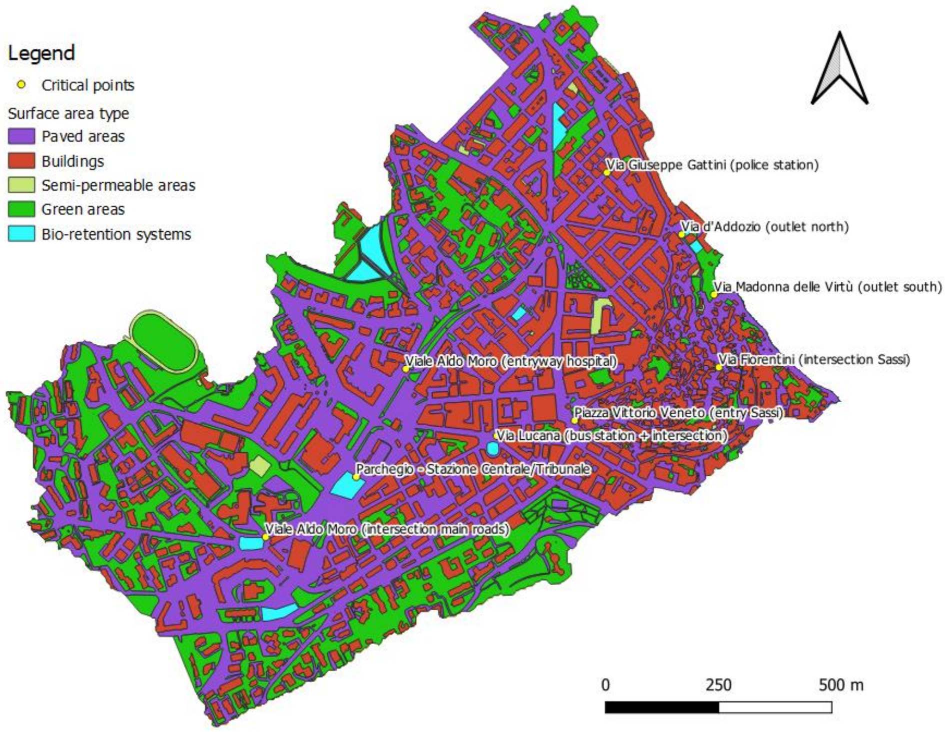


Figure 15 - Map of homogeneous surfaces in the study area in the new situation

3.5.2. Maximum inundation depth, flow velocity, and DV new situation

Figure 16, 17, and 18 show, for the entire study area in the new situation, the maximum inundation depth, flow velocity, and DV for the entire simulation period (4:15 hours). The right side of each figure shows a close-up of the characteristic in the Sassi. Appendix D shows the inundation depth, flow velocity, and DV in the new situation over time at all critical points.

The figures show that the Via Fiorentini (main road in the Sassi) and the Via Vincenzo Cappelluti (connecting road between the intersection of the main roads of Matera and the entrance of the Sassi) experience the highest flow velocity and DV. Those same roads, as well as the north-eastern section of the study area, experience the highest inundation depth. In Figure 16, it can be seen that the areas that are covered by a bio-retention system have a relatively large inundation depth. This is because pooling occurs in those areas, the elevation is lower so runoff of surrounding areas is collected. The model does not simulate infiltration, which is why after simulation a relatively high inundation depth can be seen in the output.

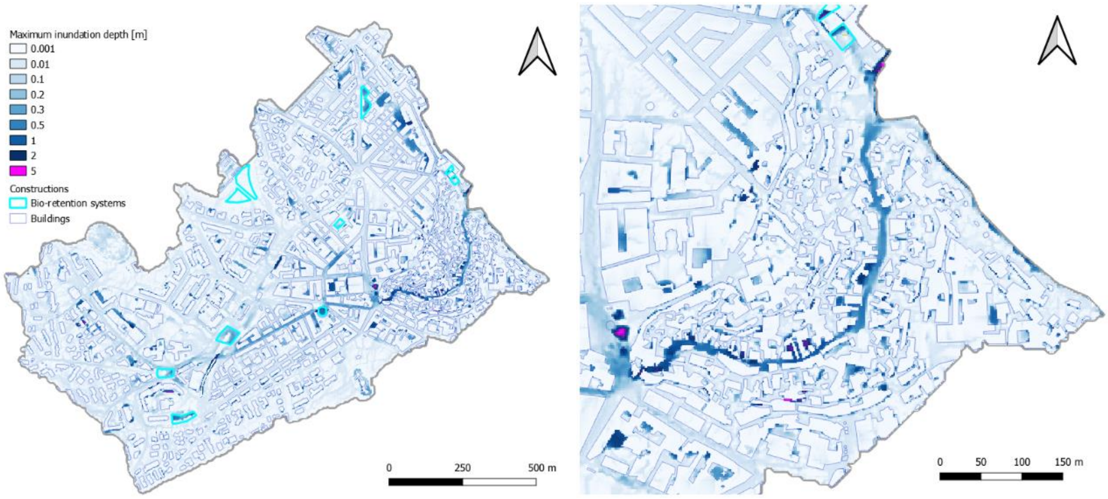


Figure 16 - Maximum inundation depth for the new situation in the complete study area, and close up in the Sassi

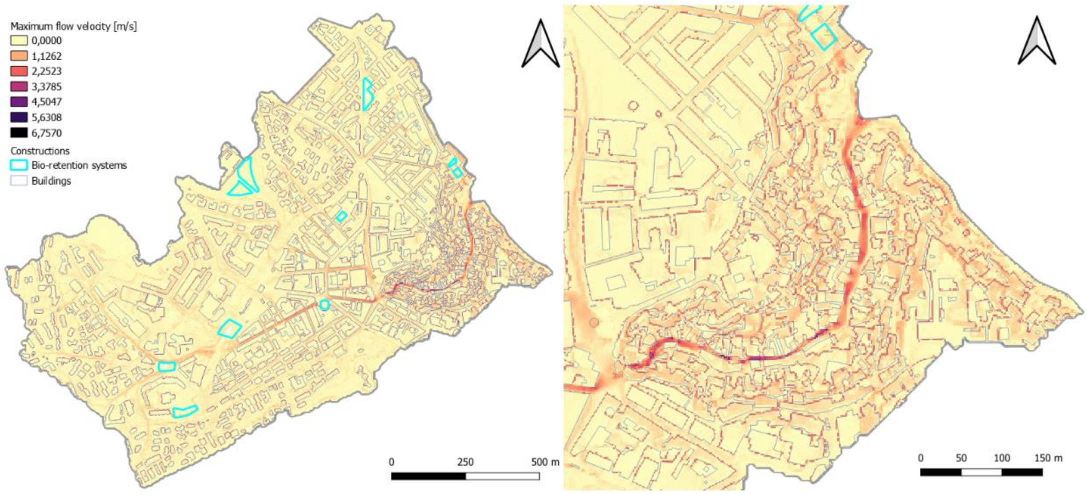


Figure 17 - Maximum flow velocity for the new situation in the complete study area, and close up in the Sassi

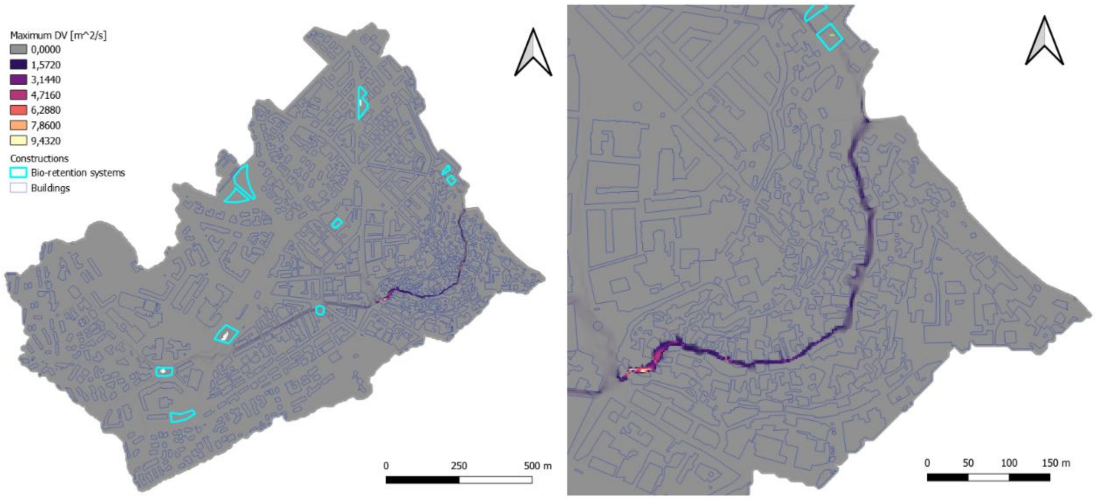


Figure 18 – Maximum DV for the new situation in the complete study area, and close up in the Sassi

3.6. Comparison of flood risk in Matera before and after implementation of measure (Q6)

This section presents the changes in maximum inundation depth and flow velocity, as well as the hydraulic invariance and the change in hazard for pedestrians.

3.6.1. Change in maximum inundation depth

Figure 19 shows the change in maximum inundation depth. Figure 22 shows a close-up of the maximum inundation depth at the entry of the Sassi, which is indicated by the red box in Figure 19. It can be seen in Figure 19 that the maximum inundation depth at the locations of bio-retention systems has increased largely, while in surrounding areas and locations downstream of the systems it has decreased. This is especially the case for the Via Vincenzo Cappelluti (connecting road between the intersection of the main roads and the entry of the Sassi), and for the north-eastern section of the study area. Runoff from the Via Vincenzo Cappelluti contributes most to the inflow of runoff to the Sassi, but even though the maximum inundation depth at this road and just before the entry of the Sassi has decreased, the upstream part of the Via Fiorentini (main road in the Sassi) has an increase in maximum inundation depth. However, further downstream on this road still a decrease in maximum inundation depth can be seen. The reason for the increase at the entry is unknown.

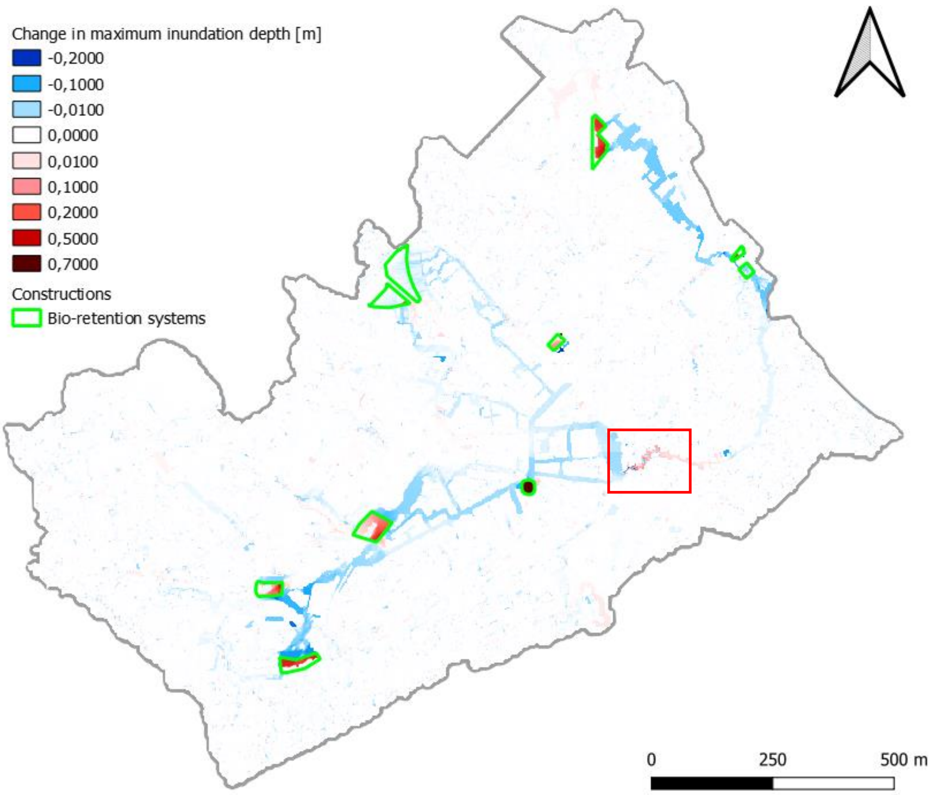


Figure 19 - Change in maximum inundation depth in the new situation compared to the current situation

The inundation depth over time at critical point number 8, which is located about halfway down on the Via Fiorentini, is shown for the current and the new situation in Figure 20. The figure shows that the inundation depth has decreased only very lightly in the new situation, with the exception of a few peaks. It is also visible that the beginning of the second peak (the one after 8000 seconds) is delayed in the new situation, but this does not clarify why there is an increased maximum inundation depth at the entry of the Sassi.

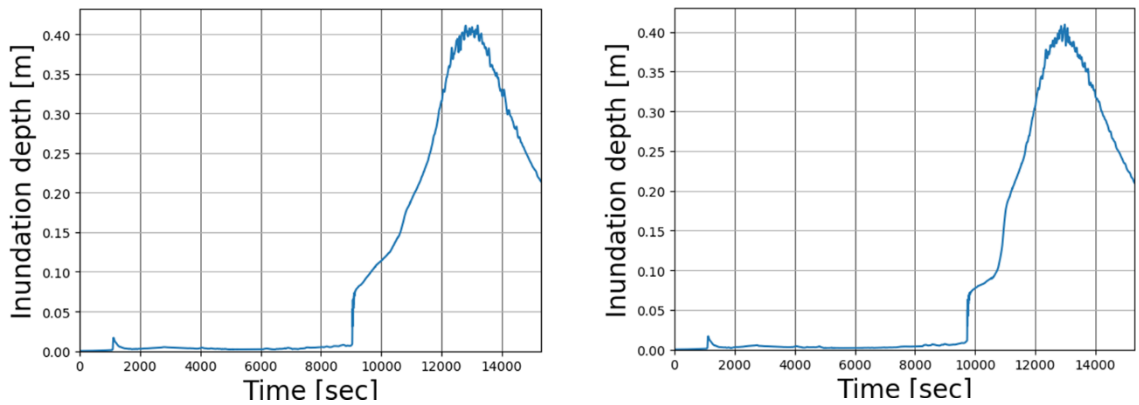


Figure 20 - Inundation depth over time at critical point (CP) #8 for the current situation (CS) and the new situation (NS)

3.6.2. Change in maximum flow velocity

Figure 21 shows the change in maximum flow velocity. It can be seen that the maximum flow velocity at the centre of most of the locations of the bio-retention systems has decreased by 0.10-0.50 m/s. In general, at the locations where the maximum inundation depth has decreased also the maximum flow velocity has decreased. Similarly, it seems to increase at locations that have an increase in inundation depth, for example at the beginning of the Via Fiorentini. The entry of the Sassi, indicated in Figure 21 by the red box, is a little more complicated, since there seems to be both an increase and decrease in flow velocity.

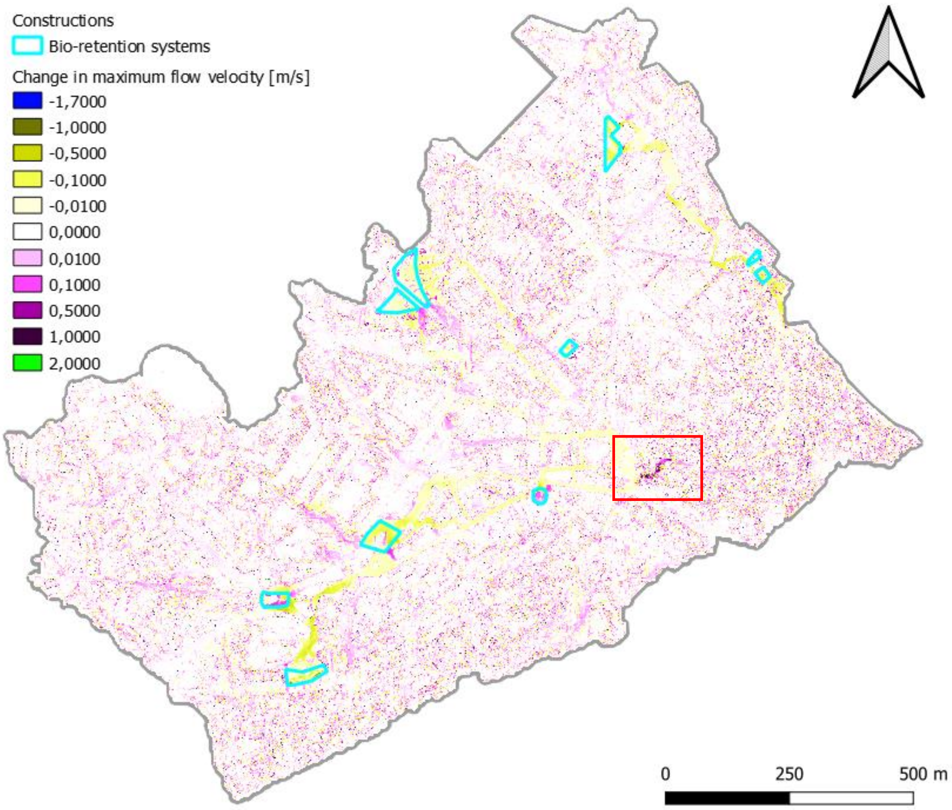


Figure 21 - Change in maximum flow velocity in the new situation compared to the current situation

Figure 22 shows a close-up of the change in maximum inundation depth and flow velocity at the entry of the Sassi. Both characteristics seem to increase at multiple points in the street, but they also decrease on a few points. For all cells it seems that if the inundation depth is lower, the flow velocity is lower as well. This also goes for increases of both characteristics. The reason for this varying change is unknown.

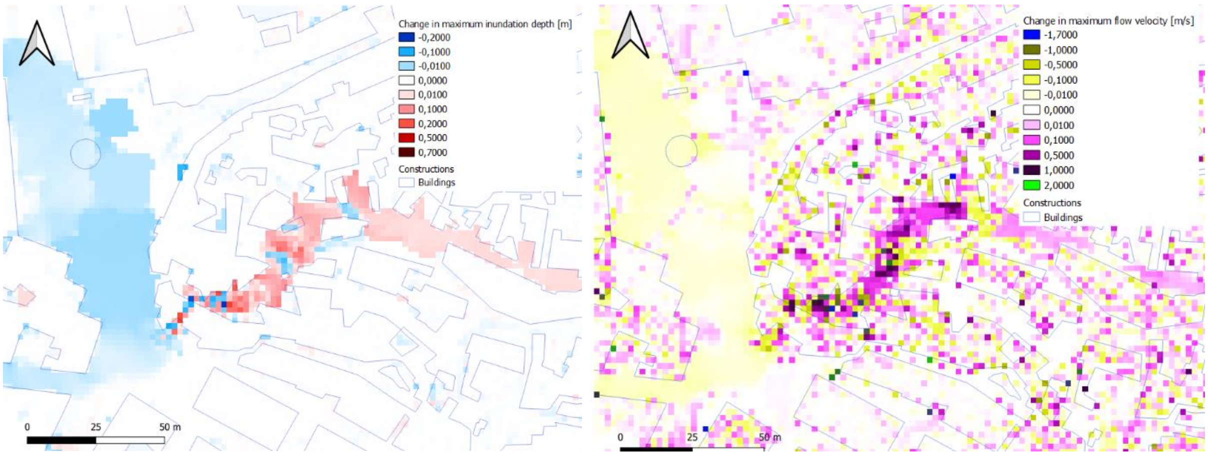


Figure 22 - Close-up of the change in maximum inundation depth (left) and maximum flow velocity (right) at the entry of the Sassi

3.6.3. Hydraulic invariance

Figure 23 shows the hydraulic invariance in the area, which has been calculated according to the theory described in section 2.7. It can be seen that, corresponding to the decreases and increases of the inundation depth and flow velocity, the hydraulic invariance decreases downstream of most bio-retention systems, and increases at the entry of the Sassi. Overall, it seems that most of the area and especially the main infrastructure are less threatened by the flood event in the new situation.

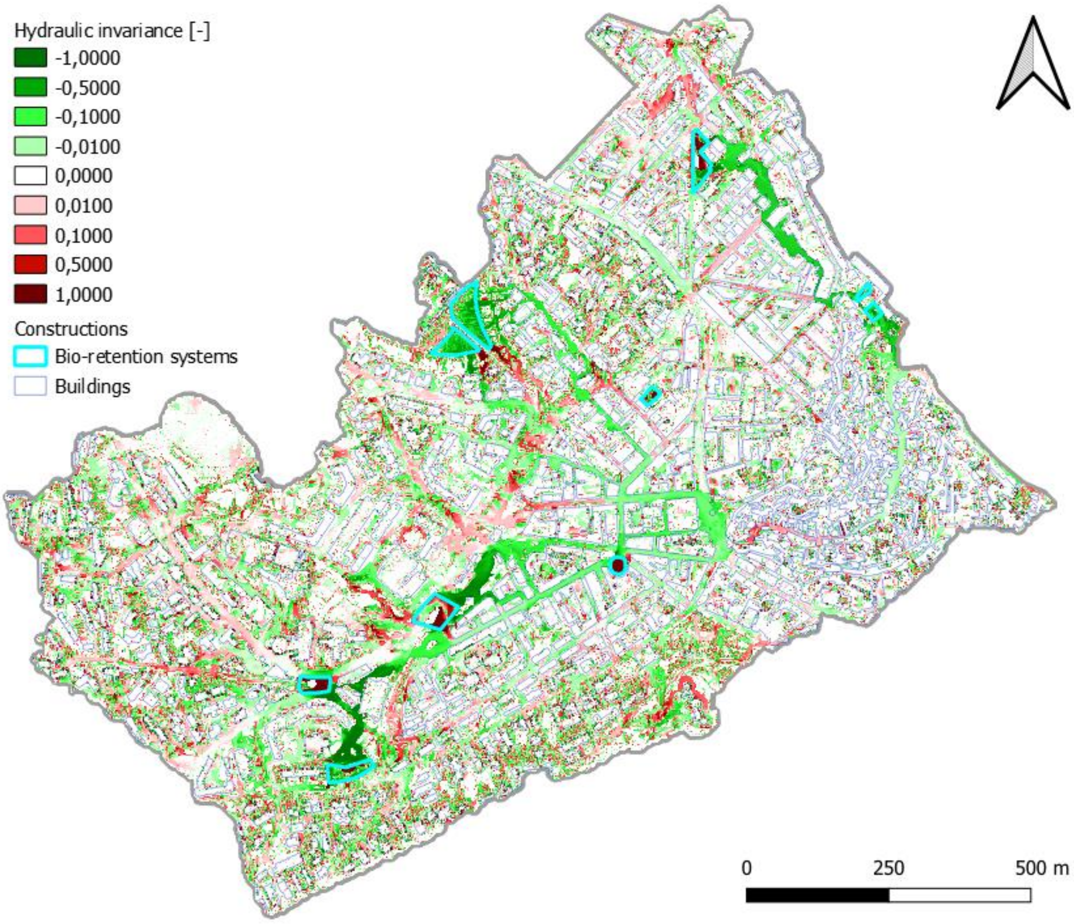


Figure 23 - Hydraulic invariance in the new situation compared to the current situation

3.6.4. Pedestrian hazard

Figure 24 and 25 show the pedestrian hazard in the Sassi in the current situation and in the new situation. Outside of the Sassi, there are no cells where a hazard occurs. Difference between the current and the new situation in the Sassi is difficult to see in the maps, but when zoomed in it shows that the few cells further downstream have a small decrease in hazard (from medium to low or from low to no hazard for 3-4 cells). For the high hazard region at the entry of the Sassi, the new situation actually increases the area in which (high) hazards can occur by a few cells. This corresponds with the positive hydraulic invariance in that region.

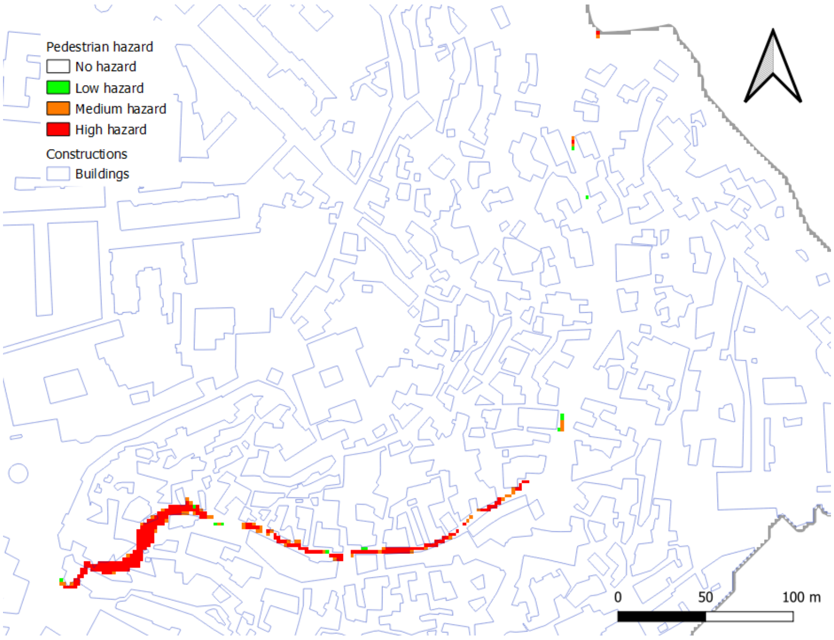


Figure 24 - Pedestrian hazard in current situation in the Sassi

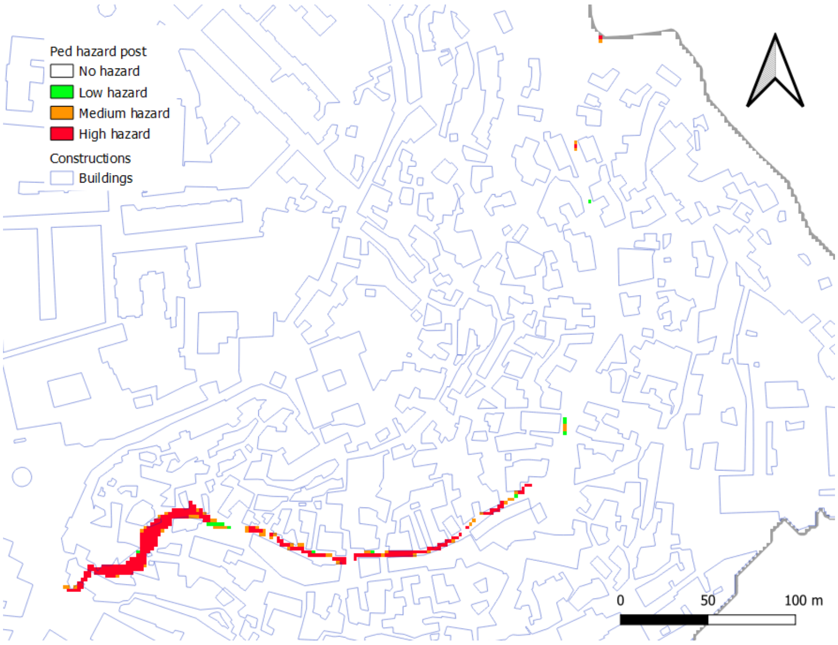


Figure 25 - Pedestrian hazard in the new situation in the Sassi

4. Discussion

The research objective was to determine a suitable flood mitigation measure for Matera and to evaluate how it affects physical flood characteristics in Matera. This section discusses how the results of the research contribute to the achievement of this objective, and how the methodology that has been used to get to these results has affected the research. This will be done in two parts, which are the MCA and the evaluation of the effectivity of the measure with FLORA-2D.

4.1. Discussion of MCA

The MCA was a means to achieve the first part of the research objective, selecting a flood mitigation measure that is suitable for Matera. It was executed in three steps, which are the set-up of alternatives, the set-up of weighted criteria, and assessment of the performance of the alternatives on the criteria.

4.1.1. Set-up of alternatives

Before setting up the alternatives for the MCA, the choice was made to neglect the effect of the drainage system on flow dynamics. This was decided because the rainfall events that cause the floods are too large for the drainage systems to drain the runoff. Besides that, FLORA-2D does not simulate the effect of drainage systems. Even though this was a deliberate choice, it could be possible due to this that the measure that scored best in the MCA is actually not the most suitable flood mitigation measure for Matera, since not all existing pluvial flood mitigation measures were taken into account. Measures that affect the drainage system were only taken into account if their implementation could be simulated with a workaround via QGIS.

4.1.2. Criteria and weights

The criteria are based on a comprehensive stakeholder analysis done for this research, which in turn is based on an existing stakeholder analysis for the area with a focus on crisis management, as explained in section 2.3.1. However, part of the mapping of interests is subjective, since it was not within the scope of this research project to ask the stakeholders for their own input with a focus on flood mitigation. Even though the scores that are assigned to the stakeholder groups do not affect the final scores of the MCA alternatives very much, the interests themselves might affect the criteria and subsequently the ranking of alternatives. Unfortunately, the limited resources for this research project did not allow for a more thorough analysis of the effect the stakeholder interests on the ranking of alternatives.

In the set-up of the criteria, the value tree hierarchies were seen as a helpful resource to not only formulate a complete set of criteria, but also to link the value of stakeholder interests to the criteria. The AHP was also seen as useful, since it shows a clear reasoning behind the division of weights, especially since the values used in the AHP were based on literature and other steps in the research.

4.1.3. Performance assessment

The choice was made to base the alternatives and their performance on the MCA criteria on literature review due to the limited time that was available for this research. Even though it gives a clear overview of the characteristics of each alternative, the information found in literature is often context specific. Even though an effort was made to find literature with a context similar to this research and study area, a complete match could not always be found due to the limited time or lack of literature with a similar context. This might make the assessment of certain performances and interactions with the measure's surroundings less accurate. A sensitivity analysis was done to cope with the largest uncertainties on this point, but it was limited to a maximum of a 10% divergence of the scores that were assumed or based on little sources. In reality, divergence may be much higher than 10%.

4.2. Discussion of evaluation of flood reduction effectivity with FLORA-2D

FLORA-2D was used as a plugin in QGIS to simulate the flooding of the study area in the current situation and in the new situation. Comparison of these two was done to determine how the flood mitigation measure affects the physical flood characteristics in the study area, which was the second part of the research objective.

4.2.1. Set-up of model

In both situations the set-up of the model included an urban basin characterization, rainfall data, and the location of critical points. The set-up of the model for the current situation (before implementation of the measure) also formed the basis for the set-up of the model in the new situation (after implementation of the measure). For the new situation, only some small alterations were made for areas at which the measure was simulated to be implemented.

For the set-up of the urban basin characterization for the current situation, the surface areas were generalized into three categories with varying permeability. Besides this generalization, for some areas the surface type was assumed if it could not be clearly retrieved from sources about the area (i.e. QGIS shapefiles from (RSDI Basilicata, 2021), Google Street View, and Google Maps). Since this was done for areas that make up approximately less than 5% of the area, these assumptions and generalization probably do not affect the changes in flood characteristics a lot, also because they are similar for the current and the new situation.

For the set-up of the model in the new situation, alterations were made to the urban basin characterization and the rainfall data based on both assumptions and literature. Firstly, the location of the bio-retention systems was chosen based on the conditions that are described in literature to be ideal for construction of the systems, but also on the areas that appeared to be available for construction. The latter was the case because there is very limited space in Matera for constructions of any kind. Secondly, the cells in the DEM that were located at an implementation site of a bio-retention system were altered, but the resolution of the DEM is relatively low for this kind of alterations. Therefore, the changes in the DEM do not match the location of the bio-retention systems completely at the edges of the systems. However, this goes for buildings as well and in previous research the model is deemed accurate enough for the study area (Sole et al., 2019). Therefore no issue is seen in this inaccuracy.

4.2.2. Interpretation of model output

Reading the output of the model was difficult for the complete study area, since the difference between cells is not very easily visible on the large scale, but when zoomed into specific areas the resolution of the grid made it hard to interpret the effect the changes in each cell had on the surrounding areas.

The data for the critical points helped to get an idea of the impact of the measures on those specific areas, but since the maps showed highly variable results in cells that were located close to each other, the data of the critical points might not represent the situation at the locations optimally. For example, the critical point at the entry of the Sassi was located at a square just in front of the actual entryway. At this critical point the maximum inundation depth and flow velocity decreased, while the same characteristics increased at the entryway. Therefore, the critical point is not fully representative of the situation at the entry of the Sassi. Following on this point, the simulation results show that all characteristics increase at the entry of the Sassi, which is strange regarding the fact that they have all decreased at the roads that lead to the entryway of the Sassi. The cause of the increase is unknown, since there seems to be no extra runoff coming from other locations.

Lastly, it must be noted that the values that were taken as averages for the hazard categorisation are based on research for inundation depths of 9-16 cm. There are multiple locations in the study area where the inundation depth is larger, so the values might not have been representative for these locations. More accurate values for those locations could result in more classifications of the cells as (higher) hazards.

4.3. Link to literature

Comparing the results of this research to literature with a similar context is difficult, since no literature about flood mitigation in Matera could be found. For the first part of the research, no comparable literature could be found, since the methods that have been used to set up the MCA (through value tree hierarchies) was an approach of which no documentation in this field could be found. MCAs have been used more often to evaluate suitability of a flood mitigation measure, but usually they include a flood reduction assessment based on simulation of a measure in the study area of the research (e.g. (Ghanbarpour et al., 2013)). This does make the ranking more accurate for deciding which measure is best for an area, since it is one of the characteristics of the MCA that is most context specific and thus most difficult to get reliable values from literature. However, the method that was used in this research proved to be a successful method for ranking alternatives about which much information could be retrieved from literature, especially for the limited time that was available. In addition, the model and input data are currently set up in such a way, that evaluation of the effects of other measures is not much extra work, which might open the door to base the assessment the flood reduction effectivity for the MCA on results of simulation in this study area.

The second part of the research is easier to compare with literature, since much research has been done into floods in the Basilicata region, as described in section 1.3. The literature that is described in section 1.3.1. often shows a more extensive analysis of the flood characteristics, sometimes using simulations for multiple rainfall events and comparing simulated results to observational records of flood events. It was known at the beginning of this research that the available time and data would be too little to do an analysis of the flood simulations that is equally extensive. But while simulating flood events for varying rainfall events is very easy to do in the model, for a general idea of the effect of implementation of a flood mitigation measure, the results as presented in this research are also sufficient.

5. Conclusion and recommendations

In this chapter the conclusion to the main research question will be given and recommendations will be done for further research into this matter and similar subjects.

5.1. Conclusion

The research question to answer was: what is a suitable flood mitigation measure for Matera and how effective is it in reducing physical flood characteristics? The previous chapters have described and discussed results that substantiate answers to six sub-questions, which together help to formulate a conclusion to answer the main research question.

5.1.1. Suitability of a flood mitigation measure for Matera

Based on a stakeholder analysis for the study area, it can be said that a flood mitigation measure that is suitable for Matera should perform well on flood prevention, easy maintenance, enhancement of the living area, varying construction aspects, and sustainability. In the current situation in Matera, the focus lies most of all on flood prevention and easy maintenance.

Based on a comparison of the performance of various flood mitigation measures on these aspects, it can be concluded that bio-retention systems are the most suitable flood mitigation measure for Matera, followed closely by urban wetlands. Urban rain barrels and detention tanks are also relatively suitable. Green roofs, retention ponds, and permeable pavement appear to be least suitable, mostly because of their limited performance on flood prevention and (for green roofs and permeable pavements) their large scale implementation.

5.1.2. Effectivity of the most suitable flood mitigation measure for flood reduction in Matera

Since a bio-retention system came out as the most suitable flood mitigation measure for Matera, its implementation has been simulated for simulation of a rainfall event. The results of this simulation were compared to the results of a simulation for the same rainfall event, with the difference that in this second simulation the implementation of bio-retention systems was not simulated. This comparison was used to determine how effective bio-retention systems are in reducing maximum inundation depth, maximum flow velocity, and maximum DV in the study area. Resulting from this comparison it was visible that the implementation of bio-retention systems in the area does reduce the maximum value of each of the flood characteristics in certain areas, but it also shows that there is an increase of the maximum values at the entry of the Sassi.

The conclusion on this part is that, while the measure appears to be effective in reducing flood risk for some critical points in the study area, the flooded area in Matera that received most attention is not helped by the implementation of bio-retention systems at the locations where they have been simulated for this research. The measure even increases the hazards in some parts of that area.

5.2. Recommendations

This research project was bound to some constraints because of limited time and means. Therefore, some recommendations are done for (similar) future research.

5.2.1. Recommendations for determining a suitable flood mitigation measure

First of all, the choice to neglect the effect of the drainage system on the flow dynamics limited the choice of flood mitigation measures. Flood mitigation measures that affect the drainage system were not taken into account in this research, as explained in section 4.1.1., but especially for flooding in urban areas, the drainage system has a large effect on the runoff in the study area. It is therefore recommended to also look into measures that affect the drainage system. If it is necessary to simulate the implementation of that measure later on, it is possible to combine FLORA-2D with another model that takes the effects of a drainage system into account.

Secondly, actual consultation of stakeholders in the study area could make the criteria that are chosen for the MCA a more accurate representation of the position and interests of the stakeholders. This would require more time than that was available for this research, and depending on the study area and the researcher, language could be a limiting factor on this point.

A last point for this part of the research, is the performance assessment of each flood mitigation measure on the criteria. As explained in section 4.1.3., the performance of the measures is highly context specific, so when literature is used for the performance assessment, it should preferably be selected more based on conditions similar to the study area.

Overall, the method that was used to determine a suitable flood mitigation measure for Matera was perceived to be a good method, since it substantiated every step from stakeholder analysis until criteria weighting and calculation of the scores of the alternatives. It might also be useful for research with a similar set-up for other study areas.

5.2.2. Recommendations for evaluating the effectivity of a flood mitigation measure in terms of inundation depth, flow velocity, and DV with FLORA-2D

When the effectivity of a flood mitigation measure is evaluated by analysis of simulation output of a model, assumptions, approximations, and generalizations will always affect this output. In case of this particular research project, the urban basin characterization was largely based on generalizations and assumptions. For further research, it might be helpful to visit the study area in person, since that gives more information about the surface type of areas that were not included in the QGIS shapefiles for the study area and also not clearly visible via Google Street View or Google Maps. This would give a more accurate categorisation of the surface type of each cell.

Another recommendation for the urban basin characterization, is to look into how the permeability of the surface area affects the runoff. If there is a strong connection between these two, it may be useful to specify more surface types with varying permeability factors to make the effective rainfall on each cell more accurate. Lastly for the urban basin characterization, it is recommended to use a grid with a higher resolution, for example of 1x1 meter and for areas of interest even 0.5x0.5 meter. Even though a grid with a cell size of 2x2 meter is faster to run, it makes the simulation less accurate and it can also make the output of the simulation more difficult to interpret.

The effectivity of flood mitigation measures depends on many factors, among which is also the severity and duration of the rainfall event. Because the time for this research project was limited, only one rainfall event was used to simulate flooding with an implemented flood mitigation measure, but to evaluate the performance of the measure more thoroughly, it is recommended to run simulations with varying rainfall intensities and event durations. Another factor that might affect the performance of the measure, is the location at which the measure is implemented. Changing the location of the measure might have different effects on the inundation depth, flow velocity, and stream power in the rest of the study area.

Overall, FLORA-2D is seen as a suitable model for simulation of urban runoff, if it is taken into account that the drainage system does not play a role in runoff reduction. The plugin in QGIS allows for fast and easy alterations of the urban basin characterization and rainfall data, which makes it easier to evaluate varying set-ups and conditions for flood mitigation measures.

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Appendix A – FLORA-2D explanation and set-up

As explained before, FLORA-2D is a two-dimensional hydrodynamic model that focusses mostly on the flow resistance that is caused by vegetation and soil roughness. The latest version of the model contains a major update consisting of the ability to apply effective rainfall (rainfall minus losses due to interception/infiltration, also called excess rainfall) directly to homogeneous areas in the flow area: this is very useful in the case study of flooding due to heavy rain in an urban areas (L. Mancusi, personal communication, June 30, 2021). This appendix explains the workings of the model and describes how the input for the model can be adjusted to be applicable to a study area.

A.1. FLORA-2D explained

The FLORA-2D model has a graphical interface consisting of a plugin that can be installed in QGIS, via which input is linked to the model. The model can be run from the plugin. If the model is run, the shallow water equations are used to calculate the flow propagation. The shallow water equations are simplified by eliminating the convective terms. The simplified equations are discretized in time and space, the latter via an orthogonal staggered grid. The exact derivation of the equations is described in the FLORA-2D user manual (School of Engineering & RSE, n.d.).

In each time step and for each cell, the inundation depth, flow velocity and direction, and the product of the inundation depth and flow velocity (DV) are calculated. Also, the model keeps track of when inundation starts to occur in each cell, which can be used to get a map of the flood wave arrival time. This is mostly interesting for modelling of river floods.

A.2. Set-up of the model for a specific study area

To set up the model so that it is useable for a study area, a DEM, homogeneous areas shapefile, and a shapefile containing the HTEM points are needed. How these files have been set up for this research has been explained in chapter 2.

Figure 26 shows the QGIS window in which the first steps in setting up the model for the study area can be carried out. It is firstly necessary to create a project, in which the study area can be set up and files can be adjusted if necessary. A DEM must be linked to this project.

Then a geodatabase must be created, in which the files can be uploaded that are needed to define the study area. After that, a coordinate reference system (SRID) must be selected. The homogeneous areas shapefile can be uploaded, containing at least one characteristic that categorises the type of surface of each polygon in the file. This file is rasterized to later be linked to the effective rainfall for each cell. As a next step, the HTEM points shapefile can be uploaded so that for designated locations the physical flood characteristics are measured over time and presented in graphs after running the model. Moving to the right column of Figure 26, it is now only necessary to update all files based on the ones that have been used as input. For the boundary conditions layer it is also necessary to assign locations where runoff can flow out of the study area, but since research had previously been done for this study area this was already set up. As a last step, the files must be copied to use as input for the model.

A.3. Set-up of simulation settings

Figure 27 shows QGIS window in which the set-up of the simulation settings can be carried out. It is firstly important to select the project for which the simulation must be done, after which the TERRENO, DOMINIO, and CONDIZ files are selected that contain information about the set-up of the model. They have been created in the steps described in the previous section. The run number must also be adjusted, to make sure that output files do not overwrite the results of previous runs.

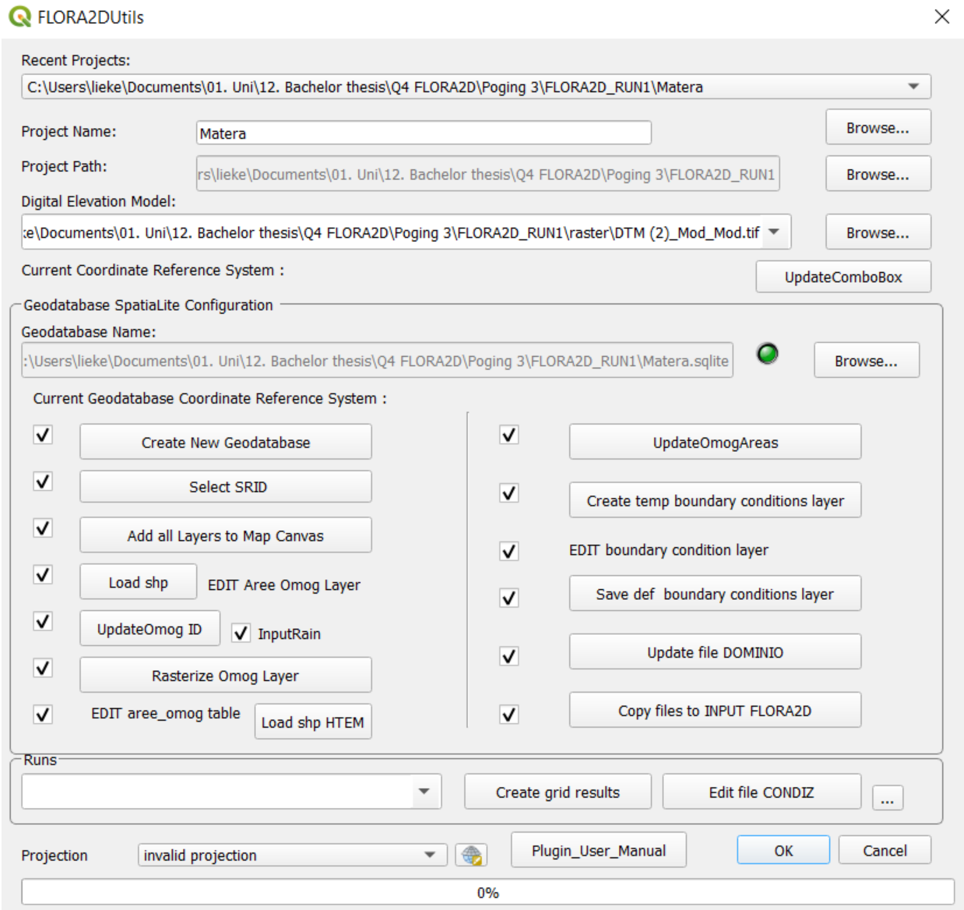


Figure 26 – QGIS window for the set-up of the model for a study area

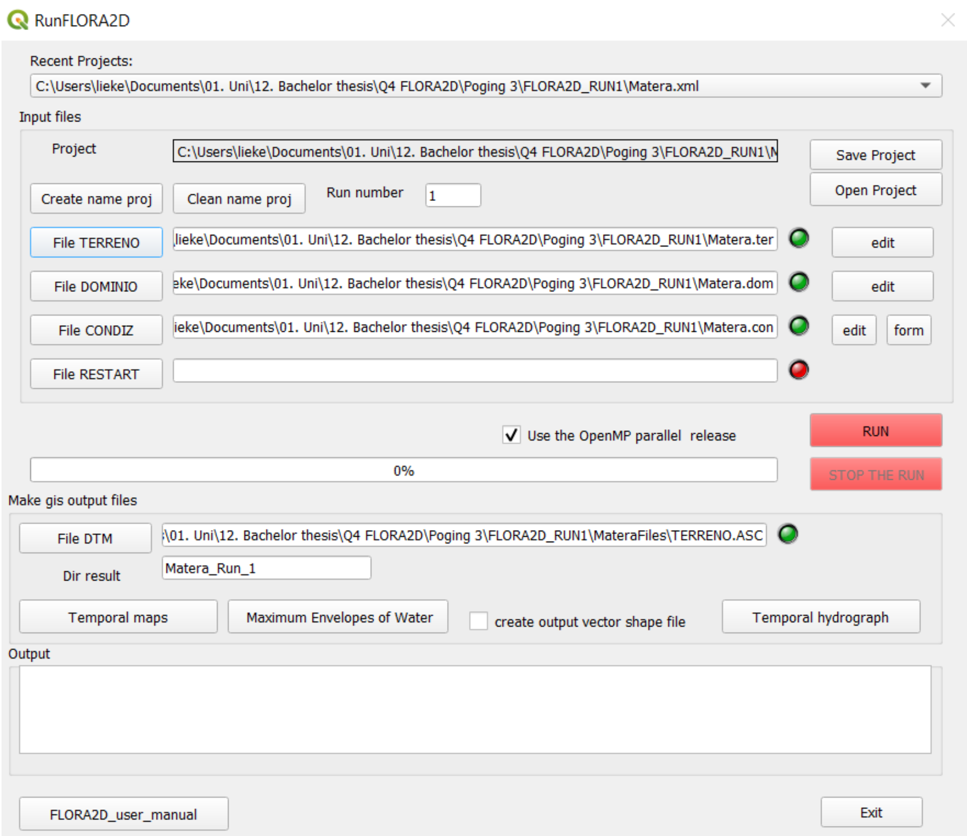


Figure 27 - QGIS window for the set-up of the simulation

The CONDIZ file can be opened by clicking on the 'form' button, which gives the possibility to alter the simulation time, the time step, and the time print that is used for the creation of temporal output files (see Figure 28, which includes the settings that have been used for the simulations of this research). Besides that, the rain input can be linked to the different surface types in this window and it can be checked if the boundary conditions (where the runoff can flow out of the study area) and the HTEM points are set up correctly. If necessary, they can also be adjusted in this window. The homogeneous areas and rain input section includes hydrodynamic characteristics, which can be seen by clicking on the 'show data' button. This presents a table at the bottom of the window that includes the manning coefficient for each surface type. The table also includes the NTABQ(I) number, which is the number that links the effective rainfall to each surface type. By uploading a csv file and selecting the column that contains the effective rainfall for that surface type, the right amount of rainfall is linked to each surface type. When selecting a NTABQ(I) number and clicking on the 'show table' button on the right, it can be checked if the rainfall is correctly linked to the surface type. If the manning coefficient needs to be adjusted for a surface type, this can be done by clicking on the edit button for the CONDIZ file, which can be seen in Figure 27. This opens a text file in which the manning coefficients can be adjusted.

If these settings are all set up correctly, the run button can be clicked to start the simulation. To create output in the form of maps, also the DEM must be selected again. The maps show the physical flood characteristics that were mentioned earlier for each cell in the study area. The temporal maps button gives the characteristics for each time print as indicated in the CONDIZ file, the maximum envelopes of water button creates maps showing the maximum values for the characteristics over the whole simulation time, the create output vector shape file checkbox gives a shapefile that contains the flow direction and magnitude of the flow velocity, and the temporal hydrographs present graphs for the characteristics over time for each HTEM point.

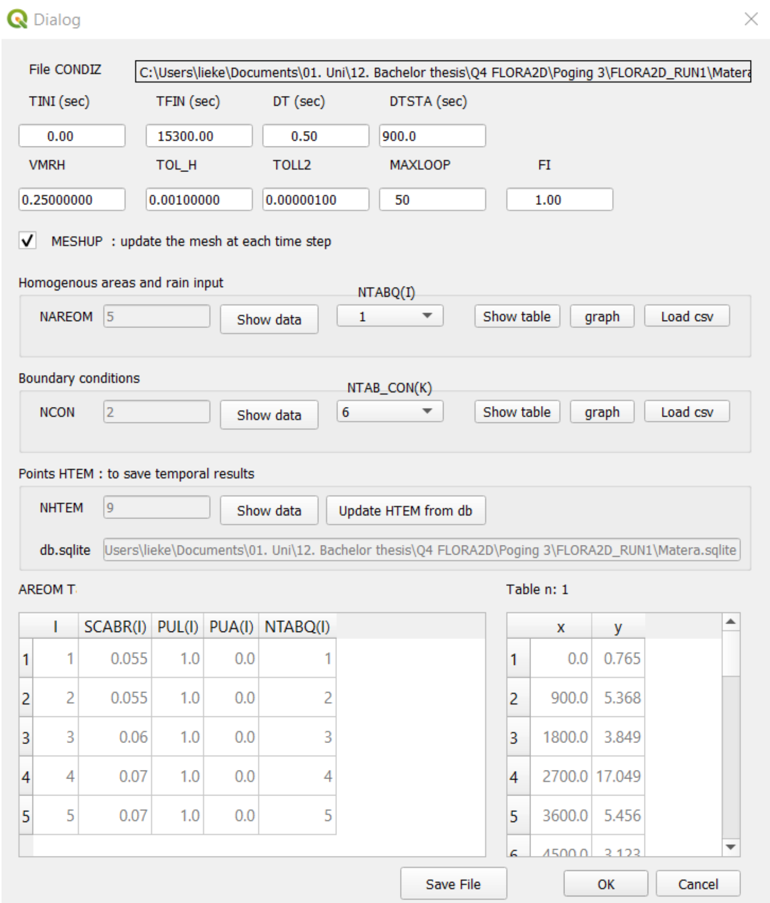


Figure 28 - QGIS window for adjustment of the CONDIZ file

Appendix B – Flood mitigation measure performances

In this appendix, for each measure its possible implementation in the study area and in the model is described, as well as the measure's performance on all criteria. Also, some additional information about each measure is given. In each case, the performance score is substantiated by literature and assumptions.

B.1. Green roofs

Technical information and information about the implementation of green roofs is described in Table 6.

Table 6 - Green roof implementation and performance on criteria

1. Green roofs
Implementation of measure
Implementing green roofs is not possible on all buildings, since some constructions might not be able to support the additional load. Based on this, combined with the fact that some property owners might not want a green roof installed on their building, the assumption is made that on 35% of the buildings in the study area a green roof will be implemented. This is an area of 156,357 m^2. Simulating implementation of green roofs in QGIS can be done by simulating an increase in infiltration capacity on the roofs. This can be done by creating a surface type in the shapefile that links the rainfall data to the cells (the homogeneous areas shapefile) for every surface that can be classified as a green roof. Besides that, the rainfall data for this surface type is multiplied with a factor similar to the value for runoff reduction that is found in literature.
Flood prevention
For flood mitigation, a green roof is most effective for rainfall events under 20 mm/h (Lee et al., 2013). As flood mitigation measure it is more effective when implemented on a large scale, it should cover at least 10% of the study area to have an impact on floods (Huang et al., 2020). Since most data about the flood reduction effectivity of green roofs is given for the roof area (not the study area as a whole), the effectivity found in literature must be multiplied with the percentage of the study area that is covered by green roofs. With the assumption that green roofs will be implemented at 35% of the total roof area, this means that 12% of the study area is covered by green roofs.
Runoff → **average reduction of 9% of total runoff, 17% reduction of building runoff** *Literature:* 27-81% reduction of roof runoff (Akter et al., 2020), = 3-10% reduction of total runoff 25-52% reduction of roof runoff (Lee et al., 2013), = 3-6% reduction of total runoff 30-50% reduction of roof runoff (Eckart et al., 2017), = 4-6% reduction of total runoff 92% reduction of roof runoff (Castro et al., 2020), = 11% reduction of total runoff 70% reduction of roof runoff (Hill, 2017), = 8% reduction of total runoff 50% reduction of roof runoff (Berghage et al., 2009), = 6% reduction of total runoff 9-37% reduction of total runoff (Costa et al., 2021)
Peak flow reduction → **average reduction of 3% of total peak flow, 9% reduction of building peak flow** *Literature:* 26% reduction of roof peak flow (Lu et al., 2019), = 3% reduction of total peak flow
Maintenance
Score is on a 1-10 scale (with 1 being the best score and 10 the worst) Maintenance infrastructure → **score of 1 (no added maintenance)** Maintenance residences & facilities → **score of 5 (medium. = 3, low effort = 2)** Maintenance Sassi → **score of 1 (no added maintenance)**

Literature: 3-6 times a year – removing weeds, applying fertilizer (Leyland, 2021; Setherton, 2021) Conditionally – watering (if dry for 4 weeks) (Setherton, 2021) Conditionally – plant replacement, soil tests (Minnesota Pollution Control Agency, 2020)
Life span → **average estimated life span of 43 years** *Literature:* 40 year life span (National Park Service U.S. Department of the Interior, n.d.) 30-50 year life span (Hanway, 2015) 50 year life span (Magnan, 2021)
Enhancement of living area
Added green and/or blue area → **the added green area is 156,357 m^2** *Assumptions:* The assumption is made that 100% of the area that is covered by green roofs is green area. This assumption is based on photos of green roofs.
Added recreational area → **the added recreational area is 7,818 m^2** *Assumptions:* The assumption is made that 5% of the area that is covered by green roofs is suitable as recreational area. This assumption is based on photos of green roofs.
Score is on a 1-10 scale (with 1 being the worst score and 10 the best, score = points/10*9 + 1) Reduces pollution of water → **score of 4.5 (reduction of P = 0.7, N = 1.9, SS = 0, HM = 1.3)** *Literature:* Reduces phosphorus, nitrogen, and heavy metal concentrations (Hashemi et al., 2015) Increases phosphorus concentration, but reduces nitrogen concentrations (Berndtsson et al., 2006)
Construction of measure
Score is on a 1-10 scale (with 1 being the best score and 10 the worst) Impact during construction → **score of 4 (people affected = few (2), nuisance = little (2))** *Assumptions:* Since a green roof is constructed on roofs, it is assumed that construction only affects the people that are in the building (except maybe for noise pollution for the surrounding area, but that is unknown). For the people in the building, no hinder is expected apart from noise pollution and presence of constructors.
Duration construction → **60 months** *Assumptions/literature:* Construction of a residential roof takes 2-3 days, for a larger (commercial/industrial) installation it takes about 1 week (Everplant, n.d.) In the QGIS shapefile, there are 757 buildings (most are large buildings). Based on the assumption that on 35% of the buildings a green roof will be installed, it is assumed that a green roof will be installed on 265 large buildings. Since the construction of a large green roof takes about 1 week, the construction of all large buildings will take about 5 years.
Costs of construction materials → **$32,271,400 (USD)** *Assumptions/literature:* Installation of a green roof costs approximately $200 (USD) per m^2 (FIXR, 2020; Hanway, 2015) Based on the assumption that on 35% of the roof area a green roof will be installed, the total construction costs will be $31,271,400.
Sustainability
Score is on a 1-10 scale (with 1 being the worst score and 10 the best) Circular materials → **score of 5.5 (half circular, half not known/not circular)** *Assumptions/literature:* Some literature states that green roofs support a transition of a city towards circularity (Calheiros & Stefanakis, 2021). However, no literature could be found that mentioned exactly why this is the case.

The assumption is made that green roofs are partially made of circular materials, based on the fact that their construction materials are vegetation (circular), growing medium (circular), filter layer (unknown if circular), drainage layer (unknown if circular), roof deck layer (unknown if circular).
Requires little energy → score of 1 *Assumption:* No literature could be found about how much energy is required by the measures to function properly. Therefore, they are all set to score equally (score of 1).
Score is on a 1-10 scale (with 1 being the worst score and 10 the best) Enhances ecosystem → score of 5.5 (moderately) *Assumptions:* It is assumed that green roofs enhance the ecosystem moderately. This assumption is based on the fact that they add green area, but it is not very diverse green area.
Additional information
Advantages of green roofs, besides their function as flood mitigation measure, are their effect on urban heat reduction, and the creation of eco-friendly spaces in an urban environment (Huang et al., 2020). Besides that, they do not require space on the ground level, which is often used intensively in urban areas. It is questionable, however, if full implementation of green roofs is possible, since it can be expected that not all buildings can bear the additional load that green roofs bring, and some buildings are private property, owned by people that do not want a green roof (Costa et al., 2021). A schematic representation of a green roof can be seen in Figure 29 (Akter et al., 2020).

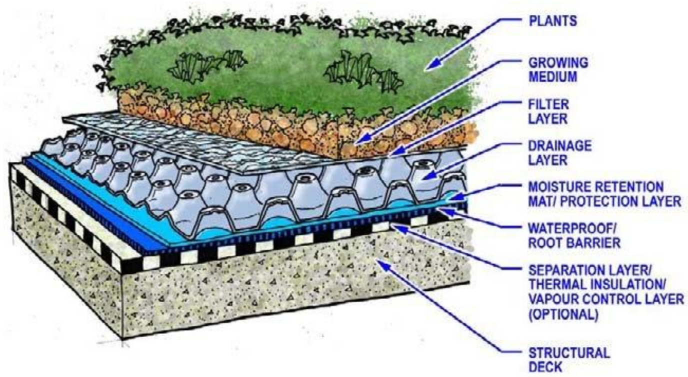


Figure 29 - Schematic representation of the layers of a green roof (Townshend, 2007)

B.2. Permeable pavement

Technical information and information about the implementation of permeable pavement is described in Table 7.

Table 7 - Permeable pavement implementation and performance on criteria

2. Permeable pavement
Implementation of measure
Implementing permeable pavements is not possible for all paved areas, since permeable pavement is not suitable for roads that are used by heavy traffic. Therefore, the assumption is made that permeable pavement will be used for all non-main roads and parking lots. This is about 55% of the total road area, which is 250,246 m^2. Simulating implementation of permeable pavement in QGIS can be done by simulating an increase in infiltration capacity on the paved areas. This can be done by creating a surface type in the shapefile that links the rainfall data to the cells (the homogeneous areas shapefile) for every surface

that can be classified as permeable pavement. Besides that, the rainfall data for this surface type is multiplied with a factor similar to the value for runoff reduction that is found in literature.
Flood prevention
The flood reduction effectivity of permeable pavement depends on many factors, such as the type of pavement, the materials that are used, the service life, the environment and maintenance of the pavement (Zhu et al., 2019). The data that are presented in this table assume optimal conditions of the pavement, and are (where possible) filtered for rainfall conditions similar to the available rainfall data for Matera. As flood mitigation measure, the effect of permeable pavement is proportional to the surface area at which it is implemented, which means that it gets more effective when it covers a larger surface area (Costa et al., 2021). It should cover at least 10% of the study area to be found effective (Huang et al., 2020). The data of the effectivity of flood reduction of permeable pavement sometimes concerns the effectivity of the whole area, and sometimes concerns the effectivity of only the area covered with permeable pavement. Therefore, effectivity values of the latter must be multiplied with the percentage of the study area that is covered by permeable pavement, which is about 16%.
Runoff → **average reduction of 23% of total runoff, 40% reduction of infrastructure runoff** *Literature:* 45-100% reduction of street runoff (Zhu et al., 2019), = 7-16% reduction of total runoff 36-40% reduction of total runoff (Hu et al., 2018) 5-10% reduction of total runoff (Costa et al., 2021) 36% reduction of total runoff (Huang et al., 2014)
Peak flow → **average reduction of 27% of total peak flow, 49% reduction of infrastructure peak flow** *Literature:* 79-100% reduction of street runoff peak flow (Zhu et al., 2019), = 14% reduction of total peak flow 32-42% reduction of total peak flow (Hu et al., 2018) 29% reduction of total peak flow (Huang et al., 2014)
Maintenance
Score is on a 1-10 scale (with 1 being the best score and 10 the worst) Maintenance infrastructure → **score of 6 (medium freq. = 3, medium effort = 3)** Maintenance residences & facilities → **score of 1 (no added maintenance)** Maintenance Sassi → **score of 1 (no added maintenance)** *Literature:* 1 time a year – inspect for surface distresses and performance criteria (Hein, 2016) Conditionally – vacuum, repair, replace (low effort) (Hein, 2016)
Life span → **average estimated life span of 25 years** *Literature:* 20 year life span (Weiss et al., 2015) 30 year life span (Canadian Nursery Landscape Association, n.d.)
Enhancement of living area
Added green and/or blue area → **the added green area is 18,439 m²** *Assumptions:* The assumption is made that 50% of the area of parking spaces that is made of permeable pavement is green area. This assumption is based on photos of permeable pavement (PICP, see 'additional information').
Added recreational area → **the added recreational area is 0 m²** *Assumptions:* The assumption is made that 0% of the area that is made of permeable pavement is recreational area. This assumption is based on the fact that no infrastructure area is added.
Score is on a 1-10 scale (with 1 being the worst score and 10 the best, score = points/10*9 + 1) Reduces pollution of water → **score of 4.4 (reduction of P = 1.9, N = 1.9, SS = 0, HM = 0)**

Literature: Reduces nitrogen and phosphorus concentration significantly compared to asphalt runoff (Bean et al., 2007) Pollutant removal varies widely (Collins et al., 2007)
Construction of measure
Score is on a 1-10 scale (with 1 being the best score and 10 the worst) Impact during construction → **score of 9 (people affected = many (4), nuisance = high (4))** *Assumptions:* To install permeable pavement, the infrastructure must be renewed. Therefore, it is assumed that the infrastructure is inaccessible (in parts) for the entire duration of construction. Also noise pollution can be expected for a large area.
Duration construction → **24 months** *Assumptions/literature:* Construction of permeable pavement goes at 140-600 m^2 per man/machine per day, depending on whether construction is done manually or mechanically (Mutual Materials Company, n.d.). It is unclear if this construction time takes the preparation of the subsoil into account. The assumption is made that the average speed of permeable pavement construction is 370 m^2 per man per day, which is based on the assumption that both man and machine will contribute to construction. The assumption is made that preparation of the subsoil is not taken into account in literature. Therefore, it is assumed that the total construction speed per day (combining the work of all workers and including preparation time) is 370 m^2 per day. Since the pavement of 55% of the streets will be replaced by permeable pavement, the total construction time is about 2 years.
Costs of construction materials → **$13,513,284 (USD)** *Assumptions/literature:* Material costs of permeable pavements are about $54 USD (Li et al., 2019) Based on the assumption that 55% of the paved area will be covered by permeable pavement, the total construction costs will be $13,513,284.
Sustainability
Score is on a 1-10 scale (with 1 being the worst score and 10 the best) Circular materials → **score of 3 (could be completely circular, but is not)** *Assumptions/literature:* Literature states that it is possible to use circular materials for permeable pavement (Rahman et al., 2015), however it is not common practice to use circular materials.
Requires little energy → **score of 1** *Assumption:* No literature could be found about how much energy is required by the measures to function properly. Therefore, they are all set to score equally (score of 1).
Score is on a 1-10 scale (with 1 being the worst score and 10 the best) Enhances ecosystem → **score of 2 (very slightly)** *Assumptions:* It is assumed that permeable pavements enhance the ecosystem only very slightly. This assumption is based on the fact that they only add very little green area that is not diverse.
Additional information
Types of permeable pavement are categorised as permeable asphalts, permeable concretes, and permeable interlocking concrete pavers by (Hu et al., 2018) (see Figure 30 for an example of each). (Zhu et al., 2019) made a distinction in drainage surface, semi-permeable pavement and permeable road (see Figure 31 for a schematic representation of each). All these types have different characteristics and effectivity in flood reduction. While permeable asphalt is a form of a drainage surface, permeable concrete and permeable interlocking pavers are a form of semi-permeable pavement.

One of the advantages of permeable pavements, besides their function as flood mitigating measure, is that they increase water availability. A disadvantage, however, is that permeable pavements are prone to clogging, which reduces their effectiveness in reducing runoff and peak flow significantly (decrease of about 60% in effectiveness) (Hu et al., 2018; Akter et al., 2020). The type of pavement that is chosen also plays a role in this, because not all types are equally likely to clog (Hu et al., 2018).

Figure 30 - Example of (f.l.t.r.) permeable asphalt (Mrugacz, 2017), permeable concrete (New Dawn, 2015), and permeable interlocking pavers (Sustainable Technologies, 2021)

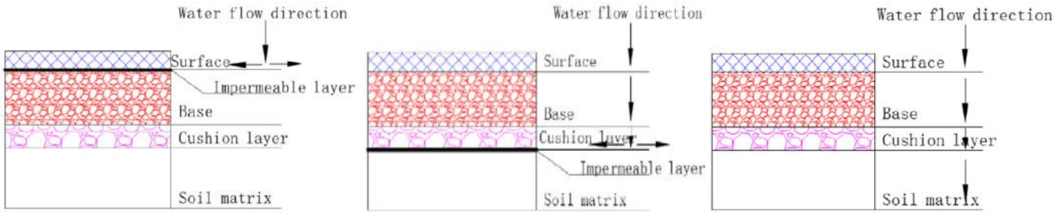


Figure 31 - Schematic representation of (f.l.t.r.) a drainage surface, semi-permeable pavement, and permeable road (Zhu et al., 2019)

B.3. Bio-retention systems

Technical information and information about the implementation of bio-retention systems is described in Table 8.

Table 8 - Bio-retention systems implementation and performance on criteria

3. Bio-retention systems
Implementation of measure
It is most easy to construct a bio-retention system at locations with a soft soil medium, in open areas (Shafique, 2016). Also, the system should be placed at a location with a low elevation, since it receives water from its surroundings. Simulating implementation of a bio-retention system in QGIS can be done by simulating an increase of infiltration in the area, in combination with an increase in water storage area. The first can be done by creating a surface type in the shapefile that links the rainfall data to the cells (the homogeneous areas shapefile) for every surface that can be classified as bio-retention system. The rainfall data for this surface type should be set to 0, since the idea of bio-retention systems is that they let not only the rainfall infiltrate that comes down in the system, but also let rainfall infiltrate from surrounding areas. For the second part, the elevation should be lowered in the area in which the system is constructed by 0.5 meter. In literature it is described that the system has an elevation that is 0.1 meter lowers than surrounding areas (Costa et al., 2021), and 0.4 meter is added to this to make up for the fact that infiltration is not simulated. The alteration can be done in the DEM.
Flood prevention
To be effective as a flood mitigation measure, a bio-retention system needs to take up a surface area that is equal to at least 2-5% of the roof area in the study area (Lu et al., 2019). The flood reduction performance of a bio-retention system is better for lower intensity rainfall events (Shafique, 2016).
Runoff → **average reduction of 47% of total runoff** *Literature:*

28% reduction of total runoff (Yang et al., 2013) 48-74% reduction of total runoff (Chapman & Horner, 2010) 97% reduction of total runoff (Debusk & Thompson, 2011) 9-18% reduction of total runoff (Costa et al., 2021)
Peak flow → **average reduction of 83% of total peak flow** *Literature:* 67% reduction of total peak flow (Yang et al., 2013) 99% reduction of total peak flow (Debusk & Thompson, 2011)
Maintenance
Score is on a 1-10 scale (with 1 being the best score and 10 the worst) Maintenance infrastructure → **score of 1 (no added maintenance)** Maintenance residences & facilities → **score of 5.5 (medium freq. = 3, low-medium effort = 2.5)** Maintenance Sassi → **score of 1 (no added maintenance)** *Literature:* 1-2 times a year – visual inspection: look for standing water, accumulated leaves, hole in soil media, signs of plant distress, debris and sediment accumulation in system (University of New Hampshire Stormwater Center, 2011; U.S. Environmental Protection Agency, 2009; Minnesota Pollution Control Agency, 2016) Conditionally – removal of leaves from system and bypass structure, vegetation care, repairs of above (low effort) (University of New Hampshire Stormwater Center, 2011; U.S. Environmental Protection Agency, 2009; Minnesota Pollution Control Agency, 2016)
Life span → **average estimated life span of 25 years** *Literature:* 25+ year life span (Spraakman et al., 2020)
Enhancement of living area
Added green and/or blue area → **the added green area is 15,636 m^2** *Assumptions:* Since a bio-retention system must take up at least 2-5% of the total roof area, the assumption is made that the total bio-retention system area will take up 3.5% of the roof area. The assumption is made that 100% of the bio-retention area is green area. This assumption is based on the construction materials and schematic drawings of bio-retention systems.
Added recreational area → **the added recreational area is 4,691 m^2** *Assumptions:* The assumption is made that 30% of the area that is covered by bio-retention systems is suitable as recreational area. This assumption is based on photos of bio-retention systems, but it must be noted that this value can vary highly, depending on the bio-retention system.
Score is on a 1-10 scale (with 1 being the worst score and 10 the best, score = points/10*9 + 1) Reduces pollution of water → **score of 7.3 (reduction of P = 2.5, N = 1.9, SS = 1.3, HM = 1.3)** *Literature:* Reduces 70-85% of phosphorus concentration and 55-65% of nitrogen concentration (Davis et al., 2009; Davis et al., 2006) Reduces 40% of nitrogen (Hunt et al., 2006) Reduces 85-94% of phosphorus, 63-77% of nitrogen and 28-66% of carbon (Henderson et al., 2007) Reduces suspended solids (Hunt et al., 2006; Kumar et al., 2013)
Construction of measure
Score is on a 1-10 scale (with 1 being the best score and 10 the worst) Impact during construction → **score of 6 (people affected = medium (3), nuisance = med. (3))** *Assumptions:* A bio-retention system is a relatively small construction project. However, it is constructed in a shared space outside, so many people will be affected by noise pollution and a (small) inaccessible area.
Duration construction → **12 months** *Assumptions/literature:*

No literature about the construction time of bio-retention systems could be found. The assumption is made that the construction of all bio-retention systems in the area takes about 1 year. This assumption is based on the fact that they cover a relatively small area and are not very construction intensive.
Costs of construction materials → **$4,143,540 (USD)** *Assumptions/literature:* Material costs of a bio-retention system are about $100-$430 USD (Low Impact Development Center, 2021), on average this is $265 USD. Based on the assumption that bio-retention systems will cover 3.5% of the roof area, the total construction costs will be $4,143,540.
Sustainability
Score is on a 1-10 scale (with 1 being the worst score and 10 the best) Circular materials → **score of 8 (largely circular, little not known/not circular)** *Assumptions/literature:* No literature about the use of circular materials for the construction of bio-retention systems could be found. The assumption is made that bio-retention systems are largely made of circular materials, based on the fact that their construction materials are vegetation (circular), filter media (circular), a transition layer (circular), drainage layer (circular), and a drainage pipe (unknown if circular).
Requires little energy → **score of 1** *Assumption:* No literature could be found about how much energy is required by the measures to function properly. Therefore, they are all set to score equally (score of 1).
Score is on a 1-10 scale (with 1 being the worst score and 10 the best) Enhances ecosystem → **score of 7 (moderately-highly)** *Assumptions:* It is assumed that a bio-retention system enhances the ecosystem moderately-highly. This assumption is based on the fact that they add green area that is moderately diverse.
Additional information
Advantages of a bio-retention system, besides its function as flood mitigation measure, include its contribution to improved aesthetic value, increased biodiversity in the area, reduction in urban heat, and the fact that it requires less area than green roofs (Costa et al., 2021). Still, the area that is required for bio-retention systems is scarce, since it needs to be on the ground level, which is highly demanded in urban areas (Lu et al., 2019). Another disadvantage is that landowners often do not have the experience required for maintenance of the system (Shafique, 2016; Akter et al., 2020), and the system is prone to clogging if the soil it is built on consists of clay-sized particles (Shafique, 2016). Lastly, research shows that the public thought that the system results in an increase of mosquitos in the area, which could cause diseases (Shafique, 2016). For a schematic representation of a bio-retention system, see Figure 32 (Shafique, 2016).

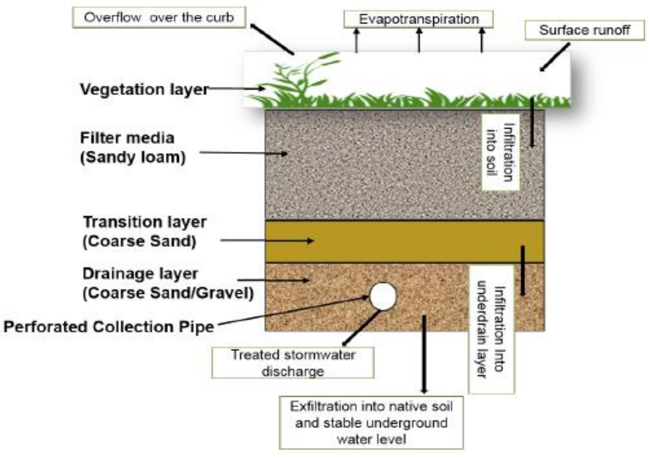


Figure 32 - Schematic overview of layers of a bio-retention system (Shafique, 2016)

B.4. Retention ponds

Technical information and information about the implementation of retention ponds is described in Table 9.

Table 9 - Retention ponds implementation and performance on criteria

4. Retention ponds
Implementation of measure
Preferably, a retention pond is constructed on a location with soft soils (e.g. mud) (Li et al., 2019). Also, it has to be possible to excavate the location to at least 0.15 meters, but preferably a bit more to 0.45-0.6 meters. An eye should be kept on the groundwater table as well (Lu et al., 2019; Li et al., 2019). Lastly, the elevation at the location of the pond should be lower than that of the surroundings. Simulating implementation of a retention pond in QGIS can be done by simulating an increase of the water storage capacity at the location of the retention pond. This can be done by lowering the elevation in the DEM at the location of the pond.
Flood prevention
A retention pond must take up a surface area of at least 2% of the study area to be effective as a flood mitigation measure (Li et al., 2019).
Runoff → **average reduction of 10% of total runoff** *Literature:* 0% reduction of total runoff (Hancock et al., 2010) 20% reduction of total runoff (Budianto et al., 2020)
Peak flow → **average reduction of 0% of total peak flow** *Literature:* 0.3% reduction of total peak flow (Emerson et al., 2005) 0% reduction of total peak flow (McCuen, 1979) 0% reduction of total peak flow ('not effective') (Fennessey et al., 2001)
Maintenance
Score is on a 1-10 scale (with 1 being the best score and 10 the worst) Maintenance infrastructure → **score of 1 (no added maintenance)** Maintenance residences & facilities → **score of 5.5 (low freq. = 2, medium-high effort = 3.5)** Maintenance Sassi → **score of 1 (no added maintenance)** *Literature:* 1 time a year – cleaning and removing debris, harvesting of vegetation, repairing embankment and side slopes, repairing control structure (U.S. Environmental Protection Agency, 2009; Hatcher, 2020) Once per 5 years – removing sediment from forebays or sediment storage areas (U.S. Environmental Protection Agency, 2009; Hatcher, 2020) Conditionally – repairs after inspection, minor maintenance and major repair (incl. permanent pool, clogging, pipe repairs, vegetation management, dredging and muck removal, mechanical components and nuisance issues (animals, waterfowl, mosquitoes, undesirable plant communities, water quality degradation)) (U.S. Environmental Protection Agency, 2009) Conditionally – prevent erosion (reseeding), clear blocked inlets and outlets (remove debris), vegetation management, stop critter damage (Schill, 2015)
Life span → **average estimated life span of 20 years** *Literature:* 20+ year life span (Waelti & Spuhler, 2020)
Enhancement of living area
Added green and/or blue area → **the added green and blue area is 27,183 m^2** *Assumptions:*

Since a retention pond must take up at least 2% of the study area, the assumption is made that the total retention pond area will take up 2% of the study area. The assumption is made that 100% of the retention pond area is green or blue area. This assumption is based on photos of retention ponds.
Added recreational area → **the added recreational area is 2,718 m^2** *Assumptions:* The assumption is made that 10% of the area that is covered by retention ponds is suitable as recreational area. This assumption is based on the assumption that water in retention ponds is not suitable as recreational area for the largest part of the year, and on photos of retention ponds. It must be noted that the value of 10% can vary highly, depending on the retention pond.
Score is on a 1-10 scale (with 1 being the worst score and 10 the best, score = points/10*9 + 1) Reduces pollution of water → **score of 4.0 (reduction of P = 0.7, N = 0.7, SS = 1.9, HM = 0)** *Literature:* Reduces >30% of phosphorus, nitrogen and suspended solid concentrations (Baird et al., 2020) Reduces suspended solids effectively, but no effect on dissolved pollutants (Pettersson, 1998)
Construction of measure
Score is on a 1-10 scale (with 1 being the best score and 10 the worst) Impact during construction → **score of 6.5 (people affected = medium (3), nuisance = medium-high (3.5))** *Assumptions:* A retention pond is a construction project in a shared space outside. Many people will be affected by noise pollution and an inaccessible area of medium magnitude.
Duration construction → **3 months** *Assumptions/literature:* No literature about the exact construction time of retention ponds could be found. However, literature does show that construction of a retention pond is 'easy' (Hancock et al., 2010). The assumption is made that the construction of retention ponds in the study area takes 3 months.
Costs of construction materials → **$363,573 (USD)** *Assumptions/literature:* Material costs of a retention pond can be found in literature at $17.50-35.00 USD per m^3 (Naturally Resilient Communities, n.d.), on average this is $26.75 USD. Based on the assumption that a retention pond covers 2% of the total study area, and that it is 0.5 meters deep, the total construction costs will be $363,573.
Sustainability
Score is on a 1-10 scale (with 1 being the worst score and 10 the best) Circular materials → **score of 8 (largely circular, little not known/not circular)** *Assumptions/literature:* No literature about the use of circular materials for the construction of retention ponds could be found. The assumption is made that retention ponds are largely made of circular materials, based on the fact that their construction materials are mostly vegetation (circular), and possibly a drainage system including pumps (unknown if circular, assumed not circular).
Requires little energy → **score of 1** *Assumption:* No literature could be found about how much energy is required by the measures to function properly. Therefore, they are all set to score equally (score of 1).
Score is on a 1-10 scale (with 1 being the worst score and 10 the best) Enhances ecosystem → **score of 7 (moderately-highly)** *Assumptions:* It is assumed that retention ponds enhance the ecosystem moderately-highly. This assumption is based on the fact that they add both green and blue area. However, the green area is not very diverse.

Additional information
Advantages of retention ponds include their relatively easy design and construction process (Hancock et al., 2010). However, they take up a lot of space if they are to be effective in flood reduction, which can be difficult in an urbanised area such as Matera (Budianto et al., 2020; Li et al., 2019). Lastly, ponding might let the public believe that there will be an increase in mosquitos, similarly to bio-retention systems (Shafique, 2016). Figure 33 shows an example of a retention pond.  *Figure 33 - Example of a retention pond (Presley, 2019)*

B.5. Rain barrels

Technical information and information about the implementation of rain barrels is described in Table 10.

Table 10 - Rain barrels implementation and performance on criteria

5. Rain barrels
Implementation of measure
Rain barrels can be installed at all buildings. Since they retain roof runoff and not all buildings have a similar roof surface area, their size or the number of rain barrels that is installed varies per building. Simulating implementation of rain barrels can be done by reducing the roof runoff. There is a lag time for the water that is retained in the barrels, but this time can be so large that the fact that the retained water must be released at some point can be neglected. Therefore, only the rainfall data must be changed for all roofs. This can be done by multiplying it with a factor similar to values for retention performance found in literature.
Flood prevention
The effectivity of rain barrels as flood mitigation measure depends on multiple factors, such as the spatial distribution of the rain barrels, the surface area that forms the catchment of the rain barrels, the rainfall amount, and tank size. Depending on the amount of impervious area, rain barrels can be more effective, performing best in an area that is 50-60% impervious (Akter et al., 2020). Especially for rainfall events up to 50mm, rain barrels are effective, but for extreme rainfalls the flood reduction they cause is neglectable (Akter et al., 2020; Freni & Liuzzo, 2019).
Runoff → **average reduction of 41% of total runoff** *Literature:* 26% reduction of total runoff (Palla et al., 2017) 30% reduction of total runoff (Zhang et al., 2012) 35-100% reduction of total runoff (Freni & Liuzzo, 2019)
Peak flow → **average reduction of 32% of total peak flow** *Literature:* 28-33% reduction of total peak flow (Akter et al., 2020) 33% reduction of total peak flow (Palla et al., 2017)
Maintenance

Score is on a 1-10 scale (with 1 being the best score and 10 the worst) Maintenance infrastructure → score of 1 (no added maintenance) Maintenance residences & facilities → score of 3.5 (low-medium freq. = 2.5, very low effort = 1) Maintenance Sassi → score of 1 (no added maintenance) *Literature:* 2-3 times a year – seasonal preparation, leaf and debris removal, water drainage, monitoring (Chesapeake Bay Foundation, 2020; Montgomery County, Department of Environmental Protection, 2013)
Life span → average estimated life span of 20 years *Literature:* 20 year life span (Environmental Services, City of Portland, 2006)
Enhancement of living area
Added green and/or blue area → the added green and blue area is 0 m^2 *Assumptions:* The assumption is made that rain barrels add no green or blue surface area. This assumption is based on photos of rain barrels.
Added recreational area → the added recreational area is 0 m^2 *Assumptions:* The assumption is made that rain barrels add no recreational area. This assumption is based on photos of rain barrels.
Score is on a 1-10 scale (with 1 being the worst score and 10 the best, score = points/10*9 + 1) Reduces pollution of water → score of 1 (reduction of P = 0, N = 0, SS = 0, HM = 0) *Literature:* Has no water pollution reducing effect (Shuster et al., 2013)
Construction of measure
Score is on a 1-10 scale (with 1 being the best score and 10 the worst) Impact during construction → score of 2 (people affected = very few (1), nuisance = very little (1)) *Assumptions:* Rain barrels are installed, they do not have to be constructed, so no noise pollution is expected. Besides that, the installing process only affects people living in the building they are installed at.
Duration construction → 30 months *Assumptions/literature:* The construction time of rain barrels depends on many factors, but most of all on their size. For regular (small) residential rain barrels, construction time is about 30 mins per rain barrel (Andrychowicz, 2021). For larger (commercial/industrial) rain barrels, construction time is about 2 days per rain barrel (Kaiser, 2021). In the QGIS shapefile, there are 757 buildings (most are large buildings). Based on the assumption that on each large building 3 large detention tanks are installed, this means that 2271 large rain barrels have to be installed. Some buildings will need residential (small) rain barrels instead of large rain barrels, but since they do not take as long to install, it is assumed that their installation time is included in the calculation when only large rain barrels are taken into account. The assumption is made that 5 barrels can be constructed at the same time. This means that the construction time for all the rain barrels together will be around 2.5 years.
Costs of construction materials → $570,021 (USD) *Assumptions/literature:* Material costs of rain barrels that are found in literature range between $35-$600 USD (Kaiser, 2021), and $70-$300 USD (Costhelper, 2021). On average, this is $251 per (large) rain barrel. Based on the assumption that 2271 rain barrels will be installed, the total construction costs will be $570,021.
Sustainability
Score is on a 1-10 scale (with 1 being the worst score and 10 the best) Circular materials → score of 8 (largely circular, little not known/not circular) *Assumptions/literature:*

The construction material of rain barrels is a plastic, polyethylene (Kaeding, 2020). The assumption is made that rain barrels are largely made of circular materials. This is based on the fact that polyethylene is circular, but of the system that is used to drain the water from the roof to the barrel it is not known if it is circular.
Requires little energy → **score of 1** *Assumption:* No literature could be found about how much energy is required by the measures to function properly. Therefore, they are all set to score equally (score of 1).
Score is on a 1-10 scale (with 1 being the worst score and 10 the best) Enhances ecosystem → **score of 1 (no enhancement)** *Assumptions:* It is assumed that rain barrels do not enhance the ecosystem. This assumption is based on the fact that they do not add any green or blue area.
Additional information
Rain barrels have one big advantage, besides their function as flood mitigation measure, which is that they are easy to install (Akter et al., 2020). Besides that, the water that is collected can also be used by households that live in the houses on which the barrels are placed, which is especially useful in periods of drought (Freni & Liuzzo, 2019). However, it might be the case that not all rooftops are suitable for collecting rainfall (Akter et al., 2020), and tanks that are larger than 5 m^3 (which are preferred for (industrial) buildings with a larger surface) fall in a different category in terms of construction effort and costs (Freni & Liuzzo, 2019). For a schematic representation of the set-up of rain barrels, see Figure 34.

Figure 34 - Schematic set-up of a rain barrel rainwater harvesting system (Richmond Vale, 2017)

B.6. Urban wetlands

Technical information and information about the implementation of urban wetlands is described in Table 11.

Table 11 - Urban wetlands implementation and performance on criteria

6. Urban wetlands
Implementation of measure
Ideally, an urban wetland is constructed at an open location with soft soils and a low elevation (Shafique, 2016; Li et al., 2019). Preferably it should also be possible to excavate at least 0.15 meters of the soil, to allow ponding (Lu et al., 2019). Simulating implementation of an urban wetland in QGIS can be done by simulating an increase of infiltration in the area, in combination with an increase in water storage area. The first can be done by creating a surface type in the shapefile that links the rainfall data to the cells (the homogeneous areas shapefile) for every surface that can be classified as urban wetland. The rainfall data for this

surface type should be altered to be similar to rainfall for green areas. For the second part, the elevation should be lowered in the area in which ponding is desired. This can be done in the DEM. Ponding does not occur in the whole area, the assumption is made that it occurs in about 50% of the area that is classified as urban wetland. Therefore, a lower elevation should be assigned to 50% of the area.
Flood prevention
To be effective as a flood mitigation measure, urban wetlands need to take up a surface area that is equal to at least 2-5% of the roof area in the study area (Lu et al., 2019).
Runoff → **average reduction of 48% of total runoff** *Literature:* 12-83% reduction of total runoff (Rizzo et al., 2018)
Peak flow → **average reduction of 80% of total peak flow** *Literature:* 86% reduction of total peak flow (Oral et al., 2020) 53-95% reduction of total peak flow (Rizzo et al., 2018)
Maintenance
Score is on a 1-10 scale (with 1 being the best score and 10 the worst) Maintenance infrastructure → **score of 1 (no added maintenance)** Maintenance residences & facilities → **score of 5.5 (low freq. = 2, medium-high effort = 3.5)** Maintenance Sassi → **score of 1 (no added maintenance)** *Literature:* 1 time a year – cleaning and removing debris, harvesting of vegetation, repairing embankment and side slopes, repairing control structure (U.S. Environmental Protection Agency, 2009; Hobart City Council, 2006) Once per 5 years – removing sediment from forebays or sediment storage areas (U.S. Environmental Protection Agency, 2009; Hobart City Council, 2006) Conditionally – repairs after inspection, minor maintenance and major repair (incl. permanent pool, clogging, pipe repairs, vegetation management, dredging and muck removal, mechanical components and nuisance issues (animals, waterfowl, mosquitoes, undesirable plant communities, water quality degradation)) (U.S. Environmental Protection Agency, 2009; Hobart City Council, 2006)
Life span → **average estimated life span of 20 years** *Literature:* 15-25 year life span (Gray)
Enhancement of living area
Added green and/or blue area → **the added green and blue area is 15,636 m^2** *Assumptions:* Since an urban wetland must take up at least 2-5% of the total roof area, the assumption is made that the total urban wetland area will take up 3.5% of the roof area. The assumption is made that 100% of the urban wetland area is green or blue area. This assumption is based on schematic drawings and photos of urban wetlands.
Added recreational area → **the added recreational area is 4,691 m^2** *Assumptions:* The assumption is made that 30% of the area that is covered by urban wetlands is suitable as recreational area. This assumption is based on photos of urban wetlands, but it must be noted that this value can vary highly, depending on the urban wetland.
Score is on a 1-10 scale (with 1 being the worst score and 10 the best, score = points/10*9 + 1) Reduces pollution of water → **score of 7.8 (reduction of P = 1.9, N = 1.9, SS = 1.9, HM = 1.9)** *Literature:* Reduces nitrogen concentration, as well as 21-38% of phosphorus concentration (Palta et al., 2017) Reduces 46-90% of phosphorus, 16-84% of nitrogen concentration and up to 88% of suspended solids. Also reduces heavy metals (23-97%), pesticides, pharmaceuticals and various other contaminants (Oral et al., 2020)

Construction of measure
Score is on a 1-10 scale (with 1 being the best score and 10 the worst) Impact during construction → **score of 6.5 (people affected = medium (3), nuisance = medium-high (3.5))** *Assumptions:* An urban wetland is a construction project of medium magnitude. It must be constructed in a shared space outside, so many people will be affected by noise pollution and an inaccessible area of a medium magnitude.
Duration construction → **8 months** *Assumptions/literature:* No literature about urban wetlands could be found. However, literature showed that after construction of the urban wetland, it takes 5-10 years before the soil will perform optimally for water quality improvement and water quantity reduction (Ahn & Schmidt, 2019). It is assumed that the construction time of urban wetlands is the average of the construction time of retention ponds and bio-retention systems. This is about 8 months.
Costs of construction materials → **$2,253,557 (USD)** *Assumptions/literature:* Exact material costs of urban wetlands cannot be found in literature. However, literature mentions that urban wetlands are cost-effective (Sharley et al., 2017). It is assumed that the total construction costs are equal to the average of the costs of bio-retention systems and retention ponds. This is $2,253,557.
Sustainability
Score is on a 1-10 scale (with 1 being the worst score and 10 the best) Circular materials → **score of 8 (largely circular, little not known/not circular)** *Assumptions/literature:* No literature about the circularity of materials for construction of urban wetlands could be found. The assumption is made that urban wetlands have construction materials that are similar to those of a bio-retention system and retention pond. Therefore, it is assumed that urban wetlands are largely constructed with circular materials.
Requires little energy → **score of 1** *Assumption:* No literature could be found about how much energy is required by the measures to function properly. Therefore, they are all set to score equally (score of 1).
Score is on a 1-10 scale (with 1 being the worst score and 10 the best) Enhances ecosystem → **score of 8 (highly)** *Assumptions:* It is assumed that urban wetlands enhance the ecosystem highly. This assumption is based on the fact that they add both green and blue area, that are both relatively diverse.
Additional information
Advantages of urban wetlands, besides their function as flood mitigation measure, include enhancement of biodiversity, provision of social benefits for citizens, and mitigation of urban heat (Palta et al., 2017). However, similarly to bio-retention systems and retention ponds, they have standing water, which can lead to an increase of mosquitos (Palta et al., 2017). Also, urban wetlands require a lot of space (> 3 ha (Oral et al., 2020)), which makes it less suitable for urban environments (Lashford et al., 2019). A schematic representation of an urban wetland can be seen in Figure 35.

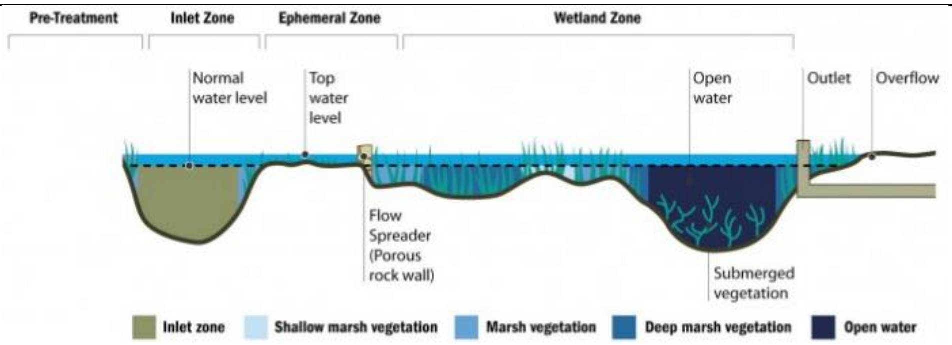


Figure 35 – Schematic representation of a constructed urban wetland (Urban Green-Blue Grids, 2021)

B.7. Detention tanks

Technical information and information about the implementation of detention tanks is described in Table 12.

Table 12 - Detention tanks implementation and performance on criteria

7. Detention tanks
Implementation of measure
Detention tanks can be constructed best at location with no large underground constructions nearby (such as railway stations), and have no large buildings on top (Li et al., 2019). Since detention tanks are underground constructions, it is easiest to install them at locations that have a soft soil medium (e.g. mud) (Li et al., 2019). In the area, it is expected that 21 detention tanks are needed. This is based on the relative impervious area and the absolute complete study area (OPUB: Singapore's National Water Agency, 2021), in combination with the volume of detention tanks (2800 m^3) that is described by (Li et al., 2019). Simulating the implementation of detention tanks can be done by reducing the peak flow. This can be imitated by altering the rainfall data for the whole study area, in a way that the cumulative rainfall remains unchanged, but the precipitation per time step is lowered. This is possible by increasing the time of the rainfall event.
Flood prevention
Detention tanks are more effective for large rainfall events. Because they form an extension of the drainage system, they are very quick in reducing runoff (Li et al., 2019). However, little sources could be found that describe the effectivity of detention tanks as flood mitigation measure.
Runoff → **average reduction of 46% of total runoff** *Literature:* 46% reduction of total runoff (Li et al., 2019)
Peak flow → **average reduction of 50% of total peak flow** *Literature:* 50% reduction (Li et al., 2019)
Maintenance
Score is on a 1-10 scale (with 1 being the best score and 10 the worst) Maintenance infrastructure → **score of 1 (no added maintenance)** Maintenance residences & facilities → **score of 6.0 (low-med. freq. = 2.5, med.-high effort = 3.5)** Maintenance Sassi → **score of 1 (no added maintenance)** *Literature:* 1 time a year – inspection, system cleaning (debris and sediment removal) with a high pressure water jet and a vacuum truck (Prinsco, n.d.; Metro Vancouver, n.d.) Maintenance frequency depends on system design, but is high effort due to underground construction (Prinsco, n.d.; U.S. Department of Transportation, Federal Highway Administration, n.d.)

Life span → **average estimated life span of 48 years** *Literature:* 20-75 year life span (G. Kowalsky, 2021)
Enhancement of living area
Added green and/or blue area → **the added green and blue area is 0 m^2** *Assumptions:* The assumption is made that detention tanks add no green or blue surface area. This assumption is based on the fact that detention tanks are built underground.
Added recreational area → **the added recreational area is 0 m^2** *Assumptions:* The assumption is made that detention tanks add no recreational area. This assumption is based on the fact that detention tanks are built underground.
Score is on a 1-10 scale (with 1 being the worst score and 10 the best, score = points/10*9 + 1) Reduces pollution of water → **score of 4.4 (reduction of P = 0, N = 0, SS = 1.9, HM = 1.9)** *Literature:* Reduces 31-57% of suspended solids, as well as about 50% of heavy metals (Stormwater Assessment Monitoring and Performance Program, 2004)
Construction of measure
Score is on a 1-10 scale (with 1 being the best score and 10 the worst) Impact during construction → **score of 7 (people affected = medium (3), nuisance = high (4))** *Assumptions:* Detention tanks are very construction intensive, since they have to be placed underground. Therefore, it is assumed that potentially local infrastructure has to be closed off, and large machinery is required. Also, noise pollution is expected.
Duration of construction → **35 months** *Assumptions/literature:* Construction of a detention tank takes about 5 months per tank (Brandl et al., 2017). Since it is assumed that 21 detention tanks will be installed, this means that construction of detention tanks will take 105 months. However, it is also assumed that 3 detention tanks can be constructed at the same time, which means that the total construction time will be 35 months (almost 3 years).
Costs of construction materials → **$44,100,000 (USD)** *Assumptions/literature:* Material costs of detention tanks that are found in literature are around $750 USD per m^3 (Li et al., 2019). It is assumed that one detention tank will have a volume of 2800 m^3. For 21 detention tanks, the total volume will be 58800 m^3. This means that the total construction costs of detention tanks will be $44,100,000.
Sustainability
Score is on a 1-10 scale (with 1 being the worst score and 10 the best) Circular materials → **score of 1 (completely not circular)** *Assumptions/literature:* The construction material of detention tanks is either polyethylene, fiberglass, or galvanized steel. The latter is mostly used in cases with a large storage requirement (Kaeding, 2020) The assumption is made that all detention tanks have a large storage volume. Therefore, they are all made of galvanized steel, which is not a circular material. At detention tanks, also pumps are installed to drain the tank. It is unknown if these are circular, but they are assumed to not be circular.
Requires little energy → **score of 1** *Assumption:* No literature could be found about how much energy is required by the measures to function properly. Therefore, they are all set to score equally (score of 1).
Score is on a 1-10 scale (with 1 being the worst score and 10 the best) Enhances ecosystem → **score of 2 (very slightly)**

Assumptions:

It is assumed that detention tanks enhance the ecosystem only very slightly. This assumption is based on the fact that they are located in an underground space which is very inaccessible, but they potentially have standing water.

Additional information

A big advantage of detention tanks is that they can be implemented at one location to reduce flooding at other locations (Li et al., 2019), as well as that they are cheaper than renewal of the conventional drainage system (Li et al., 2019). However, they are quite construction intensive, since they need to be built underground. An example of a relatively small detention tank can be seen in Figure 36.

Figure 36 - Animated underground detention tank (GRAF, 2021)

Appendix C – Value tree hierarchies to criteria

In this appendix, the conversion process from value tree hierarchies to weighted criteria is presented. This consists of the set-up of value tree hierarchies, connection of the stakeholder interests to each object in the value tree hierarchies, connection of the design requirements to the criteria, and calculation of the weights.

C.1. Value tree hierarchies

According to the theory as described in section 2.3., value tree hierarchies have been set up. The interests of the stakeholder groups have been translated in either values, norms or design requirements. For the value tree hierarchies, there are three overarching values, and when they are specified into design requirements all stakeholder interests are represented in these trees. The three values are 'human wellbeing', 'economic prosperity', and 'environmental stewardship'.

In Figure 37 and Figure 38 the value tree hierarchies are shown. There are certain design requirements that contribute to the achievement of multiple norms, such as the increase of green and/or blue area. This contributes to the achievement of a pleasant living area (under human wellbeing), but also to the achieving enhancement of biodiversity (under environmental stewardship). This shows that such design requirements contribute more to compliance with stakeholder interests, and therefore they are valued higher than other design requirements.

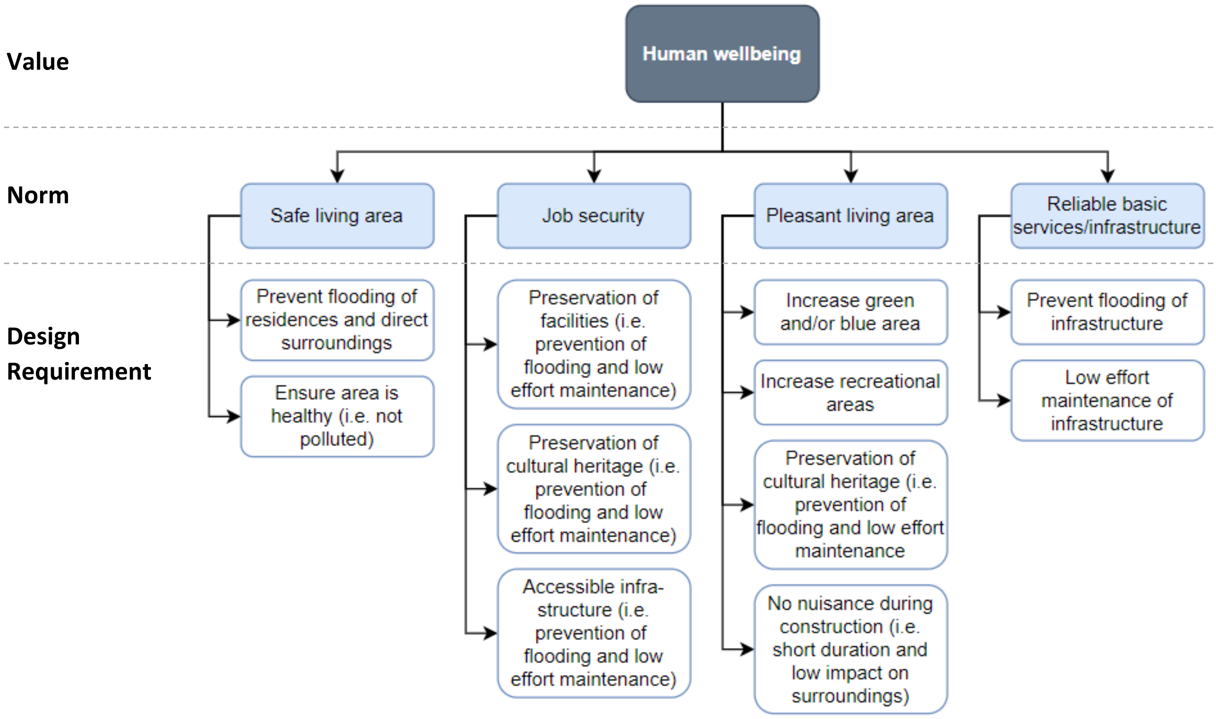


Figure 37 - Value tree hierarchy: Human wellbeing

To see which design requirements contribute to the achievement of which stakeholder interests, a visualisation as shown in Figure 39 was made. The colours of the boxes correspond to the colours of the stakeholder groups (purple = local authorities, orange = local communities, red = businesses, green = civil societies). If a box is filled by a colour, or has an outline of a colour, this means that it contributes to the achievement of an interest of the stakeholder group of that colour. It is possible that one box is outlined or filled by the same colour multiple times, since it may be linked to multiple interests. For each outline or fill of one colour on a design requirement, the value of the corresponding stakeholder group is added to the total score of that design requirement.

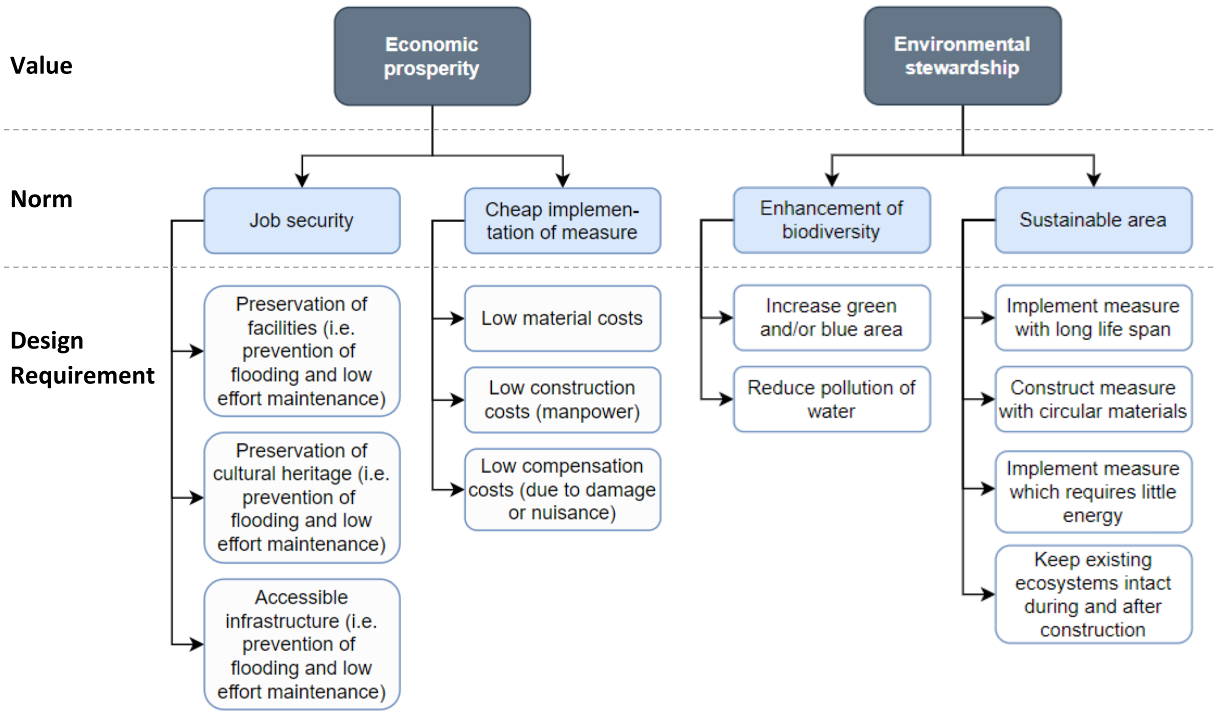


Figure 38 - Value tree hierarchies: Economic prosperity & Environmental stewardship

C.2. Criteria

According to the method that is explained in section 2.3., criteria were set up that were assessed on multiple aspects. The final criteria are presented in Table 2. To assign a weight to the criteria, the design requirements have been linked to the criteria. In Table 13, the design requirements are linked to criteria for which they ensure a good performance if they are incorporated in a design. The numbers for the design requirements in Table 13 correspond to the numbers in Figure 39. The total scores of the design requirements are then added and assigned to the criteria. These scores for the criteria are then used as input for the AHP for the individual criteria, and for the criteria groups. These are presented in Table 14 and Table 15.

Table 13 - Linking of design requirements to criteria of the MCA

DR →	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Cr 1a					X					X				X									
Cr 1b	X		X									X											
Cr 1c				X				X					X										
Cr 2a					X					X				X									
Cr 2b	X		X									X											
Cr 2c				X				X					X										
Cr 3a					X						X			X									
Cr 3b			X									X											
Cr 3c				X				X					X										
Cr 4																				X			
Cr 5						X												X					
Cr 6							X																
Cr 7		X																	X				
Cr 8									X								X						X
Cr 9																X							
Cr 10															X								
Cr 11																					X		
Cr 12																						X	
Cr 13																							X

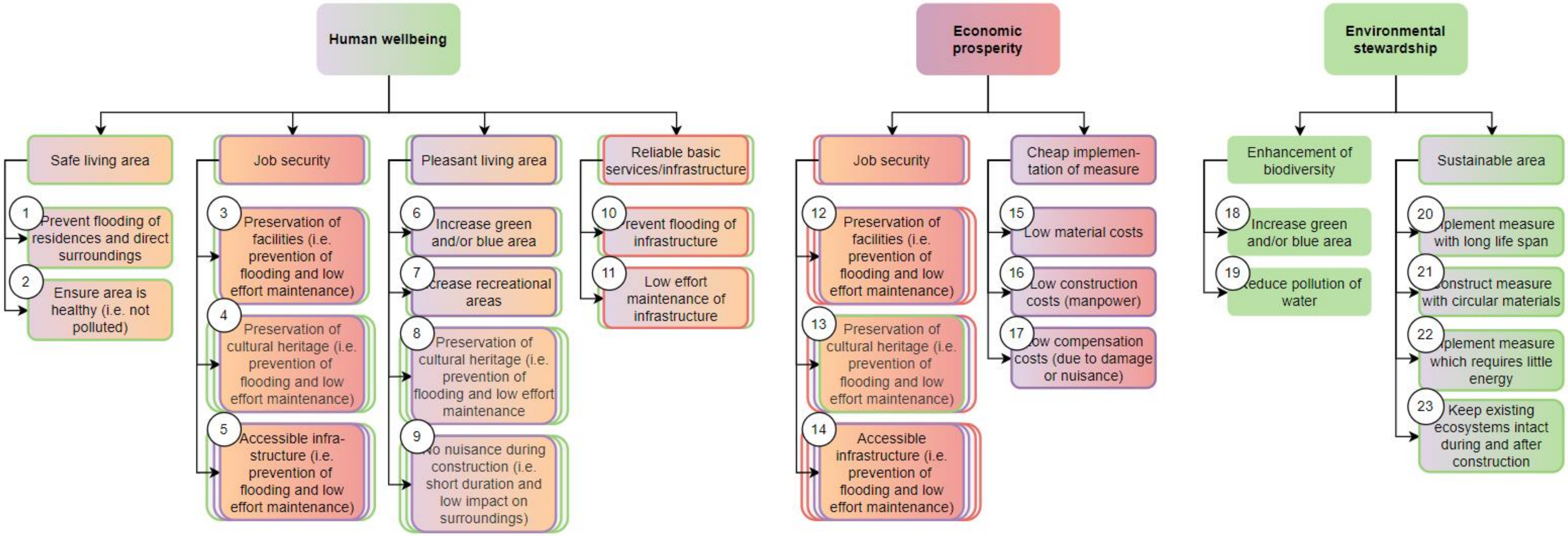


Figure 39 - Value tree hierarchies, visually representing their compliance with stakeholder interests

Table 14 - Weight of individual criteria

A: Prevention of flooding								
	1.a	**1.b**	**1.c**	**2.a**	**2.b**	**2.c**	**Geometric Mean**	**Weight**
1.a		1.3	1.1	1.0	1.3	1.1	1.155	0.19
1.b	0.8		0.8	0.8	1.0	0.8	0.845	0.14
1.c	0.9	1.2		0.9	1.2	1.0	1.042	0.17
2.a	1.0	1.3	1.1		1.3	1.1	1.155	0.19
2.b	0.8	1.0	0.8	0.8		0.8	0.845	0.14
2.c	0.9	1.2	1.0	0.9	1.2		1.042	0.17
Tot							**6.085**	**1.00**
B: Maintenance of area								
	3.a	**3.b**	**3.c**	**4**			**Geometric Mean**	**Weight**
3.a		1.7	1.2	6.0			2.971	0.41
3.b	0.6		0.7	3.5			1.594	0.22
3.c	0.8	1.4		5.0			2.421	0.34
4	0.2	0.3	0.2				0.217	0.03
Tot							**7.204**	**1.00**
C: Enhancement of living area								
	5	**6**	**7**				**Geometric Mean**	**Weight**
5		1.2	1.4				1.259	0.41
6	0.9		1.2				1.024	0.33
7	0.7	0.9					0.790	0.26
Tot							**3.073**	**1.00**
D: Construction of measure								
	8	**9**	**10**				**Geometric Mean**	**Weight**
8		3.1	3.1				3.091	0.70
9	0.3		1.0				0.662	0.15
10	0.3	1.0					0.662	0.15
Tot							**4.414**	**1.00**
E: Sustainability								
	11	**12**	**13**				**Geometric Mean**	**Weight**
11		1.0	1.0				1.000	0.33
12	1.0		1.0				1.000	0.33
13	1.0	1.0					1.000	0.33
Tot							**3.000**	**1.00**

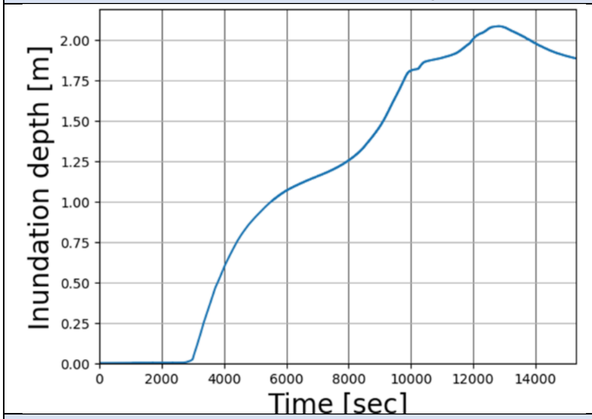
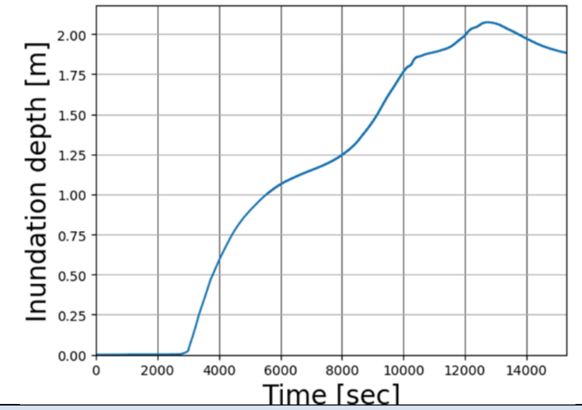
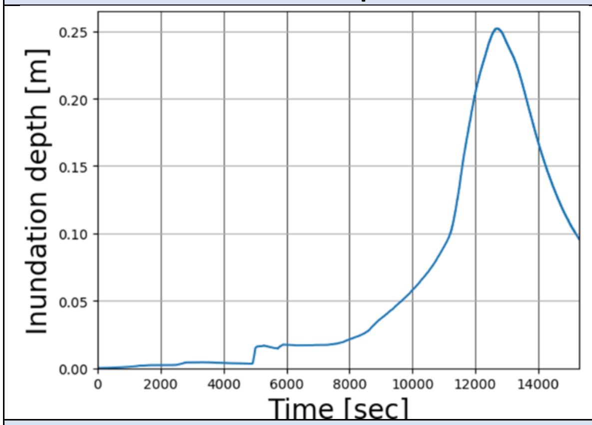
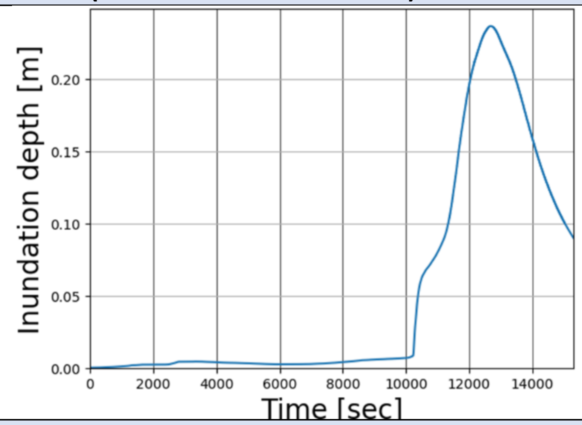
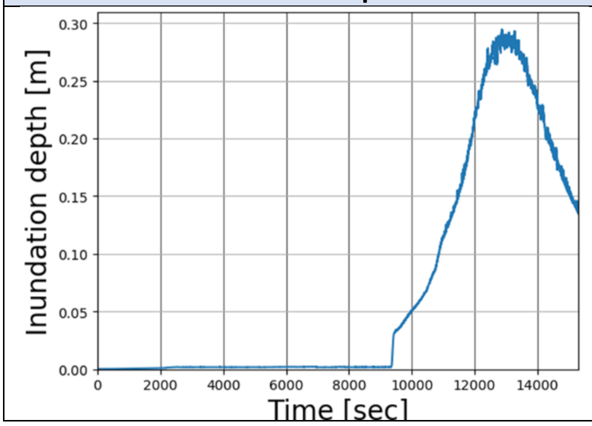
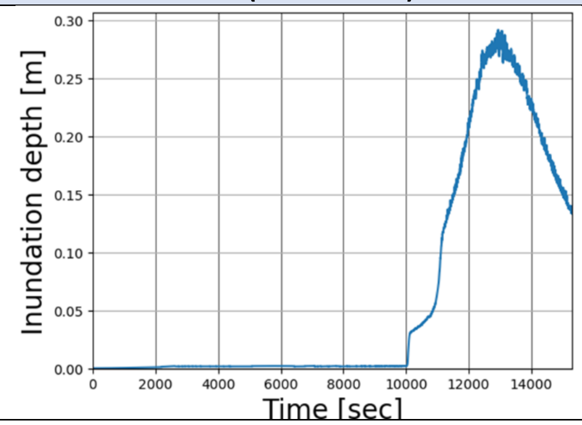
Table 15 - Weight of each group of criteria

Criteria groups							
	A	**B**	**C**	**D**	**E**	**Geometric Mean**	**Weight**
A		1.0	3.3	2.3	5.4	3.007	0.37
B	1.0		3.2	2.2	5.2	2.880	0.35
C	0.3	0.3		0.7	1.6	0.735	0.09
D	0.4	0.5	1.4		2.3	1.164	0.14
E	0.2	0.2	0.6	0.4		0.356	0.04
Tot						**8.141**	**1.00**

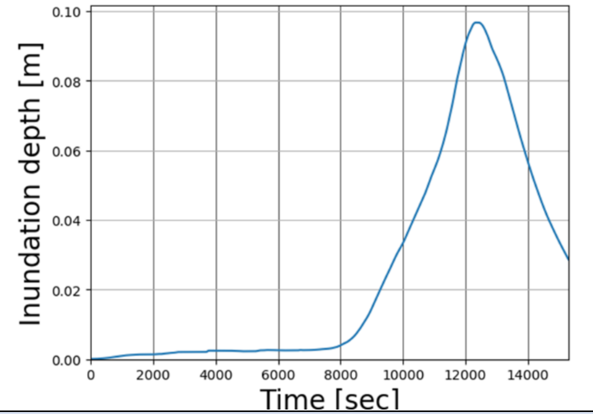
Appendix D – Inundation depth, flow velocity, and DV over time for critical points

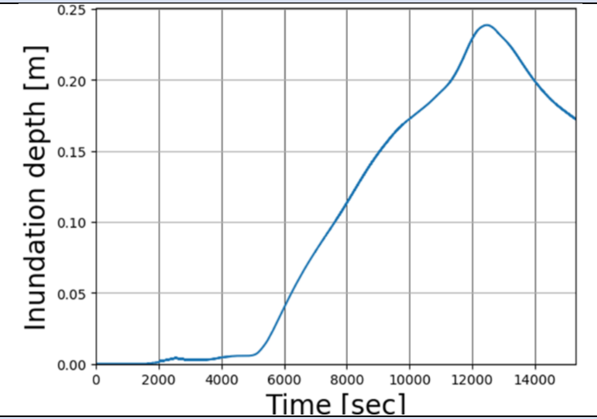
In the tables below, the inundation depth, flow velocity, and DV are presented over time for all critical points. In the left columns, the development of each characteristic is shown for the current situation, so with no implemented flood mitigation measure, while in the right columns the development of each characteristic is shown for the new situation, so with simulated implementation of bio-retention systems. The graphs are directly created as output of the model.

Table 16 - Inundation depth over time for all critical points in the current and the new situation

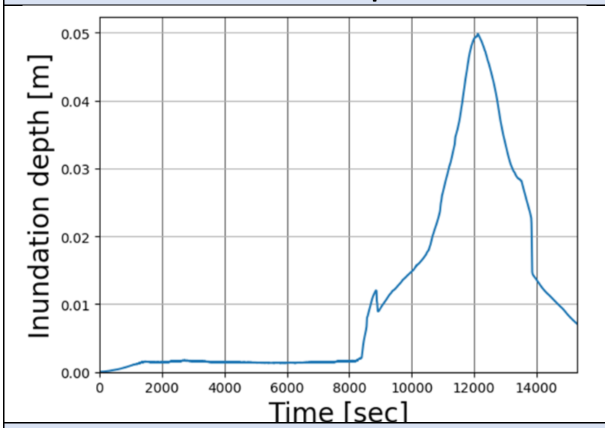
<table>
<tr><th>Current situation (no measures implemented)</th><th>New situation (with bio-retention systems)</th></tr>
<tr><td colspan="2">Inundation depth at HTEM 1 - Piazza Vittorio (entry Sassi)</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">Inundation depth at HTEM 2 – Via Lucana (bus station + intersection)</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">Inundation depth at HTEM 3 – Via Madonna delle Virù (outlet south)</td></tr>
<tr><td></td><td></td></tr>
</table>

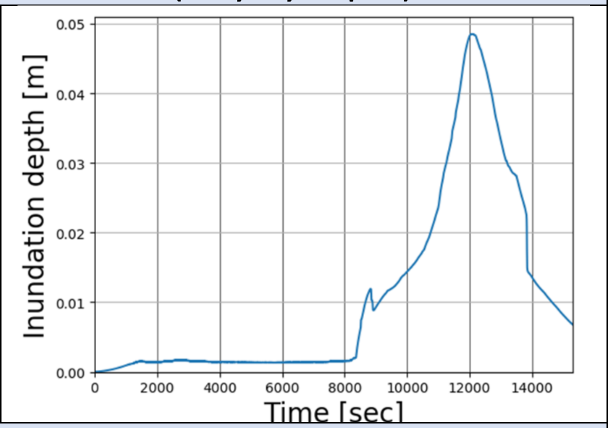
Inundation depth at HTEM 4 – Parchegio Stazione Centrale/Tribunale (parking lot station/court)



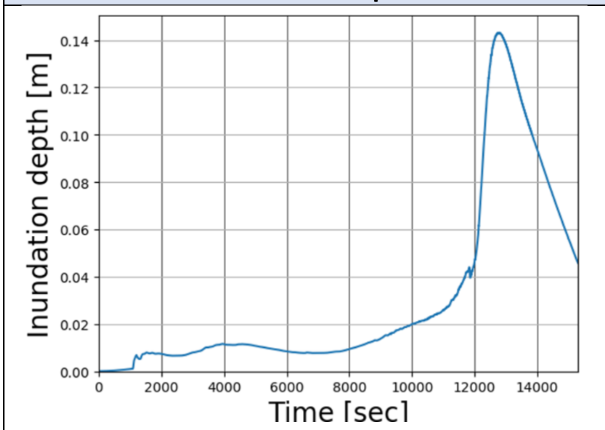


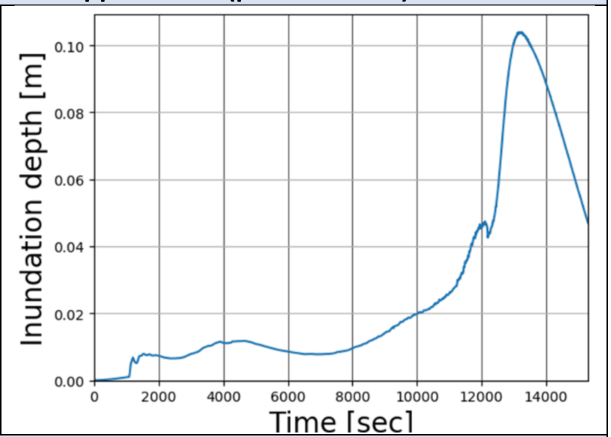
Inundation depth at HTEM 5 – Viale Aldo Moro (entryway hospital)



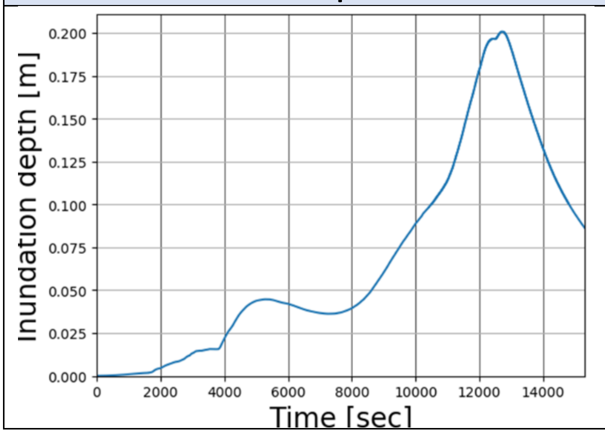


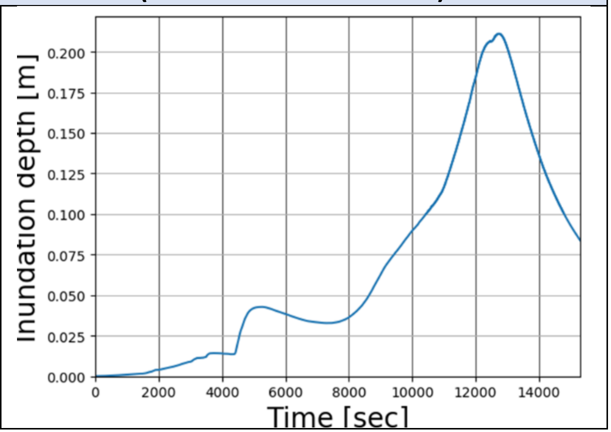
Inundation depth at HTEM 6 – Via Giuseppe Gattini (police station)





Inundation depth at HTEM 7 – Viale Aldo Moro (intersection main roads)





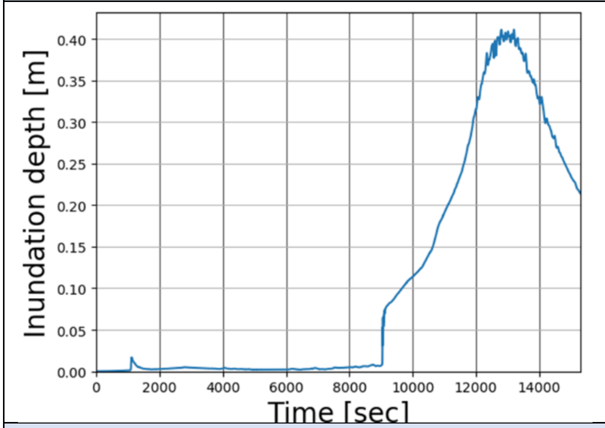
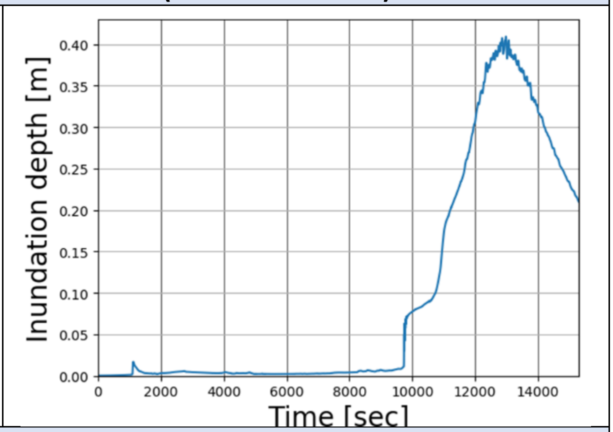
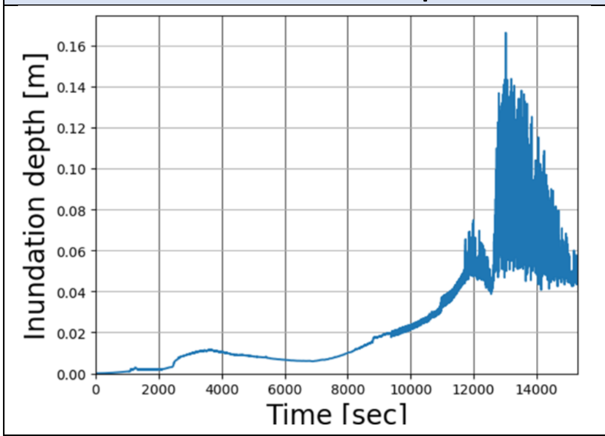
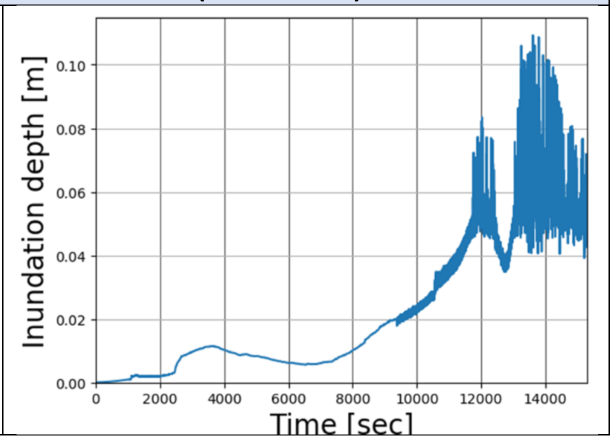
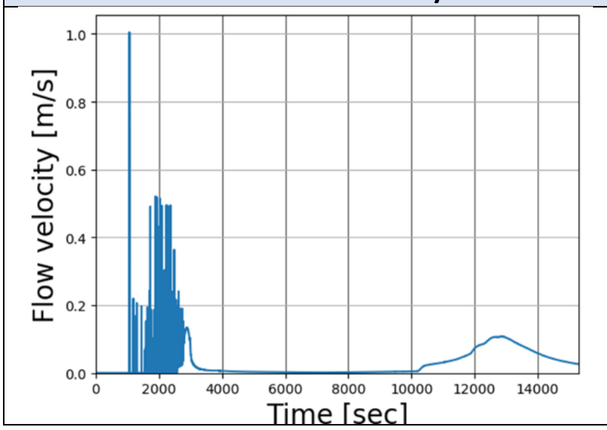
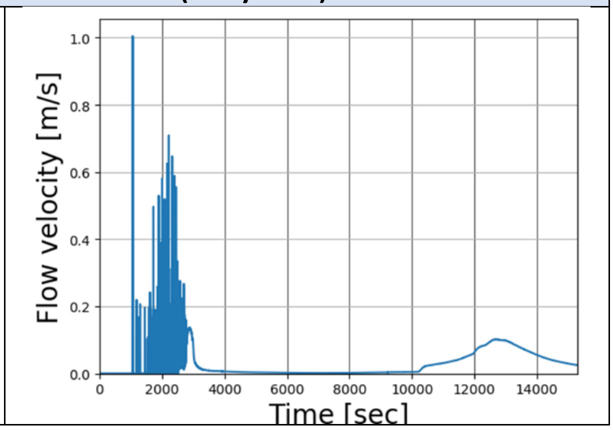
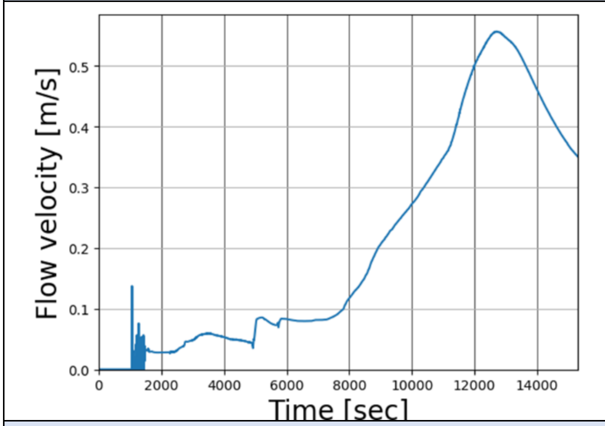
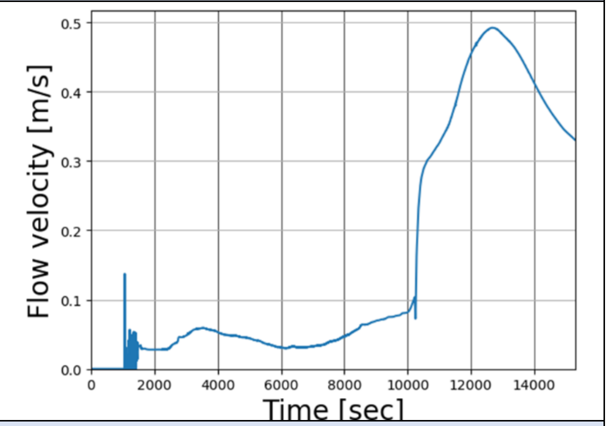
Inundation depth at HTEM 8 – Via Fiorentini (intersection Sassi)	
	
Inundation depth at HTEM 9 – Via d'Addozio (outlet north)	
	

Table 17 - Flow velocity over time for all critical points in the current and the new situation

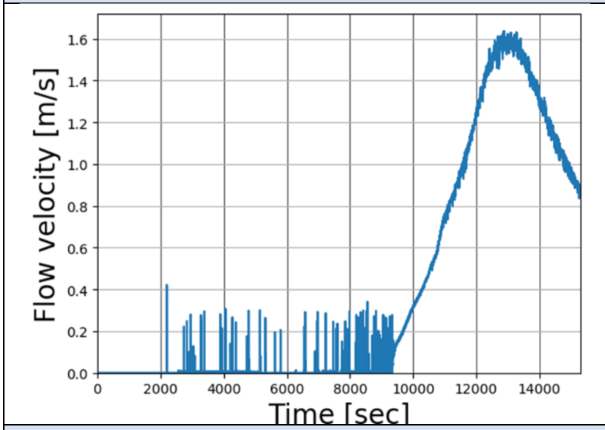
Current situation (no measures implemented)	**New situation (with bio-retention systems)**
Flow velocity at HTEM 1 - Piazza Vittorio (entry Sassi)	
	

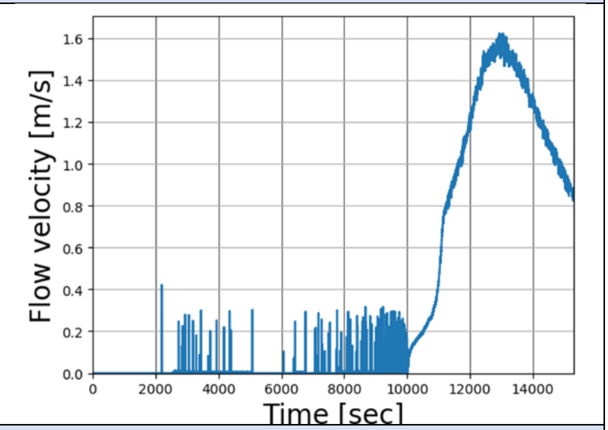
Flow velocity at HTEM 2 – Via Lucana (bus station + intersection)



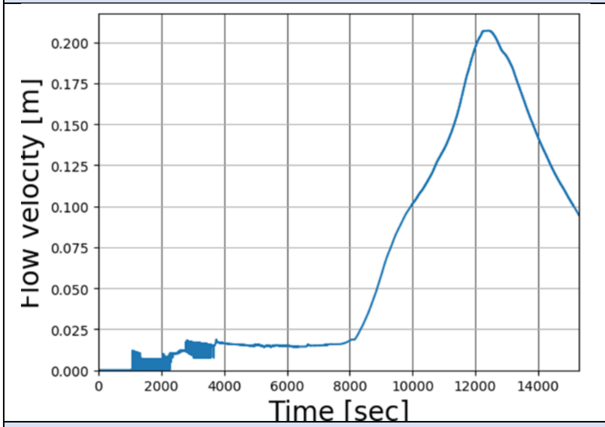


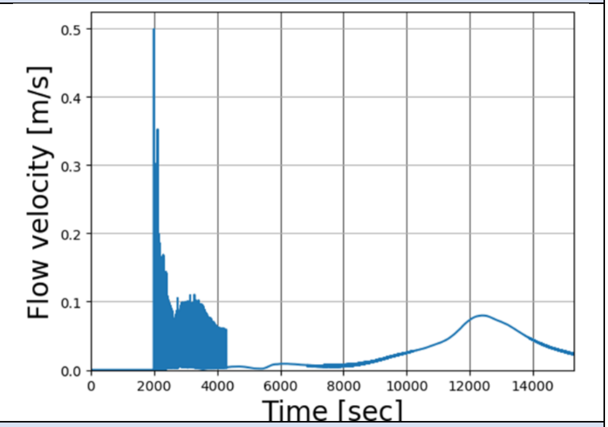
Flow velocity at HTEM 3 – Via Madonna delle Virtù (outlet south)



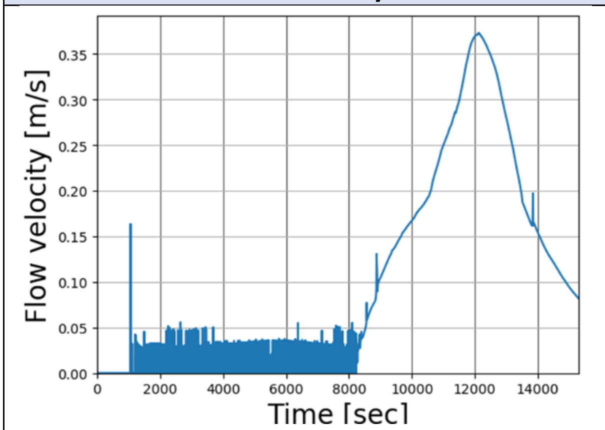


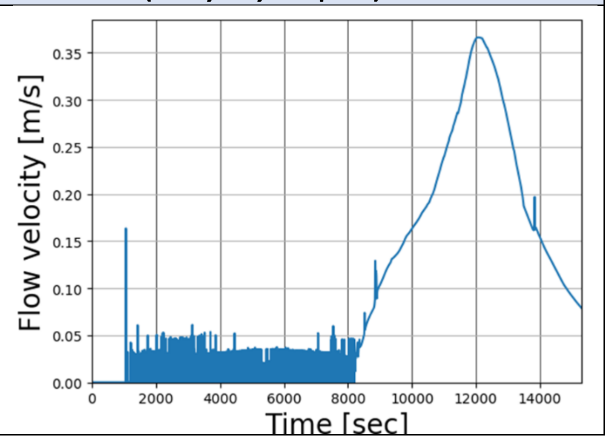
Flow velocity at HTEM 4 – Parchegio Stazione Centrale/Tribunale (parking lot station/court)



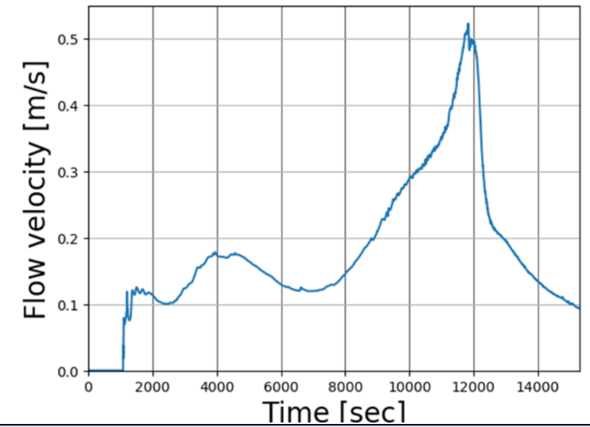


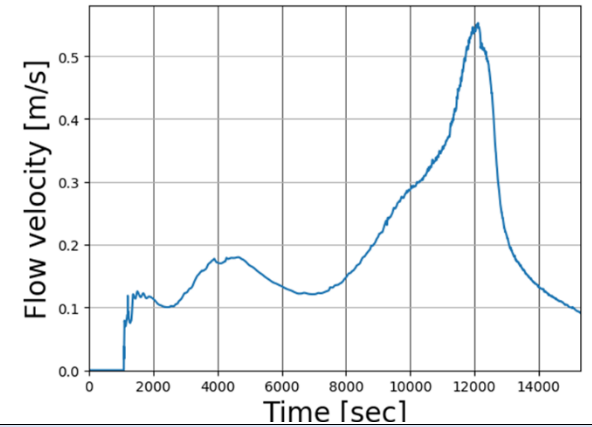
Flow velocity at HTEM 5 – Viale Aldo Moro (entryway hospital)



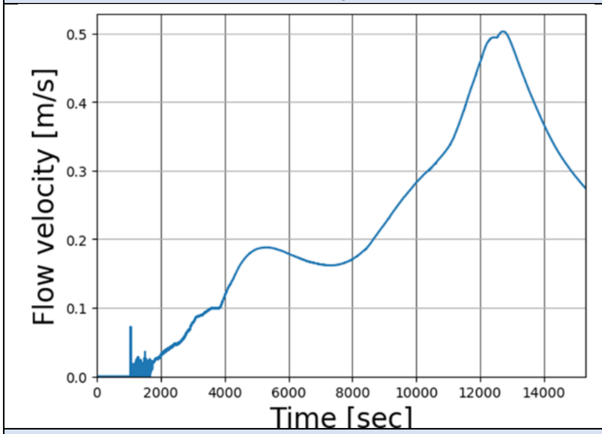


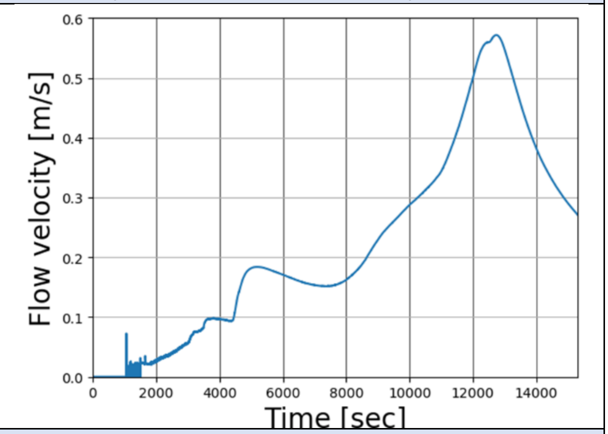
Flow velocity at HTEM 6 – Via Giuseppe Gattini (police station)



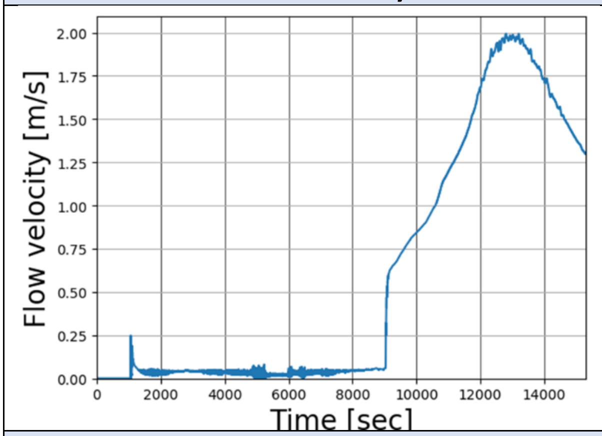


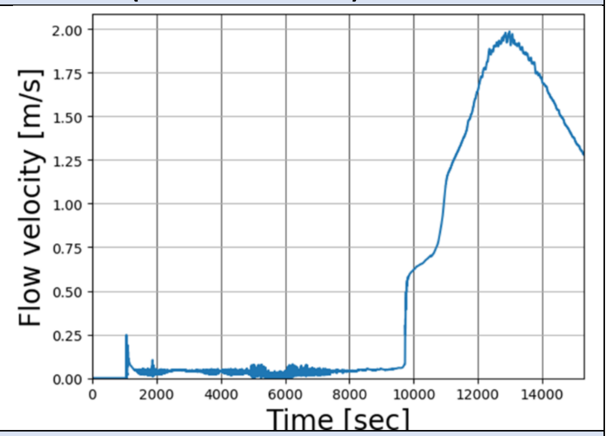
Flow velocity at HTEM 7 – Viale Aldo Moro (intersection main roads)



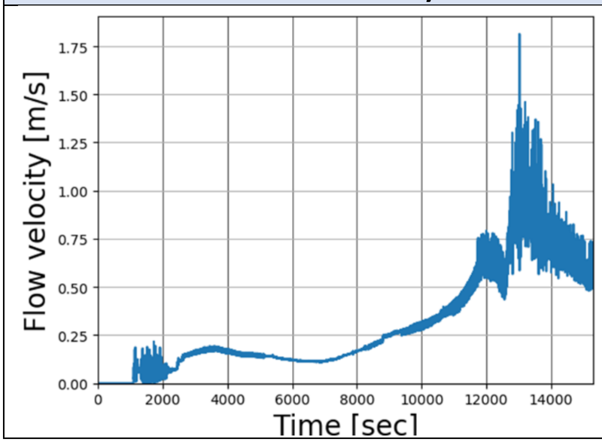


Flow velocity at HTEM 8 – Via Fiorentini (intersection Sassi)





Flow velocity at HTEM 9 – Via d'Addozio (outlet north)



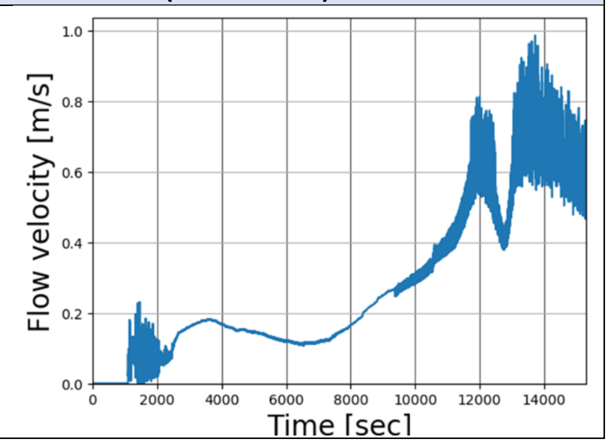
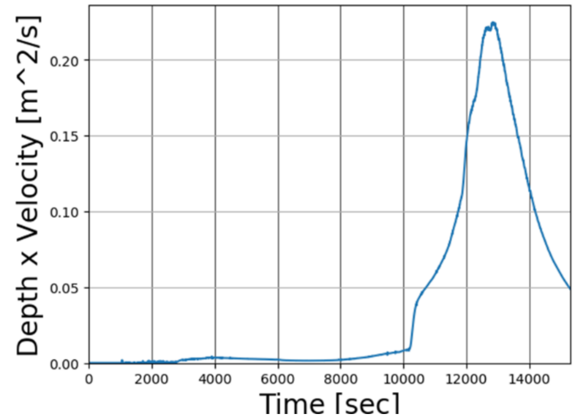


Table 18 – Depth x velocity over time for all critical points in the current and the new situation

<table>
<tr><th>Current situation (no measures implemented)</th><th>New situation (with bio-retention systems)</th></tr>
<tr><td colspan="2">Depth x velocity at HTEM 1 – Piazza Vittorio Veneto (entry Sassi)</td></tr>
<tr><td>


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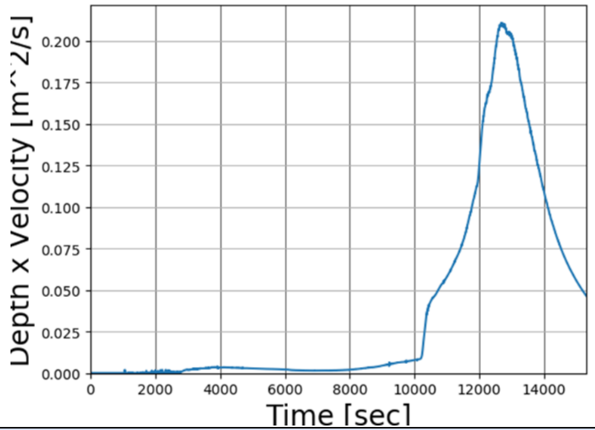

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<tr><td colspan="2">Depth x velocity at HTEM 2 – Via Lucana (bus station + intersection)</td></tr>
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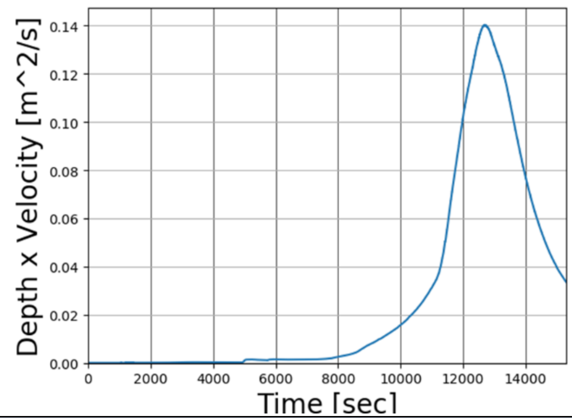

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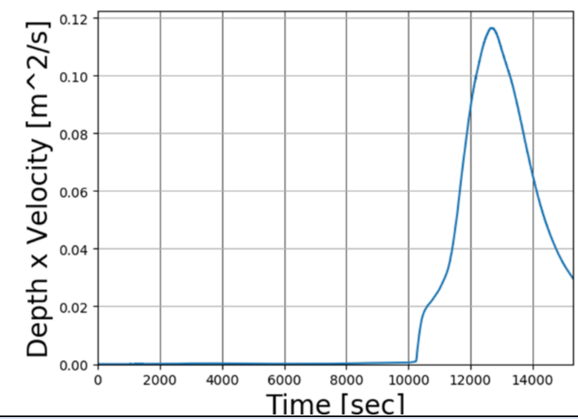

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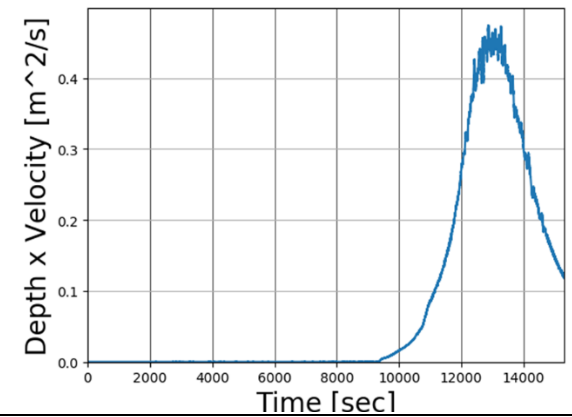
<tr><td colspan="2">Depth x velocity at HTEM 3 – Via Madonna delle Virtù (outlet south)</td></tr>
<tr><td>


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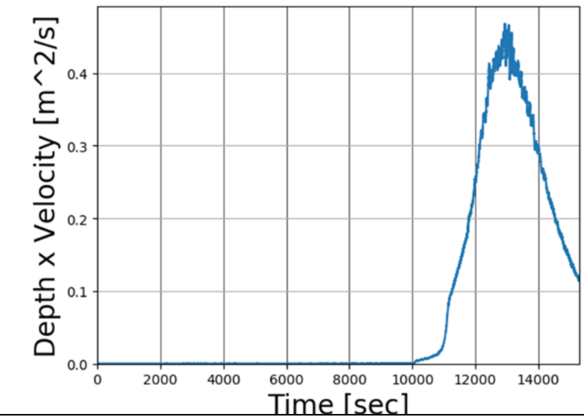

</td></tr>
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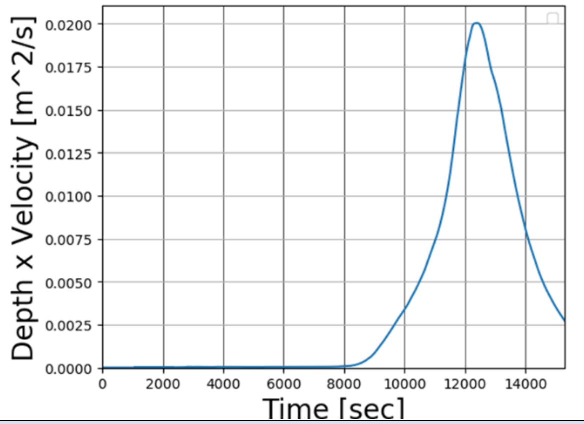
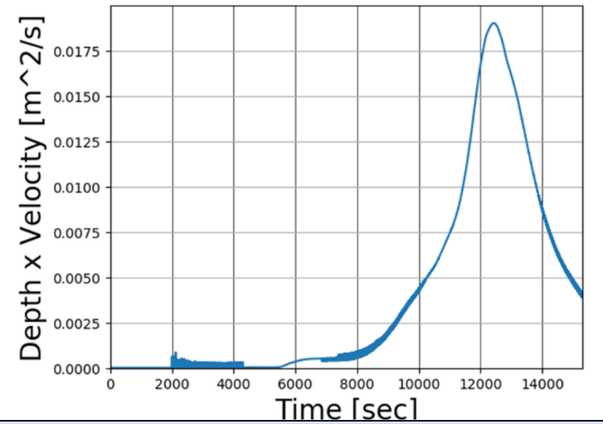
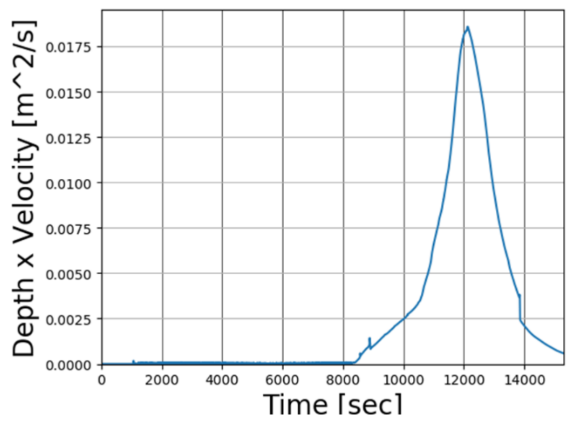
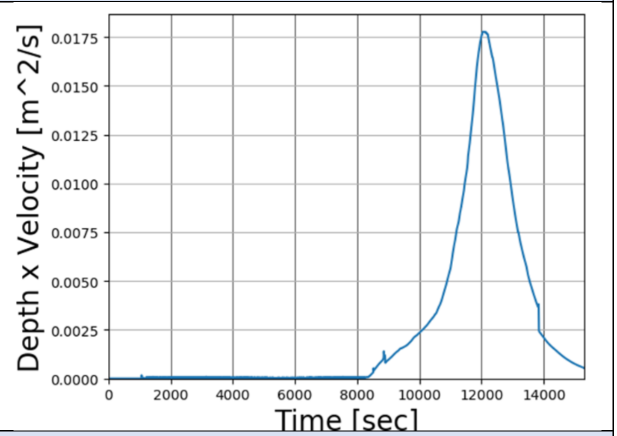
Depth x velocity at HTEM 4 – Parchegio Stazione Centrale/Tribunale (parking lot station/court)



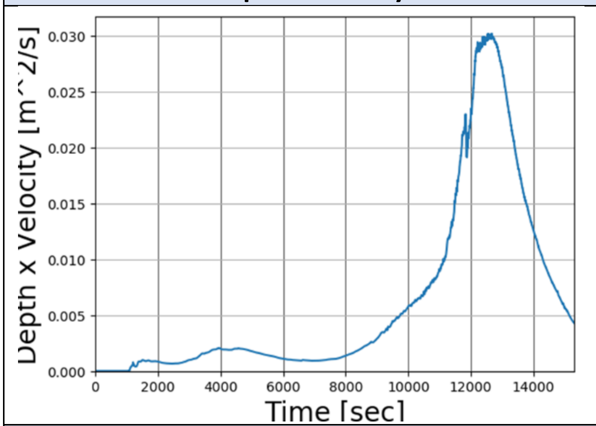


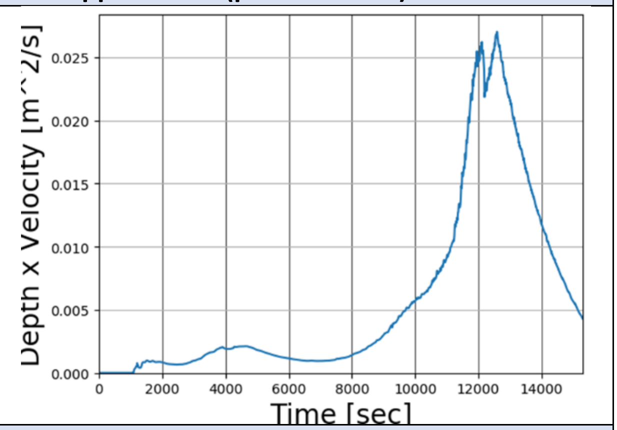
Depth x velocity at HTEM 5 – Viale Aldo Moro (entryway hospital)



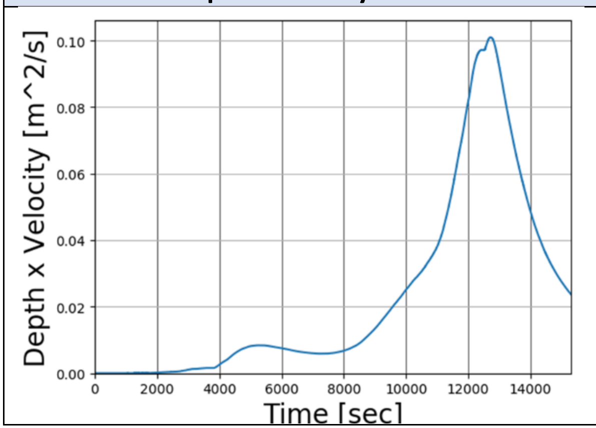


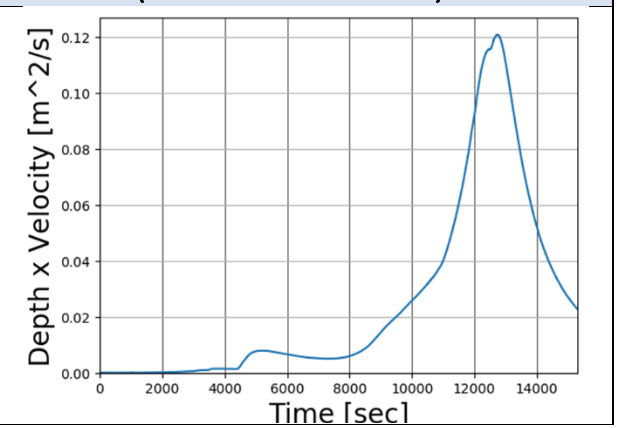
Depth x velocity at HTEM 6 – Via Giuseppe Gattini (police station)



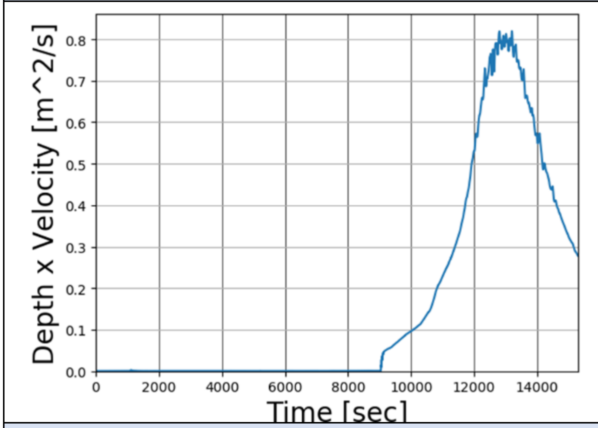


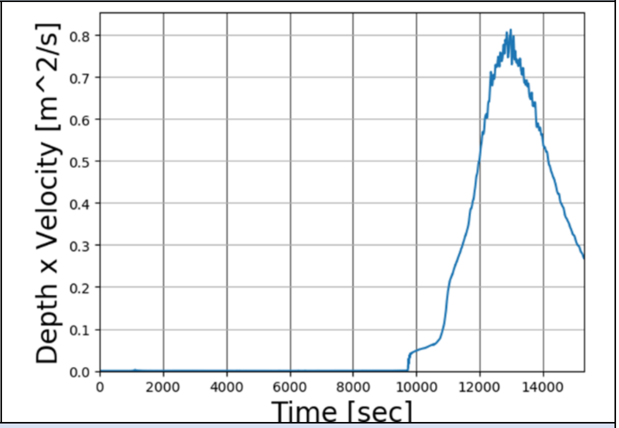
Depth x velocity at HTEM 7 – Viale Aldo Moro (intersection main roads)





Depth x velocity at HTEM 8 – Via Fiorentini (intersection Sassi)





Depth x velocity at HTEM 9 – Via d'Addozio (outlet north)