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Flood modelling and proposed Blue-Green Solutions – A case study in Lisbon, Portugal

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Abstract. This study assesses the potential benefit of Blue-Green Solutions (BGS), green rooftops, rain gardens, permeable pavements, and bioswales, in Lisbon, Portugal. These proposed mitigation measures are applied using TFM-DYN (Nilsson et al., 2021) to simulate potential fluvial flooding distributions from a 10- and 50-year rain event.

Water depth of over 30 centimeters can cause damage to infrastructure. The model results show water depths of over 40 centimeters in some parts of the study area for the 10-year return period, raising the need for action. For the 50-year return period even more areas will be affected. These floods can occur at a relatively rapid pace. Four BGS were implemented for flood mitigation. Areas with green roofs and rain gardens showed a lowering in water depth for both return periods. This study shows that even relatively simple data allows for an estimation of urban flooding and the potential effect of BGS for specific locations can easily be determined.

Keywords. flood mitigation, hydrological model, pluvial flooding, TFM-DYN, Blue-Green Solutions (BGS)

1 Introduction

Flooding is a globally occurring natural hazard responsible for fatality and material damage. Making up a third of Europe's total economic loss per year, flooding causes 4.20 billion € worth of damage (Leal et al., 2018). Costs have increased lately, enhanced by a growing population, the extension of urban areas, impermeable surfaces and climate change (Leal et al., 2018).

Future extreme precipitation events therefore pose an economic and socio-economic threat. The associated risks are not only determined by the frequency and intensity of the hazard, but also by exposure and vulnerability (Field et al., 2012). Lisbon is expected to experience increased pluvial flooding due to extreme precipitation events (Leal et al., 2018; Matos Silva et al., 2021). The conventional pipe-bound sewerage networks implemented in many European cities, including Lisbon, are not sufficient to drain extreme amounts of water, making pluvial flooding a recurring issue (Haghighatafshar et al., 2018; Matos Silva and Costa, 2017). These high intensity precipitation events can thus lead to flash flooding and may overstrain urban sewage systems, resulting in surface runoff on sloping, impervious streets, and flooding at low elevations (Leal et al., 2018; Leal et al., 2019).

Thus, it is important to locate such areas to avoid major negative impacts and introduce BGS. BGS is an effective way of combining blue and green natural landscape features, which retain runoff water from precipitation, into city planning strategies (Lamond and Everett, 2019). The usage of green infrastructure could bring Lisbon one step closer towards the 11th Sustainable Development goal of the United Nations 2030 Agenda, which encloses sustainable cities and communities (United Nations, 2019).

2 Aims and objectives

The aim of this study is to model urban flooding in central Lisbon, to determine the vulnerable areas in terms of a risen water depth and velocity, as well as, to investigate the costs and efficiency of BGS for flood mitigation. To fulfil these aims, the following steps will be carried out:

- Modelled flooding in the study area using predicted 10-year, and 50-year rain events.

- Proposed BGS for mitigation of intense flooding events.

- Evaluation of the proposed BGS on flood risk.

3 Data and Software Availability

The hydrological model used for the pluvial flood analysis, TFM-DYN (Nilsson et al., 2021), is briefly described below. Additionally, the process of data acquisition and model inputs are provided. The TFM algorithm and data is available via corresponding author.

3.1 Flow modelling

Based on Pilesjö and Hassan (2014), the TFM-DYN is user-friendly with an intermediate complexity, simulating flow, water depth and velocity. The model carries out a multiple flow algorithm where water can flow from one grid cell to adjacent ones. A cell is divided into eight triangular segments with constant slopes. Waterflow occurs both between segments and into surrounding cells (Pilesjö and Hasan, 2014). Data inputs include elevation, surface roughness, infiltration rate, and precipitation. This model is deemed appropriate as detailed mapping of the catchment is required for flood mitigation. A conceptual model of TFM-DYN is presented in Fig. 1.

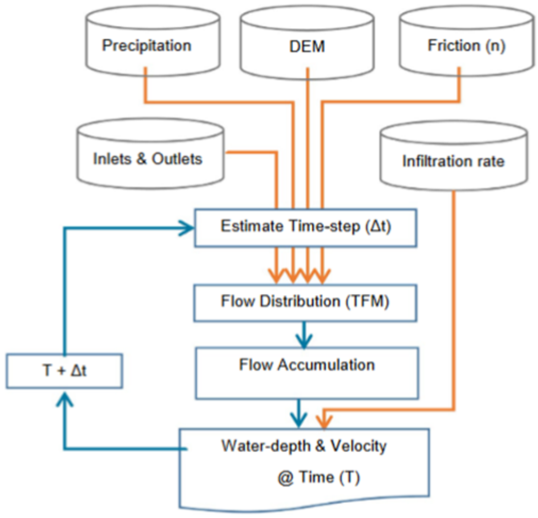

Figure 1. A schematic diagram showing the inputs and results of the TFM-DYN model. (adapted from Nilsson et. al., 2021).

3.2 Data

The following datasets were used.

3.2.1 Topography

A high-resolution Digital Elevation Model (DEM) was obtained from Catulo et. al (2018). This is a 1 meter resolution, bare soil raster obtained by LiDAR sensors. To account for urban infrastructure, the DEM was merged with a land cover layer obtained from OpenStreetMap (OSM) (n.d.). Buildings without corresponding height values were assigned a height of 10 meters.

3.2.2 Infiltration

Vegetation, water bodies, and impermeable infrastructure were derived from OSM and assigned infiltration values according to Dahlgren et al., (2008), Savva and Frenken (2002), and Food and Agricultural Organization of the United Nations (1998) (Tab. 1.).

Table 1. Infiltration values (mm/h) per land cover class.

Land use	Infiltration (mm/h)
Water	0
Infrastructure	2
Vegetation	16

3.2.3 Surface friction

Manning’s coefficients were implemented on the land cover raster layer, based on OSM (Tab. 2). These are standardized values common in flood modelling, related to surface water retention (Papaioannou et al., 2018).

Table 2. Surface friction per land cover class.

Land use	Manning's coefficient
Water	0.07
Infrastructure	0.02
Vegetation	0.25

3.2.4 Precipitation

As precipitation was not available in high (hourly) resolution to create hyetographs, other methods were utilized to create hyetographs. A hyetograph defines the temporal development of a precipitation event allowing for hydrological modelling by producing shorter daily precipitation intervals (Dias et al., 2014). The input was created with the help of intensity duration frequency (IDF) curves and the alternating block method (Chow et al., 1988), with a storm hyetograph as result. The IDF curves were calculated according to Eq. (1).

$$\mathrm{I} = \mathrm{a} * \mathrm{t}^{b} \tag{1}$$

where I represents rainfall intensity (mm/h), a and b are variables determined by region and return period, t denotes the time period in minutes.

Portugal has five measuring stations with high resolution data, allowing for a frequency analysis over 60 hydrological years from 1958 to 2017. The parameters a and b needed for the IDF curves were derived from Silva Correia (2019), who uses long term precipitation data onto which a Grumble distribution function, a type of frequency analysis, was applied to the maximum annual precipitation to determine the event's duration (Chow et al., 1988).

Based on findings from Silva Correia (2019) two return periods of 10 years (a = 403, b = -0.63) and 50 years (a = 579, b = -0.64) were chosen. The rainfall intensity for a two-hour precipitation event was estimated with a time interval of 15 minutes to show the rainfall distribution according to Eq. (1). The corresponding intensities are obtained from the IDF curves for each time duration. The different 15-minute time blocks were rearranged so that the peak intensity occurs midway of the two-hour event. The other blocks were sorted by alternating declining intensities on equal sides from the center. The designed hyetographs are presented below (Fig. 2).

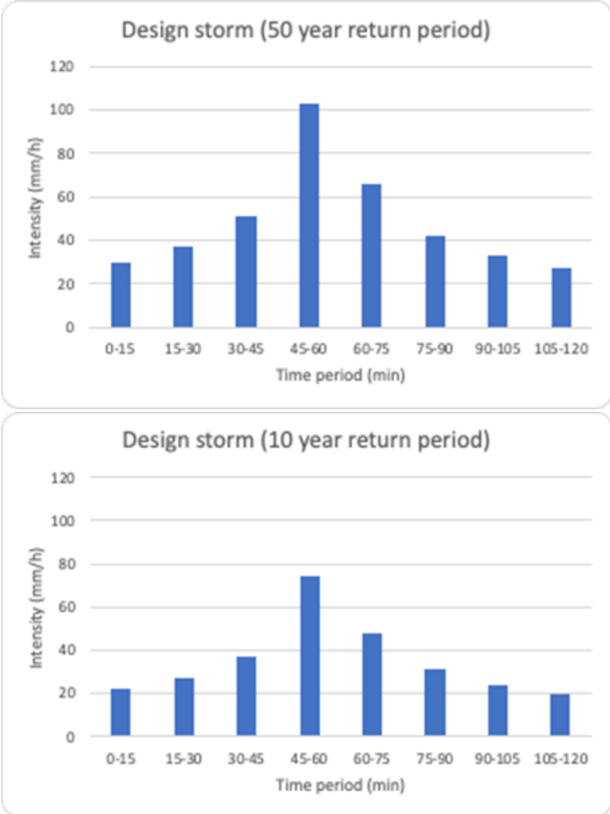

Figure 2. Design storms for a 10-year (above) and 50-year (below) return rainfall event.

3.2.5 Inlets

The sewage inlets were located manually using GPS receivers. Lengths and widths of inlets were measured to estimate their capacity, as described by Nilsson (2017). This method assumes that the inlets are able to cope with a 10-year rain of 30-minute duration.

3.2.6 Blue-Green Solutions

The implementation of BGS was performed through the digitization of various BGS in suitable areas, while considering installation and maintenance costs, installation requirements, and the spread of BGS throughout the area (Tab. 3.). The following was considered when choosing suitable locations:

[1] Bioswales were implemented upstream and along larger roads where slope ≤ 5%, ensuring a spread of BGS across the entire study area and limiting downstream flooding.

[2] Rain gardens were placed in relation to bioswales allowing infiltrating water to be transported to rain gardens. This captures runoff upstream which alleviate the flooding downstream, hence they were placed at mid and low elevations.

Table 3. Costs, infiltration rates, and surface friction for the implemented BGS.

BGS	Installation cost (€/m^2)	Maintenance cost (€/m^2/year)	Infiltration rate (mm/h)	Surface friction
Green roofs	362[(a)]	5.64[(a)]	7.90[(a)(b)]	0.25
Rain gardens	377*[(c)]	43.0[(c)]	100[(d)]	0.25
Permeable paving	141[(d)]	Not relevant	50.0**[(e)]	0.02
Bioswale	9.24[(d)]	43.0[(c)]	50	0.25

Manso et al., 2021, [(b)] Sellick, 2020, [(c)] Terrascope, n.d., [(d)] Zare, 2012, [(e)] Bean et al., 2004 *With a 79.0 soil test per rain garden. **Without maintenance

[3] Permeable paving was placed in areas of the highest flooding velocities, mainly along smaller roads in areas of low elevation. Porous paving is especially suitable for neighbourhoods with limited space for new infrastructure.

[4] Intensive green roofs were placed in the remaining upstream areas of higher elevations. This ensured an equal spread of BGS across the study area as green roofs have few installation requirements.

4 Results

The most severe flooding scenario (50-year) for water depth and velocity is presented in Appendix 1. Many locations show depths exceeding 0.8 m and velocities above 1.25 m/s. Based on these outputs, the BGS were proposed (Fig. 3). The installation cost is estimated to 70.5 million € and annual maintenance cost to 1.97 million €.

The 10-year flood scenario shows lower water depths of up to 0.4 m. Extreme depths over 0.8 m were only simulated in a handful of locations. To determine the effectiveness of the proposed BGS, their implementation was tested by comparing water depths with and without BGS. Negative values indicate a worsening of water depth, positive values indicate improvements. Generally, an improvement was found. A few locations, especially those where permeable roads were implemented, show increases (Appendix 2). When BGS were implemented for the 50-year scenario, increases are found in the same places as in the 10-year flood scenario, but with higher magnitudes of up to 1.50 m.

Water velocity is closely related to slope. When analysing water velocity results for the 10-year rain, a similar pattern to that of the water depths was observed. The highest velocities in the scenario without BGS are recorded along steep streets in the South, reaching over 1.5 m/s, while the parks show lower velocities. After applying BGS the regions in the east and west showed a decline of up to 0.2 m/s. Here, green roofs were added. The strongest decrease in velocities, between 0.2 and 5 m/s, is seen where rain gardens and bioswales are located. When the BGS were applied on the 50-year scenario, the same pattern, but a stronger reduction in velocity, was observed.

5 Discussion and conclusions

The results show that the north-eastern, northern and southern areas are most prone to flooding. Many areas showed water depths over 40 cm for the 10-year rain, and even more areas for the 50-year rain. This is alarming, as water depths >10 cm will have an impact on the traffic whilst >30 cm can cause damage to infrastructure (Plars, 2020). Extreme rain events will increase due to climate change, meaning that flooding is likely to cause severe challenges in the future. Extensive measures, such as applying BGS, would thus be needed to prevent frequent water damage to infrastructure.

The implementation of BGS generally helps to decrease flooding, although it could change water courses, directing water to locations with less friction and less infiltration. This can increase water depth and velocities, especially on low friction permeable paving. The positive water-retaining effect of green roofs from both simulations suggest that a future simulation could be retrofitted to contain more green roofs and less permeable paving.

It is difficult to determine which BGS portrays the best fit for mitigating flood risk based on only two different flooding scenarios with the exact same BGS. Most of the implemented solutions have a small positive effect on decreasing overall velocities and water depths. Based on the obtained results, the installation of green roofs and rain gardens appear to aid flood mitigation best. Multiple

Figure 3. Proposed BGS.

simulations, with one BGS implemented at a time, could give better understanding of the efficiency of each BGS.

The proposed installation cost sums up to 70.5 million €, with annual maintenance costs of 1.97 million €. In comparison, the damage in Metropolitan Lisbon during the 2000-2011 floods was assessed to 10 billion €, corresponding to about 400 million € for an area similar in size to ours (Leal et al., 2020).

We conclude that a relatively simple geographical analysis method can be used to carry out flood risk assessments and test BGS as a mitigation strategy. The extent to which BGS can be incorporated depends on the budget, but using the proposed approach allows the finding of suitable locations for effective measures.

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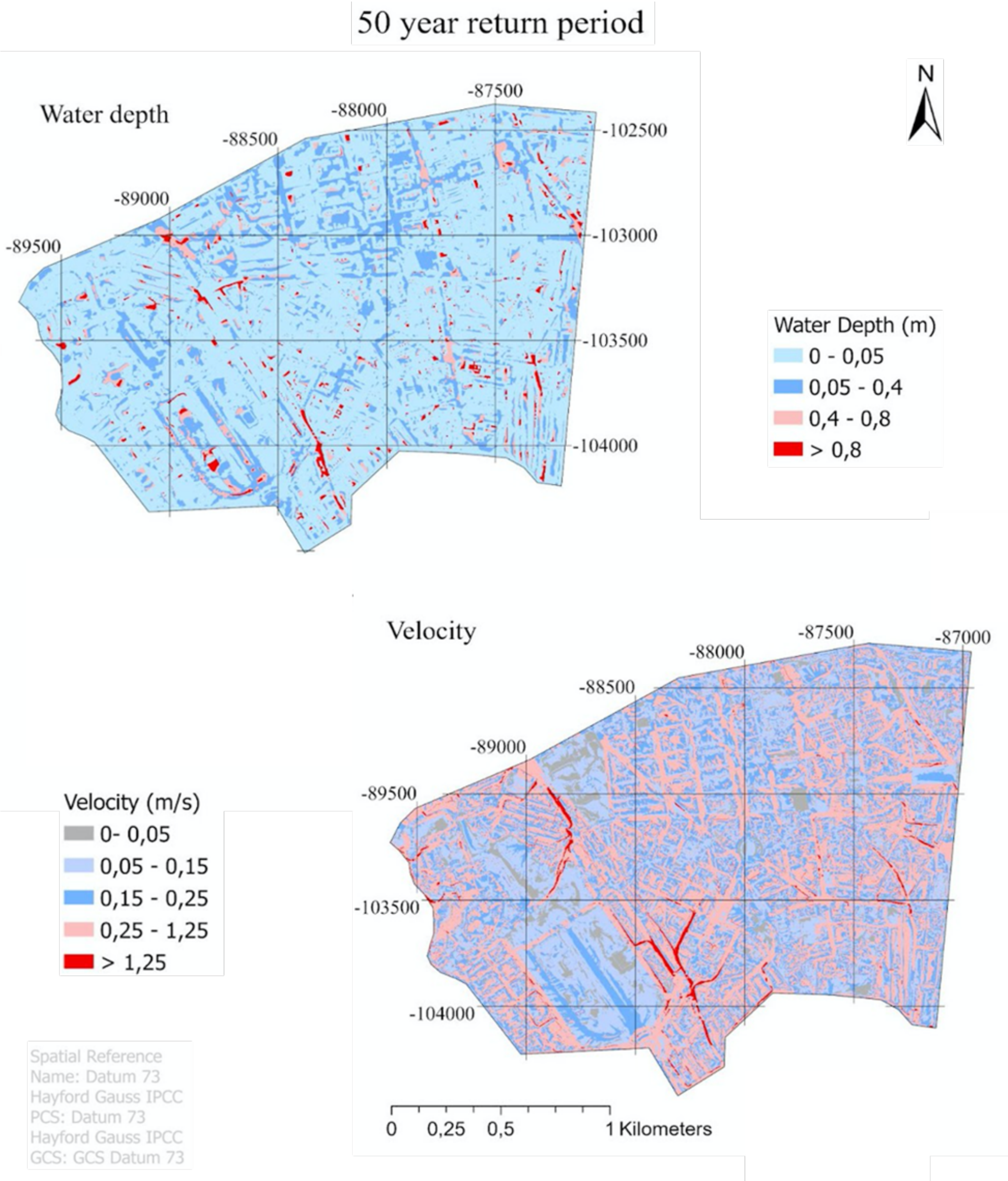
Appendix 1

Water depth and velocity assuming a 50-year rain.



Appendix 2

Water depth for the 10-year rain (below) and impact of BGS on water depth (above).