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# ASSESSING THE EFFECTIVENESS OF GREEN AND GREY SOLUTIONS FOR FLOOD RISK REDUCTION: A COMPARISON OF DAMAGE-BASED AND SCORE-BASED APPROACHES

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ABSTRACT

Nature-based solutions are increasingly recognized as a critical component of adaptation of our society to extreme hydro-meteorological events. Reliable tools for assessing the effectiveness of such measures, particularly in comparison with grey solutions, are instrumental to ensure sustainable flood risk management under climate evolution and rapid urbanization. This study compares a monetary damage model and a score-based approach to estimate the benefits of the implementation of green, grey, and hybrid measures for reducing flood risk. A representative case study was selected in the Vesdre catchment (Belgium), which was severely affected by the mega flood of 2021 in Europe. The research aims to assess the compatibility and complementarity of the two assessment approaches for evaluating the effectiveness of green solutions compared to traditional grey measures, emphasizing the added value of hybrid approaches. By addressing a key gap in flood risk evaluation frameworks, this work contributes to understanding how combined strategies can improve resilience and mitigate flood impacts in vulnerable regions.

**Keywords:** risk models; hydraulic simulations; score-based methods; flood loss model; nature-based solutions; green solutions; grey solutions; hybrid measures, resilience.

## 1. Introduction

Flood risk modelling plays a crucial role in understanding and mitigating the impacts of flooding. In this context, the integration of green solutions—such as re-meandering, retention basins—into traditional flood management approaches has gained increasing attention. These solutions are considered as environmentally sustainable alternatives to conventional infrastructure, more aligned with the concepts of resilience and sustainable development, but their effectiveness and the appropriate frameworks for evaluating them remain under-explored (Jeuken et al., 2023; Penning et al., 2023).

The primary objective of this work is to compare two approaches that address the evaluation of flood risk and damage: a damaged-based model and a scored based method. Risk models based on scores use quantitative scoring systems to characterize risks. While scores simplify complex data into straightforward metrics, they depend significantly on weighting schemes and subjective decisions in quantification. This inherent subjectivity contrasts with damage models, which are typically more data-intensive, rely on well-defined relationships between hazard characteristics and impacts, and aim to reduce arbitrariness.

Additionally, the study evaluates different flood risk management scenarios, comparing green solutions, traditional grey infrastructures, and hybrid approaches. This second objective examines how these measures interact and complement each other in mitigating flood risk, rather than focusing on the optimization of individual solutions. The terminology for this work requires careful consideration: measures like retention basins, re-meandering, and river widening are categorized as green infrastructure due to their ability to reduce flood risk while enhancing ecological resilience. However, they cannot yet be classified as Nature-based Solutions (NbS), which also consider broader social and sustainability aspects (M. Berg et al., 2024).

The research seeks to fill a gap in the current literature, where the integration of green solutions into flood risk management often lacks standardized evaluation methods and quantitative parameters. While many studies emphasize the potential of green infrastructure, there is still a lack of consensus on how best to assess its performance in comparison to traditional solutions. This work aims to provide insights into the benefits and limitations of integrating green and grey measures, contributing to a more comprehensive understanding of flood risk management strategies.

## 2. Methodology

A methodology has been developed to evaluate the effectiveness of various flood risk management strategies. This approach focuses on comparing a damage-based model with a score-based method across several intervention scenarios, including green, grey, and hybrid measures.

### *2.1. 2-D Hydrodynamic model*

The selected model for this study is WOLF, an integrated hydrological and hydraulic modeling software developed by the HECE research group at the University of Liège (ULiège). It features a GPU-based computation engine, advanced topographic analysis, and graphic output tools for detailed geospatial processing. In addition, WOLF has been officially adopted by the Walloon Public Services (SPW) for 2D flow simulations and flood mapping in Belgium. Validated through numerous experimental cases and real-world applications, it has proven effective in various engineering and research projects (Bruwier et al., 2018; Mustafa et al., 2018; Beckers et al., 2013).

### 2.2. *Monetary flood loss model*

In this study, the flood loss model INSYDE-BE was selected. It is an adaptation of the original INSYDE flood damage model developed for Italy. INSYDE is a synthetic, multi-variable flood damage model for the residential sector (Dottori et al., 2016). INSYDE-BE has been specifically tailored to the Belgian context, as detailed in Scorzini et al. (2022). The adaptation process involved modifying the model's assumptions, particularly regarding default values for hazard and building parameters, as well as adjusting the damage functions to better reflect local conditions.

This model requires detailed input data on hazard characteristics, such as water depth, flow velocity, and flood duration, as well as building-specific attributes, such as the type of building structure, building age, its height, and the presence of basements.

### *2.3. Score-based method*

The second considered method is a score-based approach, which will be compared to the damaged-based one (INSYDE-BE). The score is defined as a metric that answers the question "*To what extent is the risk acceptable under the studied scenario for the specified vulnerability and expected water depth?*". The workflow of the acceptability score-based model is summarized in Fig. 1 and explained below.

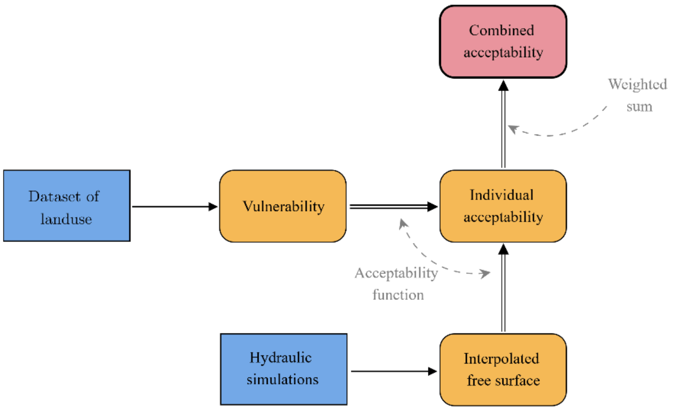


**Fig. 1.** Workflow of the Acceptability scoring model.

The model integrates multiple layers of land use data, encompassing population density, economic activities, infrastructure, hazardous sites, environmental features, and vulnerable assets like architectural and cultural heritage. Each data layer is assigned a vulnerability level on a scale from 1 (no vulnerability) to 5 (considerable vulnerability), where the level reflects the tolerance of each land use type to flooding. Table 1 summarizes these five levels of vulnerability. The final vulnerability raster is constructed by assigning to each cell the highest vulnerability level identified across the various layers.

**Table 1.** Five levels of vulnerability defined in the acceptability risk-scored method.

| Level | Vulnerability | Criterion | Typical example of infrastructures |
|---|---|---|---|
| 1 | Huge | Considerable impact with high risks; submersion is likely to cause major disruption or damage, requiring extensive mitigation measures. | Hospitals, fire stations or civil protection |
| 2 | High | Significant impact; submersion leads to severe constraints, with substantial risks and potential for severe disruption or damage. | Retirement homes, police, health service |
| 3 | Moderate | Moderate impact; some constraints are present; submersion may cause noticeable effects but can be managed with standard measures. | Residential buildings schools, economic activities |
| 4 | Low | Minimal impact ; submersion poses negligible risk, with manageable effects on functionality and operations. | Storage zones, pots, recreational areas |
| 5 | Null | No impacts; submersion could even be beneficial. | Parcs, natural reserves, floodplains |

The second key input comes from the hydrodynamic simulations and post-processing part explained in Section 2.1. These outputs are combined with the vulnerability data, leading to a score ranging from - 2 (unacceptable) to 2 (acceptable). The scoring system is based on a predefined matrix that links water depth to vulnerability levels for each flood scenario. For every cell in the study area, the water depth and vulnerability level are assessed, and the corresponding score is assigned accordingly.

Finally, these scores corresponding to individual flood scenarios (return periods of 2 years, 5 years, 15 years, 25 years, 50 years, 100 years and 1000 years) are combined via a weighted sum, with the weighting coefficients summing up to one, hence ensuring that combined score remains within the predefined range of -2 to 2. It provides a proxy for the flood risk in the study area under varying flood scenarios.

### 2.4. *Case study*

A case study is considered here, focusing on the town of Theux, located in Belgium, within the Vesdre catchment and crossed by the Hoëgne River, a tributary of the Vesdre. The town, with a population of about 12,000 inhabitants and an area of approximately 8 km², is situated in a narrow valley (geological feature called "Fenêtre de Theux"), which increases its flood exposure. The Hoëgne River was a major contributor to the catastrophic floods in the Vesdre catchment in July 2021, which severely impacted the town center of Theux. The riverbanks host residential buildings, retirement homes, schools, public facilities, and a fire station.

### 2.5. *Intervention scenarios*

A major flood hotspot in Theux has been identified at the crossing of the Hoëgne river to the right of the fire station. Upstream, the riverbed significantly narrows near a bend, leading to overflow issues. To address this, a set of green measures has been proposed, involving re-meandering, river widening, and the creation of retention basins, leveraging the available space in this area.

Hydraulic simulation has been conducted to study these measures, specifically focusing on their effectiveness in reducing flood extent. The computational domain covers the town of Theux using a 2D Cartesian mesh, with a spatial resolution of 1 m. The topographic and bathymetric data come from a green LiDAR.

## 3. Results

Final outcomes are expected to include the results of hydraulic simulations, results of the comparison of monetary flood loss model and the score-based method, and the evaluations of the proposed flood management scenarios (grey, green and hybrid). At present, only the baseline and the green scenario have been studied, and the evaluation of damage is still ongoing. The complete results will be presented during the congress.

Fig. 2 presents danger maps for the simulation of a 25-year flood, for the baseline (no measures) situation and a scenario including green solutions (widening re-meandering the river and adding retention basins). A custom color scale (*AKWS+*) has been utilized to represent water depths relative to human height, offering an intuitive reference for understanding flood impacts. "*A*" stands for ankle (0.15 m), "*K*" for knee (0.45 m), "*W*" for waist (1 m), "*S+*" for shoulders and above (>1.5 m). The 25-year flood scenario is presented here because it corresponds to the upper limit of effectiveness of the green measures: the retention basins are full, although the town center is not overflowed. However, an overflow occurs slightly downstream. As the performance of green measures diminishes for more severe events, hybrid scenarios which combine green and grey measures will be further explored to address more extreme flood events.

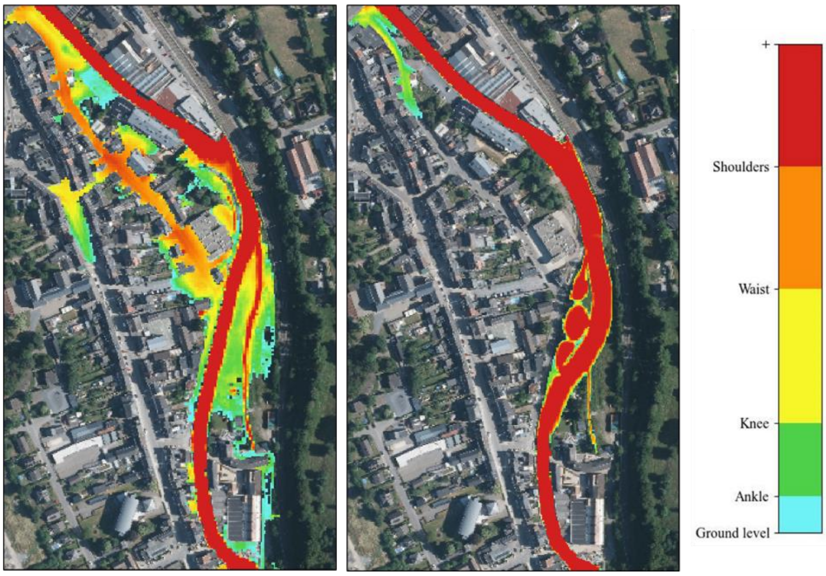


**Fig. 2.** Water depth for the baseline (left) and for green solutions (right), using a simple color scale to promote stakeholder engagement.

## 4. Conclusion

This study aims to compare two flood risk assessment approaches: a damage-based model (*INSYDE-BE*) and a score-based method (*acceptability method*). These approaches are used to evaluate the effectiveness of green measures, traditional grey measures, and hybrid strategies. The methodology includes a 2D hydrodynamic model (*WOLF*) for simulating flood scenarios. Preliminary hydraulic analyses for a case study (Theux, Belgium) indicate that green measures (retention basins, re-meandering and widening of the river) show promising effectiveness in mitigating minor flood events but lack effectiveness in dealing with extreme events. These findings justify further on-going exploration of hybrid strategies, which could provide more robust solutions for severe flood events. The final outcomes are expected to offer a detailed comparison of the two risk assessment approaches (damage-based vs. score-based), and to explore the interaction and complementarity of green and grey flood risk reduction measures, highlighting how hybrid strategies can mitigate flood impacts while enhancing resilience.

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