Application of an optimization system to manage the risks of flash floods

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Highlights

- A mathematical optimization system is a suitable tool for municipalities to identify an appropriate combination of site-specific measures to cope with the risks from heavy rainfall.
- To finally manage the risks of flash floods, not only the cooperation of various stakeholders is of major importance but also the weighting of different objectives.
- Incentives play an essential role in increasing stakeholders' cooperation to implement measures that protect both the individual and the common good.

Introduction

Extreme precipitation is one of the most severe weather phenomena. Heavy rainfall can occur anywhere, very suddenly and is difficult to predict due to the complex atmospheric processes. As a result of climate change, projections for the future suggest that the recent trend towards heavy rainfall events will continue, even if the total amount of rainfall is expected to decrease (IPCC, 2021). Because of possible high damages and dangers, it is essential to take preventive actions. However, municipalities on their own are not able to cope with the risks to society and the economy caused by flash floods due to their limited resources, responsibilities and authorities (BBK, 2015). Currently, the level of cooperation needed of the private sector (e.g., from residents or farmers) and the potential of incentives is not considered thoroughly and methodically during the development of strategies to manage flash floods. However, the potential of incentives in flood prevention has already been established as promising (Jack et al. 2008; Poussin et al. 2014).

This paper highlights the development and application of an optimization system for decision support in urban flash flood management. The model was developed within the joint project AKUT (2021) in cooperation with research, municipalities and practice. The Federal Ministry for Environment, Nature Conservation and Nuclear Safety (Germany) funded the project (2019-2021) as part of the "German Strategy for Adaptation to Climate Change". The tool is now available to municipalities in Germany.

Methodology

The developed optimization system identifies an effective and implementable combination of mitigation measures from numerous possibilities according to a given set of optimizations parameters. For this purpose, a mathematical algorithm was developed, considering the site-specific conditions of a municipality, the willingness of specific stakeholders to implement a measure, and the use of incentives to encourage the implementation of measures.

Pre-Processing

A digital elevation model was integrated within the optimization system to model the site-specific topographical conditions and the existing objects of a municipality. Based on extensive stakeholder analysis, the players are shown in Figure 1 (left) were included in the model. For an initial automated stakeholder allocation to an object, the digital cadastre information system ALKIS® was integrated within the optimization system. It was considered that the user can adjust objects or players.

The hazard analysis provides important information on the localization and extent of possible flooding. For this purpose, the runoff on the surface is calculated during the mathematical optimization process based on the digital elevation model and a user-specified rainfall intensity and duration. The water level is shown on the interface according to four hazard classes (see Figure 1, right). The hazard classes are based on a regulation of the German Association for Water, Wastewater and Waste (DWA, 2016).

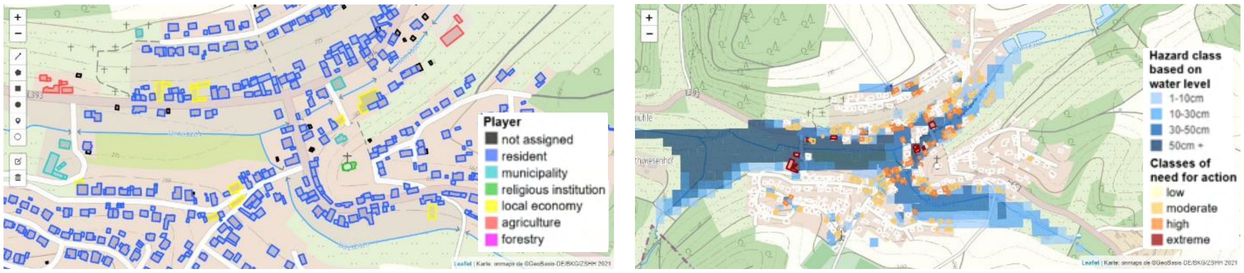

Figure 1. left: tool interface to edit objects and players, right: tool interface to display classes of hazard and need for action

In addition, an evaluation of the potential damage of the existing objects is required. For this purpose, the objects of the ALKIS® data were automatically combined with one out of four damage s classes. The damage classes are also based on the DWA regulation (2016). In this regard, it was assumed that the respective use of an object significantly influences the need for protection. Objects in particular need for protection are rated a extreme potential damage (e.g., hospitals, schools). Users can adjust the damage class of any object. The need for action for every object – and the respective stakeholder – then is determined based on the combination of hazard and damage class (see Figure 1, right).

Processing

Possible mitigation measures can be directly inserted with suitable dimensions on the map surface by using a toolbar (see Figure 2, left). Measures for retention (e.g., basins, swales or areas) and discharge (e.g., embankments, ditches or channels) are provided. Additional characteristics can be entered via another input mask (e.g., depth or costs).

Figure 2. left: tool interface to add potential measures for retention and discharge, right: tool interface to edit the level of cooperation

In the default setting, all stakeholders are shown as willing to cooperate. In practice, there is still a lack of their support. In this regard, a particular challenge is to convince those who are not affected by any major losses due to flash floods but could make a decisive contribution to protecting the common good by implementing measures. As a result, incentives are required. The user can adjust the level of cooperation of each player using one of three further cooperation classes, which range from little incentives to great incentives required up to no cooperation assumed (see Figure 2, right).
As a final step, the mathematical optimization parameters are defined. The following optimization parameters and objective functions, respectively, can be used individually or in combination:
1. weighting of classes of need for action, 2. weighting of stakeholders, 3. limitation of available incentives and 4. budget restrictions. The mathematical model was designed as a discrete "Network

Flow Interdiction“ problem with an approximation rate that is not determined by the size of the network (Boeckmann and Thielen, 2021). The solution of the problem then comprises the optimal combination of mitigation measures according to the optimization parameters.

Post-Processing

Various map layers (e.g., stakeholders involved, need for action, cooperation, mitigation measures) show the results. In addition, further measures of object protection can be considered. Object protection is not included within the optimization process since it offers protection just for one object and not the public and the common good. The presentation of results provides valuable information for decision support in risk management.

Results and discussion

At the end of the optimization process, those measures are identified that result in an optimal concept for flash flood prevention according to a given site-specific scenario defined by the user (see Figure 3). If there is still a need for action, measures can be adapted and the optimization process repeated.

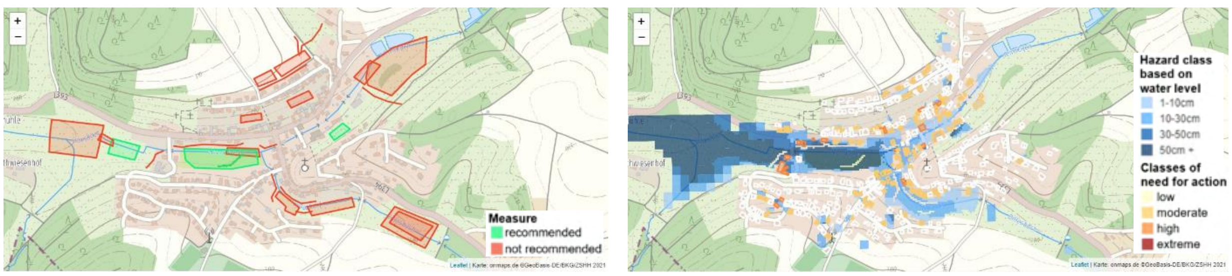

Figure 3. left: tool interface to display the result of the optimization process, right: tool interface to display the hazard classes and the need for action after the optimization process is completed

The tool's simplified hazard analysis results were verified by comparing the results with a 2D flow simulation using a geographic information system (GIS) software analyzing 30-year and 50-year rainfall events. The results showed that the modeling of the tool generally fits. While both approaches result in approximately equal water levels in the terrain, slight deviations appeared in the edge areas of the flooding areas (see Figure 4). This is, among other things, due to the different classes used to represent the water level. With the GIS software, water levels are displayed from a total height of more than 10 cm. In contrast, the tool shows water levels from a height of 1 cm.

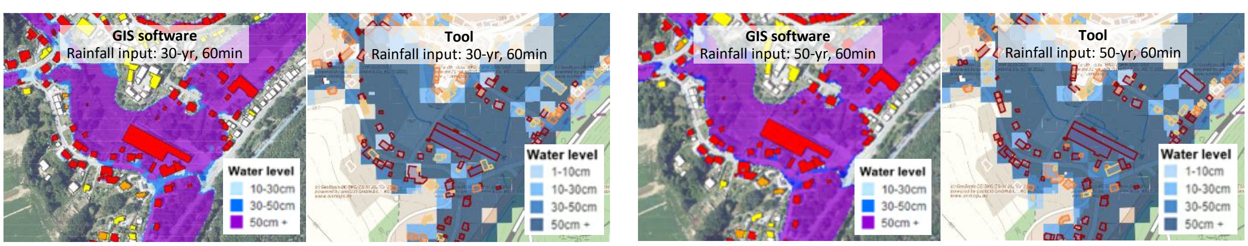

Figure 4. Comparison of calculated water levels in Neuhemsbach (Germany) with GIS software and the developed tool

Since the water level calculation is based on a simplified method, it does not replace GIS software. However, GIS software requires a high level of knowledge, has no math algorithm to identify a specific combination of measures and has no feature to consider players needed to implement a measure. It is recommended to use the tool's solution as a basis for a detailed analysis of the effects of the measures on the risk of flooding using GIS or hydraulic modeling software.

Conclusions and future work

Flash flood prevention can only be successful if private players implement measures that protect the individual and the common good. For this purpose, incentives are important to increase their cooperation. The application of the tool enables municipalities to analyze in a simplified way the effect of site-specific measure variants and to strengthen the required cooperation of private, local and municipal stakeholders. To improve the understanding of the potential damage of heavy rainfall, further research is required. There is currently no standardized assessment to evaluate the damage to objects in monetary terms. In addition to the water level, other factors (e.g., flow velocity, accumulation of sludge and sediment) play an essential role and should be considered in the further development of the model.

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