Model-based investigations for the potential of decentralised Blue-Green Infrastructure for pluvial flood mitigation

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Highlights

- 1D/2D coupled modelling of an urban catchment with decentralised Blue-Green Infrastructure
- Flood mitigation of decentralised Blue-Green Infrastructure adapted for extreme rainfall events
- Influence of the spatial distribution of decentralised Blue-Green Infrastructure

Introduction

Climate change is expected to cause an increase in heavy rainfall events (IPCC, 2023). These events can have particularly negative consequences in urban areas due to high levels of sealing, resulting in high rainfall runoff and flooding in topographic depressions. Urban areas also tend to have high levels of social and economic vulnerability. Decentralised Blue-Green Infrastructure (BGI) promotes runoff prevention through temporary rainwater storage and infiltration, which can counteract the aforementioned problem. However, in Germany, they are typically designed to handle heavy rainfall with a return period of T = 5 years (by infiltration), rather than extreme heavy rainfall with return periods of T = 100 years and beyond. The flood mitigation effects of BGI beyond design level (of T = 5 a) in case of extreme rainfall has so far only been evaluated conceptually and qualitatively (e.g. Benden et al., 2017). In this article, the effect of both established (sized to T = 5 a) and extended (sized to T = 100 a) decentralised BGI for flood mitigation is investigated in an urban catchment using a 1D/2D coupled surface runoff simulation model.

Study area

The topographically flat study area covers approx. 3.4 km² and is hydraulically delimited by its sewer catchment area as well as by neighbouring water bodies to the north, east and south. A coupled 1D/2D surface runoff model (InfoWorks ICM 2023.2, DEM1) was set up for the densely built area, which consists of 0.98 km² roof area, 0.76 km² street area with 3256 roadside trees, 0.62 km² courtyard and path areas and 1.03 km² of pervious green area. In the model, the manholes and street inlets are considered as coupling points between the sewer and the surface. This model without BGI is referred to hereafter as the base model.

Methodology

Modelling of BGI

The base model is modified for the representation of BGIs, which are modelled using the model component SWMM LID (SWMM 5.2). Table 1 lists the various BGIs with a short description of the sizing and structure. The infiltrations systems are sized for return periods of T = 5 and 100 years with sand as the pending soil. For a swale, the difference between the sizing for a return period of 5 and 100 years results in an increase in the swale area by approximately a factor of two. The infiltration trench is an underground storage for rainwater runoff, which exfiltrates in the pending soil. The swale-trench-element is a combination of a swale with an infiltration trench underneath, whereby the overflow from the swale is conveyed via a pipe directly to the infiltration trench. The layouts of the green/retention roofs and the corresponding model parameters were selected based on a literature review. The size of the BGIs depends on the connected impervious area (roof areas), except for the hydraulically optimised tree location (HOTL) and the tree trench. Their sizes are determined by the design return period of 5 years: The HOTL can be connected to 78 m² of impervious area and the tree trench to 120 m² of impervious area.

Table 1. Modelled BGIs with brief description

BGIs	SWMM LID	Description of the sizing and structure
Swale (sized to T = 5 and 100 a)	Rain garden	Pre-dimensioning according to the German DWA guideline DWA-A 138-1 for infiltration systems. Storage depth of the swale: 0.3 m
Infiltration trench (sized to T = 5 and 100 a)	Rain barrel	Pre-dimensioning according to the German DWA guideline DWA-A 138-1 for infiltration systems. Height of the infiltration trench: 0.6 m
Swale-trench-element (sized to T = 5 and 100 a)	Infiltration trench	Pre-dimensioning according to the German DWA guideline DWA-A 138-1 for infiltration systems. Storage depth of the swale: 0.3 m; height of the infiltration trench: 0.331 m (T = 5 a) and 0.523 m (T = 100 a)
Extensive green roof	Green roof	Multilayer construction, thickness of the substrate layer: 0.15 m
Intensive green roof	Green roof	Multilayer construction, thickness of the substrate layer: 0.3 m
Retention roof	Bio-retention cell	Multilayer construction, thickness of the substrate layer: 0.15 m, thickness of the retention layer: 0.1 m
Hydraulically optimised tree location (HOTL)	Rain garden	Thickness of the tree substrate layer: 1.5 m. Volume of the planting pit: 13.5 m³, area of the tree grid: 6 m², shaped as a swale with a depth of 5 cm
Tree trench	Bio-retention cell	Tree substrate layer: 1.5 m, infiltration trench (height: 0.6 m) underneath. Volume planting pit: 18.9 m³, area of the tree grid: 6 m², shaped as a swale, depth 20 cm

In the model, the roof areas are connected to the BGIs, except for the hydraulically optimised tree locations and the tree trenches, which are connected to street areas. It is assumed that every roadside tree (3256 in total) in the study area can be converted into an HOTL or a tree trench. The overflow for infiltration systems respectively the underdrain for green/retention roofs is connected to the nearest manhole. The degree of implementation of the BGIs is modelled using two different approaches: In the heterogeneous distribution of the BGIs, 50 % of the roofs are implemented as green roofs (approach 1). In a second approach, a homogeneous distribution is used, in which 50 % of each individual roof area is designed as a green roof. This approach is more theoretical, but is advantageous for the technical implementation of BGI in the model. The two approaches are transferable to the other BGIs.

Rainfall data

As rainfall loads two different model rains (type Euler II, duration D = 60 min) are used: R1 with a precipitation height of 48.9 mm (T = 100 a) and R2 with a precipitation height of 100 mm (>> T = 100 a). The simulation duration is 75 minutes to account for time-delayed runoff after the end of the rain event.

Results and discussion

Influence of the degree of BGI implementation on flood mitigation

The simulation results of the modelling approaches with and without BGI are compared to assess the effect of the various BGIs for flood reduction. The analyses described below were carried out using the implementation approach 2 (homogeneous BGI distribution). Figure 1 shows the total flood volumes at the surface in the entire study area for the base model and with different degrees of BGI implementation, here using the example of swales (sized to T = 100 a) for R1 and R2. The swales are connected to the roof areas: A degree of implementation of 100 % means, that all roof areas are completely connected to swales. The total flood volume is calculated from the maximum water level and the area of the associated calculation element (approx. 1 m²), whereby only potentially hazardous water levels of 10 cm or more are considered. As expected, the flood volume in the overall area decreases as the degree of implementation of swales increases. However, the decrease in volume is not linear for R1: Connecting 25 % of the roof area to swales results in a 12.2 % reduction in total flood volume while an increasing degree of implementation from 75 % to 100 % only leads to a volume reduction of 3.6 % (from 69.9 % to 66.3 %).
With the higher rainfall load in R2, the difference between the implementation degrees in terms of the reduction in total flood volume is significantly smaller: at an implementation degree of 25 %, the reduction is 3.9 %; between the implementation degrees 75 % and 100 %, the reduction is 3.7 % (from 88.2 % to 84.9 %).
Figure 2 shows the maximum water levels (flood depths of at least 10 cm) in the centre of flooding in the study area as a result of R1, simulated with the base model and for the swales (sized to T = 100 a) at implementation degrees of 50 % and 100 %. The flooding map shows a distinct reduction in the maximum water levels. At the lowest point in the street (marked by a black arrow), the maximum water levels are 56 cm, 46 cm and 28 cm: the swales reduce the maximum water level by 10 cm and 28 cm respectively.

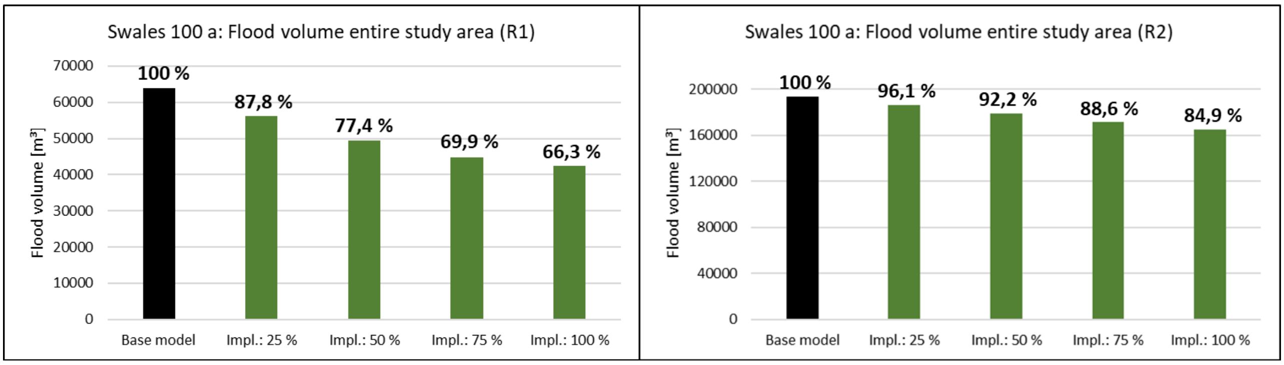

Figure 1. Total flood volume without BGI (base model) and with different degrees of implementation of swales (sized to T = 100 a). The figure on the left shows the total flood volume for R1, the figure on the right for R2

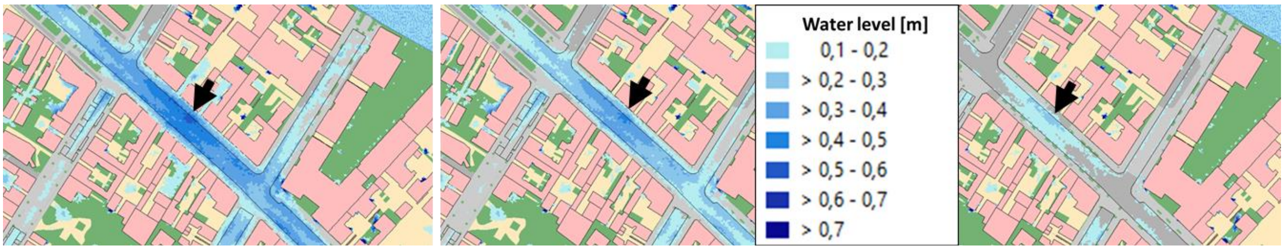

Figure 2. Maximum water levels in the centre of flooding with rainfall load R1. From left to right: base model, swales (sized to T = 100 a): degree of Implementation 50 % and 100 %

Effect of different BGIs for flood mitigation

Table 2 shows a comparison of the effects of the various BGIs on flood reduction for R1 and R2 with an BGI degree of implementation of 100 %. At first, the results of the infiltration systems and green roofs will be discussed together for each rain event, the results of the HOTL and tree trenches will be discussed separately. For R1 the BGI reduces the flooding volume by 21.6 % - 33.8 % compared to the base model. For the infiltration systems, the swale-trench-elements have the biggest effect for flood reduction: Sized to T = 100 a, they reduce the flood volume by 33.8 %. The reduction in flood volume of the swales sized T = 100 a is 12.1 % higher than for the swales sized to T = 5 a. The intensive green roofs have a slightly more positive effect (1.9 %) on the reduction of the flooding volume compared to the extensive green roofs. The effect of intensive and retention green roofs is identical: They reduce the flood volume by 33.7 with no drainage runoff.

For R2 the BGI reduces the flooding volume by 5.4 % - 33.6 % compared to the base model. While the infiltration systems sized to T = 5 a only reduce the flood volume by 5.4 % - 9.3 %, the systems sized to T = 100 a achieve almost 3 times the flood reduction with 15.1 % - 25.8 %. With the higher rainfall load, the performance of the extensive green roofs declines to 13.8 % (from 31.8 % for R1). In contrast, the intensive

Table 2. Simulation results for R1 and R2, BGI degree of implementation: 100 %

	R1			R2		
Model	**Flood volume** [m³]	**Reduction** [%]	**Overflow or underdrain** [m³]	**Flood volume** [m³]	**Reduction** [%]	**Overflow or underdrain** [m³]
Base model	63,958	-	-	193,818	-	-
Swales (T = 5 a)	50,122	*21.6*	21,947	183,273	*5.4*	74,661
Swales (T = 100 a)	42,398	*33.7*	0	164,641	*15.1*	50,418
Infiltration trenches (T = 5 a)	50,067	*21.7*	20,859	181,988	*6.1*	70,829
Infiltration trenches (T = 100 a)	43,290	*32.3*	0	162,744	*16.0*	44,444
Swale-trench-elements (T = 5 a)	48,071	*24.8*	19,542	175,776	*9.3*	66,257
Swale-trench-elements (T = 100 a)	42,368	*33.8*	0	143,814	*25.8*	29,435
Extensive green roofs	43,651	*31.8*	14,945	167,052	*13.8*	64,396
Intensive green roofs	42,393	*33.7*	0	128,917	*33.5*	4,200
Retention roof	42,393	*33.7*	0	128,785	*33.6*	0
Base model HOTL	64,786	-	-	195,860	-	-
HOTL	61,972	*4.3*	5,982	192,817	*1.6*	18,536
Base model tree trenches	64,757	-	-	196,316	-	-
Tree trenches	60,256	*7.0*	9,128	191,915	*2.2*	28,607

green roofs are almost able to hold back the complete runoff with only an underdrain volume of 4,200 m³. The retention roofs have the biggest effect for flood reduction with 33.6 % by detaining R2 completely. The HOTLs and tree trenches show the least effect for flood mitigation with only 4.3 % and 7.0 % respectively for R1. However, in total there is much less impervious area connected to the HOTLs (25.4 ha street area) and tree trenches (39.1 ha street area) in comparison to the other BGIs (97.8 ha roof area): In relation to the connected impervious area the swales (sized to T = 5 a) can reduce the flood volume by 0.22 %/ha (per ha impervious area), the HOTLs by 0.17 %/ha and the tree trenches by 0.18 %/ha. For R2, the HOTLs and the tree trenches can only reduce the flood volume by 1.6 % and 2.2 % respectively.

Influence of the spatial distribution of the BGI
Finally, a comparison is made between two different modelling implementation approaches. Approach 1 describes a heterogeneous BGI distribution, which means that the BGIs are spatially concentrated around the centre of flooding in order to investigate the spatial effect of the BGIs close to the centre of flooding. In approach 2, the BGIs are distributed homogenously in the area. Figure 3 shows the maximum water levels in comparison between both approaches for retention roofs in the study area. It is obvious that the arrangement of the BGI in the study area has a major influence on the characteristics of the centre of flooding: the maximum water level at the lowest point of the street area (black arrow) is 45 cm for the homogeneous distribution and 31 cm for the heterogeneous distribution.

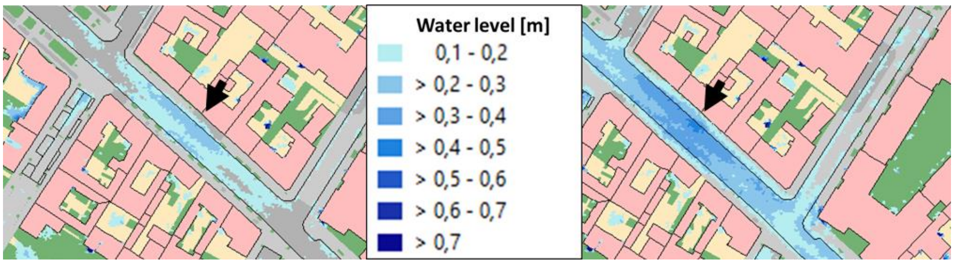

Figure 3. Maximum water levels in the centre of flooding due to R1. Left: heterogeneous distribution of retention roofs (implementation approach 1); right: homogeneous distribution of retention roofs (implementation approach 2), each with a degree of implementation of approx. 50 %.

Conclusions and future work

As expected, the degree of implementation of BGI has the biggest effect on flood reduction. However, for the less intensive rain (48,9 mm) smaller degrees of implementation already have a major effect on flood reduction. For the more intensive rain (100 mm) the infiltration systems sized to T = 100 a achieve almost 3 times the reduction of flood volume compared to the systems sized to T = 5 a. The intensive and retention green roof can even detain the 100 mm event. Compared to the infiltration systems, the performance of the extensive green roof corresponds to a sizing between T = 5 and 100 a. The hydraulically optimised tree location and the tree trench (both sized to T = 5 a) have the smallest effect for flood reduction. The biggest effect on flood reduction can be achieved with a spatially concentrated arrangement of the BGI near the centre of flooding.
As the study area has a very flat topography, it is planned for future work to apply the method to another topographically steep study area and compare the results.

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