

## Research

# Optimizing urban green infrastructure using a highly detailed surface modeling approach

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## Abstract

Urban trees and forests show a better ecosystem with many benefits, including pure air quality. The development of urban green infrastructure (UGI) creates a better management system that greatly impacts social values in an urban system. The UGI and construction activities are receiving much attention for their effectiveness in addressing various urban ecological, social and economic issues. Using green infrastructure in stormwater management can reduce the influence on urban sewerage systems and, eventually, on building water resources. The main goal of the research is to optimize the green infrastructure to provide a less-pollution, well-organized, and pleasurable environment for the inhabitants. Various models are used to study the present rainfall-runoff scenario, but the stormwater management model (SWMM) is the most preferable and suggested model. Once the parameters are accessed, optimizing the green infrastructure (GI) will be easy. A complete SWMM model is evaluated over the complete surface, and a hydrological measurement is presented. The evaluation study presents various component percentages: asphalt (37%), green (27%), ceiling (21%), grit (12%), and cemented area (2%), which provides rainproof coverage of approximately 60%. A design is developed about the diverse events of GI in urban exploiting the SWMM and demonstrates its stimulus on the rainfall-runoff behaviour. In recent years, very little attention has been given to green spaces in urban areas, which not only increases pollution but also decreases the urbanization. Therefore, urban green spaces are more important to improve air quality and resident living standards. Over the given scenario and the rainfall event, a decline of the quantitative discharge parameters is evident, such as discharge volume (i.e., from 3.6 to 61.8) and the peak discharge rate (i.e., from 5.4 to 62.7%). The simulation results show that green areas give high satisfaction with low construction costs, which shows the superlative performance ratio of the examined measures. From the investigation, it is also recommended to have green areas and public spaces in impervious urban areas, which greatly reduced the runoff in the project area.

**Keywords** Sustainable urbanization · Smart city · Urban green infrastructure · Urban heat island · Climate adaptation

## Abbreviations

UGI	Urban green infrastructure
SWMM	Stormwater management model
GI	Green infrastructure
IPCC	Intergovernmental Panel on Climate Change
RCAO	Regional climate atmospheric-oceanographic
GIS	Geographic information systems

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ESRI	Environmental System Research Institute
EIA	Effective impervious area
CA	Catchment area
DoS	Degree of sealing
OUT PT	Outlet Peter-Tunner-Gasse (PT)
SMHI	Sweden Meteorological and Hydrological Institute
UHI	Urban heat island
VR	Discharge volume reduction
NDVI	Normalized difference vegetation index
SR	Discharge peak reduction
GPS	Global positioning systems
WBM	Water Balance Model
ES	Eggenberger Straße
RWM	Rainwater management
PPS	Permeable Pavement System
OUT AP	Outlet Al-ten Poststraße (AP)

## 1 Introduction

In recent decades, the urban population has grown steadily, and these necessities increased the need for living rooms and other infrastructure, such as roads and parking lots, and are become the most demanded task. The development can be possible through the expression of urbanization and is summarized in the proposed work. Ultimately, by advancing urbanization further from an originally natural surface, the course of precipitation events can hardly occur naturally [1, 2]. In these areas, hydrogeological exchange processes (e.g. infiltration, evapotranspiration) take place, which makes it necessary in urban areas to implement a wide variety of precipitation management measures, e.g. drainage channels, to foresee [3–5]. Through surface sealing and channelled drainage of precipitation, runoff arises in the receiving water regarding water management and ecology disadvantages, such as the intensification of flood discharges, increased pollutant inputs and the reduction of groundwater recharge. Through the use of GI in rainwater area, the infiltration, evapotranspiration and surface retention from rainwater is increased, by which the rainwater coming out of the drainage system itself can be reduced, and the general drainage problem can be mitigated somewhat [6, 7]. The large-scale catchment area adjustment is an opportunity to take a closer look at the existing precipitation-runoff situation and improve through various near-natural measures [1, 8, 9].

The Smart City project is considered a lead project for use and testing more diverse alternative approaches and technologies [10–12]. The governance of smart cities is well established in [12]. Smart cities and sustainability models are developed to further highlight the impact of smart cities in the urbanization [10, 11]. To that end, among other things, the interpretation from new to erecting infrastructure also influences the rainwater management (RWM) in the project area and can be minimized. One method to achieve this is using green infrastructure in rainwater management or more natural RWM. An open-pore layer structure enables the maintenance of infiltration, retention and evapotranspiration effects, whereby the influence on the drainage system and, ultimately, the receiving waters can be reduced [1, 13].

The main goal of the research is to optimize the green infrastructure to provide a well-organized, green and pleasing atmosphere for the inhabitants. It goes through the use of various green infrastructure measures in RWM or near-natural RWM measures take place. For this purpose, different measure variants are designed and evaluated for effect on the precipitation-runoff work environment. The judgement of the measured effectiveness occurs regarding the reduction of more quantitative runoff parameters. The proposed work includes the discharge volume and the discharge peak. Also occurring in the qualitative improvements of the drain, e.g., the reduction of nutrients or heavy metals, will not be examined more closely. In addition, for improved variant comparability, the economics and the evaluation of the earnings variability with a simplified sensitivity analysis were carried out [14–16]. The following are the main contributions of the research work.

- To optimize the green infrastructure in providing a power-efficient, less-pollution, well-organized, and pleasurable environment for the inhabitants.
- The stormwater management model (SWMM) is developed over certain parameters to optimize the green infrastructure (GI). A complete SWMM model is evaluated over the complete surface, and a hydrological measurement is presented.
- The evaluation is done for various events, and the reduction in various parameters is evident, such as volume (from 3.6 to 61.8) and peak discharge rate (5.4 to 62.7%).

## 2 Background

It was considered that the global impact of human activity influenced the change in land use, mostly a deterioration of the environmental conditions, resources, and human needs. Pasture and arable land are, in addition to forest areas with 40% of the total surface use, already to a large extent. The terrestrial biomass grew and enabled one doubling of the grain harvest to two billion metric tons in the last 40 years. A huge portion of arable land's productivity has "Green Revolution" technologies, e.g., approximately artificial fertilizer and pesticides, as well as mechanization and irrigation in agriculture [6].

Modern agriculture contributes significantly to the damage of the environment through the heavy use of artificial fertilizers and pesticides, including the impairment of drinking water resources, the erosion of topsoil, and reduced fertility [15]. Land use changes directly influence the water balance as well as the regional climate [16]. The effectiveness of precipitation water in infiltration, evapotranspiration and runoff thus directly influences the temperature of the water cycle and air quality [17]. In this way, about 10% of the total "newly formed" water (approx. 3900 km<sup>3</sup>/a), of which 85% of this amount is used for agricultural purposes [6, 15, 17–19].

The Intergovernmental Panel on Climate Change (IPCC) program was founded in 1988 by the World Meteorological Organization and the United Nations Environment. The main task of the IPCC is to investigate climate change science and develop trend-counteracting behavioural strategies. The effects and implications of climate change can already be felt in many places, and there are already enough studies on the change of climates in the last century document, e.g. at IPCC [20].

The steady increase in greenhouse gas concentrations in the atmosphere since the pre-industrial era has warmed the earth's surface. The concentration of CO<sub>2</sub> (30%), CH<sub>4</sub> (145%) and N<sub>2</sub>O (15%) increased significantly, mainly due to human influence [1]. Sea levels have risen by 10 to 25 cm over the past decades due to global warming and many other factors. The global air temperature near the surface has itself elevated since the late nineteenth century in the middle, around 0.3 to 0.6 °C and the country's night temperatures have succeeded [21]. The IPCC assumes that the climate will continue to change in the coming years. The global air temperature near the surface should increase until the Year 2100 in the middle, dependent on the respective climate scenario, around 1.0 to 3.5 °C [1, 21, 22].

Global warming is often considered the most common factor when looking for climate change. A steady rise is noted in the sea level and the average air temperature in the world over a certain observation period [23, 24]. Global warming has become a serious concern and is a big global challenge. Such changes in air temperature and rising sea levels are considered occurrences of many phenomena. Both directions are opposite, as the former reduces the negative impact on the environment and climate, while the latter increases emissivity and global warming [25].

The researchers examined the impact of climate change on the mixed water drainage system of downtown Helsingborg (Sweden). A regional climate atmospheric-oceanographic (RCAO) model of the Sweden Meteorological and Hydrological Institute (SMHI) serves as a base for the appraisal of future climates. The investigation establishes twelve simulations combining two IPCC gas emission climate scenarios (medium and high) and urban development scenarios (increased population—system decoupling of the city center—reduction of water consumption). The investigation results show that with a constant or increased population, a slight or significant aggravation of the drainage problem increases in the cut-off volumes. This results in an increased nutrient input into the water bodies. However, it shows that through consistent reduction of the combined sewer system connected to the land, along with other measures, the influence of climate change can be reduced to negligible levels [26].

## 2.1 Urban heat island effect and biodiversity

Howard [27] is considered the “founder” through his observations of the London climate, the concept of the heat island effect known as urban heat island (UHI), noting that the air temperature in the city is often higher than in the immediate vicinity. The effects of the UHI are now proven by numerous studies. Olén et al. [28] observed a connection between maximum UHI intensity and the settlement population. They describe the increasing evapotranspiration through the warmer, drier air from surrounding sealed surfaces with the consequence of an accelerated drying out of vegetation. Sealed surfaces thus carry directly through noticeable heat emission to the microclimate of the environment. Cai et al. [8] found a strong linear correlation in their investigations between the surface temperature and the degree of surface sealing fixed in all seasons. Because the study of the connection between normalized difference vegetation index (NDVI) and the surface temperature led to a less meaningful result and fluctuated more strongly seasonally, the authors use the degree of sealing at least as a supplementary parameter vicinity. In addition, parameters and the NDVI can become the UHI effect indicators [28].

The term biodiversity is used as an umbrella for the wealth and variety of the species. The changes in biodiversity affect both economic (e.g. ecotourism, information acquisition in medicine) as well as non-economic (aesthetic, ethical and much more) interests and influence productivity, the carbon pool, the hydrology and the nutrient cycle of an ecosystem [29]. Olén et al. [28] studied the impact of retention basins along highways on the biodiversity of microorganisms in the area.

## 2.2 Urbanization and surface sealing

Urbanization is mainly associated with a progressive expansion of the area of a city accompanied by an increase in the number of inhabitants. It includes densification effects, demographic changes, surface sealing and land use changes. Progressive urbanization brings many problems and opportunities [17]. A clear trend is characterized by population development from urban areas in the [28]. The proportion of urban people living in these areas increased from 13% in 1900 to 29% in the year 1950 and up to 49% in 2005. In 2030, 4.9 billion people are expected to live in urban areas [30]. Bleecker et al. [31] studied the influence of sealed areas and the necessary accuracy of their determination on urban drainage systems.

## 2.3 Runoff problems in urban areas

One effect of progressive urbanization is the increase in surface sealing. In contrast to the unsealed surface, the sealed surface has less evaporation and a smaller storage capacity, leading to higher surface runoff and river levels in the cities. So, the unpaved surface comes only around 0 to 20% of fallen precipitation for the drain. However, strong sealed surfaces (e.g. Asphalt, Concrete, roofs) are expected with one discharge fraction from 90 to 100%. The sealing of surfaces in urban areas influenced the drainage system [32–34]. According to Even et al. [21], water bodies are caused by increasing surface sealing and the channelled derivation from rainwater through mixed or separation systems water management-ecological.

After reaching certain thresholds, parts of the mixed water into the receiving water are observed [34, 35]. According to Grimm et al. [17], a significant contribution of total emissions to water is made. In addition to combining dry-weather runoff with channelled surface runoff, it comes in the relief case but also to remobilization from seasoned contaminants. Discarded combined water, e.g., from combined water overflows, leads the water body to consume solved oxygen. Based on quality measurements carried out before and after the occurrence of the precipitation of water into the sewage system, degradation and conversion processes are traced, and the distribution of dirt and pollutants are detected [30, 36]. Using near-natural RWM measures, the infiltration, evapotranspiration and surface retention of precipitation water significantly increase. The impact of RWM measures is often assessed by comparing the quantitative runoff parameters next to the discharge volume reduction (VR) and the discharge peak reduction (PR) used to become the temporal shift from the drain tip to the effectiveness assessment. Kasznar et al. [35] and Guan et al. [37] found clear VR and PR. Zhao et al. [38] and Guan [37] determined VR and PR during the use of green roof systems, together with a reduction in the rejected MW volumes. Babí Almenar et al. [1] and Fassman et al. [39]

showed the effectiveness of permeable traffic areas in terms of VR and SR. Jia et al. [40] investigated the hydrological effectiveness (VR and PR) of storage basins and bio-retention zones. Montalto et al. [41] showed a profitability analysis that using near-natural RWM measures is more cost-efficient than conventional systems and can reduce the discharge of mixed water.

## 2.4 Green infrastructure

The gray and green infrastructure describes the construction and the functionality from near-natural RWM measures and the advantages of conventional systems to rainwater management (RWM). Progressive urbanization leads to changes in land use, sealing of natural surfaces, impairment of biodiversity, and thus a serious burden on the environment, including disruption of elementary cycles of nature (e.g., nutrients and water). Against this background and in the sense of sustainability, alternative methods and strategies must be used to remedy the negative effects. It could be the working of the overall system, differentiating between the greyer and greener infrastructure.

Combining green infrastructure with conventional systems through mutual support can create usable synergy effects. Ideally, by adapting existing or planned infrastructure ecological corridors, its advantages also positively influence the gray infrastructure (e.g. reduction of the UHI effect or from drain spikes in waters) [32, 42].

According to Guan et al. [37], significant improvements in the RWM can be achieved through green infrastructure. Therefore, a conventional drainage system must be part of the gray infrastructure assigned and essentially consists of street sewers (collectors) with house connections, street gullies, manholes, the wastewater treatment plant and, if necessary, culverts and relief structures. According to [43, 44], different procedures (i.e., mixed process, separation process, modified mixing process and modified separation process) are adopted. Ding et al. [45] provides preferable recommendations for the decision-making of a greener environment and saving of water in developing agriculture. Exploiting the shift-share analysis method is done to evaluate the industrial transformation in China from 2004 to 2019 [46]. Zhang et al. [47] gives a detailed discussion of the economic aspects of green bonds and their influences on green technology.

Ahiablame et al. [4] gave an overview of the results of various studies concerning the mode of action of several near-natural RWM measures. Storage troughs are depressed zones designed to absorb rainwater runoff, infiltrate it, and release it again with a delay. It is mostly in deployed residential and commercial areas and can be executed in different vegetation intensities Fields [15]. Rudnicka et al. [48] states that the system is based on areal infiltration above the animated bottom layer. It allows a very good biological cleaning of the inlet water and the retention of undissolved substances. The functioning of the measure needs regular cleaning and inspection (e.g. falling leaves in autumn) and regular mowing. This measure finds everything at moderate permeable underground application and makes only low demands due to the good cleaning performance to the seeping away water. Storage wells require less space as surface infiltration and the layout of urban habitat can be deployed [13, 49]. The construction variants of storage troughs range from just overgrown turf hollows to more overgrown bioretention zones. The latter are generally distinguished from storage troughs through significantly denser vegetation and a substrate and storage layer [50–55].

## 3 Materials and methods

The methodology of the research work consists of two main parts: (i) data preparation in the GIS and (ii) the creation and application of the hydraulic–hydrological model, including the evaluation of different measures. Section 3.2 refers to preparing and processing the output data received in the GIS. The sequence in the methodology can be divided into the following processing steps:

- i. The detailed mapping of the project area's surface is presented as this work's main aim. At the beginning of this work is a detailed review and processing of the original data, followed by the necessary area inspection.
- ii. Further processing or refinement of the original data and adding the recorded surface situation,
- iii. Viewing and processing of the hydraulic-hydrological basic data,
- iv. Creation of a preliminary catchment area map (see Fig. 1),
- v. Plausibility check as a result of an additional area inspection and Recording from subordinate Split of the drainage system,
- vi. Updating the catchment area map, adapting to newly collected data well as detecting further model-relevant runoff parameters,

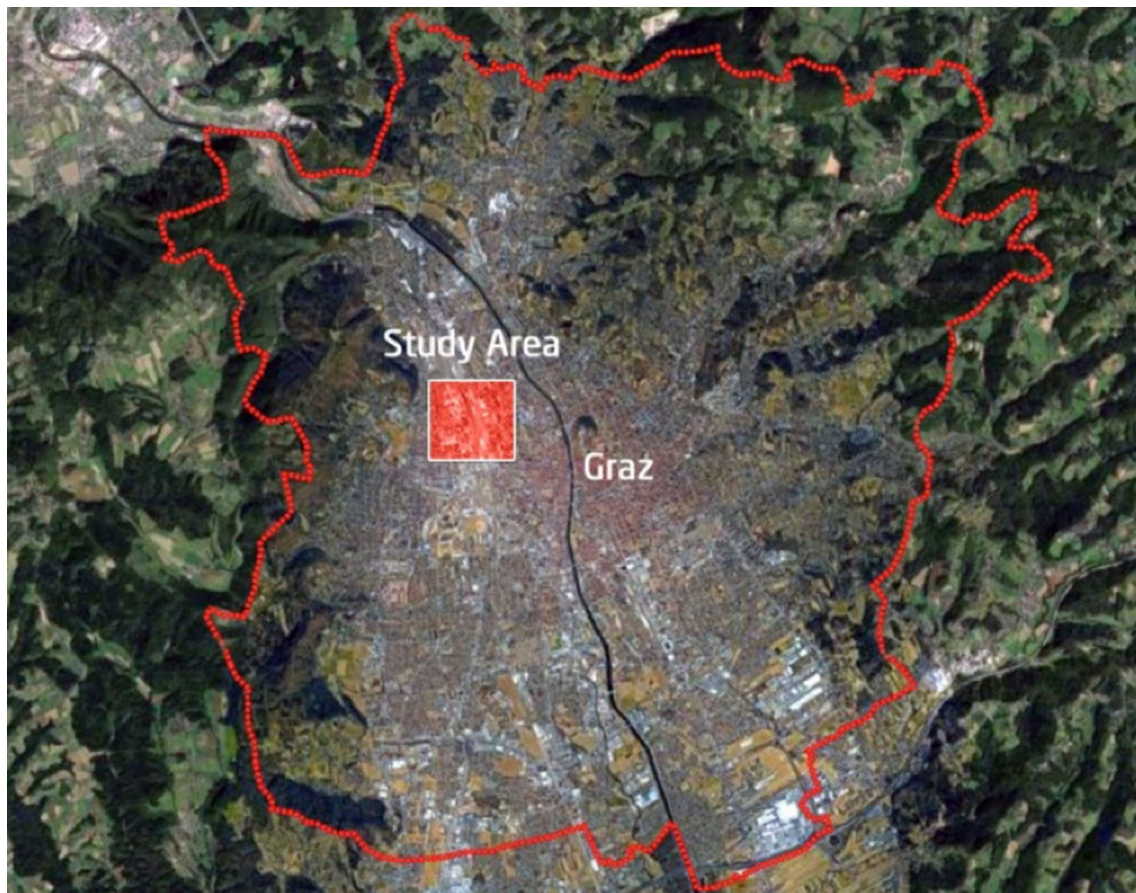


**Fig. 1** First steps in creating the surface map—representation of the building and traffic areas in the northern area offers (ArcGIS). Red color on the graph to show the projected area

- vii. Creation of an initial model of inappropriate precipitation-runoff simulation software along with the Illustration from elementary hydrological processes,
- viii. In addition to the RWM measures already present in the initial model according to the design guidelines for infiltration systems,
- ix. Conception and application of various measures and
- x. Carrying out and evaluating the simulations with a subsequent overall assessment.

### 3.1 Project area—smart city

The work is intended to provide insight into the nature of the development of the project area. The project area—the “Waagner-Biro Quarter”—is located in the north-western part of the Styrian State capital, Graz (see Fig. 2), west of the main train station, of the station belt as well as the southern railway route and covers an area of approximately 69.9 ha one-fifth of the total area of the 4th district of Graz Lend. The Waagner-Biro-Strasse does not come within a demarcation of the project area since there are still larger parts of the considered catchment area northeast of it. In the Waagner-Biro district, a former industrial area, attempts are being made to develop innovative concepts for a district that is energy-efficient or energy-self-sufficient, reduces emissions and is as resource-saving as possible to offer the people staying in it a livable environment. The Smart City project is considered a lead project for Austria and is divided into Smart City West and South, with the Waagner-Biro and Reininghaus projects being part of the Smart City West. The Smart City Waagner-Biro project area is being advanced in stages and should be completed with the construction of the new middle school in 2023. The parts are Cool City and Science Tower, which were almost completed when this work was performed. The north, middle and South (2019 to 2022) will change the appearance and surface of the area considerably redesigned. For these areas, however, planning is about the goals and principles of green infrastructure.



**Fig. 2** The map location of the project area overview map of the Graz urban area is shown—the project area is bordered in red. It shows the working place of the project. A red circle is drawn on the graph to show the projected area

### 3.2 Geographic information systems

Geographic Information Systems (GIS) enable efficient management, linking, analysis and interpretation of spatial data sets and are therefore indispensable in planning, analysis and administration processes. Geographical datasets form the most important part of any GIS because no user interaction would be possible without them. Nowadays, spatial data can be captured with the help of various global positioning systems (GPS). In addition to the geographical coordinates, the room height is recorded in a mostly country- or region-specific file format. GIS can be used for various purposes and in different ways structures exhibit. The market gives it a one-size selection from providers, whereby some quality system providers have crystallized in recent years. This will be used to process this project GIS ArcGIS used by ESRI. ArcGIS is a widely used geographic information system [developed by the Environmental System Research Institute Inc. (ESRI)], which provides many data manipulation and analysis tools. In particular, the spatial analysis tools (Spatial Analyst) offer a wide range of tools for editing infrastructure projects.

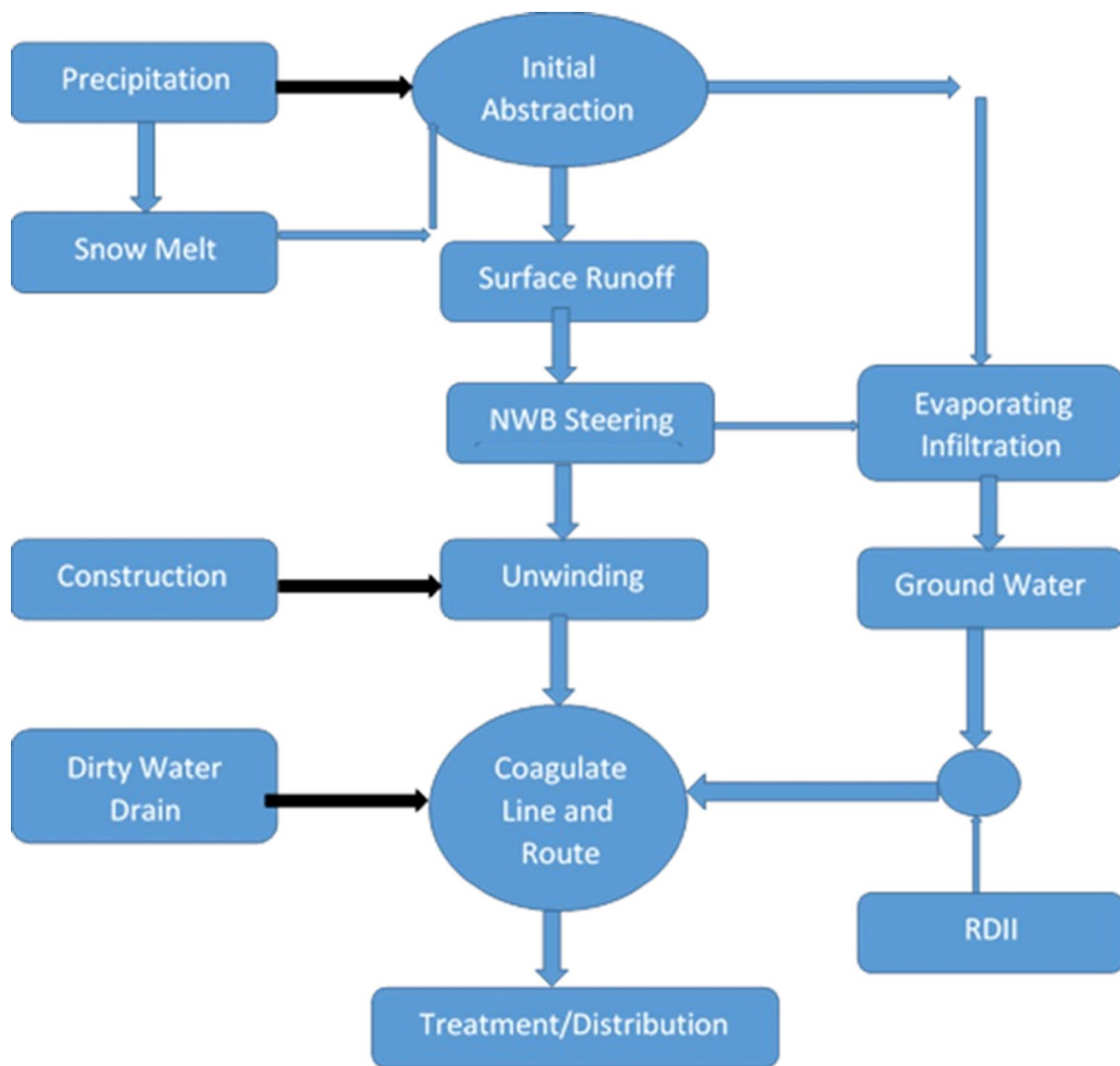
### 3.3 Rainfall-runoff simulation software

This section describes the structure and functionality of the used simulation software. To guarantee the functionality of elementary infrastructure systems, the corresponding systems, such as the city drainage system, must be continuously adapted. Manual methods of exposure assessment and verification of drainage systems are computationally extensive and useless. One verification with the help of numerical model simulations is defined as state-of-the-art and is used for numerical simulations of precipitation-runoff processes in urban areas. It can be chosen between

several systems and is regarded as a complete modelling package. Elliott et al. [3] gave an overview of the status of the modelling tools and focused on the model's ability to be meaningfully natural to map RWM measures. Storm Water Management Model (SWMM) [50] and Water Balance Model (WBM) [51] are considered to be the best models to handle the majority of the measures examined in good quality. These models stand out in the area of near-natural RWM measure modelling as to be favoured systems. In addition to the possible uses of near-natural RWM measures, the models are also based on temporal resolution. The catchment and drainage system, runoff generation and discharge (quantity) and the possibility of incorporating contamination (quality) are compared with each other.

Modelling tools in urban settlement drainage and comparing them in a multi-stage process. The possibility of implementation of green infrastructure is being studied extensively, with the main focus mainly on tools to determine execution costs or life cycle costs. Figure 3 shows the individual processes and process links shown. Based on the generated precipitation, a quite linear process structure can be seen, connected with the concluded treatment or distribution.

Based on the generated precipitation basically a quite linear process structure can be seen, which is connected with the treatment or distribution.



**Fig. 3** The working model of the project is shown using the blocks of each model. The individual processes and process links show the working links of each block. Flowgraph to show the working of the proposed method. Squares show the process and circles show the condition



### 3.3.1 Surface runoff

The model structure of SWMM allows areas with different properties to be divided into sub-areas. The influence of the spatial variability of the topography, land use and soil characteristics on surface runoff behaviour can be brought into the Model. In principle, the surface is represented in SWMM as a rectangular area with width  $W$ , area  $A$  and length  $L$ . The accumulating surface runoff of the entire area is drained towards one point. The surface runoff is determined in SWMM using an equation system based on a non-linear reservoir model. It comes through accumulating precipitation, infiltration and evapotranspiration changes in storage.

The following brief description of the underlying implementation in SWMM systems of equations for the hydraulic calculation of surface runoff is applied [50]. The model structure is expressed by (1).

$$\frac{\partial d}{\partial t} = i - e - f - q \quad (1)$$

where  $\{i, e, f \text{ and } q\}$  denote the precipitation, evaporation, infiltration and drain rate in mm/s respectively. It is assumed that the surface runoff is similar to that of more even discharge in a rectangular channel with width  $W$ , the depth  $(d - d_s)$  and the gradient  $S$  (slope). Using the Manning equation, the discharge rate  $Q$  (m<sup>3</sup>/s) can be expressed as

$$Q = \frac{1.49}{n} S^{\frac{1}{2}} R_x^{\frac{3}{2}} A_x \quad (2)$$

The factor 1.49 can use as a metric value.

$$\frac{\partial d}{\partial t} = i - e - f - \alpha (d - d_s)^{5/2} \quad (3)$$

$$\alpha = \frac{1.49 W S^{1/2}}{A n} \quad (4)$$

In (2),  $n$  is Manning roughness coefficient, (3), including (4), corresponds to a non-linear differential equation and can therefore be numerically solved if the input data is available above the individual time steps.

### 3.3.2 Infiltration

Infiltration processes are included as shown in (2), the detection of accruing surface runoff and are considered the formation of a detailed model. The relevance of this process depends on the degree of sealing of the surface since the evaporation term tends to be larger in heavily sealed areas with "losses" in discharge volume. According to Babí Almenar et al. [1], several options are implemented in SWMM, the infiltration process simplified to depict:

- A method according to Horton
- Modified Horton
- Green Ampt
- Curve Number method

### 3.3.3 Close-to-nature RWM measures

The near-natural RWM measures offer a numerous advantages compared to conventional measures. In urban areas they are usually in the immediate vicinity of runoff areas, have a hydraulic connection to those surfaces and thus serve to control the flow. The three-layer system structure is represented by (5), (6) and (7), where (5) is the surface layer, (6) is the bottom layer and Eq. 7 is the storage layer.

$$\Phi_1 \frac{\partial d_1}{\partial t} = i + q_o - e_1 - f_1 - q_1 \quad (5)$$

$$D_2 \frac{\partial \theta_2}{\partial t} = f_1 - e_2 - f_2 \quad (6)$$

$$\Phi_3 \frac{\partial d_3}{\partial t} = f_2 - e_3 - f_3 - q_3 \quad (7)$$

### 3.3.4 Hydraulics

The outflow of accumulating precipitation water through the drainage system can be expressed using mass and momentum conservation equations. SWMM allows switching between several methods of description of the flow process, whereby dynamic analyses deliver the theoretically most accurate results. The SWMM implemented equations of conservation of mass and momentum for discontinuous gravity discharge (gradually changing, unsteady water flow) in Pipes and channels, known as (12).

The system of equations basically consists of the continuity (8) and the energy Eq. (9).

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \quad (8)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial \left( \frac{Q^2}{A} \right)}{\partial x} + gA \frac{\partial H}{\partial x} + gAS_f = 0 \quad (9)$$

The friction gradient  $S_f$  (10) is calculated using the Manning equation.

$$S_f = n^2 \frac{Q|U|}{AR^{4/3}} \quad (10)$$

Equations (8), (9) and (10) can be in the form of (11).

$$\frac{\partial Q}{\partial t} = 2U \frac{\partial A}{\partial t} + U^2 \frac{\partial A}{\partial x} - gA \frac{\partial H}{\partial x} - gAS_f \quad (11)$$

Equation (11) thus enables the calculation of the flow process within half the line. An additional equation is required to solve the system (12), which is necessary to show the link between the node and the attached described attitudes.

$$\frac{\partial V}{\partial t} = \frac{\partial V}{\partial H} \frac{\partial H}{\partial t} = A_s \frac{\partial H}{\partial t} \sum Q \quad (12)$$

## 4 Results

It shows the results of the conducted research, executes simulations and compares the results of individual calculation scenarios. In addition to different combinations of measures, different simulation periods and different precipitation events are also considered. This research focuses on the quantitative discharge parameters of the different variants, scenarios and catchment areas. It includes the reduction of VR and PR that occurs as the main parameters to judge the measured effectiveness.

### 4.1 Surface elevation

Figure 4 shows a section of the completed surface map showing the surface survey's level of detail to recognize it. The differences in land use through coloured coding and surface type differences using code annotation are recognized. The completed surface map serves as a basis for implementing the surface in the precipitation-runoff model. For a meaningful model are, however, still additional parameters using ArcGIS to determine. Table 1 shows the polygon areas assigned to surface and land use types to create the most meaningful surface image. The results of the surface survey of the entire



**Fig. 4** The blocks are divided into various section of the finished surface map in the northern area of the catchment area (CA)—the land use color coded and by means of abbreviations of the respective surface type—demarcation of the project area in red (ArcGIS). Red and green square shows different types of land and their usage

**Table 1** Results of the surface survey according to the surface map (GIS)—for the entire project area (EPA) and selected sub-areas

Surface type	Code	Surface type	Code	Surface type	Code
Asphalt	A	Concrete	B	Gravel	S
Natural stone	NS	Paving stone	PS	Bricks/tracks	ZB
Lawn	R	Lawn/vegetation	RV	Vegetation	V

project area and selected sub-areas are in Table 2. It includes the absolute and relative area shares of the individual land use types and surface types. The corresponding areas’ sealing degree is determined in Table 3.

### 4.2 Long-term simulation

The results of a long-term simulation of the calculation model are presented. The applied precipitation series offers continuous event recording from 1996 to 2006 previously. The new research stating from 2018 to 2022 includes several hydrologically interesting individual events that are classified as individual events and dealt with by independent simulation. To present the determined results of the long-term simulation as clearly as possible, we develop different charts and final result listing in tabular shape application. The  $Area_1$  denotes the  $E_1$  and  $Area_2$  denotes  $F_2$  as shown in Fig. 5.

Figure 6 shows the runoff volume reduction evaluation results for the project area with a 10-year precipitation series. It includes the occurring drain volume on the ordinate, and the examined scenarios or the different spouts on the abscissa are applied. It is possible to recognize that the outlet “OUTES” is claimed at the strongest. The sewer line in Eggenberger Straße (ES) flows through with more than twice as much volume as the strands of the old one’s

**Table 2** Results of the surface survey according to the surface map (GIS)—for the entire project area (EPA) and selected sub-areas

Surface type	Surface type code	Land use type	A		Area <sub>1</sub> (E <sub>1</sub> )		Area <sub>2</sub> (F <sub>2</sub> )		EPA	
			A <sub>absolute</sub> [m <sup>2</sup> ]	A <sub>relative</sub> [%]	A <sub>absolute</sub> [m <sup>2</sup> ]	A <sub>relative</sub> [%]	A <sub>absolute</sub> [m <sup>2</sup> ]	A <sub>relative</sub> [%]	A <sub>absolute</sub> [m <sup>2</sup> ]	A <sub>relative</sub> [%]
Asphalt	A	Other	42.18	0.062	0.00	0.000	5259.70	12.817	8606.75	1.231
Asphalt	A	Parking spot	3247.15	4.811	1804.92	4.661	4566.94	11.129	38260.75	5.474
Asphalt	A	Sidewalk	2813.79	4.169	1421.10	3.669	3361.01	8.190	37708.41	5.394
Asphalt	A	Street	12501.8	18.5	11141	28.8	6522.8	16	173338	24.8
ΣAsphalt			18611	27.60	14367	37.1	19710	48	257914	36.9
Concrete	B	Other	18.1	0.03	0	0	18.1	0.04	61	0.01
Concrete	B	Parking spot	0	0	0	0	0	0	0	0
Concrete	B	Sidewalk	81.1	0.12	0	0	75.7	0.19	229.6	0.03
Concrete	B	Street	106.4	0.16	0	0	0	0	318.3	0.05
ΣConcrete			205.6	0.31	0	0	93.7	0.23	608.9	0.09
Gravel	S	Other	614.6	0.91	0	0	1182.6	2.88	67168.8	9.61
Gravel	S	Parking spot	624.6	0.93	292.4	0.76	1218.1	2.97	8539.8	1.22
Gravel	S	Sidewalk	34.8	0.05	0	0	12.8	0.031	513.4	0.072
Gravel	S	Street	155646	2.306	759.36	1.961	0.00	0.000	5109.05	0.731
Σ Gravel			2830.38	4.193	1051.71	2.716	2413.48	5.881	81331.14	11.635
Natural Stones	NS	Others	0.00	0.000	0.00	0.00	0.000	0.00	0.00	0.000

**Table 3** Results of the surface survey according to the surface map (GIS)—surface types, degree of sealing and area proportions for the entire project area and selected sub-areas

Surface type	Degree of sealing [%]	Area A		Area <sub>1</sub> (E <sub>1</sub> )		Area <sub>2</sub> (F <sub>2</sub> )		EPA	
		A <sub>absolute</sub> [m <sup>2</sup> ]	A <sub>relative</sub> [%]	A <sub>absolute</sub> [m <sup>2</sup> ]	A <sub>relative</sub> [%]	A <sub>absolute</sub> [m <sup>2</sup> ]	A <sub>relative</sub> [%]	A <sub>absolute</sub> [m <sup>2</sup> ]	A <sub>relative</sub> [%]
Green area	0	2.645	39.2	0.235	6.1	0.521	12.7	19.137	27.4
Gravel	25	0.283	4.2	0.105	2.7	0.241	5.9	8.133	11.6
Other	25	0.00	0.00	0.00	0.00	0.0	0.0	0.487	0.7
Asphalt	100	1.861	27.6	1.437	37.1	1.971	48.0	25.791	36.9
Concrete	100	0.021	0.3	0.00	0.00	0.009	0.2	0.061	0.1
Natural Stones	91	0.003	0.00	0.00	0.00	0.00	0.00	0.003	0.00
Cobble Stone	91	0.306	4.5	0.00	0.00	0.091	2.2	1.761	2.5
Roof area	100	1.632	24.2	2.096	54.1	1.270	31	14.529	20.8
ΣA		6.750	100	3.873	100	4.104	100	69.902	100
Σdegree of sealing (DoS)		57.3	%	91.9	%	82.7	%	63.1	%

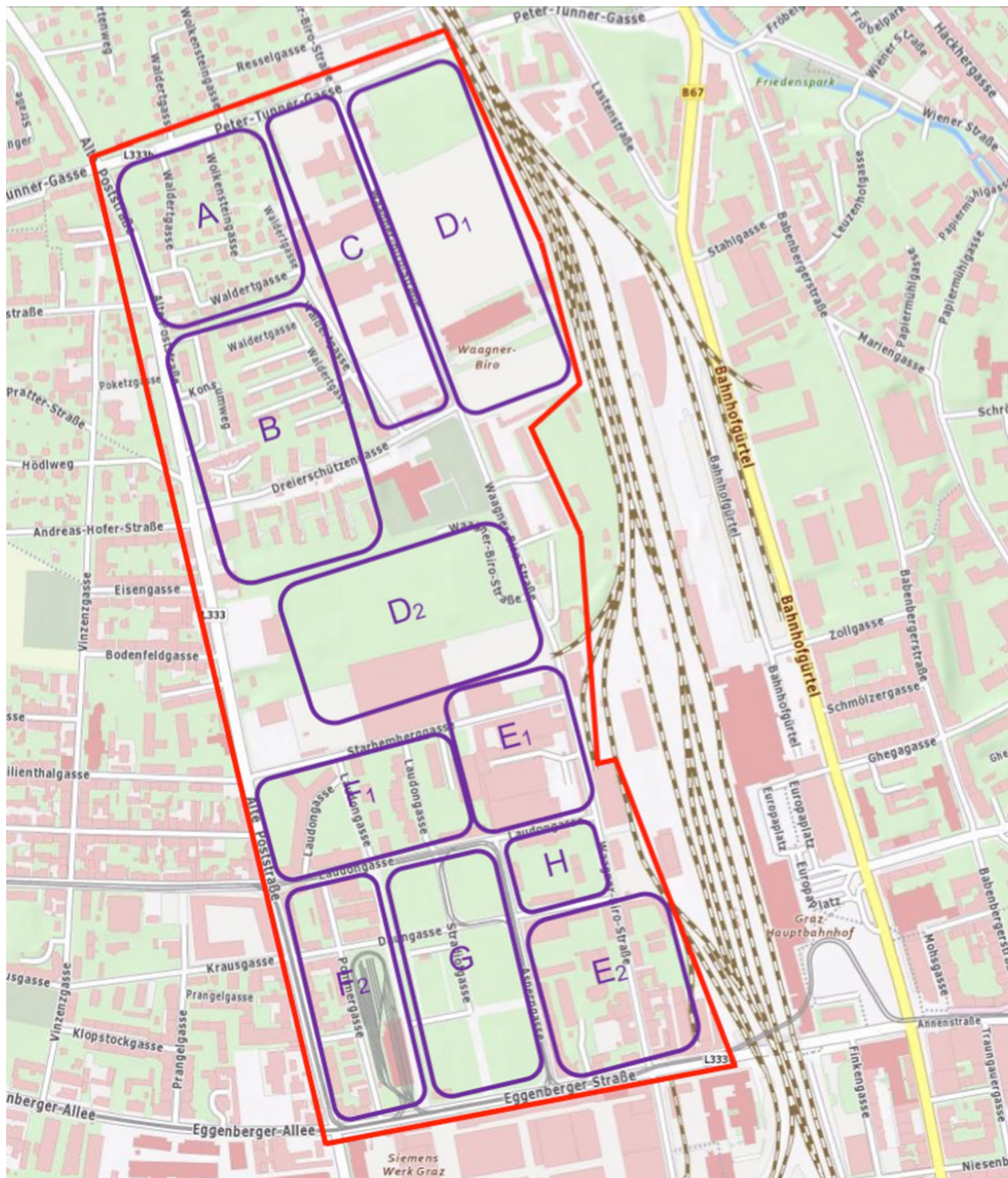
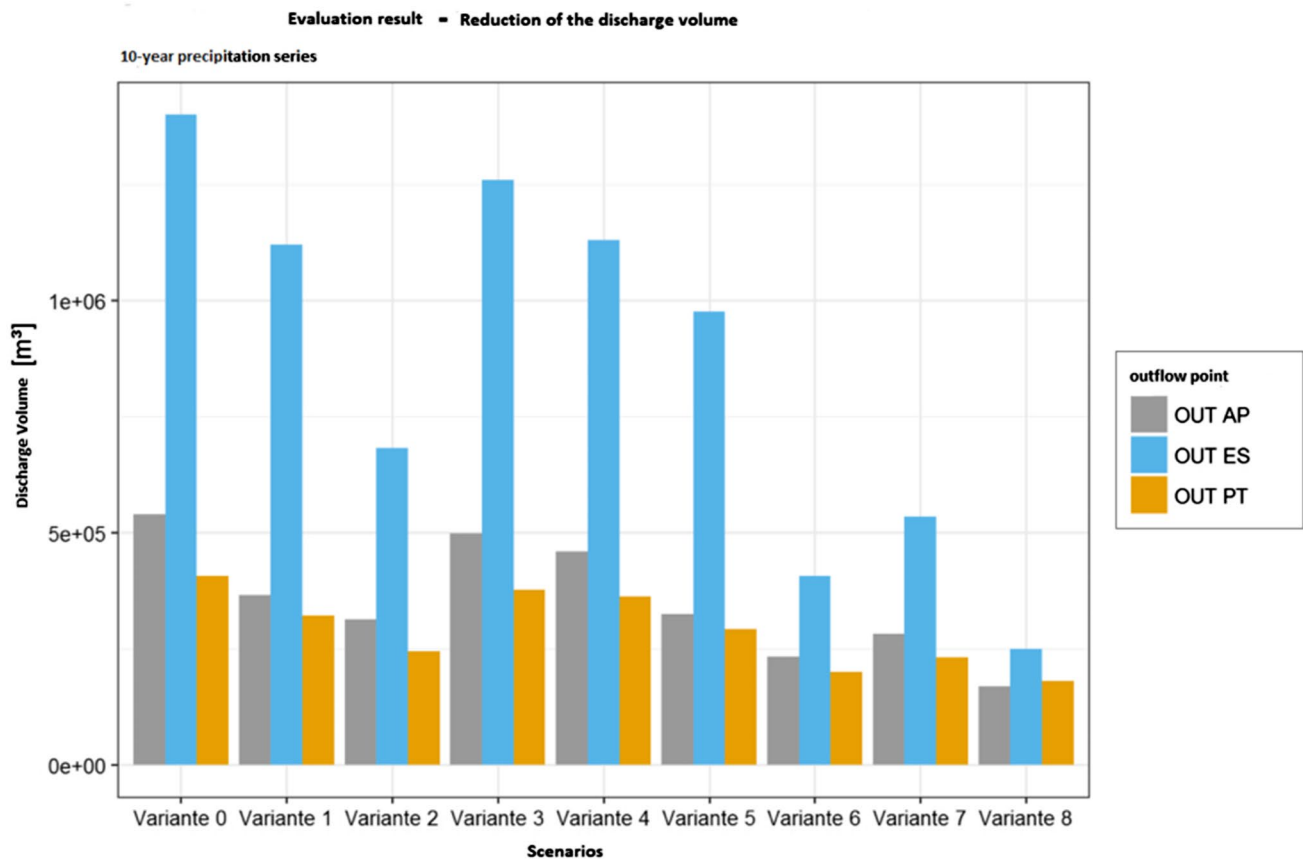


Fig. 5 Overview map of the Waagner-Biro project area. All the areas and sub-areas (purple color) are selected in the red line

post road (AP) or the Peter Tunner Alley (PT). For the outlet OUT PT, it shows up in variant 8 ( $V_8$ ). The strongest VR is accruing drain  $V_2$ ,  $V_6$ , and  $V_7$  points are already clear reductions. "OUT AP" draws itself the strongest reductions at  $V_8$  and  $V_6$ . Here,  $V_2$ ,  $V_5$  and  $V_7$  already show good results.

The reduction image at "OUT PT" is similar to "OUT AP" and shows the greatest reduction at  $V_8$ . We also examined the potential reduction in the drain spikes in Fig. 7. It is evident that the runoff peaks show fewer reductions compared to the reduction in runoff volumes. The strongest reductions are determined for the outlet "OUT IT" which permits itself at the  $V_6$  and  $V_8$ .  $V_2$  and  $V_7$  point already shows handsome reductions. The "OUT AP" show very low differences between  $V_1$  and  $V_2$  or  $V_3$  and  $V_4$ .  $V_8$  points also show the highest reductions. The evaluation of  $V_6$  to  $V_8$  shows "OUT PT" nearly identical results for the PR.



**Fig. 6** Result of the evaluation regarding reduction of the discharge volume in the EPA for a 10-year precipitation series. Bar graph shows the discharge volume for various variants. OUT ES gives the larger values over all variants

### 4.3 Result evaluation

The evaluation of the results takes place primarily above the analysis of the effectiveness parameters  $R$  and  $R_f$ . The parameter  $R$  shows a very clear picture since the highest reduction values independent of the CA at the variants reached 2 or 6 to 8th. At the strongest, the drain volume and peak discharge is included for the CA is reduced. All information about any reductions  $R$  that may take place is based on;

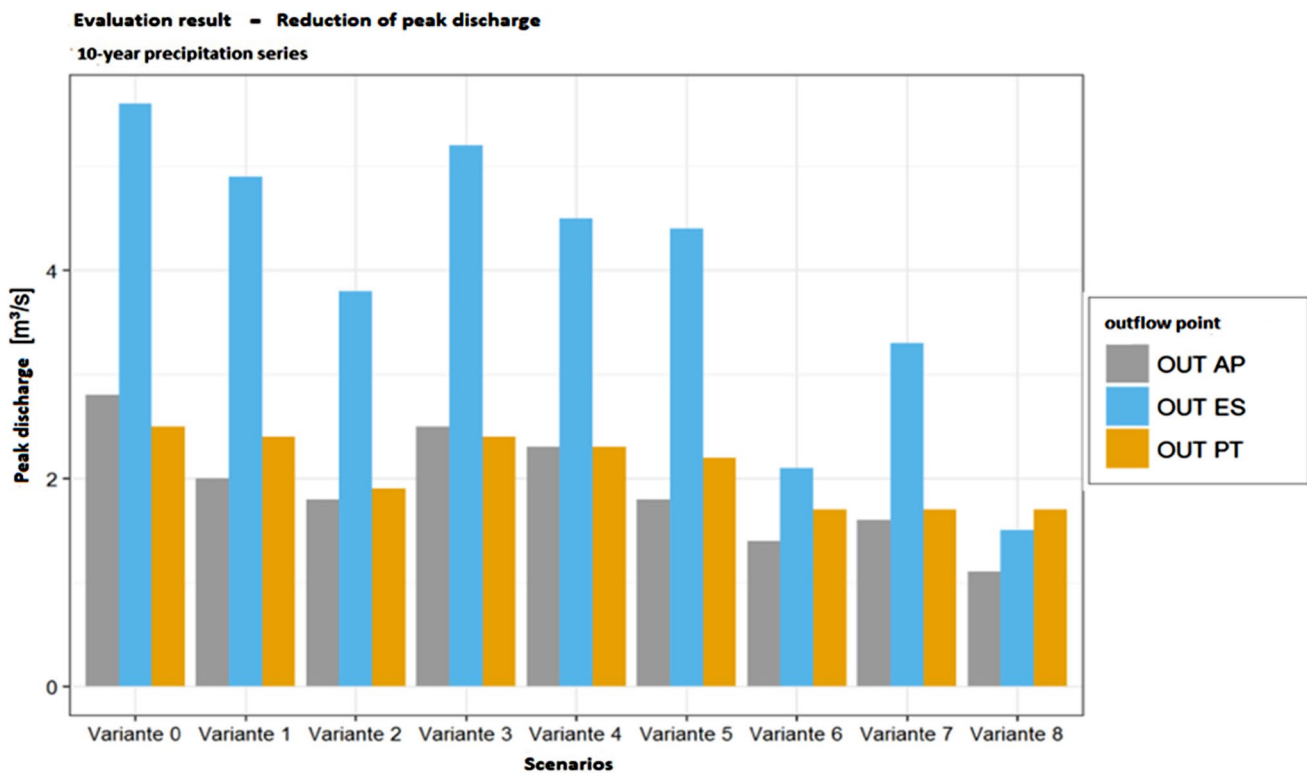
$$R = (X_o - X_s) / X_o * 100 \quad (13)$$

where  $X_o$  is the discharge volume or discharge peak reference value at variant 0, and  $X_s$  denotes the value of the corresponding measured variant discharge volume or discharge peak. Similarly, the parameters  $R_f$  is introduced to compare the effectiveness of the measured over a variant to the total area,

$$R_f = \frac{R}{(A_{RWM} / A_{CA}) * 100} \quad (14)$$

where  $A_{RWM}$  is the RWM applied measured area and  $A_{CA}$  denotes the catchment area.

For the parameter  $R_f$  the following can be ascertained: for OUT ES, the variants show similarly low results of 0.8 to 1.5. 1 to 6, stronger reductions are observed at  $V_7$  and  $V_8$  with  $\sim 10$  or  $\sim 2$ . For OUT PT shows itself compared to OUT IT, a differentiated image of variant results in  $V_4$  has a particularly low value. Again, the highest effectiveness values are at  $V_7$  and  $V_8$ , recognizable with  $\sim 17$  or  $\sim 4$ . At OUT AP show itself on  $V_7$  throughout better results as in the other drop-off points whereby  $V_4$ , compared to OUT PT, better functions. Like the other outlet points, the highest effectiveness values are shown at  $V_7$  and  $V_8$  with  $\sim 9$  or  $\sim 4$ . The best results ( $R_f$ ) can thus achieve 17.1 or 12.6 at OUT PT during variant 7.



**Fig. 7** Result of the evaluation regarding the reduction of peak discharge in the EPA for a 10-year precipitation series. Bar graph shows the peak discharge for various variants. OUT ES gives the larger values over all variants

#### 4.4 Single event simulation

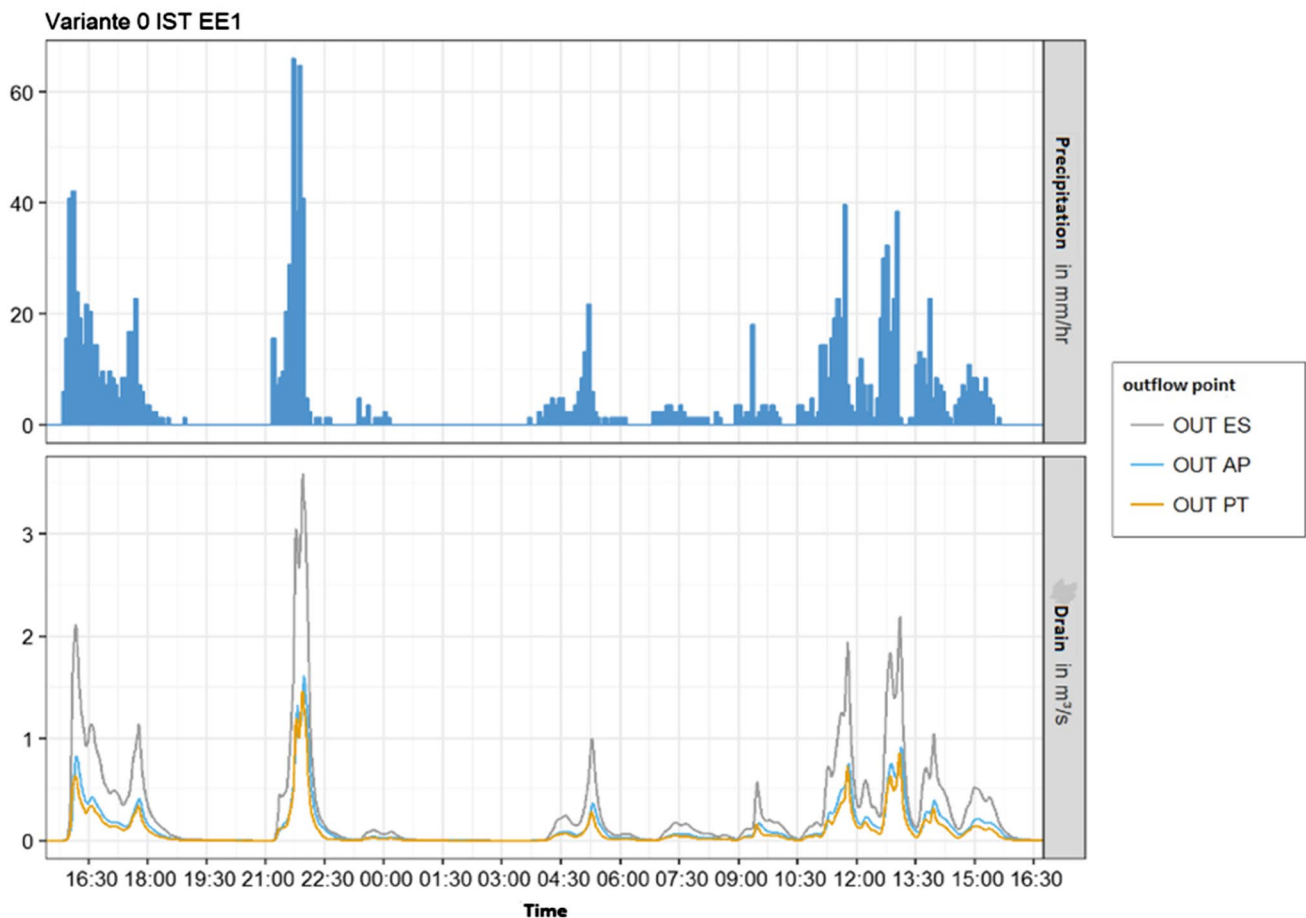
In this section, some hydrologically interesting individual events are considered in more detail.

##### 4.4.1 Individual event 1

Single event 1 is for the period of the existing precipitation data (1996 to 2006), the event with the greatest amount of precipitation, at the length of time from in approximately 24 h 124 mm precipitation attack. Figure 8 illustrates the precipitation profile of EE<sub>1</sub> point to the highest event intensity with > 60 mm/h at 10:00 p.m. Model discharges of the outlets are also plotted. Generally, one significantly greater load on the outlet OUT ES can be seen at the time of highest precipitation intensity with > 3 m<sup>3</sup>/s relieved. For the results of the EE<sub>1</sub> to be presented as clearly as possible, find different diagrams and a concluding list of results applied in tabular form. Figures 6, 7, 8, 9, 10 shows the evaluation results in a reduction in drain volume at EE<sub>1</sub>. The determined reductions of the drain spikes at EE<sub>1</sub> shown in Fig. 8 can be removed. The simulation results show a summary for the reference scenario 0 IS EE1 at OUT ES, OUT PT and OUT AP an outflow volume of 26,300 m<sup>3</sup>, 8240 m<sup>3</sup> and 11,100 m<sup>3</sup> respectively and thus a total discharge volume of the CA of 45,665 m<sup>3</sup>. Thereby peak discharges from 3.59; 1.49 or 1.59 m<sup>3</sup>/s and 6.49 m<sup>3</sup>/s  $R_f$  shows for EE<sub>1</sub>.

Across all scenarios and catchment areas, V<sub>3</sub> and V<sub>4</sub> shows the significantly smallest reductions. For the ES catchment area, V<sub>1</sub>, V<sub>2</sub>, V<sub>8</sub>, good results are achieved, while V<sub>3</sub> and V<sub>4</sub> shows a slight reduction. Similar OUTIT shows also OUT PT low effectiveness on the variant V<sub>3</sub> and V<sub>4</sub> while V<sub>7</sub> and V<sub>8</sub> show higher Values. At OUT AP show itself until on V<sub>7</sub> something better results as at OUT IT and PT. The variants V<sub>3</sub> and V<sub>4</sub> also show very low values. The total highest values ( $R_f$ ) become with ~ 10 at OUT PT in the trains the variant V<sub>7</sub> reached.





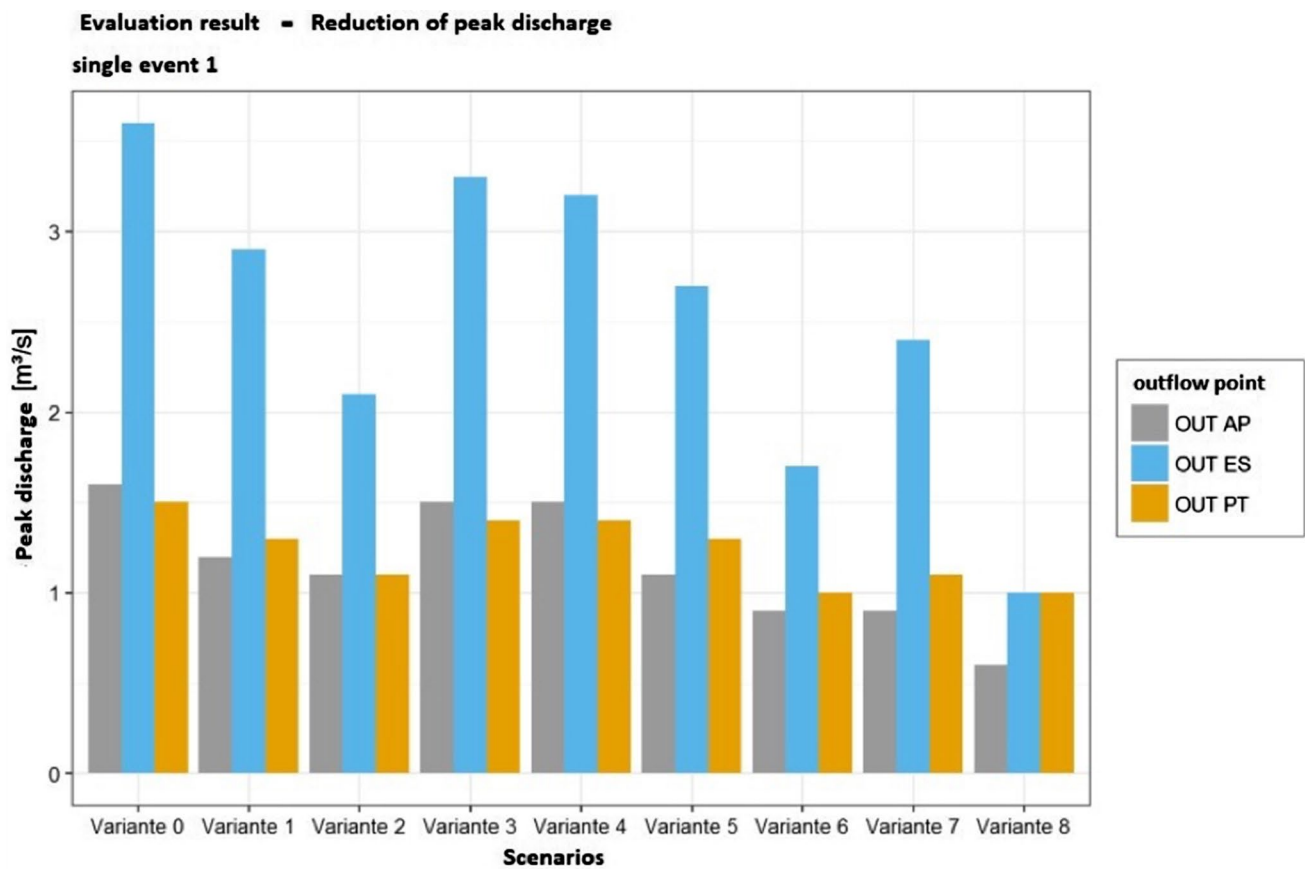
**Fig. 8** Precipitation-runoff behavior of the model (variant 0 IST EE<sub>1</sub>). Blue line graph shows the precipitation in mm/h for a period of 1 day and observe peaks during the mid day. Gray Line graph shows the drain in m<sup>3</sup>/s for a period of 1 day and observe peaks during the mid day

#### 4.4.2 Single event 25

The individual event 25 is for the period of the existing precipitation data (1996 to 2006), the event with the 25th greatest amount of precipitation. Figure 10 illustrates the precipitation profile of EE<sub>25</sub> points, the highest event intensity with >40 mm/h around 19:20 Clock. Included is one stronger burden of outlet OUT PT to recognize (Variant 0) at the time of the highest precipitation intensity > 2.0 m<sup>3</sup>/s relieved. The reference variant (0 IS) shows itself at the comparison of results on single event simulation to the long-term simulation for the CA PT deviation in the drain volume of 0.5% and the discharge peak of 1.95%. With CA PT or CA AP are 0.29% and 0.49% deviation in volume and 3.1% and 0.4%, respectively, the discrepancy is visible at the top.

Figure 11 compares the area discharges of variants 1 and 2 Permeable Pavement System (PPS) to the reference variant V<sub>0</sub>. At OUT ES, it can have a slightly better effect on the measures observed than at OUT PT and AP. Figure 12 illustrates the influence of the model on implementing green roof systems at the precipitation event EE<sub>25</sub>, which seems far less than based on PPS, whereby the greatest reductions can still be achieved with OUT ES.

Figure 13 shows the effect of combinations of variants 5 and 6 measures, whereby OUT IT through V<sub>6</sub> one strength damping having. The Application from V<sub>8</sub>th can result in significant discharge reductions at the outlets OUT ES and AP to be determined.



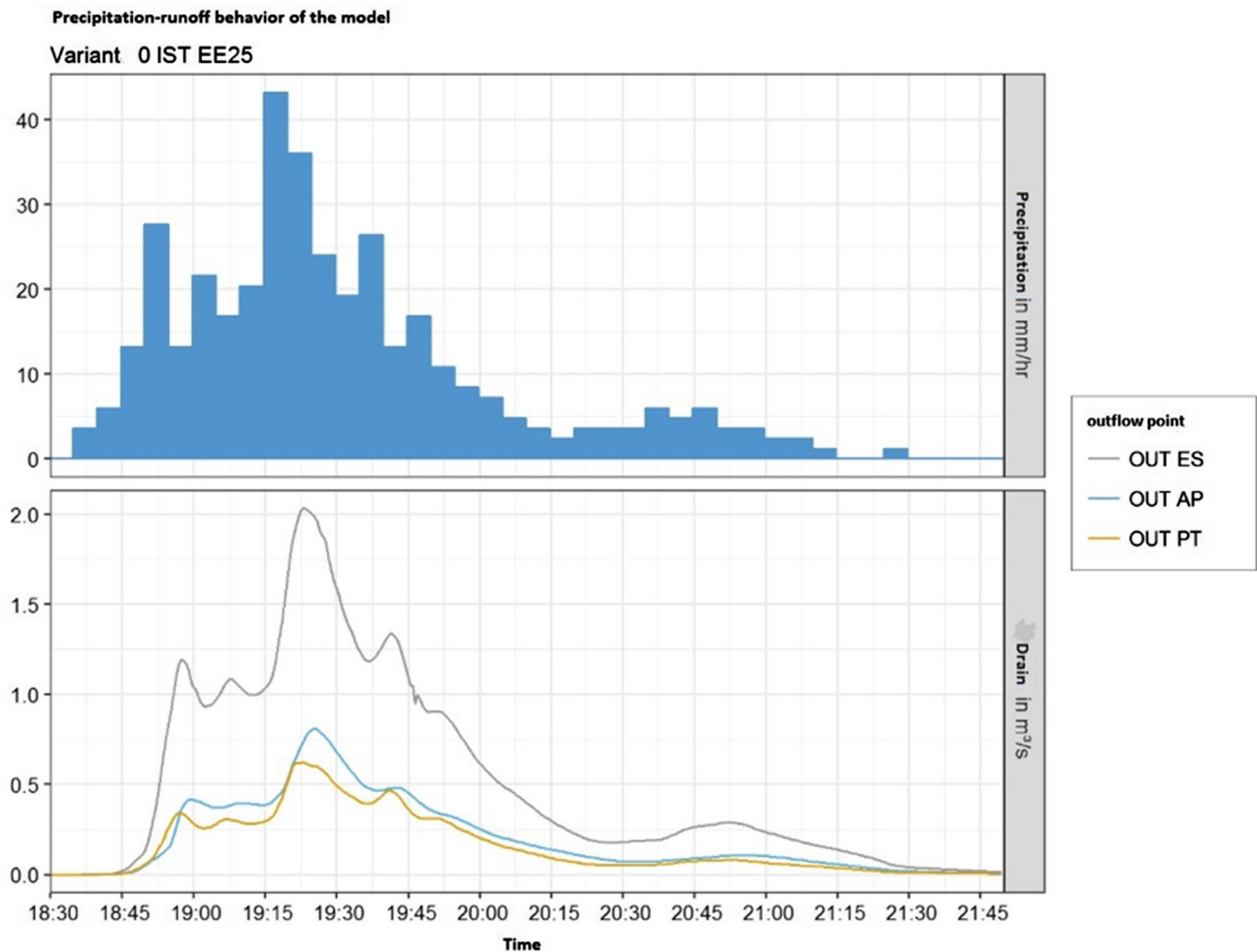
**Fig. 9** Result of the evaluation regarding the reduction of peak discharge in EPA for single event 1. Bar graph shows the peak discharge for various variants over single event. OUT ES gives the larger values over all variants

## 5 Summary and conclusions

### 5.1 Summary

Due to the advancing urbanization, urban areas have increased surface sealing. In the course of precipitation, events can. Therefore, no natural hydrogeological exchange processes (e.g. infiltration, evapotranspiration) take place, which becomes necessary in urban areas for various precipitation management measures (e.g. drainage) to foresee. Through surface sealing and channelled drainage of precipitation, runoff occurs in the receiving body of water regarding water management and ecological disadvantages, such as the intensification of flood discharges, increased pollutant inputs and the reduction of groundwater recharge. Because of the engagement, however, infiltration, evapotranspiration and surface retention from rainwater increased, by which the rainwater coming out of the drainage system reduced and somewhat defused the general drainage problem.

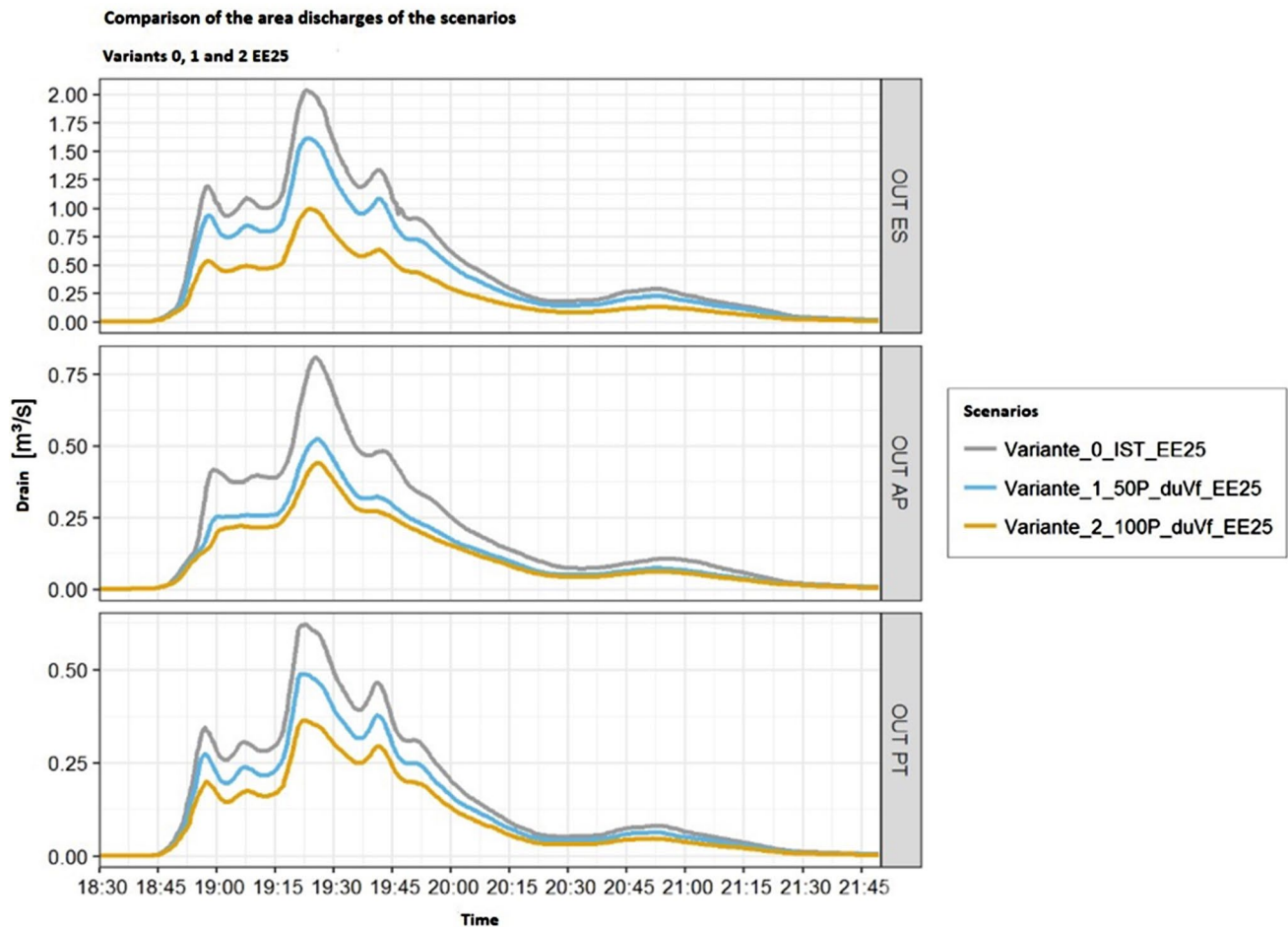
The application of near-natural RWM measures has a positive influence on the precipitation-runoff behaviour together with the reduction of quantitative runoff parameters (discharge volume and -top) is achieved. The surface could be sealed for the EPA in the elevation, with approx. 37% Asphalt-, around 21% Roof-and 2% paved areas, from around 60% established. The remaining territory area puts itself out of approx. 27% green space, around 12% gravel areas and 1% surfaces together. The hydrological analysis shows one apportionment that the EPA is divided into three main catchment areas, the Eggenberger CA being the largest in terms of area, Strasse and the catchment areas Alte Poststrasse and Peter-Tunner-Gasse.



**Fig. 10** Precipitation-runoff behaviour of the model (variant 0 IST EE<sub>25</sub>). The Blue Bar graph shows the precipitation in mm/h and observes peaks at the mean value. The Gray Line graph shows the drain in m<sup>3</sup>/s and observes peaks at the mean

The evaluation did not include smaller partial areas in the east drain towards the railway line. The investigation of the effectiveness of the applied RWM measures in reducing quantitative runoff parameters was calculated using a dynamic precipitation-runoff simulation model (SWMM). Outgoing from the present area state to improve the runoff situation in the project area and to show possible design variants with high potential, several RWM measure variants were designed.

In summary, in the model simulation, using storage wells, one height measure effectiveness at low construction costs could be achieved and thus shows a high level of profitability. A major disadvantage of storage troughs is the availability of space; see that troughs should measure around 10 to 20% of the area to be drained. In the urban area, at degrees of sealing beyond 75%, there are barely public open spaces for the erection of storage wells. PPS and green roofs point to the absence of infiltration or retention components compared to the application from storage wells. However, it is less effective and suits itself, particularly for the mission in the urban space. It should be pointed out here that there are seepage effects in the case of storage hollows and PPS in the supreme soil layers, which consequently come in the groundwater; therefore, the requirements of RWM must be fulfilled. One seepage in contaminated floor material can happen around the Smart City. One concrete implementation from RWM measures should be planned for this area because of suspicion of contamination.

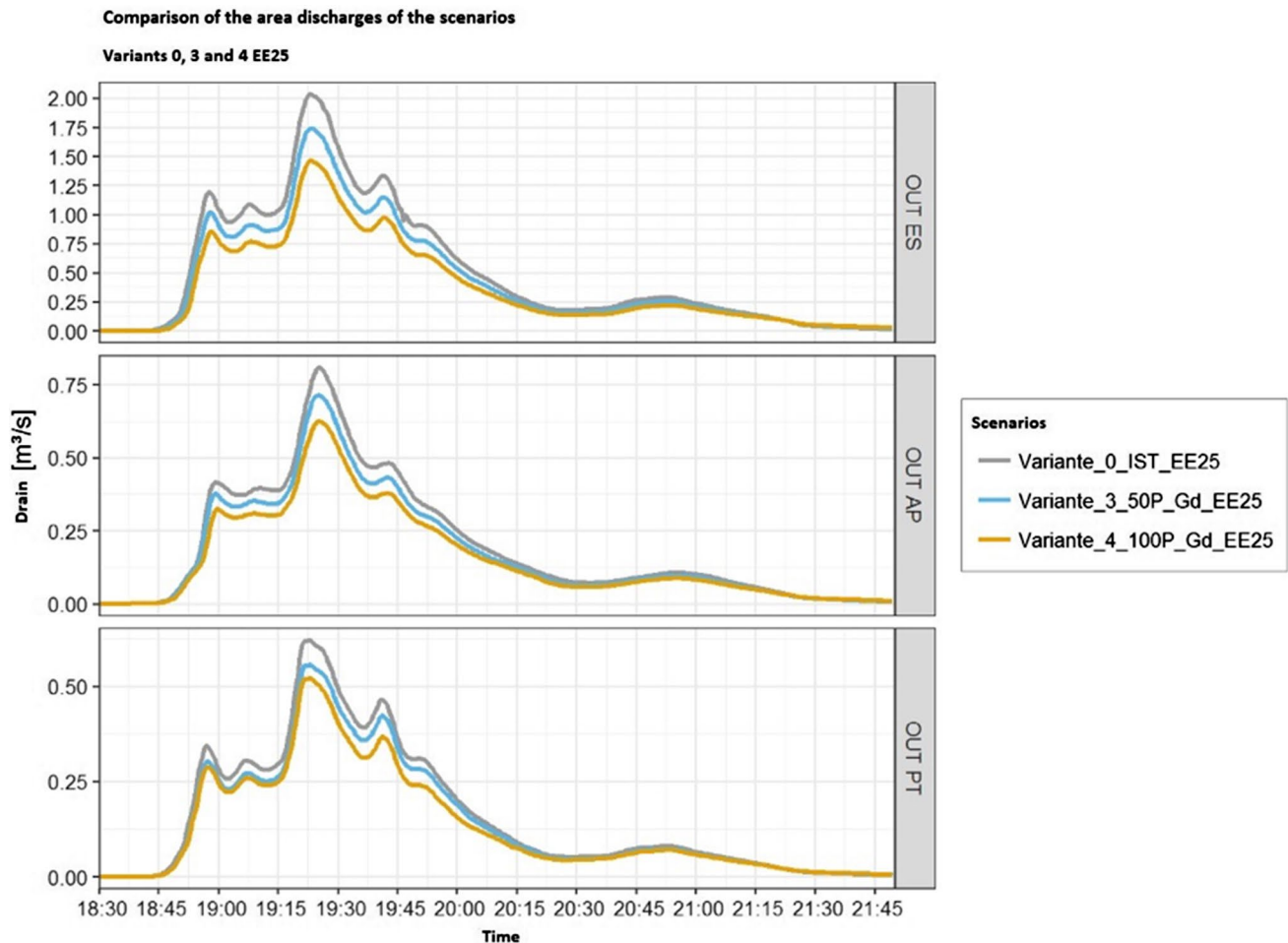


**Fig. 11** Discharge hydrographs of the outlets of variants 0, 1 and 2 EE<sub>25</sub>. Gray, Blue and Orange line graphs show the drain in m<sup>3</sup>/s for 0, 1 and 2 variants and observe peaks at the mean

## 5.2 Conclusions

The research shows a high degree of sealing at around 60%, with areas around the Laudongasse. RWM measures for the application in several areas due to insufficient public open spaces are hardly an option. Permeable traffic areas show a good effect with different precipitation characteristics; however, there is one decreasing visible effect at higher intensities since PPS has no above-ground retention space. The existing pore stores are damaged by the infiltration filled by evaporation; stored water can also return to the environment. In addition to the quantitative runoff reduction, according to several literature sources, a qualitative is also possible through PPS improvement of the drain. In the case of green roof systems, there are better ones due to their structure and function. Results at precipitation events have lesser intensity or smaller recognizable levels of precipitation. Especially in heavy rain events, however, it can come to reaching the retention maximum, where the measure protected becomes against hydraulic overload by an emergency overflow. This measure can come to no infiltration, omitted particularly at short-term considerations, more importantly, the runoff reduction, which is noticeable by slightly lower effectiveness. However, evapotranspiration effects can take place unhindered and over a large area application with it to improve urban climates.

In the case of storage troughs, there is a retention of the recorded runoff, aside from infiltration and evapotranspiration effects. The expected measure of effectiveness is included primarily from the chosen impoundment depth and the

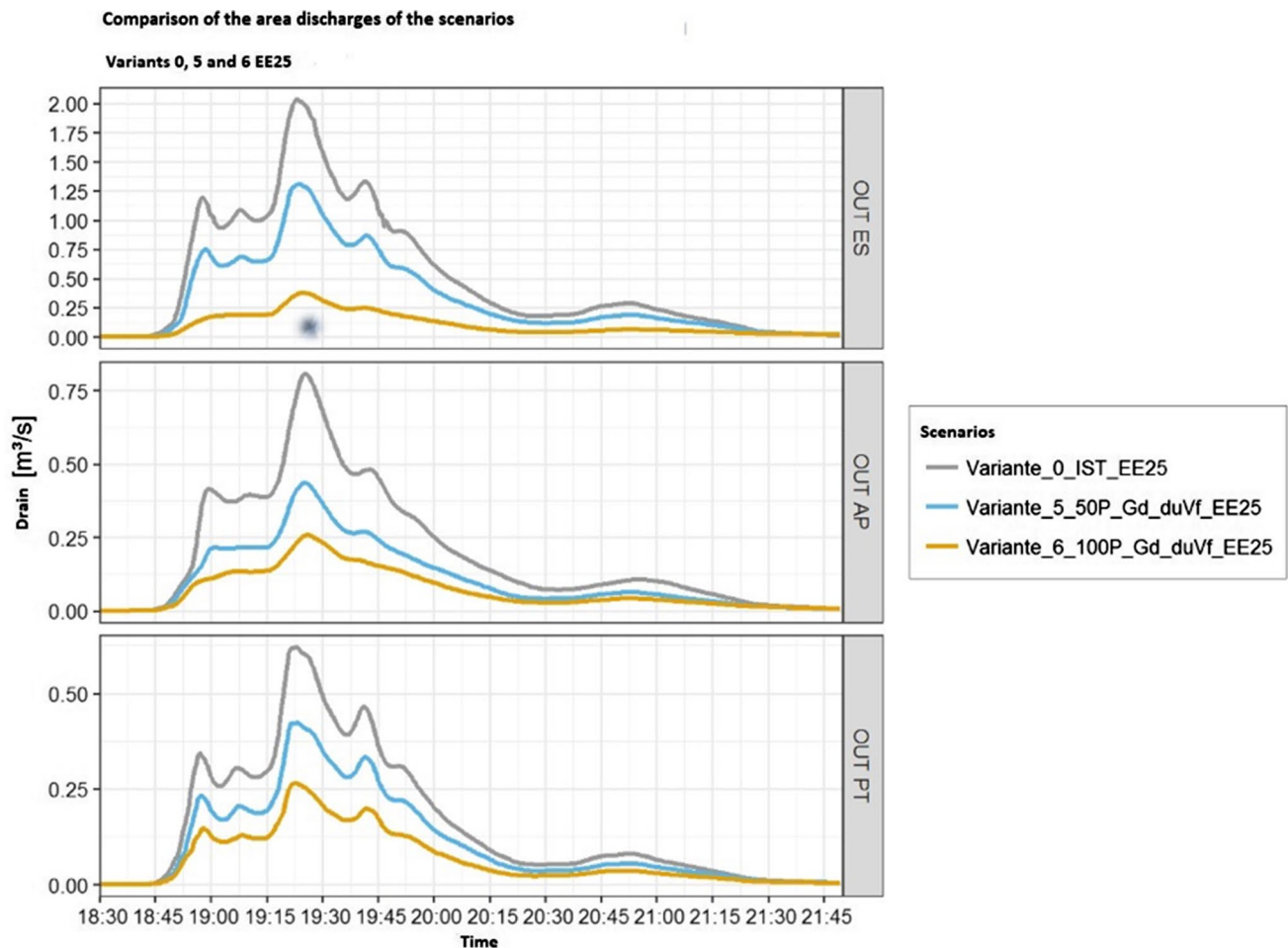


**Fig. 12** Discharge hydrographs of the outlets of variants 0, 3 and 4 EE<sub>25</sub>. Gray, Blue and Orange line graphs show the drain in m<sup>3</sup>/s for 0, 3 and 4 variants and observe peaks at the mean

existing soil permeability. The measure can be switched between sealed surfaces and the drainage system to prevent direct runoff effectiveness. Look at the overgrown case of storage troughs, and the topsoil passage should also be a qualitative improvement in drainage. The application of this measure depends not only on legal requirements but also on the availability of public open spaces despite the relatively few constructions.

Such a thing was carried out and shown in a highly simplified form for the surface parameters. There is a fluctuation range of up to a maximum of 14%, but ideally, it should be much larger to be applied in more detail. In addition to analyzing the surface parameters. The sensitivity of the RWM measure parameters or the hydraulic technical parameters of the drainage system can be examined. Besides that, with more concrete implementation plans, a more detailed economic assessment of the effectiveness of the RWM measures. In addition to the analysis and a comparison of several cost approaches from the literature, costs could also come directly from executing companies or manufacturers (post-calculation collation of production). Ideally, a specific price variability depending on the size of the areas of work carried out be averaged. The variant measures developed in this research work and the identified. The results can, therefore, serve as a reference point for further investigations.

In summary, it should be noted that in the model simulation, using a set of storage troughs ensures high measure effectiveness with low construction costs. Maintenance costs could be achieved, and thus, a high level of economic efficiency is shown. The major disadvantage of storage troughs is the availability of space, as troughs should measure around 10 to 20% of the area to be drained. In urban areas, with sealing levels beyond 75%, only a few public open spaces are



**Fig. 13** Discharge hydrographs of the outlets of variants 0, 5 and 6 EE<sub>25</sub>. Gray, Blue and Orange line graphs show the drain in m<sup>3</sup>/s for 0, 5 and 6 variants and observe peaks at the mean

available for the construction of storage troughs. Due to the lack of infiltration or retention components, green roofs have been compared to the use of storage troughs. This is somewhat lower effectiveness, but they are particularly suitable for use in urban areas. For these reasons, a combination of permeable traffic areas, green roof systems, and storage troughs is used for the Waagner-Biro project area, together with other RWM measures to reduce the urban runoff problem.

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**Data availability** The original contributions presented in the study are presented in the paper. Further inquiries can be directed to the corresponding authors.

## Declarations

**Competing interests** The author declares no conflict of interest.

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